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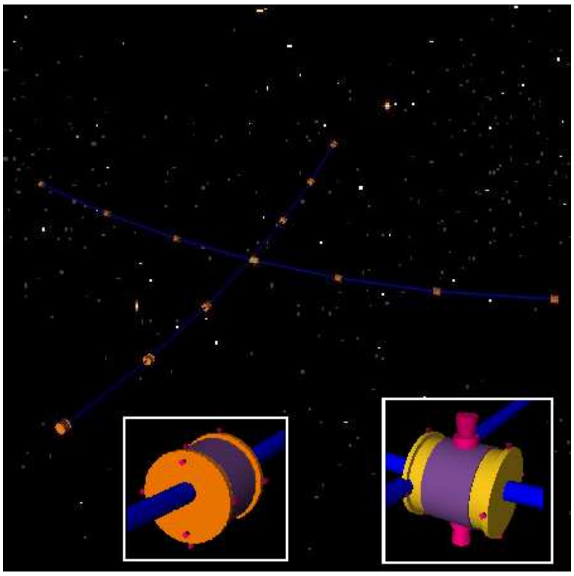
A. Lecuyot

MICROCELLS FOR METASTRUCTURES

An application of MicroSystem technology to distributed space structures



College of Aeronautics

Philosophy Doctorate

CRANFIELD UNIVERSITY
College of Aeronautics
PhD Thesis
Academic Year 2003-2004

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An application of MicroSystem technology to distributed space structures

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May 2004

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Technology.

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Abstract

In this thesis, a new concept of space systems called metastructures is studied. Applications are in very large space structures (1 km) that can take many shapes and be reconfigured during operations. This concept is explored by defining it from a systems engineering perspective, characterising the system dynamics and technical baseline, and assessing its interest with respect to proposed missions and to alternatives.

Metastructures are defined as assemblies of microcells linked rigidly. Microcells are themselves defined as Nanosatellites with reduced functionalities, and are referenced locally or globally for active position control within the metastructure. Two reference missions are considered, a centimetric interferometer and a Solar concentrator as part of Solar Power systems.

The methods used to analyse these missions and achieve the research objectives are based on strategy analysis, standard practices in mission and system design, and a simplified system dynamics simulation implemented in a custom simulator.

The analysis of dynamics demonstrates the controllability of such structures, and their ability to maintain and keep shape in most orbits to good accuracy. It also shows that the design of the distributed controller is important.

From this, subsystem requirements are derived for the microcells which are studied as highly integrated microsystems. Mass of the microcells is around 500 g, much of which is propellant.

The baseline system configuration for reference missions is derived, including costing. For these missions masses are less than a ton, with costs less that 500 Million Euros. Metastructures do not perform well in terms of lifetime given the simplistic controller used. Appropriate research of decentralised controllers may remedy to this, but a weak point of the concept is that of stowing and launching.

Finally, a preliminary analysis of the concept with respect to its alternatives tends to show that it is worthy of further investigation.

Acknowledgements

Despite the cliche of solitary PhD students, I certainly know that without the professional and personal support I received, I could not have completed the present work. So I would like to express my gratitude to:

My supervisors, first and foremost: My academic supervisor Dr Steve Hobbs kept the work relevant and on track. My industrial supervisor Dr Ian Honstvet also had the hard task of dealing with a part-time degree from the employer's point of view;

My external and internal examiners: Prof. Colin McInnes from Glasgow University and Dr Peter Roberts, for a enriching viva voce discussion, and for coming all this way.

My sponsors: The EPSRC supported and funded the Total Technology scheme within which I did the research. EADS Astrium Ltd equally sponsored and supported the work financially and practically, thanks to the successive commitment of John Hobbs and Robert Graham;

My colleagues and advisors at Cranfield University and at EADS Astrium: Martyn Snelling, who advised me on the practical side of post-graduate work; My fellow student Priya Fernando with whom I had fruitful discussions on space and microtechnologies;

Those who proved they are truly my friends as they coped with my very low sociability for all these years; Emma in particular, who provided the moral support, the coffee and the biscuits;

My family and my parents, crucially: I could not have started or finished this work without them; I thank them for raising me in appreciation of academic excellence, and for coping with the unavoidable personal issues;

Claire, who waited more than six weeks;

Thanks to all.

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Glossary

Acronyms

AFM Atomic Force Microscope.

AIV Assembly, Integration and Verification.

AMR Anisotropic Magneto Resistor.

AOCS Attitude and Orbit Control System.

ASIC Application Specific Integrated Circuit.

CMOS Complimentary Metal Oxide Semiconductor.

CNES Centre National d'Etudes Spatiales.

CoM Centre of Mass.

COTS Commercial Off The Shelf.

EGSE Electrical Ground System Equipment.

EPA Embedded Piezoeletric Actuator.

ESA European Space Agency.

FEEP Field Emission Electric Propulsion.

GEO GEOstationary orbit.

GNC Guidance, Navigation and Control.

IMU Inertial Measurement Unit.

IR Infrared.

IT Information Technology.

JPL Jet Propulsion Laboratory.

LEO Low Earth Orbit.

LOFT Lifetime OF Tethers (ESA software).

MAG Magnetometer.

MCM Multi-Chip Module.

MEMS Micro Electro Mechanical Systems.

MST Micro System Technology.

NASA National Aeronautics and Space Administration.

PI Proportional Integral controller.

PID Proportional Integral Derivative controller.

R&D Research and Development.

RF Radio Frequency.

RMS Root Mean Square.

SAR Synthetic Aperture Radar.

SMAD Space Mission Analysis and Design.

SME Small Medium Enterprise.

SOAC System On A Chip.

SWOT Strengths, Weaknesses, Opportunity, and Threats analysis.

TTC Telemetry, Telecommands, and Control.

UHF Ultra High Frequency.

VHF Very High Frequency.

Mathematical Symbols

$[A]$ Tension Multiplier matrix in Tension derivation model.

$[B]$ Energy Term vector matrix in Tension derivation model.

$[T]$ Tension vector matrix in Tension derivation model.

$\alpha_{i,j}$ Signed unit (or null) multiplier tension coefficient for tension.

β	Switching coefficient for control action.
ΔX	Relative vector X (tension, force, position) between two nodes.
λ	Wavelength of a signal in m.
$\mathbf{R_{i,j}}$	Orbital radius vector of node i, j.
$\mathbf{T_k}$	Tension vector for the link k.
$\mathbf{e_{i,j}}$	Unit vector parallel to a tension vector at node (i, j).
$\mathbf{u_{i,j}}$	Control thrust vector of node i, j.
μ	Earth Gravity's potential, value of $3.986004418.10^{14} \quad m^3.s^{-2}$.
ρ	Material density in kg/m^3.
υ	Interferometric resolution in m.
D	Interferometric baseline in m.
E	Material Young's Modulus in N/m^2 or Pa.
e_{max}	Maximum position error (m), controller design parameter.
e_p	Error in position (m).
$e_p(structure)$	Error in position for complete structure.
F	Focal length of the reflector parabola in m.
G	Global cell in cell pattern (such as L-L-G).
I	Impulse (Ns).
I_{sp}	Specific Impulse in seconds.
L	Local cell in cell pattern (such as L-L-G).
M_p	Propellant Mass (g).
Ohn	On-Off, Horizontal, Next-in-line controller microcell.
Ohp	On-Off, Horizontal, Previous-in-line controller microcell.
$u(e_p, v)$	Control law for On-Off controller.
v_{max}	Maximum velocity error (m/s), controller design parameter.
M	Line dimension of a metastructure matrix.
N	Column dimension of a metastructure matrix.

Part I

INTRODUCTION

The Whole is more than the sum of its parts, the Part is more than a fraction of the Whole. *Aristotle, Metaphysica 10f-1045a*

Chapter 1

Overview

Summary

The thesis defended here is a doctoral research in system engineering for a novel type of space system, the metastructure. Such a system uses a distributed architecture and miniaturised so-called microcells to deploy large structures in space. The objectives of this work are to define this concept and its applications, to characterise the behaviour of such a system, and to assess the industrial interest and strategic value. The logic of this report follows the realisation of these objectives through the various chapters. For fast reading each chapter has a summary section, and a conclusion recaps the work performed and the main findings.

1.1 Objectives

The research work I present in this thesis is about metastructures, which are large space structures enabled by distributed architecture and using microcells built with microtechnology. This concept must be studied both from the technical and industrial point of view, so the subject of this research is essentially the evaluation of an innovative space system concept.

I choose to focus on the system engineering aspect of this evaluation exercise. This means that most of the effort is in specifying the system architecture and analysing the system behaviour. Attention has also been focused on subsystem design and business assessment, but only addressed as analyses "downstream" from system-level work, and used to support overall assessment of the concept. Thus the objectives of the research must reflect the generic process of system analysis and design.

So first, I wish to explore the conceptual issues expressed in the definition of an actual metastructure. This means defining the scope of the system, its applications, and its physical and functional architecture. Because of the novel nature of the system, a limited formalism is developed to describe it in terms that are suitable for analysis.

Next, of course, I need to *characterise* this system. In typical system analysis fashion (see Chapter 5), this means working out the top-level behaviour of the system, deriving from this the subsystem requirements, building the system baseline, and analysing the development plan. In this case this means making an analysis of metastructure dynamics in space, designing the microcells (i.e. the subsystems) based on these results, and costing the design and manufacturing of a complete system.

Finally, I perform a critical *assessment* of the overall concept. The viability of the concept is so evaluated by considering it relative to other technical alternatives on one hand, and in its own industrial context on the other. In conclusion I examine the interest of the research itself and I discuss the validity of the analyses performed.

Definitions for the actual research topic and the precise formulation of objectives are as described in the next sections.

1.1.1 Research topic definitions

Varied definitions of the concepts used in this research can be found. The following definitions clarify which approach is used in the current work.

Metastructure An active system composed of interlinked active and passive nodes which automatically maintains a desired and changeable configuration in orbit.

Distributed structure In this context, a structure that need only be modelled by a series of nodes. An underlying but not necessary consequence is that in a distributed structure the failure of one component is not the failure of the complete structure.

Distributed control In this context, means that the control of a given domain is not centralised by a main controller. Instead it is normally obtained by addition of independent controllers of smaller capacity. This is not to be confused with another meaning of the term in terrestrial applications, in which different parts of the control system are located at different places.

Nodes A component of the metastructure that can be active as a sensor and/or an actuator. Different types of nodes can exist in a same metastructure depending on the pattern chosen. In the MST-based structures, the nodes are actual microcells, as defined below.

Microcell In this context, a node of a metastructure. It is in fact an elaborate microsystem, relying on micro and nano technology for high integration and miniaturisation.

Links A passive structure that connects the nodes together. This is what makes a metastructure different from a "virtual" structure that uses formation flying. The links can be rigid, flexibles, or cable-like, although in this work only rigid links are considered (see section 7.2.1).

Reference structure A structure defined for the purpose of studying the concept in general, aside from the specific reference missions. It is detailed in the next section.

1.1.2 Research objectives definition

As described above, the objectives are precisely:

1. **Define** the concept "metastructure":
   (a) Context and rationale: Technical readiness, background and alternatives, concept description.
   (b) Applications: suitable applications, including reference missions to be studied in detail.
   (c) System architecture: functional and physical characteristics, top-level parameters.
2. **Characterise** the metastructure for reference missions:
   (a) System behaviour in operation (dynamics in space).
   (b) Requirements on subsystem (i.e. microcells).
   (c) Subsystem design baseline at preliminary leve.l
   (d) Evaluation of cost and necessary industrial architecture.
3. **Assess** the concept as a whole:
   (a) Trade-off with respect to alternative designs.
   (b) Synthesise all the information obtained in a strategic analysis.

The objectives are illustrated in Figure 1.1. These are chosen based on what is relevant for the research, but the extent of their realisation depends on the scope of the work, detailed in section 1.2.

1.2 Scope of research

This research is conducted in fulfillment of a "Total Technology" doctorate in space systems engineering, at the College of Aeronautics of Cranfield University. This programme proposes technology research degrees oriented towards industry. So the

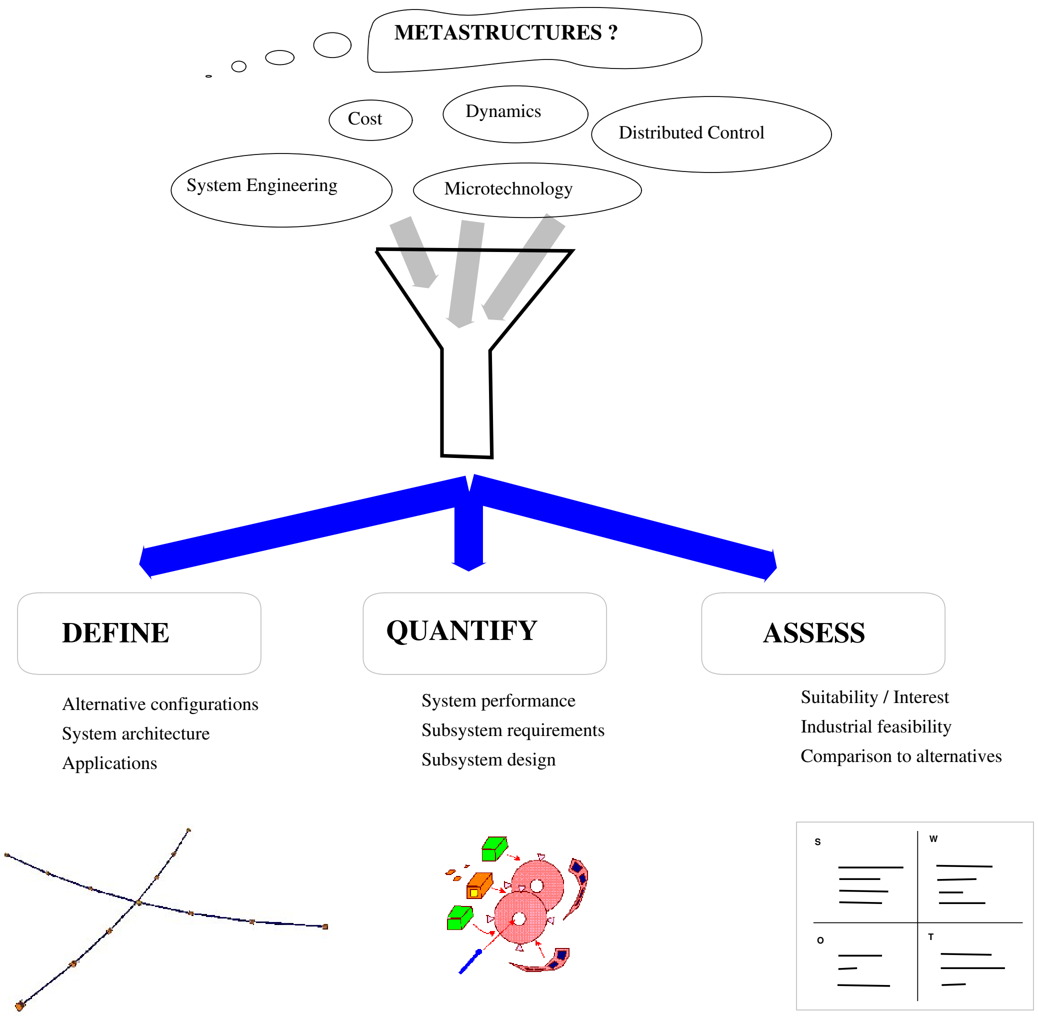


Figure 1.1: A novel concept is considered from a system engineering point of view, hence the specific objectives of the research.

subject is technological rather than scientific and includes a non-technical, business-related task as specified in the guidelines from Cranfield Press [1999].

Space systems engineering includes many disciplines. I choose to study a novel and specific application of micro-technologies to space missions. I also prefer to consider it from the point of view of system engineering. This means that the work is conceptual rather than developmental. The main findings of the research can in principle be used by technology programme planners. They can select further detailed analyses to be performed and initiate R&D (Research and Development) activities.

The industrial sponsor and potential used of this research is EADS-Astrium

Ltd[1], the UK's main prime contractor for space systems. EADS-Astrium have a vital interest in developing an understanding of the long-term impact of micro-technologies on its business. In particular, EADS-Astrium Ltd (UK branch) are the company-wide centre of excellence for this emerging field, hence their interest in the presented work.

It is also worth mentioning that I choose for practical reasons to only execute theoretical work, using only freely-available computer tools and no hardware. This influences the choice of a dynamics simulator software (see Appendix B). Finally, the thesis is organised so as to follow a logic reflecting the achievement of the objectives, which is detailed in the next section.

1.3 Thesis roadmap

The objectives are to define, characterise and assess the concept of Metastructure. The various pieces of work reported can thus be presented in relevance to these objectives, as is seen in Figure 1.2.

The overall evaluation method is described in Chapter 5. The "define" objective includes the literature survey (Chapters 3 and 4), the introduction of the concept (Chapter 2), the definition of missions (Chapter 6), and the study of generic architecture (Chapter 7). The overall system features and requirements are derived from the applications analysis. The particular technical implementation selected is itself derived from a system-level technology trade-off.

The "characterise" part is realised through the selection of a dynamics model (Chapter 8), the use this model to simulate the structures (Chapter 9), the derivation of subsystem requirements and design (Chapter 10), and the costing of the concept development (see Chapter 11).

The "assess" objective is achieved by discussing the results of these previous analyses from a technical and strategy point of view (see Chapter 12).

The achievement of these objectives through the work previously described is discussed in Chapter 13. A conclusion (Chapter 14) summarises the work done, presents the main results obtained, and proposes further work.

Each chapter begins with a summary section for fast reading. Detailed calculations are referred out of the main text by reference to Cx where x is the calculation number in Appendix (see below). Finally, appendixes refer to material used in support of the work. Appendix 15 lists the references, whilst Appendix A details the referred calculations, and Appendix D gives duplicata of Internet references. Appendix B documents the software simulator developed, and Appendix C summarises a preliminary analysis of novel microtechnology applications to space systems.

[1]See http://www.astrium.eads.net for company details

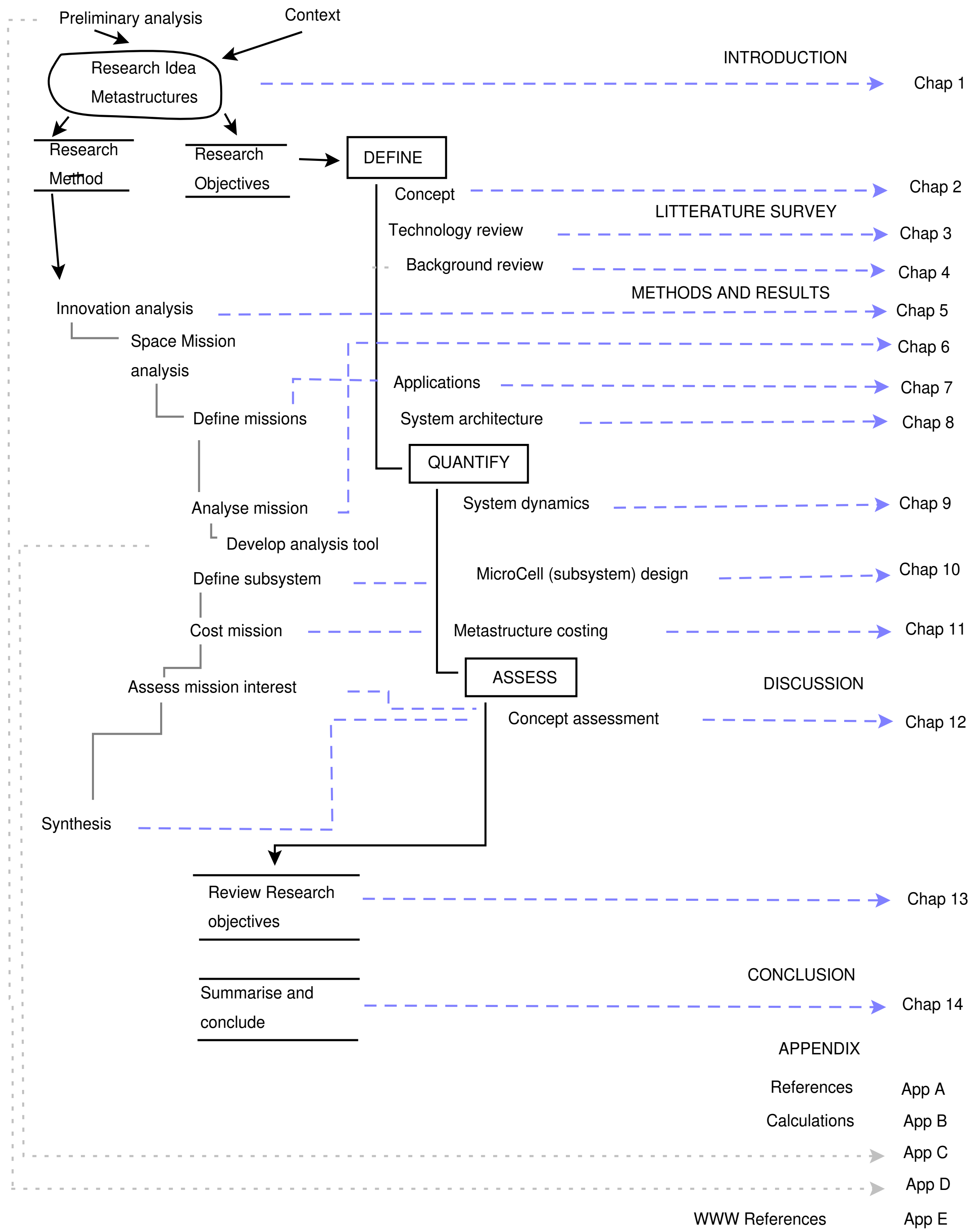


Figure 1.2: Thesis roadmap. Both the overall report structure and the specific focus of each chapter reflect the objectives.

Chapter 2

Microcells and Metastructures

Summary

Distributed system architectures can be used to deploy large sparse aperture structures in space. One possible concept for this type of system is that of a so-called metastructure. In this concept independent nodes are physically linked, and these nodes need to be complete microsystems that are able to monitor and control their position. Features of such a system include decentralised control and the ability to reconfigure itself. This design is investigated in more detail in this work.

2.1 Distributed structures in space

Metastructures are a specific type of distributed structures in space. Distributed space structures are a particular engineering application of the scientific problem of system architecture analysis, i.e. organising components of a system so that they may perform a set of required functions. In turn, the principles defined through systems science are derived from the philosophy of systems.

Even though the concept of system organisation is present in Greek natural philosophy (see p.7), it is only in the last decades that systems have been considered in the philosophy of science. Originated in biology [Bertalanffy, 1976] and computer science [Ross Ashby, 1964], “systems thinking” or holism [Klir, 2001] has many applications in the study of complexity, in social sciences, artificial intelligence, and in particular in systems engineering.

Systems Engineering practices [Halligan, 2001] are aimed at design of practical and efficient technological systems, through the analysis of requirements, the derivation of a physical and functional architecture, and the integration of functions and components. Thus technical systems are characterised mainly by their architecture, by the technical implementation of their various components, and the external and internal interfaces.

2.1.1 Distributed structures and systems

Focusing on the architectural design, recurrent and generic trade-offs identified in this work are choices between integrated versus modular systems, and distributed versus centralised systems. The former can be related to the design of system components and their interfaces, whilst the latter can be related to the implementation of overall system functions.

Typically, system modularity depends on the necessity to assemble it from pre-existing elements, and to maintain and access these elements during and after assembly. It depends ultimately on technology state-of-the art and availability of commercial components. On the other hand, the degree of centralisation depends on the understanding of the relative interaction of components, the requirements for redundancy, and the overall system size in the design space. It is a fundamental system-level design issue.

Distributed systems in general are better at coping with complex large systems. A spectacular illustration of the potential benefits of distributed systems is of course the networks of personal computers such as intranets and the Internet, and this type of architecture is increasingly being applied to other types of systems.

In the particular case of industrial technical systems, fields being influenced by distributed concepts are information systems, control systems, and in particular mechanical systems, with Distributed Parameter Systems and truss-like structures as described for instance by Tzou [1998]. Examples of such distributed systems are shown in Figure 2.1.

In this figure is also shown an area of distributed systems research that merges control and structural design in order to create so-called active and distributed structures. This enables structures to be not only distributed, but also reactive to disturbances in their environment. This is thanks to distributed controllers inserted on the structure, able to either dampen vibrations or change the shape of the structure.

The design of distributed and active structures is a very wide-ranging field where terminology and concepts are not clearly established. The degree of distribution and the functions of each individual structural controller vary widely from one concept to another. But common features of distributed structures as identified in this work are:

Robustness Distributed structures may be designed to resist to varying loads more easily than centralised structures, as the mechanical state does not usually depend heavily on the force application point.

Redundancy Equally, distributed structures can be more redundant as they usually use a more than sufficient number of elements along a load path.

Lightness Because distributed structures consider directly the load path they tend to be more efficient in terms of mass.

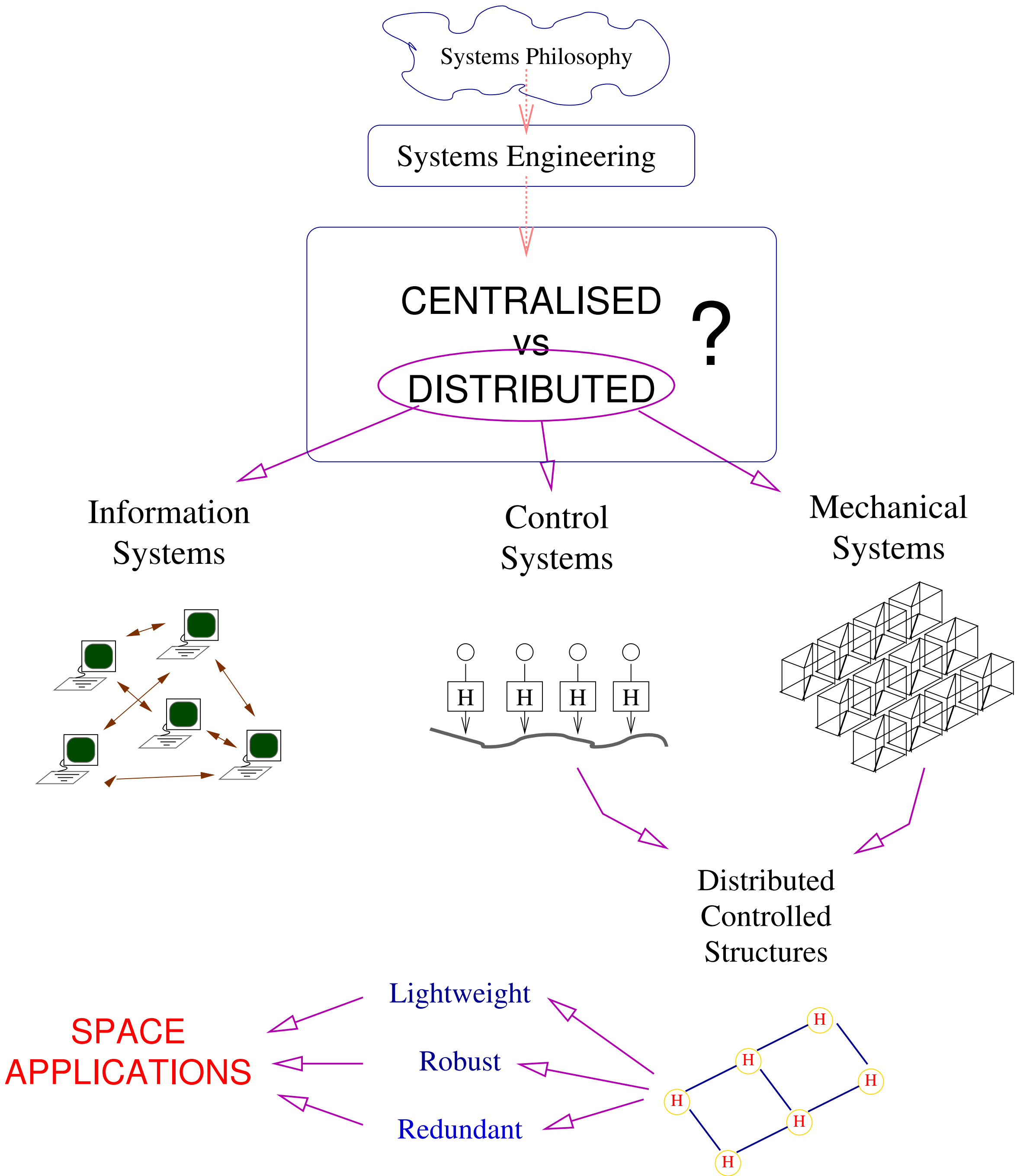


Figure 2.1: Examples of distributed systems in information, control and structural technology. At the convergence of distributed control and structures are flexible active structures.

Each of these assertions may not hold true in some particular cases, but they can be deduced from the very concept of a distributed structure. These features of redundancy, robustness and lightness are very valuable for space systems, which must operate autonomously, in not well known environments, and are constrained by launch mass. Thus distributed structures may have specific applications to space systems.

2.1.2 Applications to structures in space

The notion of distributed active structures for space systems departs from the traditional view of structures in space mission design. Indeed, in general, structures are static and closed systems as in the system engineering meaning [Blanchard, 1990]. Their configuration is usually fixed during design. For spacecraft, the structure is traditionally a passive support for active systems and subsystems.

But even then the structure has a function, if only to ensure correct relative positioning of interdependent subsystems. An example is the accurate positioning of thrust vectors and propulsion hardware relative to sensors of the control system, as seen on Figure 2.2.

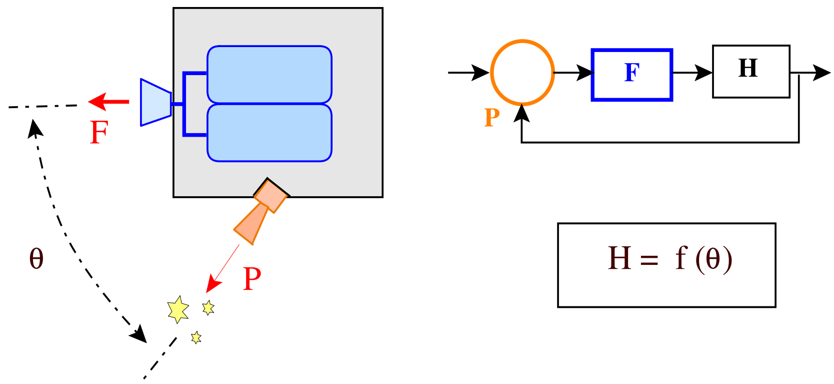


Figure 2.2: The geometry of the supporting structure can be of interest to other components space system. In this example The attitude transfer function H is function of a configuration mounting angle θ between the sensor (star sensor) and the actuator (thruster).

When spacecraft include equipment such as optical sensors, some parts of the structure have more complex functions. For instance, laws of optics dictates a reflector to have a parabolic shape so as to focus the incoming beam towards a detector [W. Stutzman and A. Thiele, 1998]. In that case the shape, dimensions, and tolerances of the structure are related to the wavelength of the signal as seen on Figure 2.3. Table 2.1 gives examples of such requirements.

In the application above, the structure is effectively modelled as a discrete geometry, a series of points in space. The position requirements are in fact on these

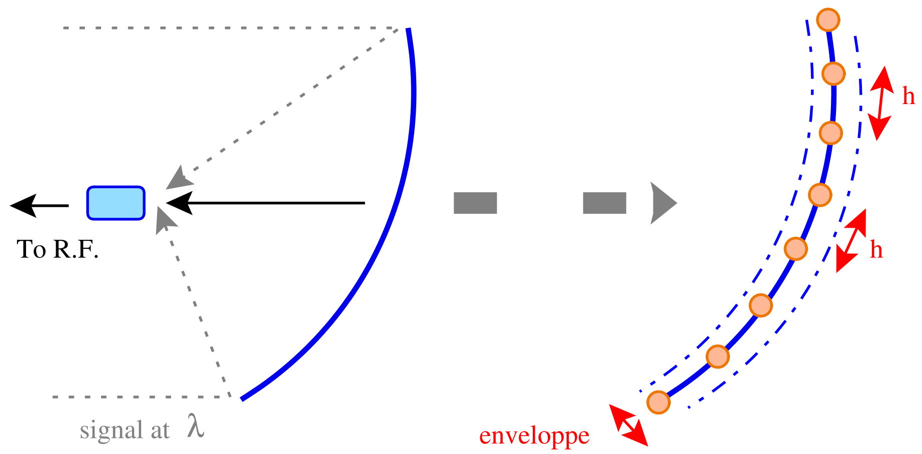


Figure 2.3: For an antenna dish structure, the tolerances h on shape and position depend on λ. What is shown in one dimension on the figure actually happens on a 2D parabolic grid, which is reflected in design for so-called "gridded" reflector antennas in current telecommunications spacecraft (Reference from internal EADS Astrium R&D).

points and for these points to be connected physically. This is where the previously described concept of a distributed structure is interesting, and where design of spacecraft structures can be improved depending on the size, the implementation and the application of the structure. The range and configuration of distributed structures is well illustrated in the presentation of Ericsson [2002] whose main points are summarised below.

Size is the primary factor for considering distributed structures. Indeed, all configurations that can fit within a launcher fairing using only a small number of deployable appendages may not benefit from the more costly option of using distributed architectures. This corresponds to satellites typically up to about 5 metres in size (such as Hubble space telescope). Missions with larger structures up to about 10 metres (such as the James Webb space telescope) may still be deployed using mechanisms, but with more and more complex and difficult solutions (see section 4.2). Above this it is necessary to use distributed structures, also called "sparse" structures in the space community. Such structures however are bound to be flexible because of their low mass, and need to use controllers to remove vibration,

Case	Shape	Size	Tolerances
CommSat Payload K-Band	Parabola $z = 4fy^2$	3 m	$\sim$1 mm
Optical or IR instrument	Parabola	1 m	$\sim$1 μm
X-band data antenna	plate	30 cm	$\sim$1 mm

Table 2.1: Examples of Requirements on reflector or antenna structures

deploy and maintain position. These are active distributed space structures.

Applications are as seen above mostly as "aperture" structures, i.e. optical or radio reflectors, or even point sensors in the case of interferometry; There are also applications in deploying very large power generation panels (see section 6.4).

Finally the implementation can use different technologies. For non-distributed structures monolithic or deployable filled apertures are preferred. For intermediate sizes flexible structures with controllers are used, including so-called "smart" structures (see Chapter 4). For larger structures (such as the SPECS mission) tethered formations can be appropriate. For still larger cases current research focuses on actually using disconnected structures, so that the various nodes fly in formation, forming a virtual structure. The spectrum of these large aperture sensing structures is illustrated in Figure 2.4 which is extracted from the keynote presentation of Ericsson [2002].

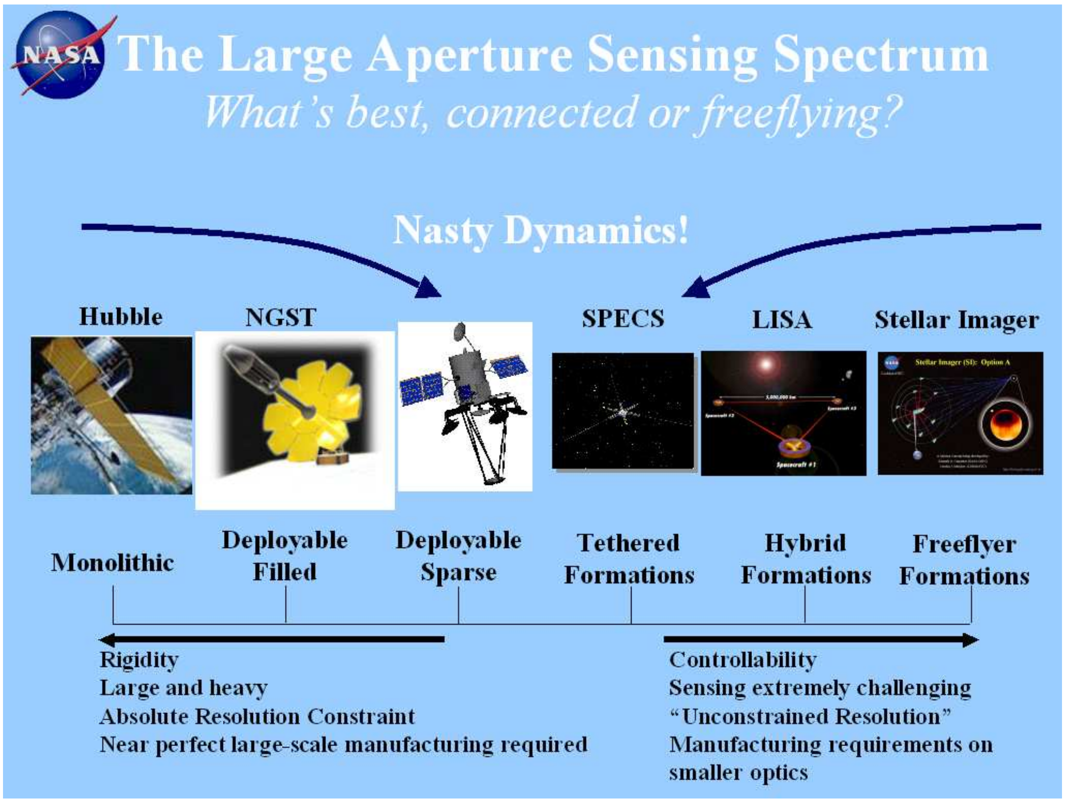


Figure 2.4: The large aperture sensing spectrum. Depending on the size of the considered structure distributed technology is interesting or not, and can be implemented using deployable and flexible structures, tethered formations, or flying formations. Courtesy NASA Goddard Space Flight Centre [Ericsson, 2002].

2.1.3 Metastructures as system concepts

It can be seen from Figure 2.4 that the reflexion on distributed structures at system level is done *ad hoc* on the basis of a particular mission. Equally, there is no consideration currently of using real structures instead of formation flying for large apertures. Thus there is a case for considering the design of space distributed structures as a specific innovative concept, to be studied on its own and for a specific mission.

When considered as an assembly of nodes which are physically linked and use decentralised control, such systems are defined conceptually as one step beyond "simple" structures, and are dubbed *metastructures*. A metastructure has nodes and links, has and must maintain a defined shape in space. The nodes realise a decentralised distributed control, whilst the links maintain structural coherence. This is illustrated in Figure 7.1. More details on the concept are in section 2.3.

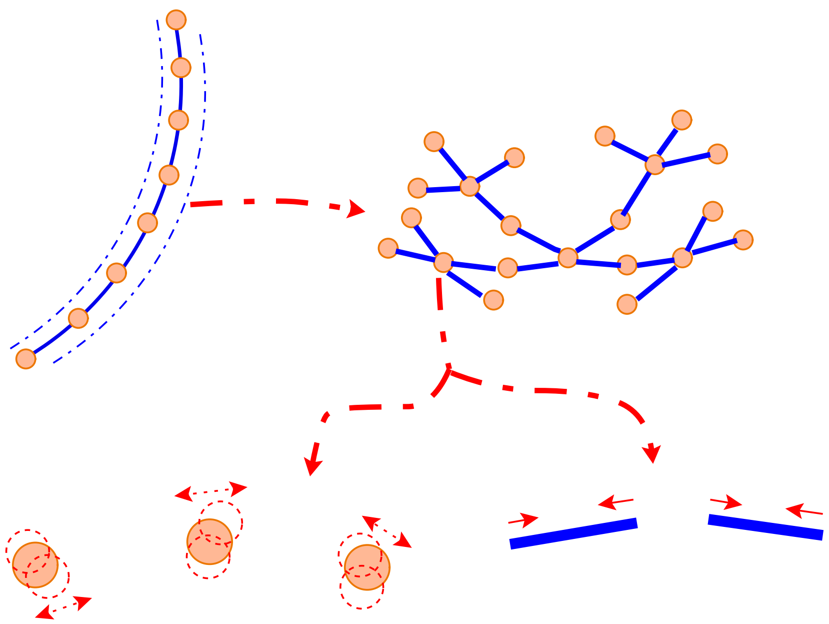


Figure 2.5: Metastructure concept. A metastructure is a systematic view of a distributed structure in space, including nodes with decentralised control, and links for coherence.

In principle, the concept can be implemented independent of the technology used for links, cells, and distributed control. However this influences heavily the feasibility of any particular application, as is studied in the next section.

2.2 Microcells for metastructures

As seen above, the main components of a metastructure system are the nodes and the links. The overall configuration and system parameters such as mass and power depend heavily on the technology used for these two components, in particular on their degree of miniaturisation.

2.2.1 Technical implementation of metastructures

The parallel has been made above between distributed structures and distributed information systems such as the Internet. However the very concept of the Internet and other networks relies on using personal computers which have autonomy of processing and storage capacity. This means they have relatively high functionalities in an integrated and miniaturised system when compared to mainframes and large computers.

This situation is also applicable to another application of distributed systems, the so-called metastructures. The feasibility of metastructure depends on the technology used for the distributed nodes and the corresponding links. And, like above, miniaturisation of these nodes is they key to making them efficient.

Indeed, in Table 2.2 are shown mass and size of the system and its elements for a reference mission studied (see Chapter 6) for different assumptions on the node mass. It can be seen that, for the system to be practical, individual nodes have got to be at least less than 1 kg in mass, with a corresponding size of a few centimetres. As seen in Chapter 3, this is only compatible with extremely miniaturised satellites, or Nanosatellites, which rely almost entirely on so-called MST for achieving low mass and high functionalities.

Node mass (kg)	Link section - mass (mm, kg)	Overall system mass (kg)
0.5	8.5 square - 0.5	> 600
1	10 square - 1.1	> 1300
5	15 square - 5.4	> 6500

Table 2.2: Comparative size and masses for a complete metastructure reference application (see Chapter 12), based on various node masses.

2.2.2 Microcells as microsystems

MST or MEMS are a series of microfabrication and integration techniques based on CMOS-like Silicon etching processes developed for the semi-conductor industry [Madou, 2002]. In the field of space systems, MST can potential lead to a radical reduction in size and mass of subsystems, as seen in Figure 2.6. So the realistic implementation of the nodes is that of very small spacecraft having similarities with Nanosatellites, and these nodes are thus dubbed *microcells*.

As for the links, the values in Table 2.2 assume low mass ($\rho = 1500 kg/m^3$) and high mechanical stiffness for advanced materials ($E = 10^{12} N/m^2$). Such materials can be derived from so-called Carbon Nanotubes, which are based on nanotechnology and use a fullerene-type molecular structures [Adams, 2003].

Thus the concept of metastructure relies heavily on assuming high levels of miniaturisation for the microcell nodes. From this the concept can be further defined for more detailed analysis, which is done in the next section.

2.3 The case for metastructures

2.3.1 Concept definition

It has been seen that distributed control and physical links are the main features of a metastructure. The system design and concept applications are further analysed in Chapters 6 and 7. A metastructure is thus defined as:

- A series of microcells which are very similar to nanosatellites, with masses lower than 1 kg; These have functions of detection and control of position with associated support functions.
- A series of links, ranging in length from 1 to 10 metres typically, which are usually considered as rigid passive rods made of advanced carbon composites.
- A decentralised and distributed control architecture, in which each microcell has its own independent controller. The system behaviour is not centralised.

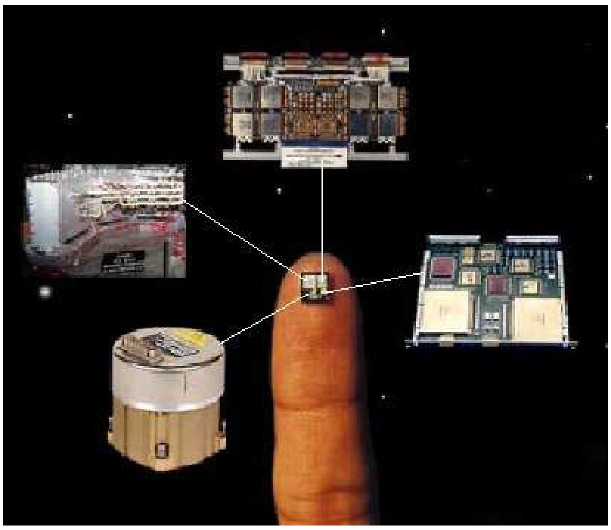


Figure 2.6: The SOAC concept from JPL. MST have the potential to drastically increase miniaturisation and integration of space components and systems.

Whilst this does not in principle encompass all the possible configurations of metastructures, this corresponds to what is deemed by the system analysis the most practical or realistic in the time frame considered. Such a concept presents specific advantages and inconvenients as detailed next.

2.3.2 Pros and Cons

The pros and cons of metastructures as a concept are shown in Table 2.3. Significant advantages of the concept appear to be the possibility to change shape, and the robustness, simplicity and redundancy inherent to the decentralised distributed control. The concept is considered autonomous in that it does not need ground intervention in any phase for operations. On the other hand, the microsystem design associated with microcells and their attachment to links may be complex. Equally the development cost of such a system may be large when compared to other alternatives.

PROS		CONS	
Lightweight	Attractive to launch and deploy	Novel design	Feasibility, development cost
Autonomous	No operation complexity	Subsystem complexity	Microcells are complete microsystems
Reconfigurable	By changing the controller references		
Simple	Simpler than other structures for decentralised control		
System view	Proposes a system point of view for distributed structures		

Table 2.3: Pros and Cons of metastructures as a concept.

2.3.3 Conclusion, background and technology

The metastructures have been derived from the systematisation of the concept of distributed structures in space. The concept presents advantages in terms of autonomy and redundancy, but it relies on a system-level decentralised distributed control and on using complete microsystems as components, and it is to be compared with other alternatives in terms of development needs. So the concept must be studied at system, subsystem and industrial levels, which is detailed in the next chapters.

The most immediate assessment is related to the availability of the necessary technologies, as described in section 2.2.2 and 2.3.1. It has been seen that microcells need to be integrated, to use inertial and position microsensors, and to possess a micropropulsion system. Similarly, thanks to the links, metastructures present similar dynamics to that of tethered and linked constellations in space. So a review of literature available and work performed in these areas is in Chapter 3. Equally, a review of the state of the alternative technologies is performed in Chapter 4. Subsequent chapters propose a method of strategic and technical analysis, present the results of such analyses, and discuss the results.

Part II

LITERATURE REVIEW

Chapter 3

Concept Technology Review

Summary

Technologies used for metastructures include integrated microsystems and microdevices, nanosatellite technology, and tethered systems. As regards microdevices the best developments are for inertial and magnetic sensors. Micropropulsion is also an area of investigation. The challenge of microsystems for space lies in the low-level and high-level integration of systems-on-chips and packaging through multi-functional structures. This will also enable nanosatellite integration. As for tethered constellations, there are missions proposed that are similar in some respects to metastructures. Tether dynamics are now better understood, in particular with respect to rigid tethers.

3.1 Metastructure technologies

The concept of metastructures involves large numbers of nodes that must be miniaturised and minimal. So the availability of some MST components for space is reviewed. Microcells are also compared to integrated nanosatellites in terms of functions and size, so they are reviewed as well. Finally, the nodes are physically linked, which means that the system dynamics presents similarities with that of tethered satellite constellations, which are also reviewed.

3.2 Microsystems for space

The development of microdevices for use in space systems builds on the very substantial research and industrial work performed in terrestrial applications. Microtechnology is used commercially in several fields and has a market of several billions Euros [Force, 2002]. It is based on microfabrication techniques [Madou, 2002] derived from silicon etching processes (such as CMOS). MST (Micro *System* Technology) in turn seeks to integrate microdevices so produced with the associated electronics and with other microdevices. This concept can provide highly functional, compact and independent microsystems [Maluf, 2000]. In Figure 3.1 shows a typical surface microengineering process.

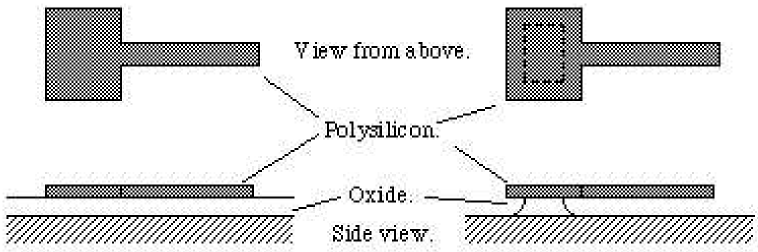


Figure 3.1: General principles of MST surface micro-machining. Image source Danny Banks.

The current MST development model includes two extremes. On the one hand, there are a few very large foundries creating mass market products by developing their own facilities (such as Analog Devices[1]). On the other hand there are several SMEs and academic research centres able to develop prototypes (such as LAAS[2] or RAL[3]).

Space applications are only a small part of this development, and are not considered a priority by MST and microelectronics developers [Howes, 2003]. Still, substantial work is taking place in the area of microsensors, microactuators, and integrated microsystems for space.

3.2.1 Sensors

The largest research in space microsensors is in the development of a so-called IMU (Inertial Measurement Unit), including rate sensors and accelerators. COTS (Commercial Off The Shelf) MST "gyros"[4] and accelerometers are available [Stein, 2001] with increasing performances [Bernstein, 2003]. It is worth mentioning that at present, performances of micro-fabricated rate sensors are much below usual requirements for fine attitude pointing of spacecraft, specifically in terms of long-term bias.

MST-based magnetometer prototypes exist using different technologies such as fluxgate or AMR [Schneider, 1998, Viera, 2003]. They are accurate to a few nanoTeslas. Some can be machined using a CMOS-compatible process (see Figure 3.2).

[1]http://www.analog.com

[2]http://www.laas.fr

[3]http://www.cmf.rl.ac.uk

[4]MST rate sensors use technologies based on measuring the change in vibrating structures to recover the rotation rate. They are not strictly gyroscopes but the term is used (although incorrectly) for rate sensors in general.

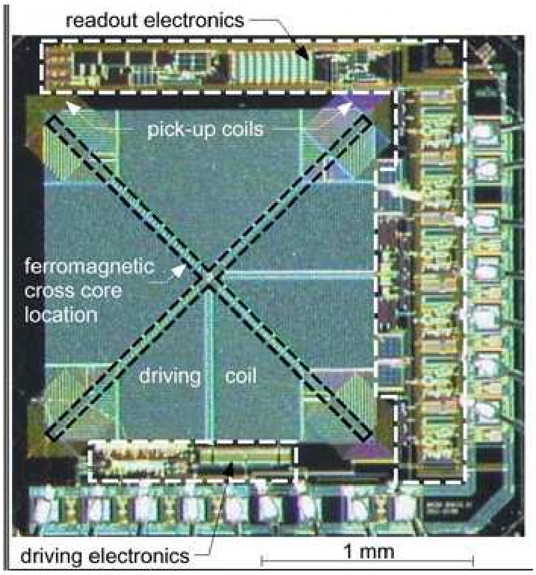


Figure 3.2: A micromachined self-assembling magnetometer [Schneider, 1998]. Image source EPFL

Some mechanical sensors are commercially, available such as strain gauges, used also in silicon pressure sensors which are a mainstream application of MST[5]. Other microsensors used in space systems include for instance nanotips used for mass spectrometers ion guns [Kent, 2000], AFM onboard planetary probes [Gautsch, 2000], and environmental sensors [Lecuyot, A. and Snelling, M., 2003a]. There are also efforts in miniaturisation of sensor arrays for microcameras and Earth or Star sensors [Ogiers, 2000] which are not usually considered to be MST.

3.2.2 Actuators and propulsion

Research on actuators for space systems is centered around RF switches for microwave systems, optical micro-mirrors, and propulsion systems. Only the latter two are of interest to metastructures, either as the actuation subsystem for position correction, or as part of a sensing subsystem.

Optical micro-mirrors are being developed in Europe for possible use on future space telescopes [Zamkotsian, 2002]. There are other applications such as micro-optics [Bright, 1999] and lasers in the longer term. In these, operation of basic optical functions has been demonstrated.

Micro-propulsion systems receive a lot of attention in the space community [Larangot, B. and Rossi, C., 2002]. There is research going on in the field on solid microthrusters or "digital propulsion" (see Figure 3.3). Larangot, B. and Rossi, C. [2002] provide a good review of micropropulsion which is summarised below and

[5]See for instance http://www.microstrain.com

where the specific references can be found.

Figure 3.3: Solid microthruster firing test. Image Source LAAS.

For cold gas system the use of piezoelectric valves enables the reduction of a commercial system in size and mass. Solid micropropulsion is also a significant area of research where several designs have been successfully tested, including flight demonstration (see section 3.2.5). For monopropellant systems a MEMS-based hydrazine thruster has been developed which has adequate performance, but an even more performing system is in development. There has also been some research into bipropellant engines which is less advanced than monopropellant so far. Finally some designs of the various electric propulsion systems have been tentatively miniaturised. In general, and in particular for FEEP thrusters, the difficulty comes from the high level of power and thus the bulky electronics necessary to produce the thrust, even with a micro-thruster. On Table 3.1 is shown a summary of the capacities of the systems described above (extracted from the work by Larangot, B. and Rossi, C. [2002]).

System	Thrust (mN)	I_{sp} (s)
Cold Gas	0.1-10	45
Digital Solid	20	-
Liquid Mono.	0.01-1	145
Liquid Bi.	1,000	300

Table 3.1: Capacities of currently developed micropropulsion systems (extracted from the paper by Larangot, B. and Rossi, C. [2002]).

3.2.3 Other subsystems

Other subsystems of a spacecraft are being investigated for miniaturisation. Long-term systems using radioactive decay as power sources are studied, which are, however, in early stages of development [Lal, 2003]. One can also make use of micromachined antennas to provide small communication systems [De Maagt, 2001]. Finally, thermal microsystems are also investigated [Larsson, 2000]. Microdevices for other subsystems have been investigated as well but are not addressed here as they are not used in microcells.

