A UNIFIED FRAMEWORK FOR SPACECRAFT OPERATIONS

By

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Abstract

This work analyses the current state of the art in the Spacecraft Operations domain. It reviews the structure and practices within the European space industry and shows how the industry is generally shaped by national or international non-governmental organisations. Although it draws most material from the author's experience in Europe whilst working on commercial space projects and international scientific projects, it compares and contrasts this with the US manned space programme and the Russian space programme.

The space industry in Europe has inefficient working practices and a poor market structure which lacks incentives. The civil service-based organisations that administer the majority of national and European space activity have a poor internal organisation, are often slow to react, exhibit little delegation and reduce individual initiative. Recommendations are made about industrial policy, and how organisations should approach risk management and how teams should be formed and should interact.

The spacecraft and instruments are normally built by specialised teams and organisations. This results in a conceptual gap between those who acquire knowledge whilst building and testing the systems and those who will operate the system. It is necessary to explicitly transfer the knowledge to the operations team, and there are weak mechanisms for doing so. At the same time, the operations team also has to prepare the ground segment to control a spacecraft and exploit a payload that, from their point of view, may be poorly defined.

It is proposed that the traditional paper-based products (user manual and flight procedures) could be usefully supplemented or replaced by a knowledge base. An ontology to define a vocabulary is developed and it is shown to facilitate knowledge capture and exploration. The availability of such a facility would then also assist

future missions (or even missions running in parallel) to understand the problems that their colleagues have, and adapt or incorporate the solution if it was applicable.

There is a significant trend for spacecraft to become more complex and to have many computers and a great deal of software on-board. This make the system difficult to operate, and can also lead to unexpected results, since the state space of a software-driven system is so large. For terrestrial systems, formal methods have been developed to try to counteract the trend: by proving certain behaviour in the specification, the number of paths that need to be tested can be significantly pruned. It is proposed here that formal methods could be adopted to test and communicate knowledge, as well as to improve the design.

The trend to have increasingly intelligent sub-systems has been occurred in parallel to the trend to have increasingly sophisticated data communication. This is applicable equally to command and monitoring. The information content of parameters is analysed, and the content of flags and simple packets is calculated.

Acknowledgements

I would like to thank Tom Bowling, my supervisor, for his many suggestions and patient support during this rather long research.

Of course, I am grateful to my parents for their patience and *love*. Without them this work would never have come into existence (literally). Without my wife, Tatiana, this would not have been worth doing.

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Glossary

ASW	Address and Synchronisation Word
BCH	Bose Chaudhuri Hocquenghem
CCSDS	Consultative Committee for Space Data System
CFE	Customer Furnished Equipment
CFI	Customer Furnished Item
CLTU	Command Link Transmission Unit
CRP	Contingency Recovery Procedure
DBMS	Database Management System
ESA	European Space Agency
ESOC	European Space Operations Centre (part of ESA)
FCP	Flight Control Procedure
FMECA	Failure Modes, Effects and Criticality Analysis
FOP	Flight Operations Procedures
LEOP	Launch and Early Orbit Phase
MSSS	Multi Satellite Support System
OCC	Operations Control Centre
OSI	Open System Interconnection
PCM	Pulse Coded Modulation
PCM standard	ESA Standard for telemetry and telecommands (superseded)
SCOS	Spacecraft Control and Operations System
SQL	Structured Query Language
TC	Telecommand
TM	Telemetry

Chapter 1

Introduction

'The unexamined life is not worth living.'

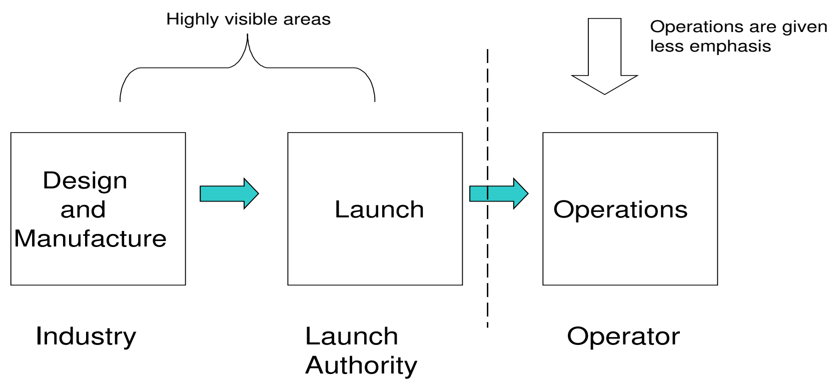
Socrates (469 - 399 B.C.)

This work relates the current state of the art in the Spacecraft Operations industry. It is based on the author's experience on commercial space projects, international scientific projects and manned space projects.

1.1 Background

The author's experience after more than 15 years in the space industry is that space projects are usually last a long time and have a lot of people working on them. Even though the recent experience indicates that rather more consideration is given to designing spacecraft that can be operated easily than used to be the case, the author identifies a number of factors that tend to make the spacecraft operations difficult:-

- Launch-centric view of the space-project.
- Fluctuating participation in development life-cycle leads to a lack of continuity in people and knowledge across the project.
- People perform different roles, have different viewpoints and use a different vocabulary at various stages in the development. This leads to a perception



The most visible aspect of a space mission is the launch. Some people are also aware that engineering goes into the design, integration and test of a spacecraft, but historically the importance of operations have been neglected.

Figure 1.1: Classical View of Spacecraft Engineering

gap, a difference between the logical understanding of different people who are really talking about different parts of the same whole.

- Structural and organisational problems lead to a lack of knowledge sharing across the project.

1.1.1 Launch-centric view of space projects

Many people seem to consider that the most difficult part of the project is when the spacecraft is designed, built, integrated, tested and launched. Some people actually consider that this is the whole project and that what comes after the launch is almost unconnected with what happens before the launch. However, this viewpoint is inconsistent with the actual purpose of the spacecraft: usually to gather data or to perform some other service or task. After launch, the industrial team that built the satellite starts to run-down, with the more experienced people usually being the first to leave a project, since they are most in demand else-where. Within the author's experience,it is even known for the management team to change or run-down before the spacecraft is launched, long before it can reveal any scientific results or enter into service, and so before it is revealed whether the decisions that were taken during the development were correct. This is a clear indicator that the operations phase is not given a very high priority.

This launch-centric view is shown in Figure 1.1. This can be highly imbalanced, since the whole reason for building and launching the spacecraft was to perform a purpose and return some results, but also the post-launch phase is usually at least as long as the pre-launch phase. It is also worth noting that the tasks of building, launching and operating the satellite are very often performed by different teams. This is true for most American missions (commercial or military), Russian missions (still mostly military or defence-oriented) and European missions.

Most of the remaining factors are linked to reducing the knowledge transfer either from one project to another or through time on the same project.

1.1.2 Fluctuating Participation Throughout Project Life-Cycle

The people who design the satellite systems are usually different from the people who build and integrate it, and in turn it is frequently the case that yet another a different group operates the satellite. This is virtually always the case in missions operated by the European Space Agency, ESA, where there is usually also a separate ESA team managing the procurement of the satellite (and payload).

After the launch, the industrial team that assembled the spacecraft disbands and the management team is assigned to another project. During the duration of the procurement, technology continued advancing and so it is rare for a completely new project to use the same kind of technology as a previous project. Whilst a particular technology (e.g. microprocessors with the mil-std-1750 instruction set) is used on a number of different project in parallel, different projects apply it in different ways and so build up different sets of experience. Unfortunately, the lifetime of a project is often comparable to the lifetime of the technology, so very few people get to use the same technology again. However, they have gained a particular experience and overcome certain problems, and so on their next project, there may be a tendency to carry out a strategy to mitigate against problems with a previous technology that may never occur with the new technology.

1.1.3 Different Roles Have Different Viewpoints and Vocabulary

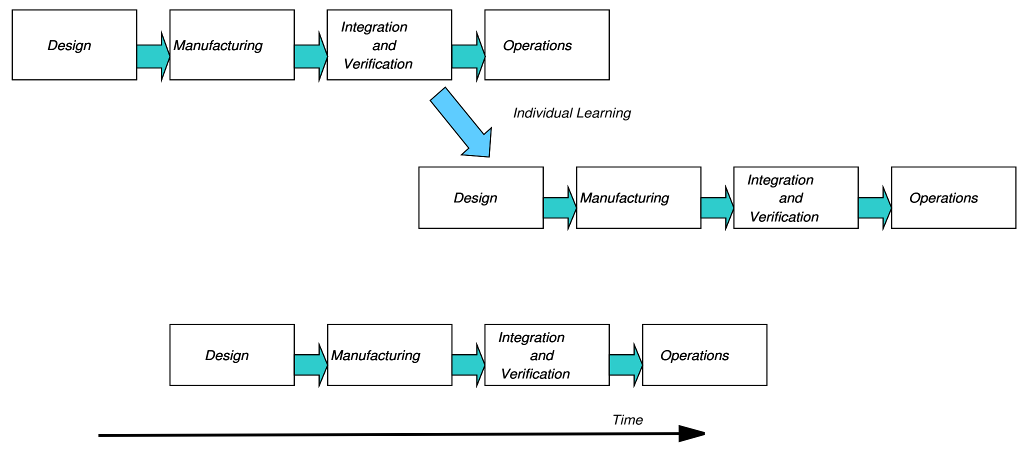
Another factor that seems to have become a problem is that people and jobs have become increasingly more specialised. This leads them to take a particular view of the spacecraft and can easily lead to the situation where different specialists cannot understand each other's points of view. The partial antidote to this situation is the systems engineer, who is supposed to be able to take an overview of all of the areas and have a high-level understanding of the main problems in each domain. Specialists also tend to develop their own vocabulary and jargon, which although it might make it easier for them to do their job, also acts as a barrier to communication across disciplines.

A further complication is that all of these points of view need to be explained to the operations team. The operations team normally has least insight into the details of the spacecraft, often never actually seeing the real flight hardware and having to build up a knowledge base from formal documentation and information transfer. The operations team normally starts out quite small, and then slowly increases in size as launch approaches. Their initial vague ideas slowly materialise with time as the actual hardware is manufactured and assembled, and as they get more contact with the documentation and perhaps even with with the satellite. However,they can never reach the same level of knowledge and understanding as a specialist who designed the spacecraft system. It may be more, or it may be less, but it is never the same. This process leaves a perception gap, a difference between the logical understanding of different people who are really talking about different parts of the same thing. The various specialists may not fully understand each others problems, and the operations team may not understand every facet of how the spacecraft works.

1.1.4 Structural and Organisational Problems

Many projects use equipment that is more or less standard, and then introduce some modification to it to tailor it to the specific mission, often including renaming the unit.This makes it more difficult for other people see the heritage of a particular unit, and thus makes it very difficult for people who work on one project to learn from other projects. If a third mission comes along, it is unclear if the technology is appropriate.

Another way in which the long project durations block knowledge transfer is because it results in de-skilling. If people stay attached to one generation of technology, since technology progresses continually, this means falling behind the current technology, giving reduced innovation and an overall loss of technical skills. The fact that people tend to stay on one project means that they can build up considerable knowledge and experience on that one project. The question is, who does this benefit? The only opportunity to transfer information is at the end of the project, when people are redeployed from one project to another. Figure 1.2 shows the problem. This transfer is ineffective, since it relies on vacancies in new projects becoming available at the same time as other projects are ending, and also as mentioned before, the technology base will have changed. Furthermore, if the development and



Knowledge transfer that relies on individuals from the development team moving from one project to another has several disadvantages:- (i) it does not include the final evaluation of the design in operations; (ii) it is very slow, since it can take place after the development is completed; (iii) it does not benefit projects that run in parallel, which are most likely to be using similar technology.

Figure 1.2: Knowledge Transfer Between Projects By Individuals

operations teams are separate, then the developers will not have any real-world feedback on how their design performed and whether or not their decisions on the design and implementation were correct.

1.2 Increasing Knowledge Transfer

This thesis proposes several ways to improve the knowledge transfer within the contemporary industrial situation and organisational frameworks that exist in the European space industry. It is shown that the current organisations are often not ideally suited to their responsibilities and functions, but this is accepted as a constraint. Trying to change the current political and industrial situation is regarded as out of scope.

The author identifies that in his experience, many projects have failed to learn from each other. There are many reasons why this is so, but some of the main reasons are:

- Poor allocation of manpower
- Inability to share knowledge within a project
- Inability to share knowledge across projects

1.2.1 Manpower Allocation

Since projects run over such long periods of time, it is too expensive to have the specialists available all the time and difficult to allocate the specialists when they are needed. The industrial consortia that manufacture satellites have an incentive to use their staff with good reputations to bring in new work, and then to try to get the work done as cheaply as possible. This usually means that most of the work is performed by people with much less experience.

At the same time, in the operations field, the peak in the manpower demand usually occurs during the launch and entry into service. This means that the operations team usually starts off small, and then gradually increases until launch, and then slowly decreases. It is the author's personal experience that many organisations try to absorb this temporary increase in staff by using external consultants. This can mean that the consultants get to work in launch preparation and the Launch and Early Orbit phase (LEOP) and then they are no longer required and they usually leave to work on another project.

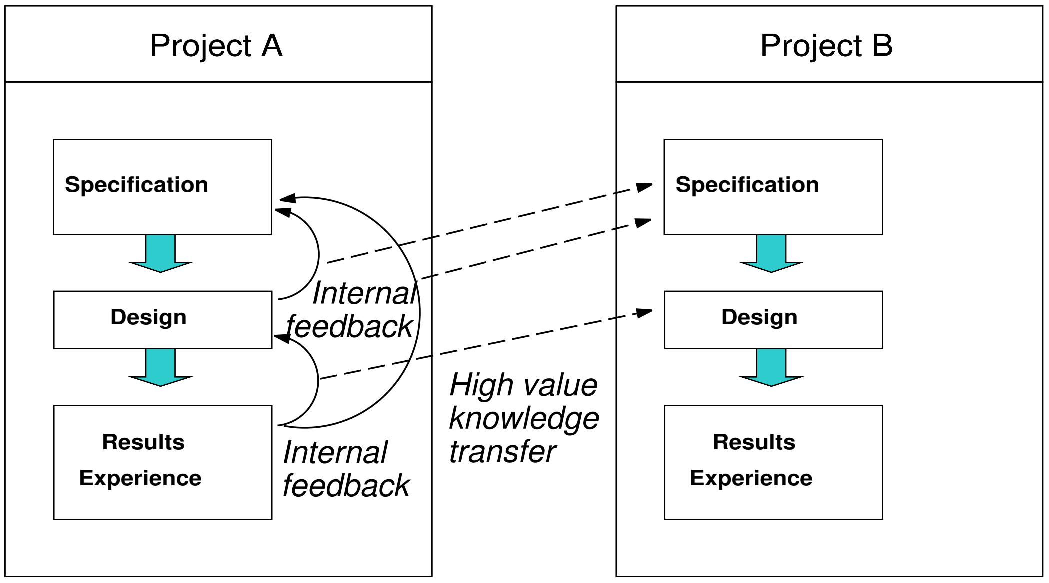
However, it is precisely during the LEOP when there is most opportunity for learning and for judging whether or not the design decisions that shaped the spacecraft and ground segment design were correct. The consultants then join another project as it builds up its manpower profile, and often have to live with the same mistakes as were discovered in the project that they had just left, or discover that the new project has implemented a completely new and different solution to an issue that was also addressed on the previous project. This can lead to the situation where a lot of the knowledge that is transferred from one project to another is only transferred via temporary workers, and most knowledge gained from the critical project phases is actually stored outside the organisation. This leads the organisation to become very dependent upon external companies and people.

1.2.2 Knowledge Sharing Within a Project

The author has known many projects where there was no overall spacecraft database of telemetry and telecommands. Often there were several, overlapping databases, where some of the data was stored, but there was initially no single configuration-controlled place where all teams could refer to for telemetry and telecommands. This is so fundamental to information sharing that most operations centres known to the author have realised that this is a problem and try to insist that there is a project-wide database. The European Space Agency ESA is proposing a standard format within the framework of the Consultative Committee for Space Data Systems, CCSDS. However, sometimes there can still be a problem with inherited systems. For example, on projects with a long duration or with multiple generations of spacecraft, the operations team might have an old control system (along with an old database format) and then the manufacturer or one of the payload providers might offer a spacecraft database that is incompatible with the existing system in some respect (e.g. identifier length or content). This can result in the operations team using a different set of identifiers from the design or integration teams, which results in much more work for everybody, as well as a clear loss in transparency.

1.2.3 Knowledge Sharing Across Projects

It can be very difficult for one project to learn from another project. The author's experience indicates that unfortunately this is as applicable to projects running in parallel as it is to projects running in series. Currently much re-use takes place either by re-using the technology 'as-is', or by re-using the specification as it was at the



Projects start of with a specification and then a design is conceived to satisfy the specification. This may generate some internal feedback which may (or not) result in an updated specification or the decision to use ”as-is”. The design is then put into service operationally which generates experience. This will generate feedback into either the design or perhaps even the specification. This feedback is valuable to any other project, since it shows what went wrong and what the team had to change (or would have changed if it had been able to). This prevents mistakes being repeated.

Figure 1.3: Critical Knowledge Transfer Between Projects

beginning of the project. This means that it is very difficult for a project to benefit from the actual experience that has been gained by another project. What would be really useful to follow-on projects would be to know the changes that the earlier project had to make during the design, why such changes were necessary, and what they would try to do differently if they had the opportunity (see Figure 1.3. For them, it is hindsight, but for the upcoming project, it is foresight! Unfortunately, it can be a non-trivial amount of work to perform such a review,and the old project has no immediate benefit and so no strong incentive to perform it.

1.3 Structure of this Thesis

Chapter 1 is this introduction to the thesis. Chapter 2 introduces the Space Business, and outlines some of the problems that can occur during a space project. It explains why the people who operate a spacecraft are rarely the people who built it.

Organisations are one of structures which provide the context for the spacecraft operations. Typically spacecraft operations are performed in teams within substantial organisations. Chapter 3 discusses the roles of the individual members of the team, the actors who perform these roles, and takes a critical look at some of the organisations in which these people perform their roles.

Risk is present in every kind of business or activity. Chapter 4 discusses the nature of risk, how it can occur in space programmes and methods used to manage the risk inherent in space exploitation. It shows that humans are often very poor judges of probability and of the risk that ensues. This is also a new application of existing methods.

Chapter 5 shows how many organisations prepare for the launch or entry into service of their satellites. It also looks at how the valuable knowledge gained during design, manufacture and testing of the satellite is transferred to the people who actually do the operations of the satellite when it is in orbit.

Computer systems are used to control the satellites and payloads before and after launch. In Chapter 6, the two systems are compared, found to have much in common, and it is proposed that cost-savings could be made via a common, or harmonised, development. This idea probably even pre-dates the author's entry into the space industry, but it is still a very topical question, since almost no projects have made use of the commonality approach. The author is working on a European scientific project to try to implement this strategy and realise the cost-savings.

Chapter 7 illustrates how the vocabulary used varies from one mission to another, and how this can be a barrier to prevent the benefits of experience being passed around. This introduces the concept of an ontology to manage the knowledge, which is a novel application of a technique well-known in the circles of artificial intelligence.

Formal Methods are introduced in Chapter 8 as one possible solution to the problem of transferring knowledge across time and place as is required on modern space missions. Formal methods are techniques which have been used for many years in the fields of software specification and high-reliability computing, and this Chapter adopts one particular method to show the benefit of a precise specification.

Complexity is one of the factors against which operations engineers must struggle throughout the project, both before and after launch. In Chapter 9 the author discuses the sources of complexity, and strategies for reducing the rate at which complexity makes itself felt. This is an innovative look at the problems associated with remote command and control.

Satellites are controlled and monitored in-orbit by a ground system via radio signals. Chapter 10 gives a brief introduction to the systems that are used in western Europe for this purpose and shows how they transfer information from the space segment to the ground segment. This is a fairly standard introduction to current practice.

In Chapter 11 the Shannon Information of a fixed format telemetry system is calculated and compared with a packet system, and an event-driven packet system. It is shown that the information scales much better with packet-based systems. This is an original result which is the sole work of the author.

Chapter 12 discusses the results of all the Chapters and brings together the individual threads of each Chapter. Chapter 13 presents a summary, a shortened discussion and recommendations for further work.

Chapter 2

Space Projects

2.1 Introduction

This Chapter gives a high-level overview of the space business. Section 2.2 looks at how the industry is structured in Europe and why the people who operate satellites and space systems are rarely the people who design and build the satellites and payloads.

The following section, Section 2.3, shows who participates in the spacecraft life-cycle, how the participation varies from one phase to another, and why this can be a problem.

Section 2.4 discusses mission operations. It proposes an 'Operations Model' by comparison with several protocol models that have been developed in industry. Using this, it is possible to see which areas are already covered international standards and which areas are left for individual missions to design and implement themselves. Sections 2.5 and 2.6 look at commonality in the mission operations concept across different missions, and then at the differences.

Section 2.7 concentrates on Europe and looks at how the industry operates in a distorted market place and some of the conflicts and inefficiencies that can result.

2.2 The Space Business

Many missions fly for many years (e.g. ten years is almost the minimum for a telecommunications satellite, with consumables such as fuel often sized for many more years). Before launch they all have a test and integration phase that lasts several years. Often the design of the sub-systems is started much earlier, and it is not unknown for negotiations prior to the start of design work to last more than one year. When Cluster 1 was destroyed in an explosion shortly after launch on the first Ariane 5 flight, V501, some experimenters had already been working on the project for fifteen years.

Historically, most of the companies and organisations that build spacecraft have been hardware-oriented, and have had little experience or desire to participate in the development of software systems or to participate in mission operations.

Within both ESA-driven missions and commercial procurements, the activities associated with mission operations and those with design, integration and test have been separated almost from the very start of a satellite procurement. This division of the procurement into separate satellite engineering and operations activities can be the source of many problems, inefficiencies and duplication of effort. For example, the prime contractor needs to develop and maintain a system for testing the performance during spacecraft integration and launch site activities. At the same time, the operations team needs to produce a control system that will be used to operate the satellite and payload after launch. As a consequence, the operations team has only a few opportunities to test the control system with the real hardware before launch, and so it is often necessary to produce a software simulator of the satellite and instruments to test the control system and train the flight control team. This division can also lead to the situation where the project management views the operations preparation as being somehow less important than the satellite integration activities.

However, this separation is likely to continue, because it sometimes make sense! In a similar way to the aviation industry, the manufacturers specialise in the manufacture of the flight hardware, but do not expect to operate it, although there are evidence of a trend for them to become involved more actively in the maintenance activities. Even though it might not be the theoretical optimum, industry must continue from where it actually is, not where it should be. Most organisations that want to operate satellites are already operating satellites built by various manufacturers, and so already have considerable 'sunk costs' in the investment in people and control systems, and so they do not want to (or cannot reasonably) change to a whole new control system every time they take a satellite from a new manufacturer, and nor do they wish to become chained to a single manufacturer. This means that they either have to adapt their existing infrastructure to the new satellite, or specify modifications to the satellite so that it suits their infrastructure.

2.3 Space Project Life Cycle: Who, What and When

This section includes a description of the life cycle of a space project, the types of resources that must be monitored and controlled for a mission and the types of users (referred to as agents) that monitoring and control the activities of the resources.

The prime contractor, sub-system manufacturers or instrument teams use a checkout system (usually referred to as the Central Checkout System, CCS) during the following phases of the project life cycle:

1. Development and test of individual units
2. Integration and test of subsystems at system level
3. Integration and test of payload at system level
4. Test of the fully integrated spacecraft as a complete mission system

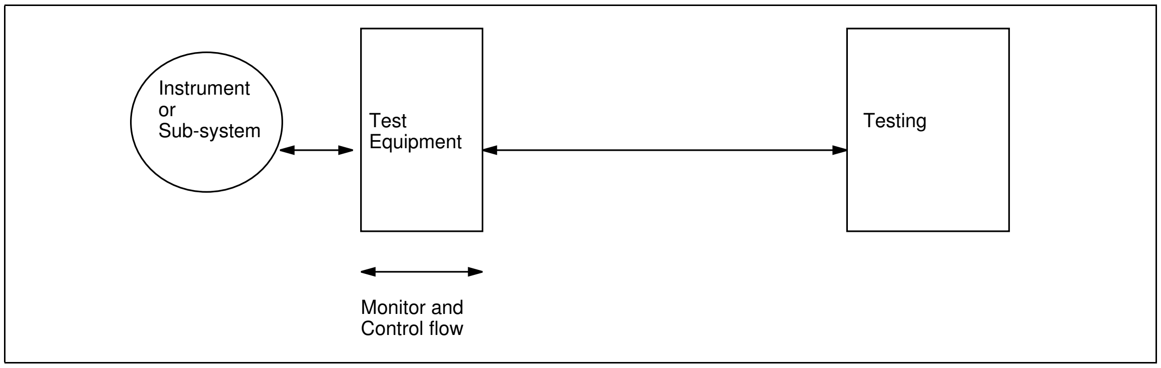


Figure 2.1: Integration Local Test (Stand-alone)

5. Launch site operations

Space projects monitoring and control the activities executed by mission resources throughout the cycle of assembly, integration, test, and operation. This requires monitoring and control of all of the subsystem elements. Figures 2.1 and 2.2 show simple schematics of the monitoring and control paths for subsystem integration and test as a stand-alone subsystem and interfaced with a simulated system. In each case there is an agent, a subsystem tester, controlling subsystem activities through signals and/or commands and monitoring subsystem activities by interpreting signals and/or telemetry. For subsystems with computing capabilities, the tester may be loading software, tables of parameters, procedures (sequences of commands) and commands to invoke software programs and procedures. The subsystem may report health status and performance summaries via telemetry. The subsystem may also perform some level of self-calibration and diagnostics and report results to the tester.

Integration of the spacecraft as a payload on a launch vehicle is conducted at a launch vehicle/payload integration centre normally located near the launch pad. During this phase, both the launch vehicle and the payload continue to be tested as systems and the integrated launch vehicle/payload takes part in a count down rehearsal. Payload test activities are monitored and controlled by testers at the launch vehicle/payload integration centre and the mission test and operations centre.

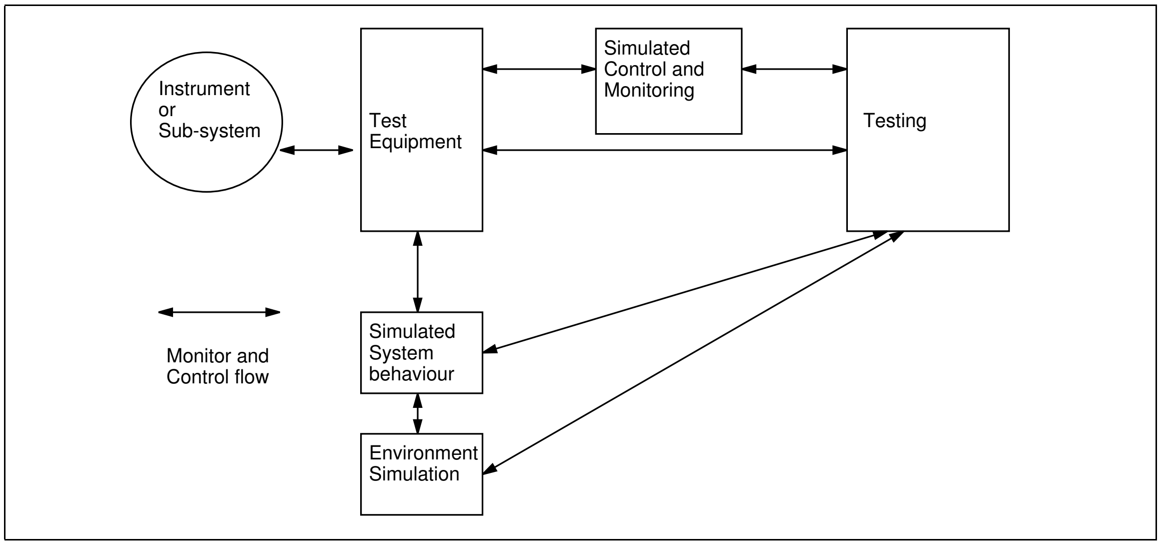


Figure 2.2: Integration and Test (in Simulated System)

Monitoring and control techniques used in this phase are similar to the ones used in spacecraft integration and test.

Finally, mission operations begin after the payload (from the point of view of the launcher, this is the entire spacecraft + instruments/payload) has separated from the launch vehicle. The mission operations centre monitors and controls both the spacecraft and the ground terminals used to track and communicate with the spacecraft. Monitoring and control techniques used in this phase usually include all those used in ground testing, the major difference being that there is no support equipment to control or monitor. The control centre uses one or more dedicated Mission Control Systems to control the satellites in flight.

In order to achieve the objectives of a space project, the activities carried out through the mission resources must be controlled and monitored. In the past, most of the agents monitoring and controlling mission resources have been people. It is now increasingly common that tasks be divided between people and computers, so the term agents is used in preference. The different types of mission resources and the agents that monitoring and control them are discussed in the following paragraphs.

2.3.1 Resources

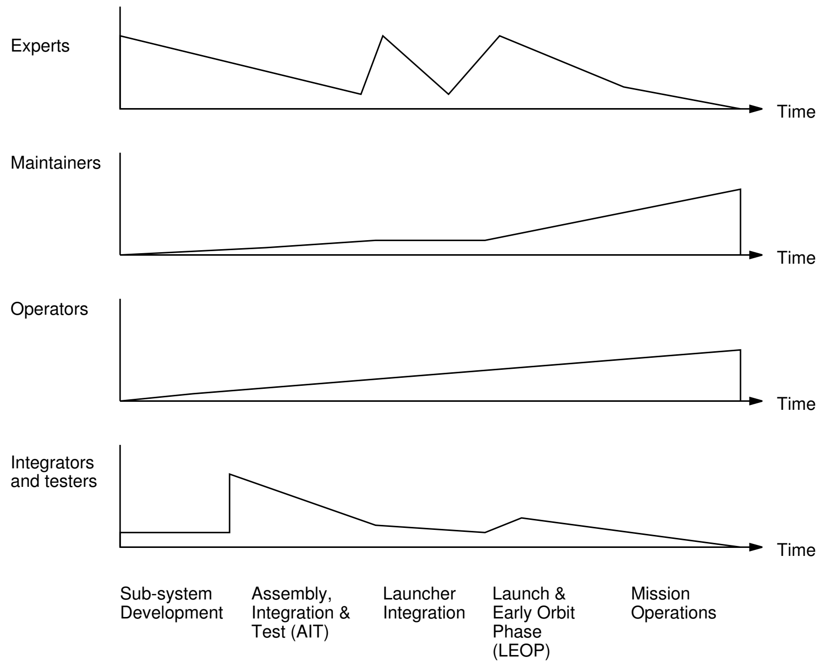
Taken as a set, the systems employed to execute a mission (e.g., spacecraft, launch vehicle, ground terminals, launch pad facility) are the mission resources. Different types of systems are employed throughout the life cycle of a project, yet the techniques for the monitoring and control of those systems have many common factors. The reasons for this commonality can be explored by considering that these systems each consist of subsystems that, in turn, consist of components.

Monitoring and control in space missions can be performed at the system, subsystem, or component level and is frequently performed at all levels simultaneously. To the extent that monitoring and control is done at the component level, the monitoring and control problems and techniques used to address them are the same for similar component types even though they are part of different systems. Different component types may have different monitoring and control problems and techniques.

As the level of monitoring and control moves up to subsystem and system level, the monitoring and control problem is less tied to the type of components. The monitoring and control problem can be dealt with in terms of higher-level abstractions (such as 'system functions' or object characteristics and behaviours). Such abstractions may be absolutely necessary if the typical agents monitoring and controlling subsystems or systems are not intimately familiar with the components that make up those subsystem or systems.

2.3.2 Agents

As discussed in the previous section, there are many different agents monitoring and controlling mission resources during the life cycle of a space project. These agents can be categorised by the roles they play in the life cycle, and by the mission resource they monitoring and control. The author, together with colleagues at the



This figure shows how the participation of the different categories of people varies over the project life cycle.

Figure 2.3: Participation in the Project Life Cycle

European Space Agency, has developed the following set of agent categories. The level of participation of each type of agent in each project phase are depicted in Figure 2.3.

Experts: These agents supply expertise on the characteristics and behaviour of mission resource components, subsystems, or systems. Typically they design the mission resources and assist in their integration and test. They may have need to monitoring and control mission resources during operations in order to respond to anomalies. They may do this from a mission operations centre or from a remote site via a link to a mission operations centre.

Maintainers: These agents maintain any mission resource components,

	subsystems, or systems that need attention in order to continue performing to specified requirements. Their location depends upon which resource they are maintaining. For the control system, they will usually based at a mission operations centre, but may also perform work 'on site' for ground terminals or at the home institute for payload team members.
Operators:	These agents operate the mission resources (e.g., spacecraft, checkout equipment, and ground facilities terminals) in order to achieve the mission objectives. They typically monitoring and control activities abstracted to the subsystem and system levels. They usually perform their function from a mission operations centre, but may perform work 'on site'.
Integrators and Testers:	These agents put together subsystems and systems and test them to create delivered mission systems to support the achievement of mission objectives. Typically these agents are mainly involved with mission systems early in their life cycle, however integration and testing of new capabilities can continue during the operational phase of a project, particularly for resources designed to support multiple missions. This may include teams of scientists and researchers operating within their own institute, as well as sub-system developers. These agents usually perform their functions from a test and operations facility. For self-testing subsystems and systems, the agent may be an automated agent operating within the subsystem or system.

2.4 Mission Operations

This section discusses several views of space mission operations in order to explain in detail the context in which space mission resources are monitored and controlled. The author found it interesting to analyse the overall system by dissecting it into layers. This approach was developed by analogy to common practice in the communications industry with great success.

The Open System Interconnection (OSI) reference model describes how information from a software application in one computer moves through a network medium to a software application in another computer. It is a conceptual model composed of seven layers, each specifying particular functions. The model was developed by the International Organisation for Standardisation (ISO) in 1984, and it is now considered the primary architectural model for inter-computer communications. The OSI model divides the tasks involved with moving information between networked computers into seven smaller, more manageable groups of tasks. A task or group of tasks is then assigned to each of the seven OSI layers. Each layer is reasonably self-contained so that the tasks assigned to each layer can be implemented independently. This has the advantage of decoupling layers as much as possible, so that technical solutions offered by one layer can be changed or updated without adversely affecting the other layers. A given layer in the OSI model generally communicates with three other OSI layers: the layer directly above it, the layer directly below it, and its equivalent layer in other networked computer systems. Table 2.1 details the seven layers of the Open System Interconnection (OSI) reference model

The users should, according the OSI model, only interface with each other at level 7, and leave the intermediate details to the other layers. The OSI model is a theoretical model which has a few implementations, although none of them implement the whole stack of 7 layers. The most faithful implementation was the x.25 set of communication standards, which was very successful for a number of

	Name	Description
7	Application	End user services
6	Presentation	Data problems and data compression
5	Session	Authentication and authorisation
4	Transport	Guarantee end-to-end delivery of packets
3	Network	Packet routing
2	Data Link	Transmit and receive packets across a physical network link
1	Physical	The cable or physical connection itself

Table 2.1: OSI Reference Model

	Name	Description
7	Application	
6	Presentation	
5	Session	
4	Transport	
3	Network	Packet Layer protocol PLP
2	Data Link	Link Access Procedure, Balanced LAPB
1	Physical	Serial standard X21bis

Table 2.2: X.25 Implementation of OSI Reference Model

years, and is still used widely. As can be seen in Table 2.2, it only addressed the lower three layers.

This means that any applications that communicate via X.25 have to handle the tasks that are attributed to the layers 4,5 and 6 themselves. It is interesting to compare the implementation of X.25 with a more modern competitor, TCP/IP. Internet protocols were first developed in the mid-1970s, when the Defense Advanced Research Projects Agency (DARPA) became interested in establishing a packet-switched network that would facilitate communication between computer systems consisting of different hardware and software. The result of this development effort was the Internet protocol suite, completed in the late 1970s. TCP/IP later was included with Berkeley Software Distribution (BSD) UNIX and has since become the foundation on which the Internet and the World Wide Web (WWW) are based.

	Name	Description
7 6 5	Application Presentation Session	Telnet, FTP, SMTP,
4	Transport	Transmission Control Protocol TCP,
3	Network	Routing protocols, IP, Address Resolution Protocol, ARP
2	Data Link	not specified
1	Physical	not specified

Table 2.3: TCP/IP Suite and OSI Reference Model

As can be seen from 2.3, the TCP/IP suite only implements a few layers in the OSI reference model, but it still became very widely used.

TCP forms part of the Transport Layer of the OSI Model, and splits the formatted application data up into segments. It provides connection orientated, acknowledgement and reliable transport services between end hosts. In layman's terms, it's responsible for establishing and maintaining the connection until data exchanged by application programs is complete, guaranteed delivery of data and for reassembling the data segments back into the order in which they were sent.

Internet Protocol or IP is part of the Network Layer of the OSI Model. IP is connectionless. Each packet is treated independently from others. IP is responsible for the delivery of data, via routing and logical addressing.

The Link layer, level 2, is not addressed by TCP/standards, and so every computer has the freedom, and the duty, to implement the services necessary to interface the Network layer in any way it pleases. This is normally handled by the Operating System device driver interface to the network interface on the computer. It is interesting to note that the standard applications, such as Telnet or ftp only allow the user to perform very simple, almost atomic tasks, however, by luck or design they were what people wanted to do between computers that were networked. Telnet is a way of getting a command prompt on a remote machine ("get me there") and the

	Name	Description
6	Activity	Mission Specific Operations
5	Decision-Support	Monitor and Control Applications
4	Message	Packet Utilisation
3	Data Link	Telemetry and Telecommand Packets
2	Coding	Encoding scheme
1	Physical	Radio Frequency Modulation

Table 2.4: Theoretical Spacecraft Operations Model

File Transfer Protocol ftp is way of getting data that is on a remote machine sent to the local machine (”bring something here”).

It is interesting to draw parallels between the communication industry and the space industry. The author developed Table 2.4 as an ”Operations” model to compare and contrast it to the implementations of the OSI model.

As with the OSI model, for each layer of the model, components in one stack can communicate with the equivalent component in another stack without knowledge of the underlying mechanisms to transfer the data. Similarly, each layer must be able to pass information one layer up or down, but the design should precludes the need for individual layers to have any greater scope. Table 2.5 shows that many of the lower layers of the model stack have already been specified by various organisations. Initially this was performed by military or national organisations such as ESA and NASA, but these standards have generally been superseded by wider multi-party CCSDS (Consultative Committee for Space Data System) recommendations. However, it is noteworthy that the upper levels of the Operations Models remain mission-specific.

In the same way as Telnet lets the user behave is if he or she is actually sitting in front of the remote computer, the different layers interact to shield the user from the complexity of the data transfer. For example, an agent (perhaps the scientific user in their home institute) has a virtual path to the resource (their

	Name	Description
6	Activity	Mission-specific operations
5	Decision-Support	Mission-specific Monitor and Control Applications
4	Message	Standard: Packet Utilisation Standard (and mission-specific extensions)
3	Data Link	Standard: Telemetry and Telecommand Packet Standard
2	Coding	Standard: Encoding scheme
1	Physical	Standard: Radio Frequency Modulation

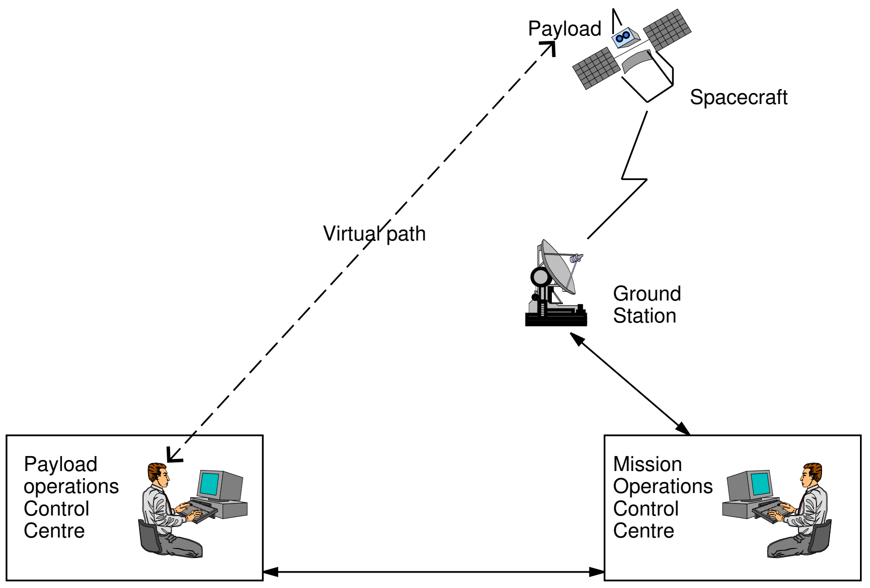
Table 2.5: Spacecraft Operations Model and Available Standards

payload instrument), even though in practice the telecommands may be routed via a central mission control centre, a ground station, the spacecraft before finally arriving at the instrument. The same also applies to data downlink, of course.

Figure 2.4 shows a simple schematic of the major flight and ground systems of a space mission operation (a similar setup for a checkout system can exist before launch by replacing the Payload Operations Centre with a Payload Checkout System). Some of the monitoring and control of the ground station, spacecraft, and payload are carried out over 'virtual paths' from the payload and S/C operations centres. Some level of autonomy resides in the spacecraft and the payload, allowing local monitoring and control.

This concept of an Operations Model can be neatly fitted in with the high-level concept of agents and resources that was introduced earlier. If the agent wishes to do something with the resource (e.g. an instrument), she interfaces through the layer with the decision support layer (e.g. a control system). This layer contains the applications that provide decision support logic to assist the agent in the monitoring and control process. These applications are programmed to determine whether commands are safe and effective, to compare monitoring data against expected responses or states, and to automatically respond to certain monitoring data by issuing commands.

As shown in Figure 2.6, the monitoring and control functionality is built upon


Payload
Spacecraft
Virtual path
Ground Station
Payload operations Control Centre
Mission Operations Control Centre

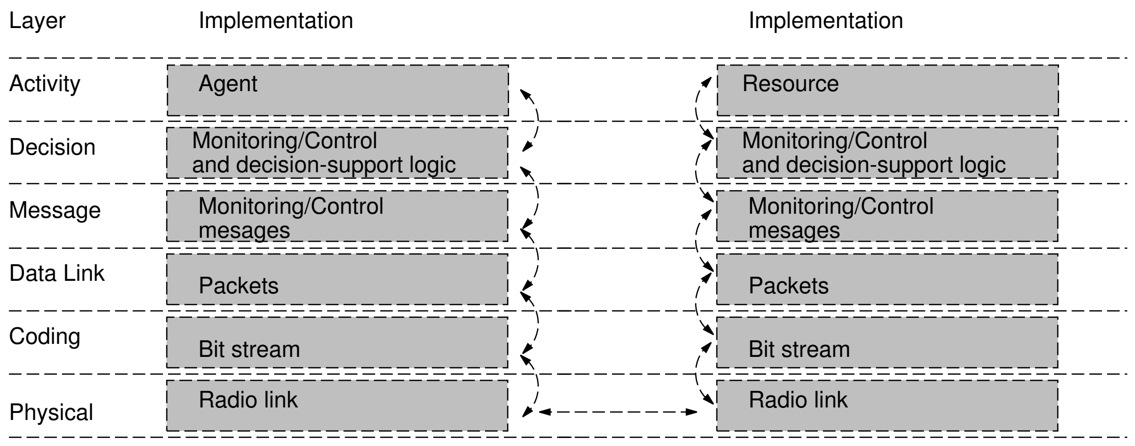
Just as with the OSI communications stack,different control loops can be performed in parallel using the same physical system. The individual layers of functions should prevent interference.

Figure 2.4: Physical and Virtual Paths

Layer	Implementation
Activity	Agent
Decision	Monitoring/Control and decision-support logic
Message	Monitoring/Control mesages
Data Link	Packets
Coding	Bit stream
Physical	Radio link

By analogy with the OSI communication stack, it is interesting to develop an Operations Model, and show how the different layers should interact with each other.