3.2.4 Integration and packaging

The integration of MST in space systems creates two challenges; validation and qualification on one hand, and integration on the other. Qualification means that the failure mechanisms of MST have to be understood in detail [Schmidt, 2003]. Equally, the space community has initiated qualification programs for specific devices [Barthe, 2003].

As for integration, there are several options that have been studied by industry [Lecuyot, A. and Snelling, M., 2003b]. Initial implementations of microsystems is done with hybrid integration. Prototypes have been developed and flown for this level of integration [Manhart, S. and Melf, M., 2000]. However for industrial uses in the middle term MCM-level integration is necessary.

The full potential of microsystems can only be realised when integration levels of the SOAC (System On A Chip) can be reached, which are currently in early research phases [Lecuyot, A. and Snelling, M., 2003b]. The key issue with SOAC is the compatibility of different processes used to make different parts of the system. JPL have prototyped such a process based on a space-compatible silicon process [JPL, 1999], but no operational applications exist yet.

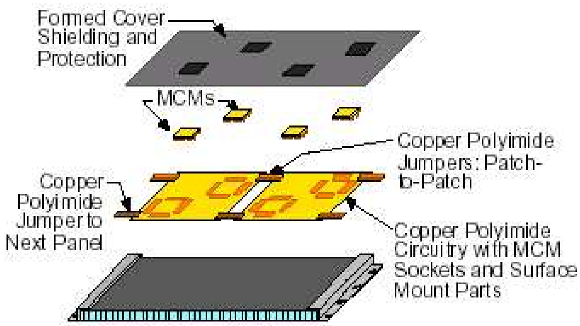
Finally packaging of microsystems is tightly related with integration for lower-level packaging (see above). For higher-level packaging (i.e. at box level) concepts such as multifunctional structures [Barnett, M. and Rawal, S., 1999] are necessary (see Figure 3.4). This enables to provide packaging with structural functions, or structures with specific functions, such as harness routing or electrical connections. This is also a key technology for nanosatellite integration.

3.2.5 Flight experiments

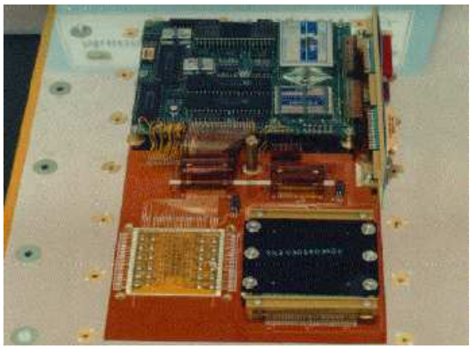
The vast majority of the developments mentioned above have been tested on the ground. For space systems qualification is vital, in particular through flight validation. In this respect, only a limited number of MST devices have flown. The Aerospace corporation[6] has flown microthruster experiments on the Shuttle rack

[6]http://www.aero.org

[Helvajian, 1999], and has flown a pair of so-called “PicoSats” that include genuine microtechnology [Aerospace, 2000]. In Europe, EADS Astrium has flown an MST-based attitude sensing package [Manhart, S. and Melf, M., 2000]. These flights experiments performed well and are shown in Figure 3.5.

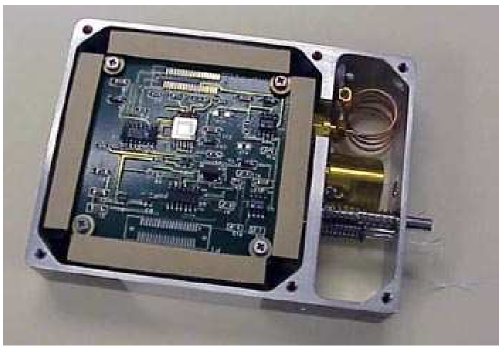


(a) Principle

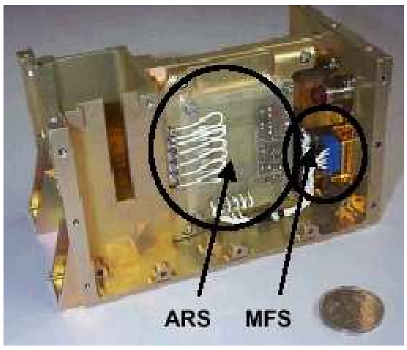


(b) Construction

Figure 3.4: Multifunctional structure on Deep Space 1. Image source NASA JPL and Lockheed Martin.



(a) One of the Picosats from Aerospace Corporation.



(b) The MTS-AOMS from Astrium EADS.

Figure 3.5: MST-based flight experiments. Both have operated successfully in space. Image source Aerospace Corporation and Astrium EADS Gmbh.

3.3 Nanosatellite concepts

The concept of Nanosatellite is usually[7] accepted to mean satellites in the range of less than 1 to less than 10 kg [Helvajian, 1999]. In the MST field it also defines a satellite which includes microsystems most if not all of its subsystems, although this is not a universal definition. On Table 3.2 are shown a few representative concepts for current nanosatellite projects and their relevance to MST. The concept which is close to the metastructure microcells is the so-called "WaferSat" [Helvajian, 1999] (see Figure 3.6). This is a fully functional satellite which is about 10 cm in size. The same organisation behind this concept has also flown so-called picosatellite demonstrator of MST-based satellites [Aerospace, 2000].

Project/Concept	Organisation	Mass	MST	Status
OPAL	Stanford Uni.	> 20 kg	None	Successful flight
SNAP-1	SSTL	< 10 kg	None	Partially successful flight
Angstrom	Uppsala Uni	< 10 kg	Some	In development
Picosat	Aero. Corp.	< 1 kg	Mostly	One successful flight
Wafersat	Aero. Corp.	< 1 kg	All	Concept only

Table 3.2: Some representative Nanosatellite projects

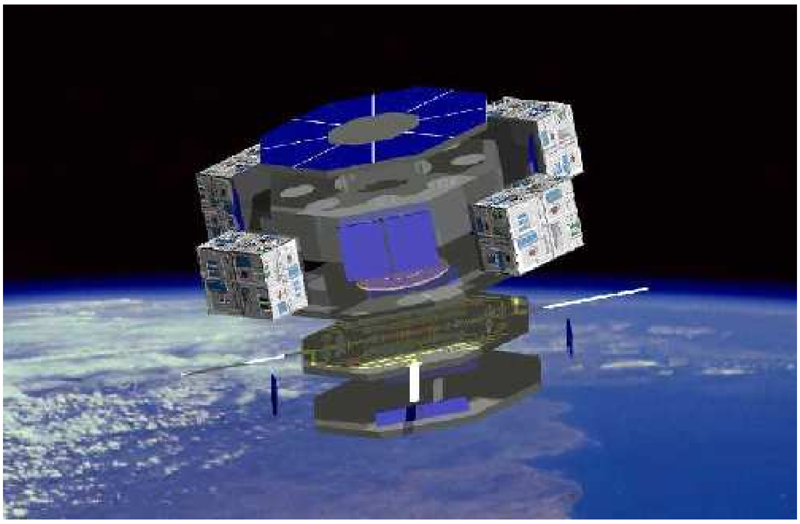


Figure 3.6: The Wafer Satellite concept from Aerospace corporation. Image source Aerospace Corporation.

[7]Although there is no strict classification.

3.4 Tethered constellations

The term applies to all missions that use long cables connecting two or more satellites in orbit. Missions have been developed, executed and completed during the past 20 years in order to test and validate tether systems, as seen on Table 3.3, extracted from LOFT Team [2000] which also presents an analysis of tether dynamics summarised below.

Name	Launch	Orbit	Length	Comments
TSS-1	1992	LEO	<1 km	electrodynamic, partial deploy, retrieved
SEDS-1	1993	LEO	20 km	downward deploy, swing & cut
PMG	1993	LEO	500 m	electrodynamic, upward deploy
SEDS-2	1994	LEO	20 km	local vertical stable, downward deploy
Oedipus-C	1995	suborbital	1 km	spin stable 0.7 rpm
TSS-1R	1996	LEO	19.6 km	electrodynamic, severed
TiPS	1996	LEO	4 km	long life tether on-orbit

Table 3.3: Recent tether missions flown

The dynamics of tethered satellites are a subject that has been studied in some detail [Crist S.A., 1970, V. Beletsky, 1993]. There are a number of models going from the point mass to the complete continuous model as seen in Figure 3.7 extracted from LOFT Team [2000]. At one end of the simplification process, continuous models aim to represent the tether in the frequency domain. These models are limited to specific missions. Lumped mass models are discretised models with elastic beams, whilst hinged rods feature rigid beams. These tend to be the most used models. Finally, at the other end, dumbbell and orbital element models are rigid body models, and the point mass one is only used for simplistic long-term propagations (for lifetime predictions). In this case, the properties are represented in the special area to mass ratio. Many works focus on modelling the string-like behaviour of the tether [Pelaez, J., 1995, M.L. Cosmo and E.C. Lorenzini, 1997a]. However a good deal of work has focused on modelling tether as rigid rods, with adequate levels of success for mission design purposes [Biesbroek, R and Crellin, E., 1999]. Control of flexible tethered systems is achieved by reeling them in and out according to a specific control law [Pelaez, J., 1995].

The closest to the concept of metastructure to be found in literature are the missions for tethered constellations. One mission proposes to use tethered satellites flying in formation from a central cluster to achieve micrometre resolution over a 1000 m distance in Lagrange point halo orbit [Quinn, 2000]. Other proposed missions for tethered configurations use natural environment to maintain the configuration

[M.L. Cosmo and E.C. Lorenzini, 1997a]. In low Earth orbit it is possible to use drag to stabilise a horizontal configuration. For other orbits it is also possible to use conducting tethers or spinning dynamics to achieve stability. Some configurations of tether constellations are illustrated on Figure 3.8 extracted from the "Tether Handbook" by M.L. Cosmo and E.C. Lorenzini [1997a].

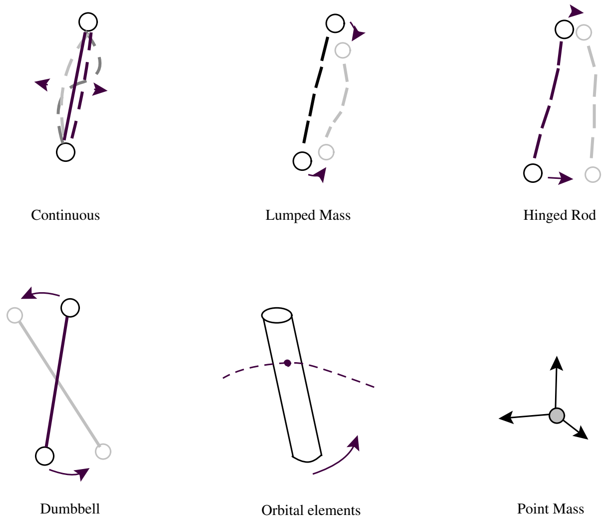


Figure 3.7: Possible tether models. For metastructures the adequate one is the rigid rods. Extracted from [Team, 2000].

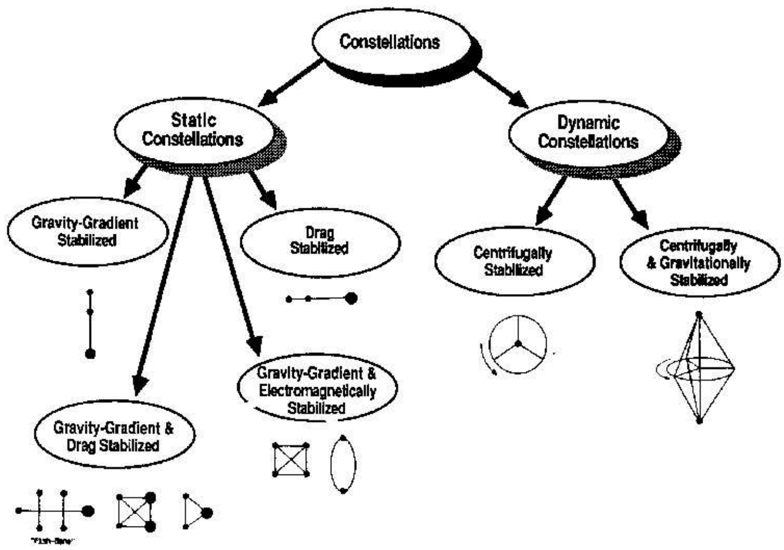


Figure 3.8: Tethered constellations possible configurations. Image source Smithsonian Institute.

Chapter 4

Concept background review

Summary

There are alternative to metastructures as large structure designs. Conventional design can manage deployable antennas and solar arrays in the tens of metres in size, which are currently commercially available. There is a lot of research to more effectively control larger and flexible structures using distributed parameter control techniques. Another interesting alternative is inflatable structures technology, which builds on extensive past developments and has flight experience. Finally, there are also some missions proposing to use formation flying spacecraft instead of large structures. In many of these areas Microtechnology is also seen as bringing benefit.

4.1 Alternatives to metastructures

The concept of using complete microsystems to form structures in space may be novel expressed in this form, but there are other solutions to deploying structures in space. For current applications many types of mechanisms exist with mature technology, which are suitable for most missions up to a certain size using basic deployment techniques. For larger applications a lot of effort has been devoted into analysis and control of flexible structures. This also includes concepts such as robust control and smart structures. Finally for 3D structures an emerging technology is that of inflatable structures also called “gossamer” spacecraft.

These three basic technologies provide some alternatives and it is important to review them as they are the background for the evaluation of metastructures as a concept.

4.2 Deployable mechanisms

Currently operational spacecraft use a variety of deployed appendages [Fortescue, 1995]. These include broadly antennas for TTC, radar and telecommunications payloads, booms for specific sensors, and solar arrays. The possibilities of deployment include hinged, linear, and surface deployment [Conley, 1998].

Hinged devices are simplest, and include the vast majority of mechanisms. Linear devices can include deployable booms, and also deployable masts which can be based on flexible rods [Warden, 1989]. Surface devices include pulley systems for deployment of solar arrays, or also a combination of linear systems to deploy for instance thin solar arrays [Cawsey, 1982], or thin flexible antenna such as the famous example of the Galileo High gain antenna [Johnson, 1994].

In this class of deployed mechanisms the current state-of-the art is examplified by large antennas used for mobile telephony in GEO, such as on Inmartsat I-4 series ([Aerospace, 2003] and see Figure 4.1). These antennas are 5 to 12 m in diameter with a mass up to 60 kg. It seems that even larger similar antennas have been produced [Vick, 2003] but these are part of classified projects and no detailed information is available.

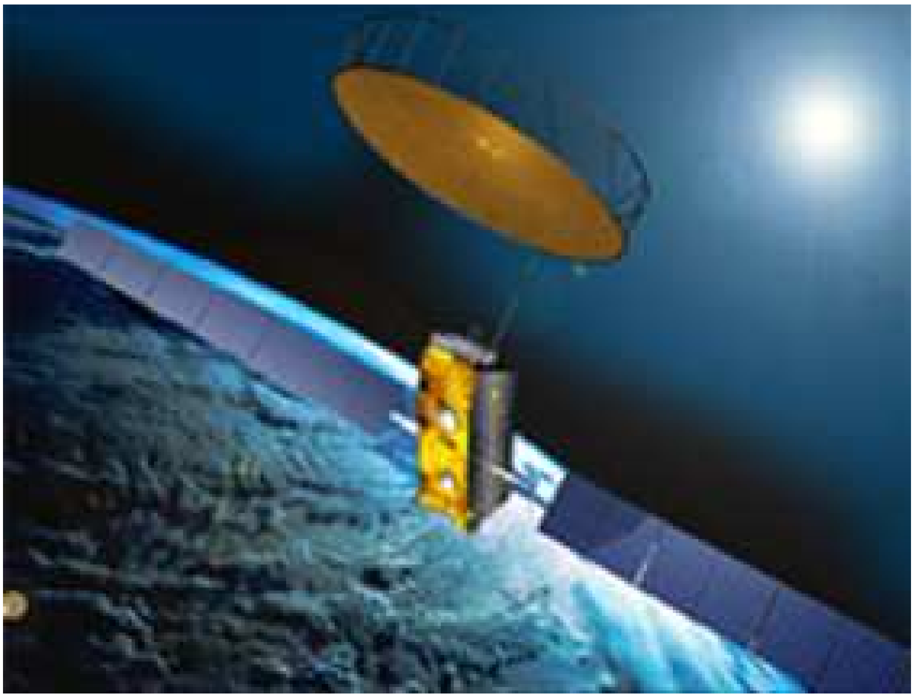


Figure 4.1: The Inmarsat-4 satellites use an Astromesh large antenna for mobile telephony in GEO (source EADS Astrium Ltd).

4.3 Controlled and Flexible structures

When structures in space become larger and lighter than the ones described above, they may have to be considered as flexible, which means they have different dynamics. A very large body of literature has been published on the subject. A generic survey performed previously [Meirovitch, 1990] shows that there are many different approaches to the problem. It is summarised below.

Control solutions use a series of different controllers for single and multiple body problems to suppress vibrations during and after manoeuvres. To solve the problem of discrepancy between the control parameters designed on the ground and the reality in space, robust control techniques are being researched [DeSousa, 1992].

In recent years such problems have been generalised as so-called "Distributed Parameter Systems" [Tzou, 1998]. The control of these systems has become practically interesting with the development of piezoelectric actuators used in so-called "smart structures" [Tzou, 2000]. Again smart structures are a very generic technology receiving a lot of attention. However scalability to real-life problems has proven difficult beyond 100 nodes or so, because of the computational overhead and increasing complexity [Frampton, 2001]. In principle, this limit can also be a problem for metastructures. But thanks to the fact that these have larger inter-node dimensions in the discretisation grid the problem is likely to be less severe. In the event, space flight experiments of smart structures to this day remain limited.

4.4 Gossamer spacecraft technologies

An alternative to structures where all parts are load-bearing is that of inflatable structures, or gossamer spacecraft [Jenkins, 2001b]. Through test balloons and flight experiments these have a history of many decades [Wilson, 1981]. There are several developments including flight experiments in the United States such as those by L'GARDE [2003] and ILD [2003], in Europe [Langlois, 2002], and in Russia [Pitchkhadze, 2002].

Applications of inflatable structures are to be found in Solar arrays [Derbes, 1999], space reflectors and SAR antennas [Huang, 1998], solar concentrator and solar shades [Jenkins, 2001a]. Inflated structures use specific technologies of thin membranes, rigidisation techniques, and deployment and inflation systems. For membranes polyimide is used in films of up to a few micrometres in thickness. For rigidisation techniques there are either flexible structures stretched beyond elastic point, solvent loss systems working by degassing in space, or cure heating composite materials.

There has been some experiments flown in space, in particular with the Inflatable Antenna experiment (see Figure 4.2) which demonstrated successful deployment in part [Freeland, 2003].

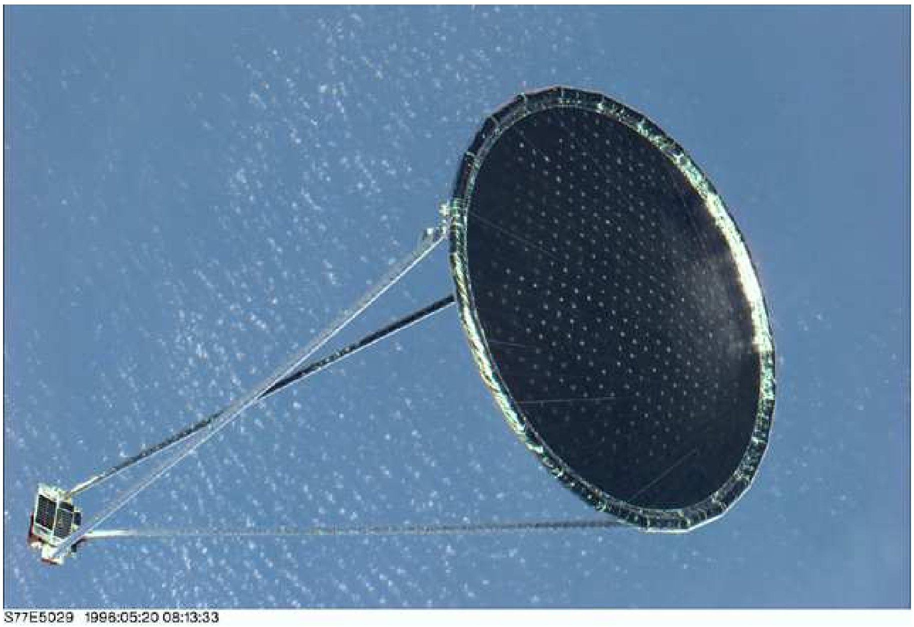


Figure 4.2: A view of the Inflatable Antenna Experiment after its in-orbit deployment from the Space Shuttle. Source L'Garde Inc.

4.5 "Virtual structures" via formation flying

For certain applications, in particular for space interferometers, there may be an interest in using separate spacecraft instead of large structures [CNES, 2002]. These so-called "virtual structures" or formation flying constellations are based on using either satellites in co-ordinated orbits [ESA, 2003] or controlled motion of satellites [Bainum, 2002]. The configurations tend to be a central spacecraft and several node satellites that are controlled or designed relative to the central one. This is the case for interferometric missions in ESA and NASA [CNES, 2002]. Other missions actually include the use of swarms of nanosatellites, but these present challenges in terms of mission design [Das, 1998]. Techniques used for control can be innovative, such as the potential method [Mc Quade, F. and Mc Innes, C., 2003].

4.6 MST in Space structures

It is finally worth noting that there is a growing work being performed to include MST in space structures. One area of investigation is in inflatable structures [Tung., 2002] where sensors and later actuators are being integrated within the rigidised structure or even in the inflated film. Equally MST is being seen as a possible solution to the problem of smart structures [Frampton, 2002]. As for the formation flying missions those using satellite swarms rely significantly on the use of microtechnologies to miniaturise individual satellites [Das, 1998].

Part III

METHODS and RESULTS

Chapter 5

Evaluation method for an innovative concept

Summary

To evaluate the concept an overall strategic analysis is performed using the SWOT technique. This analysis is backed up by interest and feasibility data. Interest data is obtained by the analysis and design of reference missions, using a space mission analysis method adapted to the concept. Feasibility data is obtained by a systems engineering analysis to identify system architecture, a dynamics analysis to identify subsystem requirements, and a microcell design activity, used as input to a further activity of costing. This costing is done both for the development and exploitation phases of the concept lifecycle.

5.1 Overall evaluation approach

The ultimate goal of an evaluation exercise conducted on a innovative concept is to indicate whether the concept is interesting, and if so, feasible. The interest of the concept is assessed by finding its applications and finding how well it performs the expected functions in these applications. The feasibility assesses technical and physical realism of the concept. Inherent to this evaluation process is an apparent pitfall in starting the process. Indeed, to know whether the concept is interesting, detailed feasibility studies are necessary. But these are only performed if the concept is thought to be interesting initially, which can be difficult to evaluate *a priori* without feasibility information...

To solve this problem, a specific approach is selected that takes the point of view of an industrial contractor or an agency having to plan and decide possible investments into development activities related to metastructures.

The information needed from this points of view is a set of recommendations based on a strategy analysis, assessing the concept in itself, and the concept compared to other alternatives. This strategic assessment can then be based on interest and feasibility analyses as described above. So the following analysis methods are used:

Mission interest: In the case of metastructure, the interest is related to what missions they can perform, and how well they perform them with respect to other alternatives. A mission analysis is thus necessary, as is an assessment of feasibility results both on their own and compared to other alternatives for the same missions.

System feasibility: For this, several system design analyses are conducted to characterise the system parameters, the performance indicators, and their values for the metastructures when used in their specific applications. One of the vital system and performance parameters is of course cost, so a cost model and costing activity is performed for metastructures as defined per the system analysis.

Strategic analysis: Several tools have been developed to realise strategic analyses of new concepts in their environment. Among these the so-called SWOT (Strengths, Weaknesses, Opportunity, and Threats) diagram described in the next section is used here to summarise and review all technical information in a simple way.

With these three levels of analysis (strategic, mission-wise, and system-wise) enough information is gathered on the concept for making a business case. This overall process is illustrated on Figure 5.1. The detailed methods necessary to conduct these analyses are detailed in the next sections.

5.2 Strategic SWOT analysis

In a SWOT analysis which assesses Strengths, Weaknesses, Opportunities, and Threats, each feature of a particular business or concept is analysed in terms of these four aspects [Manktelow, 2003]. Typically this is presented in diagram format such as shown on Figure 5.2. The outcome of SWOT identifies particular weak areas, and the ways to remove them through specific actions. When applied to metastructures, specific questions are to be addressed during the analysis:

Strengths The particular strength of metastructures is that they are automatic and minimal systems. The extent of this is to be assessed in the final analysis. Also to be assessed is what is their position in terms of cost.

Weaknesses Metastructures are not a mature concept. This will need to be compared against other alternatives for large structures in space. Also any technical flaw or poor performance is identified here.

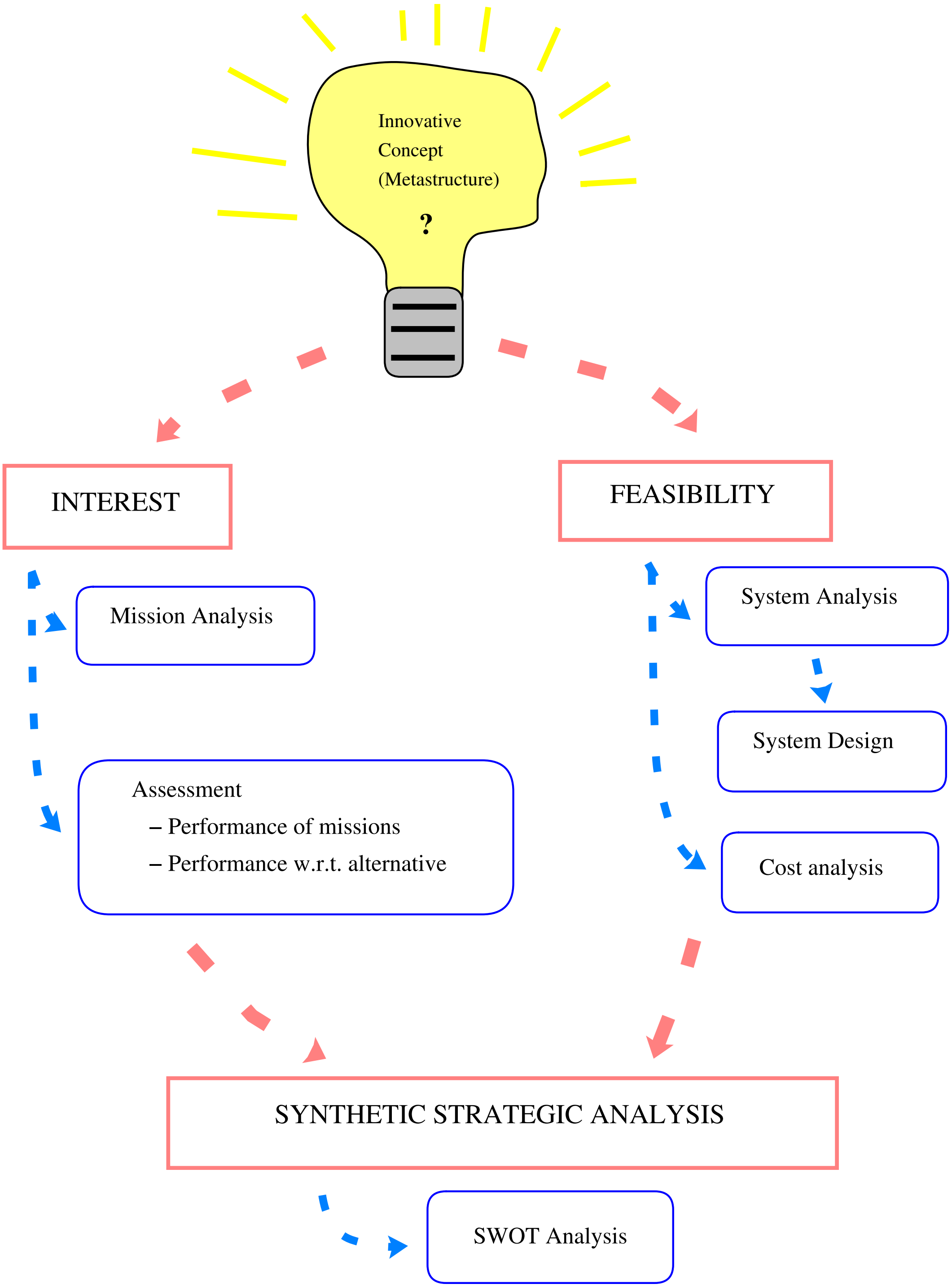


Figure 5.1: Innovation evaluation process applied to metastructures as a new concept. Fact-finding analyses of the interest and the feasibility of the concept are used as input to a strategic analysis. For each of these analyses a specific method is chosen.

Opportunities Since metastructures build on on-going concepts and development in Microsystems technology, there is a chance that they can benefit from research in other fields. Another opportunity is to identify missions that only metastructures can do effectively or that are actually enabled by the introduction of the concept.

Threats Threats to the concepts come mostly from alternative technologies that are more developed. The other source of threats may be in particular the new industrial infrastructure needed to produce metastructures.

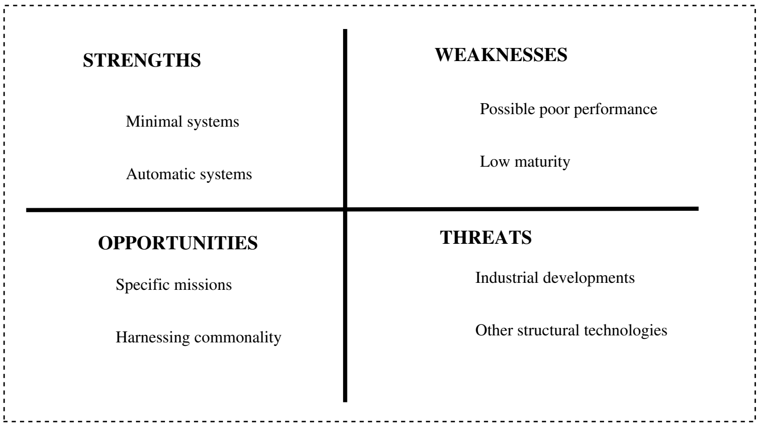


Figure 5.2: Typical format of a SWOT analysis.

5.3 Mission design for metastructure applications

Space mission design as understood here encompasses the complete definition of a space mission, as opposed the terms “Mission Profile” and “Mission Design” sometimes used, which actually refer to the analysis of the mission in terms of celestial dynamics, i.e. orbit selection and manoeuvres design. A synthetic and more generic view is applied here [J.R. Wertz and W.J. Larson, 2000]. According to this the mission design process follows four main steps which are the definition of objectives, the mission characterisation and evaluation, and the definition of system and subsystem requirements. This is illustrated on Figure 5.3, which is extracted from the book by J.R. Wertz and W.J. Larson [2000].

In the present case the tasks of mission characterisation and evaluation are performed as part of the system analysis. What is required is to focus on identifying the mission objectives, the needs, and the possible concepts and alternatives. Doing all these tasks for all possible missions is not possible in the scope of the current work. So a review of all possible missions by operational category is performed, from which a few reference missions are selected, which are then analysed in more detail

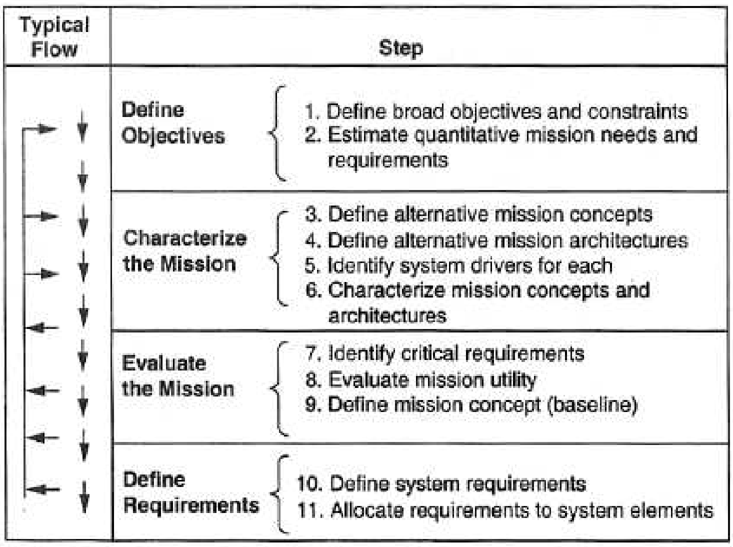


Figure 5.3: The Generic Space Mission Analysis and Design SMAD process (reproduced from [J.R. Wertz and W.J. Larson, 2000]).

using the above process. This adapted mission analysis process is shown on Figure 5.4.

5.4 System engineering applied to metastructures

The goal of the systems engineering activity in the current work is to characterise metastructures as systems, both in terms of their actual definition and in terms of their performance for the reference missions defined above. The systems engineering process comprises three main tasks [Halligan, 2001]:

Requirements Analysis This is based on the mission, the user needs, and the context.

Develop Functional solution For a number of physical architectures, decompose the requirements into a number of functions that are then mapped to the physical components in the architecture. Define interfaces and select an optimal functional solution.

Develop physical solution Based on the functional solution, develop the requirements and the configuration for each subsystem and component up to the level required.

In the current case, the requirements analysis results from the selection and analysis of the reference missions. The functional solution is developed by a systems

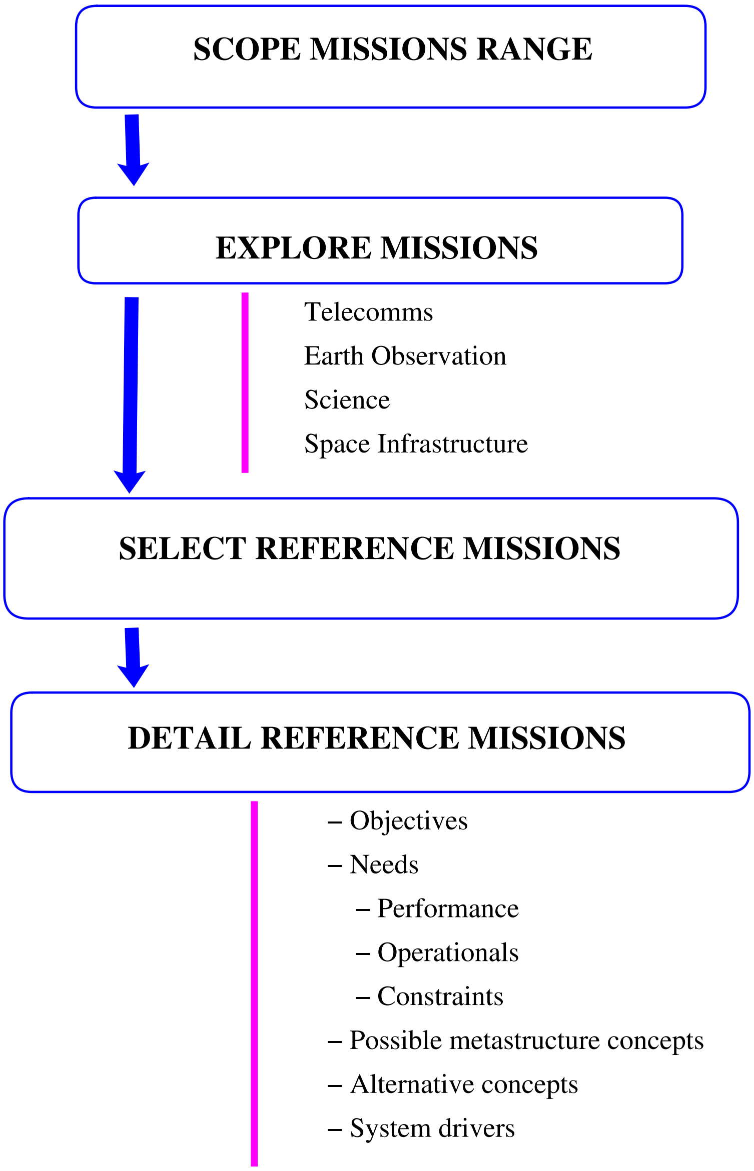


Figure 5.4: Adapted mission design process for metastructures. After a general assessment of all missions for which the concept is potentially suited, a few reference missions are singled out and the associated requirements are studied in detail.

analysis where possible architectures are analysed. The requirements on subsystems are the results of the dynamics analysis. The details of the dynamics analysis mathematical method are given in Chapter 8. Finally, the physical solution, in this case the microcell design, is developed in enough detail to ascertain its feasibility and allow the costing assessment to take place. This is illustrated in Figure 5.5.

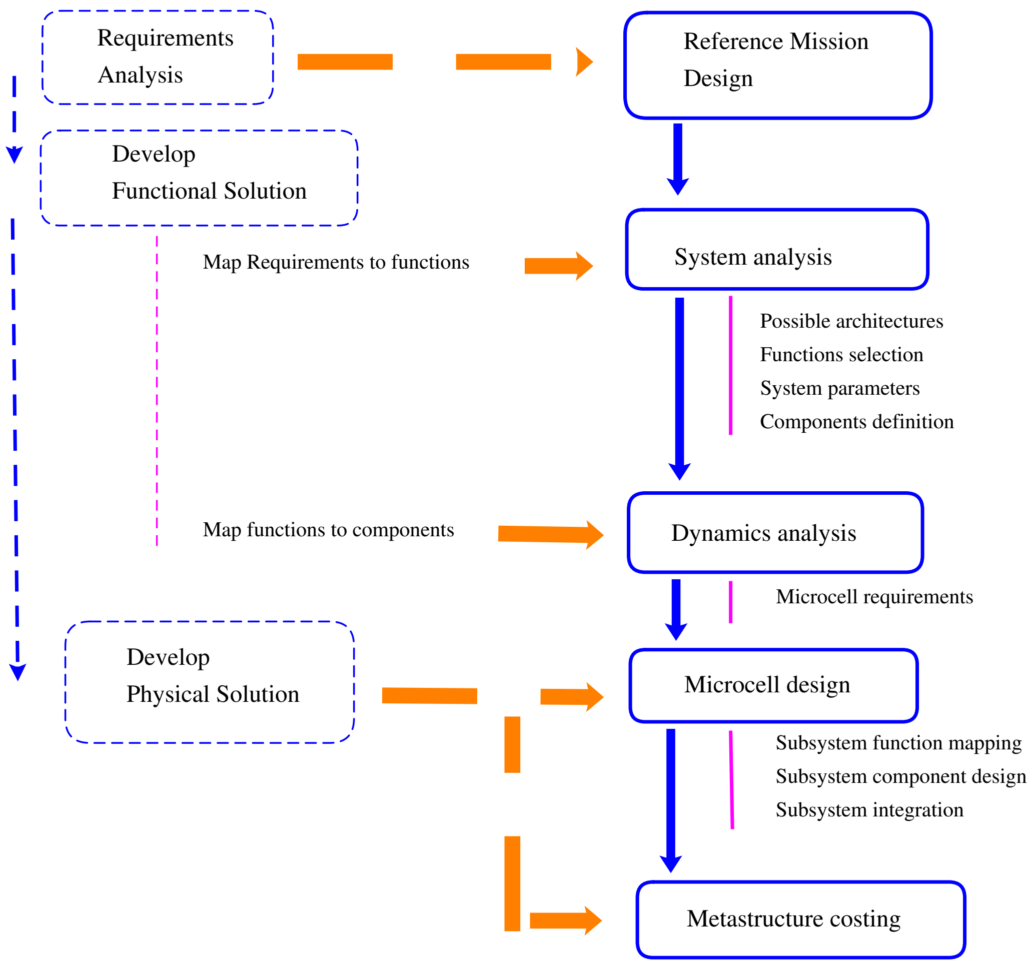


Figure 5.5: Adapted System engineering process for metastructures. The requirements analysis is done upstream as part of the mission analysis. The functional solution is developed through system and dynamics analysis, whilst the physical solution is based on microcell design and metastructure costing. The system baseline is assembled in concept assessment.

5.5 Costing process for metastructures

The final data used by the strategy analysis is a costing assessment of metastructures. Costing of space systems has become a increasingly sophisticated activity given the reduction in budgets and the need to know costs more accurately [NASA, 2002]. Typically these methods are:

Bottom-up: In this method all the components and tasks are broken down into independent units that are then costed individually and assembled to make the system cost. This usually produces the largest estimates.

Top-down: The reverse from the method above, this assigns a maximum cost for the system or mission and aims to break it down between subsystems in a fair and realistic manner.

Analogy The mission is recognised to be similar to a previously costed one.

Parametric Some top-level mission parameters are defined and a reference mission is costed. Then all other missions are estimated based on the variation of these top-level parameters.

These however usually address costing of space missions for which the technical baseline is known, and relies on available or nearly-available components. It is not possible to use this for metastructures or other new concepts. That is why some research has gone into developing methods for costing technology programs [Hazelrigg, 1991], different from the ones used to cost operational programs. These methods involve:

- Defining a series of milestones for the technology programs, quantifying significant and identifiable progress made in the field thanks to the specified research program.
- Break these milestones into activities which are then quantified, and if necessary expressed according to specific parameters.
- Run sensitivity analyses on the results to take into account the uncertainty present in all R&D programs.

In the case of metastructure both methods need to be applied. Indeed, before operational missions that use the concept can be flown, there needs to be a large technology base in place. This calls for an R&D-style costing. Once this is done it is then possible to define a parametric-style costing to apply to the reference missions. By combining these two processes the true cost of metastructures and their missions can be estimated. This is illustrated on Figure 5.6.

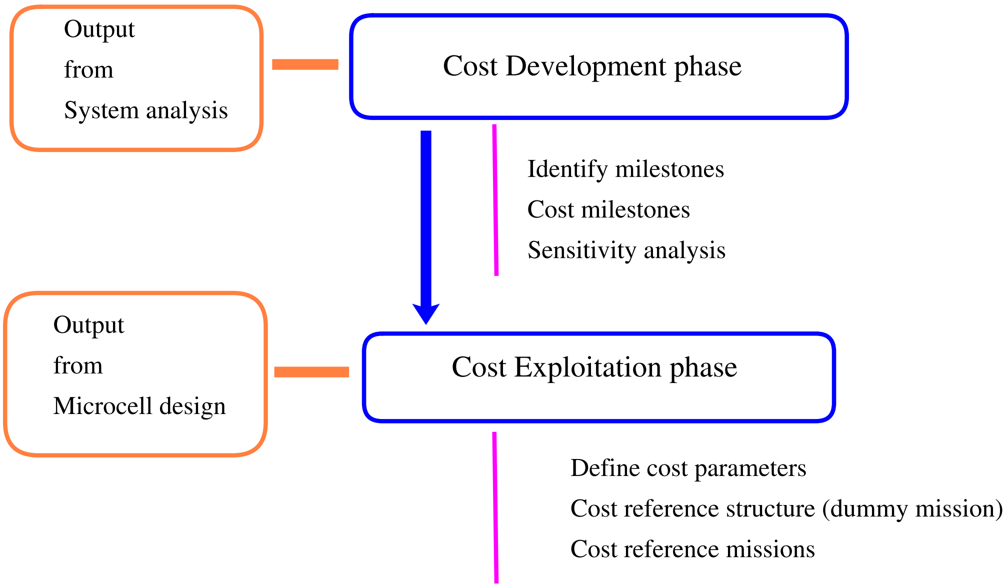


Figure 5.6: Costing process for metastructures, involving development phase and operational phase. The development phase is costed as an R&D programme, whilst the exploitation phase is costed in parametric fashion based on a reference mission.

Chapter 6

Applications analysis results

Summary

Metastructures are best used as large and free-floating space structures. Applications thus include long wavelength instruments, large reflectors, distributed array antennas, or SmarTethers. Of these possible missions two are selected for further investigation. The first one is a centimetric interferometer for either astronomical or Earth Observation purposes. It needs to be able to change its shape to modify the baseline. The second one is a reflector/deflector as part of a Lunar Space Power System. For this one the main need is the maintenance of 3D shape and attitude. These two missions are studied in detail in the next chapters.

6.1 Range of applications

As a new technical concept, metastructures are suitable for a specific range of space applications. An analysis is conducted to identify them.

It has been previously argued that metastructures cannot bear large loads, nor can they deploy very rapidly, but they are lightweight and large and they can create curved surfaces (see Chapter 2). These facts obviously define the range of applications. Metastructures in general are not interesting for structures where optimisation of well-known techniques is possible. This applies in particular to "small" systems from 1 to 10 metres long, the size of usual space structure up to date. For these, a passive structure is often good enough, like thin-gridded reflectors or panel-based structures. As for active systems, techniques exist or are in development already, like smart structures. This was discussed in Chapter 4. So only for larger dimensions (over 100 metres) may current technologies not be adequate. Metastructures can then be interesting from this size upwards. As for the upper limit, it is dependent on the maximum possible mass considered. This in turn depends on the in-orbit assembly strategy. In a single launch it is possible to deploy about a 300 m square metastructure (C1[1]). So the efficient size range is considered to be 100 m to 300 m per side for a square structure. Larger structures either need larger launch masses (which maybe available in the long-term considered), in-orbit assembly techniques, or to have less populated patterns (see section 7.2.2).

By their nature metastructures are articulated mechanisms and do not act as load-bearing structures. One could consider an extension of the concept, where the links and the shape can be "locked-up", with a magnetic bearing for instance (see Figure 6.1). Such a concept is too complex to implement at this stage, as it involves switching in and out of rigid and flexible body motion modes for the structure. So metastructures are considered free-floating rather than load-bearing.

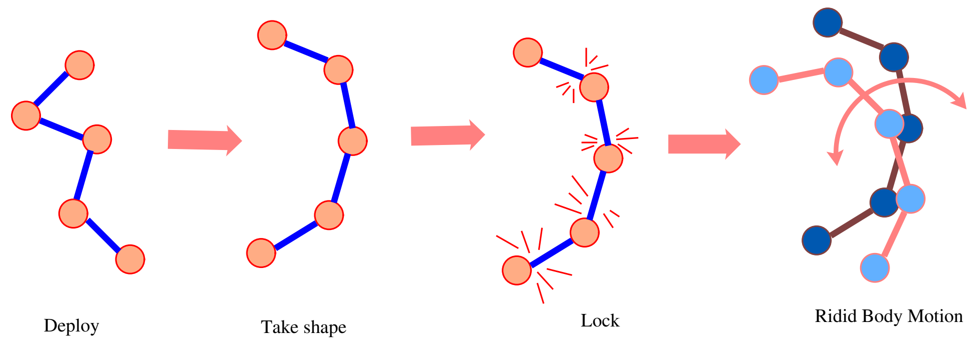


Figure 6.1: An extension of the concept is possible, where links can be "locked-up". This means the structure becomes a single body from the point of view of motion.

The main feature of this new concept, though, is really that non-flat surface shapes are possible, and so is reconfiguration of these shapes. This is the primary interest of it. Other concepts exist, but they have other problems which make the metastructures worthy of consideration as seen in Chapter 2. This is where new applications can be proposed.

Finally, metastructures can not really be deployed fast. Indeed, the system analysis shows that semi-passive deployment from the stowed configuration is used (see Chapter 7). It can take from a few hours to a few days. There are not many space systems, however, that require much higher speed at this stage of operations, so this is not a critical problem.

Having defined the pros and cons of the system, it is now possible to explore the useful applications. Then one can select some of these to be evaluated in detail, the so-called reference missions. Space applications are usually categorised in Communications, Earth Observation and Science, and Space Infrastructure (see Chapter 5). Applications in each of these fields are explored next.

[1] *Cx* refers to detailed calculations in Appendix A, see section 1.3.

6.2 Communications applications

The general trend in space communications is towards higher and higher transmission frequencies [G. Maral and M. Bousquet, 2002a]. Antennas on-board GEO satellites get bigger and bigger, up to 12 m in 2002 [Scott, 2002]. But in general they have requirements on shape stability which will be wavelength-dependent. That makes the metastructures not really interesting in this case, given the very high frequencies and conversely the very small wavelength (λ=10 mm at 30 GHz in Ka-band for instance).

However there are other interesting missions. For once, some applications use lower frequencies, like Search and Rescue, or even military communications in some cases. These usually use VHF or UHF signals (so a wavelength of several decimetres up to 10 metres). In particular Sparagna [1967] proposes a radio-wave antenna in low or medium Earth orbit that is used as an interferometer to help monitor ground-based signals. This application is considered in detail as a reference mission, given its similarity with another, scientific application (see next section).

Equally, it may be possible to create metastructures that make very long filar antennas as relays from the probes of outer space. In that case the interest of the large structure is that it may create much wider antenna far-field patterns for reception of signals from deep space, which can be interesting for communication with interplanetary probes. (see Figure 6.2).

Finally, GEO systems may eventually evolve into so-called “Megacomms”, where the concept of array antennas [G. Maral and M. Bousquet, 2002b] is extended to an extreme. This system is not wholly defined yet as it is in early phases of research [M. Snelling and J. McCall, 2001]. The concept, as seen in Figure 6.2 looks very much like a metastructure. It is unclear from previous analysis what the number and spacing of microcells is (from 400 to 1200 and from 0.25 to 1 m [Quaggiato, 2002]), depending on the power requested by the particular communication application. This makes it not so mature for detailed analysis.

Whilst communication missions relay data from the ground, Observation and Scientific missions use similar electromagnetic spectrum sensing technologies, but relay data from the external environment instead.These are studied next.

6.3 Observation and science applications

Scientific instruments make up indeed a significant number of space missions. Many instruments launched in Earth or Lagrange orbit are in fact optical or IR sensors, with characteristics similar to telecomms sensors, and wavelength typically expressed in μms. So the same is true of most of these instruments regarding the requirements on dimensional stability.

However, there is now an interest among astronomers to explore some less well explored parts of the spectrum, in particular at low frequencies [N.E. Kim and

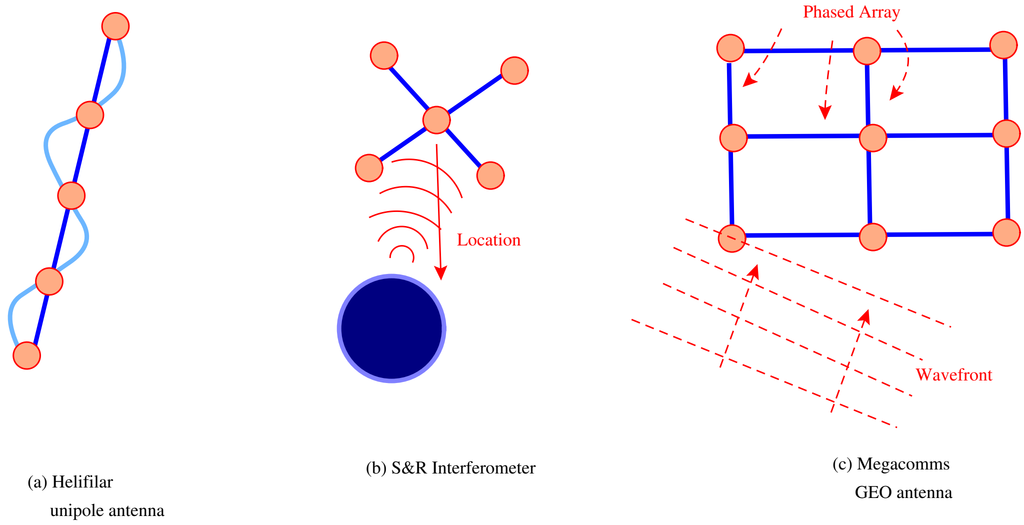


Figure 6.2: Telecomms applications. The most interesting and defined is a Search and Rescue interferometer (b).

K. Weiler, 1990]. A centimetric space-based interferometer, in particular, can be interesting for the study of long wavelengths, which so far have not been studied as extensively as short ones. There is at least one mission proposed for this by Jones [1998]. This mission is selected to be examined in detail.

One other applications of interest for metastructures is that of distributed environmental sensing, illustrated in Figure 6.3. This type of application is an extension of the tether missions proposed for atmospheric sensing [M.L. Cosmo and E.C. Lorenzini, 1997b]. A long 1D or 2D metastructure can be used to host many individual sensors for domain mapping, either in atmosphere (density, composition sensing), in deep space (magnetic fields, etc..), or even on the ground. This metastructure includes environmental and position sensors. If requested it can also use active microcells to control the position.

This type of application is related to the deployment of large structures in space, which is also useful for the next type of space missions considered, known as Space Infrastructure.

6.4 Space Infrastructure applications

These applications cover space systems that are used either to extend the human presence in space (such as space stations) or for operation of specific systems in space, like asteroid mining, solar power etc... Some metastructures may be useful for these missions.

One type of application can be in creating large surface-like structures, flat or curved. Typically, a reflector can be built of many different shapes using the discrete positioning of microcells, and adding a lightweight very thin cover on top of the system. This is illustrated on Figure 6.4. One specific example is for an add-on reflector in so-called Solar Power systems [Erb, 1991]. These proposed systems which collect Solar energy from space would benefit from a light collector, either to illuminate the solar cells when in Earth shadow, or to concentrate more energy on the cells. One other possibility is to use flat metastructures as large solar panels, if the thin film cover can be made as a solar cell substrate.