Figure 2.5: Monitoring and Control Layers



Each level in this Operations Model should directly interface only with the layers above and below it, and should carry out a dialogue with the equivalent layer in the the next protocol stack. This could equally apply to the interaction between the ground control team and the spacecraft,or the spacecraft control software and a payload.

Figure 2.6: Interfacing Monitoring and Control Layers

the messaging services in the the messaging layer. These messaging services are the mechanisms that provide a consistent way to communicate monitoring and control information. Monitoring and control information is placed in or extracted from messages at both the agent and resource conducting the monitoring and control dialogue. The implementation details of the service are hidden from the agent. Underlying the service are two way flows of messages that consist of requests and responses similar to the concepts of the client/server model.

The underlying flows of messages use the data link, coding and physical layers to get the messages to the intended recipient, the resource. The concept is extensible, in that the target resource could also be, for example, the onboard data handling system of the spacecraft, which is a resource when viewed from the ground, but can also perform as an agent with respect to another resource such as a scientific instrument. Some common monitoring and control functions can be executed either on ground or on-board and so ideally the same monitoring and control interface definition language can be used.

2.5 Operations Commonality

This section discusses the system from the spacecraft operations point-of-view. It describes features that are common to all spacecraft mission operations and those features that will vary from mission to mission. These views define the space mission operational environment in which the layered monitoring and control and communication functions must be performed.

Spacecraft engineering operations can be categorised into a few functions that are common to all space missions. These functions are 'end-to-end', that is, they are performed by coordinated activities at both the operations centre and the spacecraft. For any given mission the allocation of activities between the operations centre and spacecraft may differ, however these end-to-end functions are done for all space missions supporting a payload.

1. Orbit/Trajectory which includes those functions necessary to place the payload in the proper position/velocity in space

2. Attitude/Pointing which includes those functions necessary place the payload in the proper orientation

3. Power which includes those functions necessary to supply the payload with sufficient power,

4. Thermal which includes those functions necessary to maintain the payload within allowable temperature range,

5. Data Handling which includes those functions necessary to exchange data between payload elements, transform payload data, associate payload and spacecraft data, or preserve payload data.

6. System Executive which coordinates the functional areas listed above to the extent necessary to achieve space mission objectives. On a manned mission, this will include the crew members.

7. Life Support Systems are an additional requirement for manned missions, to provide a benign environment containing the correct availability of Oxygen,water, food, etc and waste removal.

2.6 Mission Differences

Although the end-to-end functions are common to the spacecraft operational environment for monitoring and control, there are significant differences from mission to mission in requirements on monitoring and control loop performance and constraints placed on monitoring and control loop implementation by processing power and communication bandwidths available from the mission resources.

2.6.1 Monitoring and Control Loops

The monitoring and control dialogue between the agent and the mission resource form a monitoring and control loop. The loop consists of a control instruction (e.g. command) sent from the agent to the mission resource, the execution of the instruction by the resource and an optional response (e.g., monitoring information) from the mission resource to the agent indicating the results of the executed instruction. If the mission resource is required to respond this is 'closed loop', if not it is 'open loop'.

In closed loop control, the mission resource response may give rise to another command when the agent monitors it and the cycle around the loop repeats itself. The total monitoring and control dialogue for any given mission is made of many of these loops and repeated cycles around the closed loops. The requirements on timeliness of exchanges of information in these loops is driven by the mission objectives.

Tightly coupled closed loops are necessary to execute some types of dynamic control or to protect mission resources in case of anomalies. Other loops may be loosely coupled closed loops or open loops. Tightly coupled closed loops are characterised by short turnaround times and/or intensive exchange of monitoring and control information. Loosely coupled closed loops are characterised by long turnaround times and/or sparse exchange of information.

Several different kinds of closed loop control may be distinguished. At the simplest level, the agent monitors the telemetry, observes that a change is needed and sends commands that will carry out the change. The agent can monitoring the desired change throughout the dialogue. This is a case of direct control.

The next case is when the agent sees that a change is necessary, and sends commands that will result in this change being carried out. To close the loop, the resource should report back that the change has been completed. This is supervisory control.

At the extreme level, the resource can monitoring itself, and report back to the agent that it believes that everything is in order, or even only reports to the agent when it needs assistance. This is autonomy, a strategy of great inherent risk, since the system must monitoring its own health, and there are risks that for example, one failure might mask another.

The system should allow for these variations in monitoring and control loop requirements by allowing for distribution and portability of monitoring and control applications across the set of mission resources. Note that space missions that have little space/ground communications bandwidth available to support the monitoring and control dialogue, that have long periods when space/ground communications links or not available, or that have long two-way communication times are, in general, forced to close the more critical monitoring and control loops on board the spacecraft. This will be discussed more in the next section.

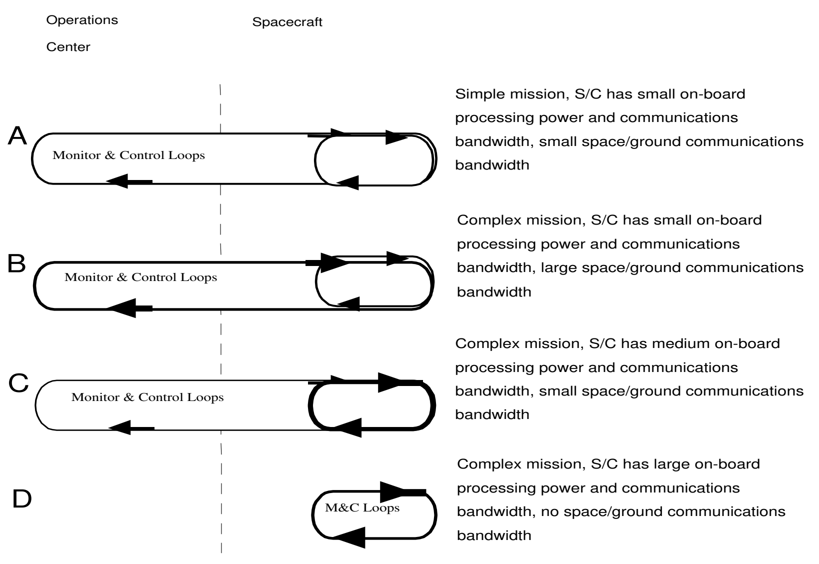
2.6.2 Available Bandwidth and Processing Power

For checkout operations there will be little or no reason to consider processing power or communication bandwidth limitations. However, for space systems, limitations (sometimes severe) are placed on computer, memory, and communications resources due to mass and power available and the radiation environment of space. The impact of this upon the mission operations concept is much more severe than the impact upon the checkout system, so it is possible the the space system can be checked-out on ground in an unrepresentative way. In this section, this author explains a simple comparison between mission types that he developed.

Simple missions (type A in Figure 2.7) may have relatively few monitoring and control loops and need to only close a few of them on-board the spacecraft. These missions can be accomplished even though there is not much processing power and not much on-board or space/ground communications bandwidth available to support monitoring and control applications. As missions become more complex with relatively many monitoring and control loops, various distributions of monitoring and control capabilities in mission resources can satisfy mission needs.

Mission type B shown in Figure 2.7 is an example of one design solution that has been used frequently in the past. The additional monitoring and control loops are closed at the operations centre, again except for those few that must be closed on the spacecraft. However, this has become quite labour intensive at the operations centre and has tended to force almost continuous space/ground communications. These features drive up mission operations costs and are unacceptable solutions for most missions being designed to hold down life cycle costs. However, automated applications at the operations centre acting as monitoring and control agents for humans can reduce life cycle costs even for these types of missions if the Earth-Space link availability and bandwidth allows it.

Mission type C (in Figure 2.7) is an example of building more 'autonomy' into


Operations
Center
Spacecraft
A
Monitor & Control Loops
Simple mission, S/C has small on-board processing power and communications bandwidth, small space/ground communications bandwidth
B
Monitor & Control Loops
Complex mission, S/C has small on-board processing power and communications bandwidth, large space/ground communications bandwidth
C
Monitor & Control Loops
Complex mission, S/C has medium on-board processing power and communications bandwidth, small space/ground communications bandwidth
D
M&C Loops
Complex mission, S/C has large on-board processing power and communications bandwidth, no space/ground communications bandwidth

Different types of mission may require different mixtures of on-board control , on-ground control or control by human intervention. A flexible control strategy should be able to move fairly easily between human interaction, to ground-automation and then to onboard automation. The optimum point will be a function of the available contact period, the required bandwidth, and the required reaction time.

Figure 2.7: Monitoring and Control Loops in Space Mission Operations

spacecraft monitoring and control. There are still many monitoring and control loops, but most of them are closed on-board the spacecraft. A minority of them are still closed at the operations centre. This reduces labour at the operations centre and allows less frequent space/ground communications, but at the cost of increased processing and communications bandwidth on the spacecraft.

In Mission type D in Figure 2.7, the spacecraft is completely autonomous. All monitoring and control loops are closed on board and therefore no space/ground bandwidth is used for monitoring and control. Of course, for a complex mission this will require a large amount of processing capability and on-board communications bandwidth.

The C type is mainly during LEOP and commissioning phase while the D type is for the deep space operations.

2.6.3 Control Strategies

Sometime it is possible that the S/C could undergo a component failure which could be recovered by the use of a back-up (redundant) unit. In order for the ground controller to be able to check the S/C configuration, it is necessary to draw attention to the fact that this has occurred.

Although the controllers pride themselves on being attentive and closely monitoring the telemetry all the time, it is inevitable that the trends or initial indicators of a problem may be missed and that problems are identified only when an alarm is raised. At most European control centres (e.g. ESOC, EUTELSAT and EUMETSAT), this change would be detected by either Status Consistency checks, which would produce an alarm at the unexpected change in telemetry, Expected Status Checks or Out Of Limit checks. Even though the spacecraft are apparently being monitored all the time, a response is made only when an out-of-limits conditions is detected. This is referred to as control by exception.

It is the personal experience of the author that some control centres in Russia have abandoned the routine analysis up TM altogether, and so even switch the transmitter off, removing all routine contact with the ground controllers. When an autonomous reconfiguration occurs, the S/C sends a Ground call by turning the transmitter on and transmitting an identifiable signal. This is subsequently detected (after an unknown interval) by a ground station, which then makes a full acquisition of TM. This can be regarded as the ultimate implementation of control by exception. Note that in this case a full history of telemetry is not available unless it is stored on-board.

The Russians are in the process of reversing this strategy, partly through the desire to meet market needs (the new customers are mostly Western, and expect to be able to monitoring and predict outages before they happen) and partly as a desire to increase the system reliability.

This author would explain this situation by looking at the underlying economics of the centralised economy. The Russian production strategy evolved in a time of central management when the factory was expected to make satellites and the only customer was the military. There were no penalties for early satellite failure, and launch costs were not paid by the military. This encouraged the development of many satellites with relatively short life-times, and some dramatic under performances. One example known to the author from his personal experience concerned a C-Band transmitter being produced by a supplier in Russia in 1998. It had an expected lifetime of 300 hours. Following the drift to a market economy after the breakdown of the Soviet Union, that the Russian satellite manufacturer has freedom to select suppliers and an incentive to do so. They selected an equivalent Japanese item which weighs less, produces more radio frequency power and has a qualified lifetime of 10 years.

The principal disadvantage of the control by exception strategy is that it reduces the quality of service provided. Seeing a unit enter a failure state that might not be recovered by the on-board automation does not change the reliability of the spacecraft, but even a warning of 2 minutes before a loss of attitude or loss of service can be sufficient to switch customers from one spacecraft to another. This *does* increase the quality of service from the customer point of view. Since almost all telecommunications providers have a constellation of satellites, some of which are collocated, this is a major advantage for them. On a science mission, this possibility does not exist.

2.7 Industrial Policy

There are a number of political and economic factors which tend to disturb the procurement process. This increases costs and reduces the quality of the final product. Most of these can be seen within the European Space Agency's processes.

1. As national barriers to trade have broken down all over Europe, but especially within the European Union, a massive consolidation has taken place, to the point that there are now only two industrial consortia capable of acting in the role of industrial prime contractor for a large satellite procurement.

   The European Space Agency failed to adapt its rules to the changing environment. ESA has rules in place which require that each member state to receive a percentage of the work (by value) of each project that is related to the amount that the country contributes to ESA. This is the policy of *justes retours*, fair returns. For example, if a country contributes 10% of the value of a project, this would indicate that companies within that country should receive 10% of the value of the project. This leads to projects being broken up into numerous small work packages which can be easily distributed geographically, which can easily drive up the price of the work, or more usually, decrease the quality of the product because so much money is wasted integrating small units and even on travelling.

2. Some countries have a very small industrial base, and this means that effectively one or two companies must be in every consortium. It is not unusual for a company in Spain or Italy to appear in both competing consortia that are bidding for work.

3. The requirement of balancing the distribution of work also means that it is difficult to write contracts that include penalties for late delivery or poor design. No project manager will let himself be left in the situation where he/she has 90% of a satellite and the prime contractor will not do any more work, and so it is difficult to impose penalty clauses. Often work packages are completed and paid before the satellite is integrated and tested, and almost always paid before the satellite enters the nominal operations phase.

4. Since the number of bidders for each contract is so low, it is difficult to negotiate payment terms which are end-loaded, to keep the suppliers working until the end. This practice is very common on other commercial contracts.

5. The bid evaluation procedure specifically excludes references to previous work on other projects, so even if a company has developed a bad piece of hardware/software on a previous mission, this cannot be included in the evaluation. The evaluation can only refer to the 'quality' of the current bid, which is a few percent of the overall evaluation.

6. For scientific missions, the funding for the instruments is completely separate from funding for the spacecraft. This brings the instrument teams potentially into conflict with the spacecraft team, but the project management has no direct leverage over the science teams. Similarly, the funding for the scientific

data processing is separate from the spacecraft, so there is little incentive for cost-saving by combining the development, integration and post-launch operations or even cooperating across different phases.

7. The size of many ESA projects means that they are often very complicated. It is always tempting a include another instrument, but the result is that projects get bigger and slower. The project Herschel-Planck spent more than one year between the end of phase A, proof of concept, to the beginning of phase B, design. The size of the satellites and the speed of the progression also drives up the costs. It is difficult to maintain staff continuity over such a long project.

8. Companies in North America are not immune to the vagaries of political mismanagement. After a number of 'Spy Crises', the USA imposed dramatically tightened restrictions upon the export of information related to almost any technology, explicitly including the aerospace industry. It is the personal experience of the author that this means that for a commercial contract e.g. for a communications satellite, American companies can offer to deliver a satellite to a US launch site, but are seldom able to provide background information that is necessary for the evaluation of the design or for operations. If the purchaser insists on receiving adequate information about what he/she is buying, then it is clearly very difficult to select an American company.

2.8 Summary

This chapter has discussed the space business from a very high-level. Section 2.2 has shown how the industry is structured and why the industry is normally divided into separate communities of satellite operators and satellite builders. This division certainly leads to inefficiencies in information transfer and usually also to cost increases for the duplicated development of checkout and control systems even though there is significant commonality between the two.

Section 2.3 has shown who participates in the spacecraft life-cycle, how the participation varies from over the project lifetime, and why this can be a problem.

Section 2.4 discussed mission operations. It proposed an 'Operations Model' to show which areas are already covered by international standards and which areas are left for individual missions to design and implement themselves.

The optimum point will be a function of the available contact period, the required bandwidth, and the required reaction time. Sections 2.5 and 2.6 looked at the commonality in the operations concept across different missions, and then at the differences. There is a broad spectrum of control activity that can be performed on-board, on ground or by human intervention. Different types of mission may require different mixtures of these techniques. A flexible control strategy should be able to move fairly easily between human interaction, to ground-automation and then to onboard automation.

Finally, since much of the space activity relies on government funding of some form or another, it is easy for activities to become dominated or distorted by political activity or interference. Section 2.7 has shown how the industry operates in a distorted market place and some of the conflicts and inefficiencies that can result.

Chapter 3

Organisational Behaviour

3.1 Introduction

Organisations perform actions by requiring an agent (human or machine) to perform according to a certain structure. These actions are governed by one or more of the following:

- Rules and Procedures
- Intervention by supervisor
- New Project/Task Force/Review Team
- New Department

All of these structures and practices are present within the space industry, and it is interesting to compare and contrast the different emphasis given to each. This Chapter examines the different kinds of behaviour that is displayed by individuals and organisations. Behaviour is broken-down into skill-based behaviour,rule-based behaviour and knowledge-based behaviour and the different benefits and disadvantages of each are discussed in section 3.2.

Section 3.3 classifies rules and procedures according to different criteria, and section 3.4 shows the structures that the author has experienced in the teams of people responsible for operating spacecraft, and section 3.4.4 looks at the dynamics of people working in teams and some problems frequently associated with teams. Section 3.4.5 presents guidelines for individuals and how they should interact within groups in order to reach a good decision.

The nature of some of the organisations that operate satellites is discussed in section 3.5. This sections looks at several European civil satellite operators, all of which started out as non-governmental organisations and one of which made a transition to a commercial company. It discusses the way that these organisations procure satellites, the internal structure of the organisations, the problems that each organisation faces and the ways that they have reacted to their challenges.

3.2 Behaviour

The aviation industry has been in existence for much longer than the space industry, and it is interesting to see what lessons can be learned from aviation and applied to the space industry.

> 'The behaviour of a skilled operator...may be broadly broken into three categories. Skill-based behaviours are those that rely on stored routines or motor programmes that have been learned through practice and which may be executed without conscious thought... Rule-based behaviours are those for which a routine or procedure has been learned. The components of rule-based behaviour may compromise a set of discrete skills. Knowledge-based behaviours are those for which no procedure has been established...[and] require the pilot to evaluate information, and then use his knowledge and experience to formulate a plan for dealing with the situation'[18].

3.2.1 Skill-based Behaviour

Skills may be acquired in different ways, for example, by practicing the whole pattern of behaviour until the desired result is achieved or by giving conscious attention to individual aspects of the skill. This may seem to be less relevant to spacecraft operations, since there is not a clear element of physical skill compared with, for example, an aircraft's manual approach and landing. However, many activities are performed so frequently that they become automated *by the operator* and as such, can be considered skill-based, and this can bring several problems. For example, the skill may be stored as 'non-declarative knowledge, i.e. the possessor of the skill may not be able to articulate what the components of the skill are, and this may cause difficulty if he wishes to pass the skill on to another person'[18]. Furthermore, the operator can, when busy or distracted, 'make the correct initial decision, inadvertently exercise the wrong skill, but fail to monitor his activity and remain completely unaware of the mistake that he has made. This mechanism is very common on flight decks'[18].

A second route to error is referred to as 'environmental capture'. It occurs with a skill that is 'frequently operated in the same environment (and becomes a habit), it may be elicited by that environment even though the pilot [or operator] has not made a conscious decision to operate the skill'[18]. Green reports that 'virtually all' pilots who have landed with the undercarriage up have combined these errors, and adds the final reminder 'it should be remembered that these errors of skill do not happen to novices, since they have to think about what they are doing. They occur only to those with experience'[18].

3.2.2 Rule-based Behaviour

Procedures and checklists should normally be stored either on paper or electronically. Procedures are widely used in the aviation and space industries, and Green[18] attributes the safety of commercial aviation to their use, together with the associated training and checking. Even though the details of the procedure may be stored, the operator still needs to retain a basic memory of the procedure in order to retrieve an action it. Green reports that 'errors in procedural behaviour are usually because the pilot has made a initial misidentification of the problem and engages the wrong procedure entirely...Errors may also occur if the pilot believes that it is safe to depart from procedure'[18].

3.2.3 Knowledge-Based Behaviour

Green provides a very simple example to illustrate some important aspects of how people tend to evaluate evidence and make decisions. 'Imagine that you are told that there is a rule that connects sets of three numbers, and that you have the task of discovering the rule. To help you, you are given an example of a set of three numbers that fits the rule; you can try out further sets of numbers and will be told if they fit the rule or not. The example set of numbers is $2, 4, 6$. A person playing this game will often try a set of numbers such as $10, 12, 14$ and be told that the set fits the rule. He will try several similar sets of numbers and come rapidly (perhaps after only one trial) tot he conclusion that the rule is $n, n+1, n+2$, only to be told that this is not the rule. Despite being told this, the future examples that the person tries are likely to be further instances that fit his own inference (eg $24, 26, 28$) and when he is told that they fit the rule, he becomes more and more sure that $n, n+1, n+2$ is the right rule, and may even refuse to believe that it is not the rule. Another person may come by a similar path, and equally rapidly, to the conclusion that the rule is $n, 2n, 3n$, try out such instances (eg $50, 100, 150$), to be told that they fit the rule, and be equally disappointed to be told that it is not the rule. The explanation is that the rule is 'Any three numbers in ascending order'[18].

Green uses this and other examples to arrive at the following conclusions[18]:

- Data may be ambiguous.
- People are very keen to structure information and make inferences from it.
- The inferences that people make are very heavily influenced by their experiences and by the probability structure of the data.
- Once a person has formulated a certain way of thinking about the problem, it appears difficult for him to get out of that way of thinking and try a different interpretation of the data.
- Even if a person tries to test his hypothesis about a set of information he is likely to try only positive instances of his hypothesis and unlikely to try negative instances of his hypothesis.
- Even if a person is presented with instances that negate his hypothesis, he is likely to disregard them.
- People make inferences in accord with their wishes, hopes and desires.
- Having a hypothesis reduces anxiety and stress compared with admitting to oneself that one does not understand what is going on.

Given these fundamental limits on knowledge-based activities and the frequent pitfalls, it is important for members of the flight control team to be aware of potential mistakes and for both individuals and the whole team, particularly the leader, to behave in a certain manner. This is discussed further in section 3.4.5.

3.3 Rules And Procedures

Rules are the "lowest levels" or fine grained source of control, and ideally they should be unambiguous and deterministic. Each of the higher levels usually uses all of the lower levels and is hence not as efficient, although flexibility is introduced as a form of compensation. It is the author's experience that people working in the industry assume that all activities to be carried out on the satellite are proceduralised and that any attempt to perform activities for which a procedure has not been provided would require specific authorisation from the project management.

Rules can be classified in many ways. One technique divides rules initially into 2 categories: constraint rules and deviation rules. Constraint rules, as the name suggests, specify policies or conditions that restrict behaviour, intervention or structure. Deviation rules help infer policies or facts from other facts.

3.3.1 Response Rules

Stimulus/Response rules constrain behaviour by defining WHEN and IF conditions that must be true for a particular operation to be triggered e.g.

```
WHEN the stock level of a product is less than re-order point then
reorder WHEN library book requested by borrower
     IF a copy available THEN
            check out this copy to borrow
     ELSE place next copy of book on reserve
```

Stimulus/Response rules constrain behaviour within an event context. The same action could be called in multiple contexts. When an IF condition must be true for an operation to be performed correctly a different kind of rule is required.

3.3.2 Operation Rules

Operation constraint rules specify those conditions that must hold before and after an action starts to ensure that the action performs correctly. Such constraints are completely independent of the event context and should be vital to the execution of the operation. In the field of software engineering Bertrand Meyer [31] states that these rules should be viewed as a contract that binds both the method (procedure call) and its requesters (execution context):

"if you call me with the precondition satisfied I promise to deliver a final state in which the post-condition satisfied" [31].

Precondition rules say that the operation cannot go ahead unless (all) these constraints are met. In contrast, post condition rules guarantee the result of an operation. In a perfect world, they might not be necessary, but if a practical point of view is adopted, the possibility of failure must be accepted and post conditions supply a mechanism for triggering an action after an unexpected failure: in software terms this is an exception handler.

3.3.3 Structure Constraint Rules

Structure constraint rules specify policies or conditions about objects (things) e.g.; attributes, and interactions between things. An attribute could be constrained:

```
IT MUST ALWAYS HOLD THAT an employees salary cannot be greater
than that of the manager
```

Structural constraint rules are not context sensitive they must be true whatever the phase of life of the object.

3.3.4 Inference Rules

Inference rules specify that if certain facts are true, a conclusion can be inferred. Note that if inference rules are specified in an IF AND ONLY IF form, they operate bidirectionally.

3.3.5 Supervision

Satellites and their associated ground segments are supposed to be operated according to procedures, as outlined above. When it is not possible to decide which procedure to run, or a procedure fails, than the catch-all clause is to refer the problem up the defined chain of supervision. Each supervisor then has to decide if she/he is happy accepting that level of risk, and taking a decision, or referring it upwards again.

3.4 Flight Control Teams

In the author's experience, the structure of most flight control teams can be compared by considering different roles to be performed, the actors who perform those roles, and the functions of the various roles.

3.4.1 Roles

Spacon (Spacecraft Controller)

Spacons generally perform routine functions. The ground control system is usually highly automated, but often each individual task must be initiated by the Spacon. They generally work in shifts and there is usually at least one spacon present all the time. Spacons generally have a secondary-level education.

Analyst

Routine trend analysis is performed by a senior spacon, or a former spacon who has moved off the shift rotation into a day job. This is a much-coveted status for a spacon.

Engineer (Spacecraft Operations Engineer, SOE)

Engineers generally either write procedures or specify/write software which form part of the mission control system. The procedures are usually executed by a spacon, and during the mission the engineer only really has to respond to anomalies. Engineers always have a university level education, usually in a technical subject: engineering, physical science or sometimes mathematics/computer science

Manager (Spacecraft Operations Manager)

The SOM is responsible for the entire team. She/he will normally assign tasks within the team and then expect a report upon their completion. Most of the activities are delegated to be performed under the supervision of the engineer, with the SOM being called in the event of a major anomaly or if it becomes necessary to interface with other organisations. The SOM usually has many years experience as an engineer on a number of different projects, and has a similar, university-level education

3.4.2 Agents

The roles outlined above have to be performed by agents, people or computer systems. EUTELSAT and ESOC are both European organisations and both have a mixture of staff types: Permanent staff (called "Staff" in the language of the industry) and temporary staff (referred to as "Contractors"). EUMETSAT also has same mixture, but suffers from a different set of problems.

1. Staff:

   Staff are European civil servants, a status which brings with it many advantages: tax free salary, private health insurance, and a subsidised education for their children. Until recently, staff were recruited directly into permanent positions. This permanence, coupled with the substantial benefits in life-style, mean that very few staff leave, and that they subsequently accumulate in the organisation hierarchy. Although now days most staff are initially employed on a 4 or 6 year contract, it is rare for a staff member who wishes to stay not to get offered a renewed contract (e.g. 6 years). EUMETSAT has been trying to enforce the principal of rotation of staff, by making it clear that staff will not be offered a third contract after the first two, which can bring problems of its own since projects tend to be very long both before and after launch.

2. Contractors:

   Contract staff are provided by various contract companies throughout Europe. In terms of providing operations engineers, Vega is the market leader in Europe. The staff are supposed to provide continuity and the contractors are supposed to be recruited to perform a particular well-defined task, on the understanding that they will leave when that task is completed. In a static market, the rationale of hiring contractors to help out in periods of intense activity would seem to be a good one, but the market for spacecraft operations seems to be expanding, and as soon as people are viewed as 'having experience', they become highly valued throughout the industry. Although the period from pre-launch through to entry into service is very stressful, it is also the time when most learning takes place, and therefore when the most valuable experience is accumulated. Relying upon contractors for this phase can therefore lead to a loss of experience, which is heightened if the staff members have been busying themselves in management positions. This becomes further amplified since engineers have a natural desire to concentrate on the most interesting part of the life-cycle, and after having gained experience of one launch or service entry, the engineer then becomes a much more attractive proposition to other projects within the same organisation or outside it.

3. Automation:

   At both ESOC and EUTELSAT, the level of automation in the ground segment is surprisingly low. The satellites are designed to be capable of 48 hours autonomy (i.e. no ground intervention) but the ground segments still have a lot of redundancy, e.g. at EUTELSAT it is possible to transfer control to a complete back-up control centre within 2 hours. There is little evidence of optimisation of the trade-off between satellite autonomy and ground segment robustness.

The control system can usually perform limited, pre-defined commanding activities once they have been enabled by the controller, e.g. send this command at a certain time, send this command when this mode equation (logical state) is true.

The experience with ground-based autonomy (of the kind often branded as 'Artificial Intelligence') is poor, in that often delivers less than it promises, it replaces one operations engineer with one operations engineer and one software engineer, and is unreliable. Despite having all actions proceduralised, there is an enormous amount of implicit knowledge that is required in order to decide which is the correct procedure to run at any given time.

3.4.3 Functions

A Spacecraft Controller generally has very little to do and those operations that are frequently necessary soon tend to be routine. Spacons are present as insurance for the time when something goes wrong. Routine trend analysis is usually performed by a senior spacon or analyst. Analysts have historically also been responsible for manually entering the satellite database of telecommands and telemetry, since an electronic import of data from the manufacturer has not been possible, largely for non-technical reasons. Analysts are generally responsible for updating the satellite database if a change needs to made, such as adding or modifying telemetry displays, or changing status texts, calibrations curves or limit checks.

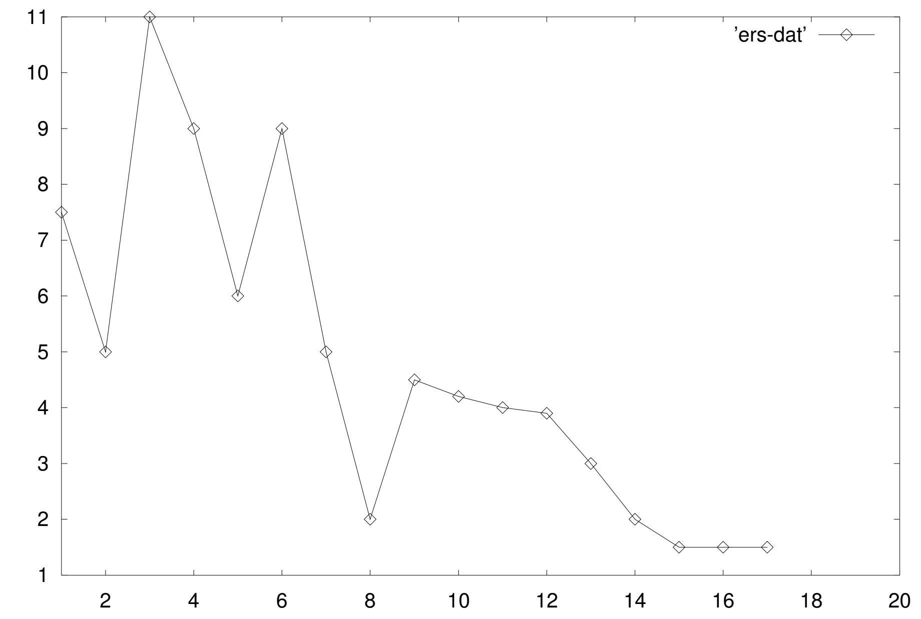
The engineer initially writes procedures or designs systems which are used by the spacon. During the mission (i.e. the very purpose for which the satellite was procured) the engineer only really has to respond to anomalies. Anomalies are difficult to classify by their nature, and when an anomaly occurs sufficiently frequently, it becomes almost normal until, of course, it changes.

Initially engineers are fully occupied in control system (be it in software or procedure) development, and the launch and entry into service are seen as high points. Spacons are usually either busy with the existing missions or are recruited so close to launch that it is difficult for them to contribute to the service entry in a useful way, and largely the launch and entry into service can be seen as 'On the job' training for the shift staff. The procedures necessary to control the satellite should be already written by the time that the satellite is launched.

Close to launch and in commissioning, the job is very demanding but it soon tails off into routine: waiting for anomalies to occur in order to recover them. These occur about once every 2 - 3 days, the same term being used for a minor glitch to a catastrophe. As the project settles down into the routine phase, the engineers often lose interest and move onto other projects or leave the establishment entirely. If a person leaves, the contractor provides a replacement. They are usually replaced with younger, less-experienced engineers.

The current contract at ESOC requires a 3 month hand-over period from one engineer to another. During this time, it is necessary to show the incoming engineer all the procedures and how to use them as well as how to work with the spacons and other elements in the ground station systems. Initially the replacement is full of enthusiasm for the new position, and can usually continue to learn on the job. However, eventually the thrill wears off and this person will also wish to be replaced. This person has less emotional loyalty to the program having missed the excitement of the launch and the other associated birth pains of a new satellite. There is evidence that people who join the mission at an earlier phase stay longer than those who join later. This is shown in figure 3.1, which shows the number of years that each person stayed with the project, in the order that they joined the project.

This is likely to be a big problem on long-term projects, such as Rosetta or the International Space Station. It means that regular rotation of staff will have to be



This figure shows the number of years that an engineer on the ERS project stayed on the project before leaving(vertical axis), in the order that they joining the project . Note the false origin. After the launches of ERS1 and ERS2 the mean duration on-project dropped and seems to stabilised at around 2 years.

Figure 3.1: Years on ERS Project

introduced to try to keep them fresh and interested, or else they will simply leave. This is a particular problem for a large institutional bureaucracy, since it requires them to perform well in one of their weakest areas: staff management.

Engineers are typically highly-qualified academically, full of enthusiasm, and welcoming of the challenge of learning how to operate a new satellite. In the space business, more than most other industries, people do it because they want to do it, not because they have to do it. Most engineers believe that their skills are highly marketable elsewhere, but still chose to stay within the space industry even when it is beset with delays or disasters.

3.4.4 Team Dynamics

There are a number of factors that impact the way people to other people and to the equipment under their responsibility. One very simplified version presented in [18] suggests that people should be evaluated in two independent qualities in order to predict how they may interact as a team. 'The first is concern to achieve task goals (goal-directed style) and the second is concern to keep team members happy (person-directed style)... The actual style of behaviour that is appropriate may be somewhat context-specific, and many of the factors bound up in successful leadership may be indefinable. For example, much has been written on why Churchill was a successful wartime, but not peacetime, leader'[18].

Other factors that will clearly influence the way team members interact with each other are perceived ability, status with respect to each other, and role within the team.

One reason for having a team of people operating the spacecraft is to produce better quality decisions and better solutions than would be produced by one alone. Green reports on the extensive results of aviation research 'It is generally true that the decision made by a group will be better in quality than the average decisions made by the members of the group, but perhaps slightly depressing that the group problem solving ability will rarely improve upon the problem solving ability of the ablest member of the group. From this point of view, therefore, the function of having more than one person in a crew is to improve the chances of having an able person there, rather than to have an interaction between crew members that produces better decisions than any would produce individually'[18].

The process of recognising and accepting a correct solution and implementing a decision of a group is subject to further factors, which include the ideas of conformity, compliance, status, polarisation and group lifetime.

conformity Sometime members of a group will say that they agree with the decision, or simply remain silent,for fear showing that they disagree with the group. This can be further exaggerated by differences in status within the group. The classic experiment cited in [18] to demonstrate this is a test where a group of people are asked to compare the lengths of some lines with the length of a standard reference line. The answer is normally obvious, but when the subject is placed in a group of 'stooges' who start off giving the right answers, but gradually switch to supply wrong answers many subjects will agree with the group even when they believe the group is wrong. Interestingly, 'this effect is almost maximised when the size of the group holding the opposing opinion is four'[18].

compliance A person's response to a situation is sensitive to the context. An experiment has shown that 'a householder would be more likely to agree to having a large road safety poster in his front garden if he had either previously refused to have an even larger sign or had already accepted having a smaller sign'[18].

status People who are perceived as having a higher status tend to force more compliance from their team. For example, after a test on a simple problem which on military flight crew, 30% of pilots (a role with high status in the group) got the correct answer, compared with 50% of navigators (medium status) and 30% of gunners (low status). However, 90% of pilots who got the correct answer were able to persuade their group that their answer was correct, whereas only 80% of navigators and 60% of the gunners were able to do so [18].

polarisation If individual members of a group already tend to hold a viewpoint, then the group will tend to that viewpoint more strongly. This can be a problem if a set of bold individuals form a group, as the result can be unduly bold [18].

group lifetime If members of a group do not know each other, then this reinforces the need for standardised procedures, whereas if a group spends a lot of time together, then it may come to rely upon interpersonal knowledge than on adherence to standard procedures[18]. It is also slightly unfortunate that in identifying an 'in' group, of which someone considers him/herself a member, then there is an implicit formation of an 'out' group. Team members may forget that they are members of more than one group (e.g. employees, local residents, human beings) and should remember to bear in mind that many of the people outside the immediate group are in fact colleagues, and that little is to be gained by treating 'them' as the enemy[18].

3.4.5 Individual Operations Strategies

Green reports that 'Aviation has traditionally been very strong in training individual skills and rule-based behaviours but has not generally provided pilots with practice at solving possibly ill-defined problems on a group basis'[18]. This is what the recent (from 1995) introduction of Flight Deck Management and Cockpit Resource

Management training as part of the formal (and mandatory) parts of commercial pilot training try to address. Green provides the following guidelines to teams to follow in order to come to a good group decision and also maintain the team morale:

- The leader should avoid giving an indication of his own opinion or idea at the outset. If any member of the team has another idea, he will then be reluctant to share it since it may appear to contradict the leader.
- The leader should specifically and overtly solicit the ideas and opinion of team members and encourage them to express doubts and objections to a particular course of action. This is to ensure that the potential problems are fully aired and not ignored.
- When the leader has made a decision, he should explain his reasons for arriving at that decision to the other members. Failure to do so could make the other team members feel as if their own ideas have either not been considered or not heard.
- All team members should not hesitate to raise uncertainties through worry of appearing foolish or weak.
- When asked for an opinion, it should be given fully and clearly without worrying about what the other people want to say, but not in an emotionally loaded or dominant way.
- Deal in evidence and not prejudice. Team members should not become too attached to their own points of view and simply try to get their own way. Members should accept group decisions unless they feel that it contains some hazard that has not been appreciated by the group.
- Don't let others progress down wrong paths just to appear clever
- Don't compete, don't get angry and don't shout[18].

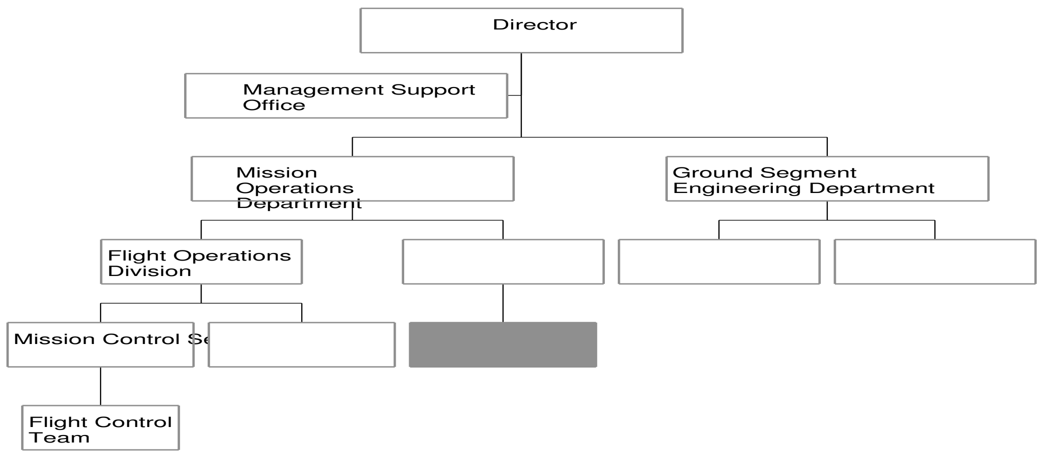
3.5 Organisations

3.5.1 ESOC

ESOC's structure has changed with time as successive directors try to inject energy into and breakdown barriers within an ageing organisation. It is a typical, mature bureaucracy, being more than 25 years old and populated by career civil servants on permanent contracts. As part of the European Space Agency, ESOC has suffered from lack of direction, intermittent funding and lack of responsiveness. Many functions are performed centrally, in the expectation that this will give cost savings, but the inefficiencies often far outweigh the cost savings. The following example illustrates this point. ESA has four large establishments, in France, the Netherlands, in Germany (i.e. ESOC) and in Italy. The catering for all four establishments is procured centrally on a single contract, with the results that for the most recent competitive tender, only 2 companies could meet the needs in all establishments. By centralising the contract, effectively local companies were unable to apply, since they lacked the infrastructure in each country. This meant that there was not very much competition in the tender.

ESOC has a deep structure with very low fan-out (see Figure 3.2). The Director tends to be a political appointment and then a number of Department Heads (2,3, or 4 Departments in recent years) report to him. Each Department consists of 2 or 3 Divisions and most Divisions consist of 1 or 2 sections. The two most recent Directors established an independent cabinet called the Management Support Office to determine what policy should be and to monitor its implementation through the Departmentalised structure. This clear duplication of resources seems to indicate that even the Directors felt that they were unable to impose policy throughout the organisation.

ESOC has undergone re-structuring several times over the recent years. Figure 3.3 attempts to show how the departments have been shuffled back and forth over

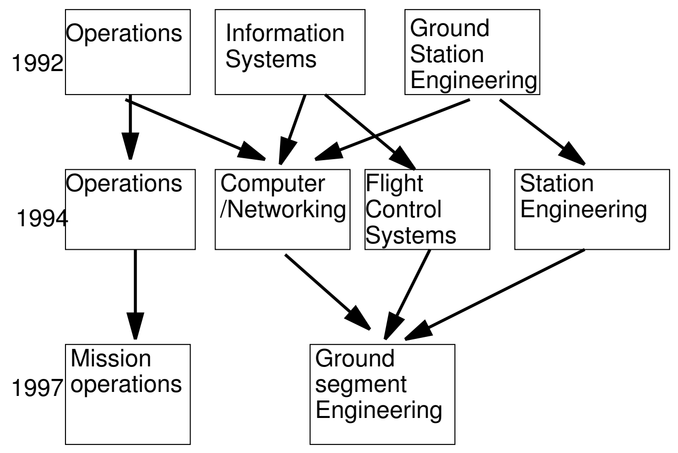

Director
Management Support Office
Mission Operations Department
Ground Segment Engineering Department
Flight Operations Division
Mission Control Se
Flight Control Team

ESOC exhibits are deep structure with very low fan-out. This is characteristic of a low level of delegation.

Figure 3.2: ESOC Structure

the five years 1992-97. The names given are not the formal ones, since those names changed even more frequently. At the Divisional level, the changes have been even more noticeable, and the organisation still has many inconsistencies. For example, in Figure 3.2, only the manager of the team reports to the section shown. The members of the team still also report to a managers of different sections, e.g. as to the grey box in Figure 3.2.

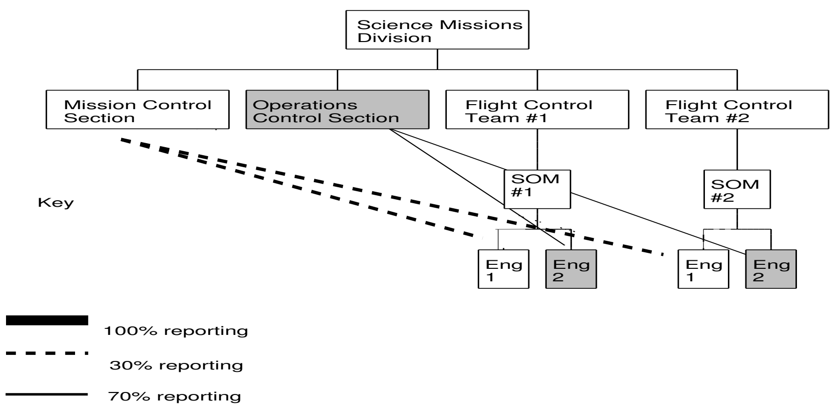
ESOC has a mixture of permanent staff and consultants provided by contract companies. The ESOC operations division consists of a series of operations teams. Each team has one or more SOMs - always a staff position. Then there is a number of engineers, most of whom are employed by a contract company. ESOC specifies from year to year how many people shall be provided to supply engineering support. The staff are supposed to provide continuity and the contractors are supposed to be hired and fired to smooth out the peaks and troughs. But, either the staff do not have sufficient time to learn the details (if they are on several projects or also have management responsibilities) or they are not sufficiently experienced in a range of topics. The current projects last so long that some staff members are made into S/C



ESOC undergoes periodic reorganisations.