Another type of application in space infrastructure is as a so-called "Smart-

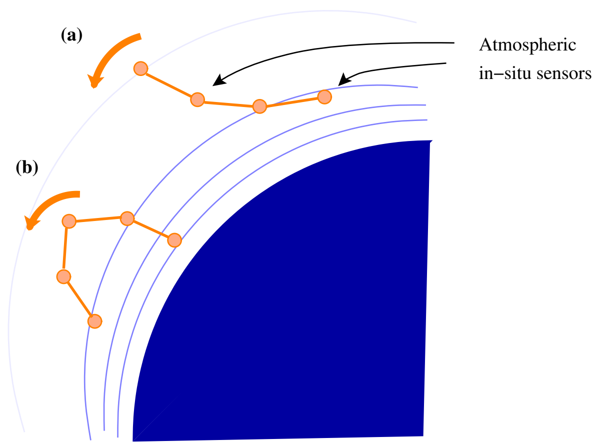


Figure 6.3: A scientific application of metastructures as a distributed planetary sensor. (a) tether-like - (b) shape controlled

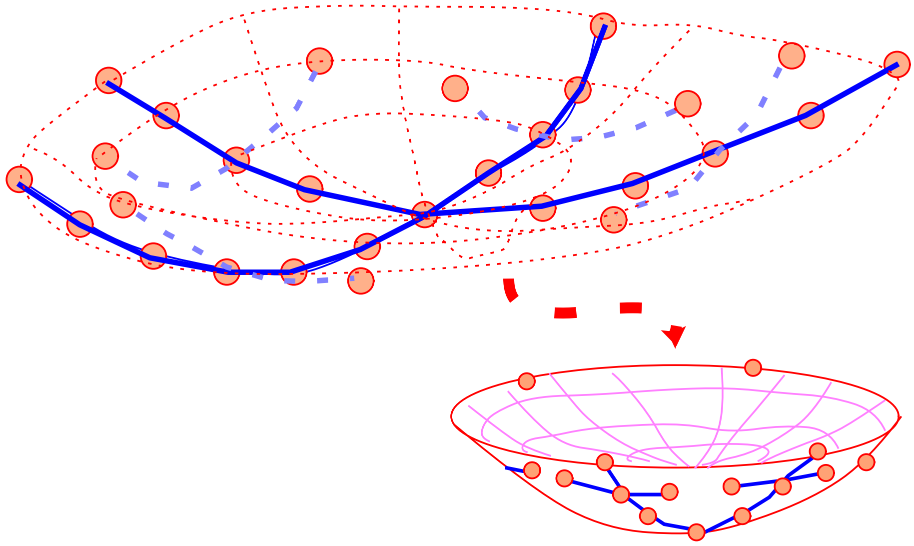


Figure 6.4: A metastructure can take the shape of a curved reflector by using non-flat patterns. By adding a solid cover it can make a reflector.

Tether" [Lecuyot, 2000]. This is a 1D space tether that can control its shape. Such a system can be made to form closed shapes for instance, from which other structures can be deployed. They can also be used as "intelligent cables", i.e. where systems are deployed that need harness, the use of a SmarTether can prevent entanglement and collision (see Figure 6.5).

Finally, a more long-term and unusual application of metastructures can be in Space Art. Indeed, if metastructures can be made to make large shapes in space, then some aesthetic effects can be obtained when viewed from the Earth (see Figure 6.5). For instance a 5 km structure in a 500 km orbit creates a object of .5 degrees field of view in the sky, and can have passes a few minutes long (similar to ISS or Shuttle passes).

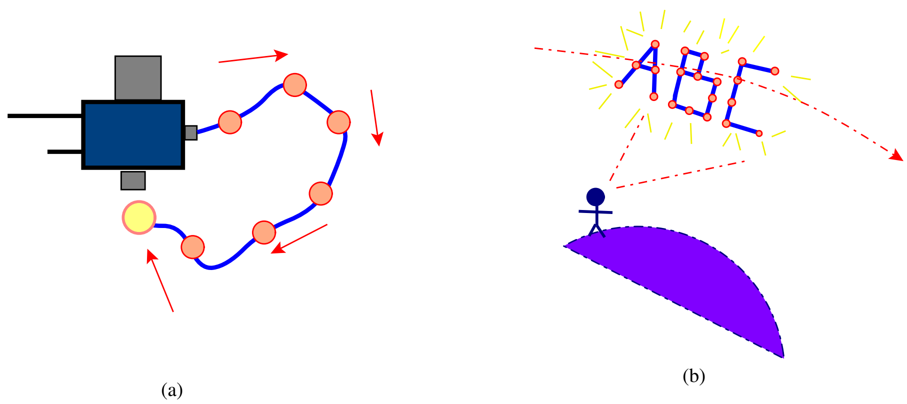


Figure 6.5: Space Infrastructure applications of metastructures. Smartether (a) and Space Art (b).

One can see that there are potentially different interesting applications to metastructures. As it is not practical to conduct detailed analysis for all of them, two reference missions are selected against which the concept will be evaluated. The selection of these missions is somewhat subjective, but it aims to include typical applications. In all cases, the concept is also evaluated as a whole in the discussion. These missions are detailed below.

6.5 Reference: Centimetric Interferometer

As seen above, there is an interest for long wavelength space-based interferometers. Two main applications are retained. One is a "science" application for scanning of these signals in the sky. The other is a "Telecomms" application for Search and Rescue or even military surveillance of radio emissions. The mission developed here will be considered for both uses. The configuration of this interferometer is shown on Figure 6.6.

6.5.1 Mission objectives

This interferometer should be able to be used both pointed skywards (for radio astronomy) and Earthwards (for planetary radio detection or imagery), although not during the same mission. To be interesting over other alternatives, it should be more advantageous to operate than a formation flying based interferometer. The operating wavelength should be radio waves (both for study of large waves astronomy, and for radio monitoring of targets on planetary surfaces).

6.5.2 Mission Needs

Only the space segment needs are considered, and in these only the requirements relevant to the metastructure.

6.5.2.1 Performance

Using a two-sensor baseline for interferometry allows to obtain a better *resolution*. One considers using several sensors, to also obtain increased *sensitivity*. Therefore the basic configuration is that of a 32×32 sensor array in the Mills-Cross configuration, as in Figure 6.6 and detailed elsewhere [R. Wohlleben et al., 1991a]. The minimum operating wavelength is $\lambda = 50$ cm, at UHF frequency. An interesting angular resolution for this mission (C2) is $\upsilon = 10$ arcsec [R. Wohlleben et al., 1991b]. Therefore the interferometer total baseline is

$$D_{Max} = \frac{\lambda}{\upsilon} = 10.3\ km.$$

This baseline varies from $D = D_{Max}$ to $D = \frac{D_{Max}}{10}$ to realise the interferometric scanning. From this are derived the main performance needs of the mission (C3).

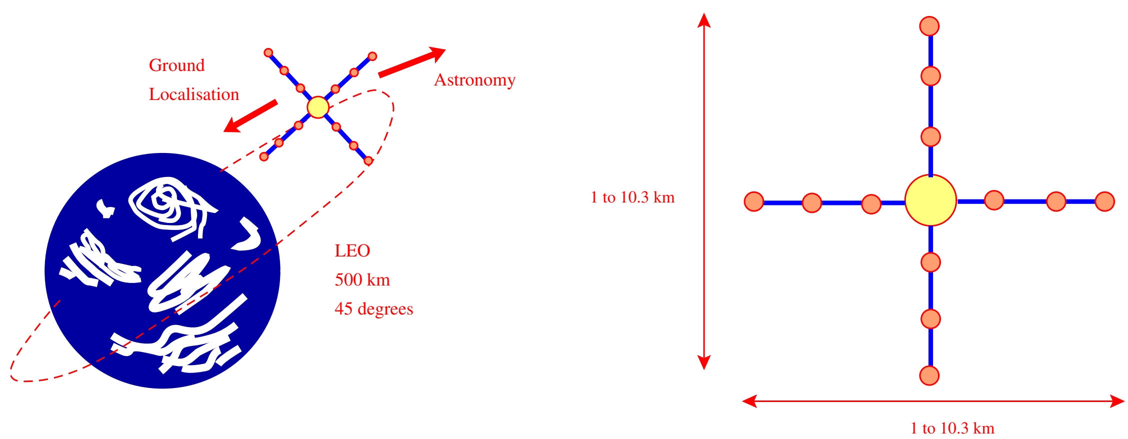


Figure 6.6: Configuration of the Centimetric Interferometer. It is in fact a cross with 4×16 sensors along the metastructure and a central hub.

6.5.2.2 Operational

A 500 km altitude circular orbit is selected for good resolution (see above). Given that the major disturbing force acting on microcells will be differential gravity, second order effects dependant on orbit angles (such as inclination) and Earth oblateness are not taken into account. The lifetime should be 5 years. The configuration is such that a hub spacecraft contains all Service Module functions and centralises the science data from the interferometers. The operation of scientific instruments is decoupled from the spacecraft and service module. The interferometers to be accommodated are defined as reflectors of 1.5 m diameter that are passive from a space dynamics point of view, and have no interaction with the metastructure. These mirrors should maintain their pointing within a few arcmin of their nominal angle, knowing that they will have their own pointing mechanism. Finally, the central hub can have a service part responsible for some orbit-keeping functions, and also commanding the metastructure to change shape.

6.5.2.3 Constraints

The main constraint on the mission is that it should be as attractive as the alternatives, in particular in terms of cost.

6.5.3 Mission concept

The only aspect of mission concept that is relevant to the metastructure design is the complete decoupling between the spacecraft functions (including the deployment) and the science functions. So it is assumed that the interferometer sensors communicate via wireless with the central hub, as opposed to using the metastructure to run cables for instance. The baseline of the interferometer itself is varied by changing the position of the structure into an “accordion-type” structure and reprogramming the micro-cells reference positions so as to obtain the correct spacing (see Figure 6.7).

6.5.4 Alternative Mission Architectures

There are various possible mission architectures possible. The first is a formation flying interferometer. The second is a very large smart structure. And the third is the meta-structure. During the concept evaluation, these architectures will be compared.

6.5.5 System Drivers

The primary driver is the baseline variation performance, i.e. the ability of the metastructure to fulfill the mission, and also the degree to which the operation of the metastructure is “transparent” to the operation of the orbital interferometer. Also, the actual design is of importance as to whether it is likely to resist disturbances and failure modes.

6.5.6 Mission summary

A summary of the mission parameters is on table 6.1.

Mission & Operations	
Configuration	32 × 32 Mills-Cross array (with central hub)
Orbit	LEO 500 km 45 degrees
Lifetime	5 years
Science Instrument	
Baseline	from 1.03 km to 10.30 km
Interface	Decoupled from TMS
Performance	
Baseline accuracy	50 cm
Angular resolution	10 arcsec
Sensor alignment accuracy	1-5 arcmin

Table 6.1: Centimetric interferometer summary of mission parameters.

6.5.7 Mission Characterisation and Evaluation

For this particular mission, what is to be characterised is the peculiar type of control used, i.e. moving cells laterally as seen on Figure 6.7. It is interesting to quantify

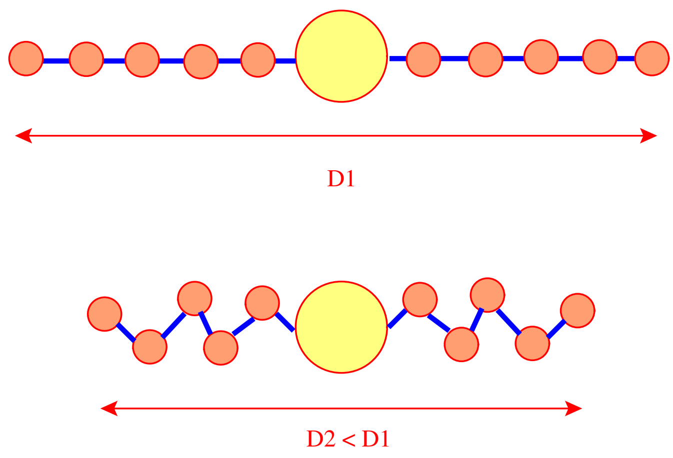


Figure 6.7: Changing Interferometer baseline is done by varying the microcells reference position.

the behaviour of this system depending for instance on the total baseline and the boundary conditions. The main evaluation parameter here is the ability to maintain position.

6.6 Reference: Solar/Lunar Reflector

The second mission chosen is more related to the use of metastructures as large "pseudo-continuous" structures in space. The need for large structures in space is perhaps illustrated best by the various large-scale projects proposed to provide global Solar power to the Earth [Glaser, 1997]. The power is gathered in space through large collectors and transferred down to Earth using microwave beams. One such proposal uses Lunar-based distributed collectors instead to form large microwave beams in space [Criswell, 1998]. These are then collected by so-called "rectennas"[2] on Earth, which are microwave flat receivers. But the Lunar Solar Power system can not always maintain permanent power supply, due to relative motion of the Earth and the Moon. To solve this and increase the efficiency of the system, large orbital reflectors are proposed in this system (see Figure 6.8). The suitability of metastructures as such reflectors is investigated in this reference mission.

6.6.1 Mission Objectives

There are in fact two types of reflectors needed; Lunar reflectors and Earth deflectors. Lunar reflectors are simply large Moon-orbiting flat panels. They focus sunlight to the photoelectric generators on the surface to increase incoming Solar flux. Earth deflectors, on the other hand, are parabolic-shaped surfaces in Medium Earth Orbit. They collect the microwave beams and focus them to the reception area on the ground. This is illustrated on Figure 6.8. Both are considered here.

6.6.2 Mission Needs

The mission needs are mainly derived from available literature [Criswell, 1998, 2000a].

6.6.2.1 Performance

Lunar Reflector The Lunar reflector's main performance requirement is to reflect sunlight to the collecting areas during night or eclipses. The reflector is not focused on one specific power base, but rather rotates so that it can distribute its power to different bases. If many reflectors are used on phased orbits, this can increase the efficiency of the system. So the surface needs to be about 1000x1000 m [Criswell, 2000b].

[2] Term used by Criswell [1998]

Earth Deflector The main issue about the deflector is pointing. Indeed, the beam needs to be focused on the rectennas on the Earth. An accuracy of 5 arcsecs is required [Criswell, 2000c], which is excessively small for such a large structure. A simple calculation (C4) shows that if a significant portion of the structure is maintained within about 1 arcmin of the target this should improve the system already. The size of such reflectors should be between 500x500 m and 2000x2000 m [Criswell, 2000c]. A 1000 m square is considered, with one side being a parabolic reflector.

6.6.2.2 Operational

Lunar Reflector The orbit of the reflect or depends on the illumination time requested, as the higher the Moon orbit the longer time will be spent in view of Sunlight, as shown on Figure 6.9. "A few minutes" is required quantitatively per individual reflector [Criswell, 2000a] . This translates into angular velocities needed for each orbit through simple trigonometry as seen on Table 6.2, which show constant rotation rates. The minimum circular orbit is thus 1000 km, but a height of 2000 km appears a good compromise and is selected.

It is difficult to specify other operational parameters without an in-depth analysis

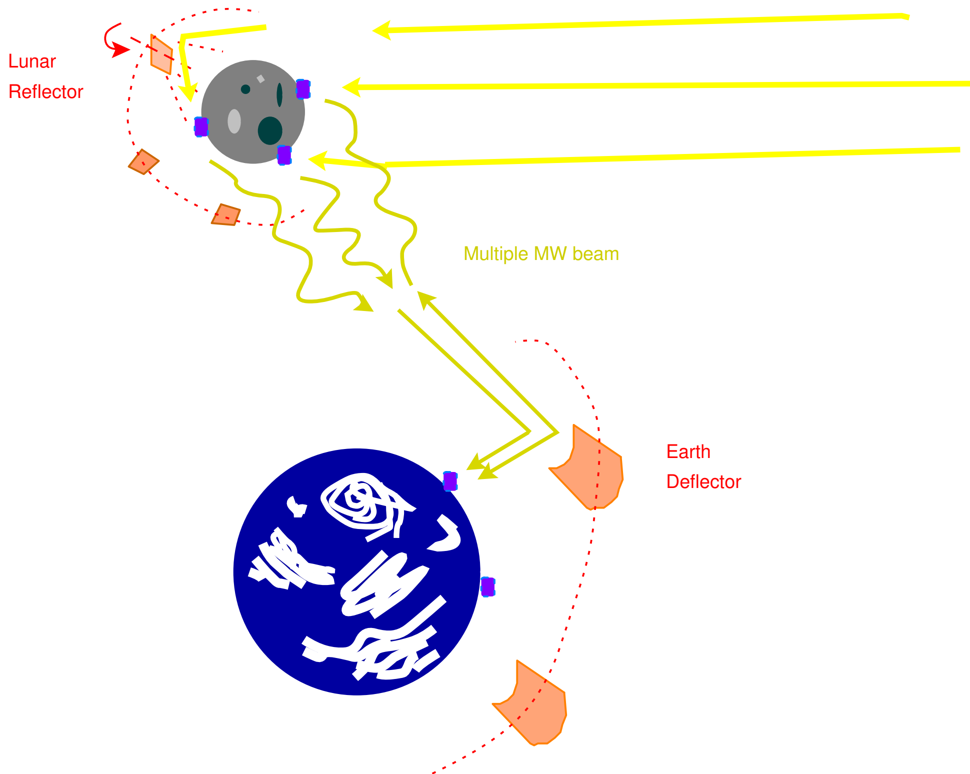


Figure 6.8: Large structure components of the Lunar Power System

of the system. The system is deployed from the Moon, so that relaxes requirements on maximum mass. A lifetime of at least 5 years is required. Deployment time is not an issue here.

Earth Deflector The maximum orbit height specified for the deflector is a 6000 km circular [Criswell, 2000c], retained here as a baseline. The deflector itself has the shape of a parabolic reflector. Considering the definition of this type of antenna and the focal length (see figure 6.10) the nodes of the metastructure should follow the relation :

$$x^2 = 24,000 \times (6,000 - z)$$

x being the local horizontal and z the zenith axis. This corresponds actually to the axisymmetric parabola, which is not strictly the case here as seen on Figure 6.10.

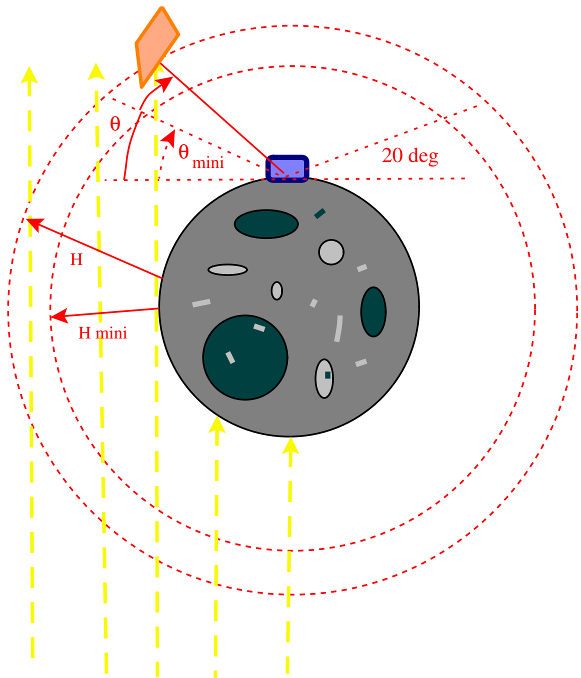


Figure 6.9: Lunar reflector Sun exposure angle θ for a specific lunar orbit height H.

H, km	1000	2000	5000
θ, deg	22	51	74
$t_{Sunlight}$, mins	1	2.5	105
Rot. rate, deg/min	0.5	1	0.5

Table 6.2: Lunar reflector rotation rate based on the time of sunlight, for various lunar orbit heights H

However the derivation of the exact equation of a parabolic reflector is not simple. So this equation will serve as a first approximation. In terms of lifetime, the same comments applies here as for the reflector.

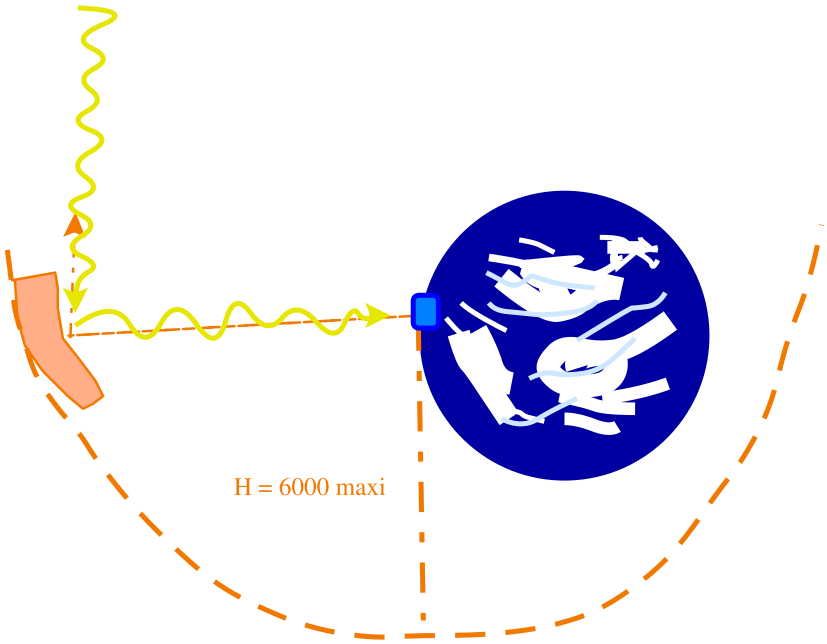


Figure 6.10: The deflectors are parabolic antennas whose focus point is the rectenna array on the Earth.

6.6.2.3 Constraints

Lunar Reflector The constraints on the Lunar concept is that it has to be made from material available on the Moon.

Earth Deflector In principle, the deflector can be made either on the Moon or on the Earth. It could be interesting to compare the production and launch prices in each case, but a detailed analysis is out of the scope of this work.

6.6.3 Mission concept

For both options the mission concept is relatively simple. The structures are launched and automatically deployed in their orbit, and then maintain their position or pointing. Communication with the ground is limited to transmitting status. When pointing is not maintained the control centre can switch off the emitters on the Moon to avoid transmitting the power away from the rectennas on the Earth.

6.6.4 Alternative architectures

Alternatives to these reflectors include those discussed in the general alternatives to metastructures (see Chapter 4). These are inflatables, mechanisms and smart structures.

6.6.5 System Drivers

For the Lunar reflector, the system driver is whether the rotation rate can be achieved, which is the main technical issue and should define the size of micro-cells. Global operation cost is also important, and in particular the Lunar-based construction.

As regards the Earth deflector, the system driver will be whether some acceptable pointing accuracy can be achieved, and how that impacts the total power transmission.

6.6.6 Mission Summary

The missions parameters are summarised below on table 6.3.

Lunar Reflector	
Size	1000x1000 m
Shape	Flat
Orbit(Lunar)	2000 km
Operation	Spinning at 1 deg/min
Lifetime	5 years
Earth Deflector	
Size	1000x1000 m
Shape	Parabola F=6000 km
Orbit (Earth)	6000 km max
Pointing	1 arcmin (or 5 arcsec)
Lifetime	5 years

Table 6.3: Lunar Solar Power reflector and deflector summary of mission parameters

6.6.7 Mission Characterisation and Evaluation

An interesting result of the detailed analysis for this mission will be whether a metastructure of this size is still manageable. Of course, the accuracy of position and attitude is also quite relevant. Having found out about the scale issue, the evaluation will be made on the changes to the system that using metastructure implies.

Chapter 7

System analysis results

Summary

Metastructures studied in this work use microtechnology-based nodes called microcells, passive rigid links and decentralised controllers. To reduce the distributed control problem, a single thrust simple controller is used which is compared to others by analogy. As for microcells they share many features with Nanosatellites, but their critical components are local sensors, global sensors, and micropropulsion actuators. The main performance parameter is the total mass for a given lifetime, which depends on individual cell parameters (physical and functional), and on the distributed control algorithm performance.

7.1 Concept definition

A space metastructure is an active structure, that can also be part of a wider space system. It is itself defined as a distributed system, composed of active and passive nodes which are structurally linked (see Figure 7.1).

7.1.1 Architecture

The system architecture is as seen in Figure 7.2. Further precise definitions of the terms used thereafter are also found in section 1.1.1.

7.1.2 Rationale

This concept is interesting for space missions where a large geometrical structure is needed, such as a giant antenna, Sunshield, or reflector, as described in Chapter 2. Its comes from the increased functional requirements put on space structures. It is interesting because it can be built from many simple elements, providing the global and distributed system behaviour is correct. Other advantages are an increased

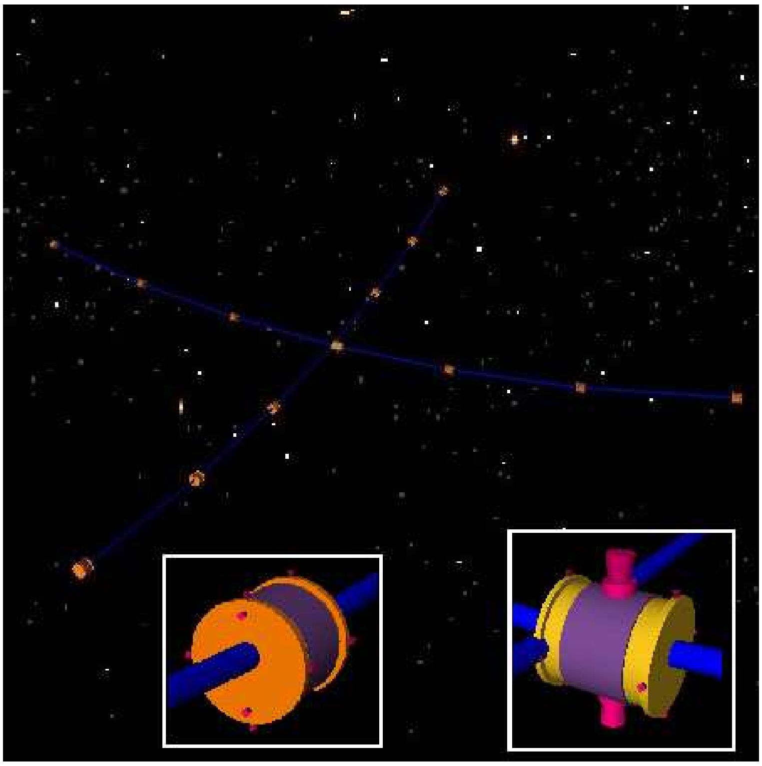


Figure 7.1: Conceptual view of a metastructure as a distributed system. It is made of links and different types of cells, and is a self-standing system.

reliability, graceful degradation, and design flexibility. All these are relevant to space structures, who must be automatic, and whose non-recurrent design costs are significant.

The implementation of this concept depends on the size of the structure considered. For metre-class sizes the nodes clearly have to be embedded inside a passive spacecraft structure. But for larger ones it becomes possible to use individual nodes which are self-contained micro-machines - or *microcells* - possessing many attributes of a nanosatellite. Given the amount of research performed on these, as reviewed in Chapter 3, it is now worthwhile evaluating metastructures with sizes of tens or hundreds of metres which use microcells for active nodes.

A more detailed argument is presented in Chapter 2 on the complete rationale for metastructures. For now the focus is on defining and analysing the concept in more detail.

7.1.3 Reference metastructure

The reference metastructure is defined for preliminary sizing calculations as a coherent set of parameters, to be used as basis for comparison. It is distinct from the reference missions. The reference structure characteristics are illustrated on Figure 7.3. This structure has the following features:

- Nodes are made of micro-cells. These cells are considered to be about 50x50x50 mm in size.
- There are two types of cells, global and local as detailed in section 7.3.
- Links are passive rigid rods articulated at their junction with micro-cells.
- Configuration is that of a 1m x 1m pattern deployed in the orbital plane in a 100x100 m structure.
- Cells use the pattern L-L-G (two locals for one global) for each branch with four branch, hence the pattern is 8l-1G.
- The assembly is considered in a 2D 1000 km altitude Earth orbit.

This initial description calls for more detailed analysis of properties of metastructure components. First the system architecture needs to be defined. Then the cells and links have to be sized accordingly, to define them in terms of technology and hardware needs. This is detailed in the next sections.

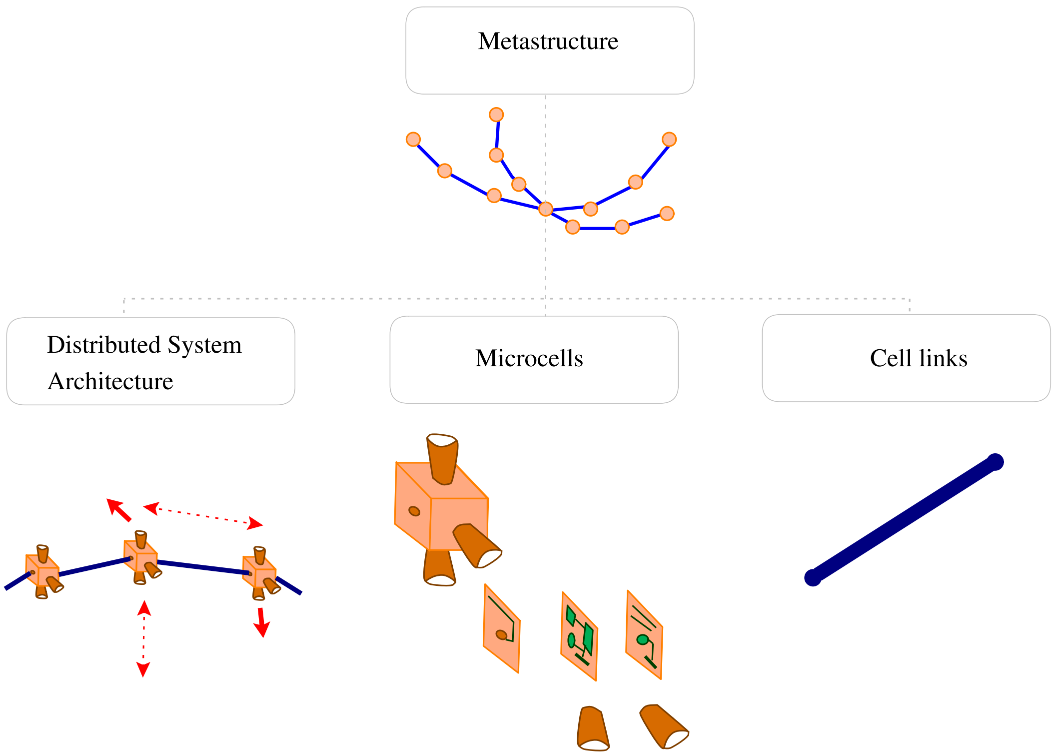


Figure 7.2: Metastructure system architecture, including several components that are distributed control, microcells nodes, and links.

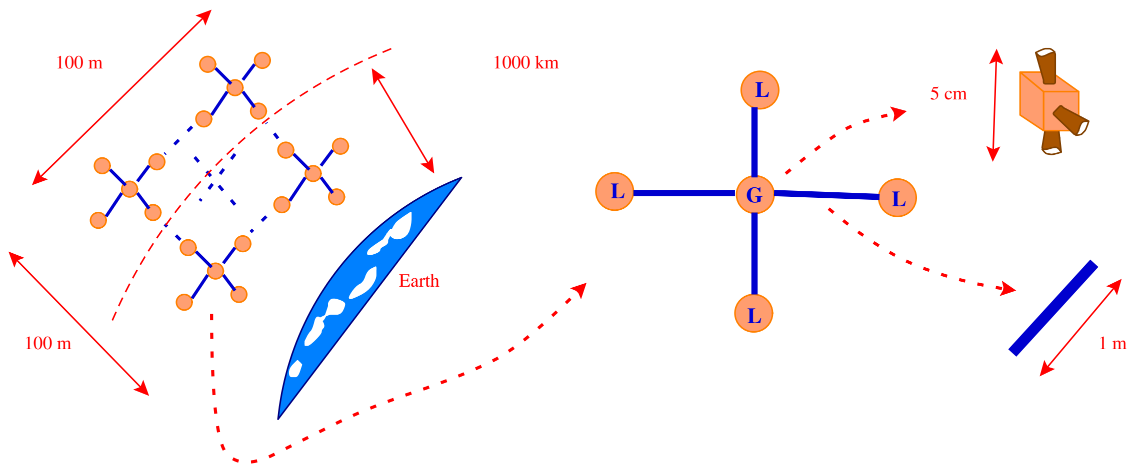


Figure 7.3: The reference structure defined to be used for generic analysis purposes. It is distinct from the reference mission.

7.2 Distributed System Architecture

Ultimately, the performance of a metastructure will depend upon the individual capacities of the low-level components, i.e. the cells and their subsystems. But it is also necessary to define a so-called distributed system architecture, which specifies how the cells are physically and functionally laid out and related. This addresses the physical configuration and cell pattern of the metastructure. The functional configuration, on the other hand, is described in this case as a distributed control system, which needs to be considered. Lastly, the global mission perspective must be taken into account; one must consider how the system is deployed and operated.

7.2.1 Configuration

In principle a metastructure can be any system using physically linked nodes to create a controlled shape. But in Chapter 2 the scope has been reduced to exclude so-called "smart structures", embedded or distributed parameter systems. Also excluded are systems that use a central controller (see above section 7.1.2). So the definition can be refined as a system composed of individual but connected nodes that interact in a decentralised fashion to create a controlled shape. For space systems, there are a number of ways in which this can be achieved, with different applications. These options are identified below, nicknamed after their typical features.

"Tent" That can be applied to smaller structures. The nodes are essentially active out-of-plane with respect to the structure's principal plane. When a cover is used, to create a reflector-like structure for instance, this is similar to a tensioned sheet. Figure 7.4 illustrates the concept.

"Snake" In this configuration the nodes are micromechanical articulations in a daisy chain pattern that changes shape by changing angular positions. This kind of metastructure can potentially achieve any kind of practical shape for a 3D line. A conceptual snake is shown on Figure 7.5.

"Net" This configuration is one of the simplest metastructures. It consists of a grid of active microcells linked together by cables or tethers. These links allow the structure to stay together, whilst the microcells control their precise relative position in a way similar to spacecraft flying in close formation. The concept is illustrated on Figure 7.6.

"Winch" A variant of the above, this uses microcells that can change the length between them along one axis. This can prevent problems happening with tethered structures going out of tension and becoming unstable. An example is shown on Figure 7.7.

"Rigid Net" Another variant from the "Net" concept is one where the links are actually rigid. These are articulated rods. The cells then control their relative position only in terms of angular position. The concept is shown on Figure 7.8.

Active links Ultimately, the links between the nodes can become active as well, and realise near-continuous local shape control, whilst the cells control the global position (see Figure 7.9).

Now, in general, the "tent" concept is akin to a smart structure. This type of system exists already for terrestrial telescopes, and is being studied and developed for use in space (see Chapter 2). So it is not studied further in this research.

The "snake" configuration can be interesting for applications where complex shapes are needed. For instance, a cable bearing a moving payload at one end can change its shape and not get entangled (see Figure 6.4 in chapter 6). However it needs very small and integrated micromachines which, at the moment are not foreseeable for space systems.

The "Net" type of metastructure appears to be a relatively simple concept to implement. Indeed, the microcells in that case are very similar to nanosatellite platforms, and the links are simple tethers. The difficulty of this concept lies in the dynamics analysis and control. Whilst it can be valid in some cases, it may not be suitable for situations where continuous precise control is required.

To solve this problem of slack tethers, the "winch" concept presents a variable tether length. For current tether applications, cables in space are controlled by tuning the cable tension and deployment/retrieval rate. If that is applied to this concept with many tethers, it can stabilise the system.But whilst such control on the tether length is practical on one axis, it is unclear this can be directly extended to two axes control. In addition, this means the microcells effectively include some sort of winch, which complicates the microsystem design.

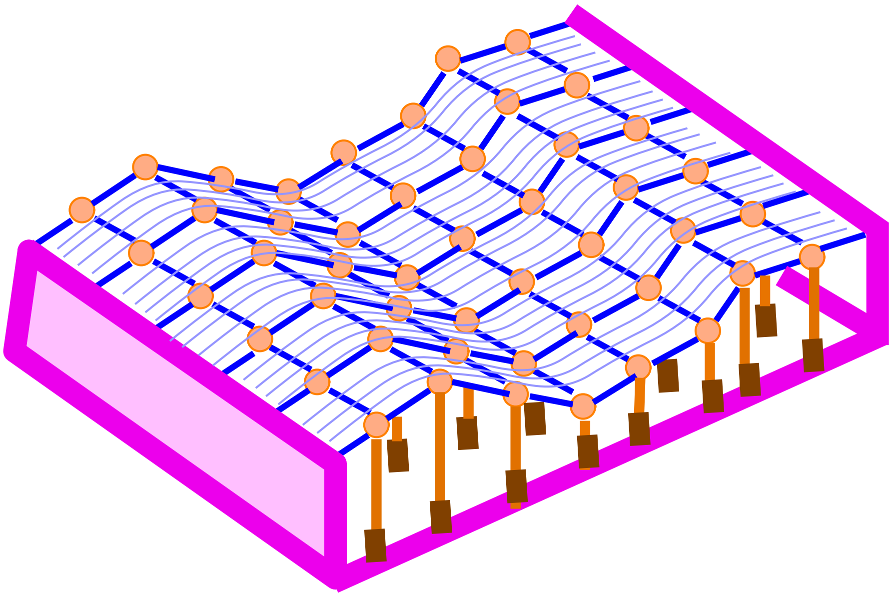


Figure 7.4: The "Tent" configuration using out-of-plane actuators and part of a larger structure .

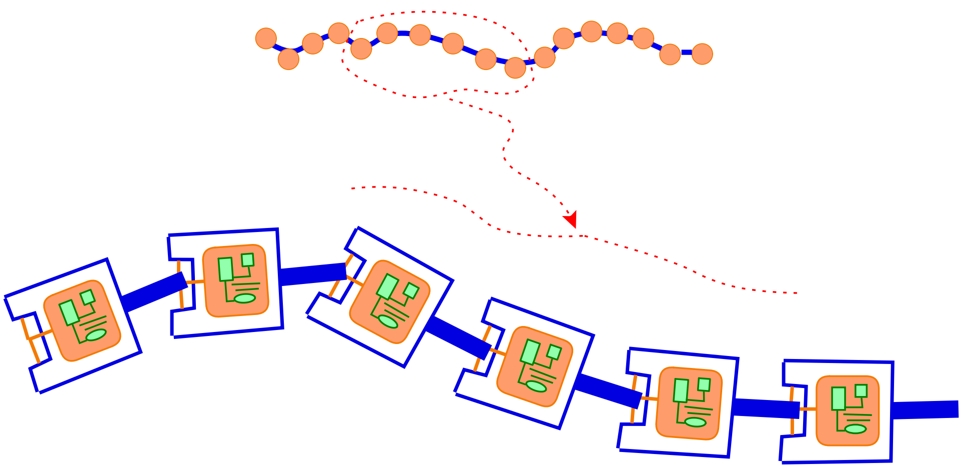


Figure 7.5: The "Snake" configuration. It is made of a chain of microactuators and is only applicable to 1D structures.

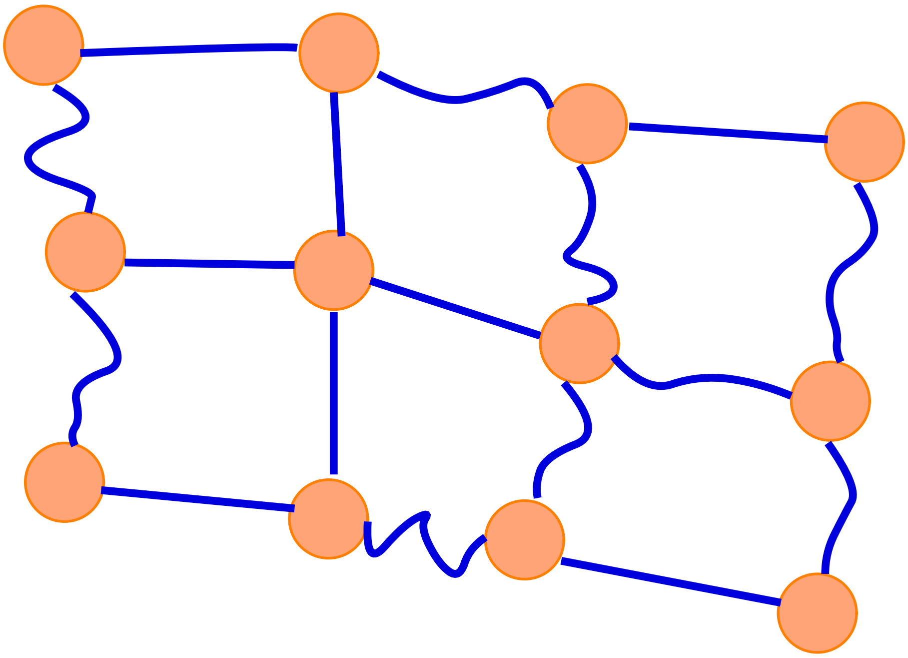


Figure 7.6: The "Net" configuration. It uses cables or tethers to link the cells.

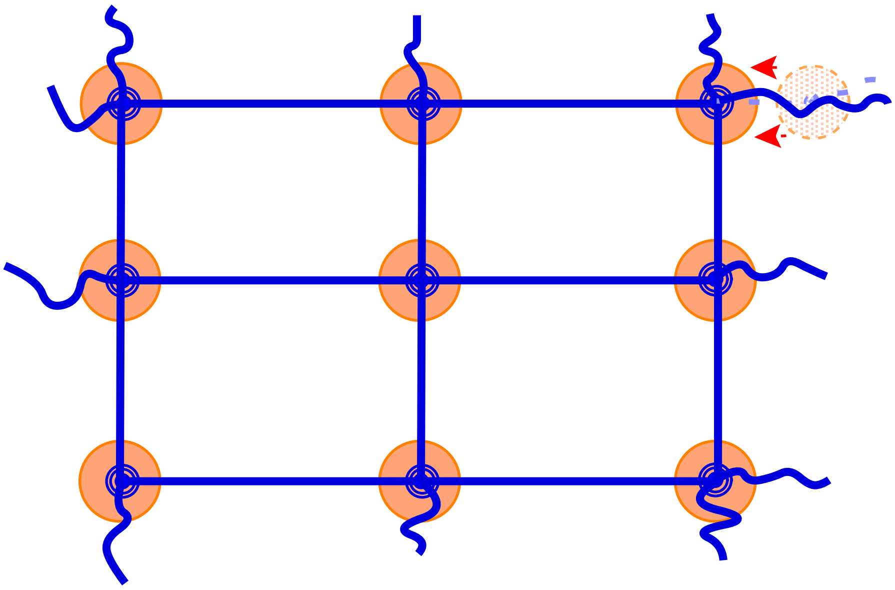


Figure 7.7: The "Winch" configuration. It adds stability by being able to control the cable lengths and tension.

The "rigid net" configuration makes for a simple and stable system when the links are made rigid. In this case the microcells need only control angular positioning with respect to one another. For this option there is a need for articulated rods, but that can be made completely passive.

Finally, an extended version of a metastructure is one where the links themselves are active components and can change shape. This is, however, out of the scope of the current work, as this means that smart structure technology is so mature that is can be miniaturised. Also the global structure behaviour in that case is much more complex than with rigid rods.

In summary, a top-level trade-off of all possible system configurations is shown on Table 7.1 for comparison. From this table one can see that there are several interesting alternatives. In the course of this research the focus is on medium to long term concepts, using technology that is foreseen currently. Therefore the snake and active link concepts are discarded on their being too far ahead. The tent idea is not a really novel idea, so it is dropped too.

In conclusion, the research will focus on net-like metastructure, with a preference for rigid links. The scope of the research does not allow to investigate in detail a concept based on winch-like microcells. So the general configuration of the metastructures considered here is that of a series of microcells linked by passive but rigid rods. The repeating pattern of these can then be studied in more detail.

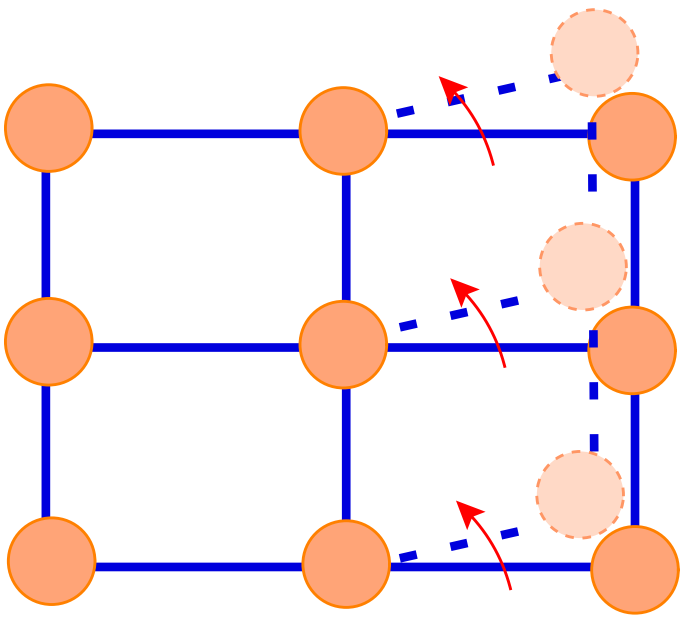


Figure 7.8: The "Rigid Net" configuration. It is the simplest of all large metastructure designs.

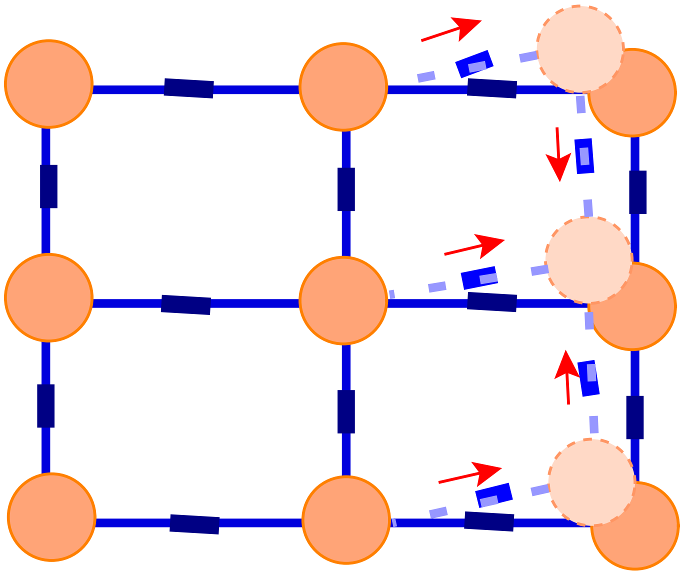


Figure 7.9: The active links configuration. It introduces actuators and sensors in the link themselves for more precise control.

Concept	Applications	Control	Microcells	Links	Comments
Tent	small structures	smart structure	actuators	covering structure	already studied
Snake	large reconfigurables and robots	normal	nano-machines	complicated	too futuristic
Net	large deployables	tether control level	nanosat platform	tether in tension	tether tension issue
Winch	large deployables	complicated	platform and winch	tethers	global control
Rigid Net	large deployables	simpler	nanosat platform	hinged rods	only issue is folding
Active links	all	not developed	global only	shape changing	too many challenges

Table 7.1: Metastructure configuration trade-off

7.2.2 Cell patterns

An adequate representation of a metastructure is that of a grid or matrix pattern which defines the nodes and the links. This is illustrated on Figure 7.10. The figure also illustrates the way chosen to describe the matrix.

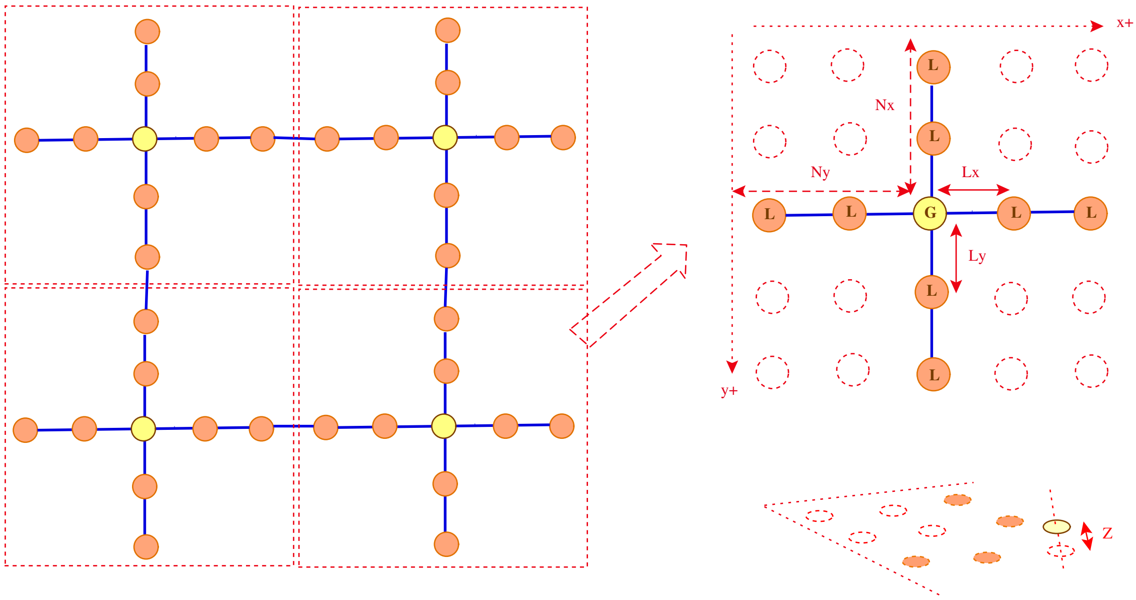


Figure 7.10: Expression of cell patterns. A metastructure matrix includes a repetition of elementary patterns which in turn are composed of local and global cells at specific matrix locations, with possibly non-flat elevations and non-equal link length.

It is defined as a $N \times M$ matrix of repeating patterns, the pattern being itself a $Nx \times Ny$ matrix. Nx and Ny are the maximum size of the pattern, but within that pattern not all elements may include a cell. So for each element of the pattern matrix, one must specify whether there is a cell and what type it is (see below). Equally, the physical length between the cells do not have to be all equal, and thus must be specified individually as Lx and Ly. However all analyses in this work have considered equal length cells.

Finally the matrix is specified in two dimensions but the surface can be curved in three dimensional shape, so an elevation Z is specified for each cell based on a reference plane. To summarise, a cell in a cell matrix is characterised by:

- The position in the matrix, Nx and Ny.
- The length of forward-looking links Lx and Ly, if applicable.
- the cell elevation, Z.

- The cell type. Typically this can be *P*ayload (P-cells) or *S*ervice (S-cells). P-cells are cells which typically contain sensing elements used for the mission. S-cells are used to control the shape of the metastructure, and can further be classified as *L*ocal or *G*lobal cells. L-cells are related to control relative to other cells, whilst G-cells are related to absolute control of the metastructure in the mission reference frame.

Different type of cells are needed mostly because of technology constraints. Indeed, in theory it is possible to use cells which can both be used to fulfill the mission and control the shape of the structure. Also it could be argued that all cells can have global sensing capacities. This depends on the integration of the cells, and how much functions can be packed into a microcell of reasonable size using advanced micro and nano technologies. One goal of this research being to characterise the sensibility of the metastructures concept to the microcells design, it is appropriate to simulate the system for different type of cells as defined above. It is possible to consider that all cells are global and payload, or that payload and service cells must be separated, or even that service cells must be separated between local and global cells. The implications of using different types of cells are detailed below.

Global cells If all cells have the ability to maintain position in the inertial (i.e. fixed) frame they are all global. The metastructure is then very similar to a distributed control system as researched in control theory, with the particularity of being physically linked. But technologically, it may be difficult to propose systems where all elements have the global capacity. Indeed, in many formation flying techniques and missions proposed there is a rationale for using local control (see Chapter 3), in our case local cells. That is why these are also considered.

Local and Payload cells Local cells can only control their situation with respect to their neighbour. This means the detectors do not have to be as sophisticated. On the downside, since local cells are relating to one another in a daisy chain manner there are errors accumulating as seen in Figure 7.11. That is why "one-way" control algorithms may not be adequate in this case, which influences the distributed control algorithm.

Finally, for communication systems such as Megacomms antennas (see section 6.2), it may be necessary to use payload cells, which would for instance be active microwave elements that would have no capacity for sensing or maintaining position. These have to be controlled by local or global cells.

7.2.3 Distributed control

For metastructures, distributed control is understood as a set of discrete decoupled plant controllers as seen in Figure 7.12 and in section 1.1.1. In addition to this, cells are controlled according to a pattern which allows cumulative errors. The issue is then what happens at pattern repetition interfaces, and what type of controller must be used for each type cells.

As regards the pattern interface, it is left out of this work as a potential source of instability. However, because the system is composed of a number of articulations, errors should be limited.

As regards the individual cell controllers, there are several alternatives (as seen in Chapter 2):

- Linear or non-linear parallel individual controllers such as On/Off controllers, PI controllers, PID controllers etc...
- Smart structures controller,
- Specifically designed control laws for distributed systems.

A simple On-Off controller is selected here as a first implementation (see section 8.3).

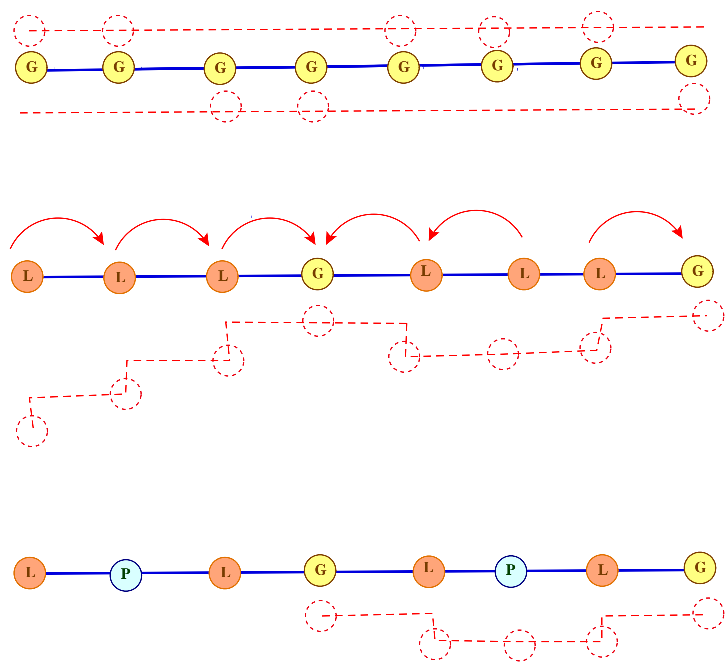


Figure 7.11: Using Local and Payload cells will impact the distributed control system by accumulating errors. Given that all cells will have errors, and that local reference points are based on next-in-line (cells that also have position errors), these errors in positioning between local cells are additive. That is why including global cells is necessary at regular intervals in the pattern.

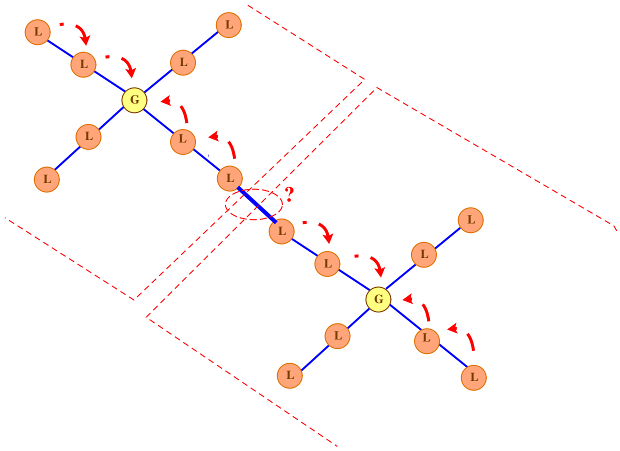


Figure 7.12: Distributed control depends on inter-pattern interface and individual cell control.

7.2.4 Deployment and operations

The main advantage of metastructures being their robustness, the deployment has to be passive or fault-proof to avoid negating this advantage by introducing a single-point failure at a potential deployment mechanism. So the cells are assumed to be folded and piled up in the launcher fairing. An initial impulsion can be given to "open" the metastructure. Then gravity gradient may be used to deploy the system in the same manner as tethers. For instance, the reference metastructure may deploy in about 9 hours (C5). There is also the need for a re-configuration mode in addition to the normal mode. Indeed, by changing the reference point of some or all of the cells it is normally possible to create a new shape in space. So for individual cells the operation modes are:

- **Launch** or idle mode
- **Deployment mode:** This is characterised by a different control mode, mostly passive, which monitors and corrects the deployment.
- **Normal mode:** This is the operational mode using the distributed controller.
- **Reconfiguration mode:** This ensures the transition from previous normal mode to a new normal mode.

Finally, the distributed control system depends on the technical capacities of the microcell nodes. These are described next.

7.3 Microcell nodes

7.3.1 Functions of microcell nodes

The current work is focused on considering nodes as microcells, i.e. MST-based micromachines. The main function of these microcells is to maintain position, whether absolute for global ones or relative for local ones. To do this they must have sensors, actuators, and also provide support functions, such as power supply, data handling, and structural support. So they appear very similar to Nanosatellites as seen in Chapter 3.

The design of actuators and sensors depends on the possibilities of microcells to provide support functions. The reference metastructure can provide 1.5 W (C6), which compares to the power used by micro-fabricated sensors and actuators (see references in Chapter 3). For data handling and computing, integrated systems can be designed that include the sensors, actuators and associated electronics, using ever-increasing miniaturisation. This impacts the design of microcells, but the key technical issues are in finding miniature sensors and actuators that can detect and maintain the position. More detail on microcell design is provided in Chapter 10.

7.3.2 Actuators

For the current work, propellant-based actuators alone are considered as other alternatives are impractical (see section 7.2.1). A practical configuration is one where the 3 translational degrees of freedom are controlled (and not the 3 rotational ones, as opposed to standard spacecraft 3-axis control). Indeed, microtechnology allows a configuration where 2 degrees of freedom can be controlled by thrusters placed at many angles in one plane, and an additional degree of freedom is controlled by adding the corresponding out-of-plane thruster. This is as seen in the Figure 7.13. This is reflected in the detailed microcell design (see section 10.3.1). Under these conditions, the critical parameter for this subsystem is really the amount of propellant necessary for a given lifetime.

7.3.3 Sensors

Because the metastructures are linked together rigidly, it is only necessary for local cells to sense in two directions. There are a number of ways in which this can be done as can be seen on Figure 7.14.

Mechanically, it is possible to include angular sensors in the revolute joints between microcells and links. Alternatively, it is also possible to use optical targeting, or microwave scanning. If passive methods are not possible, it may be possible to use micro-mirrors or antennas to find the reference micro-cell.

As for global cells, for Earth orbit cells it may be possible to use ultra-miniaturised satellite navigation receivers. For other cases or for high orbits it may be necessary to use local or global attitude and position sensors.

7.4 Node linking

This work focuses on passive rigid links. In general it is possible to define the links in possible regimes when modelled as structural rods:

Cable In this case the rod has no compression resistance. This corresponds to the "Net" configuration of the metastructure.

Flexible The rod has compression and bending resistance, but the distortion caused by the forces it experiences is larger than the minimum error considered.

Rigid The rod resistance is such that for the forces considered the deformations due to bending are negligible.

A proposition is made below in Table 7.2 to quantify these three regimes based on the mechanics of material.

Type of link	Behaviour	Limit equation
	Buckling	$P = 0.210 \times \pi^2 \times \frac{EI}{l^2}$
	Bending	$y = \frac{Pl^3}{3EI}$
	Rigid	-

Table 7.2: Possible type of passive links and associated limit equation depending on the load P. The limit between bending and rigid is used to size the links when assembling the system baseline.

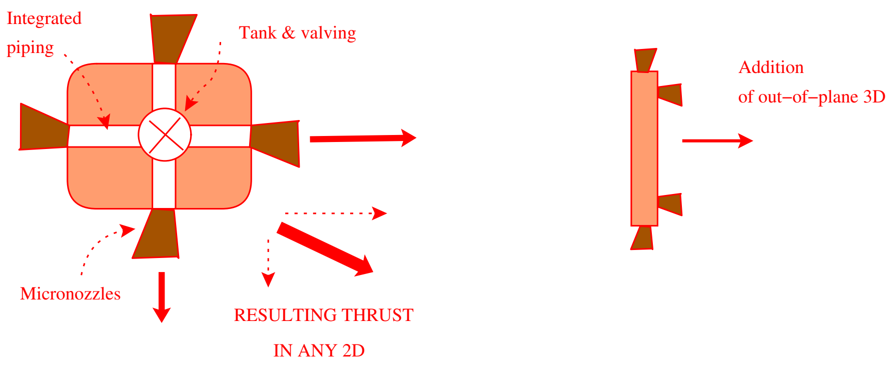


Figure 7.13: Integrated micro-propulsion systems can provide 3 degrees of freedom translational position control

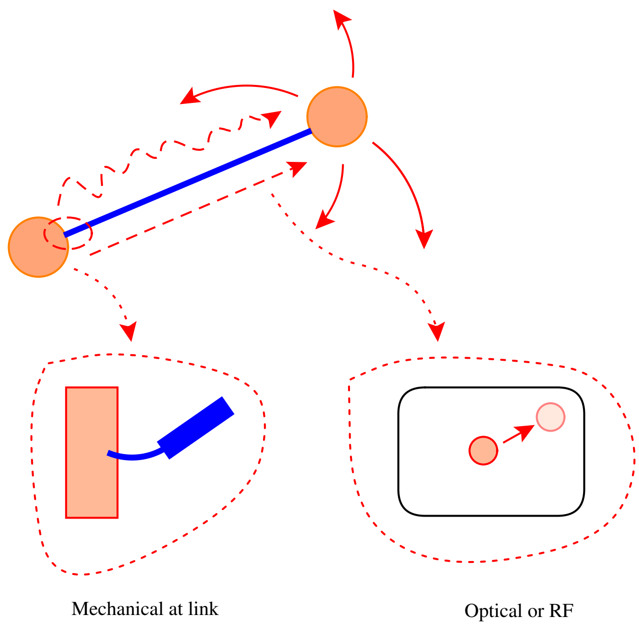


Figure 7.14: Position sensing can be done mechanically or remotely between microcells

The other point of importance for links is their attachment interface to the microcells. It is proposed to limit the rotation to only one side of the microcells (as seen in Figure 7.15) as the thrusters of the microcells need to be oriented correctly for position correction.

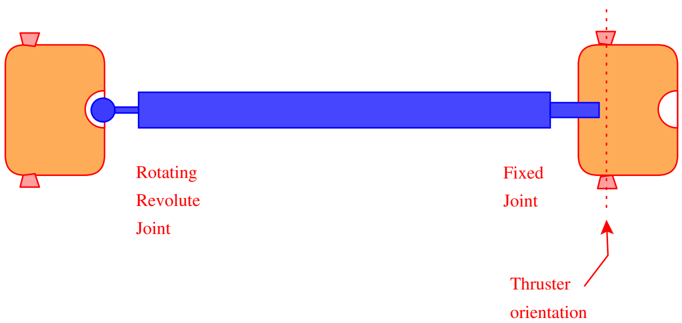


Figure 7.15: Attachment of links to microcells. Links are free to rotate at one end, and fixed the microcell at the other. This maintains an overall revolute joint at each microcell from a kinematic point of view, whilst allowing the thrusters of the cell to be correctly oriented.

Finally the material and shape for the links depend on the particular case, but in general they can be circular sections, made of carbon-based materials, i.e. Nanotubes composites for instance. If necessary the links can be used to transport electric signals between microcells.

So having examined all the components, it is now possible to describe the system parameters used in assessing metastructure designs.

7.5 System parameters

To summarise the system features are described, and the overall system design and performance parameters are listed.

7.5.1 System features

The features of the metastructure system considered for detailed dynamics analysis and subsystem design can be summarised as:

- Rigid links fixed at one end, and free at the other, realising a revolute joint at each attachment to a microcell.
- Active local and global microcells. Local microcells refer to their next or previous in line, horizontally or vertically. Global microcells refer to a reference point in the local co-ordinate frame, which is derived from a reference point in the global frame (for instance by orbitography techniques).
- On-Off single thrust controllers, such that the thrust has a fixed value but can be oriented in several directions in the plane perpendicular to link attachment, and also have a fixed value in the link direction.

7.5.2 System design and performance parameters

The system parameters include the specifications, and the performance parameters. Specifications parameters are defined for the system, the cells, and the links:

- **System**
  - Orbit and gravity environment for the centre of mass
  - System pattern, and how the local patterns are repeated
  - Local pattern and shape, including dimensions
- **Cell**
  - Cell type, including control law parameters
  - Mass and Size
  - Thrust

- **Link**
  - Shape
  - Dimensions
  - Material (i.e. density)

Performance parameters are also defined for the system, the cells, and the links.

- **System**
  - Overall Root Mean Square (RMS) position error e_p over reference, calculated as
    $$e_p(structure) = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{M}(\mathbf{R_{i,j}} - Ref_{i,j})^2}$$
    with $Ref_{i,j}$ either next-in-line neighbour or absolute reference for local and global cells respectively.
  - Total mass for a given lifetime
- **Cell**
  - Maximum positioning error
- **Link**
  - None

The range of system parameters to be examined for the reference missions is shown on Table 7.3. They are derived from the mission analysis in Chapter 6 and the technology review in Chapter 3. The values achieved for performance parameters is to be derived from the dynamics and subsystem analyses in the next chapters.

Parameter	Range
Central Body	Earth (E) and Moon (M)
Circular Orbit height (km)	6,000 (E) and 500 (M)
System patterns	from one to ten, linear repetition
Cell type and parameters	Local, Global, basic parameter e_{max}
Cell and link mass (g)	10-500 g
Cell thrust (n)	10^{-4} to 10^{-2}

Table 7.3: Range of system parameter values to be simulated with the two reference missions.

Chapter 8

Simulation Method for linked controllers

Summary

Linked controllers in space are modelled essentially as rigid tethers, using a Newtonian formulation. The difference between metastructures and tethers is that when it comes to tension calculation, the matrix equations describing the norms of tension vectors are more complicated and non-diagonal. Also, all nodes of metastructures can have controllers, not just the end nodes. These controllers here are simple On-Off fixed thrust designs depending on error and position vectors and using switching of the thrust vector. The method exposed is implemented using a dedicated software simulator described in the Appendix B.

8.1 Dynamics model

To explore metastructure dynamics it is first necessary to reduce the problem to a simplified model that can be simulated in the context of this work by taking reasonable assumptions. This model is then expressed mathematically as a numerical integration problem.

8.1.1 Problem reduction

The physical problem to model is that of the motion of several mobiles in the space environment, these mobiles being active by generating thrust, and also interdependent by being physically linked together. Similar classes of problems have been addressed in the study of the dynamics of tethered space systems (see Chapter 4). The features of the system under consideration are shown in section 7.5.2. The selected approach reduces the problem by considering simplifying assumptions:

Links are rigid: This is in fact not a simplifying hypothesis, but a consequence of the limitation of system design scope (see Chapter 7). The links considered in metastructures *are* rigid by definition. Thus all issues of slack and flexible tethers are not relevant here. The design of links to be considered rigid is detailed in sections 7.4 and 12.1.1. It involves sizing the links for a maximum tolerable displacement related to the microcell position accuracy required by the mission. As an example, a link between 0.5 kg cells and 1 m in length for a maximum displacement of 1 mm is rigid if it is a square section about 8.5 mm in width, with a link mass of about 0.5 kg as well (see Table 2.2 on p.22).

Joint are perfect: It is assumed that the revolute joints between the links and the nodes are perfect. This has two implications. First the rotations are free and there is no friction force. Second where two links attached to the same cell come close to one another, an unrealistic situation may occur where the links would "cross-over" each other. This would not happen in reality as no real revolute joint mechanism has a full solid rotation angle. This is illustrated on Figure 8.1. This is only a problem for uncontrolled dynamics in extreme disturbed state, which are of not practical interest for the study of metastructure dynamics.

Controllers are perfect and multi-directional: This means that the actual implementation of the control laws simulated is perfect. There are no time delays and no errors in measurement due to sensors and actuators inaccuracy. A very important feature is also that the thrust generated has two components; One which can be in any direction in the plane of the microcell perpendicular to the link, and the other one in the direction of the link. This reflects the design of the microcells (see section 10.3.1).

Environment is a Newtonian field: All perturbation forces of the space environment apart from pure first-order gravity are ignored. Effects of variation in gravity forces are neglected, as are atmospheric drag and solar pressure.

Nodes have same mass: All the nodes are considered to have the same mass to simplify the integration loops.

Orbits are circular: Tethered systems in elliptical orbits tend to have more complex dynamics. However, most practical applications of tethers rely on more stable circular orbits [M.L. Cosmo and E.C. Lorenzini, 1997a], and so do metastructures.

A discussion of the effects of these assumptions is discussed in Chapter 13. The points made above are illustrated on Figure 8.1. It is to note that some simulations of the reference metastructure (see section 7.1.3) are made in 2 dimensions only as they consider phenomenon taking place entirely in the orbital plane.

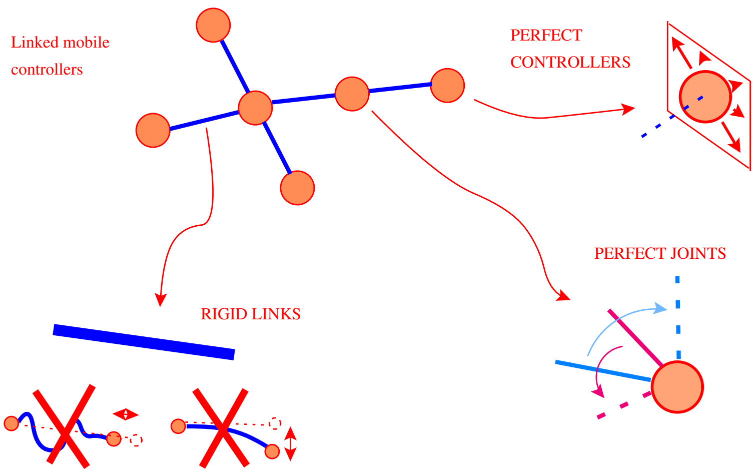


Figure 8.1: Simplifying assumptions used in modelling metastructures. These are mostly rigid links, total rotation angles, and in-plane multi-directional thrusters.

8.1.2 Mathematical approach

With these assumptions the problem is now reduced to the integration of a system of Newtonian equations of motions for a number of nodes $M \times N$, corresponding to the metastructure matrix dimensions. So the radius vectors $\mathbf{R_{i,j}}$ are propagated for each microcell i, j in the metastructure matrix, submitted to gravity potential (μ), to tension forces $\mathbf{T_k}$ for all the K links, and control forces $\mathbf{u_{i,j}}$, such that

$$\begin{aligned}
\mu\frac{\mathbf{R_{1,1}}}{R_{1,1}^3} + \sum_{k=1}^{k=K}(\alpha_{1,1,k}\cdot\mathbf{T_k}) + \mathbf{u_{1,1}} &= m\cdot\ddot{\mathbf{R}}_{\mathbf{1,1}} \\
&\vdots \\
\mu\frac{\mathbf{R_{i,j}}}{R_{i,j}^3} + \sum_{k=1}^{k=K}(\alpha_{i,j,k}\cdot\mathbf{T_k}) + \mathbf{u_{i,j}} &= m\cdot\ddot{\mathbf{R}}_{\mathbf{i,j}} \\
&\vdots \\
\mu\frac{\mathbf{R_{N,M}}}{R_{N,M}^3} + \sum_{k=1}^{k=K}(\alpha_{N,M,k}\cdot\mathbf{T_k}) + \mathbf{u_{N,M}} &= m\cdot\ddot{\mathbf{R}}_{\mathbf{N,M}}
\end{aligned}$$

for all nodes $(i, j) = (1, 1)$ to (N, M), with the value of $\alpha_{i,j,k}$ depending on the presence of a link and its orientation with respect to the microcell, such that

$$\alpha_{i,j,k} \in [0, -1, +1].$$

There are traditionally two ways to describe these dynamics problems, i.e. Newtonian and Lagrangian models. The Lagrangian formulation defines some generalised co-ordinates to analyse the system, which in this case would be the relative rotation angles of each of the cells. The motion of the system is then derived from the expression of the Lagrangian L, such that

$$L = T - V$$

with T and V kinetic and potential energy respectively. The Newtonian formulation, instead, uses frame coordinates of $\mathbf{R}$ as parameters, and solves the system created by writing the equations of motion for each node as described above.

The advantage of the Lagrangian formulation is that it may reduce the number of parameters needed to study a given system, and it allows to track directly interesting parameters such as the rotation angles of each link in this case. But the computation of the Lagrangian can involve many co-ordinate transformations. In the current case it means that the tension, control and gravity forces have to be transformed each time. For these reasons, the system is described using a simpler, Newtonian formulation.

Newtonian orbital simulations use a so-called inertial reference frame $\widehat{IJK}$, based on the central body centre of mass, in this case the Earth (or the Moon). However it is more practical to express the co-ordinates of the nodes in a local frame for processing of the results, and also for applying the relative control law between the nodes. This is illustrated on Figure 8.2, with the local frame defined such that:

- It is centered over the CoM (Centre of Mass) of the system,
- $\overrightarrow{x}$ is in the local vertical,
- $\overrightarrow{y}$ is perpendicular to $\overrightarrow{x}$ and along the velocity direction,
- $\overrightarrow{z}$ completes the frame.

Finally, the integration of these differential equations has to be numerical. Various integration techniques exist but the major ones integrate with respect to time step-wise (see section 8.4). So the mathematical logic chosen is to:

1. Start with initial (boundary) conditions of the problem in local frame.
2. Transform conditions in the inertial frame.
3. Compute gravity forces in inertial frame.
4. Compute control forces in local frame and transform back in inertial frame.
5. Compute tension forces in inertial frame.
6. Integrate the equations of motion for a time step h using a numerical integrator.

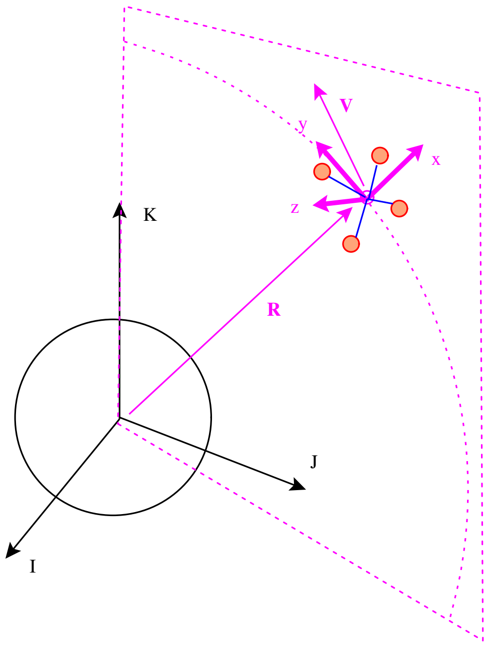


Figure 8.2: Local and Global co-ordinate frame definitions for Newtonian simulation. $\widehat{IJK}$ is the inertial global frame, whilst $\widehat{xyz}$ is the local frame relative to the CoM orbit.

7. Increment the current time by h and start at step 4 until the desired time is reached. Variable time step methods are not considered here due to the scope of the simulator development effort.

The forces to compute are control and tension, in that order, and in local and global frames respectively. The derivation of these forces is detailed in the next sections.

8.2 Tension derivation model

This model is an extension of a rigid tether model developed by Biesbroek, R and Crellin, E. [1999]. It differs when the matrix $[A]$ is derived (see below), which is a part of this work that is novel and specific to metastructures.

The model is based on a simple logic by starting from the basic assumption about rigid links that the distance between them is maintained, i.e. for two nodes of the matrix (i, j) and $(f, g) = (i, j) \pm 1$ linked,

$$|\mathbf{R_{i,j}} - \mathbf{R_{f,g}}| = Cst$$

the constant value Cst being the length of the nodes. By differentiating twice with respect to time and manipulating the equation it becomes

$$(\ddot{\mathbf{R}}_{\mathbf{i,j}} - \ddot{\mathbf{R}}_{\mathbf{f,g}}) \cdot (\mathbf{R}_{\mathbf{i,j}} - \mathbf{R}_{\mathbf{f,g}}) + (\dot{\mathbf{R}}_{\mathbf{i,j}} - \dot{\mathbf{R}}_{\mathbf{f,g}})^2 = 0$$

By replacing $\mathbf{R}_{\mathbf{i,j}}$ vectors in the above equation from the equation system in section 8.1.2, the results can be expressed (C7) as a matrix equation of the tension forces vector matrix $[T]$ such that

$$[A] \cdot [T] = [B]$$

with $[B]$ a vector matrix such that

$$B(k) = \sum_{(i,j)} (m \cdot \Delta\dot{\mathbf{R}}^2_{\mathbf{i,j}} - \Delta\mathbf{Fext}_{\mathbf{i,j}} \cdot \Delta\mathbf{R}_{\mathbf{i,j}})$$

the sum referring to all the nodes connected to the link k. It can be seen that $[B]$ represents the term related to the relative centrifugal forces of the linked nodes.

The other matrix $[A]$ is different from the one considered in the referred method. Indeed, in a tether model it is a diagonal matrix with non-zero terms only in (i,i), $(i-1,i)$ and $(i+1,i)$ as each node is connected with only two other nodes. For metastructures though, the terms are different, and the terms $A(i,j)$ can be expressed as

$$A(i,j) = \Delta\mathbf{R} \cdot \mathbf{a}_{\mathbf{i,j}}$$

which is a vectorial cross product, where $\Delta\mathbf{R} = \mathbf{R}_{\mathbf{i,j}} - \mathbf{R}_{\mathbf{f,g}}$, and $\mathbf{a}_{\mathbf{i,j}}$ is a unit vector or a null vector, and depends on the $\mathbf{e}_{\mathbf{i,j}}$ (Unit vector parallel to a tension vector at node (i,j)), which is itself the unit vector parallel to a tension vector at node (i,j). So $\mathbf{a}_{\mathbf{i,j}}$ is such that:

$$\mathbf{a}_{\mathbf{i,j}} = \sum_{(i,j)} (\alpha_{i,j} \cdot \mathbf{e}_{\mathbf{i,j}})$$

Indeed, for each link attached to the node (i,j) there is a specific $\mathbf{e}_{\mathbf{i,j}}$ as seen on Figure 8.3 with $\alpha_{i,j}$ coefficients such that

$$\begin{cases} \alpha_{i,j} = 0 & \text{if the nodes are not connected} \\ \alpha_{i,j} = +1 & \text{if the nodes are directly linked, i.e. rightwards or downwards} \\ \alpha_{i,j} = -1 & \text{if the nodes are indirectly linked, i.e. reverse from above.} \end{cases}$$

The $\mathbf{Fext}_{\mathbf{i,j}}$ are the sum of all other external forces, so they have to be computed before the tension. With this in mind the matrix equation can be solved using linear algebra, and the tension values found. This is the algorithm used for tension derivation.

8.3 On-Off controller model

In order to investigate minimal systems the simplest possible controller has been chosen, i.e. a fixed-thrust On-Off algorithm, as it is well known that the even simpler “Bang-Bang” controller can increase instability in standard dynamics.

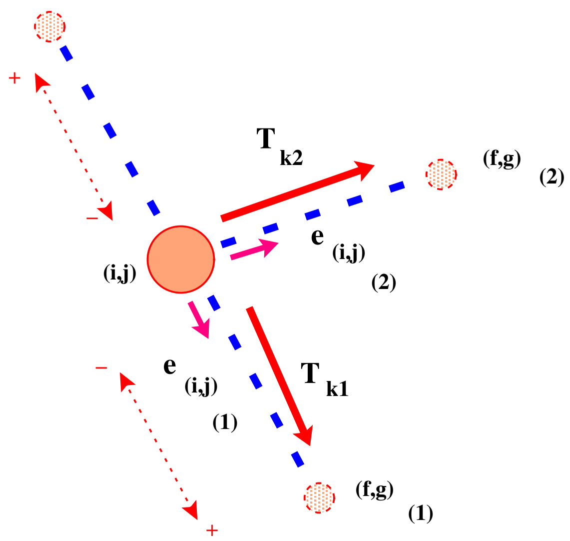


Figure 8.3: Derivation of tension matrix terms $A(i,j)$. The terms are based on the number and direction of links to which each node is connected.

On-Off controllers can only change the sign of the control signal, in this case the direction of the thrust, and only once in a given control sequence. An example of performance of an On-Off controller is shown on Figure 8.4.

The controller used here is derived from the textbook by Di Stefano [2003]. The basis for choice is simplicity of implementation, both in terms of actual simulation and in terms of nanosatellite design. So this controller has fixed thrust and uses a +1/-1 switch, the law of which being according to a phase plane derivation shown below.

This design is based on the fact that it can be demonstrated (and it is intuitively perceptible) that an on-off controller will be optimised if it only switches thrust direction once in a sequence. From this it then known that it is needed to solve the equation of the position error e_p such that:

$$\frac{de_p}{dt} = v$$

$$\frac{dv}{dt} = u(e_p, v)$$

with u the control function, being $+1$ or -1, and v the time derivative of the error. As it is known that the control is switched only once, the analysis uses properties of the phase plane starting from the instant where the switch is made, t. So between t and the time where $e_p = 0$ the behaviour of the (e_p, v) tuple is actually the integration of the equation above, which is a curve of equation

$$e_p = \pm\frac{v^2}{2}$$

depending on the quadrant in the phase plane of (e_p, v) as is seen in the Figure 8.5 below.

Therefore to finalise the switching control law one considers where the initial condition of the tuple (e_p, v) are with respect to each quarter of the phase plane and with respect to the switching curve. So the controller is defined such that:

- It relates to the position error e_p and the velocity error e_v defined as:

$$e_p = |\mathbf{R_{i,j}} - \mathbf{R_{i,j}ref}|$$

$$e_v = |\dot{\mathbf{R}}_{\mathbf{i,j}}|$$

- It uses design parameters of maximum position and velocity error e_{max} and v_{max}.

- Its algorithm provides the switching parameter α to apply to the thrust vector.

The thrust vector is recalled to be in the plane perpendicular to the link for the in-plane thrusters, and aligned with the link for the out-of-plane thrusters (see Figure 9.6 in Chapter 10). The switching parameter β, called the controller *deadband* is such that:

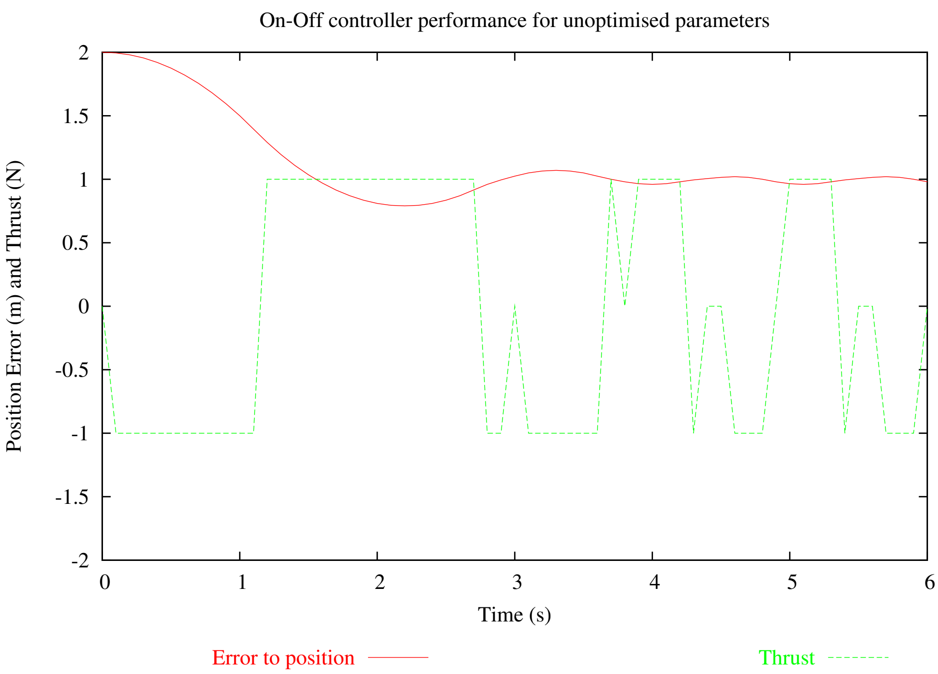


Figure 8.4: Performance of an un-optimised On-Off controller demonstrating the switched nature of the control law.

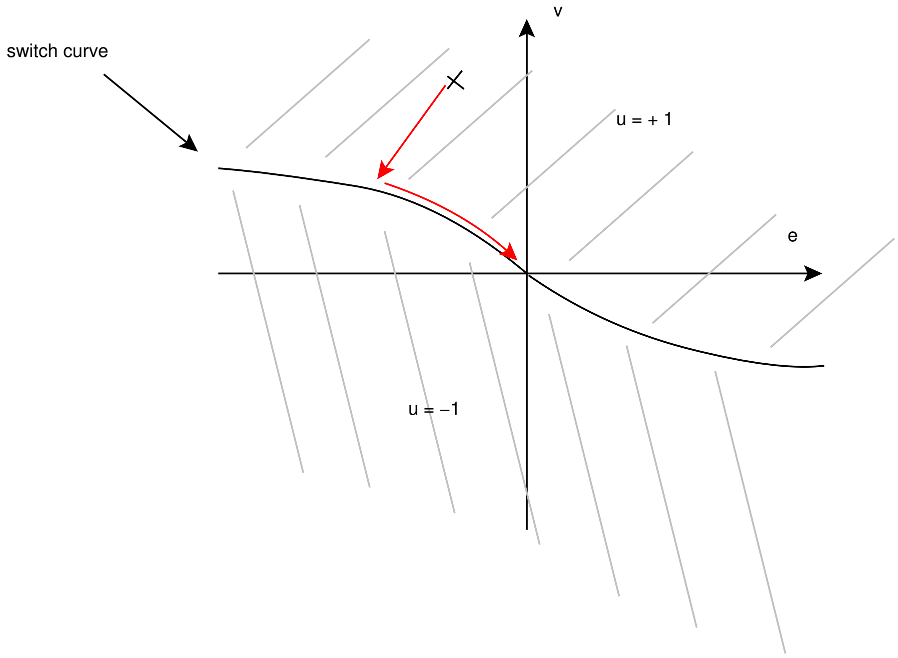


Figure 8.5: Behaviour of (e_p, v) tuple in phase plane before and after switch of control effort direction at time t. At this time the tuple enters the curve that converges to the zero error point.

$$\begin{cases} \beta = 0 & \text{if } e_p < e_{max} \\ \beta = +1 & \text{if } e_p > e_{max} \text{ and } e_v > v_{max} \\ \beta = +1 & \text{if } e_p > \frac{(e_v)^2}{2} \text{ and } e_v < v_{max} \\ \beta = -1 & \text{otherwise.} \end{cases}$$

Finally, the position and velocity error e_p and e_v are defined depending on the nature of the microcell, More details on cell definitions being found in Chapter 7. The reference position is thus defined:

- As a next-in-line or previous-in-line relative vector for relative or local cells.
- As an absolute reference position for the global cells.

This minimal controller is used to investigate the basic convergence and behaviour of a decentralised distributed control architecture.

8.4 Model Implementation and Validation

The complete mathematical model developed above is simulated using a custom-built computer program. The rationale for this approach is detailed in section

B.1.3. Using object-oriented architectures, the so-called "UniSim" simulator uses metastructure objects, which are composed of matrixes mirroring the configuration of the actual structure. This allows to specify at high levels the state matrix of the nodes. The tension derivation is computed using existing linear algebra libraries for solving systems of equations.

The validation of such a tool is done first on 1D and 2D dynamics, for both passive and active nodes to test dynamics and control laws. Then the orbital environments are also validated, and finally tether dynamics are validated against literature results. More details on the UniSim simulator design and validation are in Appendix B.

The main validation criteria are on controller performance to validate the controller design (see Figure 8.6 reproduced from Appendix B), and on simulation of tethers in space (see Table 8.1 from the same Appendix) to validate the tension derivation model.

Inclination (deg)	UniSim Period $\frac{n_\theta}{n}$	Actual Period $\frac{n_\theta}{n}$
15	~ 1.5	~ 1.6
45	~ 1.4	~ 1.4
75	~ 1.2	~ 1.1

Table 8.1: Tether libration motion validation based on the harmonic motion period. Table copied from Appendix B.

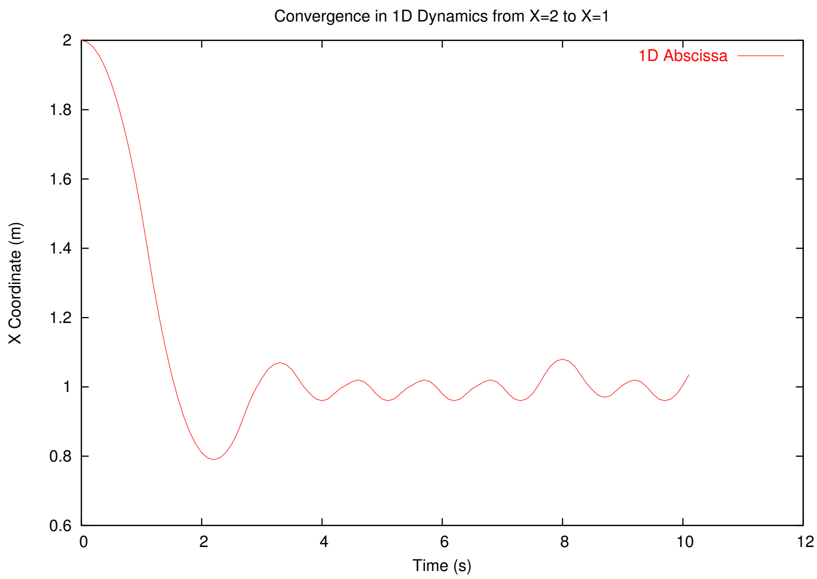


Figure 8.6: On-off controller validation run for a 1D dynamics case with initial error and velocity. Figure copied from Appendix B.

Chapter 9

Dynamics analysis results

Summary

Metastructures are designed at system level by specifying the matrix parameters (i.e. the unit pattern) and the microcell dynamics parameters. These designs depend on each application and are then simulated using a custom software dynamics simulator. Based on the dynamics of tethers, the controllability of the system is demonstrated for the reference structure. For both reference missions the repeatable unit pattern of a microcell matrix is defined and the sensitivity of control dynamics to system parameters is studied. Controllability is possible in almost all cases, but the values of overall impulse necessary are large and less reliable.

9.1 Uncontrolled dynamics

The metastructures being simulated here are microcell nodes linked by rigid rods. In this configuration, their motion has similarities with that of tethers when considered as rigid rods.

The simulations are conducted using the UniSim custom orbital simulator, which has been validated for these tether orbital simulations (see Appendix B). The simulation approach considers perfect joints (see Chapter 8). The results of the simulations presented here and in the next sections are discussed in Chapter 12, whilst the validity of these simulations is discussed in Chapter 13.

9.1.1 Tether dynamics stability

The naturally stable configuration of a tether-like structure in orbit is along the local vertical. A tether or satellite placed in this configuration remains stable if no disturbances apply. In reverse, configurations which are very inclined towards the local horizontal tend to be unstable. If the structure is in an initial state inclined between horizontal and vertical, a libration motion occurs whose amplitude and period depend on the initial inclination, as illustrated in Figure 9.1 and 9.2.

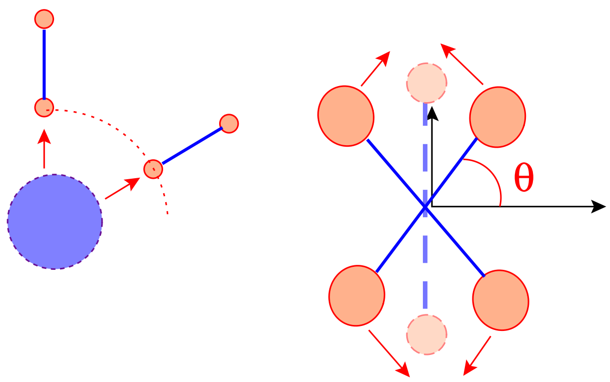


Figure 9.1: A stable configuration for tethers is along the local vertical, thanks to balancing gravity and tension forces. Starting from any inclined configuration from the local vertical, the resulting forces of tension and gravity tend to push the tether towards the local vertical.

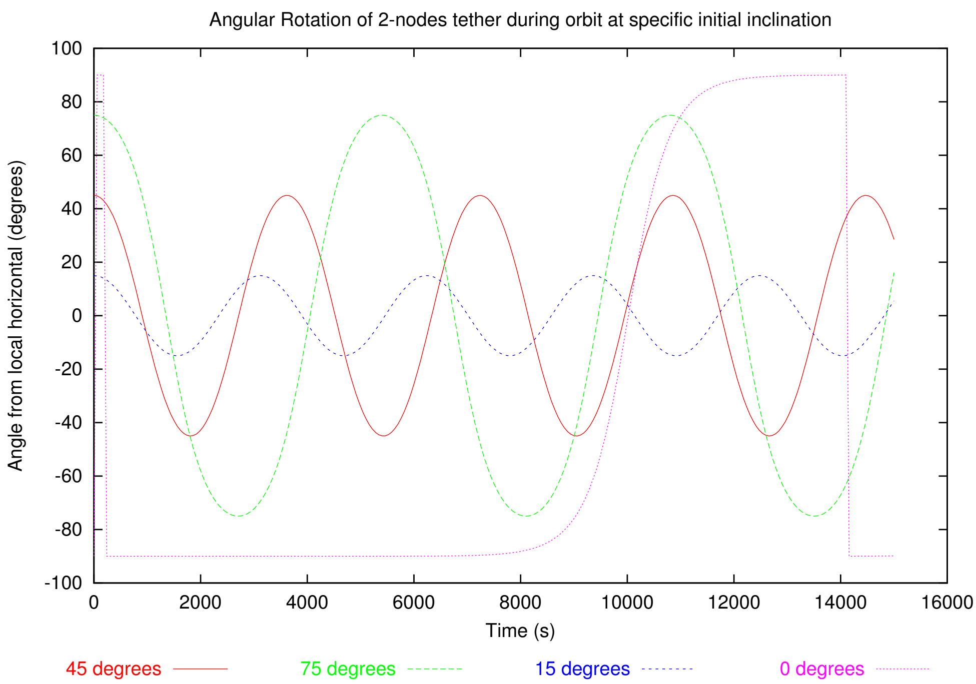


Figure 9.2: Tether dynamics for a dumbbell model with various initial inclinations, 0 degrees being horizontal (as seen on Figure 9.1), for a circular Earth orbit of 200 km altitude at unit length.

9.1.2 Application to metastructure dynamics

These fundamental tether dynamics facts are important when analysing metastructures. In particular these mean that:

- Coupling a local vertical structure with a horizontal one generates drift disturbances that spread in the whole structure, as the central node connecting them moves out of undisturbed orbital motion.
- An initially out-of-equilibrium structure does not get stable naturally but has a periodic or chaotic motion instead, depending on its angular distance from the equilibrium position (i.e. local vertical).
- Two linked structures initially inclined at different angles oscillate at different angles, because nodes are modelled as perfect rotary joints.

This is illustrated in Figure 9.4 and 9.5. So the metastructures are designed to correct initial positioning errors on the one hand, and to continuously counteract instability drift on the other hand. The magnitude of the latter drift depends to first order on the orbital environment. In Figure 9.3 it is shown that this can vary by several orders of magnitude depending on orbit height. This figures shows that a reference structure left uncontrolled will sooner or later drift because of the disturbance due to the horizontal part. That is why it is necessary to use active controllers for metastructures.

9.2 Controlled dynamics

Dynamics of controlled metastructures are defined by the parameters and performance of the controller. These are naturally interrelated and sensitive to orbital environments, and that in turns drive the system design. The controller used in the simulations thereafter is part of the UniSim software simulator and is described in section 8.3.

9.2.1 Controller design

The controller used for metastructures here has some particular features, illustrated on Figure 9.6, which are specifically that:

- It is an On-Off fixed thrust controller. This means the propulsion system and control algorithm is simpler. It works by switching thrust to reverse direction only once during a given control sequence. See Chapter 8 for details on this type of controller. In this case the controller parameters are:
  - The maximum error for position, e_{max}
  - The threshold speed for controller switching, v_{max}

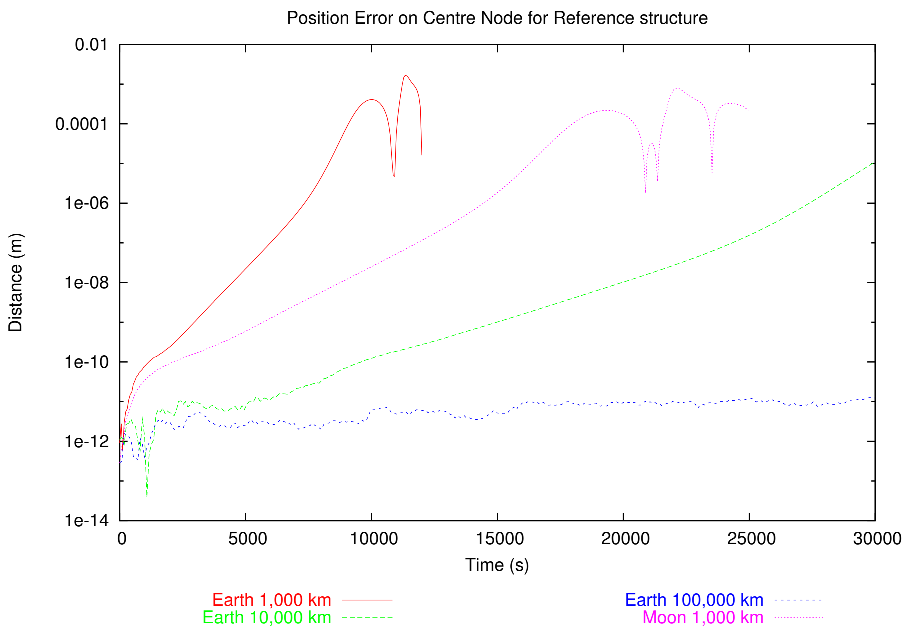


Figure 9.3: Drift of uncontrolled reference metastructure as defined in section 7.1.3. Although the simulation was stopped before 30,000 s, the drift eventually grows significant, by starting from a perfectly aligned position.

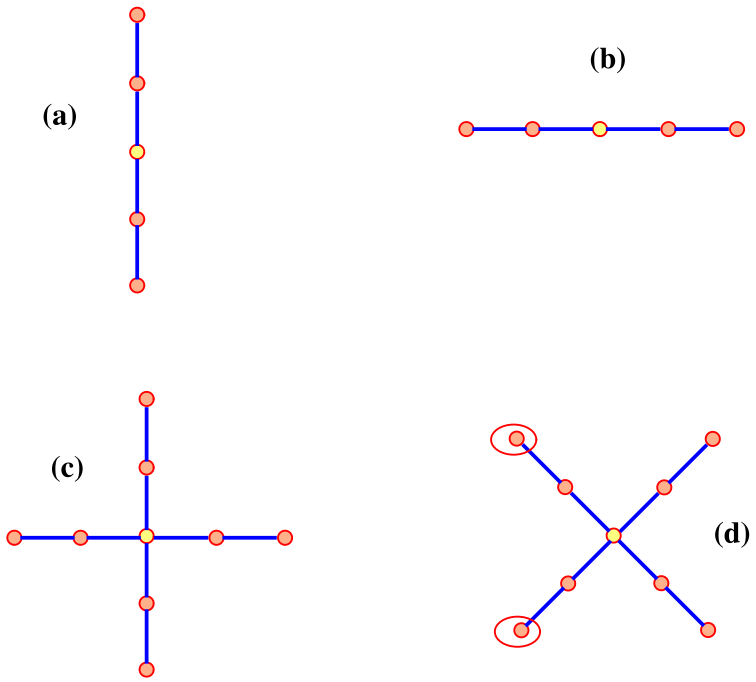


Figure 9.4: Configurations of uncontrolled metastructures cases simulated. The nodes from these configurations reported in Figure 9.5 are the top nodes or left nodes.

- It uses different reference specifications for global and local cells. Local cells refer to a vector aligned with respect to their neighbour, whilst global cells use a reference point in the local co-ordinate frame.

- There are two set of thrusters and controls, i.e. in and out of the plane perpendicular to the link. The controller is modelled as series of points so the twist around the link axis is not simulated.

9.2.2 Performance

The performance of the controller is measured by its ability to maintain position and the amount of thrust it needs to do so. The position control performance is expressed by the RMS position error of all nodes, the exact expression of the error being shown in section 7.5.2. It is demonstrated in Figure 9.7 for an initially disturbed state and undisturbed state. In both cases the metastructure can be controlled into a fixed position.

The amount of thrust needed to realise this control is measured both as instantaneous thrust and cumulative thrust or impulse. The former measures the frequency with which corrections are made, and the latter measures the overall thrust need over

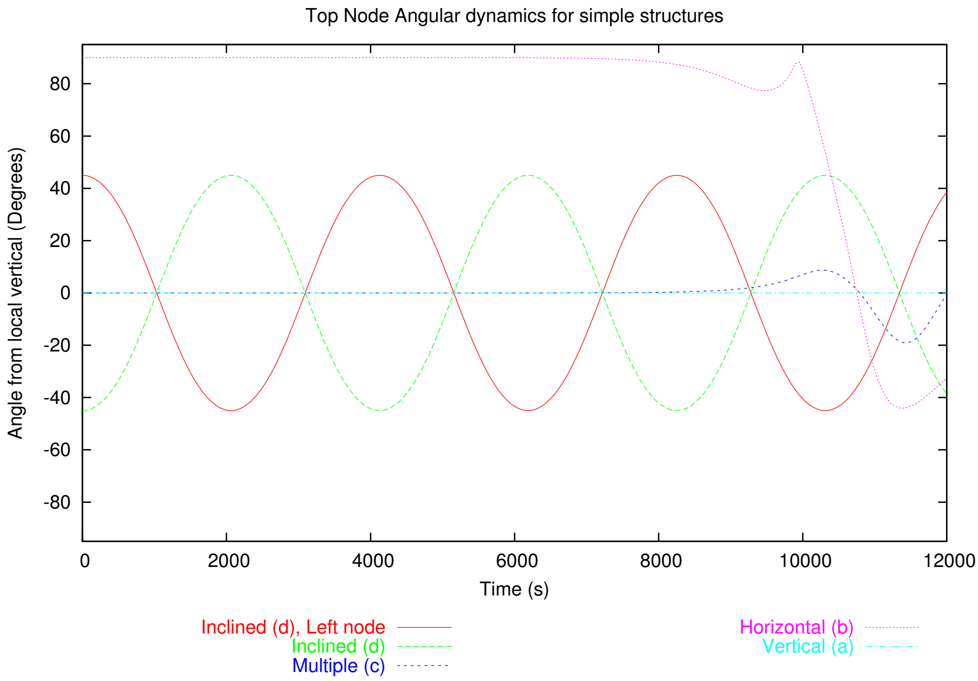


Figure 9.5: Uncontrolled dynamics of vertical (a), horizontal (b), mixed (c) and inclined (d) reference structure. Version (d) refers to an actual articulated structure, i.e. not a rigid cross.

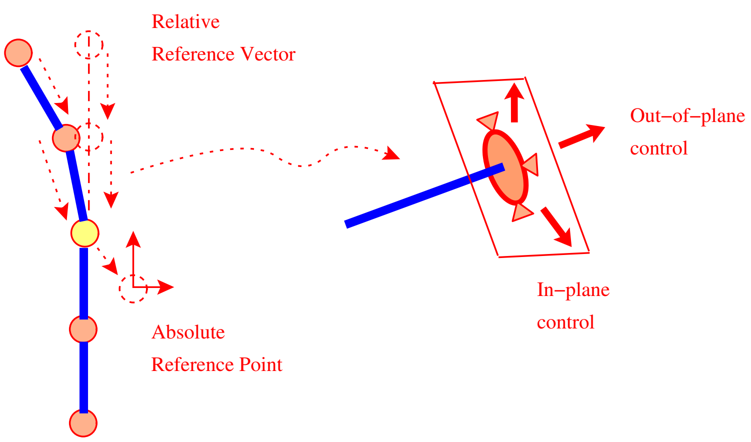


Figure 9.6: Controller specific features include different local and global cell reference, and specific thrusting strategy due to the presence of the links.

a mission, which is used to obtain the system lifetime when discussing the system baseline (see Chapter 12). For the reference metastructure the variation of instantaneous thrust and impulse with microcell values and orbit height are shown in Figure 9.8 and 9.9. One can observe on these figures that there is an initial phase showing the reduction of initial position errors (lasting about 200 s in Figure 9.8a), followed by a phase of position maintenance with a regular pattern of thrusting establishing a stable regime, as demonstrated in Figure 9.9. Note that the actual behaviour of the controller can be dependant on numerical artifacts of the simulation, mainly the time step, as is explored in section 12.2.3.

9.2.3 Sensitivity

The controller performance is also influenced by the relation of microcell mass to thruster capacity, both in terms of the control accuracy achievable and in terms of time to convergence. In Figure 9.10, it can be seen that the time to stabilise the position and the accuracy of this stable position can vary by large factors with this relation.