Figure 3.3: ESOC Reorganisations

managers after having been an engineer on one mission, or due to staff movements, never actually having been an operations engineer. This clearly leaves the SOM in an exposed position and makes the overall ESOC structure even more reliant upon contractors. The ESOC structure has evolved into a variation of the common 'matrix structure'. Dedicated teams have been built up for a particular project, although the previous structure remains as a legacy. Contractors are all supposed to report to the contract Technical Officer, and staff members are assigned to a particular Division when they are employed, which does not have to be the same Division in which they work. This has further divided the Flight Control Team structure, by leaving multiple lines of responsibility, which is shown (in an example form) in Figure 3.4. The situation is actually far more complicated, with the reporting percentages being squabbled over between the various Division and Section heads in an attempt to maintain the status quo by bolstering the number of total number of 'fractional people' in their division. In practice most of the administrative bonds are of little consequence, and most people report to the head of the Flight Control Team.



The ESOC structure tends to have multiple reporting for different projects, task-forces and working groups. Since many managers do not have full responsibility for the people who are working for them, this can make it difficult to allocate resources correctly and difficult for the engineers to prioritise the different tasks they are given.

Figure 3.4: Multiple Reporting in ESOC

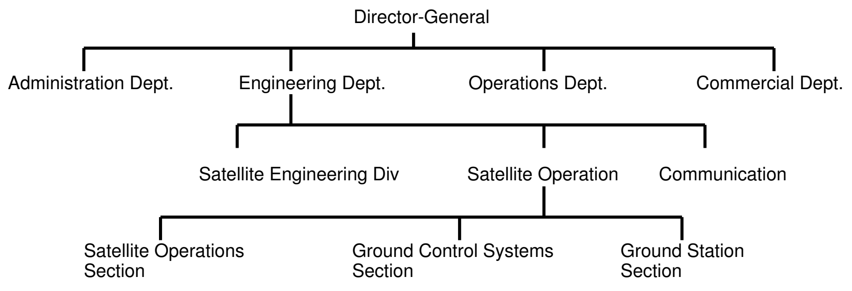


Figure 3.5: EUTELSAT Structure

3.5.2 EUTELSAT

At EUTELSAT, one division is responsible for all the satellite operations as shown in Figure 3.5 and another manages the satellite procurement process.

This is obviously a much leaner organisation, with much greater fan-out. EUTELSAT is not without its peculiarities though: for more than 2 years there was no overall organigram, since the management believed that it is not necessary and would hinder the relations between the Divisions.

On many projects the lack of coherency between operations and engineering leads to a lack of understanding of the operational needs during the procurement, and results in designs that are difficult to operate or require expensive changes in the ground segment software.

EUTELSAT has adopted the idea of a single 'kernel' control system software with special modifications for each mission. Thus every time a new 'family' of spacecraft is added, this increases the complexity of the control system. EUTELSAT allows two external companies to bid for each software maintenance work package, and normally gives the major tailoring due to a new satellite 'family' to a single contractor. The contractor then starts updating the kernel software as necessary. In the meantime, of course, the same contractor (and the competitor) is changing the software on the other satellite control systems. Since they cannot change the kernel, they have to introduce a series of local 'patches' to each system. When all changes need to be integrated with the new kernel, the result is a nightmare of dependencies. Each new family n needs to be integrated with *(n-1)!* other systems. The extra cost of developing and testing the ground system is not adequately fed-back into the procurement process. The EUTELSAT strategy makes sense if each 'family' has many members, but the last two families consisted of one satellite each!

3.5.3 EUMETSAT

EUMETSAT is also an organisation with low fan-out, and the division of tasks from the projects that procure the spacecraft from the people that will operate the spacecraft is again present.

3.5.4 Differences Between ESOC and EUTELSAT

Scope of Control

ESOC performs the launch and early orbit phase control for all of its own satellites and for some external customers. EUTELSAT does not perform its own LEOP, preferring to take delivery of a tested and checked out system on station. This is analogous to the role of an airline, as opposed to a flight test centre where almost every type operated is a fully new type. At EUTELSAT the business area is simultaneously well defined and confined to the provision of broadcast television and telephone services. Since EUTELSAT fulfils its business interests by operating the S/C and reselling the transmission capacity to other organisations, it does not need to expand the capital effort in the risky parts.

Manning Levels

At EUTELSAT it is normal to have two spacons controlling more than ten satellites, although when more than two satellites manoeuvre at the same time, an extra controller is brought in. This is because manoeuvres are perceived to be the times of greatest risk in EUTELSAT routine operations, analogous to the approach and landing of an aircraft. Software will be developed soon to perform and monitor station keeping manoeuvres. This is similar to the manning level at ESOC, even though ESOC controls unique, bespoke satellites.

EUTELSAT considers that it is worth investing in expensive training e.g. one of the new spacons at EUTELSAT underwent a 6 month training phase, including about 3 months of one to one training from an engineer and 3 months of shadowing another spacon. Spacons are viewed as a long term resource and experience is more valuable than academic ”smartness” or the ability to innovate. Both ESOC and EUTELSAT require 6 people to provide full shift coverage, although the financial pressure upon ESOC has been so great that for one particular mission, ERS-2 (when it was still operating ERS-1 every few months), the decision was taken to not use all the periods of contact with the satellite, but to only use the ground station passes where it was possible to both receive telemetry and send commands. This is obviously a management decision that increases the risk of a failure going undetected and uncorrected for a longer time.

Responsibilities

ESOC generally receives responsibility for all engineering work, including on-board software maintenance, whereas EUTELSAT writes and strictly enforces contracts with the satellite manufacturer. ESA-ESOC traditionally gets poor post-commissioning support from the manufacturer even when it is specified in the contract with industry. Unfortunately, ESA has little leverage over the manufacturers. The stage payments are typically small, and since the political condition within ESA makes it difficult (impossible) to stop contractors from winning new work, there is little incentive for industry to continue to provide high quality support. On the contrary, since ESA runs a series of procurements in parallel with the long duration missions that are already flying, industry has every incentive to use its experienced staff to win new work rather than keeping them on routine support. This is also much more popular with the engineers, who would much prefer to design and develop new things instead of maintaining the old equipment.

By comparison, EUTELSAT is able to force much better support from its contractors, since the legal team is ready to intervene, and since the contracts are drafted in a way that favours EUTELSAT.

3.5.5 Problems

ESOC

ESA has suffered from the build up of people over more than 25 years, becoming a slow-moving bureaucracy, with out of date financial techniques and little delegation of authority. Many documents require a large number of signatures, which often results in documents being 'hand-carried' around the establishment from one office to another.

EUMETSAT

EUMETSAT suffers from other problems. Rather than having an accretion of staff over the years, there is a certain deficit in experience. EUMETSAT took a conscious decision to limit the duration that anyone can stay with the organisation by limiting both the length of employment contract and the number of contract renewals. The aim was presumably to avoid the creation of an aging organisation like ESA. A result of enforcing this principle of rotation is that there very little continuity on the project, since many projects take more than 10 years to go from conception to launch. This leads to an overall loss of experience and vulnerability to external contractors. It also means that some staff may not take decisions that are in the long-term interest of EUMETSAT, since, they have no long term future with EUMETSAT, however well they perform.

EUMETSAT takes on contactors to supplement their staff numbers, like at ESOC. At ESOC there is a five year frame contract through which a number of people from one or two companies are recruited, at EUMETSAT the people are recruited directly for particular work packages of 1 or 2 years. This may increase competition on price per contractor hour, but it can also bring contractors into conflict with each other, since they are sometimes competing for the same resources (i.e. vacancies). It can also mean that contractors have little reason to cooperate with each other, and leaves potential reasons for them to make their colleagues look bad or ineffective.

EUTELSAT

EUTELSAT started as an international organisation, an off-shoot from the European Space Agency. Over the last two years EUTELSAT has been readied for a pseudo-privatisation, with the organisation being split into two parts: one part to continue with its existing regulatory functions, and the other to compete as a commercial satellite operator. This led to a massive drop in moral as people feared for their benefits, such as tax-free salaries and cars with education and family allowances.

The uncertainty over the future caused many people to leave, and the resulting recruitment process was poorly handled. The Personnel Department was used to administering according to a predefined set of rules, and avoiding setting any kind of precedent. Managers were able to say who they wanted for a particular position, but had no control over the salary that was offered by the Personnel Department, which had no experience of a commercial environment.

3.6 Summary

This Chapter has shown how organisations typically achieve their goals by encoding activities in procedures, creating teams and trying to build up a particular kind of culture. It has looked at the kinds of teams that have been encountered by the author in his experience in the space industry and broken down individual types of behaviour into skill-based, procedure-based and knowledge-based behaviour. It has suggested some best-practice guidelines for how team leaders and team members should interact in order to arrive at the best solution. In the Chapter 4, the question of how an organisation can and should manage risk is addressed, and then section 5.7 shows via the STS 51-L *Challenger* launch decision, the consequences of a break down in communication between the individuals and teams of operations, engineering and management.

The space industry, as well as facing some unique challenges, also faces many normal business and organisation challenges. Managers should be able to meet the career aspirations of their workers, and control their workload. Because so much space-related work is carried out by organisations with bureaucratic roots and a military or civil service mentality, personnel development has typically been a low priority. The amount of delegation has also been typically low, with managers often not responsible for some of the effects of their decisions.

The organisations examined here all became dependent upon the short-term supply of labour to meet their peak work-load. People who are only working on short-term contracts inevitably only have a reduced level of allegiance to the organisation that hosts them, and can easily move on. This tends to drive up wage levels within the contract companies since the supply of experienced labour is restricted, and give the contract companies an incentive to replace experienced people with more junior, cheaper people. This reduces the amount of knowledge available within the organisation.

The typical structure of a hierarchy with a low fan-out, often covering many sites that are a long way away from each other- perhaps even in different countries, can make it very easy for the management to lose contact with the people who have the first-hand knowledge of the state of the mission and the current problems. This prevents the free flow of information that is vital for taking major decisions correctly.

Chapter 4

Risk

4.1 Introduction

Every person and organisation faces risk. Risk is fundamental to the planning and implementation processes of every organisation.Risk is often treated in a negative context, but it is also the companion of opportunity. 'Business risk arises as much from the likelihood that something good won't happen as it does from the threat that something bad will happen'[12].

Some organisations, particularly in the financial sector have developed special departments to perform tasks called risk management, but few other organisations have taken such a serious approach. The literature reflects this situation: 'Even now, the literature on managing risk is slim compared to that on finance and almost without exception, it becomes preoccupied with with the management of financial risk and the use of derivatives'[3].

Risk is most often associated with insurance, but ideally companies and organisations would engineer their own approach to risk, and then seek insurance where appropriate, rather than blithely paying premiums at almost any cost. By identifying risk, risk can become another resource, and an organisation can try to distinguish itself from others in its ability to manage risk.

In the space industry, risk and risk management are often restricted to sub-issues, such as reliability and safety. However, focussing so closely on one area may leave many other areas unwatched, so that, for example, a company building a launcher may try to concentrate upon building a reliable launcher (especially after some setbacks in the development), but may fail to see the greater threats of changing markets due to over-supply or problems related to macro-economic phenomena such as currency fluctuation. More generally, risk and opportunity can be seen in the following situations:

- Finance
- Decision-making
- Process and structure
- People and Machines
- Legal and regulatory requirements
- Customer/Client needs
- Environmental considerations.

and it is management's job to ensure that the whole organisation is aware of and shares the same goals. This Chapter shows that risk management is fundamentally about people and processes, although there are many tools and techniques that can assist, but not replace, human judgement. Section 4.2 shows how people perceive risk in different ways at different times. Chapter 3 showed that one of the ways organisations can perform a task is by setting up a new project or team. Section 4.3 analyses the risk that can occur during a project or programme. Risk management is broken down into three phases, risk control, risk reduction and risk containment in Section 4.4, which shows how these techniques are used in the space industry. Section 4.5 shows in more detail risk items can be identified and the risk can be quantified.

4.2 Risk Perception

People perceive risk in different ways, so there are different types of risk. These include:

- individual risk versus organisational risk or societal risk;
- voluntary risk versus involuntary risk;
- high-probability, low-impact risks versus low-probability, high-impact risks;
- delayed impact risks versus immediate consequence risks;
- risks with low-value impacts for many, versus risks with disastrous consequences for a few;

When individuals 'voluntarily' take risks, they sometimes seem to accept rather high risks for relatively modest benefits. This can be explained by noticing that when Organisations or individuals are in 'involuntary' situations, they no longer believe that they can personally control or influence their exposure to the risk, and the perceived risk is much greater than when a person or individual is in control. One result of research into decision taking in the private sector is that decision makers tend to avoid risks rather than confronting them. Another study showed that some managers often view risk as a challenge that should be overcome through use of formal knowledge and experience. A way of reconciling these two observations would be to note that an admission of risk would then also be an admission of the lack of the latter qualities.

4.3 Risks Encountered During A Programme Lifetime

Sage [37] identified several risks present when developing a new system:

1. Technical performance risk results when the fielded system performs in a way that creates hazards or poor operating properties. A technical risk could be a risk to society or other harm that results from the way the system performs.

2. Acquisition schedule risk results when the intended entry into service needs to be migrated to some later time. This is very common in space programmes.

3. Acquisition cost risk results when the anticipated cost of fielding the system increases beyond that forecast. This is also very common with the space industry, especially in centrally-funded programmes which have little or no penalty for the introduction of delays.

4. Supportability risk arises when the operational system is unsupportable by the planned maintenance and operations efforts. This is common when the part of an organisation that operates the system is remote from the part of the organisation that procures the system.

5. Programmatic foundation risk is created by events outside the formal control of the management process. This could be due to internal factors (such as research and development difficulties) or factors outside the organisation. An example of this kind is the ESA Hermes programme, which although beset by organisational and technological difficulties, cost and schedule over-runs, was only finally terminated due to the rising costs of German re-unification[9].

It is important to note that technical and programmatic risks are generally the cause of schedule or cost risks. The latter are detected before the entry into service, whereas the technical risk is often only apparent at the entry into service (e.g. launch, hand-over). Soon after, the supportability risks become known. It is important to be able to identify the source of the perceived risk in order to implement corrective management efforts. Sage[37] also cites key potential risk areas when trying to introduce a high-technology product. With appropriate adaptation to the field of spacecraft engineering these are:

- Inadequately emerged technology, which results in a poor system;
- New systems that are not an acceptable substitute for that which they replace;
- Specification drift due to changing customer requirements, especially when the volatility was not identified;
- Technological leapfrogging by a competitive system;
- A lack of credibility, either on the part of the system or the organisation that develops it;
- Too lengthy a time scale to field a working system;
- Inappropriate standards, either because they are lacking or because they are present and conflict with other standards;
- Lack of proper infrastructure.

4.4 Risk Management

In the space industry, much emphasis is given to reliability. Reliability is the probability that a system will perform some specified function under specified conditions for a specified length of time. Risk is more difficult to define. It involves two elements:

- probability
- cost.

Although it is the author's direct experience that most organisations have some kind of risk management procedures, this seems to be used in a very narrow sense.

According to [3] in many organisations the 'Cult of the amateur' is still prevalent. 'Where it is adventurous it has too often indulged in blind speculation, leading to spectacular failure with the natural bureaucratic response of stiffening regulation'[3]. Carroll reports[3] that many commercial financial institutions generally have much more advanced risk management processes than their public-sector counterparts. However the introduction of risk management is relatively recent feature - he quotes his experience of introducing treasury management into a financial institution in 1985, which then went on to become the first in the sector to introduce risk management. There is an enormous body of literature on financial risk management, and many practices are now mandated by the regulatory authorities[1]. Carroll favours a holistic approach to risk management, extending it to the enterprise and how the enterprise interacts with its environment.

Carroll proposes a framework to allow people and organisations to evaluate themselves[3]. He present checklists and questionnaires on the following areas for individuals to fill in and answer to see how these factors impact on their organisation.

- Financial implication
- Decision making
- Process and structure
- People and Machines
- Legal and regulatory requirements
- Customer/Client needs
- Environmental considerations
- Communication requirements[3].

The traditional analytical approach to evaluating risk employs probability distributions of alternative choices. A utility function is defined which has four basic dimensions:

- The probability of winning
- Amount to win
- Probability of losing
- Amount to lose.

In most cases, management is the process of ensuring that something happens, and the aim is both to make it happen and to continue to happen. This could be, for example, to improve the quality of the product, or to improve efficiency (e.g. by reducing the resources required to perform a task). There is always a clear relation between the event (e.g. manufacturing) and the entity being controlled (time, energy, money). By comparison, risk does not have such a clear relation with events. According to Hollnagel "Risk is used to characterise a certain state of the world, or a consequence, that is (1) unwanted, (2) uncertain, and (3) in the future" [25].

Furthermore, most management systems deal with something that is monitored either continuously or periodically, but can at least be assessed on a regular basis. From the point of view of risk management, the goal is often to prevent something from happening - i.e. to ensure that the risk-initiating event does not occur, and so risk management systems must deal with something that is far from being a continuous quantity. The desired event is actually the non-occurrence of an event. The consequence of an event is the result of an event occurring, but the risk remains the same whether or not the event occurs. The consequence is uncertain until the event happens, and is always undesirable. Once the event happens (releasing the

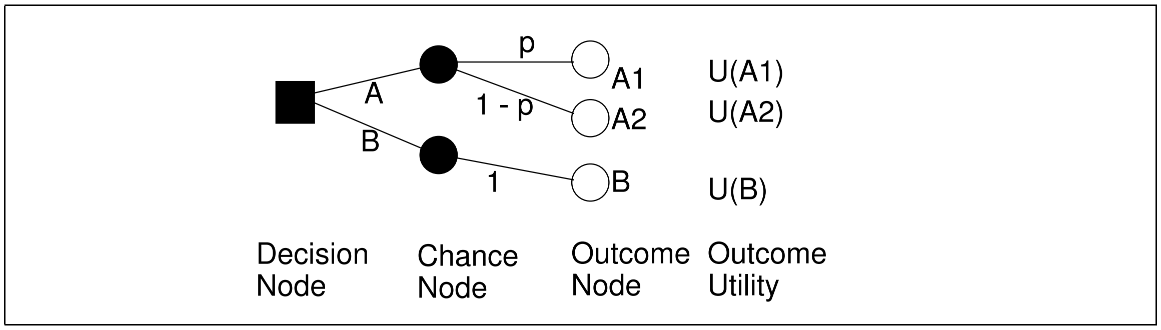


Figure 4.1: Decision Utility

consequences) we know the risk has manifested itself, but the risk remains the same (unless the system is changed).

Risk is a phenomenon with strange properties. Even though risk is always present, risk is not a continuous quantity. Risk can be calculated (e.g. a probability can be assigned to the likelihood that an event will occur) but it cannot be measured, and it does not always add. For example, when comparing the risk of an airline flight with the costs, the cost of the flight increases with time in a way that is easy to understand (e.g. fuel, interest payments, amortisation of purchase price and landing charges, to name but a few contributing factors), but most people would agree that the risk of an aircraft crashing is in general decreased every time an aircraft lands successfully.

There seems to be little doubt that risk-associated decision making is primarily influenced by responses to two questions: What are the possible event outcomes of alternative courses of actions and their valuations? How likely is the occurrence of each of the various outcomes?

The fundamentals of modelling decisions are illustrated in Figure 4.1. Following a decision, (either A or B), the natural events take their course with a probability p following decision A. The outcome after decision B is certain (p=1). Each of the outcomes then has a certain utility assigned to it. It is possible to enumerate 5 categories of decisions:

1. Decisions under certainty: $p = 1$ and the utility functions are known

2. Decisions under probabilistic uncertainty : p such that $0 < p < 1$ is known, and the utilities are known

3. Decisions under probabilistic imprecision: p is imprecise and the utility functions are known

4. Decisions under information imperfection: p may be precise, the utility functions may be imprecise

5. Decisions under conflict: the values of p and U may be changed by an opponent

It is rare that decisions under certainty involve risk, by their very nature. Decisions in category 5, conflict, in which the probabilities typically have the form of variable quantities that can be altered by the actions of a competitor, is typical of game theory. This is a situation which is mercifully rare in satellite engineering. The aim of decision assessment is to provide a framework for describing how people choose, or should best choose, when the outcomes that arise from those decisions are obscured by lack of information or the presence of uncertainty. Behavioural psychology can provide information concerning both the decision process and the judgment process. System modelling should in principle allow the decision to be represented in a clear way, and probability theory allows, in principle, the decision maker to make best use of the information available. Utility theory guarantees that the choice will reflect the declared preferences of the decision maker, if everything has been modelled correctly!

A theory of choice is said to be rational if it involves giving numerical measures to these probabilities and values, and aggregating these numbers into a single figure of merit that the decision maker should maximise in order to obtain the best strategy. In classical gambles, outcomes are simply different amounts of money, and often the probabilities of the various outcomes could be calculated from simple models with easily determined objective probabilities. In system engineering then, the objective probabilities are often subjective, and the simple value of an event needs to be replaced with the decision maker's subjective utility.

The classical formulation for maximum expected utility has a number of inherent difficulties. Cost/benefit must be integrated to produce a single number, which is then multiplied by the probability of that outcome. While this makes the computability more easy, it brings the associated problem that it is difficult to distinguish between a situation where there is a small (almost zero) probability of a very large loss, or a very large probability (nearly one) of a small loss. Another factor that is not considered is the immediacy of the result. Most people would be much more reluctant to accept a 0.001 probability of loss of life tomorrow than a 0.001 probability of loss of life over the next 20 years. This seems to indicate that some kind of integrated probability (potential) must be introduced.

Hollnagel[25] defines three different ways to manage risk according to the different parts of the life cycle. These are illustrated in Figure 4.2.

- Risk Control
- Risk Reduction
- Risk Containment

4.4.1 Risk Control

Risks can be controlled at the operational level (i.e. day to day) or at a management level. The principal difference from risk reduction is that risk control takes place when the system is already operational. Control thus tends to be tactical rather than strategic. Although this is appealing, it is a difficult practical concept since risk itself cannot be directly measured. For spacecraft operations, this would mean, for example, using existing procedures, even though a new procedure with a short-cut might be desirable, or using established hardware rather than innovative technology.

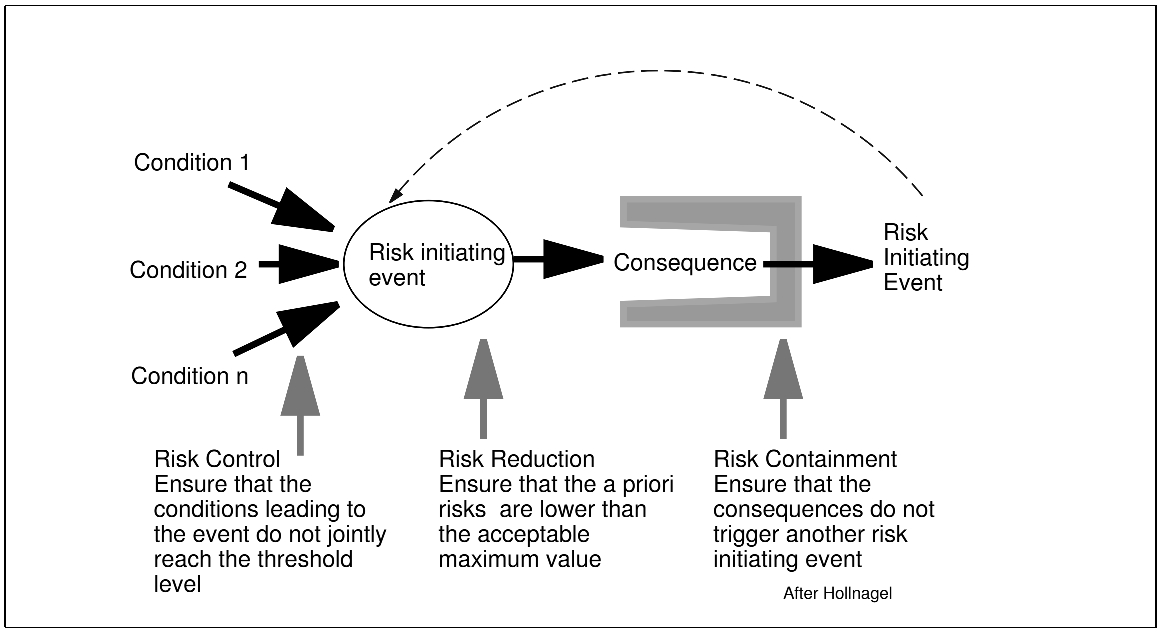

Condition 1
Condition 2
Condition n
Risk initiating event
Consequence
Risk Initiating Event
Risk Control
Ensure that the conditions leading to the event do not jointly reach the threshold level
Risk Reduction
Ensure that the a priori risks are lower than the acceptable maximum value
Risk Containment
Ensure that the consequences do not trigger another risk initiating event
After Hollnagel

Figure 4.2: Risk Management(after Hollnagel [25])

4.4.2 Risk Reduction

This is normally achieved by design improvements, often to the physical system, but also to the operating environment or the organisation, e.g. the distribution of roles and responsibilities. The aim is to get the risk below the maximum acceptable risk e.g. designing a system that has no known single point failures.

4.4.3 Risk Containment

This aims to contain the consequences engendered by an event, should it ever occur. This could be physical containment (e.g. steel/concrete containment vessel) or functional (a crash barrier to stop a car that has already suffered an accident from crossing into the on-coming traffic and causing further injury or loss of life). For spacecraft operations, this could be having extra support staff available during periods of critical operations, or using control systems with 'hot' redundancy (with two or more systems running in parallel, each capable of performing the whole task) instead of 'cold' redundancy (a replacement system is available but is not running and needs to be started in order take over control), or performing critical activities during periods of double ground station coverage.

4.5 Risk Analysis

4.5.1 Prospective Risk Analysis

This is a classical approach which places emphasis on risk reduction, which can be described as assessing the risks inherent in a system in order to decide whether or not they are below the limit of acceptable risk. This can be done by calculating the risk of specific events and predicting the likely outcomes. This is the classic Failure Modes, Effects and Criticality Analysis, FMECA. Risk containment extends this technique to look further downstream in a fault tree in order to consider the range of potential consequences of an event. This enables the responsible authorities to identify those events which may lead to serious consequences, and also to become aware of (and hopefully restrict) the possibility for one event to have consequences which trigger other events. The third part of risk management that was identified above, risk control, plays a smaller part in prospective risk analysis, being largely incorporated in risk reduction.

4.5.2 Retrospective Risk Analysis

The main emphasis is upon risk control, the aim being to identify all the conditions that jointly led to the risk-initiating event. Analysis of an incident that has already taken place provides a full understanding of what happened and the opportunity to learn. It should

- provide a probable root cause (or causes);
- identify which changes could prevent a re-occurrence
- update the data (i.e. probabilities) and methods that were used in the initial analysis.

Risk reduction and risk containment play only minor roles in a retrospective analysis, since the event has already happened. This is the classic Board of Enquiry.

4.5.3 Synchronous Risk Analysis

Hollnagel [25] proposes that a third type of risk management be studied, which he refers to as Synchronous Risk Management. Admitting that ideally retrospective risk analysis would not be needed, since there would be no accidents, he suggests that prospective risk management be continued into the operational phase. This would make it more similar to a conventional control system, in that it would monitor the relevant parameters of the system to find discrepancies, and then provide advice principally in the area of risk containment.

All three of the techniques mentioned above require an adequate basis for modelling. Each analysis is based on compound elements, assumptions about those elements and the relations between them. The relations between them would typically be of the cause-consequence type which could either link causes to consequences or consequences to causes. The analysis is based upon a simplified representation of the plant, and the two major questions that must be asked (and answered) during the model development are: what should be modelled and how should it be modelled?

For many many years it was believed[37] to be sufficient to confine the model to the hardware elements used within the system. Initially this could provided much useful information, but in many fields (and satellite engineering in particular), the reliability of the individual mechanical and electrical components has increased significantly, and it was realised that in many incidents, software systems with a human operator played an important role in how the risk initiating events occurred and developed.

It can be very difficult to model the failure modes of a software system, but some qualitative analysis can normally be performed to define some kind of boundary. For example, if the system needs to be restarted, or even completely re-installed, this should be included as a case that subsumes a number of smaller failures. However, a more difficult case to model is what happens when the software performs 'correctly' (i.e. as specified) and no failure is identified, but the wrong action was initiated. In this case software systems must be treated like their human counterparts.

Initially the human operator was incorporated into a system model by treating the human as a machine. Although difficult to justify now, it seems as if this was done because it was

- the established practice
- there was a lack of usable alternatives.

Subsequent research, and a number of high profile incidents, eventually led to the ability to analyse and describe human cognition. This proved that human errors, which had previously only been treated at the operational level, could also arise at the management level. "Factors such as training, work demands, time pressure, availability of the procedures, design of the work place and quality of information display all turned out to have a direct effect on the probability of errors occurring" [25].

Management factors affect the likelihood of errors in a number of ways. Some factors, such as training policies, procedures, equipment or work planning, have an indirect effect, whereas other factors, such as organisational culture that the management creates (and is part of) or the priority that organisation assigns to safety and productivity can have direct effects. Models must be able to account for the dynamics of how an event can develop, as well as the statics. The dynamics are needed to account for the interaction between people and between people and machines.

Although different researchers may emphasise the technological, the psychological/cognitive or the organisational/contextual parts of the system, the consensus of opinion is that a model must include all three aspects. Models that consider only one factor will not suffice.

4.5.4 Modelling Techniques

Technology pushes onwards relentlessly to change the way we work - whether there is a need to change or not. For risk management this has two implications. Firstly the target systems that are being analysed change due to the introduction of computers. This means that risk management method must be able to to model and analyse the effects of computerisation. Secondly, perhaps necessarily in response to the complexity of the target systems, risk management techniques have themselves become computerised. Manual methods (which includes methods that use computers for text processing or type setting) have always suffered from the fact that analyses are necessarily incomplete. Even for a very simple system it is just impossible to investigate all possible conditions and combinations of conditions. There is a clear reason for wanting to introduce the symbol processing capabilities of computers. But this potential advantage also has an associated cost, since the introduction of computers will bring a further layer of complexity to the analysis and may therefore increase the imprecision and uncertainty, exactly the opposite of what was intended. Hollnagel [25] refers to these as Scylla and Charybdis, two monsters from Greek mythology who lived on either side of the Strait of Messina. Scylla seized sailors and devoured them, and Charybdis, the whirlpool, created shipwrecks.

Manual Analysis

When compared with prospective risk analysis, retrospective risk analysis has two advantages. Firstly, uncertainty is virtually eliminated because the event has happened. Some imprecision may remain if it is difficult or impossible to get all the required data. Secondly, there is ample time. The investigation of an air accident may last for years and can focus upon a single event. In contrast, a prospective analysis usually needs to be completed before a certain deadline, often when the system become operational, and has to consider not one but all possible events. A retrospective analysis typically relies upon risk control and thus starts with the consequences and identifies the (chain of) events that gave rise to them. This can run into problems when the causal reasons are complex. A natural reaction is to stop the analysis at an arbitrary point or to make simplifying assumptions to allow the analysis to continue. It is in any case difficult to justify a particular stopping point. Prospective risk management relies mainly on risk reduction, which depends on the ability to correctly predict the consequence of a particular event. Here the limitation is that event trees can easily become too large to be analysed manually - or even displayed - unless some simplifications are made.

Computerised Analysis

The attraction of computers is that they can handle models that are more complex and that they can do so faster and more reliably than a human. It is tempting to use the same manual methods on a computer, but simply transferring the existing methods will not be enough to overcome the combinatorial complexity of even a simple system. Even the results of e.g. playing chess by brute-force suggest that much optimisation is necessary in order to make significant progress, as well as a great deal of domain-specific knowledge. But most risk analysis methods require a substantial input from an experienced human in order to work, whether this involves interpreting incomplete data, inventing assumptions or conditions or seeing in which sense the event trees should be developed. A hybrid system would aid both prospective and retrospective analyses.

For retrospective methods, the identification of links in the event chain by a human can be improved because more alternatives can be easily tested. Similarly the thoroughness that a retrospective analysis requires is also better provided by computers, even if this only extends to book-keeping.

Prospective analyses can be significantly improved by the use of computerised predictions or simulations. Even a limited dynamic system can produce much richer results than those of a manual, necessarily static, analysis. Even though computerised analyses need not per se be more correct than the corresponding manual work, the fact that the results differ should be a ground for fruitful discussion.

While computerisation obviously holds out promise, it suffers from the two usual shortcomings associated with information technology. It is easy to become blinded by the computer and to not really understand what it does. There is a strong bias to take the output of a computer as real, especially if that output is presented in a convincing fashion. Secondly, there is the familiar problem of verifying and validating what computers do. Most systems are verified on a very small data set. For retrospective risk analysis it may be possible to 'calibrate' the computerised method on known cases, but this does not ensure that the results will be correct in other situations. For prospective analysis, there are by definition no test cases on which the system could be tested. In summary it seems therefore that the choice between manual and computerised risk management is a choice between incompleteness and inaccuracy.

4.6 Summary

This Chapter has shown that every person and organisation faces risk and that risk is fundamental to the planning and implementation processes of every organisation. More generally, risk and opportunity can be seen in the following situations:

- Financial implication
- Decision making
- Process and structure
- People and Machines

- Legal and regulatory requirements
- Customer/Client needs
- Environmental considerations
- Communication requirements[3].

Risk management is more oriented towards people, processes and human judgement than safety and reliability, although these are important factors. Section 4.2 showed how people perceive risk in different ways at different times. Section 4.3 showed some of the ways risk can occur during a project or programme, which is one of the way that an organisation performs a task or reaches a goal. Section 4.4 broke risk management down into three phases, risk control, risk reduction and risk containment and showed how these techniques can be applied in the space industry. Section 4.5 showed how risk events can be identified and the risk can be quantified.

Chapter 5

Ground Segment Preparation

5.1 Introduction

As mentioned in Chapter 1, since the satellite is often being operated by a different organisation to the one that built or integrated it, somehow the people responsible for operating the satellite must be trained and prepared for their forthcoming tasks.

The satellite database is one of the most important interfaces between the satellite constructor(s) and the satellite operator(s). This is discussed in section 5.2. This section explains the sound theoretical basis for a relational structure, as well as discussing several other structures prevalent in European spacecraft control centres.

As outlined in the Chapter 3, the users require skill-based, procedure-based and knowledge-based behaviour. The User Manual is one of the terms used to describe the documentation that the spacecraft developer is supposed to deliver to help the end-users understand and operate the spacecraft and payloads safely and successfully. The User Manual should be the source of procedure-based and knowledge-based behaviour. This is discussed in section 5.3. The procedures are used for the routine work, and the structure of the flight control procedures is discussed in section 5.4.

According to the author's experience, spacecraft (or a family of spacecraft) are frequently being procured as part of a whole system, which often has a very large ground segment that needs to be developed, maintained and operated in parallel to the space segment. Section 5.5 discusses how the spacecraft database is validated through a series of tests between the ground segment and the space segment, which are frequently called System Validation Tests in Europe.

The role of simulations in preparing the individuals and teams mentioned in the previous Chapter is discussed in section 5.6. It shows how they are useful in preparing the individuals to cope with the stress of operational situations, as well as forging a team.

Since satellites are normally only procured by large organisations, there is normally a formalised process for checking the progress at various phases in the procurement and operations. These are referred to as reviews. They are important since it gives management an opportunity to investigate the current status of the programme, and also forces management to take a position on various items that are flagged as risks to the programme. However, this only operates correctly if the correct data is made available to the correct people. As mentioned previously, in large organisations with extensive hierarchies, this can be very difficult to achieve, and there is a danger that the reviews may become so formal that the people who have the working knowledge may not feel that they are able to participate in this process. This is discussed in section 5.7.

5.2 Satellite Database

The satellite database is one of the most important interfaces between the satellite constructor(s) and the satellite operator(s). Although there can be more important interfaces to convey the information from one party to the other, the satellite database is important because it is unambiguous and relatively concise. If an appropriate database system is used for its creation and management (see the following)

ID	Description	Units	High Limit	Low Limit	Width	Byte Offset	Bit Offset
A123	ES1 Status	None			1	45	6
A124	ES1 Voltage	Volts	4.5	5.2	16	46	0
B100	CPU Voltage	Volts	4.5	5.5	16	48	0

Table 5.1: Example Telemetry Parameter Characteristics Table

then it is relatively easy to check the completeness. A textual description may convey more understanding of how a system or unit works, but it is difficult to check it for completeness. A relational database is far easier to check for completeness and correctness, whereas arguments about the largely textual User Manual may easily degenerate into differing opinions about how to explain a piece of text or even whether or not it is relevant. With a database system the goal, at least, is usually clear, even though many implementations fall short of the ideal. It is thus interesting to examine where this strength in a database system comes from.

At the simplest level, a database system is simply a computerised record-keeping system. At first glance, a simple file system may seem to perform the same tasks, and so one can imagine a simple file (e.g. a text file containing values separated by commas) with the contents shown in Table 5.1. However, it simplifies the discussion if we initially consider only a hypothetical system, without being constrained, for the time being, by any implementation details.

The title provided in the first row may or may not actually be present in the file. Usually it is preferable for it to not be there, and it is provided here only for ease of reference. The data within a particular file is referred to as a table, for fairly obvious reasons. The rows of such a table can be thought of as representing the individual, logical records of the database. Likewise, the columns can be regarded as representing the fields of those logical records. Even from a simple example as this, several questions arise: What is in Byte Offset 45, bit 7? What byte and bit numbering convention is used? Where is Byte 0, in the telemetry transfer from header or the data field? Where is bit 0, and which way does the numbering increase? If parameters A124 and B100 are 16 bit values, are they byte swapped? Is there a calibration curve to show the relation between analogue (calibrated) value and the bit pattern (raw value)? The ESA Packet TM Standard defines the answers to some, but not all, of these questions. It is difficult to accept that a textual description of the same data would have generated as many questions, since it was the format of the presentation that rendered the gaps so obvious.

5.2.1 Why a Database?

Even though the examples given here are trivial, it most be obvious that most of the advantages detailed below become ever more significant as the database increases in size.

1. Currency: Up-to-date accurate information is available on demand.
2. Less drudgery: The sheer tedium of maintaining files by hand is eliminated, and the quality is improved.
3. Compact: No need to wade through voluminous paper files or archives.
4. Speed: A machine can retrieve (and change) data faster and more accurately than a human can.
5. Availability: usually more than one user can access the database at one time (although there may need to be some restrictions).

This means that most databases are multi-user, and in any case, the goal of most multi-user systems is to allow each individual user to behave as if she were working with a single user system. Redundancy can be controlled: in a non-database system, each application (or, for example, employee) has its (her) own private files. This can often lead to a considerable redundancy in stored data. For example, consider the simple case where a supervisor prints off a schedule for the two-week period, starting in one week's time, and distributes 12 copies to her team. During that three week time period in which the plan has (or may have) validity, all changes will need to be marked up one by one by each employee individually. If each member does not rigorously incorporate all changes, as they become known, then the team will be operating on the basis of an incoherent data set. This might mean that on one particular day, two people turn up, or worse, that one day nobody is available to perform the necessary tasks. Here the redundancy has introduced an inconsistency. This is always a risk when data is replicated in an uncontrolled manner. It can be equally disastrous whether applied to an operations schedule, design documentation, or telemetry processing information.

By using a database management system (DBMS), the data can be shared between users without introducing inconsistencies, and, furthermore, new applications can be developed that operate against the same data. In other words, this means that it may be possible to develop new applications without having to add any new stored data. This facility can act as a sort of 'future proofing', reducing the effort of introducing arbitrary new functions in the future.

Standardisation of data storage comes as an easy by-product of using a DBMS. This could include corporate, departmental, national or international standards. Data standardisation is particularly desirable since it aids data interchange and the migration of data between systems. It thus becomes easier to upgrade the system. Since a single DBMS can provide complete control over the database, its use can ensure both that the only way to access the data is through the formal channels, and can also define security rules to be checked whenever any access is made. Different rules can be defined for reading, writing, insertion, etc., on different levels of data: Table, report, query etc. Note, however, that without such rules, the organisation might be exposing its data to greater risk than in an uncontrolled, uncentralised system, so a DBMS not only permits but also requires a good security system to be set-up.

5.2.2 Why relational?

A relational database is basically just a database where the data is perceived by the user as tables (and nothing but tables) and the operators at the user's disposal (e.g. for data retrieval) are operators that generate new tables from old. For example, there will be one operator to extract a subset of rows of a given table, and another to extract a subset of the columns - and of course a row subset and a column subset of a table can bother in turn be regarded as tables them selves.' [8]. The name 'relational' is just a mathematical term for a table that satisfies certain conditions. It is now very common for the terms 'relation' and 'table' to be used as synonyms, and in many cases they are. However, the relational model [7], formulated by Dr. E. F. Codd, a researcher at IBM, deliberately introduced new terms that were not in wide-spread use in computing circles at the time. This was because many of the terms in use, such as table or record, meant different things to different people, and thus lacked the precision that Codd wanted for a formal theory. For example, the term 'record' could mean a programming structure, a logical or physical storage structure or a type definition. Thus the relational theory avoids the use of the term record completely: it uses the term 'tuple' (short for 'n-tuple').

Relational theory is a combination of set theory and first-order predicate logic. The first element to be defined is a domain. A domain provides a set of scalar values from which a relation can take its actual values. Domains are the smallest semantic unit of data i.e. they have no logical internal structure as far as the DBMS is concerned. For example, a database of employees might include an employees name as a string "DAVID", which consists of a sequence of characters, but by decomposing the name into the individual characters, we lose the meaning. A domain is a named subset of scalar values, for example the set of all possible names. Thus domains are pools of values, from which actual attribute values can be drawn, and a domain is really nothing more than data type, as the term is used in modern programming languages. For example, the following is a legal fragment of the programming language Ada:

```
Type DAY is (MON, TUE, WED, THU, FRI, SAT, SUN);
Subtype DAY_OF_MONTH is INTEGER range 1 .. 31;
```

Most DBMS available today provide only limited scope for domains as Codd defined them. Instead, they provide the ability to characterise attributes as being one of a small range of primitive data types. These could include floating point numbers, integers of various ranges, or character strings of a defined length. A relation has two parts: a header and a body. The header is a fixed set of attribute-name/domain name pairs: $\{ < A_1 : D_1 >, < A_2 : D_2 >, \ldots, < A_n : D_n > \}$. The attribute names $A_1, A_2, \ldots, A_n$ are all distinct. In the informal representation, the header corresponds to the column headings. The body consists of a set of tuples. Each tuple consists of a set of attribute-name/attribute-value pairs: $\{< A_1 : V_{i1} >, < A_2 : V_{i2} >, \ldots, < A_n : V_{in} > \}$ $(i = 1, 2, \ldots, m$, where m is the number of tuples in the set). In each tuple, there is precisely one attribute-name/attribute value pair for each attribute in the heading. The value m is called the *cardinality* of the relation, and the value n is the degree of the relation. In informal contexts it is normal to omit the attribute names from the table, because we have an informal convention that says that each individual value in the table is actually a value of the attribute whose name appears at the top of the column.

Much as the image of a table is sometimes useful, it also suggests some things that are not true. It suggests, for example, that the tuples (the rows in the table) are in some top-to bottom order, but this is not the case. It could also suggest that the columns have some predefined order. This is also false. The columns may be moved into any order, as long as the headings are moved at the same time as the attribute values. The number of attributes in a given relation is called the degree, or sometimes the *arity* of the relation. A relation of degree one is called unary, degree two is called a binary relation, and an arbitrary relation of degree n is called an n-ary relation.

It is tempting to think that a unary relation can simulate a domain, because a domain looks like a table with one column. However, there is an important difference: domains are static, whereas relations can change over time. Note also that domains contain all possible values of the relevant attribute.

Several properties follow from the definition of a relation.