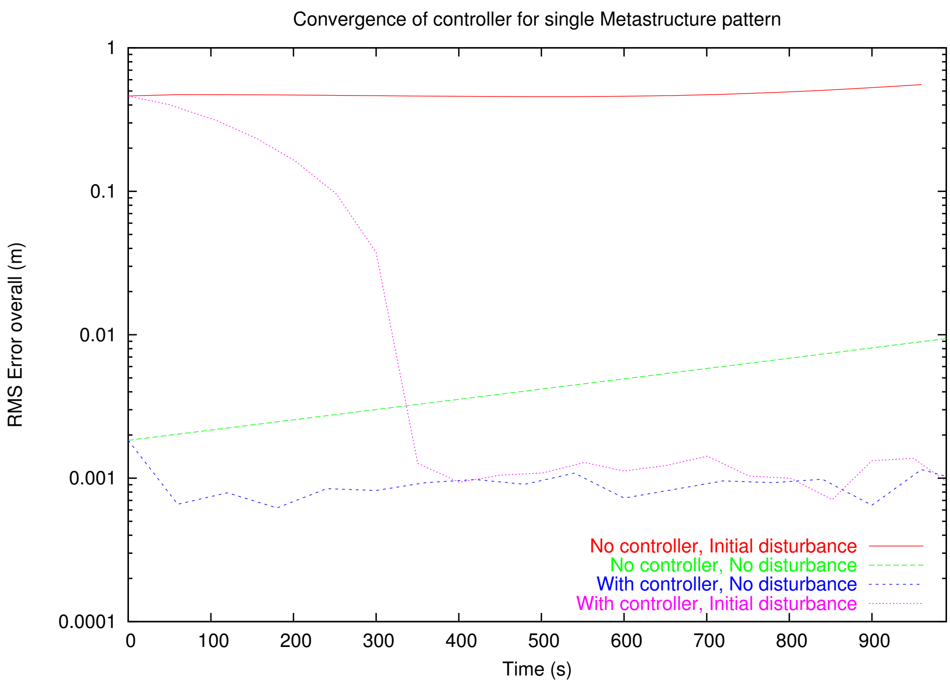
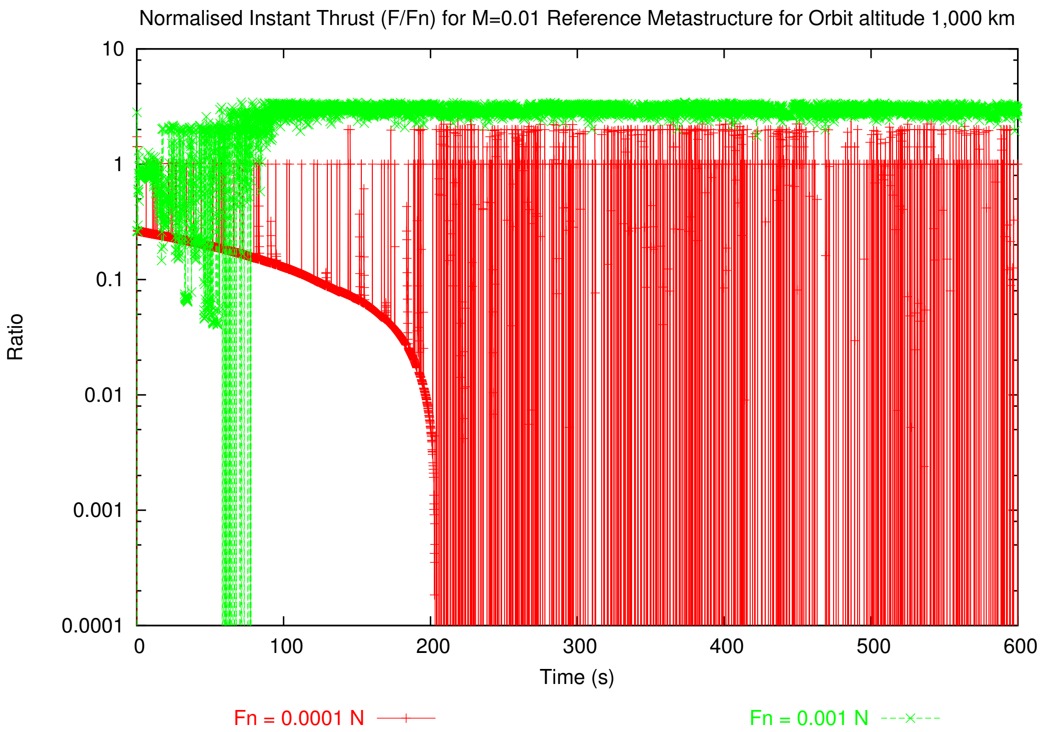
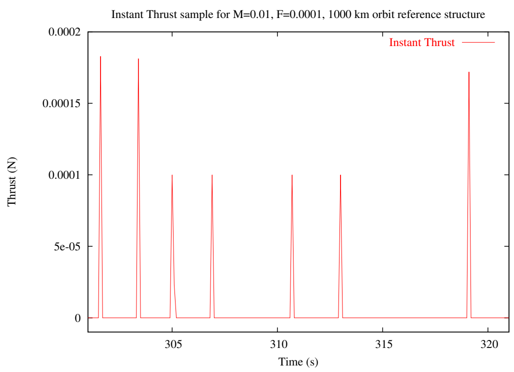


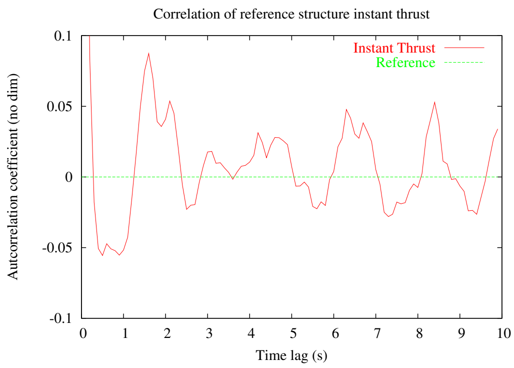
Figure 9.7: Controller performance for an initially disturbed and undisturbed state for the reference metastructure. The disturbed state corresponds to an initial inclination of 15 degrees of the structure in and out of plane. The Y axis represents the RMS Position Error overall (in m).



(a) Instantaneous thrust history for two thruster values, with M=0.01 kg of microcell mass.



(b) Zoom of Instant Thrust History.



(c) Autocorrelation of Instant Thrust History signal.

Figure 9.8: Analysis of the Instant Thrust. A stable regime is established after disturbance reduction (a). The small-scale view of the thrust history (b) correlates to a repeatable behaviour (in this case every 1.6 s) as shown on (c).

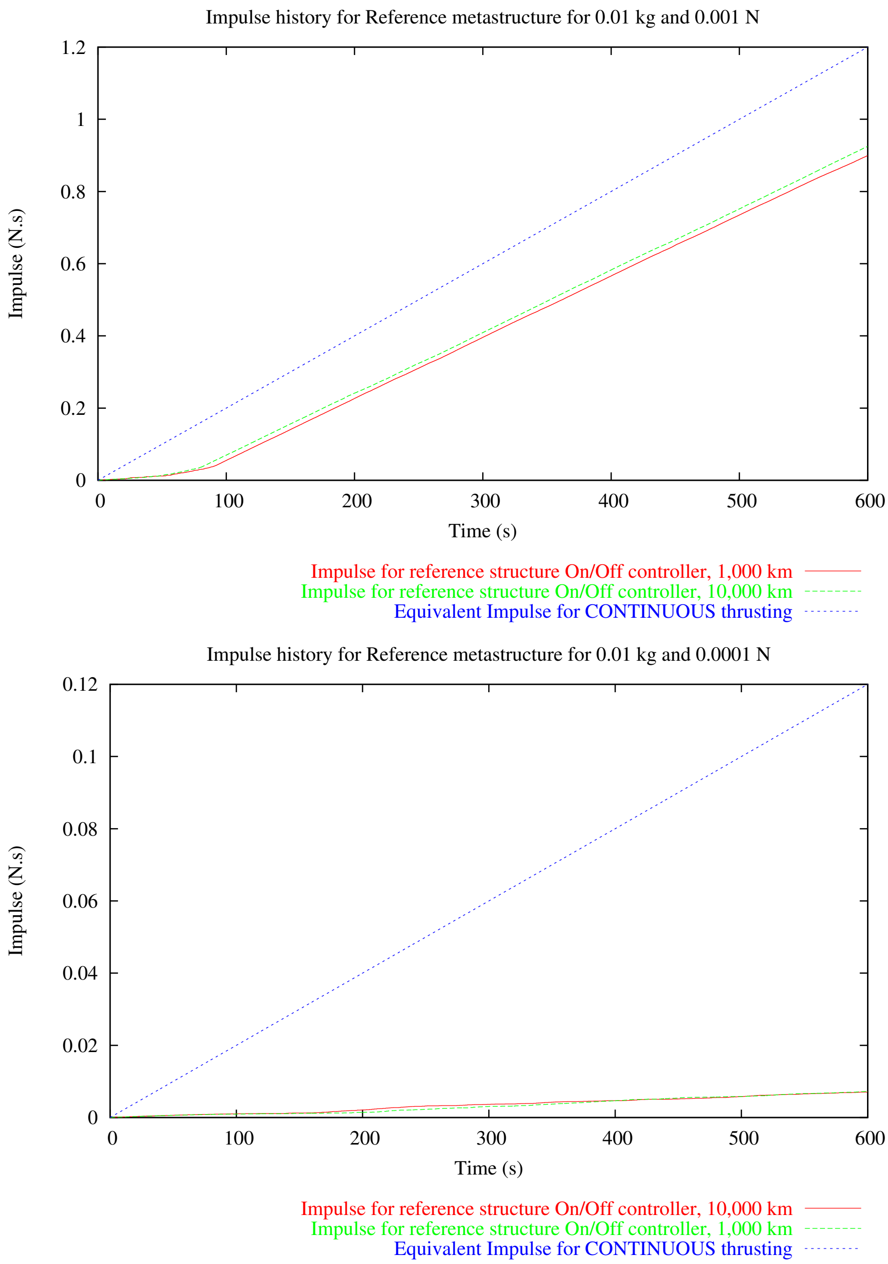


Figure 9.9: Impulse history for different orbits heights and thrust values for an initially aligned reference structure.

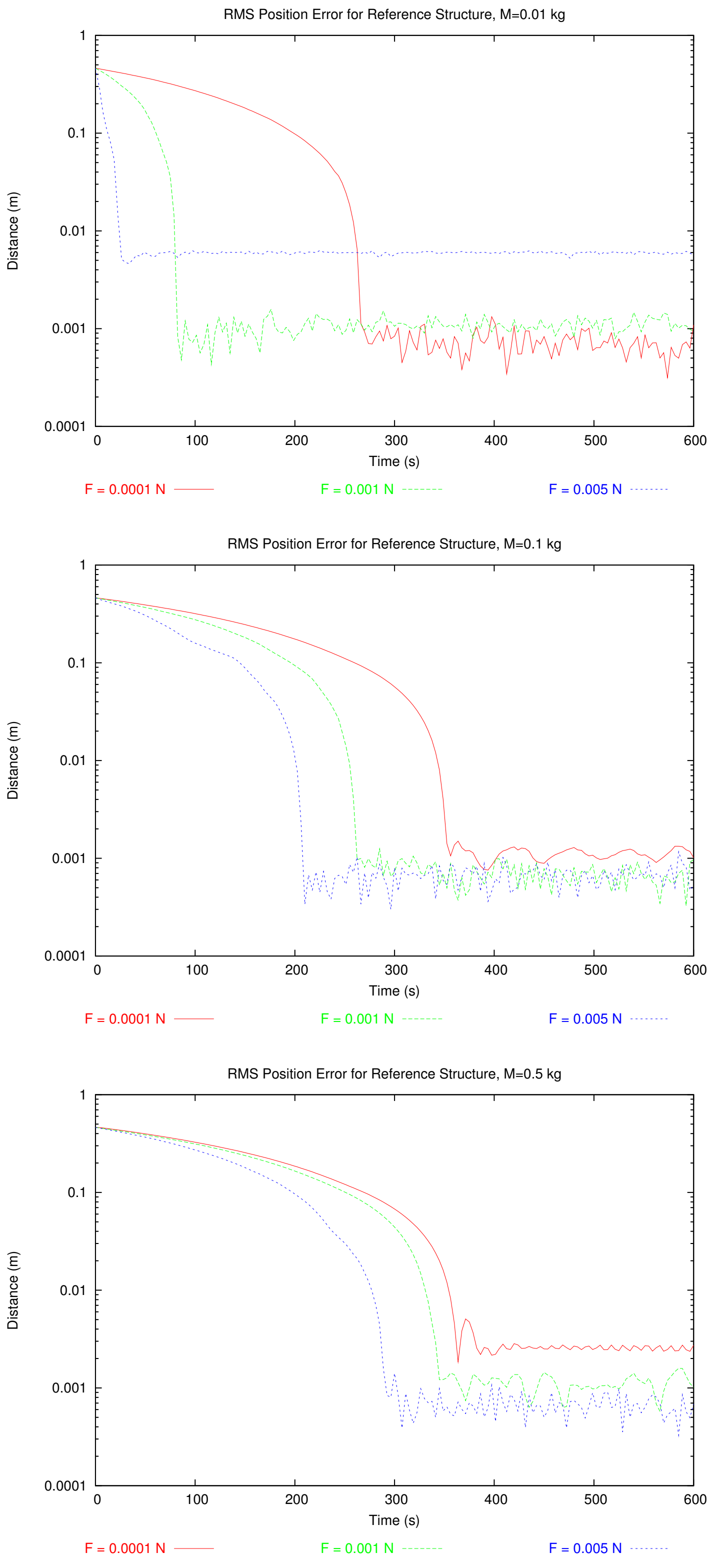


Figure 9.10: Sensitivity of controller to mass and thrust values of microcells, based on a initially disturbed state inclined out of equilibrium by 15 degrees in and out of plane.

9.3 Reference Metastructure Analysis

The controlled dynamics of the reference metastructure as described in the previous section are explored by varying the system parameters and then superposing more than one of the basic cell pattern.

9.3.1 Pattern design

The pattern of the reference metastructure is fixed, as it is used as a test case. It uses a fixed L-L-G pattern for a cross-like configuration, as seen in Figure 7.3 in Chapter 7. More details on this pattern are found in Appendix B. For this structure, the change in agent type and link length is not investigated, but all other system parameters are.

9.3.2 System Parameters variation

The variation of behaviour with orbit height is shown in Figure 9.8 and 9.9. For this structure there appears to be little variation with orbit height. The sensitivity to mass and thrust of cells and links is shown in Figure 9.10. It is apparent here that the higher the thrust to mass ratio is, the faster the convergence is. Finally the sensitivity to the control law parameters is shown in Figure 9.11.

9.3.3 Pattern superposition

It is evident that due to the differential gravity forces, the behaviour of superposed patterns is different from that of simply replicating the individual behaviour of a pattern. This is illustrated on Figure 9.13, where it appears that in this case it is mostly the central node of the outer pattern that needs to do extra compensation. The interface between patterns for the reference structure can simply be an additional link between the extreme left (or top) node of one pattern and the extreme right (or bottom) of the next one. In the particular case of the reference metastructure this can be done simply as shown in Figure 7.12 in Chapter 7.

As for the convergence, the dynamics of a vertical superposition of two patterns is shown in Figure 9.12 where the controllability is confirmed. For three patterns the same is true. So it can be said that the reference metastructure can be controlled to a good degree of accuracy, at the price of additional propellant for the furthest patterns.In principle, load levelling could be possible in the structure to even out propellant consumption, but this includes further assumptions on technology necessary (such as fuel transfer between cells) and is not explored in this work.

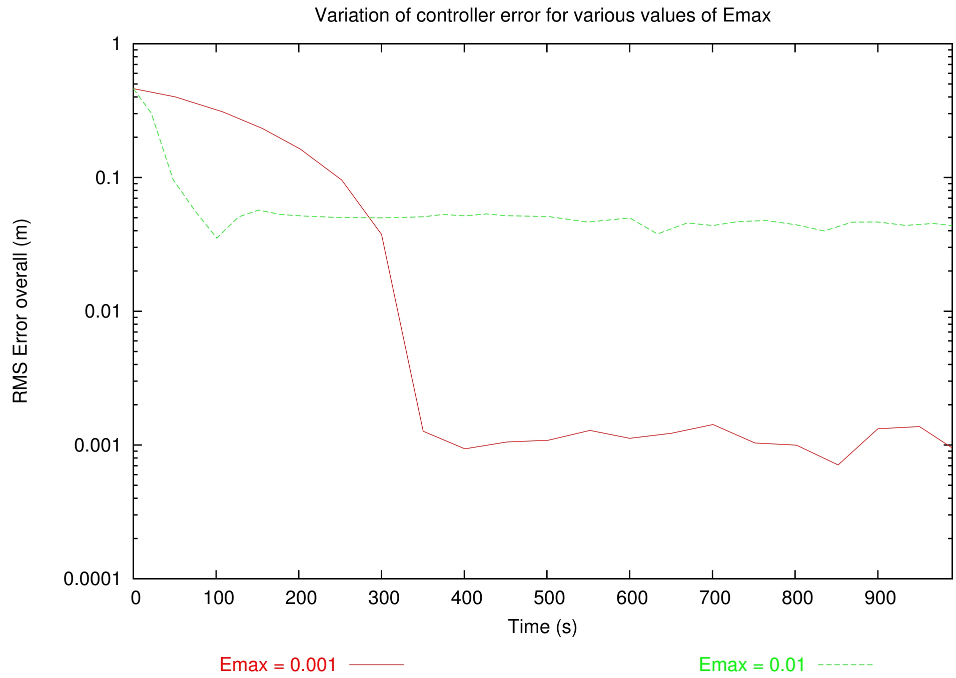


Figure 9.11: Metastructure behaviour for different values of the controller maximum position and speed error e_{max} and v_{max}. The Y axis represents the RMS Position Error Overall (in m).

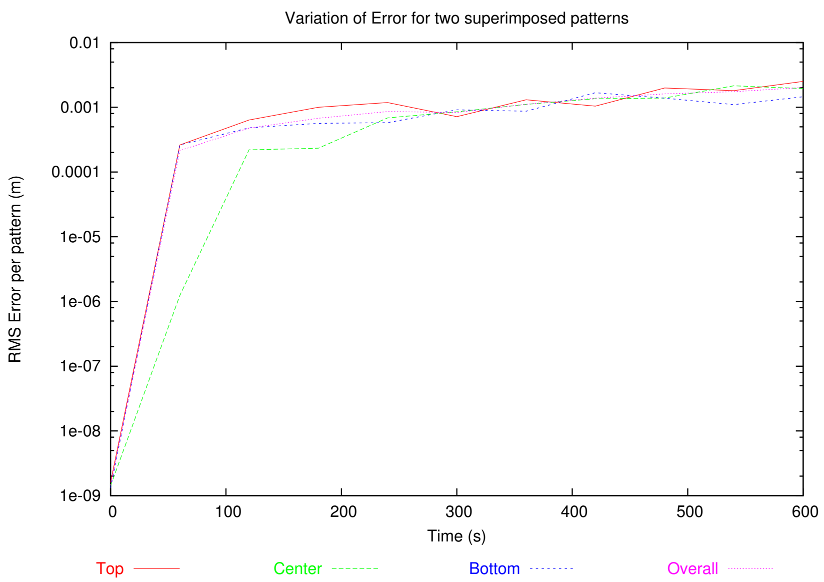
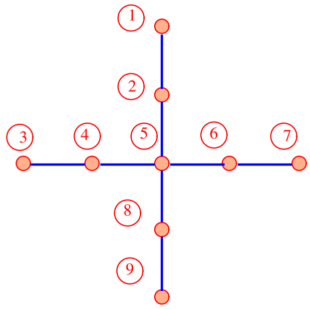
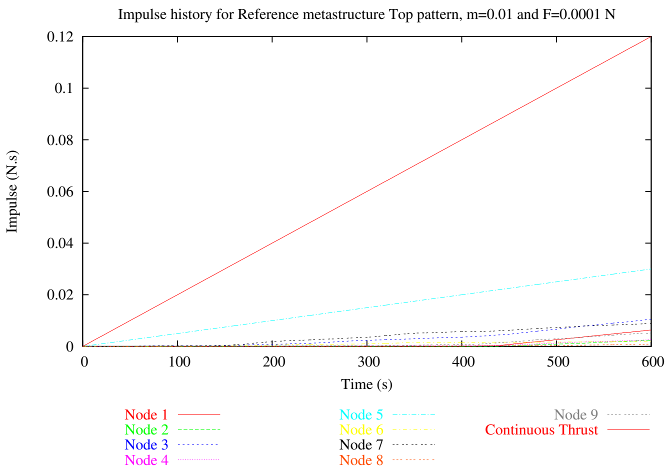


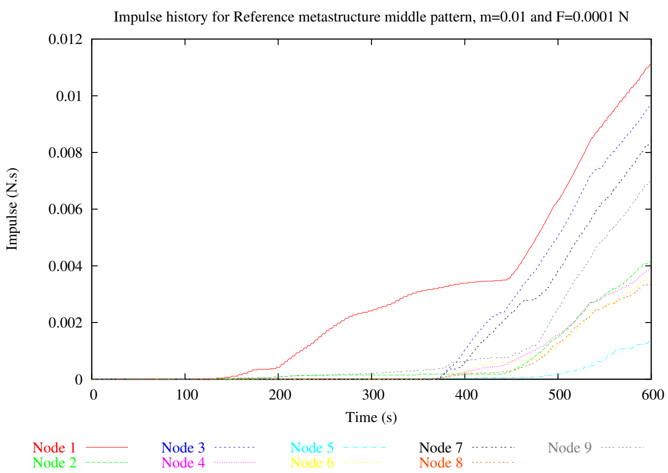
Figure 9.12: Error for two superposed panels for the reference metastructure



(a) Node numbering for reference pattern



(b) Impulse history for top and bottom patterns



(c) Impulse history for middle patterns

Figure 9.13: Impulse history variation in a 2-pattern reference metastructure.

9.4 Interferometer analysis

The interferometer uses the shape reconfiguration function of the analysed concept. It is studied primarily in free space, as a simulation of an orbit around Lagrange points for astronomy observations. The case of an Earth orbit is also considered for Earth observation applications.

9.4.1 Pattern design

The pattern of an interferometer is actually linear, as the two components of the cross can be considered independent. Modifying the baseline of the sensor nodes means that the reference vectors or positions have to be changed, as seen in Figure 9.14.

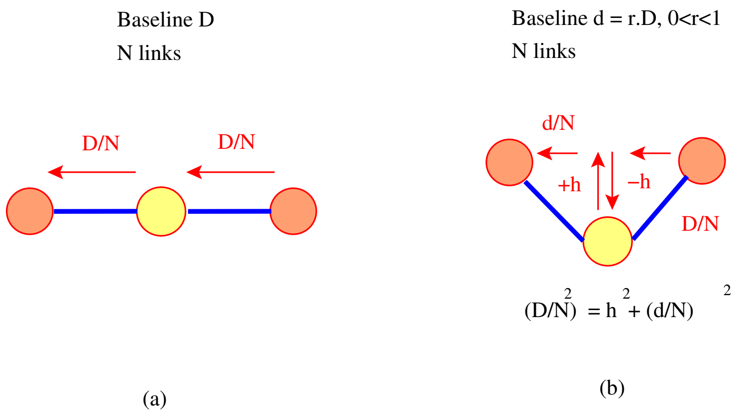


Figure 9.14: Changes to reference points in the pattern when the interferometric baseline changes. In flat case a), the reference position vector is simply $[\frac{D}{N}]$, but in case b) it is as described in section 9.4.1.

When the baseline is changed from D to $d = r.D$, with $0 < r < 1$, the reference vectors $(Ref(i,j))$ for **h**orizontal **n**ext-in-line and **p**revious-in-line On-Off local controllers ($O-h-n$ and $O-h-p$), denominated as $Ref(Ohn)$ and $Ref(Ohp)$, are changed such that

$$\begin{aligned} Ref(Ohn) &= \left[\frac{d}{N} \quad \alpha\sqrt{\left(\frac{D}{N}\right)^2 - \left(\frac{d}{N}\right)^2} \quad 0. \quad 0. \right], \\ Ref(Ohp) &= -Ref(Ohn), \\ \alpha &= -1, +1, -1, +1 \ldots \end{aligned}$$

where N is the number of nodes. The reference points for the global cells can simply be scaled.

Pattern variation is also investigated, as there are many ways to control a straight line. Finally, the interface between repeating patterns is dealt with by introducing a supplementary link of very small length, typically the smallest fraction of the baseline wished to deploy or fold. This is illustrated in Figure 9.15.

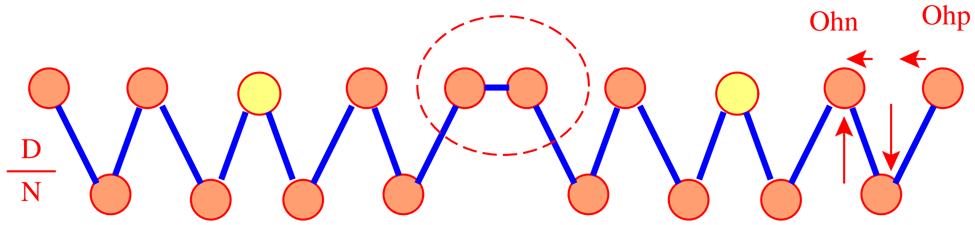


Figure 9.15: Interferometer pattern design for baseline change and inter-pattern interface. A different possibility for inter-pattern interface using an additional *inclined* line is not implemented in this work.

9.4.2 System Parameter variation

The control law parameter is fixed for the interferometer, as the best possible accuracy is desired. The environment is as described above, either free-fall or Earth gravity. The parameters that vary in this application are the cell mass and thrust, and the local pattern configuration.

The variation of behaviour with the ratio of mass and thrust is shown on Figure 9.17. It can be seen that the interferometer converges toward the new baseline that is $0.1D$ here, which is the most extreme case. In reality there is no reason not to change the baseline progressively. This is shown in Figure 9.16 where it can be seen that equivalent levels of convergence can be reached for any baseline change, and the difference lies in the time to reach the new position. Finally the change in the pattern definition is investigated, by varying the number of local and global cells. This is shown in Figure 9.18 and 9.19. This shows that a pattern with more global cells is likely to perform better.

9.4.3 Pattern superposition

Finally patterns are superposed to form longer interferometric baselines. In Figure 9.20 is seen a simulation of a $0.9D$ position change using one, two and three patterns. It can be seen that the position error achieved is very similar.

9.5 Solar concentrator analysis

Solar concentrators use the ability of metastructures to maintain 3D shapes.

9.5.1 Pattern design

For the concentrator, the nodes have to be on a parabolic surface whose equation is derived in section 6.6. For truly decentralised control it makes more sense initially to define the pattern nodes using links of equal length. The nodes need follow the surface based on the local radius in the horizontal plane, as illustrated in Figure 9.21. They are thus defined as a series of points (R_n, x_n) such that

$$\begin{aligned} x_n &= a \times {R_n}^2 + b \\ x_{n+1} &= a \times {R_{n+1}}^2 + b \\ L^2 &= (x_{n+1} - x_n)^2 + (R_{n+1} - R_n)^2 \end{aligned}$$

with L the desired length of the links and $(R_0, x_0) = (0, 0)$. This translates into the solution of a quartic equation (C8). For a parabola with a small slope a as the one used for the actual mission, the out-of-plane values are very small as shown on Table 9.1. So the metastructure is simulated with a parabolic slope much higher than the real one in order to be able to understand the phenomena taking place.

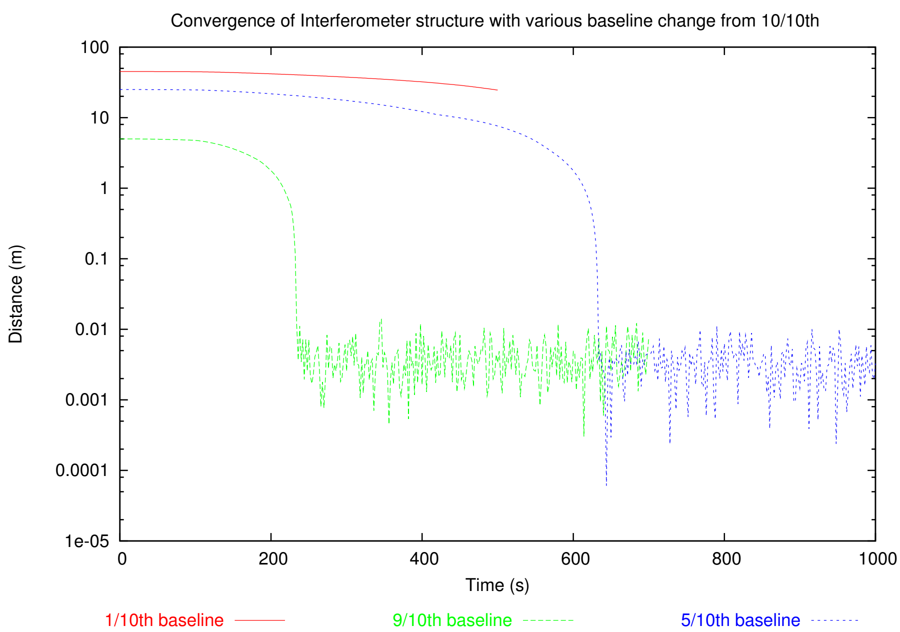
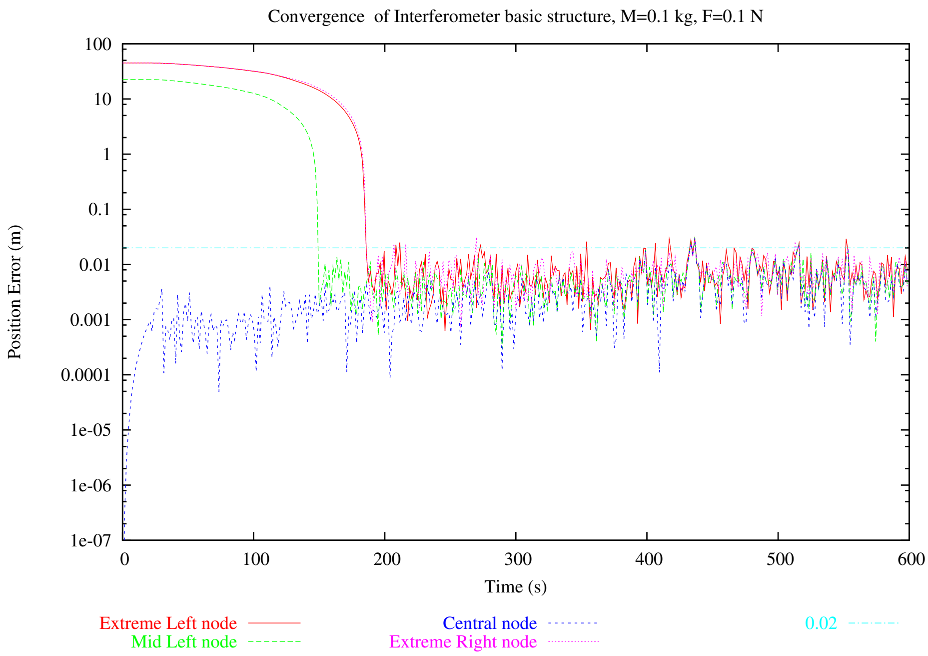
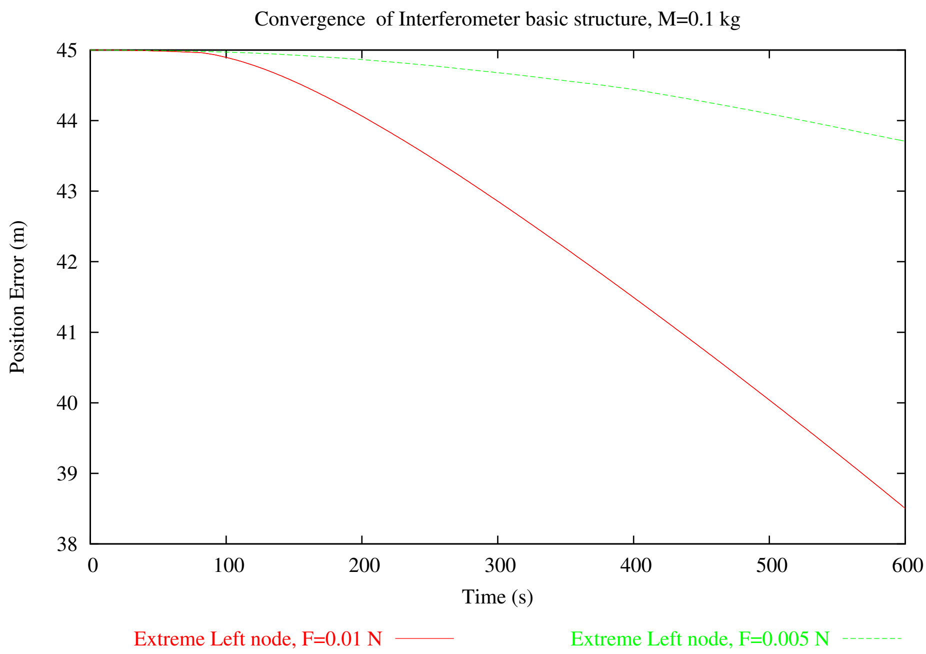


Figure 9.16: Convergence of the basic interferometer structure for a number of different baseline changes. The distance reported is the position error of the extreme nodes, forming the actual baseline.

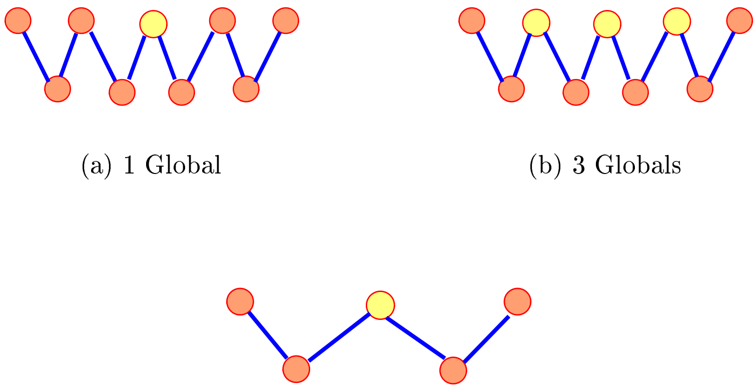


(a) Basic pattern



(b) Variation of Thrust

Figure 9.17: Sensitivity of a basic interferometer pattern to thruster capacity variation.



(a) 1 Global

(b) 3 Globals

(c) Less links

Figure 9.18: Interferometer basic pattern variation.

n	b = 240		b = 24,000,000	
	$R_n(m)$	x_n (m)	R_n (m)	x_n (m)
0	0.0	0.0	0.0	0.0
1	0.04166	9.99991	0.00004	10.0000
2	0.16665	19.9991	0.00017	19.9999
3	0.37492	29.9970	0.00037	29.9999
4	0.66642	39.9927	0.00067	39.9998
5	1.04107	49.9857	0.00100	49.9997

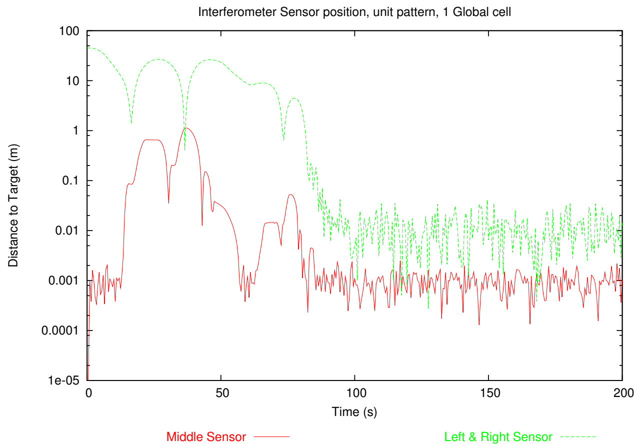
Table 9.1: Solar concentrator node locations for $L = 10$.

9.5.2 System Parameters variation

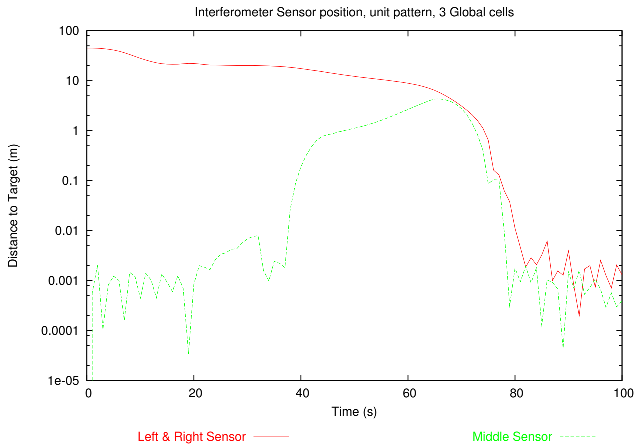
The history of RMS position error is shown on Figure 9.22 for different configurations of the concentrator. Simulations executed with linear and cross-like patterns show similar levels of convergence.

9.5.3 Reference for absolute cells

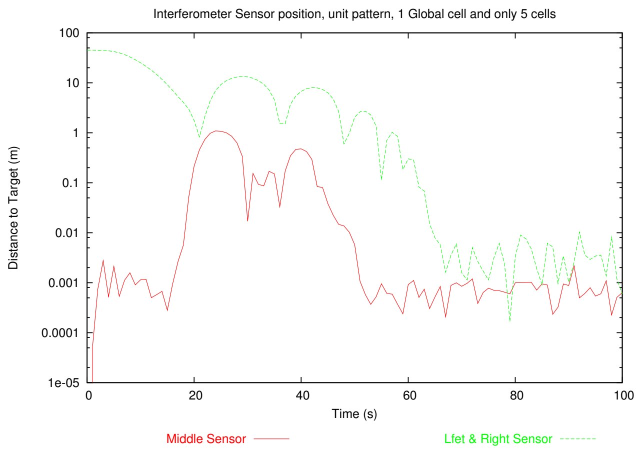
The simulation of concentrator metastructures highlights a problem in the specification of global cell reference. Indeed, for these structures the centre of mass is not positioned at the origin or at a physical node. Therefore some artificial deviations from the reference exists for global cells, as an error in the x axis. Whilst this does not affect the convergence of the structure as a whole, this biases the simulation in terms of thrust used, as the global cells tend to thrust all the time towards this erroneous reference. A possible solution is to modify the reference points of global



(a) 1 Global



(b) 3 Globals



(c) Less links

Figure 9.19: Interferometer basic pattern variation results corresponding to pattern variations as shown in Figure 9.18.

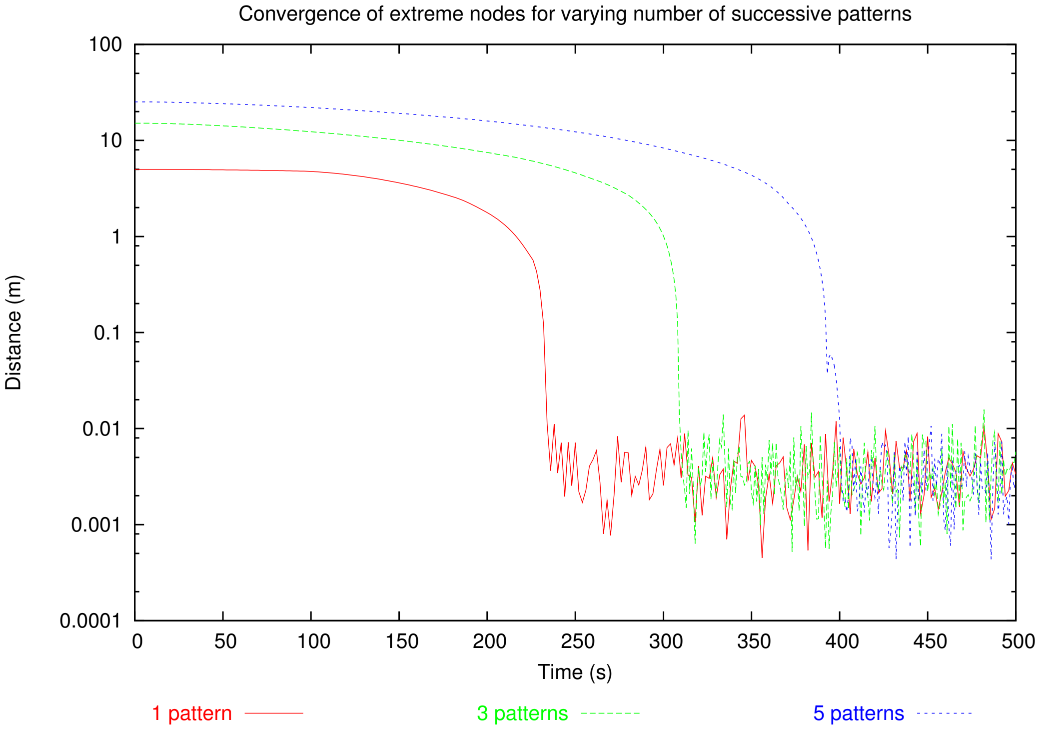


Figure 9.20: Convergence of several superimposed patterns for 1, 2 and 3 layers of patterns, meaning a structure with 1, 3, or 5 patterns in total.

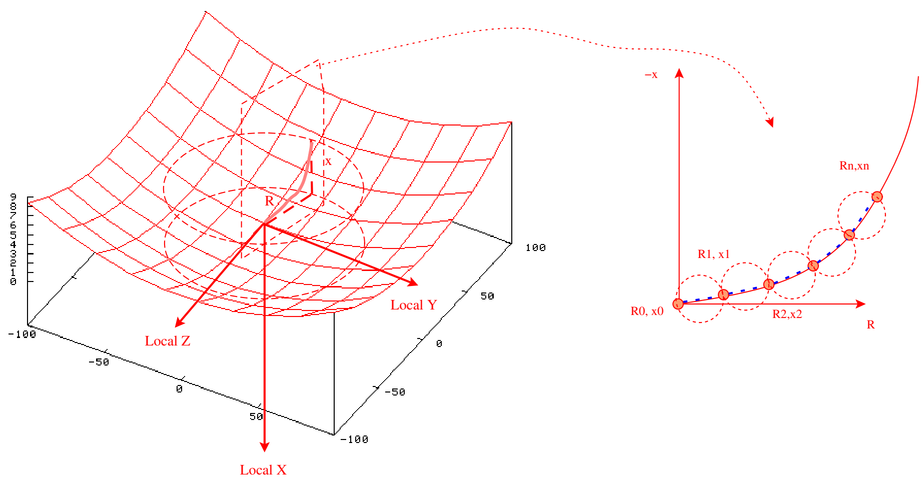


Figure 9.21: Parabolic pattern definition for Solar concentrator. The nodes are defined as being equi-spaced along the parabolic curve in the plane considered.

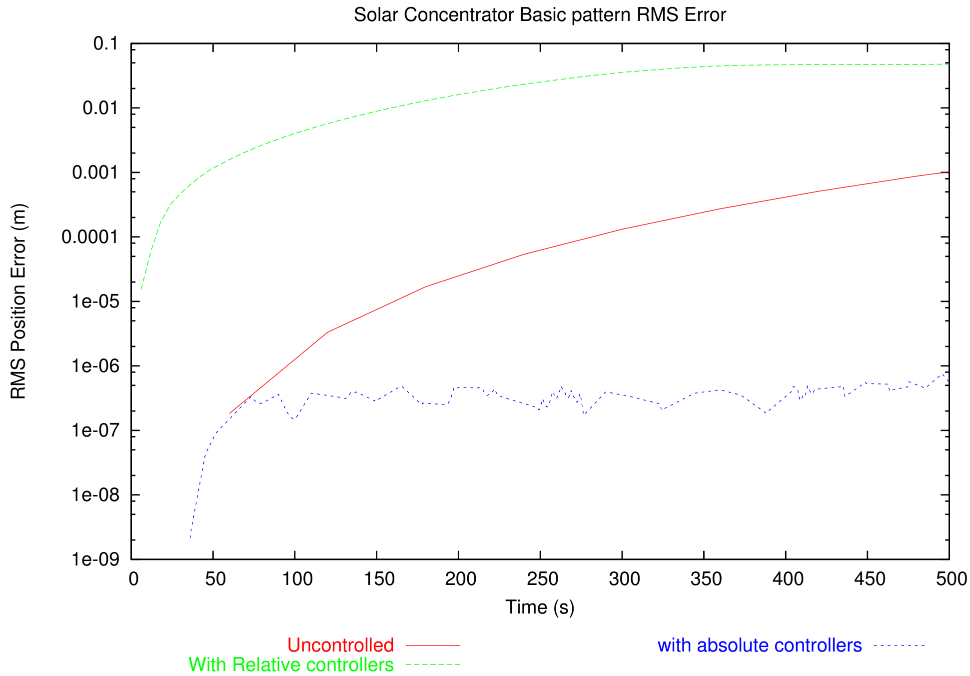


Figure 9.22: Concentrator results in Earth orbit by changing the basic cell type.

cells, but is not implemented in this research.

9.6 Results Summary

The dynamics of metastructures involve many different variables at system and subsystem level. The overall meaning of the simulation results are discussed in Chapter 12, and a summary of numeral results is presented on Tables 9.2, 9.3, and 9.4 for the reference structure, the interferometer mission, and the Solar concentrator mission. The "normalised impulse" defined on these tables is simply the Impulse given as output of the simulation compared to the maximum possible Impulse, i.e. for continuous thrust[1].

9.7 Subsystem parameters

The dynamics analysis tends to show that related to system-level design, important parameters for the microcell or subsystem design are related to the control subsystems of the cell. These are first the accuracy and range of the sensors, which should

[1]This is true because the thrust is fixed

be better than the control accuracy. These also include the amount of propellant needed, to be derived from the impulse needs calculated.

The first two are directly derived from the system parameters of control accuracy and structure dimensions (C11). As for the thrust it is related to the simulation runs performed above.

The values used for microcell subsystem analysis are shown on Table 9.5.

Orbit Height (km)	Node Mass (kg)	Cell Thrust (mN)	Error e_{max} (mm)	Normalised Impulse	RMS Error (m)
1000	0.01	0.1	1.	5%	0.91
1000	0.1	0.1	1.	N/A	1.
1000	0.5	0.1	1.	N/A	2.4
1000	0.01	1.	1.	58%	1.
1000	0.1	1.	1.	N/A	0.9
1000	0.5	5.	10.	N/A	2.4
1000	0.5	5.	1.	N/A	0.61
10,000	0.01	0.1	1.	58%	0.75
1000		2 patterns		60%	2

Table 9.2: Results summary for the reference metastructure

Environment	Node Mass (kg)	Cell Thrust (mN)	Normalised Impulse	Max Error (mm)
Free	0.01	10.	34%	5.
Free	0.01	5.	48%	2.
Free	Long links		48%	0.5
Free	More globals		48%	1.3
Free	2 patterns		N/A	2.5
Free	3 patterns		N/A	2.5
Earth	3 patterns		No Convergence	

Table 9.3: Results summary for the interferometer

Environment	Node Mass (kg)	Cell Thrust (N)	Normalised Impulse	Max Error (m)
Earth	0.5	0.001	N/A	0.05
Earth	0.5	0.005	N/A	Similar
Moon	0.5	0.005	N/A	Similar

Table 9.4: Results Summary for the Solar Concentrator

Parameter	interferometer	Solar concentrator
Thrust (mN)	0.1 - 5.	1. - 5.
Sensor range (m)	100.	10.
Sensor accuracy (arcmin)	0.34	0.27

Table 9.5: Range of subsystem parameter values.

Chapter 10

Microcells design results

Summary

Microcells are different from Nanosatellites in that they have mechanical links and more limited communication systems. Indeed, local micro-cells can be made relatively simple by using local magnetic positioning, and including a propulsion wafer-level system-on-a-chip. As for global microcells, they can use integrated navigation units, and have to carry more propellant. Overall microcells mass and power are in the range of 400 grams and 1 Watt.

10.1 Functions and architecture

Microcells are similar in functions and design to very integrated Nanosatellites (see Chapter 2). The difference is that first, they have to operate within the context of a metastructure, and second, they are primarily not concerned with remote or in-situ sensing as part of their mission. This means that:

- The on-board sensors and actuators only need to monitor the relative or absolute position in the metastructure and to control this position to the accuracy required by the mission.
- The communications with other elements or with mission control authority is limited, principally to changing the reference position for modifying the shape of the structure if required.

If the main function of the cells is indeed to maintain the position through sensing and acting, there are also support (or platform) functions needed by those elements in common with all spacecraft or microsystems. These are the data handling, the control and command, the electronics, the communications, and the structural accommodation. All these areas are assessed thereafter. Finally, the system integration and manufacturing are addressed as part of subsystem design and for costing and overall concept assessment. This functional analysis of microcell is illustrated on Figure 10.1 and is detailed in the next sections.

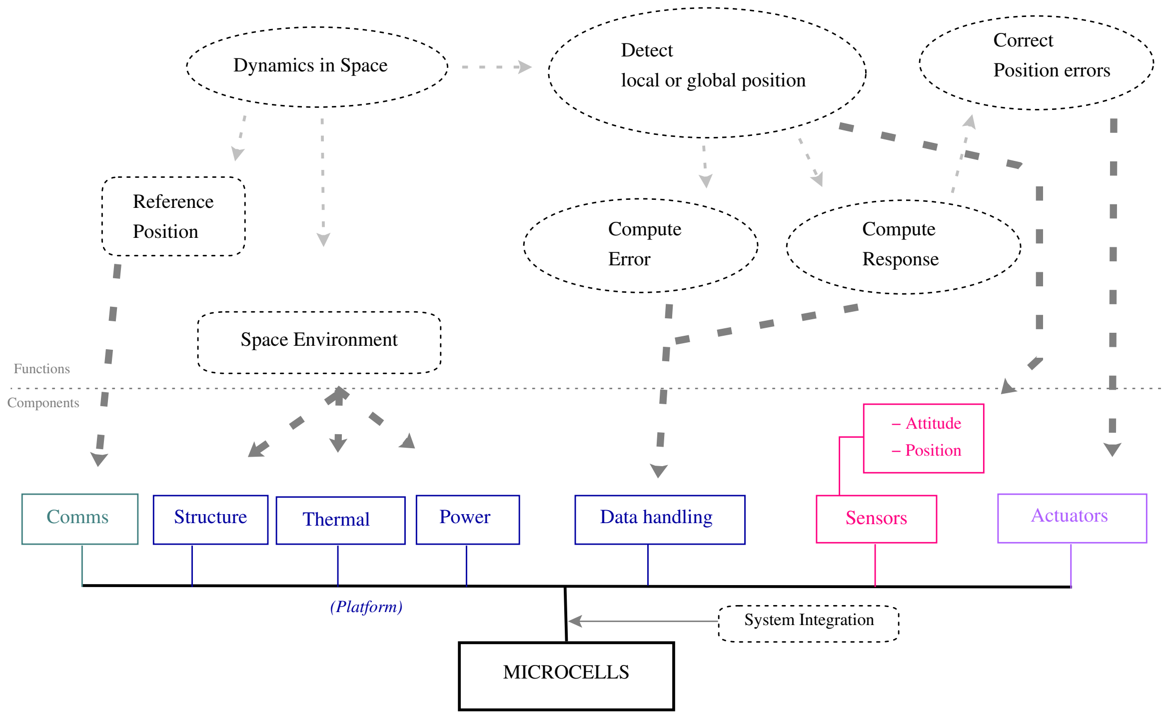


Figure 10.1: System mapping of metastructure functions to microcell components.

10.2 Sensors

Metastructures use two types of cells, global and local. They are different mostly by the reference they use (see Chapter 7). Local cells take as reference typically their "next-in-line" neighbour, whilst global cells refer to an absolute position. The absolute position is expressed in the orbital local reference frame associated to the orbit of the centre of mass (see section 8.1.2 and Figure 8.2 in Chapter 8). It is apparent from these definition that these need two different type of position sensors.

10.2.1 Local cells

In principle the local cells only need to detect a relative position vector, which is essentially the orientation of the link with the next cell. This can only be done with reference to a common frame. So the local cell need for local position sensing is:

Attitude of the sensor or the cell with respect to a reference frame common to both local cells.

Position between the two cells in the reference frame.

10.2.1.1 Attitude detection

There are several ways to detect the relative attitude of a spacecraft. The reference can actually be a global reference using rate sensors or attitude detectors like star, Earth and Sun sensors. It is also possible to use a common but local reference frame provided by global or top-level cells.

Rate sensors As described in Chapter, 3 these are an important part of MST space research.These sensors detect the rate of rotation from which the attitude can be integrated. A problem of these sensors, however, is their drift bias, usually expressed as the Angular Random Walk in deg/$\sqrt{hr}$. An estimation of mission requirements (C11) and capacities of current sensors is shown on Table 10.1. This shows that in principle they are compatible with micro-gyros being developed.

However the angular random walks reported on this table are related to one single manoeuvre, such as the change from one baseline to another for the interferometer mission. So whilst the drift may be compatible with for a localised event, in reality the rate sensors have to be calibrated regularly if they are to be suitable for microcells. Calibration techniques involve communications with an absolute attitude authority (either on the ground or in space) which has implications on the system design that tends to make rate sensors not suitable to minimalist systems such as microcells.

Mission	Rate detection (deg/min)	Attitude precision (arcmin)	Angular random walk, deg/$\sqrt{hr}$
Interferometer	0-0.45	0.34	0.34
Solar concentrator	0-0.001	0.27	0.27
Current MST gyro	±25	-	0.15

Table 10.1: Requirements and capacities of rate sensors. The drift or angular random walk appears compliant with microcell requirements, but it applies for a localised mission event in mission lifetime, i.e. a particular manoeuvre of the metastructure.

Global attitude detectors These are complex systems and are best suited to global cells. They are detailed in section 10.2.2.

Relative attitude detectors It is possible to use a local reference source of positioning via emissions of a beacon. The source can either be a magnetic field or a radio emission.

To detect magnetic fields generated by a global cell, several micro-magnetometers designs exist as seen in Chapter 3. They are designed to detect the Earth's magnetic field. As for the generated source, the values in Figure 10.2 correspond to a small electro-magnet (C10) compatible with microcell size and capacity. They are compatible with the possibilities of sensors as seen in Table 10.2, although the presence of the Earth may cause disturbances.

Mission	Typical range (m)	Generated field (nT)	Field variation (nT/m)	Local Earth field (nT)
Interferometer	100	12.5	0.1	2350
Solar concentrator	10	125	11	375
MST Magnetometer	0-500	1	N/A	N/A

Table 10.2: Requirements and capacities of Magnetometers for microcells

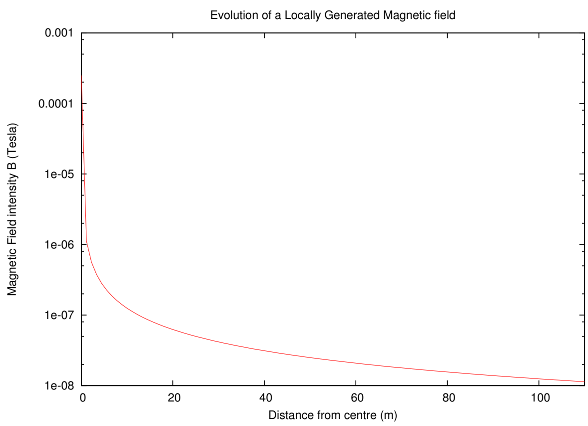


Figure 10.2: Strength of local magnetic field generated by an electro-magnet on a global microcell. For reference missions the maximum link length is in the order of dozens of metres which means detectable fields.

Other techniques such as radio positioning or even "local" positioning systems require more complicated detectors and are not considered here. So the most attractive option based on the previous analysis is the use of a local magnetic field detector referring to the field generated by an electro-magnet put on the global cells.