1. There are no duplicate tuples. The body of the relation is a set, and sets, by definition, include no duplication (Note that the database language SQL (originally Structured Query Language) [27] does permit tables to contain duplicate rows, but this means that SQL is not a purely relational language. This is probably attributable to the compromises necessary to get a standard approved in the real world when there is already a large installed user base). It follows from the absence of duplication that every relation has a candidate for a primary key. Since tuples are unique, at least the combination of all the attributes can (if necessary) serve as a primary key, and usually some lesser combination is adequate.

2. Tuples are unordered, top to bottom. As before, this property follows from the fact that the body of a relation is mathematical set, which is unordered.

3. Attributes are unordered left to right. This follows from the fact that the header of a relation is a set, which, of course, is unordered.

4. Attribute values are atomic. This means that every individual attribute does not contain any structure, i.e. there is never a collection of values. This can

ID	Description
A123	ES1 Status
A124	ES1 Voltage
B100	CPU A Voltage

Table 5.2: Example Database Table

also be restated as 'relations do not contain repeating groups'. A relation that satisfies this condition is said to be normalised, or in First Normal Form (FNF). This implies that as far as relational theory is concerned, all relations are normalised. The point is that it is easy to propose table structures that are not normalised, especially if new information is added without due attention being paid to the meaning or context of the information.

5.2.3 Relations and Predicates

Every relation has an intended interpretation or meaning. This meaning may be made available to the other users of the RDBMS by naming a table, although the name is used only as a label within the operation of the RDBMS itself. Consider the (fictitious) relation illustrated by table 5.2, and let ID be the primary key.
The meaning of the relation defined by this table could be approximately put into English as:

> there exists a relation between telemetry parameters and descriptions such that every parameter has a unique identifier (ID) and the telemetry parameter with the identifier ID can be described by the text in the Description field.

This statement can be regarded as a predicate with four arguments, which yields a proposition that is either true or false. At any one time, the relation contains exactly those tuples which make the predicate evaluate to true. It follows that when a tuple is presented for insertion into the relation, the DBMS should accept

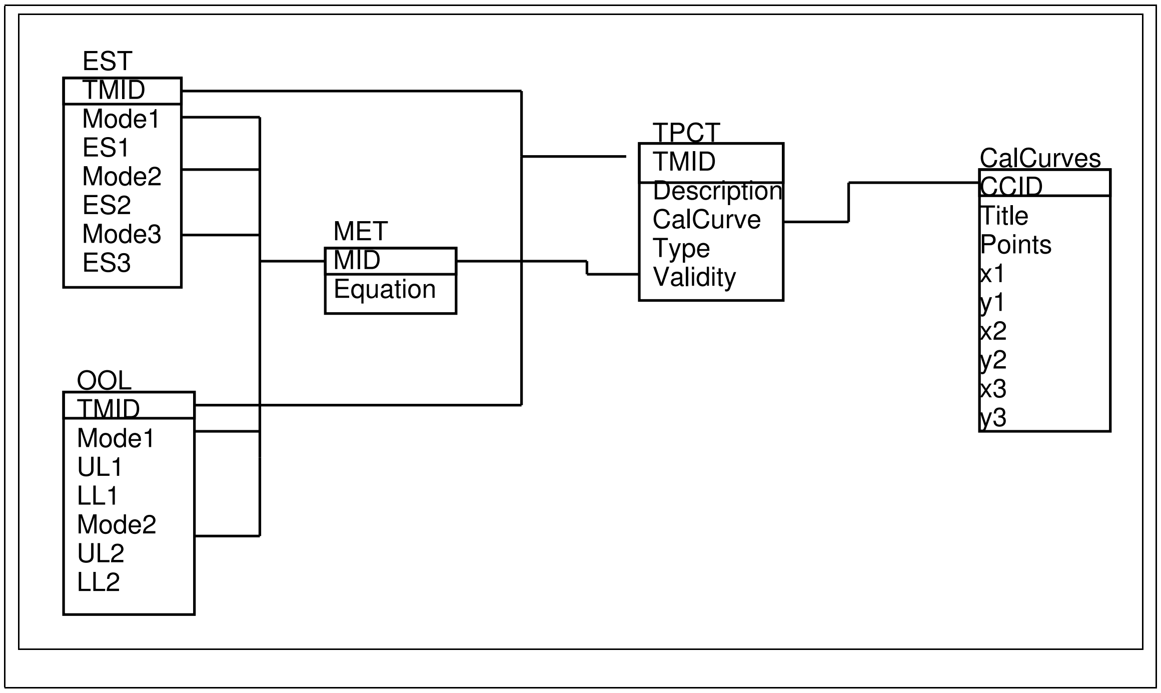


Figure 5.1: Initial Database Schema

only those tuples which make the predicate evaluate to true. This is the theoretical soundness that makes the relational model so robust [8].

A relational database is also ideal for defining interfaces. If a RDBMS is correctly normalised, then adding a relation (table) can easily incorporate further changes. Compatibility is a minor problem: either the relation exists or it does not exist. However, if the interface is a data structure that does not follow the relational ideal, then modifications may be required to an existing relation. This could mean, for example, changing the field width in a table, or more usually, adding or changing a field within a table. This means that compatibility becomes a major problem: the old table is not compatible with the new one, and databases in different places need to be changed synchronously.

5.2.4 Example Telemetry Database

Let us examine an example database in detail (see figure 5.1). The Telemetry Parameter Characteristics table (TPCT) is supposed to include all of the information pertaining to an individual parameter. It includes a description field, some type information (e.g. floating point, signed integer, unsigned integer) and a field to identifier which Calibration Curve that should be used to convert a raw digital value in telemetry to an engineering value (e.g. to a temperature in Celsius). This example database also includes a table of Mode Equations, in the Mode Equation table (MET). Mode equations are assumed to be a simple combination of logical operators on existing telemetry parameters, e.g. a certain Mode might become true when a redundant earth sensor is in use. This mode might then be used to show that angular measurements from the redundant sensor are valid. The validity mode should appear in the Validity field of the TPCT. The remaining tables are the Out of Limits table (OOL) and the Expected Status Table. Both the OOL and the EST are indexed by the field TMID.

The OOL can be used to define a normal operating range for a parameter. This could be, for example, the fact that a prime sensor was expected to be in use, and if ever it was found to be OFF, an alarm should be raised. An alternative, and perhaps better example, would be to define limits to analogue parameters, so that an alarm would be generated whenever an equipment item got too hot or too cold. An example usage of the EST would be to say that if the redundant earth sensor were selected, then one would normally expect a redundant processor to be in the status ON. Thus if the redundant processor was OFF and the redundant Earth Sensor was in use, an alarm should be generated and the operator would have to react to the situation.

The structure that is shown above is fairly typical of that used in control systems throughout Europe, being similar to that initially developed at the European Space

Agency's Space Operations Centre, ESOC in the 1970s and subsequently spread around Europe under ESA's rather flexible licensing structure. There are, however, a number of problems inherent in such a structure. First of all, let us examine the Calibration Curve Table, CCT. It is obviously not normalised.

Normalisation is the process of efficiently organising data in a database. It has two goals:

- Eliminate redundant data (for example, storing the same data in more than one table)
- Ensure data dependencies make sense (only storing related data in a table).

The database community has developed a series of guidelines for ensuring that databases are normalised. These are referred to as normal forms and are numbered from one (the lowest form of normalisation, referred to as first normal form or 1NF) through five (fifth normal form or 5NF) or sometimes even higher.

First normal form (1NF) sets the very basic rules for an organised database:

- Eliminate duplicate attributes from the same table.
- Create separate relations (tables) for each group of related data and identify each tuple(row) with a unique attribute or set of attributes (the primary key).

Second normal form (2NF) further addresses the concept of removing duplicate data:

- Remove subsets of data that apply to multiple tuples of a table and place them in separate rows.
- Create relationships between these new tables and their predecessors through the use of foreign keys.

Third normal form (3NF) goes one large step further:

- Remove attributes that are not dependent upon the primary key.

Finally, fourth normal form (4NF), also known as Boyce-Codd normal form (BCNF) has one requirement:

- A relation is in BCNF if and only if every determinant is a candidate key.

These normalisation guidelines are, of course, cumulative. For example, for a relation to be in 2NF, it must first fulfill all the criteria of a 1NF database. A clear warning of lack of normalisation is when attribute descriptions have numbers, e.g. x1, x2 etc. Calibration curves can usually have different numbers of points, a maximum of 16 points being typical, although only 5 have been shown here. This is why an entry is also required to say how many points contain meaningful data. If a calibration curve only contained 2 data points, the remaining points would be empty! Although this is an acceptable waste from a resource point-of-view since satellite databases are typically very small, with perhaps 5000 TM parameters, of which 500 might require calibration curves, it is an unnecessary evil.

As outlined in the guidelines, the standard way to normalise such a table is by splitting it into one or more tables. This is shown below. There are no extraneous indices or flags. For a given calibration curve there can only be one engineering value (y) associated with each individual raw (x) value. Furthermore, if, for example, on the previous architecture, it was desired to enter a new point between existing points, some of the existing points need to be moved, i.e. re-numbered. This is not necessary after the improvement. A point can be added anywhere in the calibration curve. A further difficulty is in the relation between the TPCT and the CCT. Not all parameters have calibration curves (e.g. a simple counter, or a status parameter will not need a calibration curve) and one calibration curve can be used by more than one parameter. This again leads to a situation where one of the fields in a table can contain a null value, and sometimes a meaningful piece of information. This is the crux of relational theory. There are no special flags linking one table to another. The tables are simply files that behave according to certain rules. It is in

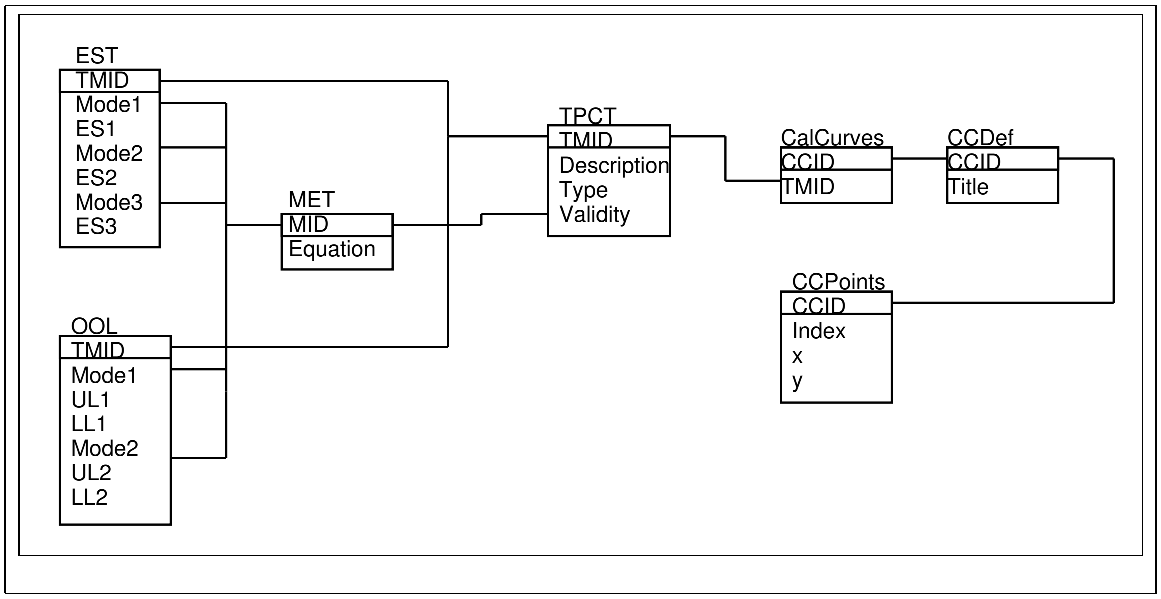


Figure 5.2: Corrected Database Schema

fact completely wrong to have a field that can sometimes contain null data. The correct procedure is once again to build a new table to link the two previous tables. This contains only the TMIDs that have entries in the calibration curve table. An updated datebase schema is shown in figure 5.2.

A similar set of problems exist in the OOL and EST. Not all parameters have out of limits values or expected statuses, and the TMID has been correctly used so as to form part of the key for these tables. However, once again, some of the attributes have names with numbers: Mode1, Mode2 etc. This is a clear indicator that things must be changed. The first step is to take advantage of the fact that for each TMID, a mode value can occur only once. The two values combined can constitute a primary key for the table. This gives two tables. Most of the MSSS:Multi Satellite Support System and SCOS:Spacecraft Control and Operations System based systems that inherited the ESOC design had a rather subtle feature that is distinctly non-relational. The order of definition of the limits and expected status was important! The telemetry processing software applies the limits in the order that they appear in the database, one of the things that is expressly forbidden in relational theory. This extra feature can be made explicit by introducing an 'index' parameter

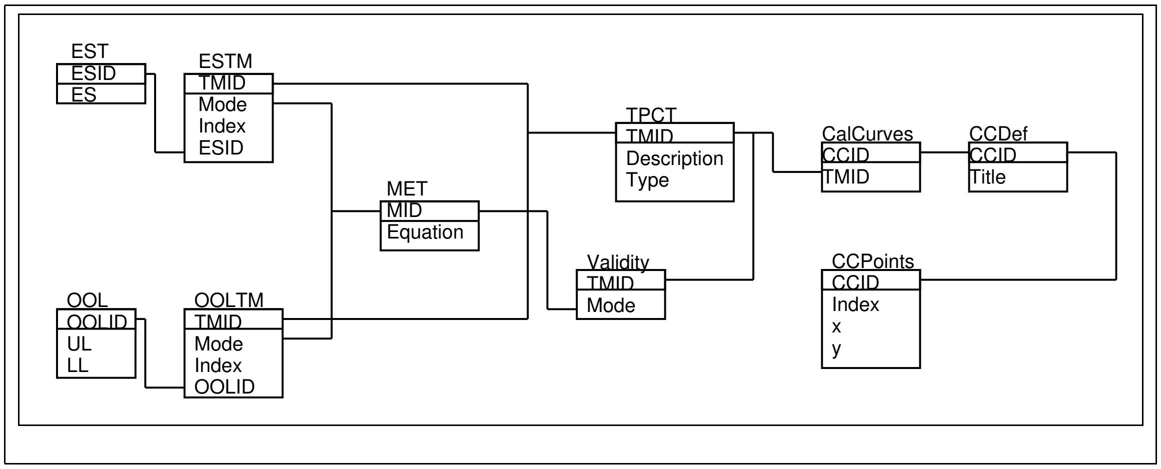


Figure 5.3: Completed Schema

to be used to show in which order the checks should be applied.

The next potential improvement is to allow for the fact that telemetry parameters may have similar limit sets or expected status sets. For example, if individual cell voltages are available, they will usually be identical. This means that perhaps 120 limits (if there are three batteries of forty cells each) will be identical. This can be performed by allowing a limit set to have an identifier. It is important to emphasise that this places no restriction upon the ability of the user to define any possible limits upon any telemetry parameter. It is simply an opportunity to reflect a real-life situation in the relations in the database structure. Any sensibly defined editor would make such changes transparent to the user. The well-protected user does not need to act upon the tables directly. She/he can access the contents of the database via forms populated with suitable queries that access the tables. These changes are shown in figure 5.3.

5.2.5 Discussion

Some of the changes that have been made to the initial database may be perceived as being cosmetic, but they brought about a substantial increase in the robustness of the database, without necessarily changing the interface for the user in terms of data entry forms or printouts. For example, in the initial case, consider what would have happened if a parameter did not need a calibration curve. In the field for the calibration curve identifier in the TPCT, there would be a null. Now consider the case when someone enters a calibration curve number in that field that does not exist. Either we accept that the database can be inconsistent for a while, or we have to write some software to check one of the other tables and to trap this error if it occurs. If the database is only single user, this is possible, but if many users can write and read from the database, either we need to take a very defensive view point and lock all records, making the database single user for a short time, or we accept that people risk working with an inconsistent database. In the relational model, flags which indicate that an item is present in another table are simply not necessary, and such a mistake is not possible. However, then it becomes important to understand the relationships between the tables. Indeed, the relationships between the tables are just as important as the contents of the tables.

5.2.6 Object-oriented Databases

Nobody who has been in contact with information technology in the last 10 years can have escaped the latest fashion, object- orientation. The general idea is that object-oriented languages enable people to program at a higher level of abstraction. Rather than dealing with bits and bytes, or integers and records, people can encapsulate a certain amount of functionality and data together to make an object. The object (some languages prefer to talk about instances of an object) can only be interfaced through a predefined set of messages. The advantage of encapsulation is that it allows the internal representation of objects to be changed without requiring any of the applications that use those objects to be rewritten - provided of course that any such change in the internal representation is accompanied by a corresponding change to the code that implements the applicable methods. In other words, encapsulation implies data independence.

Object-oriented languages have managed to tame, to a certain extent, the massive complexity of tangled computers and protocols that are used in modern user interfaces. Almost inevitably there has been trend to start using them first, to interface with databases and then within databases. The current fashion is to actually 'store' the objects in a database, however there are a number of 'standards' for doing so, none of which seem to be wholly satisfactory. There is no clear definition of what constitutes an object (some answer "Everything!"[38, 8], some exclude integers[6], some exclude strings etc. etc[35]). Moreover, difficulties exist in interconnecting object-oriented databases in a way that is not a problem for relational databases. For example, if an object is identified by an Object Identifier in one place, it is not at all clear if the same set of data should have the same Object Identifier when it is replicated to a different site or be assigned a different one [8]. The author's professional experience in this area is that in order to get differing object-oriented systems to communicate, an extra layer of software (often referred to as "middle-ware" is required. This can further chain the database, which should be a logical model, to a particular technology, which is a major disadvantage for the overall maintenance.

ESOC has developed (yet another) new generation control system [20] that is object-oriented, but all of the current control systems store the "Mission Information Base" (new generation terminology for the database) in a relational database, albeit that because so many tables were carried forward from a previous system, the tables are still far from normalised.

5.2.7 Run-time Databases

Historically, telemetry processing was so computer intensive that it could not always be performed in real-time. In order to minimise the computational effort, the information in the database was de-normalised, spread out into a form that was easier to access from the control system. This normally meant that after a change to the database had been made, a separate distribution had to be performed. This might have required anything from a short pause in telemetry processing to a restart of the system software. Operationally such a two phase system is highly undesirable. It brings with it separate problems about version control (when was the distribution started? Did my changes get incorporated?) and traceability (what was in the database when this parameter went out of limits?).

Since processor speeds are now so much greater, there is little justification for the run-time distribution, but many systems are so locked in the past it is a major change to upgrade them. For example, one previous system was hosted on a machine that was so fast that it was only ever possible to see any CPU usage when one of the tasks was stuck in a loop. The rest of the time it was using less than 1% of CPU.

5.2.8 Database Summary

With the current level of technology there is no significant benefit in moving to leading edge technology (often rightly referred to as the bleeding edge). Much benefit could be obtained by the operations engineers having a much greater knowledge of the intricacies of the database and the reasons for its current architecture.

5.3 User Manual

The User Manual (or Operations Handbook, ORH) is supposed to describe everything that it is necessary to know about an instrument or subsystem. In short, it should describe:

- what it is,
- how to operate it,
- what to do if things go wrong.

It normally consists of a mixture of plain text, diagrams and pictures. Often the prime contractor is required to make a presentation on the satellite and sub-systems. There are a number of limitations with the attempt to transfer knowledge by means of the User Manual.

1. Normally the documentation has to be supplied in English, but none of the remaining prime contractors in Europe are actually in Britain. Consequently the UM is often written by people whose first language is not English, and it is often poorly written and poorly structured.

2. Often the UM is prepared and delivered late in the project. The prime contractor has schedule pressures from a number of sources, and the UM is a low priority. Nobody will delay the launch because the documentation is not ready.

3. Few engineers enjoy writing about what they have already developed, and often do not see it as part of their main functions.

4. The writing of the UM tends to get passed down to junior staff who often do not have the in-depth knowledge that goes across departmental and professional boundaries, and do not have the position or power to get this information.

5. It is possible to review a document for correctness, but it is impossible to judge whether anything is missing.

Since the User Manual is usually produced by the team that designed the sub-system or instrument, when there is a conflict over the allocation of resources to resolve a problem with the flight article,the documentation always loses out. Furthermore, this means that the documentation tends to suffer from the same problem as the whole spacecraft life-cycle: it takes such a long time to produce, that few people stay in the same job on more than one project and so few people produce more than one User Manual in a lifetime.

Furthermore, since there is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system or instrument to another and from project to another. Just because the documentation produced by a company was good on a previous project, that does not mean that it will be good on the next project since there is no real process in place to make sure that documentation is produced, and that the quality increases with time

5.4 Flight Control Procedures

Almost everywhere within the space industry (and other places and industries), people operate according to procedures. The Flight Control Team will normally spend several man-years of effort in preparing a massive document called the Flight Operations Plan, FOP. Normally the contract with the manufacturer specifies that procedures shall be delivered, but these are often incomplete or incorrect, since the manufacturer usually has very little experience with flight operations. This is often further complicated by the presence of Customer Furnished Items, CFI: a part of the spacecraft or payload developed by a separate contractor or, on scientific missions, a consortium of scientists. The manufacturer will usually, and understandably, refuse all responsibility for CFI, on the basis that they are beyond its control. Unfortunately this can result in the database, User Manual and flight procedures being incoherent or incomplete since they were developed by different teams.

At ESOC (and according to the author's experience, throughout most of the European space industry) nominal procedures for operating the spacecraft and instruments are referred to as Flight Control Procedures (FCP). Procedures that should be executed in response to an out-of-limits condition or an emergency are called Contingency Recovery Procedures (CRP). In North America the naming differs only slightly, and in Russia same terminology is used. The term timeline is used to describe a series of activities over time. The advantages of working by procedure are that they bring reproducibility of workmanship and traceability. If the procedures are correct, they will normally produce the correct result, unless the wrong procedure is being used (or at the wrong time) or the system has changed (e.g. due to failure or aging). Even if the procedure does not work, it will usually be possible to call an expert to investigate, and restore the system to an operational condition and then improve the procedure. Thus the use of procedures should produce a knowledge base that is always improving.

The disadvantages of working by procedure are that they can result in a deskilling of the task, and a lack of flexibility in the resultant operations. The latter can be overcome organisationally, by maintaining the team so that it can respond to the changing needs of the operators by writing or rewriting the procedures.

In the author's experience there is often a lack of understanding about how to write procedures. The following guidelines encapsulate the author's experience of writing procedures, helping other organisations to write procedures and integrating sets of procedures from different authors and organisations to get a homogenous operations concept. There is more than a passing resemblance to the algorithm outlined for normalising a database. Perhaps this is not surprising, since the idea is reduce duplication and simplify the choice of procedure as much as possible. Some of the rules conflict with each other to a certain extent.

1. Procedures should be written to perform a single activity or for a single purpose.

   For example, if a system is designed so that it can fail for many reasons, but that the resultant action is always to switch to a redundant unit, then there could be one procedure for diagnosis, and then another procedure for switching to the redundant unit. This could help avoid the proliferation of procedures such as

(a) Pump failure diagnosis after low flow rate alarm

(b) Pump failure diagnosis after temperature alarm

(c) Pump failure diagnosis after voltage alarm

(d) Switch over pump due to mechanical blockage

(e) Switch over pump due to electrical failure

(f) Switch over pump due to routine maintenance

because the last three might essentially only contain the same activities. Indeed, unless the activities associated with the first three activities were found to be very lengthy, it would probably be preferable to condense them into a single anomaly/malfunction diagnosis procedure,since as a system fails, it is not always predictable which symptom will be appear first, and executing a procedure that is too focussed on one aspect may prevent the operator from getting an overview of the real problem. Thus the above six procedures could easily be condensed into the following two:

(a) Pump failure diagnosis

(b) Pump switch over

2. Procedures should generally be tied as closely to the sub-system as possible.

   This is important because procedures should normally be written by people with detailed knowledge of the particular sub-system or instrument. This helps maximise the chance that the procedure is complete and correct. However, the very fact that the procedure is being written by a specialist means that if they make assumptions about things outside their specialisation, they may be wrong or somehow in-applicable to the situation that pertains when the procedure is run. For example, this could occur when an instrument procedure makes assumptions about the telemetry rate, or power budget or attitude, all of which are factors that normally need to be managed very closely at system level.

3. The number of system level procedures should be minimised with only procedures that change multiple subsystems being considered as system level procedures.

4. A good procedure should indicate when it is appropriate, and also when it cannot be used.

5. The number of procedures should be as small as possible.

6. However,the procedures should cover every planned activity and cater for each defined failure mode.

5.5 System Validation

The database is normally developed by the industrial prime contractor and the sub-contractors and instrument principal investigator teams. They can introduce changes and tune limits, change status texts, etc. during the integration of their systems and instruments. The database is delivered to the control centre either in the form of printout, or increasingly through electronic media. Within the control centre, the database must be either entered manually into the database system used for the control system or imported electronically. This is obviously a substantial amount of work, especially if it needs to be repeated if updates are received.

If the database system in use in the control centre is different from that in use by the manufacturer, then obviously there is a need to validate the database before it is used in mission operations. The normal way to do this is to arrange a few periods where the Mission Control System can receive telemetry from the manufacturer and send telecommands to the satellite while it is still on the ground. These are referred to as System Validation Tests, SVT.

The ground segments for the most recent ESOC missions have been designed to use a single database, which can be accessed by the prime contractor, the integration team, the scientific instrument teams as well as the operations team. Changes between databases propagate automatically from one site to another.

SVT are still necessary even with a common database, since they also validate as far as possible the flight procedures, the Mission Control System and can help to confirm (or disprove) the Flight Control Team's understanding of the way the satellite works.

Since the spacecraft is often being procured as part of a much wider programme (e.g. for global navigation systems, or for scientific investigation) it is important to test the overall system. A series of tests referred to as End-to-End tests, or System Operational Verification, are used for this. Normally this should include the entire space segment (e.g. the spacecraft and payloads while they are still on the ground) as well as the ground segment, perhaps including scientific institutes, and industrial partners from around the world. As the scope of the system grows, it becomes not only more difficult to find windows when all the partners are available, but more important to do so.

5.6 Simulations

Simulation is more than a tool for the pre-launch preparation, it is one of the most useful techniques available for all phases of the mission. It does not matter that the simulator is usually not a high fidelity representation of the whole spacecraft. As in other industries, the simulator exists to replace the resource of interest (the satellite or instrument(s) or payload) but it also means that certain elements of the ground segment are not required.

At ESOC, simulators are usually built (i.e. the software is written) by an independent company, not the satellite prime contractor. This is because the simulator is procured as part of the operations activities, not part of the satellite engineering. This can lead to difficulty in accessing timely, correct, detailed information about the satellite design, but it does have the advantage of having an independent company compare the different levels of design documentation. This can be especially useful when the instruments are customer-furnished items, and the prime contractor does not need to study beyond the interfaces.

At ESOC, since the various satellites are typically very different from one another in their system design and target mission, it is usual to prepare for the launch with a very intensive simulations campaign. This consists of various stages:

OCC Simulations: The mission control team in the Operations Control Centre (OCC) work with the simulator replacing the entire ground segment and space segment. The use of the simulator means that the flight control team can rehearse procedures that might be difficult, dangerous or impossible with the real hardware.

Station Simulations: The ground station personnel train on their own using all the real ground station equipment and simulated data. Historically data tapes were recorded from satellite testing and dispatched to the ground stations, but now there is usually a simple test system (e.g. PC-based) that provides a source of telemetry and a sink for telecommands. Since most satellites now use closed loop packet telecommanding with verification of reception onboard, normally the test source can even react to telecommands by providing the correct verification of reception and command execution.

Network Simulations: The ground station staff and equipment take part in the simulation, playing their actual role at the correct time, and the mission control team interact with the simulator for data, and the ground stations for data and voice interfaces.

Integrated Simulations: Not all missions require these. This is the name given to simulations with external agencies (e.g. During the EURECA launch/retrieval, NASA Johnson Space Center, including the astronauts), but at ESOC the term is used for any participation e.g. use of an external ground station with no extra control centre.

The simulations are very important because it gives a chance for the flight procedures, control system and database to be verified in a meaningful way, as close as possible to the actual operational scenario. The learning also takes place at a higher level, since the simulations campaign is a opportunity for the control team to grow together and start operating and feeling like a team. Prior to this phase, the relevant people were working in isolation: The flight dynamics people concentrating on their own issues, software specialists on development and testing, and the flight control team were normally been concentrating on understanding the User Manual and writing procedures.

As Green reports, based on extensive results in the aviation industry, '...training has two distinct functions. The first is to provide the pilot with practice in executing the skills and procedures that he will need to to deal with real emergencies in the air. The second is to reduce the stress generated by the real emergency and to prevent it reaching incapacitating proportions by exposing him to the same, or similar conditions, in the simulator' [18].

The simulations campaign provides an invigorating way of learning to work as a team, and also in gaining confidence that the team will be able to solve the problems when they occur on the day. This can be very important for the members of the team who are new to the project.

5.7 Reviews

Reviews are the formal process that organisations try to go through in order to maximise the likelihood of mission success. The actual milestones vary from one organisation to another, but typically there will be separate reviews for the space segment and ground segment. For the space segment (and for the project as a whole) the following reviews may be scheduled:

- Preliminary Design Review
- Critical Design Review
- Flight Readiness Review
- Launch Readiness Review

These can be very intimidating to the uninitiated, since there is normally a Review Board populated by upper management who are trying to go through the details of the project, and who call for evidence to be presented to them in an almost judicial manner. Unfortunately, there is usually little time available for these excellent minds to sift through the details of the project in any real depth,and so normally the project team have to decide what is important, and draw it to the attention of the board members for their consideration.

This judicial atmosphere, and the conflicts resulting from resource and schedule pressures, can make the formal review rather adversarial. This can mean that the review board gets very little information on which to base decisions. The people empowered to speak are the line managers and team leaders, and any doubts or lack of approval from the team members can easily be missed out. Rather like the 'first past the post' election system in the UK elections, it tends to give rather extreme results than proportional representation. This is the effect referred to as 'polarisation' in Section 3.4.4. It is interesting to contrast the recorded remarks of senior management during the shuttle STS 51-L Flight Readiness Review, such as 'My God, Thiokol, when do you want me to launch, next April?' and some of the rules outlined in Section 3.4.4 designed to be used to correct a good group decision.

Vaughan [40] reports how, after having gone through the Flight Readiness Review for the Shuttle launch STS 51-L and reached a launch decision, when asked about their opinions about some new data, many specialist engineers simply thought that their ideas about how a sub-system might perform were simply not of a sufficient quality to voice in such a forum: "I felt we didn't have a real strong position. We had a lot of, you know, feelings that we were concerned about those temperatures, but we didn't have a solid position that we could quantify"[40]. The atmosphere had then changed so that "instead of proving that it was safe to fly, they had to prove it was unsafe." The mission ended 73 seconds after launch as STS 51-L, *Challenger* and its seven crew disappeared in a huge fireball.

This demonstrates how people, and organisations, must retain humility and scepticism to function correctly. NASA had basically made risk-taking part of the routine on the Shuttle programme, since before the first flight, there were six volumes on the acceptable flight risks. NASA and the contractor seemed to be participating in

"a kind of Russian roulette. ... (The Shuttle) flies (with O-ring erosion) and nothing happens. Then it is suggested, therefore, that the risk is no longer so high for the next flights. We can lower our standards a little bit because we got away with it last time. ... You got away with it, but it shouldn't be done over and over again like that"[36].

Eventually, overturning the STS 51-L launch decision would have been implicitly overturning all of the previous launch decisions as well, and that was too great a task for any one person, or organisation.

5.8 Summary

As mentioned in Chapter 1, since the satellite is often being operated by a different organisation to the one that built or integrated it, somehow the people responsible for operating the satellite must trained and prepared for their forthcoming tasks. The transfer of knowledge is an essential part of spacecraft operations engineering. This Chapter has shown that most low-level information is now transferred in the form of a database.

The satellite database is one of the most important interfaces between the satellite constructor(s) and the satellite operator(s). However, the higher-level knowledge is still transferred separately, usually in the form of documents containing textual descriptions, diagrams and procedures. This makes the descriptions and procedures potentially inconsistent with the database and because it is also manually produced, it may also be internally inconsistent or incomplete.

As outlined in the previous Chapter, the users require skill-based, procedure-based and knowledge-based behaviour. The User Manual is one of the terms used to describe the documentation that the spacecraft developer is supposed to deliver to help the end-users understand and operate the spacecraft and payloads safely and successfully. The User Manual should be the source of procedure-based and knowledge-based behaviour.

The User Manual is usually produced by the team that designed the sub-system or instrument. Thus, when there is a conflict over the allocation of resources to resolve a problem with the flight article,the documentation always loses out. Furthermore, this means that the documentation tends to suffer from the same problem as the whole spacecraft life-cycle: it takes such a long time to produce, that few people stay in the same job on more than one project and so few people produce more than one User Manual in a lifetime.

Since there is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system or instrument to another and from project to another, and just because the documentation was good on a previous project does not mean that it will be good on the next project since there is no real process in place to make sure that it is produced, and that quality increases with time. Chapters 7 and 8 of this work indicate some of the methods that could be used both to ensure that documentation thorough, and to reason with the knowledge that is encapsulated in the documentation.

Spacecraft (or a family of spacecraft) are frequently being procured as part of a whole system, which often has a very large ground segment that needs to be developed, maintained and operated in parallel to the space segment. Section 5.5 discussed how the ground segment and the space segment are validated.

The role of simulations in preparing the individuals and teams mentioned in the previous Chapter was discussed in section 5.6. It shows how they are useful in preparing the individuals to cope with the stress of operational situations, as well as forging a team.

Since satellites are normally only procured by large organisations, there is normally a formalised process for checking the progress at various phases in the procurement and operations. These are called reviews. This was discussed in section 5.7. Reviews are particularly important since they force management to take a position on various items that are flagged as risks to the programme. However, this only operates correctly if the correct data is made available to the correct people. As mentioned previously, in large organisations there is a danger that the reviews may become so formal that the people who have the working knowledge may not feel that they are able to participate in this process. A good example of this was the almost judicial nature of the NASA flight readiness review boards. This prevented the free flow of information that was vital for making the launch decision correctly.

Chapter 6

Control Systems

6.1 Introduction

The procurement of a Flight Control System (FCS) is one of the major tasks that faces a flight control team as it prepares for launch. This is also one of the major costs of the pre-launch ground segment preparation activities, since not only must the system be specified, it must be designed, tested and accepted before the mission operations can begin.

Section 6.2 examines the options for procuring a control system, first looking at the buy-or-build decision, and then the contractual implications of fixed price developments compared to time and materials developments. This section links strongly into Section 6.3, which looks at the issues of commonality between the check-out system used by the spacecraft manufacturer and then control system that is designed to be used by the operations team after launch.

It is often tempting to try to bring cost-savings to a project by introducing automation, either to the space segment or into the ground segment to control the space segment. The issue of when and how to automate the ground segment is discussed in 6.4, which presents some of the complications of doing so, as well as some of the theoretical limitations to the automated approach.

6.2 Control System Procurement

There are various options about how the FCS can be procured. One of the first major choices is whether it should be based on an existing solution, hopefully for either a similar mission or using a generic system. The fashionable phrase at the moment is COTS - Commercial Off The Shelf software. The general idea is that it is possible to define some set of core functions across all missions, and then to adapt the generic system to meet the particular needs of the mission and that this should be cheaper than writing an entire control system from scratch. A compromise architecture is to adopt a generic kernel, and then write further software as necessary. This is generally what ESOC does.

The next major choice is about how the procurement contract should be financed, typically being a choice of either Fixed-price or Time and Materials (T&M). If a fixed-price contract is to be placed, then normally the requirements must be precisely known and stable. Every change to the requirements after the contract kick-off will usually result in an additional charge from the developer. Time and materials contracts are unfashionable at the moment, the feeling being that it encourages developers to use up all available resources during the development phase, and to not be sufficiently 'goal oriented'. However, a fixed price contract is essentially a bet with a contractor about the effort needed to implement the requirements. Naturally all prudent contractors will include margin in their estimates, a risk premium on top of the estimated actual costs of delivering the system as specified. This extra margin is why a fixed-price solution is not always the cheapest development method, depending generally upon the stability of the requirements and the availability of any deliverable items that are required as inputs to the contract. A fixed price contract can lead to some very bitter negotiations about the detailed interpretation of the requirements, and usually the developer is in the stronger position: the flight control team simply cannot fly the mission without the control system, and as time continues to run, that puts increasing pressure on the purchaser to make extra funds available to keep the developers working.

There is a strong tendency for a COTS architecture to imply a fixed-price contract, but this does not always have to be the case.

As discussed in Chapter 2, during the satellite design, integration and test a control system is needed to monitor and test the satellite units and systems. This is normally referred to as the Central Checkout Equipment, CCE. Regardless of the details of the positioning of the satellite with respect to other satellite missions, there is normally a lot of commonality between the needs of the Flight Control team post-launch, and the needs of the AIV team before launch. This means that normally two systems are developed to meet a similar set of needs. This is independent of the architecture (COTS or bespoke) of the implementation, although obviously the more flexible the system, the more likely it is to be able to satisfy the diverse requirements.

6.3 Commonality Between FCS and CCE

This section examines the very high-level functional requirements for a Flight Control System and a Central Checkout System. The functional building blocks for a Flight Control System and for the Central Checkout Equipment are given in Figure 6.1 and Figure 6.2.

We can now discuss and compare the functional building blocks represented in figures 6.1 and 6.2 to show what functions are common in the CCE and FCS.

- Man Machine Interfaces - this function provides the operator with the interfaces to the monitoring and control system, including the database system. The layout and content of each display used for telemetry and telecommanding are defined in the database system. This function is identical for the FCS

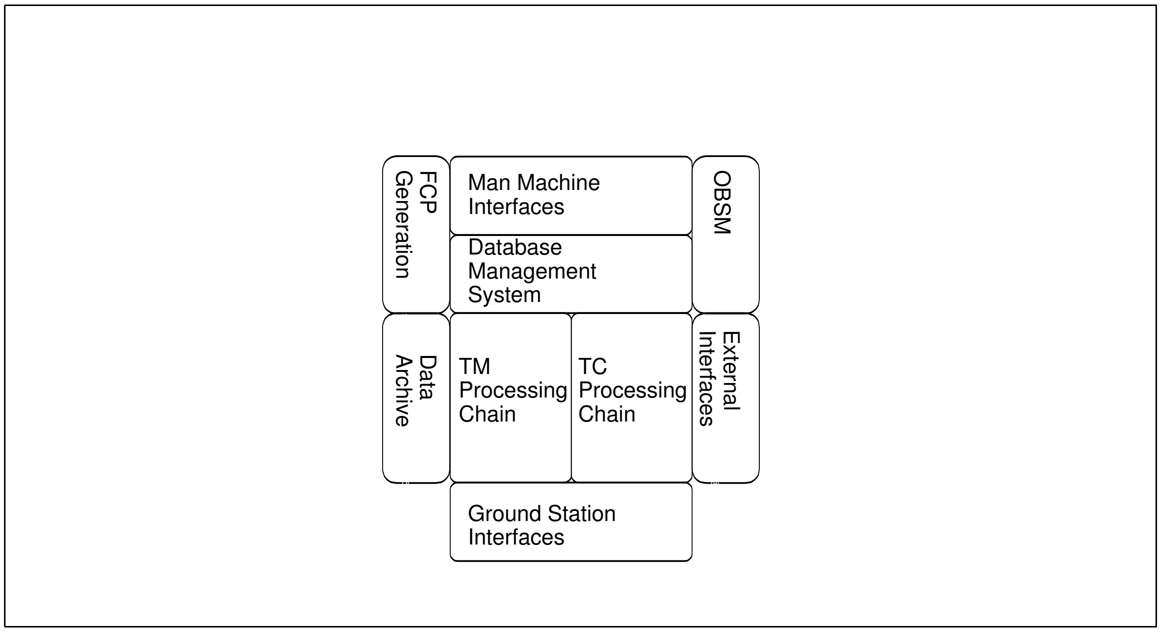


Figure 6.1: Schematic Diagram of Functions in FCS

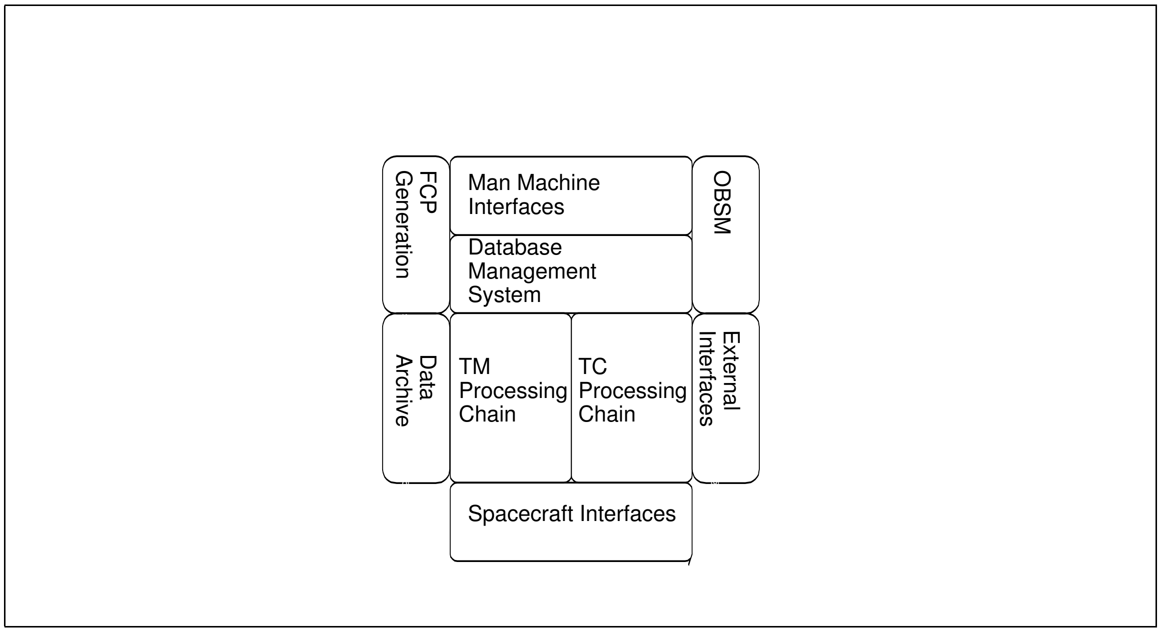


Figure 6.2: Schematic Diagram of Functions in CCE

and CCE. It must be possible to define or select screen layouts according to which tasks are currently being undertaken.

- Database System - this function allows the definition and handling of all the mission parameters required to drive the system. This includes mainly all detailed definitions of telemetry and telecommands and of the user-definable displays. The CCE must monitor and control the spacecraft and ground test equipment so the CCE database should include definitions required for these functions.

- Telemetry Processing Chain - this function performs the processing of telemetry, including parameters extraction and interpretation, automatic limit-checking, short-term filing and special processing (derived parameters). The Telemetry Processing Chain is driven by the definitions stored in the operational database. For CCE functions telemetry processing chain must also be capable of monitoring Special Checkout Equipment (SCOE).

- Data Archiving and Distribution - this function supports the long-term archiving and the on and off-line (retrieval) data distribution to a variety of external users to the FCS, in particular to the scientific community, industry and Project engineers. In the FCS this function has to satisfy strict security rules in order to prevent external access to the front-end control system.

- Telecommand Processing Chain - this function performs the processing necessary for telecommands construction, uplink and execution verification. The command processing chain is driven from the command and sequence definitions stored in the operational database. For the CCE, the telecommand processing chain must also be capable of commanding SCOEs.

- Ground Station Interfaces - this function handles all interfaces to the ground stations for a number of functions such as Telemetry, Telecommands, Tracking, transfer of station-specific files, etc. The Flight Control System must be able to simultaneously connect to several ground stations. This is clearly unique to the FCS although a corresponding, unique interface exists for the CCE, since it may be required to communicate with the spacecraft in a way that is not possible during mission operations, i.e. via a hardwired link.

- Procedures - The CCE uses computerised procedures to automatically drive the test sessions. These are sometimes referred to as test scripts. They contain instructions to the test equipment, commands for the spacecraft and decision steps using the monitoring functions of the telemetry chain (for both spacecraft and test equipment data). The analogous components for the FCS are referred to as Flight Operations Procedures. This scope of this function includes the tools to produce all the procedures and timelines necessary to carry out the flight operations. Typically the final product is a paper document, the Flight Operations Plan, but connections of the generation tool to the Database System is required to allow automatic references to the telemetry and telecommand items and generation of command sequences derived from the procedures, to be stored in the operational database itself.

- On-Board Software Maintenance (OBSM) - this system that is used to maintain the on-board software via the normal uplink, the handling of configuration control and the facilities required for uplink verification

- External Interfaces - for the FCS, these are the interfaces to other functional blocks that form the overall ground segment facilities of a typical satellite mission, e.g. the Flight Dynamics System. For a scientific mission this would also include interfaces to the Mission Planning System, the Data Distribution System, and perhaps to one or more Science Operations Centres. These are all typically considered as unique, off-line functions. For the CCE this includes the interfaces to the special checkout equipment and the payload checkout systems which are controlled by the CCE.

From the above discussion it is clear that there is a large degree of commonality between the two systems. In particular, the following functions are duplicated between the Flight Control System and the Central Checkout Equipment:

1. Man Machine Interfaces - there are clear benefits in maintaining the same man machine interface for the CCE and the operational system because AIT/AIV people are involved in mission operations and operational people are involved in checkout activities. Keeping the same interfaces save preparation and training costs and increase safety.

2. Database System - there are clear benefits in maintaining the same database for the CCE and the Operational System. This would save preparation costs and make the two systems consistent. There should be one master database for checkout and operations.

3. Telemetry Processing Chain - this function is in general the same in the two systems and can be capable to monitor spacecraft telemetry and data received from other external interfaces such as SCOE's and ground stations.

4. Telecommand Processing Chain - this function is in general the same in the two systems and can be capable to command the spacecraft and other external interfaces such as SCOE's and ground stations.

5. Control Procedures Generator - this function should combine the functions of test script and flight procedures generation, using a common control language that can be interpreted by the ground systems into single telecommands for debugging.

6. Data Archiving and Distribution - this function is identical in the two systems and should be combined with the obvious advantage to present to external users the same functional interfaces for acquisition of data in all phases of the project.

7. On-Board Software Maintenance - this function is identical in the two systems and should be combines with the obvious advantage to present the same functional interface for on-board software maintenance.

6.4 Automation

It is often tempting to try to bring cost-savings to a project by introducing automation, either to the space segment or into the ground segment to control the space segment.

When new automation is introduced into a system or when there is an increase in the autonomy of automated systems, developers often assume that adding "automation" is a simple substitution of a machine activity for human activity – this is referred to as 'the substitution myth'[43]. Woods suggests that partly because in reality tasks and activities are highly interdependent or coupled 'adding or expanding the machine's role changes the cooperative architecture, changing the human's role often in profound ways. New types or levels of automation shift the human role to one of monitor, exception handler, and manager of automated resources'[43]. This is shown in Table 6.1. 'What is needed is better understanding of how the machine operates, not just how to operate the machine'[43].

The theoretical problem with any attempt to automate is the following: Gödel's Theorem seems to indicate that any formal language above a certain complexity used to describe a system is either inconsistent or incomplete. Incomplete in this sense means that there are true statements about the system that cannot be derived

Putative benefit	Results found in studies[43]
better results, same system (substitution)	transforms practice, the roles of people change
frees up resources: 1. off loads work	create new kinds of cognitive work, often at the wrong times
frees up resources: 2. focus user attention on the right answer	more threads to track; makes it harder for practitioners to remain aware of and integrate all of the activities and changes around them
less knowledge	new knowledge and skill demands
autonomous machine	team play with people is critical to success
same feedback	new levels and types of feedback are needed to support peoples' new roles
generic flexibility	explosion of features, options and modes create new demands, types of errors, and paths towards failure
reduce human error	both machines and people are fallible; new problems associated with human-machine coordination breakdowns

Table 6.1: Intentions of automation compared with results

from the system axioms. Gödel dealt with first order systems, for example a series of statements about a system. He then showed that going to a higher order system (for example, making statement about *all* statements) introduces the problem of either inconsistency or incompleteness.

Turing then went even further, looking at how a logic is applied to produce deriving proofs, and he showed that even if a logic system contains only first-order statements, it is possible to write a program that will not reach a conclusion in finite time. Even worse from the point of view of applying logic to a control a system, he showed that there is no way to tell in advance if a conclusion will be reached in finite time i.e. the only way to see if a statement can be proven in a logic system is to try to prove it!

Initially the 'system' is defined as being the system, and the controller is separate; the next stage is when the system equals controller + system, etc. This is not to say that automation is impossible, it is aimed at sounding a note of warning to those who think that automation can solve all problems. If a control system is designed to maintain a system within certain boundaries, then this is possible. However, when the system 'suddenly'(i.e. faster than the controller can cope with) moves into an area where the controller was not designed to operate, the controller may not be able to recover the situation and may even exacerbate it.

The key point seems to be the introduction of self-references. This ensures that any system described in a language that is powerful enough to be expressive is also incomplete. Without them, the language is not expressive enough. It is possible to side-step this constraint for one moment, by introducing a meta-language which can reason about the first language, but the same question then immediately arises in the meta-language. The solution to this problem is then a meta-meta-language ... and so on.

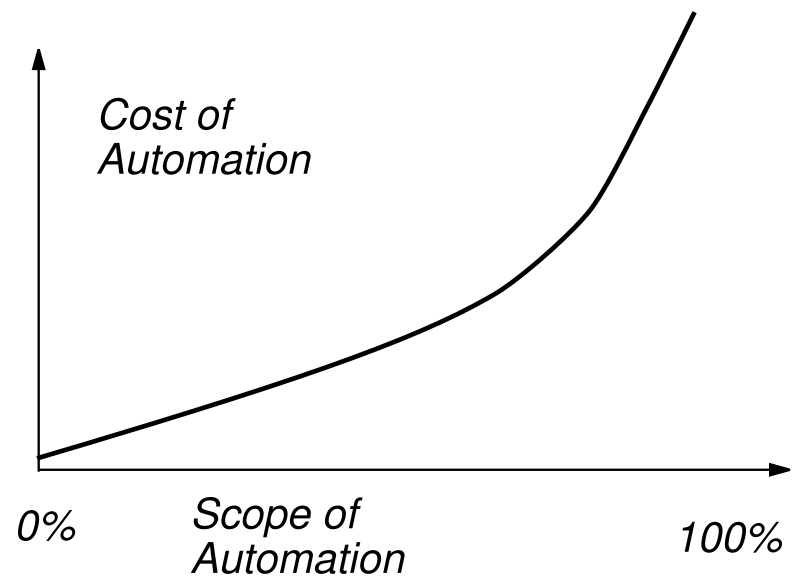
The only way out that still produces something useful is to try to transcribe some of the problems and pitfalls that have already been incurred on various projects, describe some of the lessons learned, and generally provide a 'check list' of things that should be considered on various missions. The problem that is encountered straight away is that descriptions differ from one project to another, and even from one person to another on the same project.

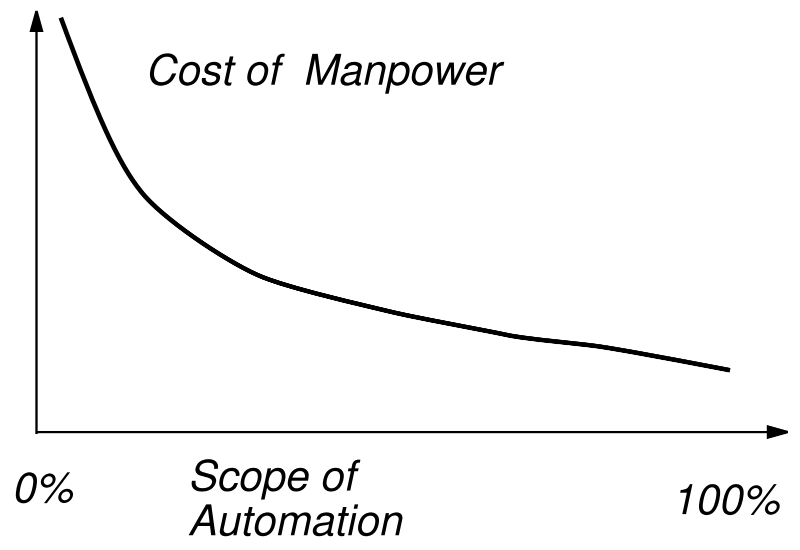
Hofstadter[24] introduced the terms I-mode and M-mode to describe two different kinds of reasoning. In M-mode, it is possible to work only "in your capacity as a machine", thus applying axioms or production rules to the already proven set of theorems. In I-mode, by contrast, the work is "in your capacity as a thinking being". If the documentation is perfect (even if it presented in some pseudo-mathematical notation such as a formal method) it is possible to get a lot of information using M-mode to generate new theorems. Perhaps that will be sufficient to cover almost every situation that is likely to be encountered, but there will still be room for I-mode thinking, to assess commonality, and spot differences in behaviour. The operations engineer needs to be able to perform in both modes.

One of the more practical reasons against major automation can be explained by comparing the cost of automation compared with the the cost of manpower. The author proposes that these can be broadly modelled as expecting to scale as shown in Figure 6.3. The cost of automating the first stage of the operations should be quite low, but the cost will increase, probably at an increasing rate, as the automation is required to do more, e.g. handle all different failures, special cases cases that might occur, restart after any problems, handle exceptional cases. Conversely, the manpower costs for a very low level of automation will be very high, if this includes manually generating telecommands and checking telemetry raw values. This will reduce as the automation increases, but eventually the saving will be very small, since it is difficult to eliminate all positions, since the manpower analysis should also include the problem of who maintains and operates the automated system.

Each organisation should decide for itself how much it would cost to develop each level of automation, compared with the savings that would be realised by reducing the manpower level. In making this decision, it is also important to include the amount and level of training that will be required to operate the system over the lifetime of the project and to maintain the skills of the staff at the appropriate level. Dekker *et al*[10] report a number of organisational problems associated with the introduction of automated systems, particularly illustrated by a ship which run aground after nearly two days of being guided precisely off-course by a GPS-based system that was displaying an error message after its antenna became disconnected. However the meaning of the message was not understood by the crew, and the crew failed to investigate the difference between the location reported by the GPS system and the other means available [10]:

- During the entry into service, the manufacturer provided familiarisation training to the first crew. However, at the time that the ship ran aground, only





The authors model: the cost of automation will generally increase with the scope of automation whereas the cost of manpower will decrease as the amount of automation increases. The optimal point will be for each organisation to decide, perhaps on a mission-specific basis, as a function of how efficiently it can develop or re-use automation, compared with the cost of the manpower available to it.

Figure 6.3: Automation and Manpower

one member of the crew remaind from that original session;

- Training of other crew members had been 'on the job';
- None of the crew was fully proficient in the navigation system, and certainly did not understand its failure modes;

Training restricted a basic set of modes, and how these modes work in routine situations. Often this is all an organisation can offer in terms of preparation, because instructors themselves (often colleagues) are not proficient in or exposed to the systems broader functionality. Dekker refers to this as 'teaching of recipes'[10]. 'Recipes restrict the range of options and modes taught, and they concentrate on the systems input-output relationships rather than on its internal workings...pedagogically and operationally, recipes are problematic. They work only if the basics provide a coherent foundation that aids learning the more difficult parts. That is, if they equip practitioners with the appropriate skills for coordinating the automation in more difficult circumstances...Generally, recipes create the ironic situation that training focuses on those parts of the automated systems that are the easiest to learn. The more complicated parts, the surprising mode transitions, the unexpected failure modes, these are all for individuals to learn later on their own... And for them to learn on the line[operationally], where slack to recover from going sour ... may not exist'[10].

Dekker gives a further examples, quoting an airline pilot as saying, 'I can't fly anymore, but I can type fifty words a minute now' and another captain (about the interaction with the aircraft mode control panel), 'Oh now it goes into this mode - that means I can...uh... I cant ...uh...move the throttles by hand, or...I'm not sure exactly'[10] which reinforce the fact that the organisational aspects of the introduction and maintenance of automated systems must be fully accounted for in the decision-making process.

6.5 Summary

This Chapter has examined briefly some of the strategic choices that must be made in developing a control system for spacecraft operations. There is substantial commonality across missions, holding out the possibility of large-scale reuse of software and systems. This has resulted in an increasing number of COTS solutions being proposed. This Chapter has shown that a common approach to checkout and control system development is possible and that it might bring cost benefits. Even though it might cost more in the initial phases such as review of the design specifications, benefits and cost savings are expected to occur in the following areas:

- Overall development cost of the common building blocks
- Preparation of the mission database and flight operations procedures
- Consistency between checkout system and flight control system
- Validation of mission database and flight operations procedures

The approach of maintaining a single mission database has been followed on the ESA projects Rosetta and Mars Express, and the integration between the ground control system and the Electronic Ground Support Equipment (EGSE) has been further extended for the ESA project Herschel/Planck.

This Chapter has also shown that automation is often introduced with the aim of reducing costs, but studies have shown that the impact is often to change the skill set required to do the job, and to drive up the indirect costs e.g. to maintain proficiency at a level required for manual operation to take over from the automation when the situation deteriorates, often under time pressure. The way automation can contribute to the complexity of the overall operational scenario is further discussed in Chapter 9.

Chapter 7

Vocabulary

7.1 Introduction

The User Manual is one of the names used to describe the documentation that the spacecraft developer is supposed to deliver to help the end-users understand and operate the spacecraft and payloads safely and successfully. Section 5.3 identified several frequent problems with the documentation that describes the spacecraft and its systems.

The User Manual is usually produced by the team that designed the sub-system or instrument. Thus, when there is a conflict over the allocation of resources to resolve a problem with the flight article,the documentation always loses out.

Furthermore, the documentation tends to suffer from the same problem as the whole spacecraft life-cycle: it takes such a long time to produce, that few people stay in the same job on more than one project and so few people produce more than one User Manual in their career.

Since there is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system or instrument to another and from project to another, and just because the documentation was good on a previous project does not mean that it will be good on the next project since there is no real process in place to make sure that it is produced, and that quality increases with time. Overall, it is fair to say that it is difficult to produce a user manual because there is not standard to say what it should contain or how to produce it.

This Chapter indicates some of the methods that could be used both to ensure that documentation complete and correct, and the following chapter, Chapter 8, illustrates a way to reason with the knowledge that is encapsulated in the documentation.

Section 7.2 illustrates how the introduction of new names for existing concepts makes it difficult to produce the User Manual to a consistent standard and prevents re-use of documentation from one project to another, and section 7.3 illustrates a powerful new technique to make information available to the users in a systematic way, that allows them to browse it graphically or scan hierarchies in a way that is convenient for them.

7.2 Jargon

As Hamming[22] reports, 'Every field seems to have its own special jargon,one which tends to obscure what is going on from the outsider - and also, at times, from insiders.' He defines jargon as a special language to facilitate communication over a restricted area of things or events. However, it also blocks thinking outside the original area for which it was defined to cover. Hamming even asserts that the use of jargon is an instinctive social phenomena to increase the coherency of a group and exclude outsiders[22]. Since groups now have much more interaction than before, and projects often span countries or even continents, the use of such jargon can be a significant impediment to the free flow of knowledge.

People (or at least, scientists and engineers) seem to have an inexhaustible ability to introduce new names for things, even though they may be fundamentally the same as existing devices. Once the name 'television' was coined, nobody tried to insist on giving a different name to the technique of viewing pictures at a distance, even after it went from black and white (monochrome) to colour (polychrome) technology.

Consumers did not want to talk of CTV, instead of TV. But now the consumer is weighed down by a whole new burden of vocabulary, such HDTV, D2MAC etc.

The same thing, and worse, happens in the space industry. For example, one instrument on the Mars Pathfinder mission was called the MPC. This name hardly gives any information about its function or architecture, but the name is clearly tied to the mission: MPC stands for Mars Pathfinder Camera. The same unit was designed to fly on a series of subsequent missions, but the prime contractor had to change the name of this unit for each one. This is a classic way of obfuscation: Any procedure or database item for this unit would need to be changed for each mission, and if it were not otherwise known, the operations team might never realise that their experience with one unit could have been relevant on a following mission.

Perhaps this is being done for commercial reasons: the magic though smoke and mirrors of the Marketing Department might be able to present each unit as more innovative, more important, more worth having if the name keeps changing. Or perhaps this helps a Project Manager feel that he/she really is getting value for money, since the unit now caries the name of the project embedded inside it. However, this technique can sometimes backfire in other ways, besides loss of operational knowledge. For example, High-resolution Radiometer for FIRST (HiFi) was an instrument on the FIRST spacecraft, due to be launched in 2007. But the project name has recently had its name changed from FIRST to Herschel, leaving the instrument with a name that is almost devoid of meaning.

Some rules for avoiding this kind of (trivial and serious) problem are as follows:

- Avoid naming a unit after the technology that went into it.
- Avoid naming a unit after what it supersedes (advanced, improved, next-generation etc).
- Name a unit after what it does, not how it does it, since functions are more

likely to persist with time.

- Never name a unit after the project or mission.

7.3 Ontology

An ontology is an explicit specification of some topic. It could be viewed as the antidote to jargon, since each term has an explicit definition, and the relationships between terms are also defined. The term ontology seems to generate some controversy in AI circles. The word 'ontology' is used in philosophy to refer to that part of meta-physics which relates to the nature of existence.

In the context of knowledge sharing, the term 'ontology' is often used to mean the specification of a conceptualisation. It is 'a formal and declarative representation which includes the vocabulary (or names) for referring to the terms in that subject area and the logical statements that describe what the terms are, how they are related to each other, and how they can or cannot be related to each other. Ontologies therefore provide a vocabulary for representing and communicating knowledge about some topic and a set of relationships that hold among the terms in that vocabulary.' [19].Thus it is really a formalised dictionary.

Ontologies are designed to help share knowledge. For pragmatic reasons, it is usual to write ontologies as a set of definitions of a formal vocabulary, although this is not the only way. They are often equated with taxonomic hierarchies of classes, but class definitions, and the subsumption relation, but ontologies need not be limited to these forms. Ontologies are also not limited to conservative definitions, that is, definitions in the traditional logic sense that only introduce terminology and do not add any knowledge about the world.

When the knowledge of a domain is represented in a declarative formalism, the set of objects that can be represented is called the universe of discourse. For knowledge-based systems, what "exists" is only that which can be represented (perhaps this is the cause of the adoption of 'ontology' to express this concept). This set of objects, and the describable relationships among them, are reflected in the representational vocabulary with which a knowledge-based program represents knowledge. However it is important to maintain a distinction between an ontology and a knowledge base. An ontology is a common understanding of concepts. Knowledge may be represented with an ontology and stored in a knowledge base.

In such an ontology, definitions associate the names of entities in the universe of discourse (e.g., classes, relations, functions, or other objects) with human-readable text describing what the names mean, and formal axioms that constrain the interpretation and well-formed use of these terms. Formally, an ontology is the statement of a logical theory.

We say that an agent *commits* to an ontology if its observable actions are consistent with the definitions in the ontology. We use common ontologies to describe ontological commitments for a set of agents so that they can communicate about a domain of discourse without necessarily operating on a globally shared theory. The idea of ontological commitments is based on the Knowledge-Level perspective [33] . The Knowledge Level is a level of description of the knowledge of an agent that is independent of the symbol-level representation used internally by the agent. Knowledge is attributed to agents by observing their actions; an agent "knows" something if it acts as if it had the information and is acting rationally to achieve its goals.

Gruber [19] proposed a preliminary set of design criteria for ontologies whose purpose is knowledge sharing and inter-operation:

- Clarity: An ontology should effectively communicate the intended meaning of defined terms. Definitions should be objective. While the motivation for defining a concept might arise from social situations or computational requirements, the definition should be independent of social or computational context. Formalism is a means to this end. When a definition can be stated in logical axioms, it should be. Where possible, a complete definition (a predicate defined by necessary and sufficient conditions) is preferred over a partial definition (defined by only necessary or sufficient conditions). All definitions should be documented with natural language.

- Coherence: An ontology should be coherent: that is, it should sanction inferences that are consistent with the definitions. At the least, the defining axioms should be logically consistent. Coherence should also apply to the concepts that are defined informally, such as those described in natural language documentation and examples. If a sentence that can be inferred from the axioms contradicts a definition or example given informally, then the ontology is incoherent.

- Extendibility: An ontology should be designed to anticipate the uses of the shared vocabulary. It should offer a conceptual foundation for a range of anticipated tasks, and the representation should be crafted so that one can extend and specialise the ontology monotonically. In other words, one should be able to define new terms for special uses based on the existing vocabulary, in a way that does not require the revision of the existing definitions.

- Minimal encoding bias: The conceptualisation should be specified at the knowledge level without depending on a particular symbol level encoding. An encoding bias results when representation choices are made purely for the convenience of notation or implementation. Encoding bias should be minimised, because knowledge sharing agents may be implemented in different representation systems and styles of representation.

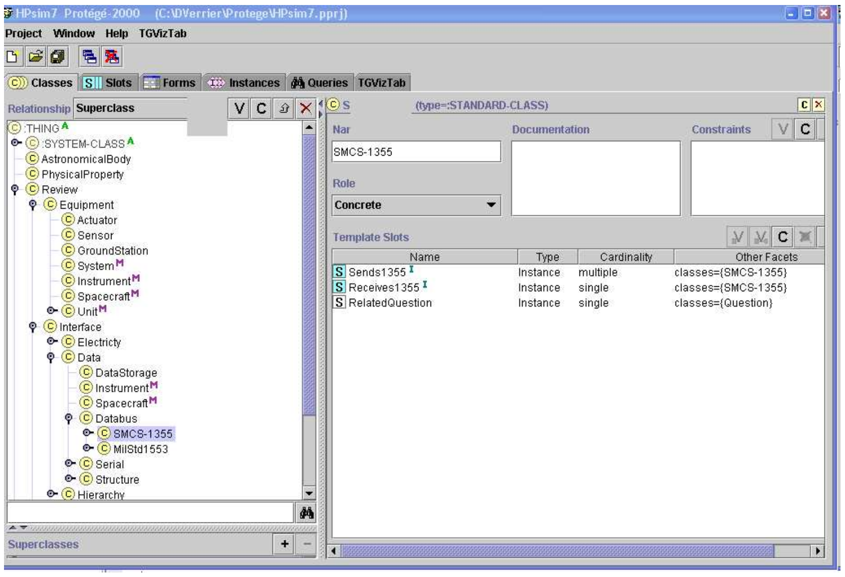
- Minimal ontological commitment: An ontology should require the minimal ontological commitment sufficient to support the intended knowledge sharing activities. An ontology should make as few claims as possible about the world being modelled, allowing the parties committed to the ontology freedom to specialise and instantiate the ontology as needed. Since ontological commitment is based on consistent use of vocabulary, ontological commitment can be minimised by specifying the weakest theory (allowing the most models) and defining only those terms that are essential to the communication of knowledge consistent with that theory.

Ontology design, like most design problems, will require making tradeoffs among the criteria. However, the criteria are not inherently at odds. For example, in the interest of clarity, definitions should restrict the possible interpretations of terms. Minimising ontological commitment, however, means specifying a weak theory, admitting many possible models. These two goals are not necessarily contradictory: the clarity criterion talks about a definition of terms, whereas ontological commitment is about the conceptualisation being described. Having decided that a distinction is worth making, one should give the tightest possible definition of it.

Formal languages are required to express an ontology which, as said earlier, is nothing more than a formalised dictionary. A number of languages have been designed or constructed to express ontologies. Just some of them are KIF (Knowledge Interchange Format[17]), OKBC (Open Knowledge Base Connectivity[41]) and OIL (Ontology Inference Layer[26]). There are many tools available on the Internet for developing ontologies. Indeed, most representations have at least one tool set that has been used to test the representation language, and many have many more. OKBC is, in fact, a definition of a programming interface to allow different tools to communicate with each other.

Part of an ontology created by the author is given in Appendix A as an example. It works at the descriptive level, showing how a vocabulary can be structured from the operational point-of-view, not going into too much detail when it would not be visible either directly or indirectly to the ground-based team. The ontology presented in Appendix A was originally developed by the author using a semi-graphical User Interface onto a freely available web-accessed server-based system Ontolingua[15]. This system was very useful, but it had the significant disadvantage of being difficult to capture the output in a textual form suitable for incorporation into a thesis. A further ontology was implemented by the author using the tool Protégé [30, 32] to meet the specific needs of an on-going project, and a snapshot of the "index" of this ontology is given in Appendix A. The following screen shots illustrate the user interface and demonstrate how easy it is to use the tool. After starting the application, the first window that the user can see is the Class Editor, shown in Figure 7.1.

A Protégé ontology consists of classes, slots, facets and axioms. Classes are the concepts of a particular domain and, in terminology reminiscent of the object-oriented approach popular in software engineering, each class has a set of attributes called slots. A Protégé knowledge bases includes both classes and instances of



Nar: SMCS-1355

Role: Concrete

Template Slots

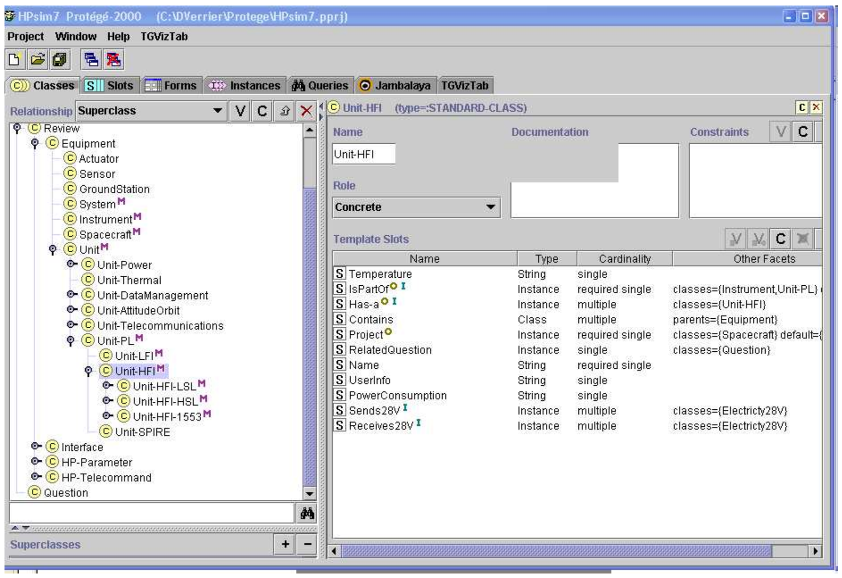
Name	Type	Cardinality	Other Facets
Sends1355	Instance	multiple	classes={SMCS-1355}
Receives1355	Instance	single	classes={SMCS-1355}
RelatedQuestion	Instance	single	classes={Question}

The main window of the Protégé tool. This is the Class Editor.

Figure 7.1: Protegé Overview

classes. The Class Editor is used to control or create relationships between classes (by moving classes around the hierarchy). Classes can have multiple super-classes (”parents”) and multiple sub-classes (”children”).

The ”Relationship” window on the left of Figure 7.1 shows the hierarchy. It is possible to click on one of items in the Class-Relationship window and ’drill-down’ through the hierarchy. If the user clicks upon a class in the Relationship window, then the ”Template Slots” window shows the slots (attributes) of that class. This is shown in Figure 7.2.



```
Review
  Equipment
    Actuator
    Sensor
    GroundStation
    System
    Instrument
    Spacecraft
    Unit
      Unit-Power
      Unit-Thermal
      Unit-DataManagement
      Unit-AttitudeOrbit
      Unit-Telecommunications
      Unit-PL
        Unit-LFI
        Unit-HFI
          Unit-HFI-LSL
          Unit-HFI-HSL
          Unit-HFI-1553
        Unit-SPIRE
  Interface
  HP-Parameter
  HP-Telecommand
  Question
```

Name: Unit-HFI

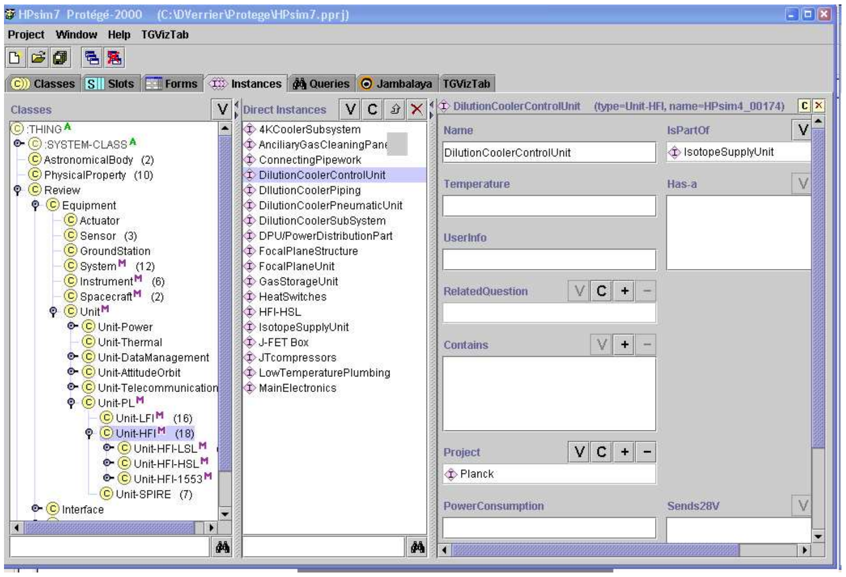
Name	Type	Cardinality	Other Facets
Temperature	String	single	
IsPartOf	Instance	required single	classes={Instrument,Unit-PL}
Has-a	Instance	multiple	classes={Unit-HFI}
Contains	Class	multiple	parents={Equipment}
Project	Instance	required single	classes={Spacecraft} default=
RelatedQuestion	Instance	single	classes={Question}
Name	String	required single	
UserInfo	String	single	
PowerConsumption	String	single	
Sends28V	Instance	multiple	classes={Electricty28V}
Receives28V	Instance	multiple	classes={Electricty28V}

In the Class Editor, it is possible to click on one of items in the Class-Relationship window and ’drill-down’ through the hierarchy. The slots (attributes) of each class can be seen on the right-hand side in the area labelled ’Template slots’.

Figure 7.2: An Ontology in Protégé

The author implemented the ontology in two main branches: the Equipment hierarchy and the Interface hierarchy. The Equipment branch follows the typical breakdown of the spacecraft according to the author’s experience, having separate branches for System, Instrument, Unit, Actuator and Sensor. The Interface branch was designed to show how the items specified in the Equipment branch are connected with each other, which might include electrical interfaces, such as 28V power supply, or a data exchange. The data exchange interface was further refined into a serial link or a data bus, which were then further refined into different standards frequently encountered by the author, such as an SMCS-1355 link, and a Mil-Std 1553 data bus. Since the ontology is checked by the editor, it is possible to specify that a certain kind of relationship can only take place between certain classes, for example, that a only classes that have the "28V class" as a superclass can supply or receive 28V i.e. it is possible to check the knowledge base for internal consistency. Conversely, it is also possible to specify the "arity" of relationships, the number of participants, so that a Mil-Std-1553 bus class might, for example, require precisely one class to be specified as a bus master, and at least one class to be specified as a remote terminal.

The ontology is augmented by the presence of instances which illustrate how the ontology would be used to describe a particular mission. Figure 7.3 shows how the user can create instances of a particular class and fill out the data for their slots (attributes).



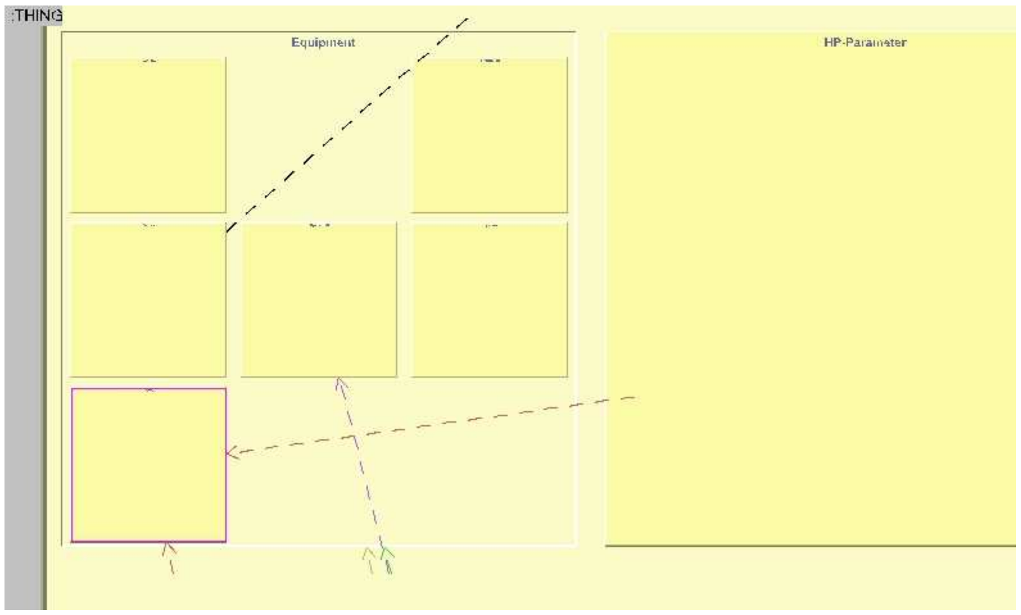
Name: DilutionCoolerControlUnit
IsPartOf: IsotopeSupplyUnit
Project: Planck

This screen shot shows the Instance Editor. It is used to populate the ontology. This makes it possible to test how suitable an ontology will be, as well as also permitted Protege to serve as a knowledge base for a project.

Figure 7.3: Protégé Instance Editor

The ease of editing instances and classes in parallel makes it relatively easy to develop a knowledge base. The Protégé editor is being developed largely by the Stanford Medical Informatics at the Stanford University School of Medicine as an open-source project. There is a well-defined Application Programming Interface (API) and as a result, many other groups in both academia and industry have developed a range of "plug-ins" that add further functionality, either by adding a storage format or new functions. There is a plug-in for an expert system, as well as a plug-in for a prolog-like language. These make it easy to change classes and slots, as well as to perform queries on the whole knowledge base.

One of the exceedingly interesting plug-ins for the user interface is the Simple Hierarchical Multi-Perspective Views[29] plug-in called Jambalaya. The following figures show how useful this ability to have different views on a sub-system can be.

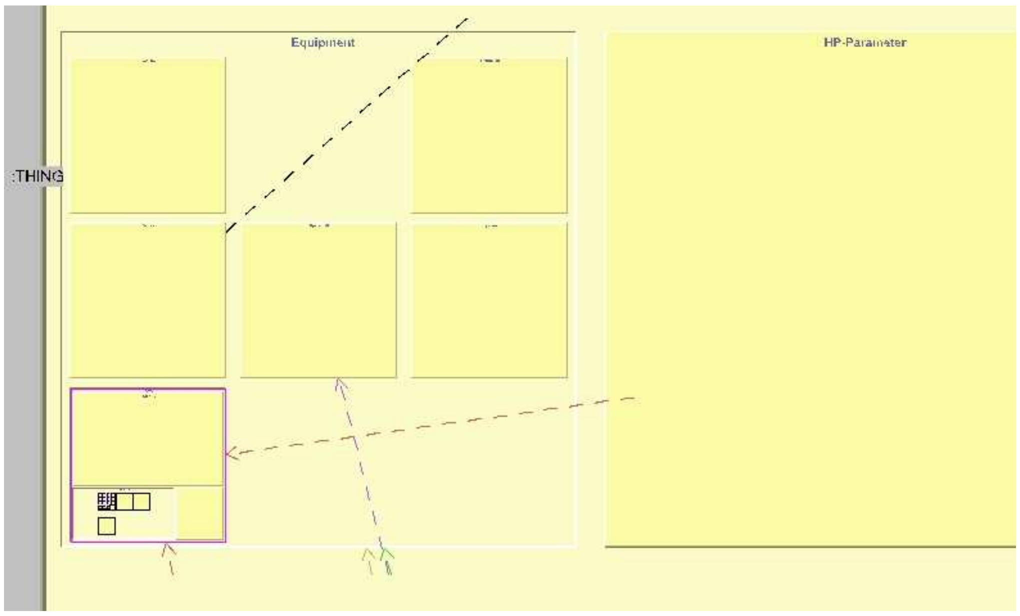


Using one of the plug-in components, it is possible produce a more graphical layout to illustrate different relationships between different classes. This makes it very easy to explore a design.

Figure 7.4: Herschel-Planck Equipment types

In Figure 7.4 the classes are shown as a network of boxes, with the arcs and arrows between them corresponding to the relationships between classes.

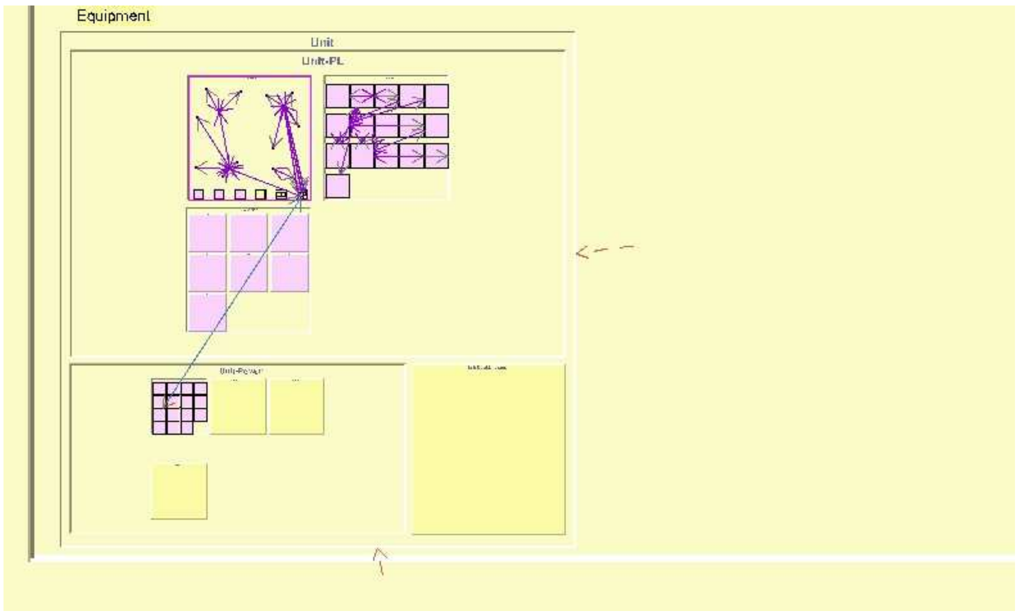
The user can view the structure at different levels of detail and from different viewpoints. When the user uses the mouse to double-click on one of the boxes, it opens to reveal the internal structure as in Figure 7.5.



The user can view the structure at different levels of detail and from different viewpoints. In this diagram the internal structure of one of the equipment classes is revealed.

Figure 7.5: Herschel-Planck Units

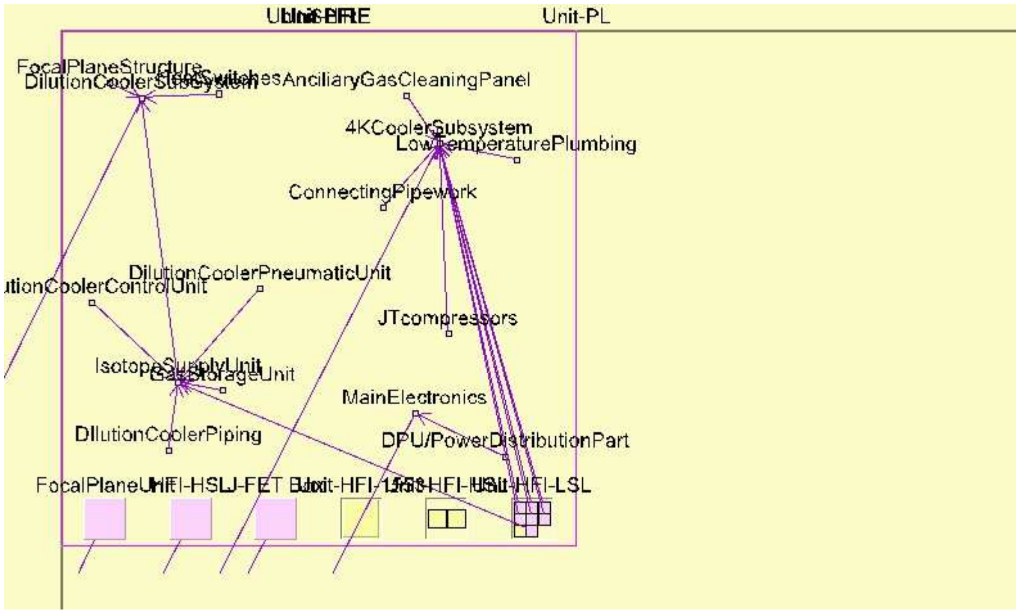
It is possible to filter which set of relationships (arcs) are shown in order to increase the clarity of the diagram, or to facilitate the search for a particular piece of information. In Figure 7.6 the details of the instances of the payload units (of the Unit-PL) class are shown.



This figure shows that it is possible to zoom in on one area and see in which relationships units participate, for example,relationships between payload units and power units.

Figure 7.6: Herschel-Planck Instrument HFI

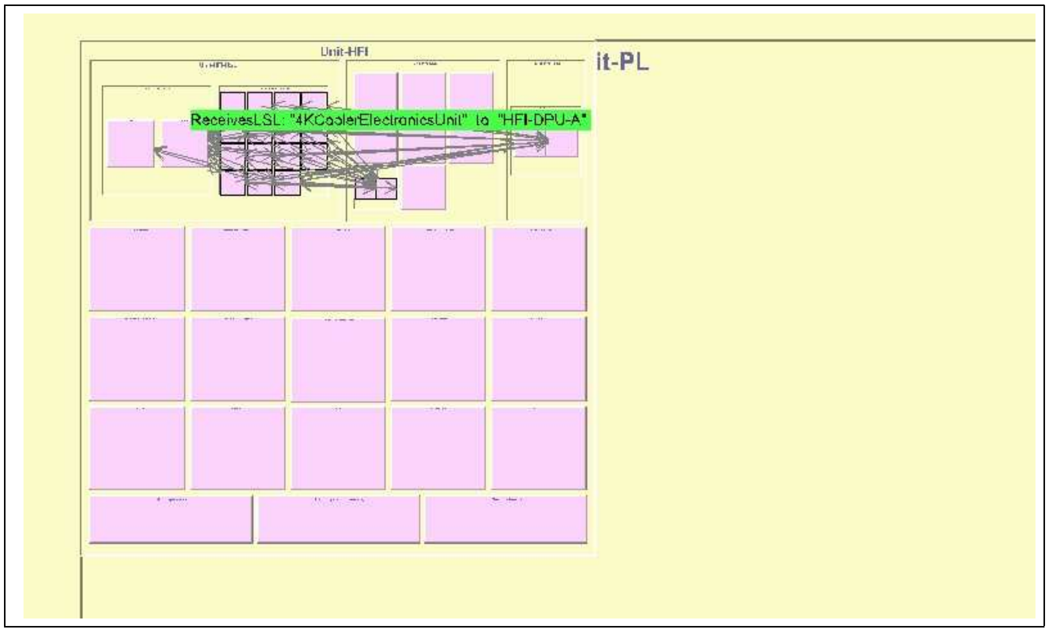
This tool make it very easy to browse for information and generally learn about a particular instrument or subsystem. It is possible to zoom in and out and view the data that is stored in the knowledge base in different ways. Figure 7.7 shows this.