10.2.1.2 Relative position detection

Once the attitude is known, there are two ways to detect the relative position of two local cells; either by the orientation of the link, or by detecting the neighbouring cell's projection in a 2D grid. In the case of the metastructure there is no need for ranging of course, as the distance between two cells remains constant thanks to the links.

Link angle detection The most direct method to know the position of the next-in-line cell is to measure the orientation of the corresponding link. The primary method of sensing this orientation is by detecting the strain due to deformation of a gauge in-between the link and the cell. MST-based structures that measure strain are widely used in pressure sensors and less widely in MST strain sensors (see Chapter 3). In general, to simplify stress coupling effects uniaxial measurements only are made in a [100] silicon substrate. In this case for basic silicon substrate the resistivity changes with the angle as seen on the Figure 10.3. To make the sensors simpler the best configuration is to mount them on each axis between the link and the microcell as seen on Figure 10.4.

Another alternative could be to use electrostatic sensors. However the gaps between straight and inclined configurations (on the order of millimetres) may lead to using electric fields too large to be compatible with MST. So this is not an alternative at this time.

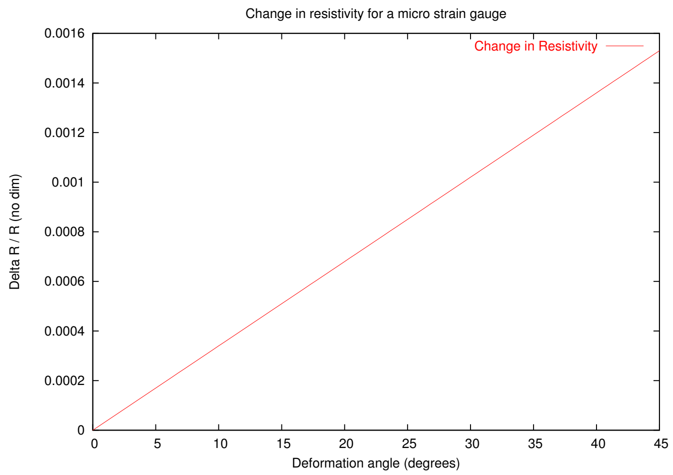


Figure 10.3: Resistivity variation in strength gauges at link interface. For the expected rotation angles, resistivity variation is acceptable.

Remote detection The other possibility is to use remote sensing. Technologies for shape and orientation recognition in formation flying [Jenkins, J., 2002] can not be considered here, because they require complex picture processing software and large photosensor arrays. Instead a design can be proposed based on recognition by a scanning micro-mirror of a reference signal or feature on the referring microcell. This can be complemented by a small array of photosensors to refine the location detection and detect motion for easier tracking of the reference.

Such a system is more complex mechanically than using the angle sensors, and it has design issues associated with the selection of the emitter and signal used for cell recognition. A passive emitter such as a hot source may be blinded by the Sun or the Earth in the field of view. An active emitter using a LED creates the need for a signal generator at the other cell. The design of such an optical system is out of the scope of this work and it is not considered a viable alternative. So the preferred position sensor is an angular sensor in the links.

10.2.2 Global cells

The global cells also need attitude and position sensing. For these cells however similar technologies to the ones of nanosatellites can be used. In Chapter 3 is given a more detailed review of MST navigation and IMU units in development. From this review it can be said is that for microcells design highly integrated units such as seen on Figure 10.5 can be considered available in the time frame of interest.

10.3 Actuators

The actuators in the microcells are essentially the micro-propulsion system, and the link mechanisms and possible actuators used at the link junction.

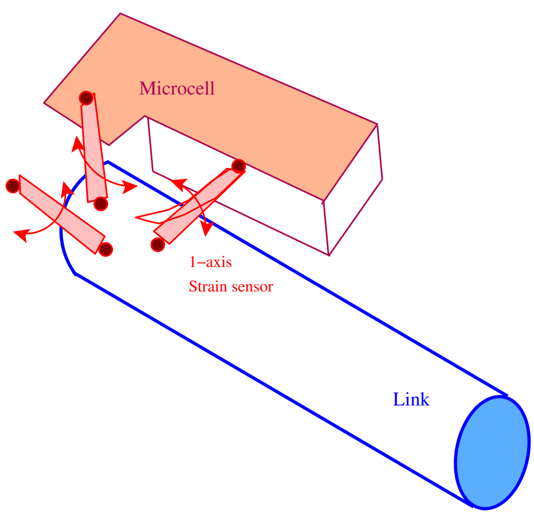


Figure 10.4: Inclination angular sensor configuration. It is simpler to use 3 1-axis articulated simple sensors rather than complex ones at the attachment interface between the link and the microcell.

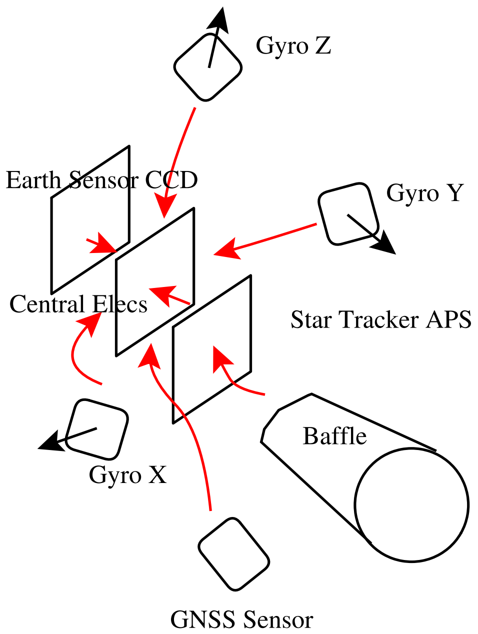


Figure 10.5: Integrated IMU for navigation are an important part of MST research

10.3.1 Propulsion

There are several alternatives for micro-propulsion systems (see Chapter 3). These are the various solid and liquid chemical propulsion, and to a lesser degree the electrical propulsion. The trade-off depends on their maturity and their compatibility with the concept of microcells, and on their efficiency in terms of propellant mass.

10.3.1.1 Technology trade-off

As seen in Chapter 9, estimating the amount of thrust needed by the controller is a difficult problem. The sizing of the propellant mass is normally based on the rocket equation, the lifetime, and the characteristic of the propulsion system which is the Specific Impulse I_{sp}, such that

$$I_{sp} = \frac{\int F \cdot dt}{\int \dot{m} \cdot dt}$$

with $\dot{m}$ the mass flow and F the thrust. I_{sp} depends on the propulsion system used. So the propellant mass M_p for continuous thrusting (so that $\int F \cdot dt = I = F \cdot t$ and $\int \dot{m} \cdot dt = M_p * g$) is such that

$$M_p = \frac{F \cdot t}{I_{sp} \cdot g}$$

with $g = 9.81 m.s^{-2}$ the Earth gravity constant and t the overall system lifetime in seconds. In this research the propulsion system has been sized for $I = 350$ Ns, due to heritage with respect to preliminary studies (undocumented here). For a propulsion with a thrust $F = 10^{-4}$ N this corresponds to a lifetime of 40.5 days of continuous thrusting. However, it should be noted that the microcell controller is designed such that it is not thrusting continuously, but as little as possible (see Chapter 9). The actual lifetime of the system depending on controller performance in discussed in Chapter 13. Thereafter the impulse of 350 N is used as a reference value in the trade-off of technology[1].

Of all the concepts considered, solid and liquid monopropellant are the most mature. Using micro-technology it is much easier to implement a solid propulsion system using the concept of so-called "digital" propulsion, that can deliver repeated and small thrust increments. Liquid propulsion is made more complicated by the creation of different flow conditions in miniaturised micro-pipes , mostly through low Reynolds numbers (in the order of one or less [Gad-El-Hawk, 2002]). As for bipropellant and electrical propulsion, they are still in early phases of development. In particular the problem with electric propulsion is miniaturisation of the power supply unit.

Technology	Solid	Liquid Monoprop.	Liquid Biprop.	Electrical
Thrust (mN)	20.	0.01 - 1.	up to 1,000	Varies
I_{sp} (s)	< 100	< 200	< 300	$> 3,000$
M_{prop} (grams)	370	180	120	10
Influence of "Miniaturisation"	Uses "digital propulsion"	Different Microfluidics regime	Micro-mixing more complicated	Small components by design

Table 10.3: Micro-propulsion alternative technologies for microcells. The propellant mass M_{prop} corresponds to a total Impulse $I = 350 \quad Ns$.

10.3.1.2 Subsystem configuration

The subsystem configuration depends on the type of propulsion system. For solid propellant there are issues associated with the overall assembly of successive layers of single thrusters as seen in Figure 10.6.

As regards a more feasible liquid monopropellant option, it is possible to design it as a monolithic wafer-level systems, providing the piping can be sealed, and it makes it an attractive solution which is retained as the baseline.

10.3.2 Link mechanisms

The size of links and rotary joint may preclude the use of MST for structural design. But it also looks difficult to use off-the-shelf articulated heads, which have larger

[1] What matters ultimately is to know the total impulse this provides, which is detailed above.

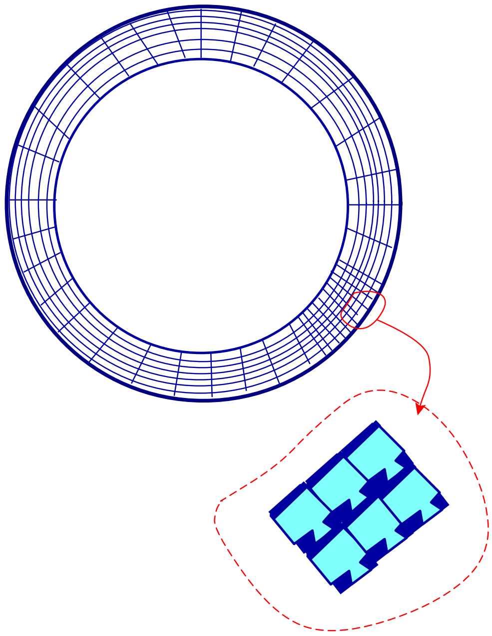


Figure 10.6: A “digital” solid propulsion system presents integration challenges

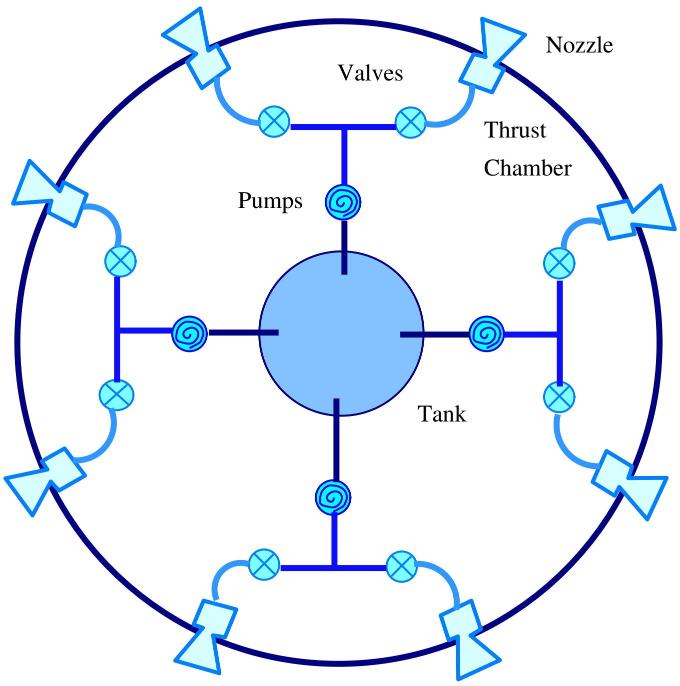


Figure 10.7: A liquid monopropellant system integrated on a single wafer. This allows to have multi-directional in plane thrust.

sizes and come as pre-packaged mechanisms[2] (see Figure 10.8a). For microcells a custom design is thus necessary for configuration reasons . The rotary head inserted into the microcell is surrounded by friction material (Figure 10.8b).

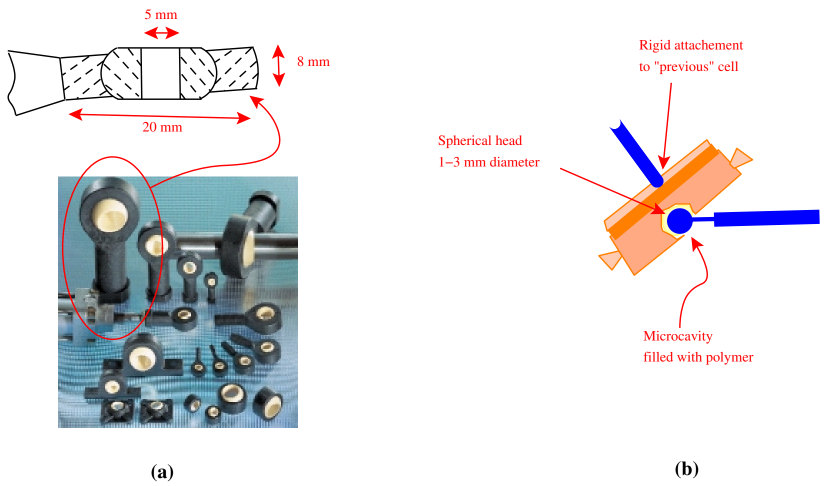


Figure 10.8: Link mechanisms - (a) Off-the-shelf - (b) custom-made, integrated with the micro-cell.

10.3.3 Link sizing

In Chapter 7 in Table 7.2 it was shown that the sizing of links is based on their maximum deformation given the loads to which they are submitted. These loads are normally enveloped by the thruster used to compensate them, so the forces should not be larger than this. For a maximum deformation of 1 mm the sizing of the links can be shown on Table 10.4. This assumes Carbon nanotubes having an average Young's Modulus of 1 TPa [Adams, 2003] and takes a 30% margin on the sizing of the section. In reality the actual modulus of the carbon composite would be less than the maximum value quoted above.

10.4 Platform functions

The platform functions are limited to physical accommodation, to providing power and data handling and very basic communication.

[2]The example presented on Figure 10.8 comes from the IGUS manufacturer (http://www.igus.com), but other off-the-shelf devices exist which are similar in size.

Force (N/m)	Length (m)	Moment of Inertia (mm^4)	Square equivalent section (mm)
10^{-3}	1	0.333	1.51
10^{-2}	1	3.333	2.86
10^{-3}	10	433.333	8.49

Table 10.4: Link size variation for different lengths and disturbance forces. The links are assumed to be made of Carbon nanotube composite (close to pure fiber composite), and are sized for rigidity as seen in Table 7.2.

10.4.1 Communications

For local microcells, there is no need for telemetry nor for remote sensing data transmission, because metastructures are decoupled and distributed control systems. So the only real need for communication in this case is when the reference position of the microcells is changed. This represents a very small amount of data to transmit. Even if one assumes that some of these transmissions are relayed via the global cells, the amount of data to be is still small, i.e. a few kilobytes per cell at maximum. To make systems as simple as possible, a Frequency Division Multiple Access scheme (FDMA) can be proposed. Using this scheme, a simple tunable analog circuit and a dipole antenna makes for a minimal communication system.

10.4.2 Power

Functions needed for space power systems are generation, storage, regulation and distribution.

Using Solar cells is an obvious alternative for power generation. It is considered realistic to assume 40% efficiency for space-grade solar cells on microcells in the development time frame, thus generating 50 mW of power per cm^2. For cell accommodation, there has been some attempts to combine solar cells on spacecraft structural materials, or create functional structures within the cell itself (see Chapter 3). But these are very process-dependant and it is difficult to generalise about the feasibility of using one side of Silicon wafer as solar cells. However the cells can always be bonded and connected on the microcell structure easily if this structure is made of Silicon.

The review in Chapter 3 has found out that whilst more promising alternatives exist for power generation they are not mature enough to be considered here. Solar cells remain the main possibility for energy generation.

As regards storage and distribution of energy it is driven by the power cycle of the microcell. The metastructure reference missions will have eclipses, either around the Earth or the Moon. In the worst case, about half the orbit is spent in eclipse. An corresponding adequate off-the-shelf battery is shown on Table 10.5.

Battery	Danionics
Dimensions (mm)	44x25x3
Mass (g)	22 g
Capacity (mAh)	770

Table 10.5: Commercial battery parameters that can suitable for Microcells.

10.4.3 Electronics

Electronic functions needed by microcells include:

- Low-level control of microdevices
- Basic data handling functions between the components
- Basic communication protocols
- Microcell control law implementation

The low-level control of devices is usually part of the microdevice itself. In principle a totally integrated microcell can also use direct communication between the chips via the microcontroller. However it is very likely that elements of microcell electronics will be procured separately, thus creating the need for an actual data bus. There are such buses which are suited to MST control and that can be used here, like CAN[3].

Finally, the central processor used to implement the cell control law is implemented as an ASIC-type technology. For microcell less than 50 gates are needed given the corresponding number of different devices. With current-day ASIC techniques a small design will be quite adequate [Einspruch, 1990].

So by using an integrated bus controller - processor ASIC it is possible to reduce the size of the corresponding chip, which is reflected in the mass and power budgets.

10.4.4 Structure and thermal

For structural integration the material of choice for structure has got to be Silicon. Silicon is proven to be a good material for Aerospace uses (see Chapter 3) which allows easy integration of all components of the micro-cell together if functional structure technology is used. It is assumed here that thermal design can be entirely passive by using the same functional structure technology. In fact it may be necessary to use a limited amount of regulation via heaters or heat pipes for critical microcomponents such as the battery. However thanks to the high system integration (see next section) fluidic loops can be included in the nanosatellite wafer design.

[3]Controller Area Network, see http://www.semiconductors.philips.com/buses/can/

10.5 System integration

The various microcell components are integrated into a coherent system defined by its product tree, and depending on the integration technology. The baseline retained for this system is used to estimate mass and power, and for costing.

10.5.1 Microsystem Integration

For microsystems such as the microcell there are really two possibilities for implementation. Assuming the current development of system-on-a-chip technologies comes to pass (see Chapter 3), it is technically feasible to build microcells as completely monolithic systems, with a relatively small number of parts and simple integration procedures.

On the other hand, it is also possible to specify the cells as systems built mostly from off-the-shelf electronic components packaged and connected together, with obviously a more complex integration process. This integration trade-off is a recurrent problem of system design [Halligan, 2001].

In the case of the microcell, he difference between the two architectures are outlined on Table 10.6. For sizing and defining the microcells the more favourable option of monolithic integration is assumed.

Integration	Hybrid (Nanosatellite)	Monolithic
Functional design	Bock-diagram type. Separate functions with codified interface data. More hardware.	All-in-one type. Low-level data controlled directly. More software.
Assembly	Flip-chip type bonding and wiring on substrates	Direct integration using systems-on-chips and functional structures.
Mass (g)	> 1	0.4
Size (mm)	$>$ 200x200x200	90x90x60

Table 10.6: Comparison of Hybrid and monolithic architecture for microcell system integration.

10.5.2 Product Tree

Based on the integration technology baselined, the microcell product tree is derived as seen in Figure 10.9. It includes three main subsystem, the sensors, the actuators, and the platform. The inner structure is where all sensors and actuators are connected. The outer structures includes the solar array and thermal insulation material. This product tree is used as a common reference for deriving the configuration, mass and power budgets, and for costing.

10.5.3 Configuration

A preliminary configuration for the microcells is shown in Figure 10.10 for the local model and on Figure 10.11 for the global model. Specific points shown about the configuration include:

Interface with links The next-in-line neighbour is articulated, whilst the previous one is fixed. This is done by using the same configuration but filling the cavity with either a polymer lubricant or an adhesive.

Central and Outer Structure The central structure includes all electronics and inner sensors. The outer structure is used for thermal protection and includes the solar array.

Modular tank size The tanks are made separate from the tank wafers and integrated later. They are sized for the propellant mass derived in section 10.3.1.

Structural Propulsion wafers The propulsion wafers are structural. They accommodate the interface with the tanks.

10.5.4 Power and Mass Budgets

Preliminary power and mass budgets are shown on Table 10.7 and 10.8 based on the product tree derived above. It can be seen that the microcells are below the 500 g mark, which means they are considered real integrated microsystems. The relative

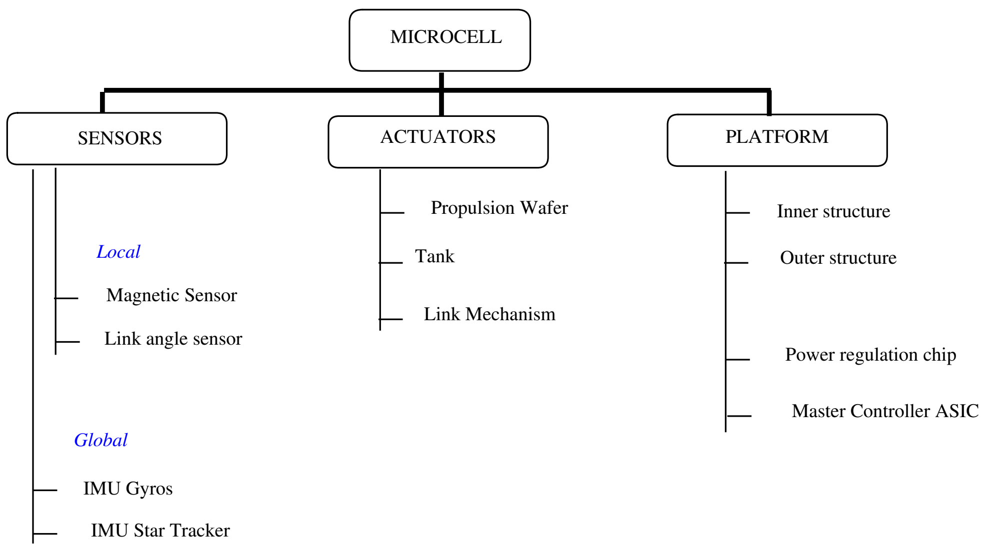
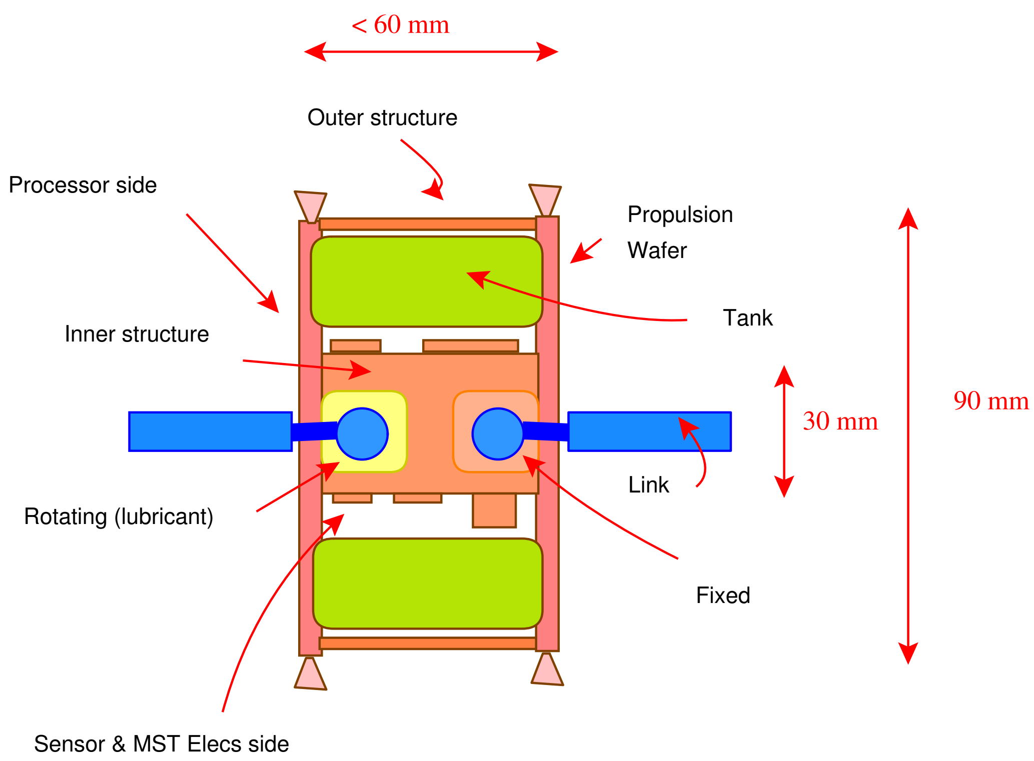


Figure 10.9: Microcell product tree derived from the design activities. This is used to evaluate mass and power, and for subsystem costing later.



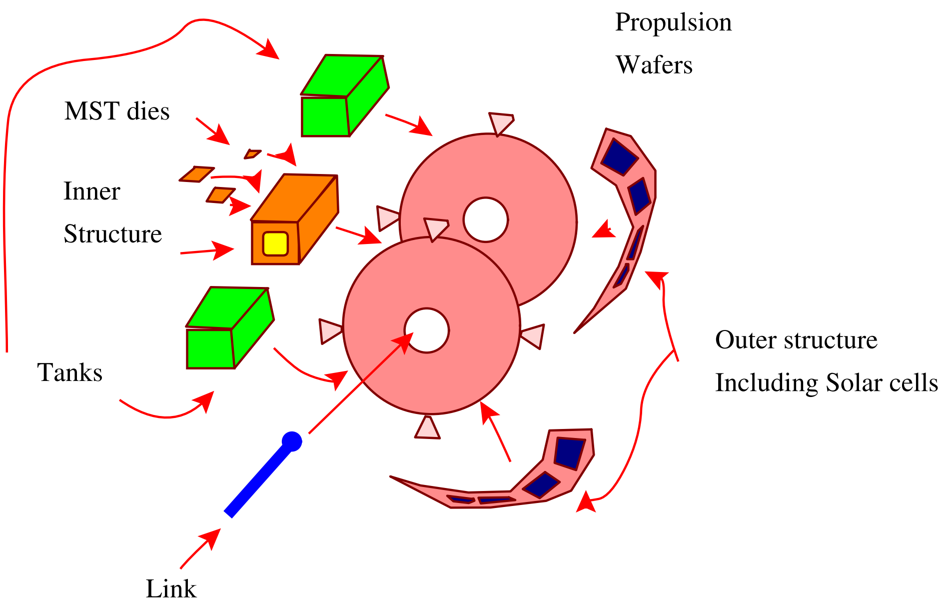


Figure 10.10: Local Microcell configuration and integration logic based on a monolithic architecture.

density expressed is relative to Silicon density (2330 km/m^3 used here), to account for machining of parts in the dies. Based on this the Solar cell area needed is also derived and is about 30 cm^2 for the global cells.

10.5.5 Manufacturing, Integration and Testing

10.5.5.1 Manufacturing

For the hybrid architecture the system-on-a-chip process is necessary, altogether with the functional structure technology, both of which are under research (see Chapter 3). This allows to use small microcomponents and to integrate them directly on the inner structure. The outer structure is fabricated for Solar cells on one side and for connection to the power system on the other. Then thermal interfaces can be added if necessary. The links can be batch-made and cut to order. These necessary technologies are to be taken into account when costing the metastructures in Chapter 11.

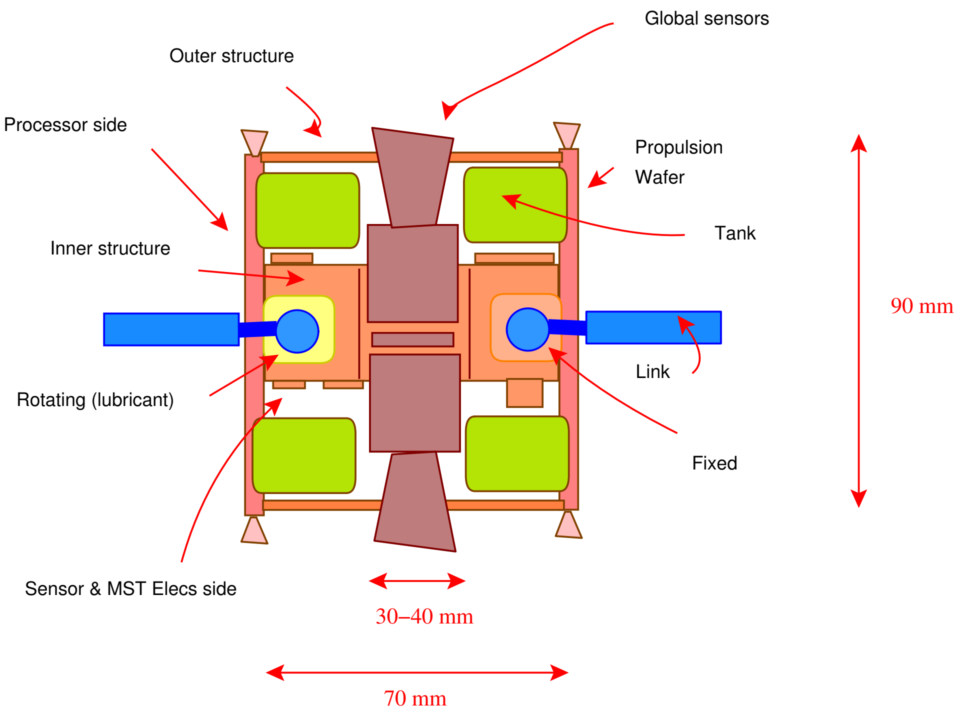


Figure 10.11: Global Mirocell configuration based on a monolithic architecture.

Unit	Shape	Dimensions (mm)			Volume (mm^3)	Relative Density	Number	Local (g)	Global (g)
	SENSORS								
Magnetometer	CMOS chip	10	10	1	100	0.75	3	0.50	-
Link angle sensor	Blade	5	1	0.5	2.5	1	3	0.02	-
IMU Gyros	Chips	25	25	2	1250	0.75	3	-	6.27
IMU Star Tracker	Cylinder	30	30	60	42412	0.15	1	-	14.19
IMU Elecs	Chip + Array	30	30	2	1800	0.75	1	-	3.01
	ACTUATORS								
Wafer	3.94"-10cm Cylinder	90	90	3	6362	0.9	1	12.77	12.77
Tank	Rect. shell 0.5 mm	50	50	37	3065	0.9	2	12.30	12.30
Link mechanism	Cavity with lubricant	20	20	20	8000	0.1	2	3.57	3.57
Electromagnet	Iron core coil	50	50	3	7500	0.5	1	-	8.36
	PLATFORM								
Central ASIC	CMOS chip	30	30	1	900	0.75	1	1.5	1.5
Power control	CMOS chip	10	10	1	100	0.75	1	0.17	0.17
Inner structure	Rectangular with holes	55	55	25	75625	0.2	1	33.73	33.73
Outer structure[4]	Polygonal shell	90	60	1	8435	0.9	1	16.93	16.93
	DRY MASS							81.5	112.8
	PROPELLANT MASS							180	180
	Margin (30%)							≈ 80	≈ 80
	TOTAL MASS							**340**	**381**

Table 10.7: Local and global microcell Mass budgets based on the product tree, the preliminary configuration, and adding an overall margin of 30%.

Unit	DC Power (mW)	
	Local	Global
SENSORS		
Magnetometers (3)	30	-
Link angle sensors (3)	30	-
IMU	-	100
IMU Star Tracker	-	100
IMU Elecs	-	50
ACTUATORS		
Wafer	500	500
Tank	0	0
Link mechanism	0	0
Electromagnet		30
PLATFORM		
Central ASIC	50	50
Power control	5	5
Inner structure	2	2
Outer structure	2	2
Margin (30%)	*183.1*	*251.7*
TOTAL POWER	**802.1**	**1090.7**
Additional Solar Array Sizing Margin	*30%*	*30%*
Solar Array surface (mm^2)	2085	2835
Solar array length (mm)	34.7	47.8

Table 10.8: Microcell Local and Global power budgets based on the product tree and the preliminary configuration.

10.5.5.2 Assembly and Integration

The assembly needs to be automatic, due to the large number of cells involved, i.e between hundreds and thousands depending on the applications. There is currently research going on into robotic assembly of microsystems [Faitkow, 1998], which tends to show it is technically feasible. The other technology needed is a relatively precise positioning of the elements, typically in the order of the size of connector pads, i.e 0.1mm. This is also possible with current technology [Puig, 2000]. A detailed discussion of the assembly and integration process is not relevant here, but the following points are important for industrial evaluation:

- Need for an assembly line and regular supply chains

- Need for micro-positioning and automated micro-systems assembly

10.5.5.3 Testing

In the case of an hybrid architecture, each component can be tested separately. At system level, and in the case of a monolithic architecture, a so-called “Integrated System Test” is necessary to test the complete functional sequence. This requires EGSE to be used for monitoring the various functions. A drawback of completely integrated systems is that they are very difficult to test this way. Moreover for microsystems it is difficult to ”plug in” connectors for testing systems. One possible solution is to include a wireless communication system in the microcell for remote monitoring. This is also proposed for upgrading EGSE for current spacecraft test benches, and may be adequate for microcell testing.

With this overview a first iteration of the design of microcells is complete. It is used to assemble and discuss the system baselines in Chapter 13, but first it is used to evaluate the cost of microcell and metastructure missions, as detailed in the next chapter.

Chapter 11

Metastructure Costing analysis results

Summary

The cost of developing the concept includes a development phase and an exploitation phase. For both of these, estimates of cost are based on the available literature for MST development and on internal industrial cost sources. Parameters are used to account for the efficiency of the R&D phase and the variation in mission specifications in the exploitation phase. The cost of the development phase is around 340 M€. Cost of operational missions vary between 70 and 180 M€.

11.1 Project Breakdown

As described in chapter 5, there are two different cost sources for the metastructures. These are, first the development of technologies and demonstrators, and second the design, realisation and operation of an operational mission. These are addressed differently.

11.1.1 Development phase

The development phase includes broadly the development of control system technologies for distributed systems, the R&D activities necessary to progress the microtechnology relevant for microcells, and the various processes and tasks that a space industrial needs to undertake to be able to design and produce these systems. These are analysed below.

11.1.1.1 Distributed systems

There are two tasks necessary to get the distributed control system working. The first one is really the enabler and builds on other research, whilst the later increases the cost benefit by reducing the amount of necessary propellant:

- Monitor and adapt non-linear distributed control theory to linked structures, and in particular to linked structures in space.
- Find optimisation technique to tune controller parameters for minimising fuel consumption.

11.1.1.2 Microcell Technology

The following microtechnology developments are necessary to be able to build a microcell:

- 3D Magnetometer, including the processing.
- GNC-on-a-chip, including 3 gyros, 3 accelerometers and associated electronics, or all this plus the Earth/Sun and Star sensors in the case of global cells.
- Propulsion Wafer, including specific pump design and nozzle design, and in particular tank integration.
- System-on-chip high-level integration, i.e. integration of wafer-level subsystems into a compact microcell (or nanosatellite). This also includes functional structure research.
- Micro-batteries, from using small batteries used in current miniaturised systems to using thin film and paper-thin batteries based on genuine MST.
- Micro-power sources using nuclear batteries, including radioactive decay illumination, and using nano-cantilevers.

11.1.1.3 Industrial Architecture

These are essentially related with mass assembly of microcells and integration of the very large structures.

- Mass micro-positioning and micro-assembly to be able to mount and integrate the microcells with the required accuracy, repeatedly and in a timely manner. For the level of serial production of nanosatellites and microcells some scaling and automating is necessary. This is reflected in the costing of this item.
- Mass and low-cost production of Carbon nanotube profiled rods and their low-level assembly in links for metastructures.

- Metastructure integration and testing. This is not well defined currently. It is unlikely that sufficiently large assembly facilities can be built, so it is necessary to use complex GSE to assemble some parts whilst others are folded, and also to test each pattern segment partially.

11.1.2 Exploitation phase

In contrast to evaluating one-off activities, costing the exploitation phase relies on using parametric practices in use in space industry, based on an estimate of a reference metastructure mission (see Chapter 5). There is also the evaluation of a demonstrator mission that is necessary to flight validate such new techniques as used in metastructures.

The mission costing can be derived from the space mission phases as used in ESA [1996]. Adapted to Metastructure missions, this means:

- Phase A: Mission Analysis and design, focusing on preliminary system design and trade-off. In this case a fixed cost has been used.
- Phase B/C/D: This is the phase of detailed design, production and integration of the space system. In the current case this means detailed design, manufacturing, assembly and test of microcells components and links. There is also an overhead for system design.
- Phase E: This is the launch and operations phase. In this case a launch cost is used based on the mass of metastructure (see Larson [2001] and C12).

11.2 Costing Approach

For each phase as seen above, costs are based on estimation of manpower resources and hardware procurement. In addition, a distinction between recurring and non-recurring costs is made for the exploitation phase, where microcells costing is based on serial production.

11.2.1 Development phase

The selected approach (see Chapter 5) recommends that milestones are defined for incremental results of R&D activities. These are, in chronological order:

- Demonstrating real-life controllability of distributed control systems.
- Building and testing successfully a real-scale and space-qualified microcell.
- Manage integration of the two previous ones into a spaceworthy metastructure which includes a demonstrated flight, hence the need for a demonstration mission similar in purpose to SMART missions of ESA [WWW, 2003].

- Subsequent milestones can be defined to optimise metastructures by minimising propellant use by the controller, and increasing microcell integration levels.

These milestones can so be related to the listing of technology R&D tasks identified in section 11.1.1. The structured progression towards metastructure technology is summarised in Table 11.1. In this table are also shown how each activity is evaluated for cost , and in particular so-called commonality factors. These factors take into account the fact that a number of technical developments are related to non-space specific fields of activities, or space-specific but not metastructure-specific tasks. At this point a simple percentage factor quantifies how much saving can be done on this by harnessing results from these other fields. Finally the cost items are evaluated based on previous cost estimates of MST developments [Lecuyot, A. and Snelling, M., 2003b] or on internal cost data (C13).

11.2.2 Exploitation phase

The exploitation phase is based on a bottom-up approach which costs the tasks identified in section 11.1.2. On Table 11.2 are shown the details of which tasks are costed. The parameters also described in this table are the ones used to do parametric costing for specific missions. The basic mission cost is based on the reference metastructure, and is used for the flight demonstration mission cost as well[1]. The sizing parameters used are:

- At microcell level: Mass ratio, representing actuator sizing, and control accuracy, representing sensor and control law sizing.

- At system level: The number of patterns ratio, representative the system design complexity. It is defined such that a system with twice as many patterns as the reference is 50% more expensive, which is a preliminary estimation.

- At mission level: The environment ratio, representing the gravity environment.

11.2.3 Summary of cost model

A summary of the cost model is shown in Figure 11.1. It shows that it is in line with the method selected of separating development activities and exploitation activities insofar as costing is concerned.

[1] With a premium of 20% in this case for additional design and in-orbit verification activities.

Milestone	Estimation basis: Manpower	Hardware	Commonality Factors
Distributed controller	Estimation	10% of Manpower	Control, 0 to 1
Distributed System design			
3D MAG-on-chip	MST Devlpt cost	50% of Manpower	MST, 0 to 1
GNC-on-chip	MST Devlpt cost	50% of Manpower	MST, 0 to 1
Propulsion Wafer	MST Devlpt cost	50% of Manpower	MST, 0 to 1
Micro-batteries	MST Devlpt cost	50% of Manpower	MST, 0 to 1
Functional structures	Estimation	50% of Manpower	MST, 0 to 1
Functional Microcell			
Development of AIV Sequence	Estimation	-	
Mass Micro-assembly	Industrial prices, clean room work		
Mass production of links	Industrial prices, composite materials		
Demonstration mission	Reported from basic mission costing		1.2 Margin
Spaceworthy metastructure			
Control law Optimisation	Delta from controller development (50%)		
Optimised Controller			
Micro Power source	MST Devlpt cost	50% of Manpower	MST, 0 to 1
Microcell-on-chip	Double of Functional cell cost		
Optimised Microcell			

Table 11.1: Detailed costing hypotheses for the development phase.

11.3 Results

11.3.1 Development phase costing

The results of the basic development costing is shown in Table 11.3. It can be seen that the demonstration mission is a substantial part of the development phase cost. The predominance of hardware cost for this particular item is due to the fact that it represents the procurement of a complete mission. So it actually includes lots of manpower cost hidden in the mission and spacecraft design. The associated manpower cost corresponds to effort necessary to include this mission in the overall

	Basis for costing	
Cost Item	Non-Recurring	Recurring
	UNIT CELL COSTING	
REFERENCE CELL		
Sensor wafers	GNC subsystem design	SOAC production
Propulsion Wafer	Propulsion Subsystem design	SOAC production
Inner structure Mechanical Subsystem design	SOAC production	
Outer Structure	Power subsystem design	SOAC production
Subsystem Integration	Microsystem design	30% overhead
LINK		
Link production	-	Composite Manufacturing
OTHER COSTS		
Launch	5k€per cell	-
	PARAMETRIC RATIOS	
Cell Mass (Actuator ratio)	Direct ratio	Direct ratio
Cell Accuracy (Sensor ratio)	Direct ratio	Direct ratio
No of patterns (Complexity ratio)	Ref. cost $\times(\frac{1}{2}Ratio + \frac{1}{2})$	
Gravity (Mission ratio)	Ref. cost $\times(\frac{1}{2}Ratio + \frac{1}{2})$	
	MISSION COSTING	
PHASE A		
Preliminary design	2,000 k€	-
PHASE B/C/D		
Cell design & Build	"ratioed" cost	"ratioed" cost
Metastructure cost	-	Based on patterns
Metastructure complexity	"ratioed" cost	-
System Integration	30% overhead	-
System Design	"ratioed" cost	-
PHASE E		
Launch cost	-	-
Margin	30%	30%

Table 11.2: Costing of Generic and Reference mission for a metastructure in exploitation phase.

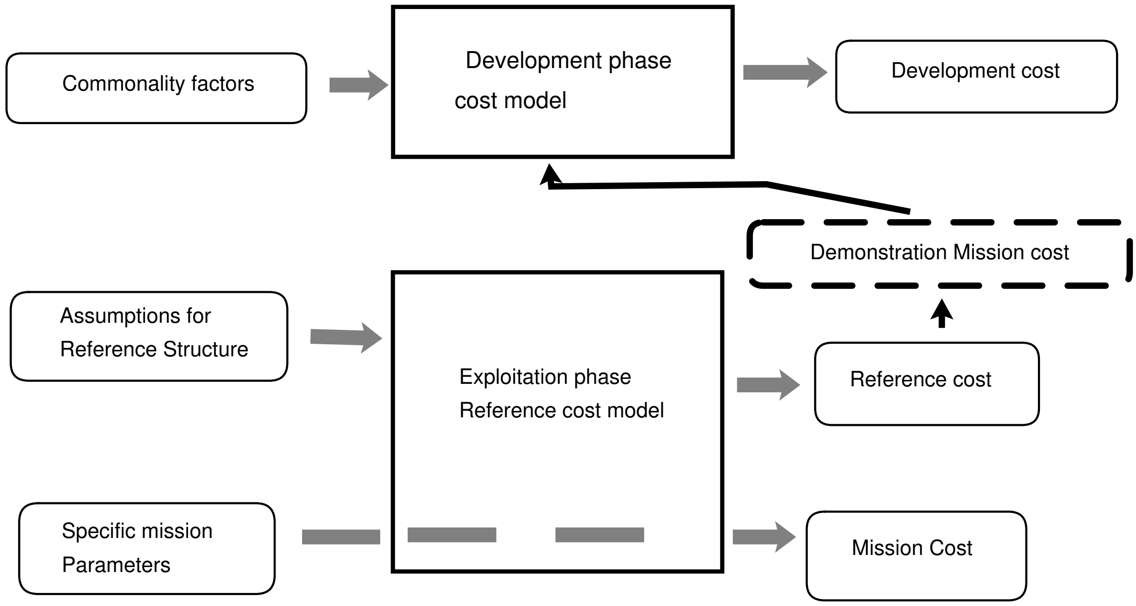


Figure 11.1: Cost model flowchart.

development program (such as in-orbit performance tests). In general, the way the model is set-up shows that hardware development costs are higher than control algorithms costs.

When factors are entered, the results are shown in Table 11.4, with and without the demonstration mission costs. It can be seen that high has a real impact on the development cost, which means that space-specific costs are not overwhelming for this R& D development exercise. As expected, a high commonality in MST development is more beneficial.

11.3.2 Reference missions costing

The results of the reference mission costing are shown in Table 11.3.2. The reference missions can then be costed according to various choice of factors, and various patterns used. This is shown on Table 11.6. The factors used are such that:

Interferometer The environment is simpler as it is in Lagrange point orbit. Equally the interferometer is a simple array involving linear patterns. So mass and mission factors are simple. Given that it needs centimetric accuracy, it is also considered simpler here. The Earth interferometer is not considered here as it does not work technically at the moment.

Solar concentrator - Earth The solar concentrator is more complex (i.e. 3D) than the reference structure. It also has longer operational life and needs cover, hence the larger factors.

Item	Manpower, k€	Hardware, k€	Total, k€
Distributed Controller	16,800	1,680	
DISTRIBUTED CONTROL			18,480
3D MAG-on-chip	5,000	5,000	
GNC-on-chip	5,000	5,000	
Propulsion Wafer	5,000	5,000	
Micro-batteries	5,000	5,000	
Functional structures	5,000	5,000	
MICROCELL			50,000
Metastructure AIV	5,000	5,000	
Mass micro-integration	10,000	1,000	
Mass production of links	10,000	10,000	
Demonstration mission	15,700	146,500	
SPACEWORTHY CONCEPT			230,200
Control Optimisation		9,240	
OPTIMISED CONTROLLER			
Power Source	5,000	5,000	
Microcell on a chip		50,000	
OPTIMISED MICROCELL			60,000
TOTAL			**340,960**

Table 11.3: Basic bottom-up cost for Development phase. The very large hardware cost for the demonstration mission actually includes a lot of engineering manpower, as it represents the procurement of a complete space mission.

FACTORING	COST M€	No Demo COST, M€
C=0,M=0	341	179
C=0.5,M=0.5	282	120
C=0.25, M=0.25	311	149
C=0.5, M=0	327	165
C=0., M=0.5	290	128

Table 11.4: Variation of Development phase cost with commonality factors (C=Control, M=MST).

Solar concentrator - Moon This mission is similar to the previous one except for the environment which is more benign (Moon gravity, no atmosphere).

Item	Non-recurring, k€	Recurring, k€	
		Local	Global
CELL COST			
Sensor wafers	1,200	5	10
Propulsion Wafer	2,000	10	12
Inner structure	900	2	3
Outer Structure / Power	1,200	5	5
Subsystem Integration	900	6.6	9
Total Cell	6,200	28.6	39
Link cost	-	1	1
PHASE A			
Phase A	2,000		
PHASE B/C/D			
One pattern	-	280	
Metastructure	-	80,920	
System Integration	1,860		
PHASE E			
Launch	13,005		
TOTAL			
Totals	10,006	93,925	
Total with Margin	**135,180**		

Table 11.5: Cost of reference metastructure Mission used for parametric analysis.

Mission	Factor Comb.	Cost, M€
Reference structure	Ma=1,Ac=1,Mi=1	135.2
Interferometer	Ma=0.75,Ac=0.75,Mi=0.75	69.5 1
Interferometer	Ma=1,Ac=1,Mi=1	111.5
Interferometer, More globals	Ma=0.75,Ac=0.75,Mi=0.75	72.7
Interferometer, longer links	Ma=0.75,Ac=0.75,Mi=0.75	47.4
Interferometer, shorter links	Ma=0.75,Ac=0.75,Mi=0.75	92.1
Earth Concentrator	Ma=1,Ac=1,Mi=1	58.4
Earth Concentrator	Ma=2,Ac=1.5,Mi=2	168.8
Earth Concentrator, More globals	Ma=2,Ac=1.5,Mi=2	177.4
Earth Concentrator, 2km	Ma=2,Ac=1.5,Mi=2	639
Moon Concentrator	Ma=2,Ac=1.5,Mi=0.75	155

Table 11.6: Results for reference missions costing.

11.3.3 Sensitivity of estimations

The sensitivity is of course to the factors used to characterise missions, but also to the reference values used in costing the reference missions. The impact of changing these values is shown in Table 11.7. It appears that an important factor is the estimation of the development cost of a microcell component.

Result	Previous value	Parameter changed	New value
Reference Mission	135.2	Hourly rate (0.1 to 0.075)	132.5
Development phase	341	MST research cost (10 to 5)	291
Development phase	341	Industrial costs (halved)	325

Table 11.7: Sensitivity of results to basic cost values.

Part IV

DISCUSSION

Chapter 12

Concept Assessment

Summary

Based on the results from all previous analyses, the system baselines for both reference missions can be assembled. These appear to be realistic estimations of the mass, size and performance of the missions. However in terms of lifetime, the concept as analysed and simulated does not perform well. Improvements to the baseline are proposed, to minimise the disturbances and optimise propellant consumption. When compared overall to other alternatives, metastructures present the advantage of having potentially a more robust architecture, a larger scope of applications, and a high commonality with MST developments. The low maturity of the deployment phase needs to be addressed to remove a weakness of the concept.

12.1 Metastructure baseline Performance

In order to assess the concept, a baseline system is defined according to the results of design and analysis efforts in Chapters 9, 7, 10, and 11. This is derived for both reference missions. The performance of these baselines is then examined.

12.1.1 Common features

The baseline features common to both missions and derived from Chapter 6 and 7 are:

- The selected concept of rigid links and articulated joints for system architecture.
- The use of distributed On-Off controllers for each microcells.
- The use of either local or global cells, depending on the reference being used for control of the position.

- Cells mass is 340 g for the local ones and 381 g for the global ones.
- Links size is defined as per Table 10.4 in Chapter 7, and the mass is derived from a density of Carbon Nanotubes of 1500 kg/m^3 [Adams, 2003].

The features common to both missions and the basic system and performance parameters are listed in Table 12.1. It is worth noting that the subsystem parameter of thruster sizing listed in the table has an impact at system level, as the total impulse provided (and hence lifetime) depends on the thruster capacity.

Parameter	Value
Architecture	distributed controllers and rigid links
Link sizing	such that $y_{max} = \frac{Pl^3}{3EI}$
Cell reference	Local: next-in-line vector
	Global: Reference in local frame
Cell Mass	Local: 340 g
	Global: 381 g
System parameters	
Orbit	Mission dependant
Unit pattern	Dynamics dependant
System pattern	Configuration dependant
Performance parameters	
Position accuracy	Controller and dynamics dependant
Lifetime	microcell and controller dependant
Subsystem parameter	
Thruster capacity	depends on controller and orbit

Table 12.1: Common features and parameters for baseline definition at system level.

Thus the definition of a baseline for both reference missions must derive basic parameters of unit pattern design, thruster capacity, and link design from the results of analyses. Then the system parameters and the overall mass and cost of each mission are derived from these basic parameters.

12.1.2 Interferometer baseline

The results of the dynamics analysis have confirmed the controllability of the interferometer for the case of a Lagrange orbit, but not for the case of a low Earth Orbit. So only the former case is considered. As described above the baseline depends on the thruster size and on the configuration (based on the unit and system patterns) which in itself depends on the accuracy.

Thruster sizing depends on the necessity for fast reconfiguration of the structure. Three values have been simulated, 0.1, 0.01 and 0.005 N. Convergence is demonstrated for 0.1 and 0.01 values in less than 1000 s or less than 20 minutes (see Figure 9.17), assuming ideal sensing with On-Off fixed thrust actuators. It can be reasonably expected for lower values as well, though the lower limit is not found by the analysis. Figure 9.16 tends to indicate that the sizing of the thruster is the same for all baseline changes, with of course the time to stabilisation depending on the thruster capacity.

The final sizing of the thruster depends on the necessary movements of the interferometer baseline. The instrument may either need to scan one particular baseline value, or need to sometimes scan the range of baseline values to detect fringes, and in general this is understood here to be a slow process as it involves "live" image processing.

So a medium to low value of thrust to mass ratio is thought to be adequate and 0.01 is retained as the baseline. Thus, for a constant mass to thrust ratio and an envelope cell mass of about 400 g, a 0.04 N thrust is necessary. This is used for the performance assessment in the next section.

As for the configuration, the unit pattern that appears to have the best accuracy based on the Figure 9.19 is the "3 globals" pattern, which is retained as baseline.

Thus the baseline mass and cost of the interferometer based on the mission profile derived in section 6.6 are estimated. The interferometer baseline is summarised in Table 12.2.

System parameter	Value
Orbit	Lagrange halo orbit
Unit pattern	2L-G-L-G-L-G-2L
Links	12.5 m length, 3.77 mm size)
System pattern	2×10 (cross)
Thrust capacity	0.04 N
Size	1.2 km square
Mass	97.1 kg
Price (Max)	72.7 M€

Table 12.2: Interferometer baseline configuration. The thrust capacity and configuration pattern is derived from dynamics analysis, and the mass and cost are in turn estimated based on this configuration.

12.1.3 Interferometer performance

Figure 9.18 tends to show that RMS position errors for the structure in stabilised configuration (after manoeuvre) are below 0.02 m, whilst the requirement in Table 6.1 is 0.5 m, which means that the interferometer meets the position control requirement. This result assumes that the sensors and actuators are perfect. When broken down at node level it can be seen on Figure 12.1 that the discrepancies between the nodes are not large, and weakly depending on the configuration. So the metastructure interferometer performs well when it comes to position accuracy.