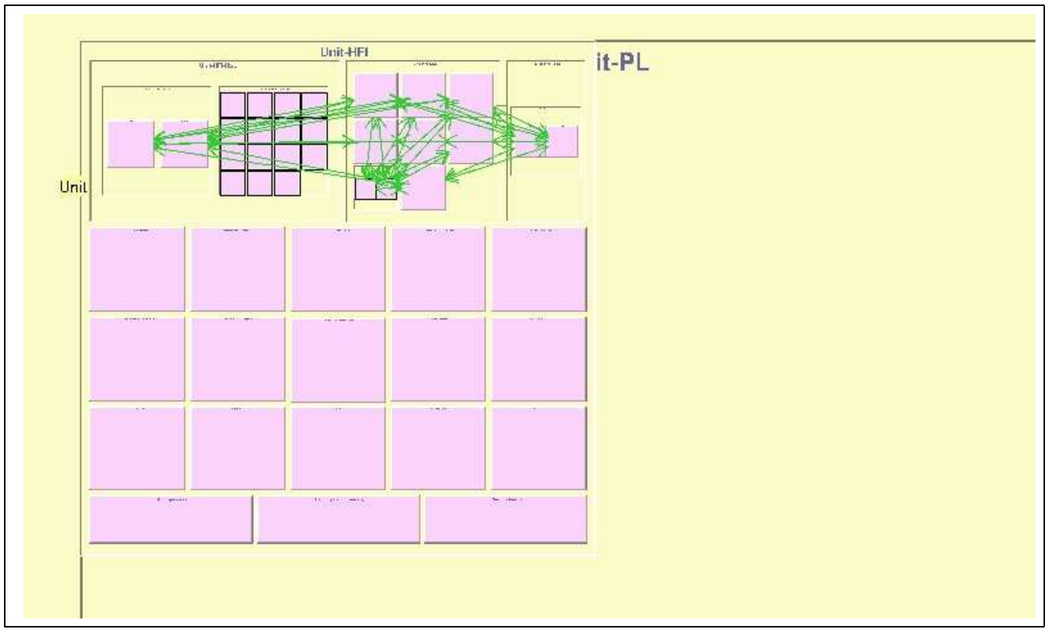
It is possible to zoom in on one area and see in which relationships units participate. If the diagram become too cluttered, the labels on the arcs can be removed, or set to appear when the mouse is moved over a particular arc. This facilitates exploration.

Figure 7.7: Herschel-Planck Instrument HFI

As further examples of how this innovative tool allows the user to explore a knowledge base, Figure 7.8 shows which parts of the instrument HFI are connected by the High Speed Link (HSL) serial communication link and shows which parts of HFI are connected by the Low Speed Link (LSL) serial communication link. These diagrams illustrate how easy it is to see and display different sets of information from the knowledge base in a visually appealing manner.



By filtering to show certain arcs, the architecture of the instrument can be revealed. This figure shows which parts of the instrument use the High Speed Link.



By filtering to show different relationships (arcs) different aspects and and viewpoints can be shown. This figure shows which parts of the instrument are connected via the Low Speed Link.

Figure 7.8: Herschel-Planck Instrument HFI architecture

7.4 Summary

The User Manual is to help the end-users understand and operate the spacecraft and payloads safely and successfully.

Since there is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system or instrument to another and from project to another, and just because the documentation was good on a previous project does not mean that it will be good on the next project since there is no real process in place to make sure that the quality increases with time. Overall, it is fair to say that it is difficult to produce a user manual because their is not standard to say what it should contain or how to produce it.

This Chapter has shown a method that could be used both to ensure that documentation complete and correct,and the following chapter, Chapter 8, illustrates a way to reason with the knowledge that is encapsulated in the documentation.

Section 7.2 has shown how the introduction of new names for existing concepts makes it difficult to produce the User manual to a consistent standard and prevents re-use of documentation from one project to another, and section 7.3 illustrated a powerful technique with its roots in artificial intelligence that allows users to browse data and display relationships graphically, whilst at the same time permitting writers to check their input obeys certain consistency constraints which will highlight when or where information is incomplete.

The short example in Appendix A is sufficient to show that even a consistent ontology is not a panacea.

The Appendix contains examples about one instrument (HFI) and the Low Speed Link that some units within HFI use to communicate. The current ontology would require an additional 250 pages to print out or view via a web browser. It is apparent that the volume of a complete ontology would be a significant burden upon any contractor to produce, or any operations team to read. However, it is something that only needs to be done once, and it is better to do a minimal component of it properly rather than aim for a complete Theory of Everything that can never be completed. Since this shows how much information is require for an incomplete model, it also shows how much information would really be required for a complete set of documentation.

Without an approach that makes it easier to develop a knowledge base that can be checked and transferred easily, future projects are destined to repeat many of the mistakes of their predecessors simply because it is too difficult to learn from them.

Chapter 8

Formal Methods

8.1 Introduction

Modern spacecraft and their payloads are extremely complex devices. Often they are required to have high autonomy, they are often sent on unique missions, they are expensive and the subject of high expectations. However they are still being design and tested using fundamentally the same methods as their predecessors: personal experience, manual design and limited testing of a few scenarios with the real hardware.

One of the most lucid arguments in favour of formal methods is presented in [34] "..the building of ships has been practised for over two thousand years, and the construction of houses and bridges for considerably longer. Small wonder, then that the many principles of civil, nautical, structural and mechanical engineering have become part of our collective consciousness. For instance few would begin to build even a model boat without a set of drawings, and one hardly remarks on the need for plans to be prepared for a new house or even an extension to an old one. Time has not yet allowed us to acquire the equivalent body of expertise with which to surround and support the development of software-based systems. Consequently many systems are constructed with little or no overt attention to any underlying theory, and without the benefit of centuries of experience in the selection of those techniques which are likely to to confer success."

Discrete systems are based a very simple logic, usually binary logic, in which the system is usually either in one state or another. By comparison, in structural mechanics a material is subject to a either static or continuously varying forces and responds in a continuous fashion. The structural system has a clear boundary, and the limits can be calculated and tested. If a new phenomena is discovered, such as shock-loading, or fatigue, then that can also be calculated and extrapolated and tested. "By testing a structural system to its limits, we can be reasonably sure that if we stay in a well-defined envelope, the structure will be able to carry out the task intended"[34]. Although the discrete system may sound simpler, it scales differently. In contrast , for a discrete system "for a medium sized system containing 1000 decisions ..would require more than 10^{300} test cases"[34].

Formal methods bring the benefit of being able to argue a particular case based upon a rigorously defined specification. "Proof of one property at the specification stage may yield a result which corresponds to the behaviour of a very large number of possible execution sequences, offering an increased level of confidence with the opportunity of reducing test cases"[34]. The method chosen here is the Z language. This chapter demonstrates how formal methods may be applied to analyse the malfunctioning of a real-world system.

8.2 What is Z?

Z is a formal specification notation based on first order predicate logic and set theory. It was developed at the Programming Research Group at the Oxford University Computing Laboratory (OUCL) and elsewhere in the late 1970s. International ISO standardisation is ongoing (Z is already adopted as a British Standard). This thesis cannot hope to replace a good tutorial (e.g. [34, 42]) and the interested reader is referred to these or the many other for more detailed information however this section and the following sections give an introduction to Z and show how it can be applied in the context of spacecraft engineering.

The main ingredients in Z are the following:

1. The use of mathematical data types to model the data in a system.

2. The use of the notation of predicate logic to describe abstractly the effect of each operation of a system and to enable us to reason about its behaviour.

3. The way of decomposing a specification into small pieces called schemas. By splitting the specification into schemas, we can present it piece by piece. Schemas are used to describe both static and dynamic aspects of a system. The static aspects include

   - the states it can occupy;
   - the invariant relationships that are maintained as the system moves from state to state.

   The dynamic aspects include:

   - the operations that are possible;
   - the relationship between their inputs and outputs;
   - the changes of state that happen.

4. The Z Schema Calculus

   This is the way "objects" are introduced. Schemas can either refer to objects as nouns or to operations as verbs (actions). As mentioned in the chapter on Relational Theory, the relations between objects are as important as the objects themselves. The Z schema calculus combines the schema descriptions into one schema and defines how they can be manipulated.

   - Schema Name: Each schema must have a name. By naming them we have a method to refer to them.

- Schema Signature: The signature sets out the names and types of the entities introduced in the schema.
- Schema Predicate: The predicate sets out the relationships between the entities in the signature by defining a predicate over the signature entities.

Normally these features are 'packaged' typographically in a box to enhance the clarity of the specification although these shapes can be visually quite intimidating for the newly initiated! A schema is shown in Z as follows:

SchemaName

Signature : defines objects used the predicates section

logical predicates

Note that although we can specify the various requirements for an operation separately, and then combine them into a single specification of the whole behaviour of the operation, this doesn't mean that each requirement must be implemented separately, and the implementations combined somehow.

The separation of normal operation from error-handling which is the simplest but also the most common kind of modularisation possible with the schema calculus.

8.3 Outline of a Specification

A Z specification should follow a fairly standard structure. As an introduction to the notation a simple example is given, although it cannot replace a detailed tutorial.

Preliminary analysis

First the requirements are analysed to identify the important parts of the problem; they are described by sets and constants. The first section should include the basic elements which are to be used throughout the whole specification. They are given what is referred to as global scope. Given sets are used as types in the rest of the specification.

Application-oriented theory

Often some special purpose theory has to be developed when writing specifications - after the global declarations, and before the description of the state.

Describing the abstract state

Next, the abstract state is described using one or more schemas.

The initial state

A schema that describes the initial state of the system is given.

Specifying the successful case of operations

Each operation is specified, ignoring any error conditions.

Preconditions

The preconditions of the partial operations are calculated.

Schemas describing error cases

Normally, we wish to build complete interfaces so that systems can handle any input and provide sensible results.

Making the operations total

The partial operations that describe the successful cases and the various errors are combined to give a total description.

8.4 Tools

There are a number of tools[11][28] available which provide a great deal of support for maintaining and checking a specification. Some tools include limited automatic theorem proving, although for non-trivial specifications, the user must guide the tool in certain places.

8.5 Example Specification: Satellite Operations

Controlling a satellite involves a combination of hardware, software and human operators. It can be difficult to predict how this distributed system can fail. The components are each designed and built by specialists in individual areas, and it becomes the responsibility of the operations team to safely operate the system so as to maximise availability.

8.5.1 Given Sets

This defines the things that we will talk about.

$$[SWITCH]$$

Define some specific types.

$$DischargeSwitchState ::= DOpen \mid DClosed$$

$$ChargeSwitchState ::= COpen \mid CClosed$$

8.5.2 State Definition

An individual battery is described in the following schema :

$$
\begin{array}{|l}
\textit{BasicBattery} \\
\hline
DischargeSwitch : DischargeSwitchState \\
ChargeSwitch : ChargeSwitchState \\
\hline
DischargeSwitch = DClosed \Rightarrow ChargeSwitch = COpen \\
ChargeSwitch = CClosed \Rightarrow DischargeSwitch = DOpen \\
\hline
\end{array}
$$

which simply says that in this model, a battery has two switches, one for charging the battery and one for discharging it. A constraint that the switches should not be closed together at the same time is made explicit here.

8.5.3 Operation Definition

Within this simple model, we then say that to charge the battery we close one of the switches.The use of the ”prime” notation (shown by a $'$) permits to differentiate between the states *before* the operation and the states *after* after the operation. The Z view of an operation is then as being a relationship between a set of all *before* states and the set of all *after* states. It makes no presumption about how the particular operation is implemented.

$StartCharging1$

$BasicBattery$

$BasicBattery'$

$ChargeSwitch = COpen$

$ChargeSwitch' = CClosed$

$DischargeSwitch' = DischargeSwitch$

Z allows certain abbreviations and conventions to be used within the notation that do not impair the mathematical rigour. The line ΔBasicBattery shows that this schema imports the schema BasicBattery and BasicBattery′ and modifies the state only as shown. The *before* and *after* versions of the other variables are the same, and so do not need to be explicitly shown. With this abbreviated notation we can write that to discharge the battery we close the other switch.

$StartDischarging1$

$\Delta BasicBattery$

$DischargeSwitch = DOpen$

$DischargeSwitch' = DClosed$

$ChargeSwitch' = ChargeSwitch$

and then develop schema to describe the end of charging and the end of discharging too.

$StopCharging1$

$\Delta BasicBattery$

$ChargeSwitch' = COpen$

$DischargeSwitch' = DischargeSwitch$

$StopDischarging1$

$\Delta BasicBattery$

$DischargeSwitch' = DOpen$

$ChargeSwitch' = ChargeSwitch$

8.5.4 Pre-Condition Calculation

One of the advantages of using a formal method is to investigate under what cases the defined operations can succeed. This is called calculating the preconditions of an operation. In English. this would be equivalent to defining an function called *pre Op* such that for an operation *Op*, there exists a state after the operation *Op* as long as the preconditions are satisfied. More mathematically, the pre-conditions for an operation *Op* are defined as:

$$\text{pre } Op = \exists\, State';\ Outs \bullet Op$$

where

$State'$ is the modified state variables

Outs are the output variables of the operation.

For the operation to be total, it should be possible to start it in any state, and thus $\forall\, State';\ in : IN; \bullet \text{ pre } Op$ should be a theorem that can be proved in our system. This then gives:

theorem PreStartCharging1

$\forall\, BasicBattery' \bullet \text{pre } StartCharging1$

By expanding this gives

$BasicBattery$
$\exists\, ChargeSwitch' : ChargeSwitchState,$
$DischargeSwitch' : DischargeSwitchState; \bullet$
$StartCharging1$

Which expands to

$DischargeSwitch : DischargeSwitchState$
$ChargeSwitch : ChargeSwitchState$
$DischargeSwitch = DClosed \Rightarrow ChargeSwitch = COpen$
$ChargeSwitch = CClosed \Rightarrow DischargeSwitch = Dopen$
$\Rightarrow ChargeSwitch = COpen \wedge DischargeSwitch = DOpen$

Which should have been 'intuitively' obvious from the outset, but has been calculated here. These preconditions can then be added and tested:

theorem ModifiedPreStartCharging1
$\forall\, BasicBattery \mid ChargeSwitch = COpen \wedge DischargeSwitch = DOpen$
$\bullet\ \mathrm{pre}\ StartCharging1$

This can be expanded to give the result *true* in a theorem checker[11] or type checkers [28].

8.6 Detailed Specification

Now let us examine a more complicated situation, a little closer to real life. In order to measure the performance of a battery, and to re-condition it if necessary, this battery is fitted with a resistor, of known resistance, referred to as a *shunt*. The battery can be switched out from the support of the Main bus, and then discharged through this shunt. The time taken to reach a standard voltage (equal to end of discharge limit) allows the stored energy of the battery to be measured. The battery then needs to be recharged very slowly (trickle charge) to avoid damage. This is because if the battery voltage is low, the current into it from the normal charger would be too high.

8.6.1 Component Specification : Shunt

Component Data Type Definition

$$\mathit{ShuntState} ::= \mathit{ShuntOn} \mid \mathit{ShuntOff}$$

$$\mathit{TrickleState} ::= \mathit{TrickleOn} \mid \mathit{TrickleOff}$$

Component State Definition

$$\begin{array}{|l}
\textit{Shunt} \\
\hline
\mathit{ShuntRelay} : \mathit{ShuntState} \\
\mathit{Trickle} : \mathit{TrickleState} \\
\hline
\end{array}$$

Component Operations

The following operations are possible:

DeepDischargeStart

$\Delta Shunt$

$ShuntRelay = ShuntOff$

$ShuntRelay' = ShuntOn$

$Trickle = TrickleOff$

$Trickle' = TrickleOff$

DeepDischargeCompletion

$\Delta Shunt$

$ShuntRelay = ShuntOn$

$ShuntRelay' = ShuntOff$

$Trickle = TrickleOff$

$Trickle' = TrickleOff$

After the deep discharge, the battery is then charged with a low current (referred to as trickle charging):

TrickleCharge

$\Delta Shunt$

$ShuntRelay = ShuntOff$

$ShuntRelay' = ShuntOff$

$Trickle = TrickleOff$

$Trickle' = TrickleOn$

TrickleCompletion

$\Delta Shunt$

$Trickle = TrickleOn$

$Trickle' = TrickleOff$

8.6.2 Component Specification : Pressure Detectors

Component Data Type Definition

Let us define three ranges of pressure: a nominal range and a low threshold and a high threshold, together with two signals which trigger when the appropriate threshold is breached.

$$PressureRange ::= Plo \mid Pmid \mid Phi$$

$$HPSignal ::= High \mid NotHigh$$

$$LPSignal ::= Low \mid NotLow$$

```
┌ PressureSensor ──────────────────────────────
│ CellHighPressure : HPSignal
│ CellLowPressure : LPSignal
│ Pressure : PressureRange
├──────────────
│ Pressure = Phi ⇔ CellHighPressure = High
│ Pressure = Plo ⇔ CellLowPressure = Low
└──────────────────────────────────────────────
```

8.6.3 Main Specification

The rest of the battery is similar to the previous example. It would be possible to simply refer to the the previous schema *BasicBattery* or repeat the definition here.

Data Type Declarations

$$DischargeSwitchState ::= DOpen \mid DClosed$$

$$ChargeSwitchState ::= COpen \mid CClosed$$

State Definition

$$\begin{array}{|l}
\textit{BasicBattery} \\
\hline
\mathit{DischargeSwitch} : \mathit{DischargeSwitchState} \\
\mathit{ChargeSwitch} : \mathit{ChargeSwitchState} \\
\hline
\mathit{DischargeSwitch} = \mathit{DClosed} \Rightarrow \mathit{ChargeSwitch} = \mathit{COpen} \\
\mathit{ChargeSwitch} = \mathit{CClosed} \Rightarrow \mathit{DischargeSwitch} = \mathit{DOpen} \\
\hline
\end{array}$$

The *ComplexBattery* has all of the same features of *BasicBattery* with some additional ones, including the *shunt*. The following schema shows the state of the *ComplexBattery* and shows that it includes a *shunt*.

$$\begin{array}{|l}
\textit{ComplexBattery} \\
\hline
\mathit{BasicBattery} \\
\mathit{Shunt} \\
\mathit{PressureSensor} \\
\hline
\end{array}$$

Operations

In the following, we introduce the symbol Ξ in Z, which is the same as Δ which introduces the *before* and *after* schema, but with the addition of predicates to equate (all) of the *before* and *after* states of the declared variables.

Here we describe the charging process. The pressure increases when charging takes place i.e. when the charge switch is closed, the pressure is allowed to increase until the high limit.

$$\begin{array}{|l}
\textit{Charging} \\
\hline
\Delta \mathit{ComplexBattery} \\
\Xi \mathit{Shunt} \\
\hline
\mathit{ChargeSwitch} = \mathit{CClosed} \\
\mathit{Pressure}' \neq \mathit{Phi} \\
\hline
\end{array}$$

Similarly, when a battery is discharging, the pressure drops, but should not be allowed to drop below the low limit.

$$
\begin{array}{|l}
\multicolumn{1}{l}{\textit{Discharging}} \\
\hline
\Delta \textit{ComplexBattery} \\
\Xi \textit{Shunt} \\
\hline
\textit{DischargeSwitch} = \textit{DClosed} \\
\textit{Pressure}' \neq \textit{Plo} \\
\hline
\end{array}
$$

Normally the battery is kept almost fully charged. It discharges slowly, and the internal pressure drops. When the low pressure threshold is reached the battery is charged up again until the pressure reaches the high threshold.

$$
\begin{array}{|l}
\multicolumn{1}{l}{\textit{RoutineControl}} \\
\hline
\Delta \textit{ComplexBattery} \\
\Xi \textit{Shunt} \\
\hline
(\textit{Pressure} = \textit{Phi} \wedge \textit{DischargeSwitch} = \textit{DClosed}) \vee \\
(\textit{Pressure} = \textit{Plo} \wedge \textit{ChargeSwitch} = \textit{CClosed}) \vee \\
\textit{Pressure} = \textit{Pmid} \\
\hline
\end{array}
$$

8.6.4 Error Cases

It is possible to define two error cases; that is charging when the pressure is at the high limit, or discharging when the pressure is at the lower limit.

$$\textit{report} ::= \textit{Ok} \mid \textit{HighPressure} \mid \textit{LowPressure}$$

$$
\begin{array}{|l}
\multicolumn{1}{l}{\textit{OverPressure}} \\
\hline
\Xi \textit{ComplexBattery} \\
r! : \textit{report} \\
\hline
\textit{CellHighPressure}' = \textit{High} \wedge \textit{ChargeSwitch}' = \textit{CClosed} \\
r! = \textit{HighPressure} \\
\hline
\end{array}
$$

$$
\begin{array}{|l}
\multicolumn{1}{l}{\mathit{UnderPressure}} \\
\hline
\Xi \mathit{ComplexBattery} \\
r! : \mathit{report} \\
\hline
\mathit{CellLowPressure}' = \mathit{Low} \land \mathit{DischargeSwitch}' = \mathit{DClosed} \\
r! = \mathit{LowPressure} \\
\hline
\end{array}
$$

It is now possible to combine the *RoutineControl* and the error cases to make a schema *NominalOperations*.

$$\mathit{NominalOperations} \mathrel{\widehat=} \mathit{RoutineControl} \lor \mathit{OverPressure} \lor \mathit{UnderPressure}$$

8.6.5 Test Cases

After performing DeepDischarge, DeepDischargeCompletion, TrickleCharge and TrickleChargeCompletion the battery should be back in its starting state.

Here we construct a series of test cases by sequentially composing the schema, one after the other.

$$\mathit{Test}1 \mathrel{\widehat=} \mathit{DeepDischarge} \fatsemi \mathit{DeepDischargeCompletion}$$

$$\mathit{Test}2 \mathrel{\widehat=} \mathit{TrickleCharge} \fatsemi \mathit{TrickleCompletion}$$

$$\mathit{Test}3 \mathrel{\widehat=} \mathit{Test}1 \fatsemi \mathit{Test}2$$

theorem BackToNormal3
$\mathit{Test}3 \Rightarrow \Xi \mathit{Shunt}$

i.e Test3, the result of applying all of these schema, implies that the end state is the same as the beginning state. This Theorem can be expanded to give the result *true*, as desired.

8.7 Summary

Formal methods bring the benefit of being able to argue a particular case based upon a rigorously defined specification. By proving a property of a design early in the mission life-time, perhaps even before hardware is built, it may result in a cost saving, by reducing testing, or a dramatic increase in reliability. Formal methods were developed to be applied to software systems, but are applicable to any discrete system.

One of the main benefits of formal methods is that it requires a statement of the problem. This is also sometimes a disadvantage, since some of the knowledge might not be available. Obviously the main advantage of using a formal method for the design specification and testing would arise if the overall life-cycle were to be improved, and the same knowledge of the state space that was tested at the design phase were also to be used in the testing and qualification phase, and even if the same source of data were to be used in the user manual. With the idea of an ontology from Chapter 7 this idea of a single knowledge base for the entire mission can be applied.

Chapter 9

The Nature of Complexity

Of three ordinary people, two must have the same sex.

Daniel Kleitmam

9.1 Introduction

Complexity is defined as the opposite of simplicity, but in terms of trying to evaluate the complexity of a system, that (almost recursive) definition does not help. When trying to compare different designs of satellite, one could initially try to count the number of distinct telecommands that a satellite can accept, but several questions arise. Should this number include telecommands with parameters? How are different parameter values taken into account? How does the number of telemetry parameters affect this value? If we avoid these questions for the moment, this definition would lead logically to the concept that the complexity of a system was related to the length of its description and it is interesting to analyse this concept in more detail. For example, what characterises the complexity of a group of interconnected computers? As discussed by Gell-Mann[16], a number of nodes can be interconnected in many different ways and it is interesting to examine the relative complexity of such networks as shown in Figure 9.1.

Most people will agree that A is simple - no nodes are connected. In case B, some, but not all, nodes are connected. In C, all the dots are connected, but not

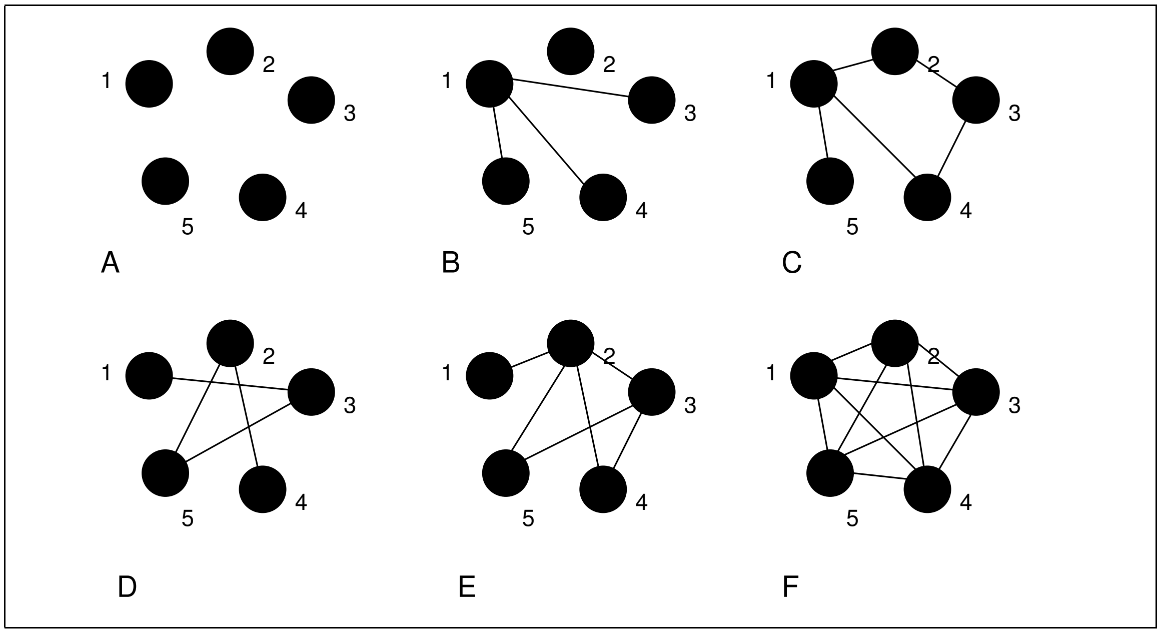


Figure 9.1: Comparative Complexity

in all possible ways. In D, the connections that are present in C are absent, and those that are absent in C are present; C and D are thus complements of each other. Similarly E is the complement of B, and F is the complement of A, since all nodes are connected in all possible ways. This results in what can also be referred to as an undirected graph. The same information can be shown in matrix form, where each node represents a column and a row, and a '1' indicates that a connection exists between the two nodes. It is assumed that no node can be connected to itself, and so the items on the leading diagonal can be disregarded.

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} B = \begin{pmatrix} 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} C = \begin{pmatrix} 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

$$D = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \end{pmatrix} E = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{pmatrix} F = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{pmatrix}$$

Most people will agree that case A is simple, i.e. has the least complexity, and that case B, is more complex than case A. One immediate reaction might be that case F is the most complex, but there is potentially a good argument to be made that the property of having all the nodes connected is the same as having none of the nodes connected. If the convention used in the matrix notation is inverted, ie. 1 = not connected, case F is the same as case A, so perhaps case F belongs at the bottom of the complexity scale, with case A. The patterns shown in B and E are evidently more complex than A (and therefore F), and the same can be said for cases C and D. Note that this analysis might break down if the links between node are not identical, or change in nature. For example in the domain of control, one is generally more interested in imposing one's will upon a system, and so the diagrams need to be enhanced to include the introduction of information from the outside world, and then flowing from one node to another. This means that the topology cannot be represented by an undirected graph.

On a more philosophical note, it should be remarked that if the complexity of a system is related to the length of its description, then complexity is not an intrinsic property of that which is being described. Any description of complexity is necessarily context-dependent, and may even be subjective. Not only is the level of detail at which the system is being described subjective, it depends upon the vocabulary available. For example, to someone with experience in the space industry, it might be sufficient to say that a satellite has an Earth sensor, whereas to communicate the same information to a novice, one would have to start from first principles, perhaps even with an introduction to orbital mechanics! These ideas can be integrated into what Gell-Mann refers to as 'crude complexity': "the length of the shortest message that will describe a system, ...,to someone at a distance, employing language, knowledge and understanding that both parties share (and know they share) beforehand."

9.2 Algorithmic Information Content

During the 1960s, three authors (Kolmogorov, Chaitin and Solomonoff) independently developed the concept of Algorithmic Information Content, AIC[16]. They envisaged that a description to a given level would be encoded into a string of binary digits, and assumed the existence of an idealised, all-purpose computer with no limit on its storage capacity. They then defined the length of the shortest program that would make the computer printout the string and then stop as being the Algorithmic Information Content of the string. These theorists were interested in how description of systems such as those defined above would vary as the number of nodes was increased towards infinity, and so the initial differences that would result from the use of one computer or one language instead of another were dwarfed by the effects due to scaling up the problem. One curious property of Algorithmic Information Content is that it is not computable. We can never be sure that the Algorithmic Information Content of a string is not lower than we think it is. There may always be a theorem or algorithm that would permit the description to be further compressed. This result is reminiscent of Gödel's Theorem, that stunned the world of mathematics by proving that it was not possible to formulate a system of axioms for all of mathematics and prove them consistent, and was thus impossible to derive the truth or falsity of all mathematical propositions. However, it is possible to put an upper bound on the Algorithmic Information Content of a description, although the AIC may of course be lower than this.

A further flaw in the use of Algorithmic Information Content to define complexity for our purposes is that since Algorithmic Information Content effectively deals with the compressibility of message strings, Algorithmic Information Content is largest for random strings, and randomness is not what is usually meant by complexity. In fact it is the non-random aspects of a system (or of a string) which contribute to its effective complexity, which can be characterised as the length of a concise description of the regularities of that system.

What we are really interested in is the knowledge gained by separating the regularities in a system from the random occurrences, since we wish to understand the behaviour of the system. This is analogous to learning a language. If the student's native language is 'similar' in some way to the new language to be learned, a system consisting of some rules and a look-up table might be very effective. However, for every exception to the rules, the length of the description increases. The new student (or young child) is able to effectively separate grammatical features from the other factors that gave rise to the sentence that was heard or read. One thing that does become obvious from the calculation of the Algorithmic Information Content is that comparisons between systems of differing complexity become more meaningful as the descriptions become longer. At the absurd extreme, it is evidently meaningless to differentiate between the simplicity or the complexity of a one bit string. This leads us to the idea that complexity is linked to the presence of similarities in descriptions, but not absolute identities. The description of the system thus contains a series of patterns that may re-occur throughout the description.

9.3 Effective Complexity

If the system being described has absolutely no regularities in it, then the compressed description (which can also be referred to as a schema) will contain no patterns. To put it differently, the schema will have zero length. This gives us the kind of property that we desire in a useful definition of complexity, since if we study a random string, even though its Algorithmic Information Content is maximal for its length, we can learn nothing useful from it. At the other end of the scale, when the Algorithmic Information Content is near zero, the bit string is entirely regular, the effective complexity should also be zero, since the message is so easily compressed. Thus for the effective complexity to be high, the system must be neither too well ordered,

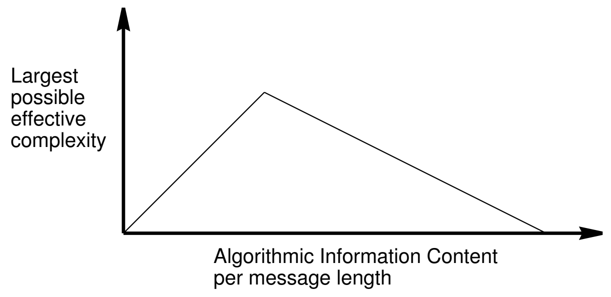


Figure 9.2: Effective Complexity

nor to disordered. This is sketched in Figure 9.2.

9.4 Causes of Complexity

In simple words, almost anything can cause complexity. The time-honoured idiom ”Any fool can invent something complicated. It takes a genius to invent something simple” is very apposite. Complexity has a number of origins: large numbers (too many things to control), small numbers (resource constraints), interactions, and time constraints. Often features related to complexity arise much sooner, with much smaller numbers than expected.

The Birthday Problem

For example, consider the Birthday problem[21], which is apparently well-known , but manages to fool or mislead a high fraction of people.

If we consider that a year always consists of 365 days, and that births are equally likely throughout the year, how large must a group be, for it to be more likely than not that two members of the group share the same birthday?

Most people (including this author) guess about 183, the obvious reason being that it is just over half of 365. However, the real answer is 23! The trick here for finding the probability that something happens is to calculate the chance that it does not happen, and then subtract it from 1.

With two people, the second person has a different birthday 364 times out of 365.

A group of three people will all have different birthdays if the first two are different (probability 364/365), and the third persons birthday is one of the remaining 363 days. So the chance of having three different birthdays is

$$\frac{364}{365} \times \frac{363}{365}$$

For four people, the first three must be different (as above) and the fourth must be on one of the remaining 362 days.

$$\frac{364}{365} \times \frac{363}{365} \times \frac{362}{365}$$

Statisticians introduce a notation to express products such as $364 \times 363 \times 362$ more concisely. Write this as $(364)_3$. Then the probability of 5 people having different birthdays is

$$\frac{(364)_4}{365^4}$$

and the chance that ten people will have different birthdays is

$$\frac{(364)_9}{365^9}$$

If we extended this calculation down to a group of 366 people, the probability would be zero. But to solve the problem in hand, it is sufficient to use a calculator or spreadsheet to evaluate

$$\frac{(364)_{21}}{365^{21}} and \frac{(364)_{22}}{365^{22}}$$

which give 0.5243... and 0.4927...respectively, so 23 is indeed the point at which it becomes more likely than not that a group contains two people with the same birthday. This surprising result can be partly explained as follows. Consider that when the group contains 10 people, an eleventh person has 10 chances of size $\frac{1}{365}$ of having a common birthday. If there is no common birthday, then the twelve person has 11 chances of $\frac{1}{365}$, and so on. There are $K \times (K-1)/2$ ways of choosing two objects from a group of K objects, which means that there are 253 chances, each of size $\frac{1}{365}$ in a group of of 23 people.

This analysis has been shown in a trivial, amusing case, but it could have more significant implications in for example, assignments of a limited number of frequencies, or slots on a bus. A constraint has shown to be much more likely to appear than initially expected.

Ramsey Theory

H.Burkhill and L.Mirsky [2] state "There are numerous theorems in mathematics which assert, crudely speaking, that every system of a certain class possesses a large sub-system with a higher degree of organisation than the original system." All of these structural problems can be grouped under the general heading of Ramsey Theory. The classic Ramsey problem can be phrased in terms of the number of guests at a party. What is the minimum number of guests that must be invited so that either at least three guests will all know each other, or at least three guests will be mutual strangers? To clarify the assumptions, let us assume that the relation 'knowing' is symmetric: if Alan knows Bill, then Bill also knows Alan. Now let us consider the situation of the sixth guest, Fred. Since Fred either knows the other five, or does not know the other five, then by inclusion he will either know at least three of them, or not know at least three. If we assume that Fred knows at least three of them, Alan, Bill and Charlie (the argument works the same way with the other assumption) then we consider what relationships the three acquaintances might have amongst themselves. If any two of them know each other, then they, together with Fred, will make up a group of three who know each other and we are done. If all three of Fred's acquaintances are mutual strangers, then we are done too, since that gives us a group of three. This could have been proved by brute-force evaluation of all $32,748$ possibilities but combinatorics allows some limits to be explored without enumerating and testing every possible combination. R. Graham referred to this as 'Counting without counting".

For example, if we want to guarantee a group of four people who either all know each other or are mutual strangers, then 18 people are necessary and sufficient. For five people, the answer is not known, but it is known to lie between 43 and 49. For six people, the range is even bigger: 102 to 165. These are normally written as $R(3, 3)$, for the first example, $R(4, 4)$ for a group of 4 who know or do not know each other. Sometimes these symmetrical numbers are abbreviated as $R(3)$, $R(4)$ etc. Ramsey numbers are not always symmetrical: it is possible, for example to define R(4,3)=6, the number necessary to ensure either a group of 4 people who know each other, or a group of 3 strangers, or (since the relation 'not knowing' has the same properties as the relation 'knowing') a group of 4 strangers or a group of 3 people who know each other. In fact, Ramsey Theory does not have to be restricted to a binary relationship (which is the equivalent of two-colouring a graph), Higher-order Ramsey numbers are defined, but none of the non-trivial ones are known, apart from $R(3, 3, 3) = 17$, the number necessary for a 3 colouring of a graph.

The importance of Ramsey Theory in engineering is difficult to evaluate. It stresses that given any number of any articles, and some kind of relationship between them, there must be some kind of structure, and it might not be the kind of structure that you are expecting. Part of the difficulty arises since the Ramsey numbers specify that one of two subgraphs will be contained within the graphs, but it does not say which. Either 3 people will know each other, or 3 people will not know each other. If we replace the relationship 'knows' with the relationship 'communicates with', or 'shares power with', or 'is physically next to' and the implications become a little clearer. Of course, nobody would design a spacecraft where the components could not communicate with each other when they needed to, and so we can assume that the main functions will be implemented in a way that corresponds to a 'connected solution', as opposed to the 'unconnected' or isolated solution. But in some of the ancillary functions, limitations may only becomes apparent after design, in testing or operations.

An example may help to illustrate where it may be possible to see more relevance to design issues. Without giving the theory, if we look at a sequence of $n^2 + 1$ integers, there will always be a sub-sequence of at least $n + 1$ increasing integers or n decreasing integers[23]. In its more general form, this can also explain the probability of, for example, a series of stars appearing to line up to form a straight line to an Earth-based observer. This is particularly relevant given the propensity of human operators to see patterns (as outlined in section 3.2.3).

Ramsey theory is telling us that there will be a higher level structure in what we create, even if we are not expecting it because we do not create it explicitly. Ramsey theory has been applied to all sorts of communication and thermodynamic problems with successful outcomes[23].

Self-References

Gödel worked in Peano arithmetic to construct a statement that affirms its unprovability. Peano arithmetic is quite basic, consisting of the formal axiomatic theory dealing with natural numbers with the operators for addition, multiplication and equals. Gödel numbered the symbols, the well-formed formulae (WFFs) and the axioms and proofs in a formal axiomatic system. This was his way of converting the assertion that a specific proof establishes a specific theorem into an arithmetical assertion. He converted the assertion into the fact that a certain natural number (the Gödel number of the proof) stands in a numerical relationship with another natural number (the Göedel number of the theorem). The really clever part is in how Göedel created the self-reference, because the statement doesn't refer to itself by containing a quoted copy. It refers to itself indirectly, saying that if a certain calculation is performed, then the result is a statement that cannot be proved.

Five years later, Turing, often referred to as the first computer scientist, found a different reason for incompleteness, almost the source of incompleteness. This was his Halting problem. He determined that there is no algorithm, no mechanical procedure that can ever determine in advance if another computer program will halt.

Chaitin [4, 5], one of the founders of algorithmic information theory, has spent most of his life developing the theory, and is now convinced that complexity is best measured by the binary size of a program trying to simulate the system in question: "The general flavour of my work is like this. You compare the complexity of the axioms with the complexity of the result you're trying to derive, and if the result is more complex than the axioms, then you can't get it from those axioms" [5].

9.5 Example

Everyone would (probably) agree that a pile of wires could not be too complex, but depending upon how it is wired together complexity can emerge.

Consider a basic (I hesitate to use the word simple) system: a heating circuit for a room, operated from a mains supply. We want the room to maintain a certain temperature, so we wind the wire in a coil, put a thermostat in the circuit and plug it into the mains supply . The thermostat opens when it is hot (above the desired temperature) and closes when it is cold (below the desired temperature). This means that current flows in the heater circuit when the thermostat is cold, and heats the air in the room, and the heater current stops when the thermostat reaches or exceeds its desired temperature. This sounds fine.

We then realise that this is an important function, and are worried about the impacts of failures. If the thermostat fails open, then the room gets too cold. If the thermostat fails closed then the room gets too hot. If we duplicate the heater circuit with another thermostat, then we protect against the case that the thermostat fails open, but if either thermostat fails closed, then the room still gets too hot. One possibility would be to implement a complicated switch, so that each thermostat also controls the power line of the heater circuit. Another alternative would be to introduce even more heater circuits, but make them of such a low power that a failure in one circuit only could not make the room get too hot. The problem with this strategy is that then the reliability of the whole system decreases in the long term, since there are more items that can fail.

Then perhaps as an investigation of the performance of the prototype, we decide to actually measure the temperature of the room. This requires the insertion of one or more thermistors into the room. These thermistors provide much greater precision (and accuracy) than the low-tech thermostats. With this data we see that the temperature is cycling up and down within a deadband. To reduce the temperature fluctuations, we decide to use the temperature measurements from the thermistors to operate the switches on the heater cycles. This means that if a switch fails closed, the thermostat will open, and the room will not get too hot. However, the problem is now that a switch might fail open, and then the room gets too cold. Furthermore, the thermistor could fail, and this might cause the switch to stay open too. This has introduced another failure mode.

So it seems as if we cannot rely on a single thermistor. If we have two, we cannot tell which one is correct, so we need at least three, and possibly more, ideally an odd number. But if we decide to average the readings of the thermistors, if one has failed and is giving an exceptionally low reading, then this might distort the average so that it is out of the permitted range, and then the switch will be open, and the room will get too cold.

So the next step is to introduce some kind of plausibility processing on the output of the thermistors. If we have a sufficient number of measurements, we can disregard the highest and the lowest, and then average the remaining measurements. Another alternative would be try to actively detect a thermistor failure as it happens, by looking for a sudden step in the output. Yet another implementation could be to assume that the temperature must always be between the minima and maxima of the thermostat, and that any reading outside of this region is erroneous and must disregarded. The problem with the latter? If we flush the room with cold air (or hot air, if the system is in use outside the British Isles) outside the expected temperature range, all of the healthy thermistors will be declared failed and the outputs ignored. What is the output of the thermistor processing when all inputs are to be ignored? Does it have 'memory'? This could enable it to keep the same state as previously. If a thermistor is declared failed, is it disregarded 'for now and for ever more' or only for the current set of measurements ? How can the customer be informed that a component has failed? Should the customer be informed? Is it reasonable to expect the customer/owner/operator to repair components? Can the customer 'reset' the thermistor processing unit to make it start taking a repaired thermistor into account?

Another solution could be to have two separate 'control systems'. One system with a powerful heater and a coarse thermostat with a wide deadband, and smaller heater circuit to be operated by the output of the thermistors. But then we come down to the reliability of the original components again and what redundancy is necessary. Can the 'fine' heater be operated in parallel with the coarse heater? Can it run all the time? This could be important if the room starts off cold, and we had not considered the fact that the fine heater might have a limit to its duty cycle.

This example has shown how the complexity of a single circuit could be driven up by a number of items including :-

- Environment

- Reliability

- Performance
- Changing Scope
- Usability

Initially we considered only the heater circuit, basically taking a known solution and trying to impose it upon the problem. But slowly the scope of the problem got bigger, so that not just a heater was required, a whole heating and monitoring system was required.

The example system also suffered from 'requirements creep', as we slowly expanded from a system specified to maintain a given temperature to one that was intended to take a room from almost any temperature to the desired temperature, and we had not even addressed any cooling requirements. As an aside, a colleague has a real central heating system for his house, bought off the shelf which includes factors for giving weight to the outside air temperature and the amount of sunshine incident upon the house, as well as the obligatory interface for Internet accessibility.

The really interesting questions are triggered by considering the answers to the question 'Who monitors the monitor?'. Every time a monitoring requirement is added, it imposes a 'new level' to the design. Not only should the monitoring system be more reliable than the system that it is monitoring, it should also behave correctly over the entire potential range of operation of the system which it is monitoring, including starting and stopping and all possible operations in between. Exactly how much do you trust a unit that says that it has failed?