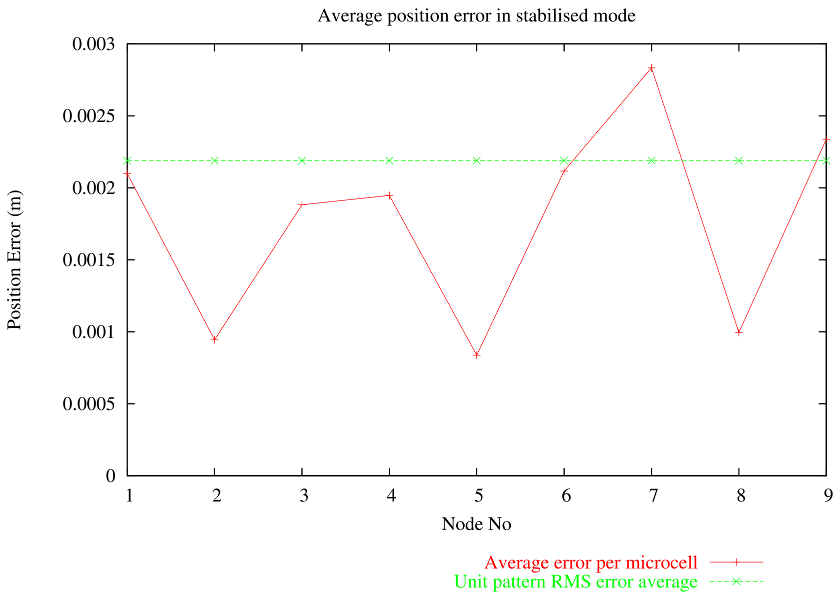


Figure 12.1: Average of position error for individual nodes after stabilisation in new configuration. The errors are weakly dependant on the node position in the unit pattern, but not by a large amount.

The other performance parameter is the lifetime, which is dependant primarily on propellant use. Table 9.3 shows a normalised use of about 50% for one manoeuvre of less than 1000 s. For the thrust capacity of 0.04 N (see section above) the overall impulse used for one manoeuvre is

$$I = 0.04 \times 1000 \times 0.5 = 2\,Ns$$

By considering that:

- All manoeuvres use a similar amount of propellant
- One manoeuvre per week is required
- a 20% margin is applied to account for propellant use between manoeuvres

the lifetime is found to be about 140 weeks, or 3 years. Thus it does not strictly speaking meet the requirement of 5 years, but offers a similar performance to what is required. The possibility of improving the capacity of this baseline is discussed in section 12.2.

12.1.4 Solar concentrator baseline

The results of the dynamics analysis have also confirmed that the Solar concentrator is controllable, even in the orbit assigned to it (6000 km Earth orbit).

One possible configuration for which convergence has been demonstrated is for a cell mass of 500 g and a thrust capacity of 5 mN. This configuration uses 10 m links in a parabolic pattern. Thus a thruster capacity of 5 mN corresponds closely to the actual microcell mass.

So the configuration is as shown in Table 12.3. This configuration supposes that some patterns are added to the basic parabolic cross structure so as to make it possible to lay the cover on. This is shown in Figure 12.2 where locations for some of the additional pattern is shown. The additional mass for a 1000x1000 thin film cover is based on the numbers by [Jenkins, 2001b] and assumes a film density of 1.4 g/cm^3 for a 1 μm film.

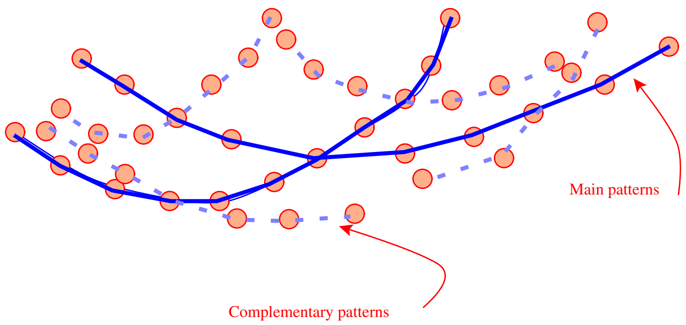


Figure 12.2: Assumed configuration for the Solar concentrator baseline. The mass and cost calculations assume that more patterns are added (seen as dotted lines on the figure) across the ones in the main directions (seen as full lines on the figure) to be able to deploy the thin film cover in a correct shape.

System parameter	Value
Orbit	Earth or Moon
Base pattern	5L-G-5L for 10 m links (8.5 mm size)
No of patterns	6 × 10 (cross)
Size	1 km width
Thrust capacity (mN)	5
Total Mass	2000 kg
Structure Mass	593 kg
Film Mass	1400 kg
Price (Max)	168 M€

Table 12.3: Solar concentrator baseline configuration.

12.1.5 Solar concentrator performance

The mission performance of the Solar concentrator is demonstrated in Figure 9.22, which shows that the shape and position is maintained to an accuracy better than 0.01 m. This compares favourably to the mission requirement of 0.014 m as seen on Table 6.3. The accuracy requirement thus appears to be feasible.

As for the operational performance, the simulations in this work tend to show a more or less continuous thrusting of the structure. In such conditions of course, the lifetime of the Solar concentrator is very short. In these conditions, to get a lifetime of one year a propellant mass of 657 g is necessary compared to the 180 g used now. On this account the current baseline is not meeting the mission requirement which is also of 5 years. It is to be noted that this behaviour may be very dependant on simulation parameters (in particular the time step size) and that the situation may get better with refined simulations. Such simulations are presented in section 12.2.3.

Having described the baseline it appears that the lifetime or propellant use requirement is the most challenging. So possibilities of improvements to the baseline design are proposed.

12.2 Improvements to baseline

From the previous section it can be said that, with respect to the reference missions baselines:

- In general the metastructures designs studied do meet the controllability and mission functionalities for each of the reference missions at least in one of the possible environments.
- Based on the baseline of cells and link design, the overall system baseline configuration, mass and cost appear to be within realistic target, compared to masses of space missions expressed in hundreds or thousands of kilograms, and prices expressed in hundreds of millions of Euros.
- However in terms of operational performance it appears that the lifetime of the cells is limited, in particular for the Solar concentrator mission.

The downsides of the concept are mostly due to the lack of efficiency of the controller on one side and to the lack of optimisation of system parameter on the other. This is addressed below at system level, and for the microcell and controller system components.

12.2.1 System design

From a technical design point of view, the main optimisation possibilities at system level are in system architecture, in particular in link and design pattern.

For links, changing the cross-section shape of the link may save up a factor of 2 on the link mass by applying techniques from resistance of materials.

The patterns may also be further optimised. One possibility for instance is to make the links gradually shorter as differential gravity forces increase, or to explore different pattern variations to the ones described in Chapter 9. At this point it is difficult to quantify the potential benefits of this, as the current analysis is limited to links and patterns of regular distribution and equal lengths.

12.2.2 Microcell design

By design, the cell controllers are activated when:

- The position or shape of the complete structure is off from the desired one,
- The position is globally correct but residual dynamic disturbances remain (like a correct position but with a non-zero speed),
- The disturbance forces constantly present, like gravity differentials, create a distortion too large with respect to the positioning requirement.

The first cause of action is inherent to the metastructure concept, but the two others can waste a lot of propellant to correct quite minor disturbances.

So at microcell level, this could be alleviated by controlling the friction, either passively (by joint design), or actively. The amount of stability this will bring in the system depends of course on the coefficient of friction. Using a typical value of 0.15 for this coefficient one could assume that the propellant consumption is reduced as much, and so is increased the lifetime. Another possibility is to switch to the "lock-up" concept described in section 6.1 and rejected before. By enabling the local microcells to lock their relative position when it is correct, it is possible to avoid this problem. This, however, creates a more complex system as is discussed in Chapter 13. This could potentially decrease the propellant expenditure and thus increase the lifetime by a significant amount.

12.2.3 Distributed controller

The results of the simulation of the distributed controller present two problems; First, the fact that it is possible that time step as a numerical simulation parameter biases the result, and second the actual nature of the controller and its implementation. These are considered separately below.

Controller sensitivity to time step

A possible source of discrepancy is in the numerical simulation of the controller. This is investigated by simulating the reference metastructure in the same conditions but for different time steps of numerical integration. In Figure 12.3a and b is seen the thrust history of the corresponding simulation results, whilst in Figure 12.3c are seen the Impulse history. It can be seen that the behaviours are similar and that the resulting total Impulse is also similar. This is due to the fact the maximum error allocated to the controller is very small (here $e_p = 0.001\,m$), and also to the switched nature of the controller. So from these limited sensitivity study it appears that no numerical artifacts create a bias in the results.

Microcell control system design

The cell design is based on a controller used in the simulations which is truly distributed, in that each controller is independent from the other. At this point the controllers used are probably simplistic. The thrusting strategy is not necessarily convenient to the problem at hand:

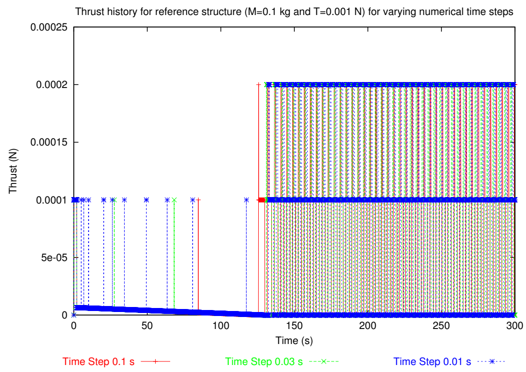
- The distributed nature of the controllers is not taken into account.
- A fixed thrust is considered.
- The thrusting is done continuously instead of in pulses.

There is a substantial amount of work done in non-linear control, in particular in the domain of smart structures (see Chapter 4). One interesting and relevant path specialising on the distributed control of spatially interconnected systems tends to show dramatic improvements can be obtained with clever controller design [D'Andrea, 2003]. Table 12.4 extrapolates results from this study that compares various controllers for distributed system. The grade-like efficiency estimations[1] on this table are estimated *as part of this work*, and are not presented in the work that is referred to.

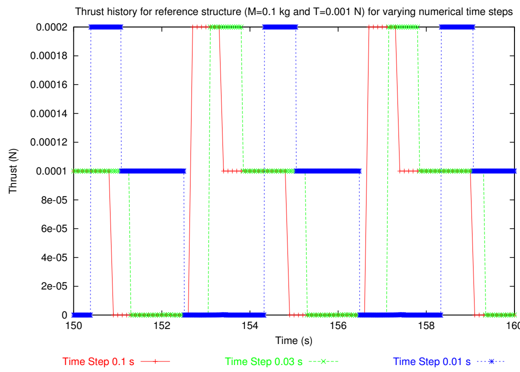
Controller type	"Efficiency" estimation
Open loop	1
PID	3
$H\infty$ and $H2$	4-5
Novel decentralised	7

Table 12.4: A proprietary estimation of the improvements in control "efficiency" that can be brought by using dedicated controllers for distributed systems. The figures here are simply qualitative estimations based on the results of the work by [D'Andrea, 2003], which does not present these figures but present qualitative simulation result visualisations instead.

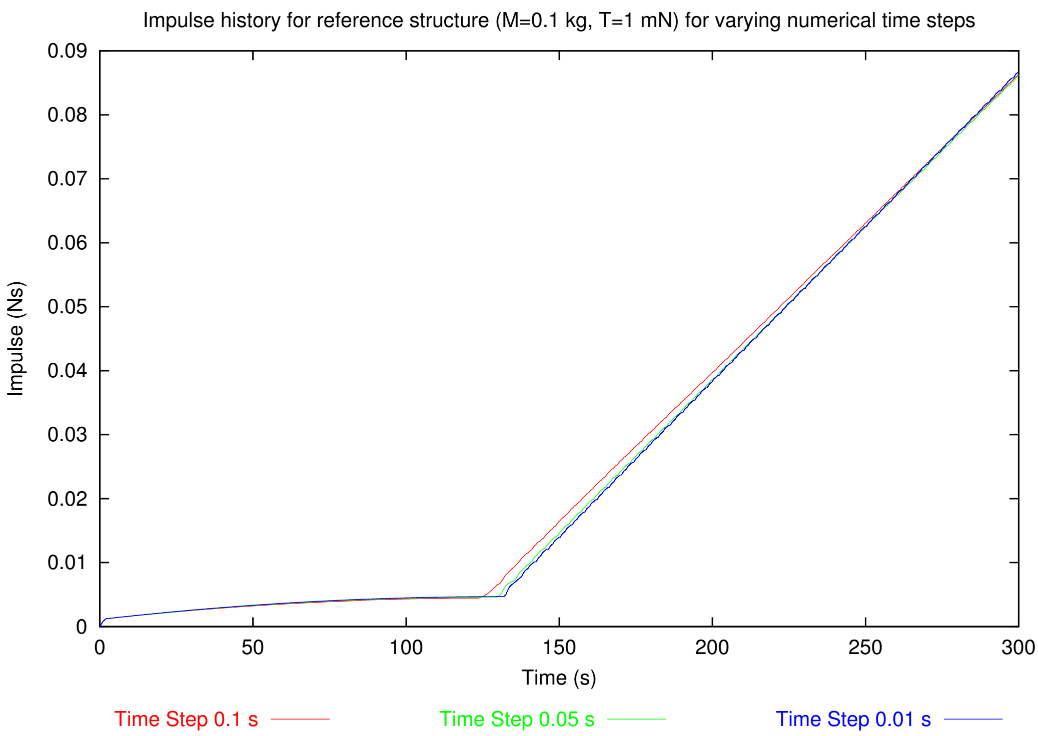
[1]On an arbitrary scale of 1 to 10



(a) Instantaneous thrust history for various time steps



(b) Zoom of Instant Thrust History.



(c) Impulse history for various time steps

Figure 12.3: Analysis of Instant Thrust and Impulse variation with numerical integration time step for the reference metastructure in 1000 km Earth Orbit. No major difference is observed in the overall Impulse.

In the present case it is assumed that an On-Off controller is slightly better that an open-loop one and is rated 2 on this scale, therefore simplistically and potentially gaining a several-fold decrease in propellant consumption and corresponding increase in lifetime by applying optimised decentralised controllers.

To summarise the benefits to be obtained from baseline improvement it can be said that:

- The position control and stability can be brought within limits acceptable by the mission, as it is already quite similar to the mission requirements.
- The lifetime can potentially be expanded significantly, meaning possibly a lifetime of one to two years for the concentrator, and three to five years for the interferometer.

This means the mission and operational performance parameter targets may be met adequately after design refinements.

12.3 Comparison to alternatives

Having suggested that it may be possible for the metastructures meet the reference missions requirements using potential improvements in baseline design, it is now possible to compare them against alternatives technologies.

The comparison is made against overall end-to-end concepts. Thus one must first acknowledge the issues associated with metastructures that the system analysis has not considered so far. These are the launching and deployment phase, and the inclusion of solid thin films in structure.

Finally, the comparison is done in relation with the objectives of the research of definition, quantification and assessment of the concept. This means that the alternatives are qualitatively compared with respect to system design features (i.e. definition), system behaviour and performance (characterisation), and subsystem design and implementation (characterisation/assessment).

12.3.1 Metastructure overall concept

In the work on the concept as reported in previous chapters, two issues identified in Chapter 7 have been scarcely addressed: The launch and/or deployment phase, and the configuration with a solid cover. These are discussed below at conceptual level.

12.3.1.1 Launch and folding

The configuration of a metastructure in “folded” configuration is that of a stack. If that is so, then it is possible to assign to each cell a specific reference for this phase. As regards local cells, it should be such that the direction vector is oriented towards the desired position, i.e. downwards or upwards for a linear position for instance. The global cells can keep the same reference. For all cells however the control law should allow time for passive deployment as well, that is to use non-continuous thrusting (see section 12.2.3). Mechanically the stowed configuration needs the cells to be able to rotate with respect to the several links around it, as shown in Figure 12.4.

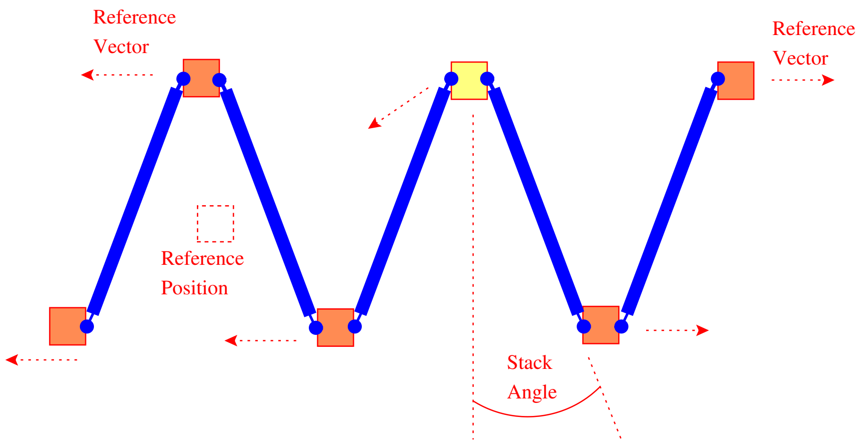


Figure 12.4: The problem of Metastructure deployment. Deployment can be done by changing the reference, but stacking depends on the configuration and stacking angle.

This is different from the currently considered configuration where each cell is fixed to the previous link for ease of orientation of the thrusters. Even with a more flexible configuration, the stack size of a complete metastructure is large. A stacking angle of 5 degrees[2] means the stack size is 87 m[3], which makes it impossible to launch with current launchers.

So whilst one can conceive how the deployment issue is a problem, the launch issue may in fact be a weakness of the concept. Solutions to this may include a different, more flexible design of the revolute joint, or, in long-term concepts, in-orbit assembly of the structure from several parts launched separately.

12.3.1.2 Solid covers

The other issue is the presence of solid covers. It is interesting to note that the mass of a thin film is actually larger than the mass of the metastructure as it stands (see Table 12.3). What may have been not taken into account here is the fact that more unit pattern superpositions may be needed in order to control the shape of the cover accurately. So this result is to be treated with caution.

[2]corresponding to a gap of 4 mm along the 45 mm length of the microcell
[3]for a link length of 10 m

One potential configuration problem is that, as the microcell is designed currently, the solid covers have got to have holes as the cells protrude out of the structure plane. That may turn out to be a problem for the Solar concentrator mission where thrust plume may burn the cover or microwave signals may be perturbed. Solutions may include either a different configuration of the microcell, or a discrete cover which is not present around the microcell.

Finally, the other impact of using a solid cover may be an additional disturbance in the way of Solar pressure. Solar pressure as a disturbance on an individual cell is manageable, as for a 10×10 m cell the solar force is in the range of 10^{-3} N, which can be corrected by 2 to 4 micro-thrusters as currently designed (so as many cells). However at system level it may prove a large source of propellant consumption. This is not, however, different from other large structures in space which are all submitted to Solar pressure. In this case a possible solution is to use the global cells to change their global position so that an orbital correction manoeuvre is performed to correct the orbit drift.

Having thus considered the concept in most of its aspects, the comparison can be made with alternatives ones.

12.3.2 Comparison with alternatives

The concepts compared are, as described in Chapter 4, the deployable structures, the active or controlled smart structures, the inflatables, and the formation flying.

The comparison is made with respect to the objectives of the research, which are to define, characterise and assess a concept. So to support the strategic analysis the comparison is made on system design features (concept definition), on system behaviour and performance (concept characterisation), and on implementation and subsystem design (concept assessment). In particular, the specific criteria are:

- System design features, including:
  - Concept Formulation
  - Architecture
  - Applications identified
- System behaviour and performance
  - Dynamics
  - Mass range
  - Positioning performance
  - Orbits and environments possible
  - Autonomy

- Implementation and subsystem design
  - Components
  - Technology needed
  - Technology maturity
  - Technology commonality
  - Development cost

Table 12.5, 12.6 and 12.7 show the qualitative comparison of all concepts with respect to the points above.

Alternative	Metastructure	Deployables	Active structures	Inflatables	Formation Flying
Concept formulation	Using MST in minimal design for large structures	Extending "mainstream" capacities	Realising Distributed Parameter Systems	Minimising structural mass for functional surfaces	Using only the active nodes
Architecture	Totally decentralised and distributed, can do rotating structures	Sequential and single point failure	Centralised but actuation distributed	Centralised with single point failure	Variable but usually centralised
Applications identified	Large slender structures, possibly many, can change shape	Many currently, breaking down at current size	None clearly identified, considered from a generic point of view	Reflector clearly, Human spaceflight possibly	Interferometry

Table 12.5: Comparison of alternative large structure concepts with respect to system design features.

12.4 Strategic Analysis

12.4.1 SWOT diagram

Based on the tables in previous sections, it is now possible to build the SWOT diagram, by considering the strengths, weaknesses, opportunities and threats of the concept, related to the system features, the system behaviour, and the implementation considerations. This is shown on Table 12.8.

12.4.2 Synthesis and Recommendations

From a qualitative and preliminary point of view, it can be proposed from the SWOT analysis that the architecture and the functions offered by metastructures tend to have unique advantages (seen as a strength), which may make them suitable for many applications (seen as an opportunity). This is thanks to the point of view of overall system engineering that was used during the design work.

On the other hand, the low maturity and high development costs associated (seen as threats and weaknesses) come from the novelty of the concept. However, it is to be noted that the high commonality possible with other developments can balance this problem to some degree. To conclude, some recommendations can be made with respect to technology planning of the metastructures:

- Remove the weaknesses and threats associated to distributed control by applying or developing a more adequate controller.
- Remove the weakness associated to low maturity by considering the folding, deployment and launch phase in more detail.
- Explore the opportunity of commonality by identifying projects that may be part of the development plan for metastructures.
- Balance the low maturity threat by exploring other possible missions, ultimately to find niche applications.

Alternative	Metastructure	Deployables	Active structures	Inflatables	Formation Flying
Dynamics	Good in disturbance mode. Less so in standard mode. Enables ultra-large structures	Uncontrolled. Large structures get flexible	Good for shape maintenance. No change possibility	Stable if rigidified or inflation maintained	Good but potentially much propellant consumption
Possible Environments	All except very low LEO	All	All	All except LEO (Debris)	In principle all but EO difficult
Positioning Performance	probably possible for mm or cm	lower than mm for rigid structures	Probably similar or better than deployable	Similar for rigidified structures	Very good for high-perf control systems
Mass range	100-2000 kg	10-500 kg	unknown	1000 kg	4000 kg (Darwin)

Table 12.6: Comparison of alternative large structure concepts with respect to system parameters and behaviours.

Alternative	Metastructure	Deployables	Active structures	Inflatables	Formation Flying
Components	Microsystems similar to simpler nanosats, passive links	Standard structural components and commercial mechanisms	Embedded Piezoelectric Actuators (EPA) and large computing power	Inflation and rigidisation systems	Fully functional satellites
Technology needed	Complete microsystem, distributed controller	Not much	Space qualified actuators, miniature processors	End-to-end system design, rigidisant	Several ultra precise AOCS systems
Technology maturity	Low	Very High	Medium to low	Medium	Low to Medium
Technology commonality	High with Microsystems	High	High (with smart structures)	Very low (only in space)	Very low (mission based)
Development cost	High > 300 MEuros	Low	Unknown	Unknown, maybe medium (flight proven)	Probably high

Table 12.7: Comparison of alternative large structure concepts with respect to Implementation and subsystem design.

	System features	System behaviour	Implementation
Strengths	Architecture more robust	Can change shape	-
Weaknesses	-	Dynamics in standard mode	Low maturity
Opportunities	Potentially novel and many applications	Positioning for medium accuracy systems	Very High MST commonality
Threats	-	Formation flying can change shape too	High development cost

Table 12.8: SWOT Diagram for the Metastructure concept based on the comparison with alternatives. The comparison is made related to the objectives of the research, i.e. definition (system features), characterisation (system behaviour) and implementation (system assessment).

Chapter 13

Objectives achievement review

Summary

Following the reported work, the objectives are met either fully or adequately with some reservations. The definition of the system is progressed enough that a specific implementation can be selected, simulated and analysed. The characterisation of the system allows to assemble and examine a system baseline. Some limitations of the simulation results are in the specific controller used. Finally, the concept assessment allows to assemble and criticise an overall concept for the reference missions. But comparison to other alternatives can only be qualitative at this stage. However it appears that the concept of metastructures is justified in terms of both its relation to other fields of research, and its interest as an operational concept.

13.1 Review of methodology

The research set out with the objective of defining, characterising and assessing metastructures. The achievement of these objectives by the presented work is reviewed below. First, it is also interesting to also examine how these objectives are defined, as well as the approach and method used to achieve them.

13.1.1 Definition of objectives

The objectives of the research derive from a preliminary survey of the impact of MST for space. This survey in itself is quite a large area of research (see Appendix C), but here the focus is on applications in distributed systems, and in particular distributed structures concepts. Ideas associated with this concept are then iterated [Lecuyot, 2000]. Finally it is chosen to define, characterise, and assess this concept as a whole.

The choice of these objectives reflects the technical field of work chosen, which is system engineering and concept evaluation. As a results the emphasis is on breath more than on depth. An alternative choice may have been to focus on either of the main objectives, such that for instance:

- More detailed definition means more research into possible functions offered by metastructures (such as shape change), or more detailed mission analysis. There is also a case for the development of a better formalism and mathematical expression of the system architecture as a series of linked nodes.
- Characterisation could also have been made more detailed, with a simulation including more sophisticated controllers and more realistic space environments, including drag, solar pressure, Earth gravity disturbances, etc... The costing may also have been more detailed in terms of the development phase, with more sensitivity analysis as is done in industrial technology programs costing [Hazelrigg, 1991].
- A more detailed assessment can include back-to-back comparison of alternatives for a common mission. It can also be argued that the synthetic strategic analysis is "soft" in that it does not rely on numerical parametrics.

However for each of these it is necessary to have some input from the other phases. For instance it is difficult to trade-off the alternatives without having a substantiated case made for or against the metastructure concept, which is the result of the characterisation. Equally, an efficient characterisation activity necessitates to have a relatively clearly defined concept. Finally it is difficult to progress a costing exercise forward without a view of the system more detailed than the one currently available. So the choice of a set of high-level objectives appears relevant when it comes to evaluating a novel concept such as a metastructure. Otherwise any single more detailed task is made potentially less relevant by hypotheses necessarily made.

Finally, the novelty of the concept is asserted by the rationale discussion (see section 7.1.2 below), which finds that the research makes sense in its context. The objectives are thus considered to be correctly set.

13.1.2 Innovation analysis methods

The method taken for analysing metastructures as an innovative concept relies on separating between interest and feasibility, and selecting detailed techniques for assessing each of these.

13.1.2.1 Overall approach

The top-level approach has not been derived from an established method of assessment of novel concepts. It can be argued for instance that the division between feasibility and interest is somewhat artificial, the two being in fact often interdependent.

However during the course of the study no widespread method was identified to assess innovations in the context of space systems. Currently space policy is mission-based, and technologies are developed on a ad hoc basis. So it appears that a simple custom approach as selected is not duplicating established methods and allows to conduct an end-to-end concept analysis.

13.1.2.2 System and Mission analysis method

The methods for analysing and estimating both a technical system in general, and a space mission in particular, are more defined. General processes are recognised in the various specific methods found in the literature such as the book of J.R. Wertz and W.J. Larson [2000], or the books of Halligan [2001] and Blanchard [1990].

The methods involve successively analysing the needs or requirements of the mission or system, and from these deriving a physical and functional architecture for the system which turns into requirements on the subsystems. This method is then iterated for subsystems and components. Finally the baseline can be built up and analysed in terms of cost and value.

The value assessment technique used (SWOT) is meant to be a simple way to identify good and bad points of an idea or concept from a marketing or management point of view. Other alternatives exist for analysing concepts. But techniques such as SWOT are adequate in that they do not necessitate too much hard information. As a result though, the results are qualitative instead of quantitative. This can be seen as a potential shortcoming of the evaluation results, however more precise assessment needs more specific analyses, which is not performed in this work. The aim of this technique is to identify an action list. Such a list has been derived and is shown in section 12.4.2, so in that respect it is adequate.

13.1.3 Dynamics analysis method

The dynamics modelling method used is characterised by the hypotheses made and the mathematical approach selected. As far as the mathematical approach is concerned, using the selected Newtonian approach has not caused any problems and has eased the simulation of the model.

If it was to be extended to include rigid body motions for "locked" configurations (see Figure 6.1), it may be more interesting to switch to a Lagrangian representation where the relative angles between links are chosen as variables. This is better at representing rotation motions for metastructures considered as a single rigid body.

As for the selected hypotheses, one can make separate comments on the dynamics and the controller modelling. As regards the dynamics, a limiting hypothesis is that the same mass is used for all nodes. It does not allow to take into account differences in cell masses between local and global cells. Other hypotheses are not so restraining; Indeed, only circular orbits are considered, but the proposed missions use circular orbits anyway. As for orbital perturbations, Solar pressure has been discussed in

Chapter 12, and atmosphere should not in general be a problem at the considered altitudes (6000 km for the Earth mission). The validation performed on the software (see Appendix B) shows that it behaves well with respect to controller and tether dynamics simulation.

One feature that is absent from the dynamics simulation which may bring some important information is the presence of friction and motion damping in the joints. This is identified as an area for further work. The possible effects of introducing this in the design is discussed in section 13.3.2. As for the controller, section 12.2.3 identifies shortcomings of the simulated approach that may change the results of simulations.

An initial objective not implemented is the simulation of rotating structures, like the ones used in actual Moon reflectors for the Lunar Solar power system. However it has been seen that with adequate thruster capacity and controller, a metastructure is able to accommodate changing reference points. Thus it may be possible to realise a rotating structure, maybe by including a controller related to the reference speed, such as a PID controller. This can be subject to further work.

13.1.4 Summary

In summary it can be said that the overall methods used in the work allow to fulfil the objectives, with the following limitations:

- The comparison analysis is limited to making qualitative statements.
- The dynamics analysis used too limited a controller, which does not represent the errors inherent to a real-time controller.

13.2 Definition activities

Out of all analyses reported in Part III, the ones particularly related to the definition of the concept are the selection and definition of the concept, and the mission and system analysis. These are examined below.

13.2.1 Concept rationale and definition

Based on the analyses and the concept assessment in Chapter 12, it can be said that:

- It appears to be a worthwhile line of study to implement MST into large space structures, as it has been suggested that MST may be applied to smart and inflatable structure designs [Frampton, 2002, Tung., 2002, Jenkins, 2001a]. Equally, tethered or linked distributed structures are of interest (see Chapter 3).

- It is interesting to address the programmatics issues of identifying strong positive points for MST-based space systems, and costing the development of operational microtechnology in the space industry, as this proves to be non-trivial (see section 5.5).
- The dynamics and systems design problem investigated fits within generic problems in the area of distributed control [Frampton, 2001, D'Andrea, 2003] and the "grey" area between rigid structures, tethered satellites and formation flying options [Ericsson, 2002].
- However this latter point must be nuanced; It appears as a result from the analysis that it is difficult to evaluate the performance of the concept without an in-depth analysis of this distributed control issue. In the present work the focus has been put intentionally on the implementation of microcells and system integration to the detriment of distributed control, which makes it maybe more difficult to relate to the works cited, more focused on the control side and less on the implementation one.

It appears that in principle the generic area of work and specific topic of the research is relevant. However the scope is maybe too large to allow an in-depth analysis of one of the key components of such systems; This tends to diminish the value of the overall concept analysis. Nevertheless such level of analysis corresponds to what can be expected from the point of view of an industrial strategist as described in the introduction.

13.2.2 Mission and system analysis

The choice of missions and system architecture for the metastructures depends on the technological scope. For instance, it is estimated that structures behaving in a snake-like fashion (as in section 7.2.1) are too advanced technically at the moment as no immediate configuration of the corresponding microsystem can be found. So that rules out missions involving "Smart tethers" as described in section 6.4. The combination of mission interest and system feasibility leads to the current definition of metastructures, which is that of global and local cells connected by rigid rods. In view of the results of the analysis, it appears that the system considered is adequate for its missions.

It is worth noting that the problem of balancing a mission performance compared to the necessary technology needs is a fundamental one of space technology research. It adds uncertainty to the system design process as it acknowledges the fact that the requirements are not all, and not necessarily, absolute. In general, the trade-off between system complexity and cost and mission performance is expressed in the concept of "aims" and "system requirements review" in systems engineering practice [Halligan, 2001]. But when considering a system based on a technology still to be developed, there is an additional system design parameter which is the technology level consideration. In this work this is addressed in Table 7.1 which presents a justification for the technical choices of the system simulated here. At this stage this qualitative justification appears to be sufficient for the purpose of concept evaluation.

13.2.3 Summary

In summary, it appears that the concept definition activities have allowed to identify a baseline concept for metastructures that is technically feasible with foreseeable technology and has the potential to achieve its appropriate missions, whilst also exploring other issues and alternatives associated with the overall concept. This objective is thought to be achieved satisfactorily.

13.3 Characterisation activities

The characterisation activities performed in this work include system design, system dynamics analysis, microcell subsystem design, and development and application of a costing model.

13.3.1 System design

In the previous section it is seen how the interaction of mission analysis and system concept analysis lead to the overall design. The points of discussion for system design are the choice of parameters, the cell type and formal definition, and the link rigidity criterion.

For the system studied the main parameters retained are the cell thrusts and mass. Indeed, the main behaviour characterisation work is a dynamics analysis which is used for microcell design. As appears from subsequent subsystem design analyses, these are really the driving system parameters, together with the distributed control law, which is also identified as a key component of the system. From this it can be said that the system design parameters identified appear to be the ones effectively sizing the system.

As for the formal definition of the system, the simple approach retained enables to perform technical analyses at a level coherent with concept assessment, importantly including the necessary functions of the cells and links. A more formal and more mathematical approach may be used in subsequent work, when physical and technical properties of the system are better understood. It also appears that global and local cells have different physical characteristics (such as mass and power), even if the dynamics analysis does not highlight dramatic difference in the ability to control position. So the work on cell type and patterns is adequate for the objective set.

For links, the proposed sizing factors is the threshold at which deformations in a beam become significant compared to the positioning performance requirement. This definition can be questioned, but a superficial review of flexible multi-body dynamics in the scope of the work (see Chapter 4) did not identify a specific or generic approach for quantifying the flexible/rigid boundary. So at this time this is thought to be coherent. It could also be argued that the limit should actually be much lower than the maximum allowable deformation. But it is also true that profiling the links's cross-section can increase their stiffness significantly (see section 12.2). Thus the link sizing is adequate for an order-of-magnitude assessment such as considered here.

13.3.2 Dynamics analysis

The points for discussion of the results of the dynamics analysis are the behaviour of the controller, the validity of hypotheses in terms of mechanics, and the impact of possible improvements of the system design.

As regards the controller behaviour, it must be noted that:

- The position is monitored and controlled every simulated time step, which is about 0.1 s. In reality the controller has time delays, and is not necessarily thrusting all the time. As a result this modifies the dynamics. Whilst an individual controller design as used in the simulations is possible it is not necessarily the best one, let aside issues of distributed control. This is potentially a benefit for the concept as reality in this case may be less severe (as addressed in section 12.2.3).

- Simulations run with and without the out-of-plane control compensation show that this feature is necessary, in particular in free-floating-like Lagrange environment, where dynamics alongside the linear direction may be unstable otherwise.

Thus the controller behaviour may need to be changed. As a result, it may be that convergence and propellant consumption are affected, the latter positively, the former negatively. This is a scope for further work.

As regards the mechanics of the system, the main issue is about damping effects due to passive and active friction. Passive friction torque M_{fric} in a rotating joint of diameter r submitted to a force F_{dyn} is expressed such that

$$M_{fric} = \mu.F_{dyn}.r$$

with μ in the range of 0.02 to 0.2 at extremes [Conley, 1998]. This can be used to know the threshold of movement and the reverse damping force that can slow the relative motion of the cell and the link. Friction *at rest* will help the overall control by stopping minor disturbances. Friction *in motion* may have a positive or negative effect by reducing disturbances but also opposing to the action of the controller, thus probably cancelling out in terms of net effect. Section 13.3.3 addresses specific issue of motion damping at subsystem level.

13.3.3 Subsystem design

The design philosophy that drives microcells is minimality and simplicity. The effective application of this philosophy is reviewed for the main subsystems, i.e. sensors, propulsion system (including propellant mass), and link joints.

Section 10.2 suggests that attitude and position sensors are both necessary, even for local cells. Equally, hydrazine monopropellant propulsion is probably more complex than solid-based motors, but at system level it is more realistic to consider (Figure 10.6). So at subsystem level, it appears that the microcell needs functions very similar to equivalent ones in fully functional nanosatellites. However, microcells are much simpler from a point of view of communications, payload (in that they have none), or processing and data handling.

As for link joints, an active system design improvement may be the replacement of solid joints by "smart" joints using electro-rheological materials [Gilbertson, 1996], such that the viscosity and friction coefficient can be changed by an electrical field in the microcell, thus allowing control of the motion damping in each microcell.

The chosen mass of propellant corresponds to an arbitrary total impulse. But from the mass budget (Table 10.7) it can be seen already that in fact a very large portion of it is the hydrazine fuel (about 69%). This reflects the fact that the main mission of cells is to maintain position and that they do so with a reaction propulsion system. Section 12.1.5 shows that this amount of propellant is about the realistic maximum allowable as provisioning for full requirements means excessive amounts of propellant as compared to the rest of the system. Thus the emphasis must not be placed on making larger cells, but rather on diminishing the propellant consumption as discussed in previous sections.

Finally, the mass and power budgets and configuration studies appear to be relatively realistic when compared to other nanosatellite concepts (see Chapter 3). Both assume that integrated microsystems are possible for space.

13.3.4 Costing model

Costing is always an exercise in which estimation takes a significant place, in particular when it comes to evaluating manpower efforts for R&D projects. The results are sensitive to a number of factors as seen in section 11.3.3. It must be kept in mind that estimates for projects based on new technologies can vary by over 100% or even more, as demonstrated by the early cost estimates of the NASA Space Shuttle, the International Space Station, or ESA's Ariane 5 cryogenic launcher. However, the order of magnitude of the costs derived are believed to be sound, based on all the assumptions described in the analysis. Furthermore, what is interesting is to compare designs against each other as the relative costs variations are more indicative than the absolute costs themselves, if the cost model is set up properly. The conclusions of the costs exercise are that:

- The development of the concept and specific missions using metastructures is currently foreseeable with current and upcoming MST research.
- There is a justification for considering or using different type of cells, as the change in cell type and pattern type modifies the cost of cells in a visible fashion.

13.3.5 Summary

The characterisation activities have given enough information to be able to assemble and discuss a system and concept baseline, which means that in this respect the objectives are fulfilled. However, a resulting shortcoming of the work is really that the controller design. It does not allow to make real-world prediction of the dynamics, nor does it allow a properly designed decentralised control law to be used. This can be seen as a partial failure based on too simplistic assumptions. This should not, in principle, disprove the design choices made for assembling the baseline in terms of patterns choice and thrust selection, as these are based on relative performances. Thus the objective of concept characterisation is for the largest part fulfilled.

13.4 Assessment activities

By assembling the various results of previous analyses, Chapter 12 finds that system baselines can be described for the two reference missions. These appear to be realistic and perform well in fulfilling the missions except for the issue of lifetime.

The discussion that follows in the referred chapter tries to explore alternatives for improving the baseline. At this stage it is difficult to fully substantiate claims made in this discussion. However various possibilities exist for improving the system and subsystem baseline design, and it appears reasonable to assume that the system may be brought to full compliance with the operational requirements of the mission.

However a comparison of metastructures with alternatives must take into account the full concept life cycle. In particular, the issue of launch and deployment has been left aside of the work. Whilst slow and semi-passive deployment may be possible according to this very preliminary analysis, it is apparent that the launch and folding issues will need further consideration.

Finally, the value of the strategic analysis following is undermined by the mostly qualitative nature of it. However it still shows that metastructures have got strengths of their own for their specific missions, and can size the opportunity to take advantage of MST developments in other fields.

13.4.1 Summary

Overall the concept assessment discussion identifies areas for improvements of the concept and the assessment techniques, whilst providing partial information on its relations with alternative concepts. This objective is partially met in that some propositions are made. At this stage, however, it is difficult to make an informed decision whether, for instance, the space industry needs to commit large resources to metastructures development in the near terms. But a positive result is certainly that the concept deserves further investigation.

Part V

CONCLUSION

Chapter 14

Conclusion

14.1 Work performed

This work has set up to explore and assess a concept of space structures which is believed to be novel. This concept is based on the assumption that using micro and nano technologies can not only reduce mass, size and power for traditional spacecraft components, but also make possible new types of space systems. In particular, it can make it easier to implement distributed or decentralised systems, i.e. systems without a single-point failure central operational authority. One specific application of these is the concept studied here and called metastructures, which implies discontinuous large structures in space. Such a concept is composed of nodes which are actually made using Micro-System Technology (MST) and linked together. Applications include different types of large structures such as space interferometers, reconfigurable cables, and giant reflector structures.

Following this idea it was proposed to define, characterise, and assess the concept. Generic and simple methods were used for strategic analysis, mission and system design.

First, the technology and previous work was reviewed. It was found that many developments exist in the field of MST sensors and actuators in space. Although microsystems for space are not a mature technology, it appears reasonable to foresee integrated microcells in the medium to long term (10 to 20 years). As for metastructures, it is found that there has been significant theoretical and practical work done into large structures and tethers in space. But no concept resembling metastructures has been identified specifically.

A review of possible missions and technical architectures was then performed. The trade-off of these allowed to define a concept, based on rigid links and global and local cells. Ensuing dynamics analyses demonstrated that controllability is achieved for most reference mission cases. From the results of the dynamics analysis, the microcell subsystem were designed and then costed.

Finally, an assessment of the system baseline for the two reference missions tended to show that the concept deserves further investigation and has some possible benefits, although a detailed back-to-back comparison with other alternatives such as inflatables or active smart structures proved difficult without a common case study.

In general the concept and system analysis methods used in these assessments are appropriate. It is acknowledged, however, that the technique used for evaluation of alternatives is limited to making qualitative statements. Equally, the technical design of the controller used for dynamics simulation biases it in terms of propellant expenditure. Overall the level of detail considered by the various analyses is thought to be compatible with the aim of the research, which is to consider metastructures from the point of view of concept assessment.

14.2 Contributions and objectives assessment

As for the definition of metastructures, it fits in with other current problems currently being researched. Indeed, decentralised and distributed systems and the associated control laws are a large area of research. The approach taken in this work is certainly simpler than the complex mathematical treatments used in other works on the topic, however the results of the definition activities can provide a framework for new applications of such distributed controllers.

The characterisation of metastructures was done in order to prepare an end-to-end vision of the concept as an opportunity for industrial development. To this end the detailed technical analyses are less detailed than if the work had focused on any of these. However they still provide valuable insight.

First, the microcell design investigated minimal nanosatellite-like systems, and can be compared to other similar concepts. The result is that the necessary technologies involve probably as much in terms of functional structures and integration as they do in terms of microdevices design and performance. Then the dynamics analysis finds that complex structures of rigidly linked active microcells can be controlled and change shape in space. It also finds that there is probably a relationship between using different types and patterns of these cells and the dynamics behaviour of the system, although it does not identify a detailed insight into this relationship. The costing equally shows that the space industry may benefit significantly by trying to exploit commonality with terrestrial MST research, which has been proposed by previous strategic analyses.

Finally, the assessment and discussion finds that in principle it is possible to find system baselines for the specified missions which are attractive mass-wise and cost-wise, providing that some improvements can be made to the folding and distributed control of the structure. A particular finding is that to get a proper comparison of alternative technologies, a common case study may help identify particular features of advanced designs for large structures in space.

Overall the objectives are reached in terms of demonstrating the relevance of the concept, of executing technical and industrial analyses, and providing with new material for further research. From this, two possibilities are identified for dissemination of the results. First, the systems engineering and space systems community may use the results of the description of the end-to-end evaluation process and results. This would be for reviewing them, but also for proposing new activities such as the definition of a more considered evaluation process, or a case study in distributed controller dynamics. Second, a detailed presentation of the dynamics analysis results presents an opportunity to review the results and propose refinements to the simulation method. These two topics can be singled out as the main contributions of the current work.

14.3 Conclusion and further work

In this work I tried to focus on an end-to-end system design approach as a mean to study the influence of the advent of MST on space structures design. The concept I called metastructures exemplifies one effect of this influence. Metastructures, I believe, are by themselves worthy of more research, keeping in mind that the technical scope of the current work makes a parameter-based comparison with alternatives difficult. In exploring the context and the details of the concept, I found out that there is an emerging field of research in flexible or sparse space structures, between rigid deployables and formation free-flying structures. Certainly MST can help address the associated technical issues as other researchers have suggested. I believe an original contribution is present in the definition of a new concept of space structure, the proof of basic performance, and the use of an end-to-end process to analyse this concept at preliminary level.

The results of the work carried out suggest further work topics for more detailed assessment. First comes a more detailed dynamics simulation, in particular with regards to distributed control. The UniSim custom simulator can be extended to include time-driven events through standard real-time simulator practices. This in turns allows a distributed controller of spatially interconnected systems to be included. The design of such a controller would be a novelty to the best of my knowledge, including the rigid links and the gravity environment. Another simulation task is the verification that rotating structures are possible, with programmed continuous changes in reference position of cells.

Secondly some specific components of the microcells would benefit from more detailed analysis. The design of minimal sensing systems appears interesting, as this research may be generalised to other applications. Minimal optical or microwave position sensing systems can have Nanosatellite applications. I have also left aside the problem of stowing and launching metastructures, which at the moment is certainly a weakness compared to other alternatives. A conceptual work can be performed in this area that would identify alternatives techniques based on MST technology and microcell configuration.

Finally, a generic and high added-value task would be to do a quantitative comparison of alternatives for structural design of large structures, in the footsteps of NASA's "Fresh look" study of the Solar Power systems. A common case study of all the possible technologies would provide an ideal back-to-back comparison of parameters such as overall mass, performance, etc... detached from analyses presented by proponents or opponents of each particular solution.

In conclusion I believe this work has made an original contribution to knowledge by proposing a new concept of space structure, defining, characterising and assessing it. The results show the work to be worthwhile and relevant in its scientific and industrial context. I therefore think it fulfils the requirements for a Total Technology Philosophy Doctorate Degree.

Chapter 15

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Part VI

APPENDIX

Appendix A

Calculations Reference

Summary

*Here are all the calculations and footnotes referenced throughout the thesis. Calculations are referred to in the thesis text as (C**x**), where **x** is the calculation number as seen in this appendix. The bibliographic references are presented in chapter 15.*

A.1 Metastructure Mission Analysis

C 1 *Maximum structure size, p.56: Launch mass is assumed to be 10 tons maximum. So for the mass of microcell plus one horizontal and one vertical link of 100g, and assuming a square matrix of dimension N, it comes*

$$N = \sqrt{\frac{10,000}{0.1}} = 316$$

which for a 1 m link length makes a 300×300 *m metastructure.*

C 2 *Interferometer resolution, p.61: Given a wanted resolution* $\upsilon = 10'' = 48\mu rad$ *and an operating wavelength* $\lambda = 50$ *cm, the baseline D is*

$$D = \frac{\lambda}{\upsilon} = 10.3km$$

For astronomy this corresponds to what is expected from a space interferometer in radio waves. For ground observation and tracking from a LEO orbit at $h = 500$ *km altitude, that corresponds to a resolution of*

$$r_\upsilon = 2 \cdot h \cdot \tan(\frac{\upsilon}{2}) = 24 \quad m$$

which is probably enough for vehicle tracking, for instance.

C 3 *Interferometer Pointing accuracy, p.61: In general, the precision asked on the results is about* $\Delta\upsilon = 5\%$*. It is expressed as*

$$\Delta\delta D = 2 \times D \times \cos(\nu) \times \Delta\upsilon$$

with ν *the declination of sensing relative to the instrument zenith. At zenith, the formula reduces to*

$$\Delta\delta D = \frac{\lambda}{10} = 5\ cm.$$

However, for interferometric astronomy much depends on post-processing of data, which may recover up to an order of magnitude of error. So the accuracy requirement is considered to be $\Delta\delta D = 50$ ***cm****.*

C 4 *Earth Deflector resolution, p.65: Based on a 6000 km orbit and a 1-2 km ground footprint.*

A.2 Metastructure System Analysis

C 5 *Metastructure deployment time, p.81: At an altitude of R=1000 km, the gravity gradient is*

$$\Delta g = \frac{2\mu}{R^3 \times 9.81} = 2.10^{-7} \quad g$$

So to deploy a 100 m structure at first order the time necessary is

$$t = \sqrt{\frac{2d}{\Delta g}} = 8.73 \quad hours$$

C 6 *Reference Metastructure power, p.82: This is based on using 40% efficiency of solar cells and considering 1 wall illuminated at the same time for a Solar flux of about* $1500 \quad W/m^2$*, so* $P = 1 \times (5.e^{-2})^2 \times 0.4 \times 1500 = 1.5 \quad W$*.*

A.3 Simulation Method for linked controllers

C 7 *Tension derivation model, p.94: For the nodes* (i,j) *and* (f,g) *linked by the link* k*, the equation system is*

$$\begin{aligned}
\mu\frac{\mathbf{R_{i,j}}}{R^3_{i,j}} + \mathbf{T_k} + \mathbf{u_{i,j}} &= m \cdot \ddot{\mathbf{R}}_{\mathbf{i,j}} \\
\mu\frac{\mathbf{R_{f,g}}}{R^3_{f,g}} + \mathbf{T_k} + \mathbf{u_{f,g}} &= m \cdot \ddot{\mathbf{R}}_{\mathbf{f,g}} \\
(\ddot{\mathbf{R}}_{\mathbf{i,j}} - \ddot{\mathbf{R}}_{\mathbf{f,g}}) \cdot (\mathbf{R_{i,j}} - \mathbf{R_{f,g}}) + (\dot{\mathbf{R}}_{\mathbf{i,j}} - \dot{\mathbf{R}}_{\mathbf{f,g}})^2 &= 0
\end{aligned}$$

By posing:

- *for a vector variable* X*,* $X_{i,j} - Xf, g$ *is written* ΔX*,*
- $\mathbf{Fext_{i,j}}$ *is the sum of all external forces on one node such that*

$$\mathbf{Fext_{i,j}} = \mu \frac{\mathbf{R_{i,j}}}{R_{i,j}^3} + \mathbf{u_{i,j}}$$

- $\mathbf{e_{i,j}}$ *is the unit vector between* (i, j) *and* (f, g)*, and* T_k *is the corresponding value of the tension (in N)*

The resulting equation can be rewritten as

$$\frac{\Delta \mathbf{Fext_{i,j}}}{m} \cdot \Delta \mathbf{R} + \frac{2 \times T_k \cdot \mathbf{e_{i,j}}}{m} \cdot \Delta \mathbf{R} = \Delta \dot{\mathbf{R}}^2$$

with $T_k = |\mathbf{T_k}|$ *the magnitude of the tension vector for link k, which applies for simple tethers. When the equation is applied to each node having more than one link attached, the term in* T_k *may include several terms* T_{k1}*,* T_{k2}*, ... which means that the matrix* $[A]$ *is non diagonal (see main text).*

A.4 Metastructure Design

C 8 *Earth Solar concentrator parabola equation, p.114: The problem is that of the intersection in 2D of a parabola and a circle. It is resolving the system of equations seen on the text. By substitution the equation obtained is*

$$b^2({R_{n+1}}^2 - {R_n}^2)^2 + (R_{n+1} - R_n)^2 = L^2$$

which is equivalent to solving a quartic (or 4^{th} *degree polynomial), such that*

$$X^4 + AX^3 + BX^2 + CX + D = 0$$

with

$$\begin{aligned} X &= R_{n+1} \\ A &= 0 \\ B &= -2{R_n}^2 + \frac{1}{b^2} \\ C &= -2\frac{R_n}{b^2} \\ D &= {R_n}^4 + \frac{{R_n}^2 - 1}{b^2} \end{aligned}$$

using, for instance, Euler's method described by Ward [2003]. The different values for the parabola slope b lead to the values shown in Table 9.1.

A.5 Microcell design

C 9 *Microcell sensor parameters, p.125: The range is simply derived from the maximum link length, either from one element to another or for an entire pattern length. The pointing accuracy is derived by using a fraction (here 33% as a preliminary budgeting) of the control accuracy, which is related to maximum position error and link length by trigonometry. Maximum link lengths for interferometer is 12.5 m and 10 m for the Solar concentrator.*

C 10 *Magnetic field calculation, p.126: Simplistically, the field B at the centre of a simple DC iron core electromagnet is*

$$B = \mu \frac{N}{L} I$$

, with I current, N number of turns and L the length, and $\mu = 200\mu_0 = 2.5e-4$ permeability of the iron core. So for a micromagnet (L=0.1 mm over 10 turns for a 5 mm diameter coil) the field at the centre is about 250 μT, and then decreases with the inverse of the distance at first order. As for the Earth Magnetic field it is given [J.R. Wertz and W.J. Larson, 2000] as

$$B(R, \lambda) = \sqrt{(1 + sin^2\lambda)} \frac{B_0}{R^3}$$

with R in Earth radii and B_0 = 3000 nT at R=1.

C 11 *Rate sensor requirements, p. 125: The accuracy requirements are derived in Chapter 9. The rate requirements are estimated from the time it takes to converge for an interferometer shown on Figure 9.20, i.e about 90 degrees in 200 s. For the Solar concentrator the worst case is that of a rotating structure rotating at orbital rate which is lower than 10^{-3} rad/s. The Angular random walk is based on a sampling every second for the duration of a manoeuvre and on expecting the random walk to be less than the required accuracy.*

A.6 Metastructure Costing

C 12 *Microcell launch cost, p.145: A widely accepted figure (see reference in text) is of 10 k€(or k$) per kilogram to orbit. Cells are about 400 g in mass, so a figure of 5k€per cell is used for launch cost.*

C 13 *Industrial costs, p.146: It is not possible to give accurate figures for internal industrial activities within the space industry. However the basis for cost estimations are:*

- *Recent re-furbishing and upgrading of clean room facilities in EADS Astrium Ltd, Stevenage for a cost of around 10 M€.*

- *Acquisition of filament-winding and composite manufacturing facilities, for 10-20 M€.*
- *MST development cost from a recent report (see reference in text): for one device from 2 to 10 M€.*

Appendix B

UniSim software Reference

Summary

A specific simulation tool is developed to implement the algorithms developed in Chapter 8 and to carry out the simulations reported in Chapter 9. This tool, called UniSim, is developed using object-oriented techniques and is focused on defining case studies and simulation objects that propagate metastructure objects in time and space using context and integrator objects. Validation against the requirements and test cases show that UniSim fulfils its functions correctly.