Hofstadter [24] introduced the terms "Strange Loop" and "Tangled Hierarchy" to explain the phenomenon of, when moving in a single direction through the levels of hierarchical system, the observer or participant suddenly finds herself back where she started. Hofstadter illustrates this phenomenon in a wonderful book with examples from music (e.g. Bach Canons), art (the works of M.C. Escher) and dialogues reminiscent of Lewis Carroll's Alice in Wonderland. He explains how complexity can "emerge" by creating another level, almost as a way of avoiding a logical conflict. For example, if we consider the sentence

"This sentence is a lie"

we run into a conflict, since each of the individual constituents of the sentence is (or may be) true, but when we move to the semantic level, the sentence itself is telling us that it is false. Which do we wish to believe? Mathematicians have continued doing mathematics, long after Gödel produced his paper, and indeed long after he died. It is always possible to work around this conflict by introducing another axiom, and continuing happily along in the new system, i.e. at a higher level, with greater complexity and a greater risk, since the more axioms there are, the more there is that can be wrong. Nothing is *too* complicated. Almost everything is more complex.

9.6 Complexity Management

As we have seen, as systems grow, there is an unavoidable increase in the complexity. Although it is not possible to have a 'big' system that is simpler (in all ways) than a 'small' system, it should be possible to make the complexity scale at a rate less than the size of the system by trying to localise as many functions as possible within modules and reducing the coupling between modules as much as possible. This practice has been established as classic software engineering as well as in other disciplines. This means, for example, trying to encapsulate functions such as control and monitoring of a particular sub-system, without involving other sub-systems. This can often be achieved for the nominal case, but is much more difficult at the extremes of the performance envelope.

For example, when batteries charge, they get hot. Conversely,when they discharge, they get cool. For everyday use as a source/sink of extra power in stabilising a bus voltage, these effects can be largely ignored, however during eclipses batteries have to work much harder, and this can cause large temperature excursions which often require a change in the thermal control system. One telecommunications satellite known to the author had a thermostatically controlled heater to control battery temperature operating directly from the battery. In the nominal case this system performed satisfactorily but after a few years of service, as both battery capacity started to dwindle and the solar array no longer performed as well as at Beginning of Life, the battery charging was taking longer and longer because the heater was draining the battery. Left alone, it would have taken more than the time between two eclipses to recharge, so a ground procedure was implemented to manually regulate all the loads in order to ensure that the batteries were charged before the next eclipse.

If we define the goal to be to make a system as simple to operate as possible, then at first glance, automation seems to be the key. A Russian manufacturer known to the author from personal experience NPO-PM tries to automate as much of the operations as possible. To this end, each sub-system is controlled by a software model within their control system, which is supposed to model all feature of the sub-system including known failure modes. This laudable goal is achieved with a group of approximately 70 programmers all specialists in their own area, which would be a massive cost in the West. The result is a control system that is highly tailored to one satellite, and became almost useless when somebody else was commanding the satellite! Basically, they have optimised the system for a single path through the satellite state-space, and even with its detailed models it was 'confused' very easily by small changes from the current state in an unexpected direction.

Essentially NPO-PM have simplified operations until they do not exist. The satellite is 'highly autonomous', and designed to be capable of continuing service tolerant to any single failure, and many double failures. Typically, the company does not even routinely monitor telemetry from all of their satellites, since they are designed to switch on a beacon as a signal that ground intervention is required.

This is similar to the way in which vending machines and lifts operate: nobody expects to have a human operator in attendance, or technicians present on site all the time. What has happened is that the market accepts that for certain services, it is acceptable that either people lose small amounts of money in vending machines, some people are unable to buy from vending machines when they want, or that people may have to wait for a while inside a broken lift. The common theme is that the loss of service has been accepted. Perhaps because of the high costs, and higher profits, associated with satellite broadcasting networks, this has not yet occurred in the West. For scientific missions, which from their nature, tend to be very specific and non-repeatable, the costs associated with major automation in the ground segment are still thought to not be beneficial. In any case, since the data gathered by the science mission is the product, there must still be a link to a ground station in some part of the control chain.

9.6.1 System Design

Sometimes the reliability and the availability of a system are linked in strange and often contradictory ways. By definition, a safely-critical system, should always be safe, even when this design decision adversely affects its availability. For a mission critical system, the availability of the whole system is paramount, and so this could conflict with individual safety. Naturally, if the system (like most satellites) is intended to be exploited by humans rather than being necessary for their survival this does not increase the conflict, although there might be other examples where the decision is not so clear cut, for example, anywhere where people are involved, such as in a train or lift. If given the chance say, to travel in a lift that has failed its safety checks, most people would probably use the stairs, but if a company was seeking to install a lift in its 10 storey HQ building, and it was given the choice between a cheaper lift with 99.99% availability and a more expensive one with 99% availability, most companies would be very tempted to take the cheaper one, even if the second lift was more expensive and less available because it carried out certain checks that were not mandated by the safety legislation in force.

Ground controllers should be provided with transitions that can cover the entire state-space, ie. it should be possible to command all actions from the ground (and more) that can be performed by the on-board autonomy. From the control point-of-view, it makes little or no sense to differentiate between automatic functions that are performed by hardware and those performed by software. The only difference is that there is more chance of being able to correct (or change) those functions implemented in software after the satellite has been launched.

The introduction of automation (frequently through use of software) into the control loop (or the environment) is performed with the best intentions, however it is frequently increases the complexity of the system. Whereas in the nominal condition, operations may have been simplified (e.g. a single command 'Configure Attitude Control System'), in terms of monitoring, the task remains the same (ensure that the correct number of each type of sensor have been powered on and are working) and any attempt to override the system for manual becomes much more difficult. Manual configuration of an autonomous system must:

- Identify what changes have been made by the system to itself;
- Disable the system from making changes to any further units;
- Undo the changes that have been made, where necessary;
- Manually perform the changes themselves.

Software reliability is notoriously difficult to predict. One instruction executed incorrectly (due to change or error in specification, or development) can have global impact. Common techniques used by hardware engineers, such as extrapolation and interpolation, have almost no applicability in software reliability.

9.6.2 Software Use

Certain 'classic' failures can be readily identified in the industry.

- Fashion following - e.g. the way many firms adopted object-oriented approaches and languages, perhaps without any real thought or justification. It is reported that the useful life of an office personal computer is now approximately six months. At the end of this period, the PC can still run the same software that it was bought to run, but the relentless march forward of the industry, the introduction of new features and bloated software, means that the PC can no longer run the *current* software.

- Exaggeration - This is closely linked to trend-setting. A new design methodology, a new language or a new operating system is often marketed (and hence perceived) as a panacea.

- Too trusting - A tool can easily be developed to return an answer ('Okay', 'true', or 'false') but the quality of the answer depends upon the quality of the data used by the tool as well as, of course, the correctness of the tool itself. People have an innate tendency to believe an answer that is produced by a machine and to treat as unchangeable, whereas a human can be challenged.

Another failure or mistake is referred to as 'clumsy automation'. 'Clumsy automation is a label coined by Wiener to describe such poor coordination between the human and machine. The benefits of new technology accrue during workload troughs: when there was already virtually nothing to do, technology will give the user even less to do. But the costs or burdens imposed by the technology (the additional tasks, new knowledge, forcing the user to adopt new cognitive strategies, new communication burdens, new attentional demands) occur during periods of peak workload; during fast-paced periods of high criticality. This creates opportunities for human error and paths to system breakdown that did not exist in simpler systems'[10].

Woods reports his research from 'highly automated flight decks in aviation, space mission control centers, operating rooms and critical care settings in medicine'[43] where automation, was introduced 'in the hope that they would improve human performance by off loading work, freeing up attention, hiding complexity' and indicates that the 'pattern that emerged is that strong but silent and difficult to direct machine agents create new operational complexities'.

Woods reports how users described their interaction with automated systems and the challenges that they faced. The users 'revealed clumsiness and complexity. They described aspects of automation that were strong but sometimes silent and difficult to direct when resources are limited and pressure to perform is greatest'[43]. Woods reported that the users frequently indicated their confusion and increasing workload with the following phrases or their equivalents:

- "What is it doing now?"
- "What will it do next?"
- "How did I get into this mode/state?"
- "Why did it do this?"
- "Why won't it do what I want?"
- "I know there is some way to get it to do what I want."
- "How do I stop this machine from doing this?"

and that 'the potential for surprising events related to automated systems appears to be greatest when automated systems act on their own without immediately preceding directions from the human crew ...and when feedback about the activities and future behaviour of the automated system is weak'[43]. Dekker asks what a user should do to prevent being surprised by the automation, and 'from a variety of accident and incident reports'[10], makes the following recommendations. 'The user must:

- have an accurate model of how the system works;
- call to mind the portions of this knowledge that are relevant for the current situation;
- recall past instructions which may have occurred some time ago and may have been provided by someone else
- be aware of the current and projected state of various parameters that are inputs to the automation;
- monitor the activities of the automated system;
- integrate all of this information and knowledge together to assess the current and future behaviour of the automated system'[10].

9.6.3 Individual Operations Strategies

Given that Ramsey Theory indicates that in any system there will always be some kind of pattern even in random structures and the human tendency to make and stick to hypotheses outlined in Section 3.2.3, Green[18] suggests a number of techniques and steps to be followed by pilots as they maintain mental models of their environments. These are summarised and slightly paraphrased as:

1. Gather as much data as possible from every possible source before making an inference

2. Take as much time as is available before making one's mind up (ie Don't jump to conclusions).

3. Consider all of the possible interpretations of the data - including the unlikely ones - before deciding which data fits the problem

4. After having embarked on a course of action, stop occasionally to take stock of the situation and question if the hypothesis still fits the data as events progress

5. Consider ways to test the hypothesis in a positive and negative way

6. Be aware of the tendency to disregard data, so if new data does not fit the hypothesis, do not disregard them but make time to reconsider the situation and retrace the steps back to the first sign of a problem

7. Ensure that the world is not interpreted in terms of how you would like it to be, but in terms of how it is.

8. Hope for the best, but plan for the worst

9.7 Summary

Spacecraft and spacecraft operations are complex for a number of reasons.

Space systems are usually still quite recent inventions compared with shipping, railways, cars and the aviation industry. Systems designers (and, in the author's experience, also those that procure space systems) are risk averse, which has yielded an approach to the design and implementation of evolution rather than revolution. The disadvantage of this evolutionary approach is that each design brings a lot of heritage with it, so there has been a gradual accretion of complexity as functions and automation have been added on, rather than a clean overview.

From the point of view of the operations, the spacecraft are generally automated and safe, but this provides little chance for learning for those in charge of the operations.

Since virtually all spacecraft operations are a form of remote control, the data used for a hypothesis often incomplete. The information on difficult (or pathological) cases is often not available and generally no physical examination possible at all, compared with the case of aircraft or marine accident investigations. There is generally no sharing of data between different organisations, and the author's experience is that there is very little data is shared from one project to another.

There is no general measure of complexity, and no general agreement that complexity is bad, so designs are not optimised for this aspect. The manufacturers of spacecraft and instrument have little incentive to keep designs and operations simple, and significant incentives to maintain schedule for the delivery of the flight hardware and software. This situation is reminds the author of the situation in the air transport industry and the attitude of ignoring human performance and and limitations evaluation and bundling them together as 'pilot error'. This attitude was eventually changed by a combination of legislation and financial incentives to improve flight safety.

Chapter 10

Telemetry and Telecommand

10.1 Introduction

This Chapter provides a simple introduction into Satellite Telemetry and Telecommand Systems. It introduces the concepts of how commands are sent to the spacecraft (telecommands) and how data is sent from the spacecraft to the ground control centre (telemetry). It outlines the techniques which have developed with time (fixed format telecommands and telemetry) and introduces the concepts of variable length packets, which make better use of the available bandwidth. The issues associated with the information transfer are extended in the next Chapter.

Satellites are commanded by sending radio signals from the Earth to the receiver on-board the satellite. To enable the personnel on the ground to monitor the status of the satellite, the satellite itself sends out radio signals that can be detected by equipment on the ground. Normally there is an Operations Control Centre (OCC, sometimes referred to as Satellite Control Centre, SCC) and one or more ground stations. Each ground station is equipped with one or more large antennae that can support communication with the spacecraft. In the early days of space flight, commands were sent and telemetry was received at comparatively low frequencies, for example VHF or UHF band. For these frequencies the familiar parabolic 'dish' antenna were unnecessary, and stick-like Yagi antennae were common. It was also common to have separate antennae for transmission and reception, although this is now rare. When low frequencies were being used, antenna pointing did not need to be very precisely controlled, either on the satellite or on the ground. Frequencies used for communication with satellite have generally got much higher, S-Band, C-Band or Ku-Band being common. This means that

- Higher data rates are possible
- Beam width is reduced
- Pointing requirements greater
- Losses are less.

Telecommands are sent to the spacecraft in a fixed data unit. Part of the data unit identifies the target, just in case the telecommand should be received by the wrong spacecraft. The remainder contains the data which will be interpreted by the spacecraft as an instruction, with some redundancy in the form of checkbits. There are two well-defined standards in Europe which dictate the format of the data block. The first was the PCM Telecommand standard[13] Telecommand standard in the industry), which was eventually superseded by the Packet Telecommand Standard [14].

10.2 PCM Telecommands

The basic data unit is a 96 bit frame which is shown in Table 10.1.

The term ASW means Address and Synchronisation Word, which dates from before the time that a word was conventionally (but not incontrovertibly) taken to be 16 bits. The ASW was originally supposed to be a unique identifier for the spacecraft decoder, but the proliferation of spacecraft forced people to reuse ASW.

The Hamming code is a 4-bit code capable of detecting a 2-bit error in the 8-bit data and detecting and correcting 1 single bit error, although the error correcting

16 bit ASW		= 16 bits
4 bit Mode		= 4 bits
8 bit Data Word 1	+ 4 bits Hamming Code	= 12 Bits
8 bit Data Word 2	+ 4 bits Hamming Code	= 12 Bits
8 bit Data Word 3	+ 4 bits Hamming Code	= 12 Bits
	Repetition of Mode, DW1,DW2,DW3	= 40 Bits
	Total	= 96 Bits

Table 10.1: PCM Telecommand

capability is not used as part of the PCM standard. It is clear that the PCM standard requires a significant overhead (96 bits transmitted for 24 bits of useful data, giving a 16-bit range (address space) within the spacecraft. It also shows a very poor use of error correction codes. ESA became the issuing authority for the ASW Spacecraft identifiers (SCID) in Europe. When it realised that there would be a conflict over the reuse of SCIDs, ESA decided to stop issuing ASW and encourage (force) people to use the packet telecommand standard.

10.3 Packet Telecommanding

The basic unit of transport of the packet TC standard is the CLTU. This uses a longer 'frame' length, and more sophisticated error control. Instead of repeating the data and using Hamming Codes, a BCH polynomial is iterated over the contents of the data field. While this is theoretically more efficient, using 1 octet of checksum for 7 octets data, it is solving a non-problem, since no European spacecraft in flight are actually limited by the uplink speed. The uplink bottleneck has always been in the on-board processing.

When ESA first started to control satellites, commands were sent from the ground station. The control centre personnel (the Flight Control Team) usually had a voice link with the ground station, and would request that one or more commands be sent. These would be manually entered one by one into a telecommand encoder, checked manually, and then transmitted. Readouts of the value of particular positions in the telemetry format could also be requested by voice. The whole data stream was often recorded on tape and then shipped back to the control centre.

The next increase in sophistication was to allow the control centre to connect to the telecommand unit in the ground station and send the telecommand electronically. Similarly the telemetry could also be relayed back to the control centre in real-time. This was possible since the data rate for the early spacecraft was still very low. Only the scientific data of Giotto (launched in 1985) and Hipparcos (1989) could not be sent in the bandwidth of an ordinary telephone line, and both could be fitted into a 64 kbps leased line. EURECA (launched in 1993) required a return to the previous method of record and playback data, since the data rate of 256 kbps was thought to be too high for the equipment of the day. Thus EURECA (and subsequently CLUSTER) was equipped to pass the real -time data necessary for monitoring the health of the spacecraft back to the control centre, while the stored data could be captured in a high-speed transfer from the satellite to the ground station, which could buffer the data and pass it back to the control centre as necessary.

By comparison, in the Soviet Union (and in present day Russia) the use of any space segment was initially reserved for the military. This meant that the USSR's major communication satellite operator, NPO-PM, could not have direct access to the ground stations, so control remained as something that had to be requested from the ground station staff. This could partly explain why the Russian approach even now favours a much more autonomous approach to spacecraft control.

10.4 Telemetry

Satellites modulate a digital stream onto a sub-carrier, sometimes via an intermediate frequency. The use of multiple analogue components onto a carrier is possible, but that would provide a high time resolution of a small number of parameters, exactly the opposite of what is needed. Generally only ranging data is modulated directly onto the downlink. This enables the ground personnel to determine the distance between the spacecraft and the ground station (and sometimes the radial velocity) which, when successive measurements are made and/or multiple ground stations used, means that the orbit of the spacecraft can be determined.

Telemetry, usually abbreviated to TM, contains different kinds of information. Some it is needed with a high frequency (e.g. if it is necessary to show the fluctuations in a signal that varies at high speed) and some things only vary at a lower speed, so requiring less bandwidth. It would seem to be desirable to have a single data structure that could then be sent when needed. If the situation was changing rapidly, then the telemetry would be sent faster. However, this has a number of associated disadvantages. The analogue properties of the radio signal would change if no telemetry were to be modulated onto the r.f. carrier, and certain equipment within the ground station might lose lock on the signal. It is thus necessary to always transmit some data, even if it is only to fill the downlink. These are sometimes referred to as idle frames.

The usual technique used in PCM type telemetry systems is to send the TM parameters in a fixed order. This is referred to as a TM format. By splitting the single format in smaller units, variously referred to as TM frames, TM sub-frames or sometimes sub-formats, a certain amount of flexibility concerning the rate at which information is transmitted. If, for example, a format is defined to consist of 16 frames of telemetry, information that changes very slowly may be transmitted in a single frame (i.e. once per format), whereas information that is varying more quickly (or is deemed to be more important) can be transmitted in every frame. Several situations in between the two extremes are also possible: every second frame, every fourth frame or every eighth frame. All of these options mean that the same fixed format, defined before flight, can be used to transmit information at different rates. It is now appropriate to introduce some terminology that is often used within

Frame offset																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	ASM	A123		B100	C200			B100				B100				B100
1	ASM	A123		B100	C201			B100				B100				B100
2	ASM	A123		B100	C202			B100				B100				B100
3	ASM	A123		B100	C203			B100				B100				B100
4	ASM	A123		B100	C204			B100				B100				B100
5	ASM	A123		B100	C205			B100				B100				B100
6	ASM	A123		B100	C206			B100				B100				B100
7	ASM	A123		B100	C207			B100				B100				B100
8	ASM	A123		B100	C208			B100				B100				B100
9	ASM	A123		B100	C209			B100				B100				B100
10	ASM	A123		B100	C210			B100				B100				B100
11	ASM	A123		B100	C211			B100				B100				B100
12	ASM	A123		B100	C212			B100				B100				B100
13	ASM	A123		B100	C213			B100				B100				B100
14	ASM	A123		B100	C214			B100				B100				B100
15	ASM	A123		B100	C215			B100				B100				B100

Table 10.2: Telemetry Format

the industry, but unfortunately is not used consistently. Super-commutated usually means that a TM parameter occurs more that once per frame and sub-commutated means that a frame occurs less than once per frame. However, some people use the same terms to describe the distribution of parameters per format, rather than per frame. Thus it is always preferable to use the full term, e.g. frame sub-commutation, to avoid ambiguity.

A simple example of a PCM format is given in Table 10.2, containing 16 frames per format, and only 16 octets of data per frame. This example format shows some of the basic features of fixed format telemetry. Each frame starts with a synchronisation marker, which is detected by the ground equipment. Usually each frame contains a frame counter, and each format then also contains a format counter. Each frame contains a mixture of frame super commutated and sub commutated data. For example, the parameters B100 occurs 4 times per frame, and is therefore frame super commutated. The parameter A123 occurs once per frame, and is frame commutated. The parameters C200-215 are frame sub-commutated, but format commutated.

However, one of the principal disadvantages of PCM Telemetry remains the fact that, even if multiple format-types are developed, the channel sampling must be fixed a long time before launch and it is difficult to modify it afterwards. If modifications that are made to the spacecraft to change the way that parameters are sampled, then the ground control system must also be changed.

To overcome some of the limitations of fixed period sampling, a further feature is sometimes introduced. If one sub-system was normally producing a range of parameters, there sometimes a feature called 'dwell' mode. This means that rather than transmitting a range of parameters to give a complete view of the sub-system, it is possible to focus in upon one particular parameter and dedicate the whole telemetry channel to one parameter and see many more measurements. Despite the terrible contortions that this requires on the ground control system, this is still quite a common feature since it enables the ground control team to see detailed variation of a parameter over time. This can be particularly useful for short term or single events, such as trying to monitor the current as a pyro device fires, to be sure that it operates correctly.

As spacecraft have become more sophisticated and have incorporated more software, some more complications have developed, such as the idea of a Polling Sequence Table, where a programmable look-up table is used as the source of each format. Whilst this can overcome the problem of defining the channel sampling a long time before launch, it can still leave the problem of requiring the control team (or the control system, if it is automated) to identify when the Polling Sequence Table was changed, and what the changes were.

Naturally, Dwell Mode and other similar delights, completely ruin the normal processing of the telemetry frame, and mean that extra processing must be performed i.e. the frame must be received, decoded, a particular location checked for a parameter to indicate whether or not Dwell Mode is in operation, and then the format must be processed accordingly. This means that all nominal activities, such as limit checking, status checking etc. may have to be suspended for some or all parameters in the format. This also means that it is difficult or impossible to get detailed information from 2 or more different sub-systems at the same time. The scheme proposed by ESA (and adopted by the CCSDS) as an answer to all of the problems of fixed format telemetry is Packet Telemetry.

10.5 Packet Telemetry

The basic principle of packet systems is that different parameters change at different rates at different times, and so they can be grouped according to how often we think it is important for the ground operations team to see 'fresh' values. Some temperatures might not change at all for days, whereas a thruster temperature could change rapidly whilst being prepared for firing, during the firing and even after the firing. Similarly, we might not need to send telemetry from a scientific instrument when the instrument is off, but when it is in use, the telemetry must be receive and checked. This means that each sub-system or instrument can be given an overall budget, or bandwidth of telemetry parameters in bytes per second or per minute in different modes.

Some intelligent packet systems (usually a complex instrument or subsystem, such as the ADCS) can change their own telemetry mode, sending data whenever appropriate, for example, during manoeuvre operations, whereas other subsystems might need to rely on the central data handling subsystem to poll them at the appropriate interval to get their telemetry. Reassigning the bandwidth according to events onboard can lead to much improved availability of pertinent information, as long as it is done without error. The disadvantage is that it is much more complex system, and there is more that can potentially go wrong. However, with the more recent PCM systems (ERS-1, ERS-2), or transfer frame-based systems (Cluster), telemetry stops updating or stops completely if the software stops running, so true

Packet TM is only a small step beyond the intermediate steps which are offered as an alternative.

10.6 Summary

This Chapter has shown that there have been a number of standards to govern how telemetry and telecommands should be formatted. The initial approach was to use fixed messages for both telemetry and telecommands. As the complexity of satellites increased, it became desirable to have more flexibility in the way the uplink and downlink bandwidth were used, as well as to permit a larger address space to distinguish the information sources and sinks within the spacecraft. This lead to packet-based communication, in the same way that ground telephone networks went from a series of point-to-point connections, to packet-switched networks. It brings the advantage of using the available bandwidth better, as long as not everyone wants to talk to everyone else at the same time. The idea of how to allocate parameters and packets to a system so as to maximise the information rate is the subject of the next Chapter.

The other trend of note is that the standardisation process initially consisted on locally or nationally-mandated standards (in Europe, the standards coming from ESA) and has then tended to include a wider and wider participation, both within Europe, with the participation being extended to include industry, and internationally, with the establishment of more independent, international bodies, such as the European Cooperation for Space Standardisation, ECSS, and the Consultative Committee for Space Data Systems (CCSDS).

Chapter 11

Information Theory

11.1 Introduction

The standards described in the previous Chapter give the syntactical information on how to build a telemetry frame, or telemetry format or a packet, but they do not describe how to allocate parameters to sources or sinks, what size of parameter is optimal, nor how the split between periodic and non-periodic information could be made. To examine this issue, this Chapter starts off from Shannon's information theory (Section 11.2). Section 11.3 then looks at an example structure of a discrete system, in this case, an array of perfect switches, and shows how the information content of this system will vary. In Section 11.4 this example is expanded to consider how it could be monitored by a fixed-format telemetry system and how well such a monitoring system conveys information about the state of the system it is monitoring.

11.2 Information Theory

The Shannon information[39] is defined according to the number of possibilities Z, which in the case of a coin is two and for a die is six.

It is interesting to view information in terms of the information per symbol. Let us consider a simple example R_o different possible events which have the same *a priori* probability , e.g. the tossing of an un-biased coin. When tossing a coin, we have two possible outcomes, and hence $R_o = 2$. If we were rolling a die, we would have 6 possible outcomes, and hence $R_o = 6$. Thus the outcome of tossing a coin (or rolling a die) can be perceived as the reception of a message, and only one of the possible R_o outcomes is actually realised. Apparently, the greater R_o, the greater is the uncertainty before the message is received and the larger will be the amount of information after the event. In the initial situation we have no information ($I_o = 0$) with R_o probable outcomes. In the final situation we have an information $I_1 \neq 0$ with $R_1 = 1$, i.e. a single outcome. We desire that I is additive when we have two independent events, so that if we have two such sets, the total number of outcomes is

$$R_o = R_{o1} * R_{o2}$$

then we require that the information

$$I(R_{o1} * R_{o2}) = I(R_{o1}) + I(R_{o2})$$

This relationship can be fulfilled by choosing

$$I = K * ln(R_o)$$

The constant K is arbitrary and can be fixed by some definition. Usually we consider binary systems, so when we consider all possible 'words' or sequences of length n, we find that there are $R = 2^n$ realisations. If we wish to identify I with n in a binary system, we therefore require

$$I = K * ln(R)$$
$$I = K * n * ln(2)$$
$$I = n$$

which is fulfilled by

$$K = 1/(ln(2))$$

or

$$K = log[2](e)$$

With this choice of K we have

$$I = log[2](R)$$

This has the property that I is now the number of binary digits in the system, ie if $R = 8$, $I = 3$. It is important to note that that word 'bit' is frequently used with two different meanings:

- To describe a Binary Digit , a usage credited to John Tukey
- To describe the amount of information in a message, if the conventions of using logarithms to base 2 are followed, as here.

If we now consider the case where we initially have R_o equally probable initial cases and R1 equally probable final cases, the information is

$$I = K * log(R_o) - K * log(R_1)$$

If we want to derive a more convenient expression for the information we can proceed as follows.

Consider a symbol stream being generated by a controller by reading off the statuses of n flip-flops. An initial guess at the entropy might be calculated according to the following reasoning: Each flip-flop can have two positions, referred to as on (N) and off (F) (in information theory terms, each generator has an alphabet of two) and each position is equally likely. This leads to the following calculation of the entropy of the source

$H := -p \log_2(p) - (1 - p) \log_2(1 - p)$

On average, each digit will be a 1 with probability p (and a 0 with probability $(1 - p)$), giving the curve of Shannon information as a function of probability that is shown in Figure 11.1. Note that when 'information' is almost certain, at either extreme, the value of the information is much less. The maximum information comes when the probabilities of a 0 or a 1 are equal i.e. for a binary stream, $p = 0.5$, and for other probabilities the information is much less.

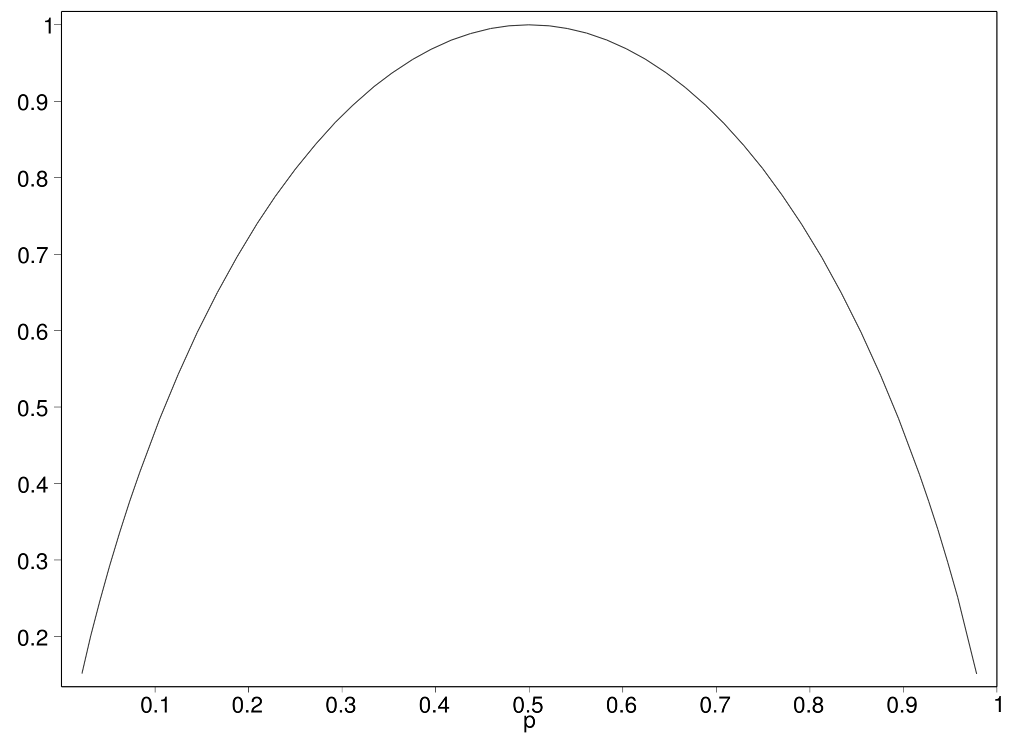
11.3 Background: Hypergraph

Now let us turn our attention to the stream as a whole (for example the TM of a fixed format satellite, with format length n symbols. The problem is that now the symbols are now no longer random when seen as a whole, and hence the entropy of the source is lower (recall that a biased coin is easier to predict than a fair coin). If there are 2 symbols, the alphabet is 2^n. Because of the relatively slow dynamics, single symbol changes are more likely than two symbol changes, which in turn are more likely than 3 symbol changes etc., etc. The state space of this system then looks like a hypergraph.

A hypercube is a regular graph. Each vertex has degree n, and, just like for a 3 dimensional cube, no vertex is initially distinguishable from any other i.e. the choice of origin is arbitrary. In a hypercube of dimension n, there are n vertices that are one step away, from each of those there are $(n-1)$ vertices which are 2 steps from the starting point, although there is some overlap between second nearest neighbours, and even more with 3rd nearest neighbours (see Figure 11.2).

In the following, let p be the probability of a transition, and then in each case, the transition probability needs to be divided by the degree of the vertex to get the transition matrix from the adjacency matrix. We can see that the total number of vertices in an n-cube is 2^n and that in each row r from the origin there are $\binom{n}{r}$ vertices.

In the steady state, the probability of a particular vertex being occupied is uniform (1/16 in this case). But since the numbers of vertices in each row is a



This graph shows how the Shannon information of a binary digit varies with the probability p of a change. It is maximum when the next value is unknown, and decreases in both directions as the value becomes more predictable.

Figure 11.1: Shannon Information of a Binary Digit

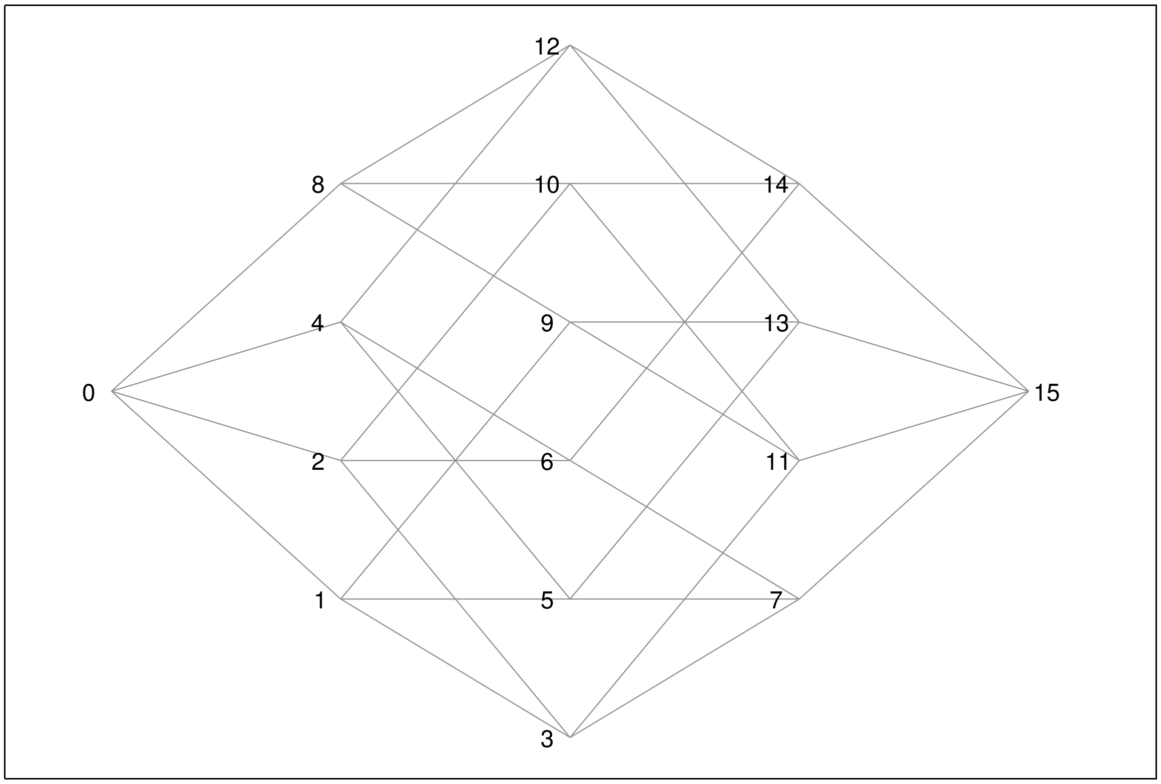


Figure 11.2: Example Hypercube - a 4-cube

binomial distribution, the likelihood of being in a certain row is proportional to the number in that row

11.4 Fixed Format Telemetry

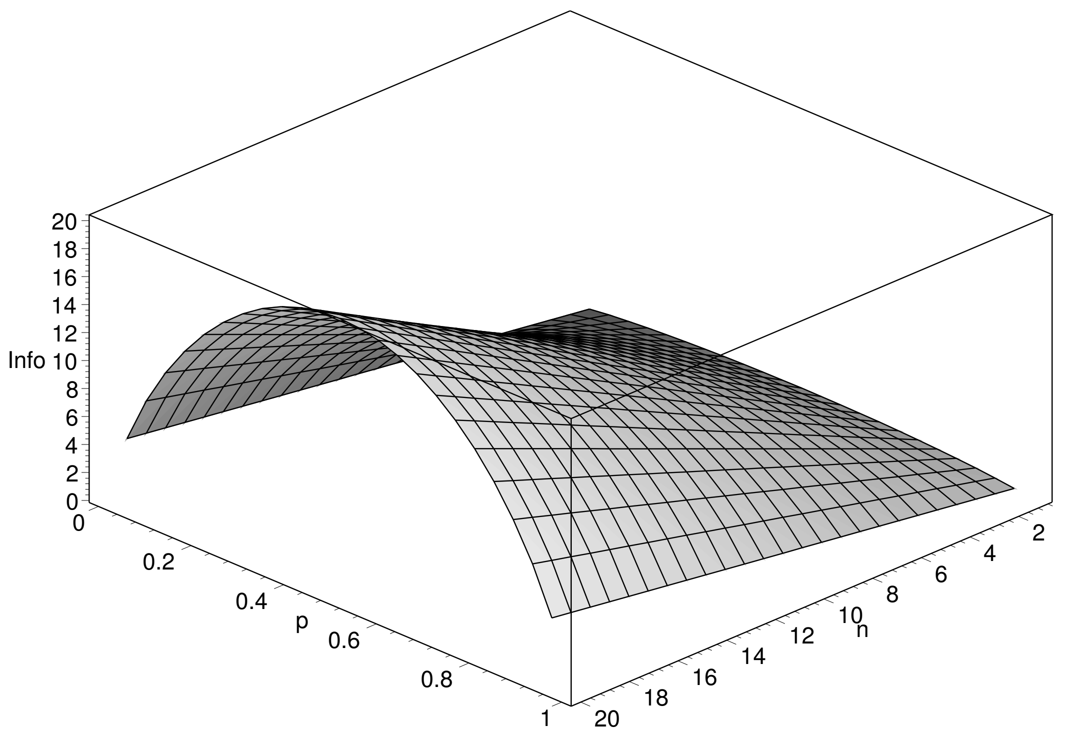
Consider a hierarchy of switches and flags. The flags are used for monitoring an array of n switches. For a leaf flag, it changes state if one of its relays changes state. For a non-leaf-flag, it changes state if one of its child 'flag' nodes changes state. If there are n switches, and $n+1$ flags then the total depth of the monitoring tree is 2. Let the probability of each switch changing state be p, then the parent node has a total information of

$$\sum_{i=1}^{n} \left(-p\log_2(p) - (1-p)\log_2(1-p)\right)$$

$$= n\,(-\frac{p\ln(p)}{\ln(2)} - \frac{(1-p)\ln(1-p)}{\ln(2)})$$

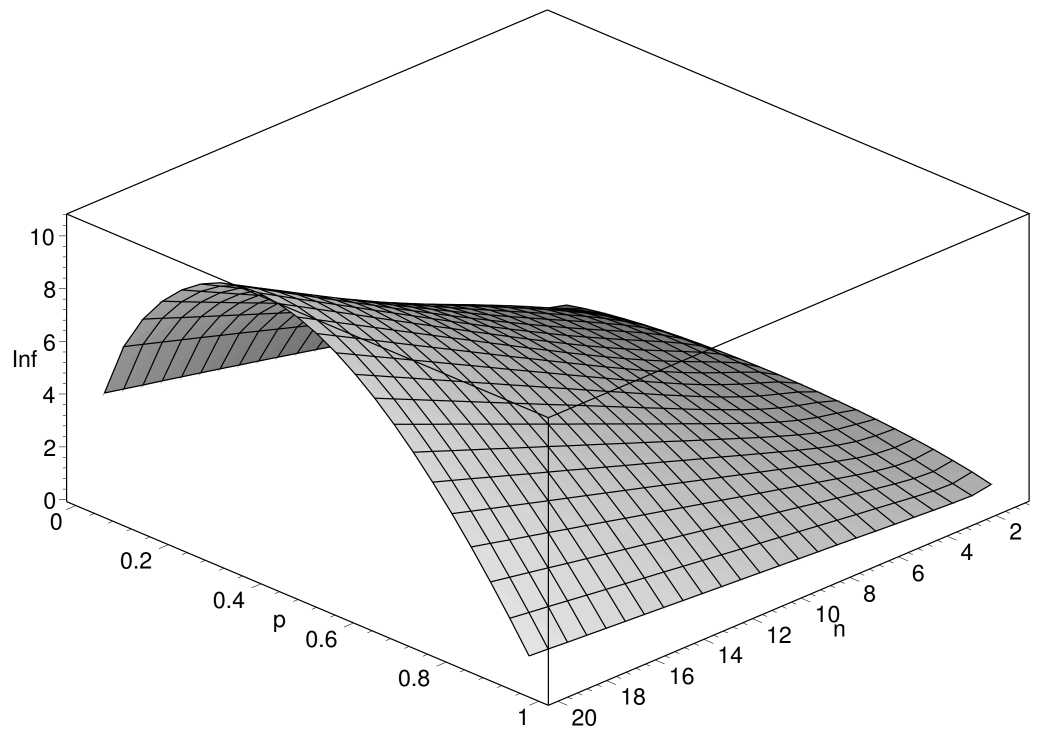
So it would seem from this analysis that the information increases linearly with n, the size of the frame, and that is indeed the case (see Figure 11.3). Unfortunately, the situation becomes more complex. Although the individual relays are independent, they are still covered by statistical analysis, which says, for example, that a group is less likely to go from being all 'on' to all 'off' than it is for one of the individual members to go from 'on' to 'off'. This is where the properties of the hypercube become important. Most of the symbols involve changes in more than one digit, and from an operational point of view, this is not desirable. We want to be able to see the first change, not the last one.

Our desire to see the first change in n relays means that most of the information alphabet is ignored, or never seen. We design the spacecraft (for safety's sake) so that the parameters are sampled fast enough to spot any change quickly, but this reduces the information content of whole stream, since it becomes very repetitive. Instead of having 2^n symbols in our alphabet, we only have $n+1$.



This 3-dimensional graph shows the Shannon information (labelled *Info*) plotted against the probability of a transition *p*and the number of switches *n*.

Figure 11.3: Information of a Multi Digit System



This shows that in a system which issues a new report after every single change, the maximum information is much lower than if some messages contain changes in multiple bits. This is because the alphabet of the system has been artificially constrained. This effect can be seen by comparing the vertical scale *Info* on this graph and Figure 11.3.

Figure 11.4: Information of Single-Change System

By comparing Figure 11.4 with Figure 11.3,and comparing the numbers on the Info scale, it is obvious that a great deal of information has been lost by this artificial constraint.

11.5 Analysis of Flags

If we now consider the case where the hierarchy gets extended, so that there are n relays, and $n+2$ observers. Each leaf group generates Inf(n,p) information, and passes it up the tree. The non-leaf nodes have g relays going into them. The behaviour of each node is now: it passes the status if there is a change (which has probability p^g, zero otherwise (probability $= 1-(p^g)$). The status consists of g relays, which can always be encoded in $\lceil(log[2](g))\rceil$ digits.

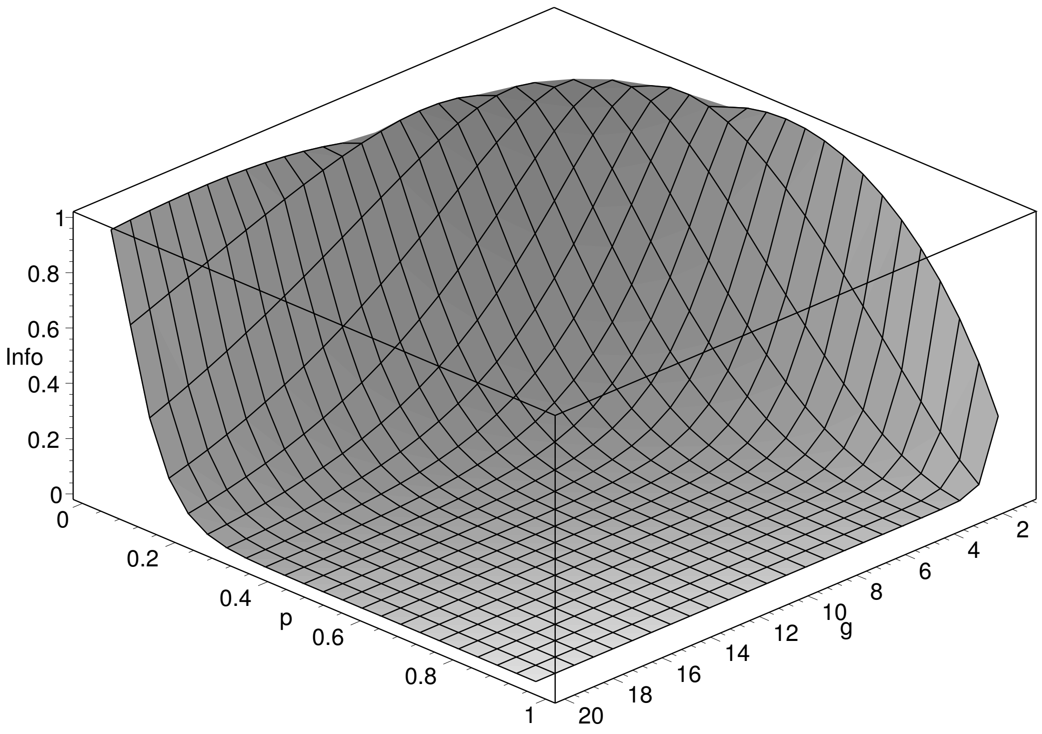
First we consider the case where manager/parent node raises a flag if there is a change, else shows no change with a lowered flag. This has 2 symbols, with information: $Iflag := -\frac{(1-q^g)\ln(1-q^g)}{\ln(2)} - \frac{q^g\ln(q^g)}{\ln(2)}$, where $q = 1-p$. This is because q^g is the probability of the state machine still being at the origin, i.e. all bits unchanged, and $1-q^g$ is the probability of it being anywhere else in the graph. We can recast the same expression in p to get

$$Iflag := \{-\frac{(1-(1-p)^g)\ln(1-(1-p)^g)}{\ln(2)} - \frac{(1-p)^g\ln((1-p)^g)}{\ln(2)}\}$$

This function is plotted in Figure 11.5. The information is very low for middle and high probabilities, since as g increases, the likelihood that a change will occur also increases, and if the flag is always either 'on' or 'off'. This means that it becomes predictable and the information content is lowered. At the low probabilities, the flag becomes less predictable unless group size is large. If we partially differentiate this function w.r.t. p to trace the maxima, we obtain

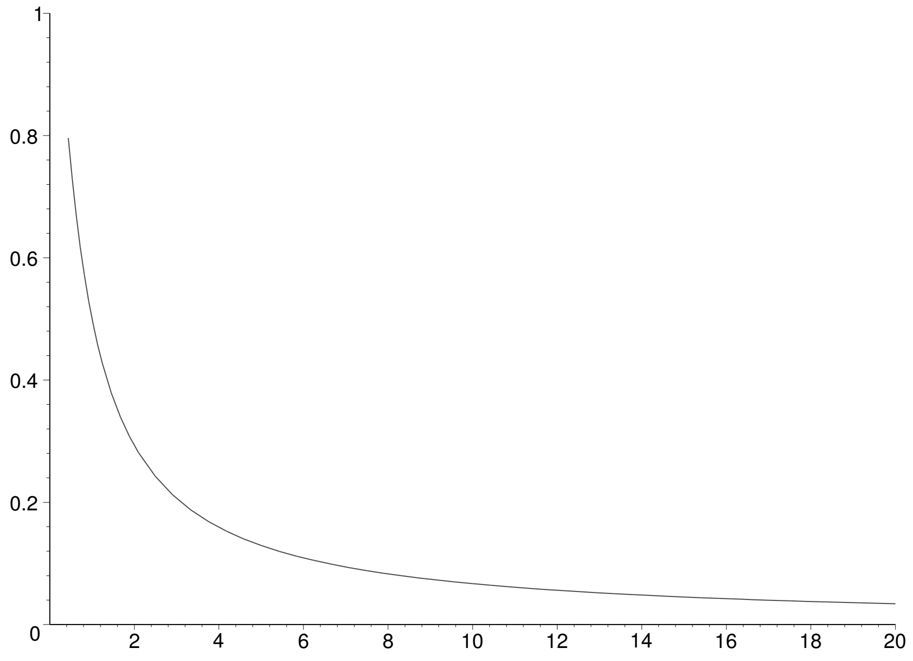
$$Idash := \frac{\partial}{\partial p} Iflag.$$

$$Idash := \{-\frac{(1-p)^g\,g\ln(1-(1-p)^g)}{(1-p)\ln(2)} + \frac{(1-p)^g\,g\ln((1-p)^g)}{(1-p)\ln(2)}\}$$



This graph shows the information of a flag that signals a change in a group of bits being monitored by it. The group size is g and the probability of a change in one bit of the group is p. When p is small, the information is high, but as p increases, the information content reduces since the flag is then always indicating that change has occurred.

Figure 11.5: Information of Flag-based Monitoring



This plots the probability p against group size g for maximum information content.

Figure 11.6: Information of Optimum Flag-based Monitoring

If we solve for the Idash =0, we obtain the solution:

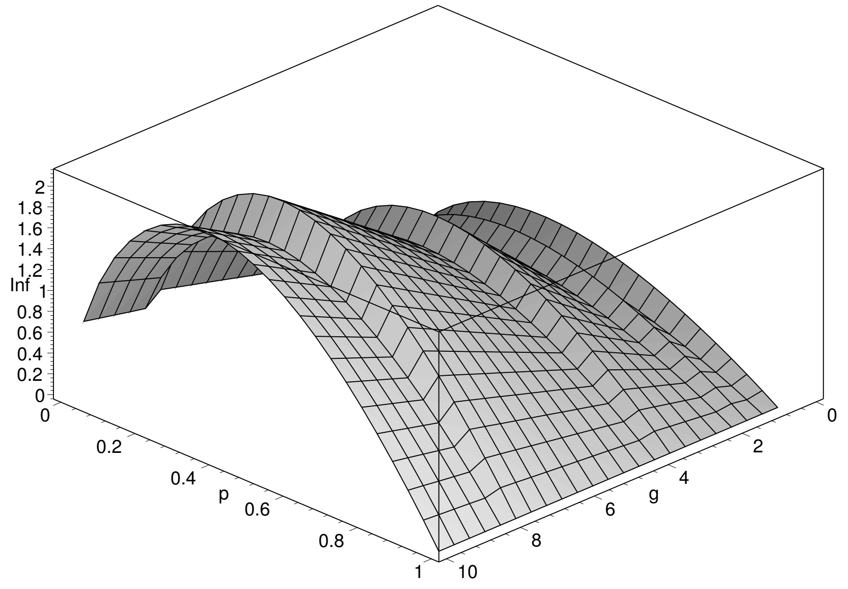
$g = g,\ p = -e^{(-\frac{\ln(2)}{g})} + 1$

Which if we plot it (Figure 11.6), shows the form of p as a function of g. Of course, in a design scenario, it should used in the opposite sense to guide the size of g according to the estimated probability of a transition.

11.6 A Packet: With Details Please!

The flag is interesting, but of course, in an operational scenario, it simply says that something has happened, without actually saying what. This is interesting and often even useful, but in practice we would also like to know what has happened.

If a single digit in a group changes, we need $\lceil log_2(g) \rceil$ digits to say which relay has changed, and then another digit to say what the current value is. This gives $2g$ symbols, each of length $\lceil 1 + log_2(g) \rceil$ and each of probability p. So the information



This shows the Shannon information of a packet that says which of the relay statuses that it is monitoring has changed, and the current value. It is plotted against group size g and probability p.

Figure 11.7: Information of Packet-Based Monitoring System

is.

$-2gplog_2(p)$ and the information per digit is

$$\frac{-2gplog_2(p)}{\lceil log_2(g)+1\rceil}$$

This compares very favourably with the coefficient of n that was calculated for the multi-digit system. This is shown in Figure 11.7.

11.7 Information Usage

There is a very simple but very powerful way of modelling a system, which is to construct a Markov Model. In a Markov model, the probability that a system makes a transition from one state to another depends only upon the current state, not the history of the system i.e. its path to the current state. Shannon[39] developed his theory of information by considering discrete Markov processes, and in particular, a special class of Markov processes, the ergodic processes.

The general idea behind an ergodic process is one of statistical homogeneity. For example, that the thermodynamic properties of one molecule over a long time are similar to the thermodynamic of many molecules when considered in a 'snapshot' moment. In Shannon's terms, every sequence produced by an ergodic process has similar statistical properties, so as longer and longer sequences are considered, the frequencies of each symbol occurring in a particular sequence will approach definite limits.

We saw in the previous section that as something becomes predictable, or less 'random', its Shannon information goes down. This is the information that would be sufficient to allow an agent (computer or human) to follow the state of the satellite.

Unfortunately, when a human gets used to a certain behaviour, they tend to take it for granted, and sometimes do not even perceive changes when they do occur. This is the disadvantage of a human's intrinsic ability to learn.

This is reminiscent of what can happen in a Kalman filter: The optimally tracking filter tracks the target so well that the error between the predictions and the measurements can go to zero. Unless care is exercised in the design, the Kalman filter will then cease to use the real measurements at all when it propagates the state vector. This can be a problem if the target starts behaving differently. One way to avoid this is to hard-code ranges for the Kalman gains, or even to artificially inject noise into the measurements. The equivalent technique for a human operator is to have frequent shift-changes to relieve the monotony.

11.8 Summary

In this chapter we have shown that simply repeating the telemetry as in a fixed format telemetry system does not give a very high Shannon information. By monitoring for changes, we generate much more information per bit. In an event-driven packet system that transmits telemetry packets when something has changed, the Shannon information scales very well.

It has been shown that the information available on the ground to help an operator synchronise his internal model with the physical situation on-board the spacecraft can be very low. There seems to be fundamental discrepancy between the way that operators perceive information and what the information is actually telling them.

One major assumption in this analysis is that 'all bits are equal', i.e. that *a priori* no telemetry parameter is more important that another. This is decidedly not true, but the differences are difficult to analyse in a generic way.

This technique holds out the promise that, if, combined with queuing theory, it could give better estimates about the best way to define synchronous and non-synchronous packet systems.

Chapter 12

Synthesis

This thesis started with the author's identification of a number of factors that seemed to to make the spacecraft operations difficult. To reiterate, these were:-

- Launch-centric view of the space-project.
- Fluctuating participation in development life-cycle leads to a lack of continuity in people and knowledge across the project.
- People perform different roles, have different viewpoints and use a different vocabulary at various stages in the development. This leads to a perception gap, a difference between the logical understanding of different people who are really talking about different parts of the same whole.
- Structural and organisational problems lead to a lack of knowledge sharing across the project.

All spacecraft operations take place within some kind of organisational framework or team. By analysing some existing organisations we have seen several shortcomings. We have also shown several expected properties: that people often want new challenges, new projects, i.e. that they often want a career and are ambitious. For a healthy organisation to remain healthy, these aspects must be planned and monitored in just the same way that the technical operations of a satellite are controlled.

This work has presented how organisations usually prepare for mission operations and has attempted to identify the current best practice, as well as pointing out anomalies and inefficiencies when they occur. The short-comings has been traced in Chapter 2 and Chapter 3 to the project-based work with a short-term structure. This is particularly prevalent on many ESA projects.

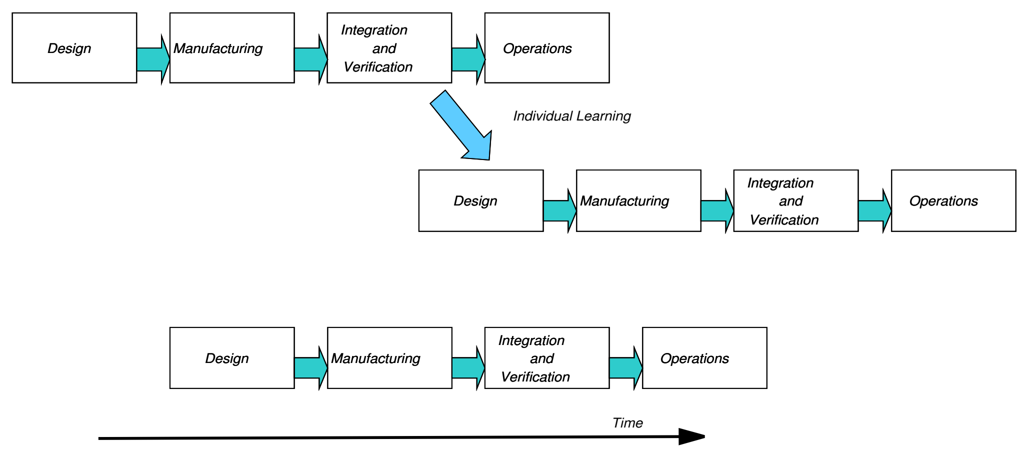
Chapter 4 has shown that risk can be positive as well as negative, if the people and organisation understand it and are willing to manage it in a systematic way.

Since the responsibility for the design integration, launch and in-service operations normally lie with different teams,there are normally several different viewpoints of the spacecraft. For example, the designer might see a electrical circuit, the integrator might see a wire in a harness, and an operations engineer might see a control loop.

It has been shown that this kind of structure creates a need for knowledge sharing across the different actors in the space business, whilst at the same time providing no practical mechanism to facilitate sharing of knowledge within or across projects. The satellite designers conceive a design that satisfies a certain specification. The components, units and systems are then built and integrated and the whole assembly is tested. The units and systems will continue to be changed or tuned until the assembled satellite is believed to have been proven to be able to fulfil its mission. Then the knowledge gathered in designing and building the satellite takes two different paths - into the design of a future spacecraft, and into the operations phase of this spacecraft.

The people designing the spacecraft have to try to document the design on the form of User Manuals, operations procedures and the spacecraft database and pass all the necessary information to the operations team.

At about the same time that the operations are starting, the design team will normally be moving onto another project. However, any project that has kicked-off



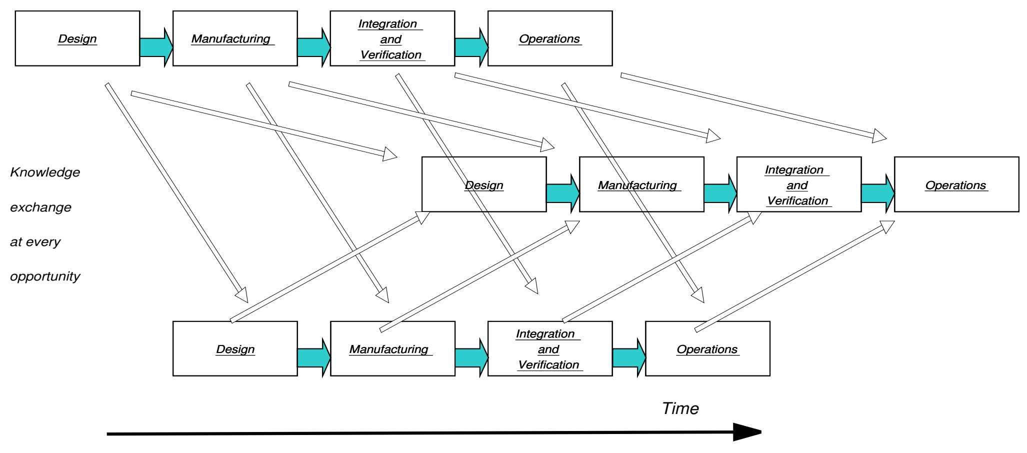
Knowledge transfer that relies on individuals from the development team moving from one project to another has several disadvantages:- (i) it does not include the final evaluation of the design in operations; (ii) it is very slow, since it can take place after the development is completed; (iii) it does benefit projects that run in parallel, which are most likely to be using similar technology.

Figure 12.1: Knowledge Transfer Between Projects By Individuals

in the time between the beginning and end of this project will be unable to benefit from the lessons learned in this project. Any members of the design team who leave before the spacecraft has entered service will then also not have the opportunity to evaluate their design and implementation in a real-life situation.

The only opportunity to transfer information is at the end of the project, when people are redeployed from one project to another. Figure 12.1, repeated from the Introduction, shows the problem. This transfer is ineffective, since it relies on vacancies in new projects becoming available at the same time as other projects are ending, and also as mentioned before, the technology base will have changed. Furthermore, if the development and operations teams are separate, then the developers will not have any real-world feedback on how their design performed and whether or not their decisions on the design and implementation were correct.

The desired situation is shown in Figure 12.2. If knowledge can be encoded in a way that makes it understandable to people on other projects, then they will be


Design
Manufacturing
Integration and Verification
Operations
Knowledge exchange at every opportunity
Design
Manufacturing
Integration and Verification
Operations
Design
Manufacturing
Integration and Verification
Operations
Time

Knowledge transfer by making knowledge available at each stage means that projects can access it as they need it, when they want it. Projects can benefit from the experience gained on other projects that are running in parallel or have already completed.

Figure 12.2: Effective Knowledge Transfer Between Projects

able to see whether other projects had related problems and then be able to learn from the experience that has been gained. They do not need to wait for a parallel or preceding project to finish in order to do so.

At the highest level, satellite operations is about information processing. This can take place over a long time-span, such as the strategic design and procurement of control system, or in shorter time-scales, where more tactical decisions have to be taken, such as who does what, when and how. Scientific missions are almost always challenging, seeking for the new areas to be 'first' in. This puts the projects under high risk, and many projects do indeed suffer cost,schedule and quality problems.

We have seen that the people who design and build satellites, the very people who gain insight into the the spacecraft behaviour during its integration are not normally present throughout the useful lifetime of the satellite. This means that the knowledge and tools that they have gained must be either transferred to the operational team, or in the case of tools, re-implemented.

Currently the vast majority of operational effort (and expense) goes into the preparation of the ground segment for launch,which includes all aspects necessary to ensure satisfactory entry into service: procurement, verification, validation and early operations. The spacecraft procurement process becomes an enormous documentation project, with the documentation often being written by non-native speakers. Individual companies frequently have their own jargon, and equally often they invent new names and abbreviations to describe the units that they produce or the processes that they perform. This acts as a substantial impediment to the transfer of knowledge to the operations team and from one operations team to another.

An ontology has been drafted which would overcome some of these problems, and guidelines have been proposed as to how to name new developments in a way that reduces barriers to knowledge transfer. An ontology was suggested as a possible solution to the problem of transferring knowledge across time and place as is required on modern space mission. This could be a substantial contribution to ease the transfer of information. In order to try to encapsulate the knowledge embodied in the design, it is necessary to use better tools than plain text.

Formal Methods hold out the hope of an extensible framework, that not only enables the writer to say precisely what he means, also allows the readers and writer to prove certain features about the system being described. Formal descriptions of units or sub-systems can be combined to allow reasoning about the greater entity. The ability share knowledge, and to reason about it and the spacecraft behaviour from the start, before the satellite has been integrated, would be a great risk reduction and an enormous improvement to the current process.

As spacecraft steadily increase their performance and autonomy,the complexity increases. Already the scientific instruments on some modern spacecraft are more sophisticated in terms of their processing power, autonomy, or telemetry rate than many spacecraft that are flying. The fact that the flight control team on the ground sometimes need to struggle with or around an autonomous system in space is now unfortunately common place. Flight control teams must be careful in how they form hypotheses about the spacecraft, since often the data is ambiguous and sparse, and the spacecraft may actually still be (mis)-behaving, even as the flight control team try to get it to do something else. This presents a significant training challenge for the longer-term missions, as well as missions that reuse systems from earlier spacecraft.

Very few operations engineers get a chance to participate in the design of the data of the system that they will eventually control. Chapter 10 presented some of the historical standards, although now there are more in progress. Chapter 11 took a fresh look at the information that is transmitted by fixed and packet-based systems. This is an area which could benefit from more work, and from investigating the additional overhead that is enforced by the various packet standards. More understanding in this area would help future operations engineers guide those projects who are willing to listen in the right direction and could make the definition of parameters and packets rather less haphazard than it is today.

Chapter 13

Conclusion

13.1 Summary

13.1.1 Space Projects

An 'Operations Model' has been proposed to show which areas are already covered by international standards and which areas are left for individual missions to design and implement themselves.

There is a broad spectrum of control activity that can be performed on-board, on ground or by human intervention. Different types of mission may require different mixtures of these techniques. A flexible control strategy should be able to move fairly easily between human interaction, to ground-automation and then to onboard automation. The optimum point will be a function of the available contact period, the required bandwidth, and the required reaction time.

The space industry operates in a distorted market place and some the conflicts of interest and inefficiencies result. Many activities are dominated or distorted by political activity or interference.

13.1.2 Organisation

Organisations typically achieve their goals by encoding activities in procedures, creating teams and trying to build up a particular kind of culture.

Individual types of behaviour into skill-based, procedure-based and knowledge-based behaviour. Some guidelines have been proposed for how individuals in their roles as team leaders and team members should interact in order to arrive at the best solution. The catastrophic consequences of a break down in communication between the individuals and teams of operations, engineering and management has been shown.

The space industry, as well as facing some unique challenges, also faces many normal business and organisation challenges. Because so much space-related work is carried out by organisations with bureaucratic roots and a military or civil service mentality, personnel development has typically been a low priority. The amount of delegation has also been typically low, with managers often not responsible for some of the effects of their decisions.

The organisations examined all became dependent upon the short-term supply of labour to meet their peak work-load. This reduces the amount of knowledge available within the organisation.

The typical structure of a hierarchy with a low fan-out, often covering many geographically distinct sites, can make it very easy for the management to lose contact with the people who have the first-hand knowledge of the state of the mission and the current problems. This prevents the free flow of information that is vital for taking major decisions correctly.

13.1.3 Risk

Risk and opportunity can be seen in the following situations:

- Financial implication
- Decision making
- Process and structure

- People and Machines
- Legal and regulatory requirements
- Customer/Client needs
- Environmental considerations
- Communication requirements.

Risk management is more oriented towards people, processes and human judgement than safety and reliability, although these are important factors.

People perceive risk in different ways at different times.

Risk management can be broken into three phases, risk control, risk reduction and risk containment

13.1.4 Ground Segment Preparation

The satellite is often being operated by a different organisation to the one that built or integrated it, so somehow the people responsible for operating the satellite must be trained and prepared for their forthcoming tasks. The transfer of knowledge is an essential part of spacecraft operations engineering.

Most low-level information is now transferred in the form of a database. The satellite database is one of the most important interfaces between the satellite constructor(s) and the satellite operator(s).

The higher-level knowledge is still transferred separately, usually in the form of documents containing textual descriptions, diagrams and procedures. This makes the descriptions and procedures potentially inconsistent with the database and because it is also manually produced, it may also be internally inconsistent or incomplete. When there is a conflict over the allocation of resources to resolve a problem with the flight article, the documentation always loses out.

There is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system to another and from one project to another.

Spacecraft (or a family of spacecraft) are frequently being procured as part of a whole system, which often has a very large ground segment that needs to be developed, maintained and operated in parallel to the space segment.

Simulations are useful in preparing the individuals to cope with the stress of operational situations, as well as forging a team.

There is normally a formalised review process for checking the progress at various phases in the procurement and operations. These reviews are particularly important since they force management to take a position on various items that are flagged as risks to the programme. However, this only operates correctly if the correct data is made available to the correct people.

13.1.5 Control System

There is substantial commonality across missions, holding out the possibility of large-scale reuse of software and systems. A common approach to checkout and control system development is possible and it might bring cost benefits. Even though it might cost more in the initial phases such as review of the design specifications, benefits and cost savings are expected to occur in the later phases.

Automation is often introduced with the aim of reducing costs, but the impact is often to change the skill set required to do the job, and to drive up the indirect costs e.g. to maintain proficiency at a level required for manual operation to take over from the automation when the situation deteriorates.

13.1.6 Ontology

The User Manual is intended to help the end-users understand and operate the spacecraft and payloads safely and successfully.

Since there is no standard structure for the information to be provided, it varies enormously in quality and quantity from one sub-system to another and from one project to another. It is difficult to produce a User Manual because there is no standard to say what it should contain or how to produce it.

The introduction of new names for existing concepts makes it difficult to produce the User Manual to a consistent standard and prevents re-use of documentation from one project to another. An Ontology is a powerful tool with its roots in artificial intelligence and knowledge management that allows users to browse data and display relationships graphically, whilst at the same time permitting writers to check that their input obeys certain consistency constraints which will highlight when or where information is incomplete. Without an approach that makes it easier to develop a knowledge base that can be checked and transferred easily, future projects are destined to repeat many of the mistakes of their predecessors simply because it is too difficult to learn from them.

13.1.7 Formal Methods

Formal methods were developed to be applied to software systems, but are applicable to any discrete system. Formal methods bring the benefit of being able to argue a particular case based upon a rigorously defined specification. By proving a property of a design early in the mission life-time, perhaps even before hardware is built, it may result in a cost saving, by reducing testing, or a dramatic increase in reliability.

One of the main benefits of formal methods is that it requires a statement of the problem. This is also sometimes a disadvantage, since some of the knowledge might not be available. When combined with the idea of an ontology, a single knowledge base for the entire mission can be developed: the knowledge from the design phase could also be used in the testing and qualification phase, and even be the source of data for the user manual

13.1.8 Complexity

Spacecraft and spacecraft operations are complex for a number of reasons.

Systems designers are risk averse, which has yielded an approach to the design and implementation of evolution rather than revolution. Each design brings a lot of heritage with it, so there has been a gradual accretion of complexity as functions and automation have been added on, rather than a clean overview.

Since virtually all spacecraft operations are a form of remote control, the data used for a hypothesis often incomplete. The information on difficult (or pathological) cases is often not available and generally no physical examination possible at all, compared with the case of aircraft or marine accident investigations. There is generally no sharing of data between different organisations or from one project to another.

There is no general measure of complexity, and no general agreement that complexity is bad, so designs are not optimised for this aspect. The manufacturers of spacecraft and instrument have little incentive to keep designs and operations simple, and significant incentives to maintain schedule for the delivery of the flight hardware and software.

13.1.9 Telemetry and Telecommands

There have been a number of standards to govern how telemetry and telecommands should be formatted. The initial approach was to use fixed messages for both telemetry and telecommands. As the complexity of satellites increased, it became desirable to have more flexibility in the way the uplink and downlink bandwidth were used, as well as to permit a larger address space to distinguish the information sources and sinks within the spacecraft. This lead to packet-based communication.

The other trend of note is that the standardisation process initially consisted on locally or nationally-mandated standards (in Europe, the standards coming from

ESA) and has then tended to include a wider and wider participation, both within Europe, with the participation being extended to include industry, and internationally, with the establishment of more independent, international bodies, such as the European Cooperation for Space Standardisation, ECSS, and the Consultative Committee for Space Data Systems (CCSDS).

13.1.10 Information Theory

Simply repeating the telemetry as in a fixed format telemetry system does not give a very high Shannon information. By monitoring for changes, we generate much more information per bit. In an event-driven packet system that transmits telemetry packets when something has changed, the Shannon information scales very well.

The information available on the ground to help an operator synchronise his internal model with the physical situation on-board the spacecraft can be very low. There can be a fundamental discrepancy between the way that operators perceive information and what the information is actually telling them.

13.2 Discussion

This work has presented how the people and organisations usually prepare for mission operations and has attempted to identify the current best practice, as well as pointing out anomalies and inefficiencies when they occur.

At the highest level, satellite operations is about information processing. This can take place over a long time-span, such as the strategic design and procurement of control system, or in shorter time-scales, where more tactical decisions have to be taken, such as who does what, when and how.

We have seen that the people who design and build satellites, the very people who gain insight into the the spacecraft behaviour during its integration are not normally present throughout the useful lifetime of the satellite. This means that the knowledge and tools that they have gained must be either transferred to the operational team, or in the case of tools, re-implemented.

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Formal Methods were suggested as a possible solution to the problem of transferring knowledge across time and place as is required on modern space mission. This could be a substantial contribution to ease the transfer of information. In order to try to encapsulate the knowledge embodied in the design, it is necessary to use better tools than plain text. Formal Methods hold out the hope of an extensible framework, that not only enables the writer to say precisely what he means, also allows the readers and writer to prove certain features about the system being described. Formal descriptions of units or sub-systems can be combined to allow reasoning about the greater entity.

All spacecraft operations take place within some kind of organisational framework or team. By analysing some existing organisations we have seen several shortcomings. We have also shown several expected properties: that people often want new challenges, new projects, i.e. that they often want a career and are ambitious. For a healthy organisation to remain healthy, these aspects must be planned and monitored in just the same way that the technical operations of a satellite are controlled.

For ESA missions, industrial policy encourages poor performance from industrial consortia, and the lack of either penalties for late deliveries or incentives for good long-term performance decrease the quality of the product. There are no real incentives for scientists, industry and ESA to cooperate or coordinate their developments. Since the industrial environment has changed so much since ESA was founded, the procurement policy, in particular the principal of *justes retours*, should be reconsidered. There is considerable scope for saving costs by re-using infrastructure software and getting the different parties to cooperate across the different phases. Whilst some phases might become more expensive, the life-cycle costs should be reduced.

We have discussed the nature of risk, showed how it can occur in space programmes and methods used to manage the risk inherent in space exploitation. Planning and learning are essential parts of risk management, but in order to be able to learn from similar cases, it must be possible to recognise similar cases! This is where use of an ontology would help, as would the use of formal methods to help recognise similar patterns.

To continue at the strategic level, we have shown that there is a great deal of commonality between the computer systems are used to control the satellites and payloads before and after launch. Cost-savings could be made via a common, or harmonised, development, and this would also reduce the risk at a project level, since so many elements of the ground system would have been thoroughly tested during the satellite integration.

Complexity can be portrayed as the eternal enemy of the operations engineer as it must be dealt with at all phases. It is easy to render a system more complex at one level, by trying to simplify it at another level. We have shown that many systems have an inherent complexity even if they do not contain or rely upon software. If they do contain software, then this brings great flexibility, at the cost of even greater complexity. Even with a 'perfect' ontology or with formal methods, there may still be true statements about the physical world that cannot be proved: incompleteness is a necessary property of all logic systems above a certain power. The operations engineer must be able to operate within the formal system, but also maintain enough scepticism and imagination to be able to raise up a level, and act intelligently.

At the tactical level, the Shannon Information of a fixed format telemetry system has been calculated and compared with an event-driven packet system. It is shown that the information scales much better with packet-based systems. This means that operators get much more relevant information to analyse. People adapt to the monotony inherent in continuous telemetry by a form of learning, which unfortunately means that they do not understand everything that is shown to them. Alarms and warning lights can mitigate the loss of information by attracting attention to changes or out of limit conditions. Information theory shows just how little information is transferred when people believe that they know what is going on.

The job of an Operations Engineer is changing. More organisational and soft skills are necessary since almost every development is a cooperation between different institutes, organisations and companies. Care must be taken to nurture the relationship with the partners, but at the same time, to steer the project in an effective manner. The steady increase in the size of space missions and their associated ground segments means that a different set of skills are needed from the flight control team. Knowledge of the flight hardware is no longer sufficient. Much more experience with software and systems, in particular with the structure and content of the database, is now necessary.

13.3 Further Work

The following areas merit further investigation:

- A mission model to examine current missions should be extended to propose a more detailed framework.
- The idea of an common, extensible ontology should be further developed.
- The information transfer of different packet concepts should be analysed and extended.

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Appendix A

Ontology Outline

This Appendix gives a snapshot of the real ontology. The Protégé software allows the user to link units and set interface types and also export a wealth of documentation. This is one of the automatically generated index pages.

A.1 Interface

A.1.1 Electricty

Electricty5V

Electricty28V

- Instrument

  Instances: Spire, PACS, HIFI, LFI, HFI, SCS

- Spacecraft

  Instances: Herschel, Planck

- SolarGenerator

  Instances: H-SolarPanel, P-SolarPanel

- Unit-LFI

  Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B

- Unit-HFI

  Instances: FocalPlaneUnit, J-FET Box, DPU/PowerDistributionPart, DilutionCoolerSubSystem, FocalPlaneStructure, IsotopeSupplyUnit, HeatSwitches, GasStorageUnit, DilutionCoolerControlUnit, DilutionCoolerPneumaticUnit, DIlutionCoolerPiping, 4KCoolerSubsystem, JTcompressors, AnciliaryGasCleaningPanel, ConnectingPipework, LowTemperaturePlumbing, MainElectronics, HFI-HSL

  – Unit-HFI-LSL

    Instances: DilutionCoolerElectronics, 4KCoolerDriveElectronics, 4KColdUnit, 4KCoolerAncillaryUnit, 4KCoolerCompressorUnit, 4KCERegulator, 4KCoolerElectronicsUnit

    ∗ DataProcessingUnit

      Instances: HFI-DPU-A, HFI-DPU-B

  – Unit-HFI-HSL

    ∗ DataProcessingUnit

      Instances: HFI-DPU-A, HFI-DPU-B

    ∗ ReadoutElectronicsUnit

      Instances: REU-Chain-00, REU-chain-01, REU-Chain-02, REU-Chain-03, REU-Chain-04, REU-Chain-05, REU-Chain-06, REU-Chain-07, REU-Chain-08, REU-Chain-09, REU-Chain-10, REU-Chain-11, REU, REU-proc-A, REU-proc-B

    ∗ Unit-HFI-1553

    ∗ DataProcessingUnit

      Instances: HFI-DPU-A, HFI-DPU-B

  - LCL

    Instances: HFI-01, HFI-02, HFI-03, HFI-04, HFI-05, HFI-06, HFI-07, HFI-08, HFI-09, HFI-10, HFI-11, HFI-12, HFI-13, HFI-14, HFI-15

  - PowerControlUnit

    Instances: P-PCU, H-PCU

  - PowerDistributionUnit

    Instances: H-PDU, P-PDU

A.1.2 Data

DataStorage

- Instrument

  Instances: Spire, PACS, HIFI, LFI, HFI, SCS

- Spacecraft

  Instances: Herschel, Planck

- Databus

  - SMCS-1355

    - Unit-LFI

      Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B

  - MilStd1553

    - Instrument

      Instances: Spire, PACS, HIFI, LFI, HFI, SCS

    * 1553Bus

      Instances: H-1553Bus, P-1553Bus

    * CDMU

      Instances: H-CDMU-A, H-CDMU-B, P-CDMU-A, P-CDMU-B

    * Unit-LFI

      Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B

    * Unit-HFI-1553

      · DataProcessingUnit

        Instances: HFI-DPU-A, HFI-DPU-B

- Serial

  - HighSpeedLink

    * Unit-HFI-HSL

      · DataProcessingUnit

        Instances: HFI-DPU-A, HFI-DPU-B

      · ReadoutElectronicsUnit

        Instances: REU-Chain-00, REU-chain-01, REU-Chain-02, REU-Chain-03, REU-Chain-04, REU-Chain-05, REU-Chain-06, REU-Chain-07, REU-Chain-08, REU-Chain-09, REU-Chain-10, REU-Chain-11, REU, REU-proc-A, REU-proc-B

  - LowSpeedLink

    * Unit-HFI-LSL

      Instances: DilutionCoolerElectronics, 4KCoolerDriveElectronics, 4KColdUnit, 4KCoolerAncillaryUnit, 4KCoolerCompressorUnit, 4KCERegulator, 4KCoolerElectronicsUnit

- DataProcessingUnit

  Instances: HFI-DPU-A, HFI-DPU-B

A.1.3 Hierarchy

System

Instances: H-DMS, H-AOCS, H-Power, H-Thermal, H-TTC, H-RCS, P-AOCS, P-DMS, P-Power, P-RCS, P-Thermal, P-TTC

Instrument

Instances: Spire, PACS, HIFI, LFI, HFI, SCS

Spacecraft

Instances: Herschel, Planck

Unit-PL

- Unit-LFI

  Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B

- Unit-HFI

  Instances: FocalPlaneUnit, J-FET Box, DPU/PowerDistributionPart, DilutionCoolerSubSystem, FocalPlaneStructure, IsotopeSupplyUnit, HeatSwitches, GasStorageUnit, DilutionCoolerControlUnit, DilutionCoolerPneumaticUnit, DIlutionCoolerPiping, 4KCoolerSubsystem, JTcompressors, AnciliaryGasCleaningPanel, ConnectingPipework, LowTemperaturePlumbing, MainElectronics, HFI-HSL

- Unit-HFI-LSL

  Instances: DilutionCoolerElectronics, 4KCoolerDriveElectronics, 4KColdUnit, 4KCoolerAncillaryUnit, 4KCoolerCompressorUnit, 4KCERegulator, 4KCoolerElectronicsUnit

  * DataProcessingUnit

    Instances: HFI-DPU-A, HFI-DPU-B

- Unit-HFI-HSL

  * DataProcessingUnit

    Instances: HFI-DPU-A, HFI-DPU-B

  * ReadoutElectronicsUnit

    Instances: REU-Chain-00, REU-chain-01, REU-Chain-02, REU-Chain-03, REU-Chain-04, REU-Chain-05, REU-Chain-06, REU-Chain-07, REU-Chain-08, REU-Chain-09, REU-Chain-10, REU-Chain-11, REU, REU-proc-A, REU-proc-B

- Unit-HFI-1553

  * DataProcessingUnit

    Instances: HFI-DPU-A, HFI-DPU-B

• Unit-SPIRE

  Instances: HSFPU, HSJFP, HSJFS, HSDCU, HSFCU, HSDPU, HSWIH

Unit

• Unit-Power

- PowerDistributionUnit

  Instances: H-PDU, P-PDU
- PowerControlUnit

  Instances: P-PCU, H-PCU
- LCL

  Instances: HFI-01, HFI-02, HFI-03, HFI-04, HFI-05, HFI-06, HFI-07, HFI-08, HFI-09, HFI-10, HFI-11, HFI-12, HFI-13, HFI-14, HFI-15
- SolarGenerator

  Instances: H-SolarPanel, P-SolarPanel

• Unit-Thermal

• Unit-DataManagement

  - CDMU

    Instances: H-CDMU-A, H-CDMU-B, P-CDMU-A, P-CDMU-B
  - 1553Bus

    Instances: H-1553Bus, P-1553Bus
  - RTU

• Unit-AttitudeOrbit

  - ACC

    Instances: H-ACC-A, H-ACC-B, P-ACC-A, P-ACC-B

• Unit-Telecommunications

  - Receiver
  - Decoder
  - Antenna

- Unit-PL
  - Unit-LFI

    Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B
  - Unit-HFI

    Instances: FocalPlaneUnit, J-FET Box, DPU/PowerDistributionPart, DilutionCoolerSubSystem, FocalPlaneStructure, IsotopeSupplyUnit, HeatSwitches, GasStorageUnit, DilutionCoolerControlUnit, DilutionCoolerPneumaticUnit, DIlutionCoolerPiping, 4KCoolerSubsystem, JTcompressors, AnciliaryGasCleaningPanel, ConnectingPipework, LowTemperaturePlumbing, MainElectronics, HFI-HSL
    - Unit-HFI-LSL

      Instances: DilutionCoolerElectronics, 4KCoolerDriveElectronics, 4KColdUnit, 4KCoolerAncillaryUnit, 4KCoolerCompressorUnit, 4KCERegulator, 4KCoolerElectronicsUnit
      - DataProcessingUnit

        Instances: HFI-DPU-A, HFI-DPU-B
    - Unit-HFI-HSL
      - DataProcessingUnit

        Instances: HFI-DPU-A, HFI-DPU-B
      - ReadoutElectronicsUnit

Instances: REU-Chain-00, REU-chain-01, REU-Chain-02, REU-Chain-03, REU-Chain-04, REU-Chain-05, REU-Chain-06, REU-Chain-07, REU-Chain-08, REU-Chain-09, REU-Chain-10, REU-Chain-11, REU, REU-proc-A, REU-proc-B

∗ Unit-HFI-1553

· DataProcessingUnit

Instances: HFI-DPU-A, HFI-DPU-B

– Unit-SPIRE

Instances: HSFPU, HSJFP, HSJFS, HSDCU, HSFCU, HSDPU, HSWIH

A.2 Equipment

A.2.1 Actuator

A.2.2 Sensor

Instances: Gyro, QRS, StarMapper

A.2.3 GroundStation

A.2.4 System

Instances: H-DMS, H-AOCS, H-Power, H-Thermal, H-TTC, H-RCS, P-AOCS, P-DMS, P-Power, P-RCS, P-Thermal, P-TTC

A.2.5 Instrument

Instances: Spire, PACS, HIFI, LFI, HFI, SCS

A.2.6 Spacecraft

Instances: Herschel, Planck

A.2.7 Unit

Unit-Power

- PowerDistributionUnit

  Instances: H-PDU, P-PDU

- PowerControlUnit

  Instances: P-PCU, H-PCU

- LCL

  Instances: HFI-01, HFI-02, HFI-03, HFI-04, HFI-05, HFI-06, HFI-07, HFI-08, HFI-09, HFI-10, HFI-11, HFI-12, HFI-13, HFI-14, HFI-15

- SolarGenerator

  Instances: H-SolarPanel, P-SolarPanel

Unit-Thermal

Unit-DataManagement

- CDMU

  Instances: H-CDMU-A, H-CDMU-B, P-CDMU-A, P-CDMU-B

- 1553Bus

  Instances: H-1553Bus, P-1553Bus

- RTU

Unit-AttitudeOrbit

- ACC

  Instances: H-ACC-A, H-ACC-B, P-ACC-A, P-ACC-B

Unit-Telecommunications

- Receiver
- Decoder
- Antenna

Unit-PL

- Unit-LFI

  Instances: RadiometerArrayAssembly, FrontEndUnit, FeedHorn, OrthomodeTransducer, FrontEndModule, Reference Load, WaveGuides, BackEndUnit, BackEndModule, DataAquisitionElectronics, RadiometerElectronicsBoxAssembly, PowerSupply, LFI-DPU-A, LFI-DPU-B, SPU-A, SPU-B

- Unit-HFI

  Instances: FocalPlaneUnit, J-FET Box, DPU/PowerDistributionPart, DilutionCoolerSubSystem, FocalPlaneStructure, IsotopeSupplyUnit, HeatSwitches, GasStorageUnit, DilutionCoolerControlUnit, DilutionCoolerPneumaticUnit, DIlutionCoolerPiping, 4KCoolerSubsystem, JTcompressors, AnciliaryGasCleaningPanel, ConnectingPipework, LowTemperaturePlumbing, MainElectronics, HFI-HSL

  - Unit-HFI-LSL

    Instances: DilutionCoolerElectronics, 4KCoolerDriveElectronics, 4KColdUnit, 4KCoolerAncillaryUnit, 4KCoolerCompressorUnit, 4KCERegulator, 4KCoolerElectronicsUnit

    * DataProcessingUnit

      Instances: HFI-DPU-A, HFI-DPU-B

  - Unit-HFI-HSL

        * DataProcessingUnit

          Instances: HFI-DPU-A, HFI-DPU-B

        * ReadoutElectronicsUnit

          Instances: REU-Chain-00, REU-chain-01, REU-Chain-02, REU-Chain-03, REU-Chain-04, REU-Chain-05, REU-Chain-06, REU-Chain-07, REU-Chain-08, REU-Chain-09, REU-Chain-10, REU-Chain-11, REU, REU-proc-A, REU-proc-B

    - Unit-HFI-1553

        * DataProcessingUnit

          Instances: HFI-DPU-A, HFI-DPU-B

- Unit-SPIRE

  Instances: HSFPU, HSJFP, HSJFS, HSDCU, HSFCU, HSDPU, HSWIH

This completes the automatically generated index pages. The real ontology would take more than 250 pages to print out as a hard copy, but can be easily browsed either using an internet browser or the development user interface. The following pages show some of the details that are available for two items, a generic HFI unit, and a HFI unit that is connected to the High Speed Link, HSL.

Class Unit-HFI

Concrete Class Extends

Unit-PL,Electricty28V

Direct Instances:

1. FocalPlaneUnit
2. J-FET Box
3. DPU/PowerDistributionPart
4. DilutionCoolerSubSystem
5. FocalPlaneStructure
6. IsotopeSupplyUnit
7. HeatSwitches
8. GasStorageUnit
9. DilutionCoolerControlUnit
10. DilutionCoolerPneumaticUnit
11. DIlutionCoolerPiping
12. 4KCoolerSubsystem
13. JTcompressors
14. AnciliaryGasCleaningPanel
15. ConnectingPipework
16. LowTemperaturePlumbing
17. MainElectronics
18. HFI-HSL

Direct Subclasses:

1. Unit-HFI-LSL
2. Unit-HFI-HSL
3. Unit-HFI-1553

Slot name	**Documentation**
Project	Which spacecraft this unit belongs to
Name	Unit name
IsPartOf	Relation between instances
Temperature	to differantiate hot units and cold units
PowerConsumption	Power
UserInfo	Description
Has-a	Relation between instances
Receives28V	
Contains	Relation between Classes
Sends28V	
RelatedQuestion	Clarifications

Class Unit-HFI-HSL

Concrete Class Extends

Unit-HFI,HighSpeedLink

Direct Instances: None

Direct Subclasses:
1. DataProcessingUnit
2. ReadoutElectronicsUnit

Slot name	**Documentation**
Project	Which spacecraft this unit belongs to
Name	
IsPartOf	Relation between instances
Temperature	to differantiate hot units and cold units
PowerConsumption	Power
UserInfo	Description
Has-a	Relation between instances
Receives28V	
SendsHSL	
Contains	Relation between Classes
ReceivesHSL	
Sends28V	
RelatedQuestion	