B.1 Requirements

To follow standard software design practices [ESA, 1999], UniSim is designed based on top-level user requirements. These are turned into software requirements from which an approach for implementation can be selected.

B.1.1 Scope and User Requirements

The scope of UniSim development is related to the scope and the context of the work (see section 1.2). This is essentially characterised by the need to simulate tethered matrix-like multi-agent systems, in gravitational and free-floating environment. There is also an interest in defining easily custom control systems and environments. Finally, there is the specific context of not necessarily having access to simulator software tools or high-performance hardware. This translates into the main user requirements that are listed on Table B.1.

B.1.2 Software and Implementation Requirements

Based on the user requirements above it is possible to precise the software specific requirements. The simulation requirements implies having text and graphic output for easy visualisation, and also powerful mathematical functions. The requirement on access to software translates into a preferred use of multi-platform and free software. The derived software requirements and the mapping to user requirements are shown on Table B.2.

B.1.3 Implementation selection

There are a number of possibilities for implementing the software requirements above. Based on *S3* all professional mechanical and dynamics simulation software have been discarded, such as SIMULA, NASTRAN, DADS etc... In fact the simulation of metastructure uses effectively techniques of multi-agent simulation systems [Charpillet, 2003].The alternatives to simulate these include coding low-level language routines [Liberty, 1997], developing applications using high-level scripting languages [Ousterhout, 1998], using a generic mathematical simulator, or using a specific multi-agent simulation package, the only currently available being SWARM [Group, 2003]. These are compared against the requirements on Table B.3.

It was chosen based on this trade-off to use Python, an object-oriented high-level scripting language, that has a specific Numerical analysis package (NumPy) and several bindings to graphics libraries [community, 2003].

B.2 Architecture

The software architecture takes full advantage of two features of Python; The high-level object-oriented possibilities [Harms, 1999], and the presence of a high-level numerical analysis package [Hinsen, 2003].

B.2.1 Top-level architecture

The main functions of the tool, so-called UniSim, is to create simulation results by having integrated the equation of motion of a metastructure in a certain context. A metastructure itself is composed of agents which when they are active use controllers

Number	User Requirement
U1	Simulate Controlled tether systems in free space and in orbital environment
U2	Implement easily custom control systems and matrix-like tethered systems
U3	Develop and Use software without accessing non-available software and hardware

Table B.1: UniSim User Requirements

Number	Software Requirement	U.R. Mapping
S1	Automatically define and simulate tethered matrix systems	U1
S2	Powerful mathematic functions for efficient computing	U1
S3	Use Free Software	U3
S4	Run on Windows and Unix/Linux platforms	U3
S5	Allow rapid Prototyping	U2
S6	Have easy graphic and text interface	U2

Table B.2: UniSim Software Requirements

Option	S1-Simulation	S2-Maths	S3-Free	S4-Platform	S5-Dev. Speed	S6-Graphics
C$\hat{+}$+ / C	Very Good - Fast language	Good - Low-level libraries	Very Good	Very Good	Poor - Complex language	Poor - Complex libraries
Python	Good	Very Good - High-level libraries	Very Good	Very Good	Very Good - High-level language	Good - GUI packages
Tcl/Tk	Average	Poor - No maths	Very Good	Very Good	Very Good	Very Good - Natural GUI
MatLab	Average - Not for large structures	Very Good	Poor - Not free	Average - No Linux port	Average	Average
SciLab	Same as above	Same as above	Very Good - Free	Very good	Poor - Not much documentation	Average
Swarm	Good	Poor	Good	Poor - Objective C used	Poor	Average

Table B.3: Software Implementation trade-off to react to their environment. So the main classes of objects identified for Unisim are:

Case study A top-level object that includes all the results from a simulation run, and that is able to manipulate them and store or present them in a user-friendly format, i.e. graphical or text file output.

Simulation A simulation is used by a Case study as the engine that computes the results. It includes the information about the case being studied, and the space-time continuum that is the result of any time-domain integration.

Metastructure The metastructure object contains all the information about the "real" structure being simulated, and is close symbolic representation of it. It contains agent and link matrixes and a state matrix that evolves in time.

Context The context object represents all that is specific to the particular environment in which the simulation is taking place. In general a metastructure or simulation object can be run independently with any context. Typical context objects are 1D, 2D or 3D dynamics either in free fall or gravity environment.

The overall architecture of UniSim can be seen on Figure B.1.

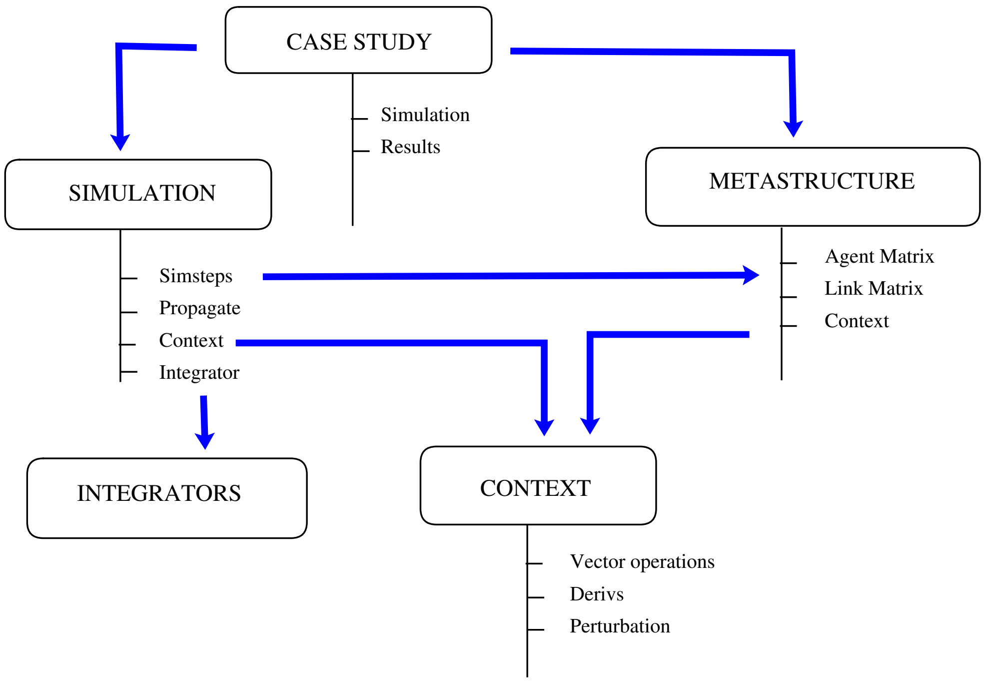

Figure B.1: Unisim Top-level Architecture

B.2.2 Data structures

The top-level data structure of UniSim is the list called Simsteps of a series of simustep objects, which are essentially a time-tagged state vector. The state vector is represented as a state matrix object, which is a mirror of the metastructure matrix.

The metastructure's state matrix is propagated in time based on its agent and link matrix, as defined in Chapter 7. These are all matrixes the same shape which follow the rules for describing a metastructure, using top-down and left-right description for their properties. Finally there is a parameter matrix, which for each agent contains the context-related parameters.

The state matrix contains context-based sate vectors (i.e. 2D or 3D Position-Velocity vectors), the agent matrix contains Agent objects of types Passive ('P'), On-Off absolute ('Oa') or relative controllers, either relative to horizontal or vertical neighbours, previous or next-in-line ('Ohp', 'Ohn', 'Ovn', 'Ovp'). The type of agent is then used during the computation of position error with respect to the reference. The link matrix contains descriptions of where the links are, either as vertical ('vv'), horizontal ('hh'), or both ('hv'). The parameter matrix contains parameter vectors, such as for instance a $[m, F]$ double to represent active controllers with mass and thrust.

As an example, the reference metastructure defined in Chapter 7 and shown on Figure B.2 is described in UniSim as follows.

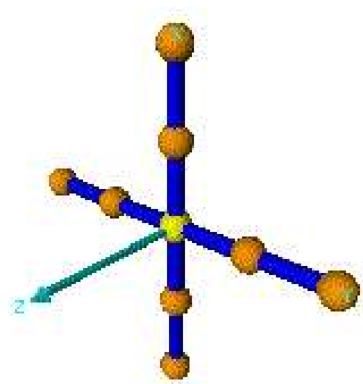

Figure B.2: Reference metastructure

A *Metastructure()* object is created, with dimensions 5×5, which uses a *Grav2D()* context (representing 2D gravity), and uses *Agent-link-controller()* agents (see next section for details on theses classes). This object's *agent matrix* is

$$\begin{bmatrix} 0 & 0 & 'Ovn' & 0 & 0 \\ 0 & 0 & 'Ovn' & 0 & 0 \\ 'Ohn' & 'Ohn' & 'Oa' & 'Ohp' & 'Ohp' \\ 0 & 0 & 'Ovp' & 0 & 0 \\ 0 & 0 & 'Ovp' & 0 & 0 \end{bmatrix}$$

where the non-zero matrix terms are defined above. The *link matrix* is

$$\begin{bmatrix} 0 & 0 & 'vv' & 0 & 0 \\ 0 & 0 & 'vv' & 0 & 0 \\ 'hh' & 'hh' & 'hv' & 'hh' & 0 \\ 0 & 0 & 'vv' & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

with the terms as defined above as well. Note the zeros in the last row and column reflecting the fact that agents there can not have links with next-in-line or next-in-column agents. The *parameter matrix* for one case of the reference metastructure where $m = 0.1$ kg and $F = 0.01$ N is

$$\begin{bmatrix} 0 & 0 & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & 0 & 0 \\ 0 & 0 & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & 0 & 0 \\ \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} \\ 0 & 0 & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & 0 & 0 \\ 0 & 0 & \begin{bmatrix} 0.1 \\ 0.01 \end{bmatrix} & 0 & 0 \end{bmatrix}$$

Finally the state vectors are expressed in a 2D dynamics format, such that

$$V = \begin{bmatrix} X \\ Y \\ V_x \\ V_y \end{bmatrix}$$

and for the initial state expressed in the local co-ordinate frame, the state matrix is therefore

$$\begin{bmatrix} 0 & 0 & \begin{bmatrix} 1. \\ 0. \\ 0. \\ 0. \end{bmatrix} & 0 & 0 \\ 0 & 0 & \begin{bmatrix} 0.5 \\ 0. \\ 0. \\ 0. \end{bmatrix} & 0 & 0 \\ \begin{bmatrix} 0. \\ -1. \\ 0. \\ 0. \end{bmatrix} & \begin{bmatrix} 0. \\ -0.5 \\ 0. \\ 0. \end{bmatrix} & \begin{bmatrix} 0. \\ 0. \\ 0. \\ 0. \end{bmatrix} & \begin{bmatrix} 0. \\ 0.5 \\ 0. \\ 0. \end{bmatrix} & \begin{bmatrix} 0. \\ 1. \\ 0. \\ 0. \end{bmatrix} \\ 0 & 0 & \begin{bmatrix} -0.5 \\ 0. \\ 0. \\ 0. \end{bmatrix} & 0 & 0 \\ 0 & 0 & \begin{bmatrix} -1. \\ 0. \\ 0. \\ 0. \end{bmatrix} & 0 & 0 \end{bmatrix}$$

B.3 Flow diagram

The flow diagram of Unisim is shown in Figure B.3. It shows the flow of operations as well as the way the data structures are manipulated.

B.4 Classes and methods

The classes, subclasses and associated methods of UniSim are seen on Table B.4. More details can be found in the source code distributed with this report.

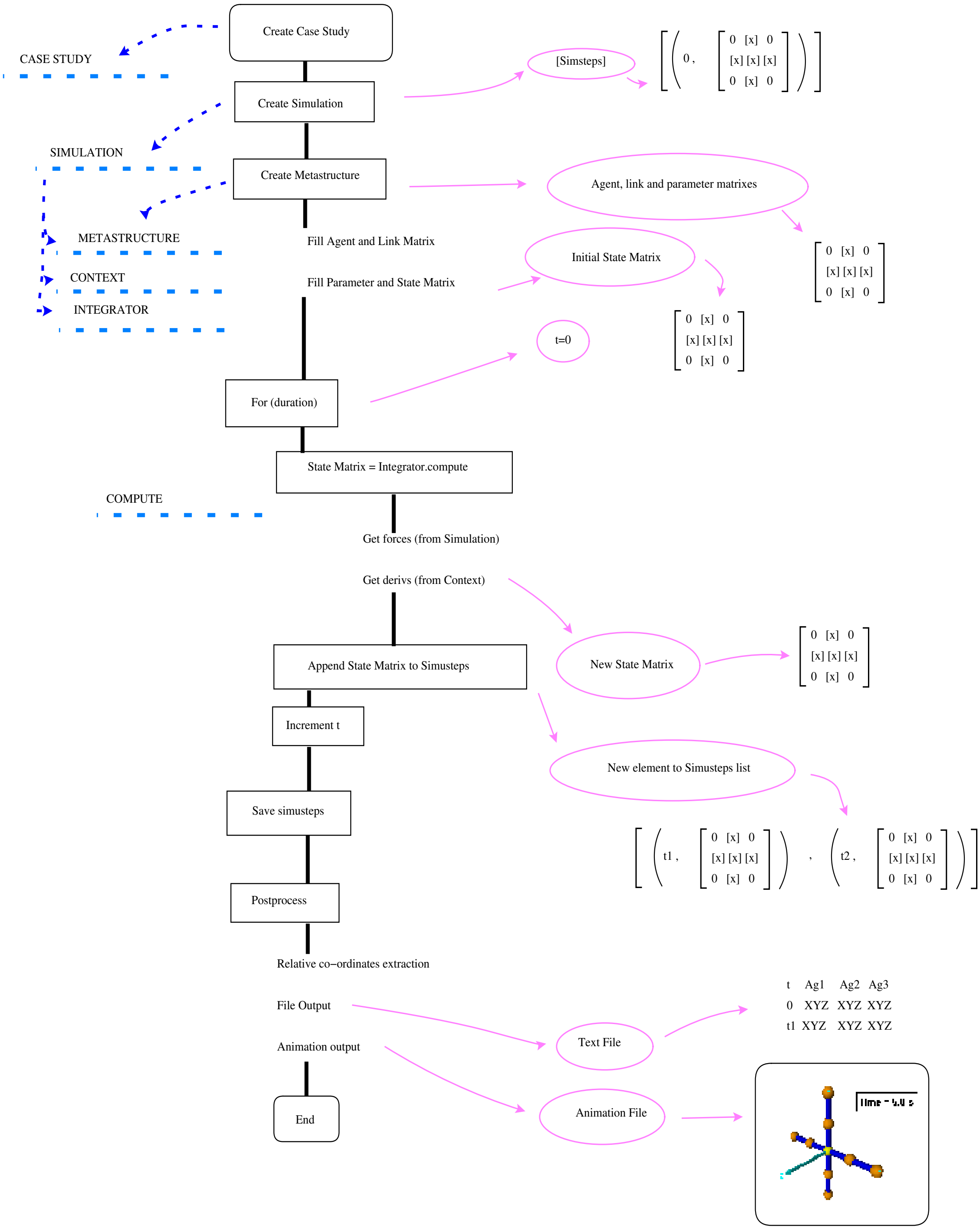

Figure B.3: UniSim flow diagram

Class	Method	Function / Comments
Agent		
	Controlfunction	controller implementation
	Agent-controller	Free-flying controller
	Agent-link-controller	Linked controller
Case-study		Top-level wrapper
	outputfile	writes text output
	results-relative	computes results in local frame
	results-animate	creates an animation in local frame
Context		
	Perturbfunction	Computes context dynamics
	Derivs	Relates position and velocity derivatives
	Norm	Position vector norm
	Verror	Out-of-plane velocity extraction
	G2L	Global to Local co-ordinates
	L2G	Local to Global co-ordinates
	Action	Computes thrust
Context-Dyn1D		1D Dynamics
Context-Dyn2D		2D Dynamics
Context-Grav2D		2D Gravity
Context-Grav3D		3D Gravity
Context-ODE		ODE Integration
Integrator		
	Calculate	Integration method, using derivs from Context and Getforces from Simulation
	Integrator-RK2	Euler's rule method
	Integrator-RK4	Basic Runge-Kutta Method, $4\hat{t}h$ order
	Integrator-RK7	$7\hat{t}h$ Order Method
Metastructure		
	Agentfunction	get neighbours and controller function
	linkfunction	identifies links and compute tension forces
	Handfill	to fill in a metastructure by hand
	Autofill	creates a metastructure based on list inputs
Meta-Single		For one element
Meta-rigidlink		Basic metastructure
Simulation		
	Build	Basic propagation loop
	getforces	Get environment and link forces
Sim-ODE		Special for ODE simulation
Simustep		Basic time-space object

Table B.4: UniSim classes and Methods

B.5 Validation

Validation for UniSim includes validating basic control and orbit orbital dynamics, validating tether dynamics against literature, validation numerical stability and errors, and comparing the functions against the requirements. Similar results are obtained in 3D.

B.5.1 Controller Dynamics

The controller is validated in free space dynamics. It can be seen from Figure B.4 and B.5 that it converges adequately and works when side speed compensation is applied (see Chapter 8).

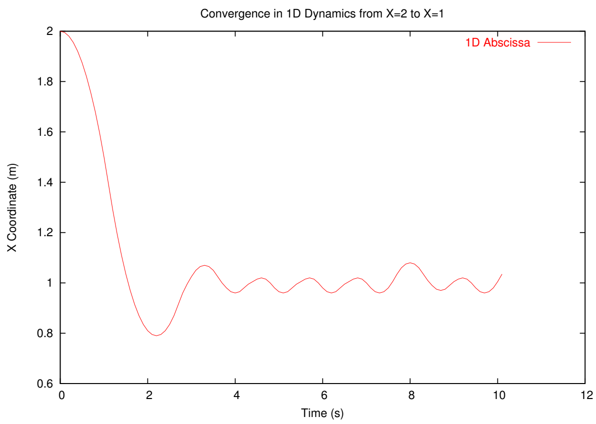

Figure B.4: Controller test run in 1D

B.5.2 Orbital Dynamics

To validate orbital dynamics in 2D and 3D, the main comparison is done on orbital periods for circular orbits. Unisim work equally with elliptical and circular orbits, however metastructures and tethered structures are preferably put on circular orbits to avoid dynamic unstability. The results are seen on Figure B.6.

These results are compared with the circular Earth orbit period T for an altitude h which is

$$T = 2\pi\sqrt{\frac{(R_e + h)^3}{\mu}}$$

The results are shown on Table B.5

B.5.3 Tether dynamics

The validation of tether dynamics is done on the orbital resonance dumbbell movement taking place when tethers start in initially inclined configurations. From Chap-

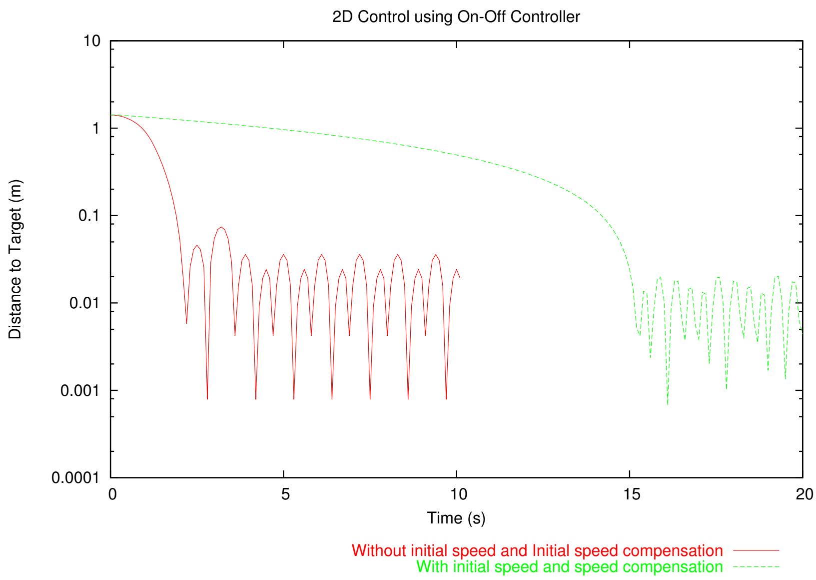

Figure B.5: Controller test run in 2D, with and without speed compensation

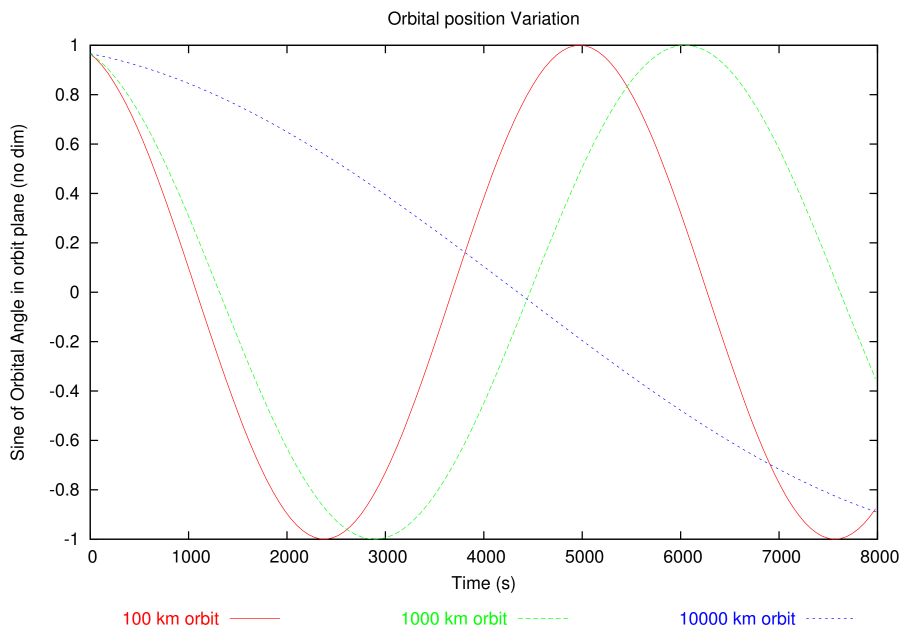

Figure B.6: Orbital period tests

Orbit Height (km)	UniSim Period (s)	Actual Period (s)
100	$\sim$ 5,200	5,190
1,000	$\sim$ 6300	6,307
10,000	$\sim$ 20,00	20,589

Table B.5: Orbital period validation ter 9 the Figure B.7 shows a periodic motion depending on the inclination. This can be correlated with results compiled from previous studies [M.L. Cosmo and E.C. Lorenzini, 1997a], where Figure B.8 is extracted.

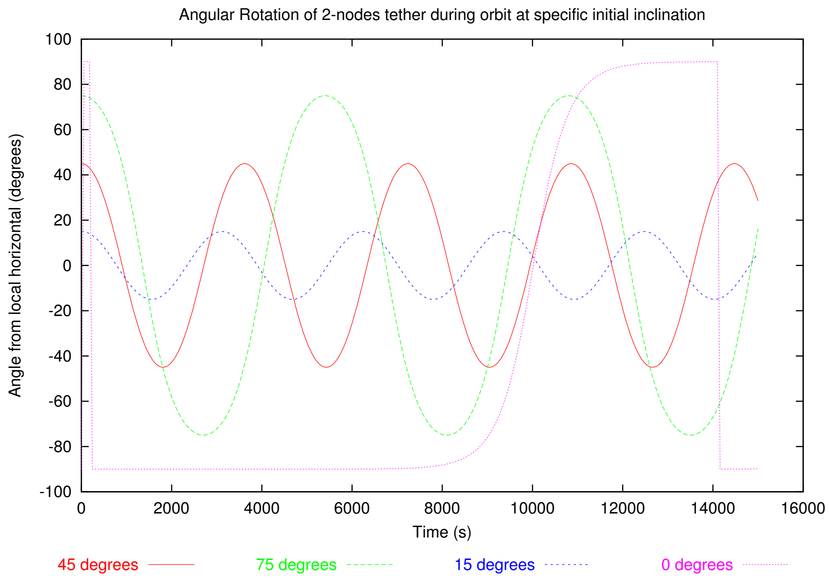

Figure B.7: Tether simulations for a dumbbell model with various initial inclinations, for a circular Earth orbit of 200 km altitude at unit length

Inclination (deg)	UniSim Period $\frac{n_\theta}{n}$	Actual Period $\frac{n_\theta}{n}$
15	~ 1.5	~ 1.6
45	~ 1.4	~ 1.4
75	~ 1.2	~ 1.1

Table B.6: Tether libration motion validation

The results are compared on Table B.6. Finally, on Figure B.9 different runs are shown with different number of nodes. This also validates the dynamics, as the oscillations are the same in the case of an initial 45 degrees inclination. For an unstable configuration, the dynamics depend on the number of nodes. Note that for metastructures the number of nodes is representative of a physical reality as opposed to the tether where it is a model of a flexible rod. So in the case of metastructure there is no issue with node modelling.

B.5.4 Numerical stability and errors

A simulation of the controlled reference metastructure is run with different time steps and Integrators as seen on Figure B.10. Guidelines for running simulations with Unisim are thus:

- Passive (i.e. non-controlled) tether simulations can be run with time steps of several seconds, up to 15 or 30 s.
- Active (i.e. controlled) tether simulations can be run with time steps of 0.2 s, 0.1 s or less in low Earth Orbit.
- The best Integrator is used, i.e. Runge-Kutta 7t̂h order.

B.5.5 Validation of requirements

Finally Unisim is validate against the software requirements. The achievements of the software are compared against initial goals on Table B.7. It can be seen that as a research software tool UniSim achieves all its goals reasonably.

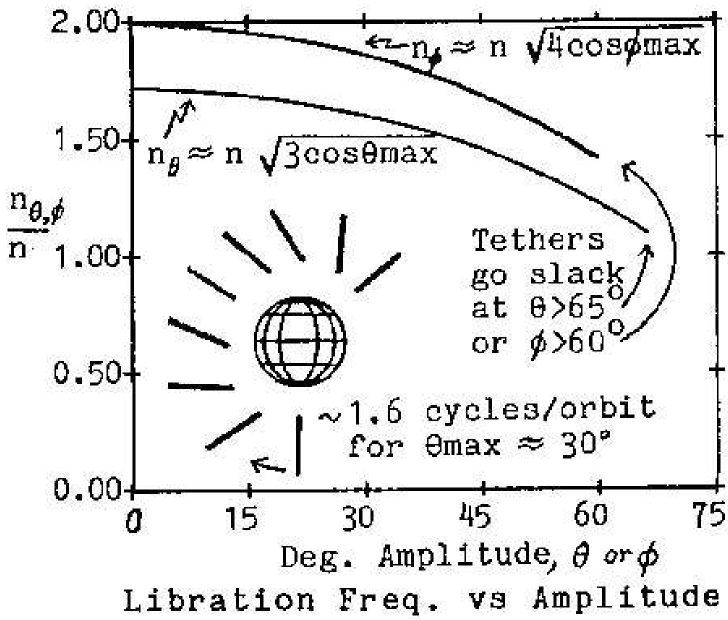

Figure B.8: Variation of tether libration motion with initial inclination (extracted from the Tether Handbook).

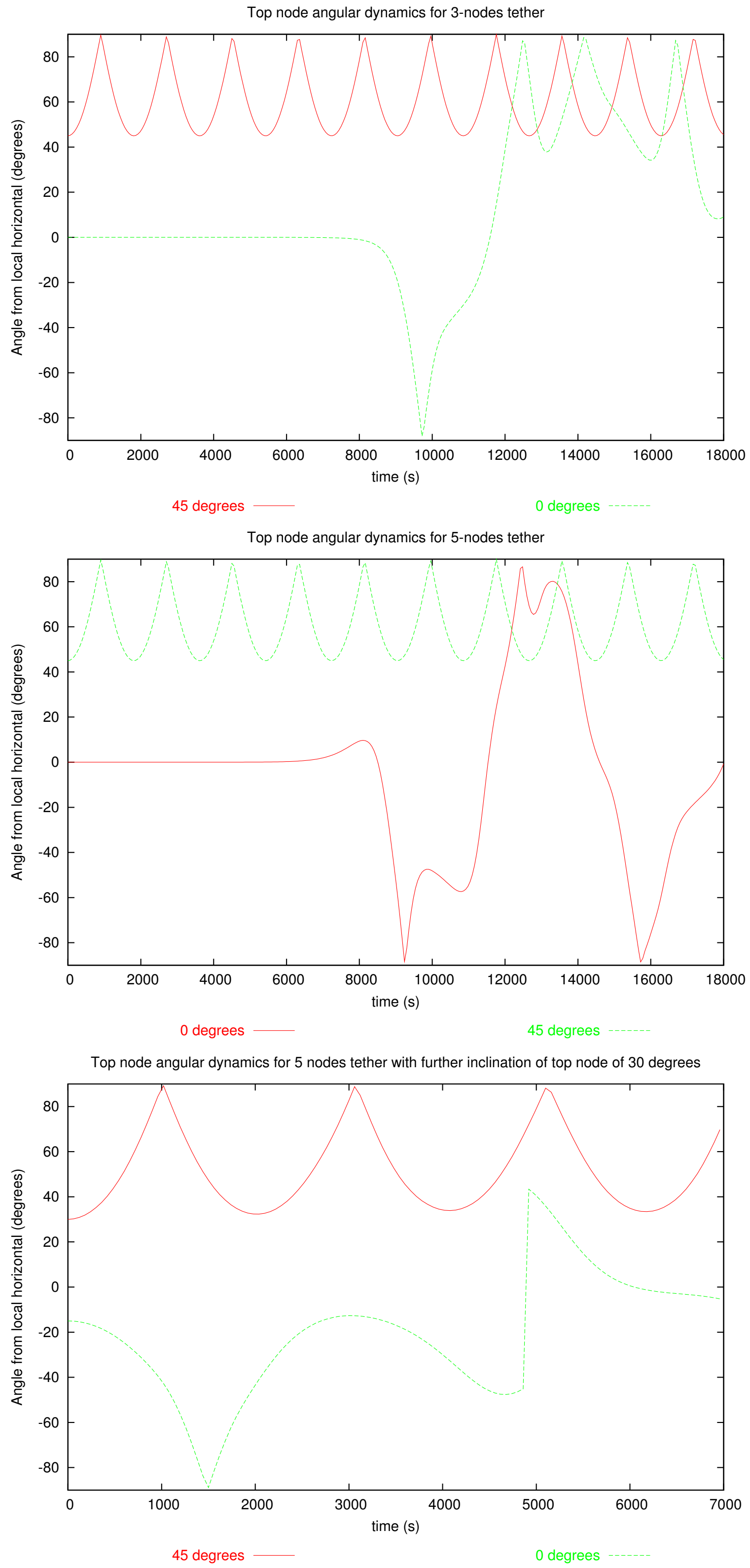

Figure B.9: Tether simulations with various number of nodes

Software Requirement	Function achieved	Comment
S1-Simulate	Complete 3D simulator validated	Achieves goal. Room for more automatic definition.
S2-Computing	Use NumPy	Easy to program and relatively efficient (max time < 1hr).
S3-Free	All free	Success.
S4-Platforms	Win32, Unix, Linux	Success.
S5-Development	Developed in < 6 mths	Success.
S6-Interface	Text files plus screen animations	Good. Misses a GUI.

Table B.7: UniSim Requirements validation

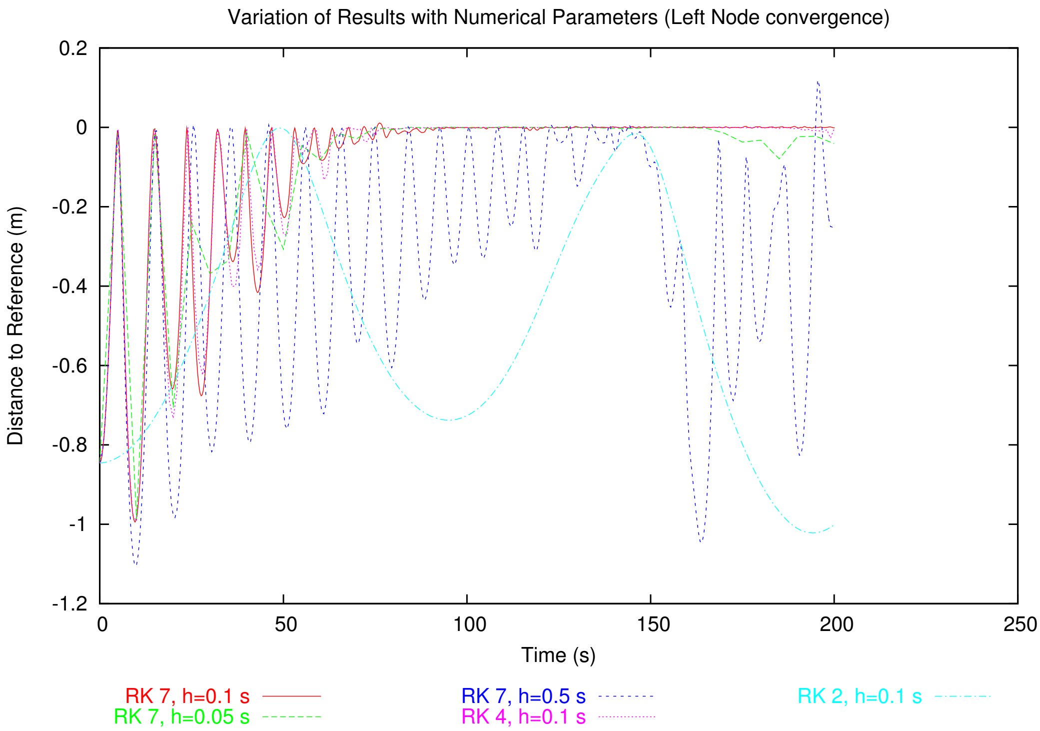

Figure B.10: Variation of simulation results with numerical parameters

Appendix C

Novel Space Missions Reference

Summary

As part of a preliminary evaluation of the impact of MST on space applications, a small study of novel missions was conducted to give background to the research. The results are that many missions exist to enable distributed or fast response systems using Nanosatellites. Equally, several applications of MST are found in large structures in space. Some of these applications are being researched already, some are still to be assessed. Metastructures are one of these applications.

C.1 Impact of MST on Space Mission

The advent of devices and systems generally regarded as Micro and Nano Technology (MNT) is to be addressed by space system designers. Unmanned space systems can benefit from the features of MNT in three main areas:

- An increased performance to mass ratio, for instance by integration of a complete functionality of a spacecraft through MNT devices.
- A lower in-orbit delivery cost per function, from launch mass (payload mass) reduction mainly, and also from batch production.
- A high degree of miniaturisation, which is the cause for the two direct advantages above.

The advantages of these are being evaluated in terms of mission design in the following sections. Currently the main development prospects are for integrated micro-scale devices, generally called in Europe as Micro System Technology (MST). At the implementation and development level, three ways of introducing MST in space systems can be contemplated:

General technology MST applications: Some technologies, like for instance distributed sensing in a structure, can be used in other terrestrial domains, not only in space. These will come to be employed naturally enough. Their largest scope of applications may be in Ground Segment, where MST will probably make receiving of data from space much easier and cheaper.

MST-based complete spacecraft subsystems: Entire subsystems or equipment can be replaced or improved gradually, using relatively integrated devices, primarily in AOCS and sensing subsystems (see Chapter 3).

Integrated MST for space missions design: MST is not only about making things smaller. It is believed that MST and Nanotechnology can enable new missions or improve the current ones by considering new concepts for system level spacecraft and mission design, using such tools as the Nanosatellite, a completely integrated satellite composed almost entirely of Micro devices and able to perform significant tasks.

The focus is now on these applications based on the last point above, i.e. missions that are specifically based on MST at system design level. Their development needs and their expected benefits are estimated.

C.2 Missions

These missions can be loosely classified in three categories: "current" missions, which can be currently accomplished by present-dat satellites but are improved in a significant way by MST based devices; Missions considered before but made more plausible/profitable by Micro Systems, and otherwise new missions.

C.2.1 Improved missions

C.2.1.1 Planetary exploration

MST can develop all its advantages in interplanetary missions for distributed monitoring of planets. For Mars ground exploration, for instance, one solution is to use several small robots with mini and micro subsystems called Micro-Explorers [Lecuyot, A. and Snelling, M., 2003], having increased capabilities with respect to the current ones.

Another solution, more mass-effective, is to drop dozens of nanorobots all over the planet using a gliding plane as launch base (see Figure C.1). For instance, based on a 1 ton mission to Mars[1] and using 5kg robots, this mission could increase the Surface explored / Mass ratio by 20 compared to current missions.

[1]comparable to ESA's Mars Express 1100 kg

Another application of Nano-spacecrafts can be the exploration of gaseous giants atmospheres. To monitor detailed wind fluxes or atmosphere composition for instance, it could be useful to use tiny simplistic atmospheric probes. Picosatellites (smaller than one kilogram) can probably be implemented [Helvajian, 1999] that are able of surviving being moved by strong winds, acting as radio beacons thus imaging the flow profile, and possibly transmitting continuous measurements for a single physical parameter. Power generation of one Watt or less can be ensured either via solar panels, chemical reactions or turbines.

C.2.1.2 Telecomm rings and low rate missions

Preliminary studies [Stuart, 1995] shows LEO constellations designers believe the next generation of constellations will feature the Nanosatellite concept. It is not clear at present at what level and how this will be introduced.

Given the limitations of MST in terms of power transmission, it may well be that the reasonable solution lies in mixed systems, including "normal-sized" transmission satellites for downlink, and Nanosatellites for uplink and crosslink. Low data rate missions can also be enabled by Nanosatellites. Typically, a rate of around 50 kbauds corresponds to a few parameters monitored every 30 seconds for 5000 users per satellite. This can probably be received by a single unit and still provide useful input.

C.2.1.3 Meteorological Skymesh

Meteorological models use a "mesh" of Earth's atmosphere to make their prediction. Each of the elements has to be assigned values of the atmospheric parameters like pressure, temperature, humidity,... The current problem is correlating these values with reality for elements above the sea, and in non-populated areas. To help solve that problem, it can be envisioned to set up a swarm of hundreds of small identical units in LEO, each one being able to sound its "square" of the mesh, with the help of adjacent units for lateral scanning (See Figure C.2). Based on current UK Met Office's requirements [WWW, 1999], the requirement on individual unit is a scanning resolution for basic parameters (pressure, temperature, humidity) on 120

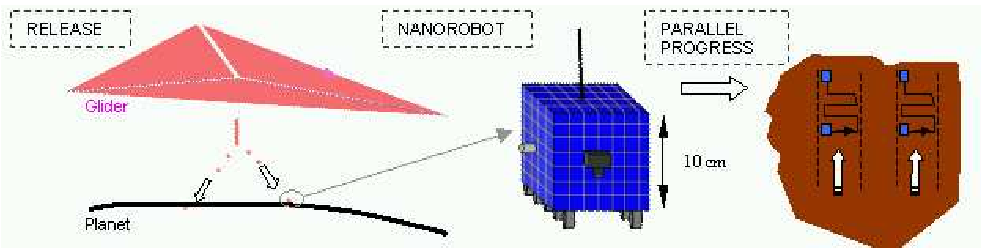

Figure C.1: Planetary Exploration Swarm concept km-wide squares for 38 different levels.

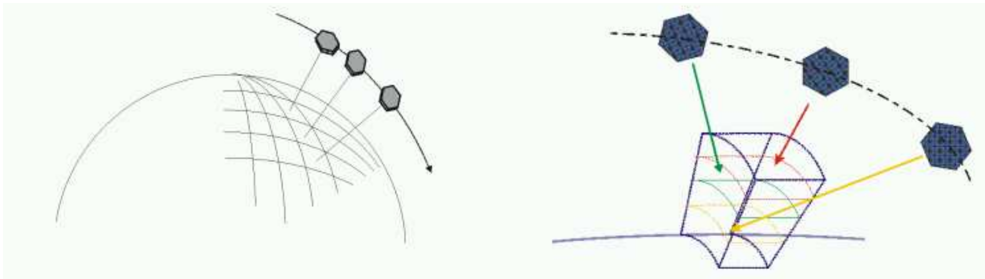

Figure C.2: Skymesh satellites - Each Nanosat corresponds to a mesh element

C.2.2 Enabled missions

C.2.2.1 Asteroid Exploration and Mining

Researchers in that field [Kargel, 1994] emphasise that asteroids are potential source of precious metals. However, it is difficult to exploit them economically with current technology. Development of mining facilities at molecular or atomic level using large numbers of collaborating units would probably reduce dramatically the mass of a processing "plant". A single 1 ton mission for instance could explore up to 40/50 asteroids. Also, Nanosatellites may be used for geological exploration of a given asteroid field. It is to be noted that some carboniferous asteroids can be used as primary construction materials for space infrastructure using the same processing technique.

C.2.2.2 Space Elevator

The project of setting a space Elevator between the Equator and GEO orbit (see Figure C.2.2.2) may become more plausible as Nanotechnology allows Nanotubes manufacturing on an industrial scale (see Table C.1). It is to be noted that these tubes are made of carbon that can be processed using the output of asteroid mining mission.

Material	$\sigma_{rupture}$ (GPa)	ρ (kg/m$\hat{3}$)	Lc^2 (km)
Steel	~ 4	7800	50
Kevlar	~ 3	1400	220
Graphite Whiskers	~ 207	1700	1240
Nanotubes	¿100	1200 maybe	8500

Table C.1: Different Materials for Space Evelator Cable construction

C.2.2.3 Self-Controlled Solar Sails and Solar arrays using Microthrusters

The main problem in the deployment of thin sail-like devices in space is that small dynamical perturbations can quickly wreck the sail. To control the deployment, arrays of 500 or 1000 self-regulated microthrusters can be tied to the deploying edges (as seen on Figure C.4). They can then realise the cable or structure deployment if perturbations can be kept small. Some similar research has started in this area [News, 1999].

C.2.2.4 Pluto Express "GrapeSat"

The Pluto Express mission is made difficult because of the extreme cost of sending a worthwhile payload so far away. Using MST, a 10-kg payload can include useful instruments, even if they are not as accurate as larger ones, and be sent itself on a mission to Pluto. Keeping the same ΔV profile for an 8-year long hyperbolic trip thus requires need 10 times less propellant, rendering the mission much more attractive. This mission can act as a demonstrator project to show the capabilities of Nanosatellites.

Figure C.3: Artist's rendering of a Space Elevator using Nanotubes. Image source Scientific American.

C.2.3 New missions

C.2.3.1 Smart Space Mechanism

As discussed above, MST could be used to introduce mechanisms in space systems. Distributed actuators can be used to ensure smooth deployment (see Figure C.5), and distributed micro-wheels can act as lubricant-less bearings. Where the perturbations can be kept small (such as high orbits) then MST can probably be introduced.

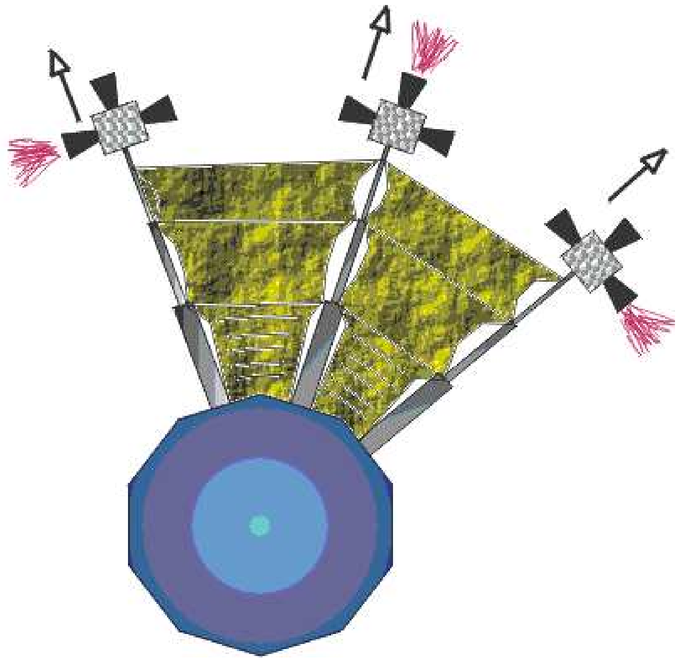

Figure C.4: Deployment of Solar sails using microthrusters

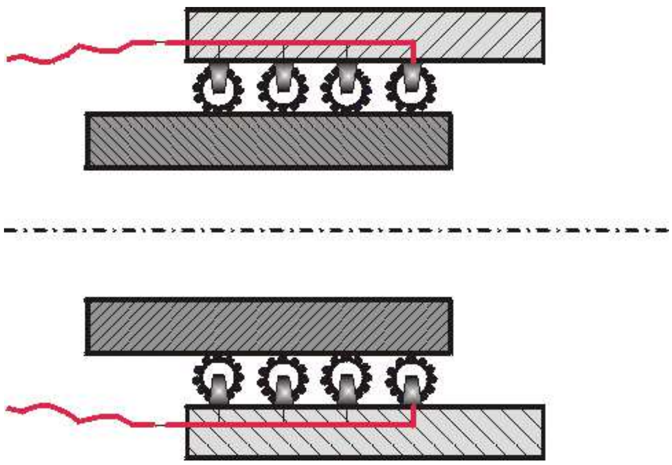

Figure C.5: Deployment of a boom using MST micro-rollers

C.2.3.2 Sparse Array antennas

Extending the concept of phased array antenna, it can be conceived that lots of coordinated sensing units can act as individual sensors, therefore enabling very large equivalent aperture diameters (see Chapter 4). Given the fact of orbital mechanics, the best design may comprise of physically linked satellites, instead of rotating clusters on elliptical orbits, who moreover require complex software. This system has interesting applications in defence (signal monitoring), in weak signal sensing, and in Astronomy, and can be used as a receiving antenna on interplanetary missions. It is later developed into the concept of metastructures.

C.2.3.3 De-orbit subsystem or de-orbit NanoSatellites

MST can help to address the Space Debris problem. By including in each newly launched spacecraft an autonomous subsystem that actuates independently a low-thrust de-orbiting device, the de-orbit is made less expensive and totally autonomous. Also, a mobile version of this device can be used to clear LEO and GEO of all dead satellites and rocket upper stages by having autonomous boarding and navigating capabilities. A de-orbit time of 3 to 10 years for 1 ton-class LEO debris can be considered with 10kg FEEP engines, or reasonably small solar sails of around 200x100m. This mission has been proposed and tested already [da Silva Curiel, 2003].

C.2.3.4 "Instant satellite" for Disaster Monitoring

Using Nanosatellites with limited autonomy and capacity but cheap and reliable design, it can be possible to post several of them on an in-orbit infrastructure that can "launch" satellites on demand. It can be used to release an optical observation payload over a disaster zone, or to allow a private temporary store-and-forward telecom capacity. Ejection can be realised mechanically or in another way. One polar and one equatorial base provide access for any site to be covered (see Figure C.6). Using a 2kg payload for instance, a 10 kg-class satellite can be sent on any orbit up to 45 degrees.

C.3 Technology development needs

C.3.1 Technology needs

All the above missions depend on expected developments in technology, computing science, and organisation. These are mainly:

Micro devices space qualification: The study of long-term applications will obviously be influenced by the resulting behaviour of MST in space conditions.

Nanosatellite Integration: A challenge to the realisation of Nanosatellites is the integration of all functions at chip level so that no interconnect is needed between subsystems.

Macro/Micro technology interface: A non space-specific issue to MST implementation is the interfacing of micro-devices with the "macro" world. All application requesting power transmission face this problem. In that respect, space will have to use results from other industries concerned or participate to the technology development.

Low thrust / Low consumption propulsion: For de-orbiting missions it is requested to have low thrust or low consumption propulsion systems available. This can be achieved through a number of ways: electrical propulsion, small solar sails, electromagnetic tethers. Some of these concepts have not yet been fully demonstrated for use in current spacecrafts. It is believed, however, that due to the low masses involved, these engines may work efficiently on a Nanosatellite.

Autonomous behaviour-based systems: Projects involving large number of units will inevitably have to be managed using autonomous "intelligent" systems. Behaviour-Based automatons programming are probably a good way to solve the complex systems problem [Lecuyot, 2001].

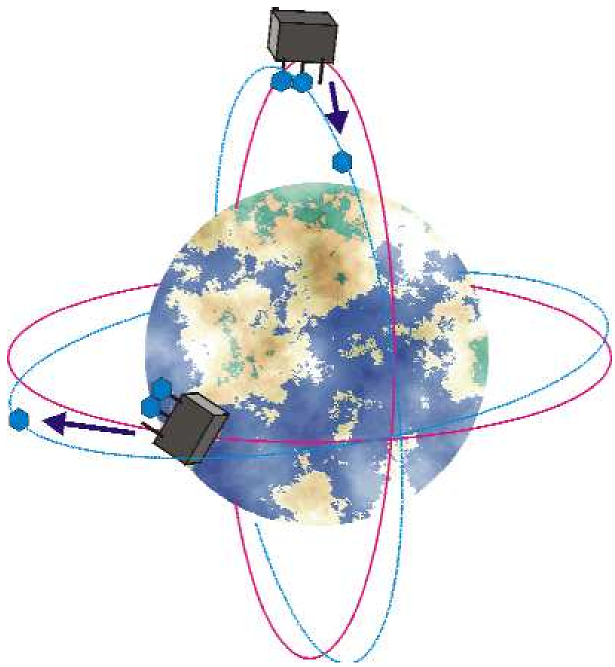

Figure C.6: Two in-orbit launchers, able to send instant satellites

C.3.2 Integrated design and operations need

It can be seen through a review of the missions and requirements presented above that the long-term improvements expected by using MST require a shift in space mission design. This will occur on the design and operations side, where all subsystems will have to be defined in a much more interdependent way, and using more off-the-shelf technology. But it will also be the case for organisational and financial issues too. Global Meteo coverage of Earth, for instance, may require multi-government co-ordination.

C.4 Benefits

Considering changing the space mission design by introducing MST at the mission and system level presents several advantages. The most expected is the increase of value per money spent, which is a direct translation of the mass efficiency increase. This in turn is due to increased autonomy, and the fact that the value of a sum of small collaborating units is usually much more than the sum of the individual values.

Serious business opportunities are thought to exist in the middle to long term for Earth Observation and Telecom applications. In Telecoms particularly, a set of very simple spacecrafts can be used to perform tasks that are not very demanding in term of data rates. Applications like electronic tagging or remote medical monitoring of mobile patients can probably be implemented at reasonable cost, thus extending the range of public applications of space.

Most of the applications discussed participate of the globalisation movement, so they will probably put forward international collaboration in technology as well as organisation. For a single country, MST-based missions can help develop a useful and significant space capability at the price of technology development for one payload alone.

Being designed in a serial production mind, Nanosatellites can easily be made upgradable and changeable, therefore ending the one-off satellite mission era. So in the long term, MST can lead to a real change in the space business, changing the way policy makers have to think about space application. On both technical and political grounds it appears useful to research Nano and Micro technology as a design base for space missions.

Appendix D

Internet Duplicata Reference

Summary

This chapter proposes a duplicata of selected InterNet reference as proposed by guidelines for modern thesis submissions. These are referred to in the text and appear in the Reference in Appendix 15.

D.1 List of duplicated documents

Numerical Models for Meteorology From the Met Office's website, as in [WWW, 1999].

Lunar Solar Power System , From the World Energy's website, as in [Criswell, 1998].

ALFA Mission , From JPL's website, as in [Jones, 1998].

MEMS in Smart Structures , from Spacedaily's news website, as in [Frampton, 2002].

Distributed Control of Spatially Interconnected System from Cornell's University College of Mechanical and Aerospace Engineering, as in [D'Andrea, 2003].

D.2 Numerical Models for Meteorology

Operational Numerical Modelling

Numerical Models of the Atmosphere

Operationally, the Met Office runs two configuration of its Unified Model. The global model has a horizontal resolution of 0.8333° longitude (432 columns) and 0.5555° latitude (325 rows) giving an approximate resolution of 60km in mid-latitudes.

The global model is used to provide boundary conditions to the mesoscale model which is a regional model centered on the United Kingdom. This model has a resolution of 0.11° latitude by 0.11° which is approximately 11km. In the mesoscale model there are 146 columns and 182 rows. Both the global and mesoscale models have 38 levels in the vertical.

In the mesoscale model the model North Pole is not located at the geographical North Pole. This is done in order to obtain a fairly uniform horizontal resolution over the area of interest, ie the UK. The mesoscale model has its North Pole situated at 37.5°N 177.5°E.

In both models, the variables are arranged in the same fashion. In the horizontal, an Arakawa C grid is used, the u wind components are east-west staggered from temperature and the v wind components are north-south staggered, and in the vertical Charney-Philips grid staggering is used which means that (potential) temperature, scalars (moisture variables and tracers) and vertical velocity are staggered from (Exner) pressure, density and horizontal wind.

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The Numerical Weather Prediction System

The forecast models run within a system known as the operational suite. Once initiated, the operational suite will perform all tasks needed to produce the forecast with no further manual intervention. There are however, facilities to manually override tasks should any problems occur.

The operational suite embraces all the individual tasks that are required to produce a forecast. Most of the software within the operational suite has been written in-house. The suite itself is controlled by what is known as the suite control system (SCS). The SCS can be used to select which tasks are run, how they are run and when they are run.

The first task is the observation processing to extract all the observations that have been received, to quality control them and finally reformat them into a form ready for use by the model.

For certain runs of the model, a reconfiguration then occurs. This is a procedure to incorporate data fields from external files into the model. This is required to update fields that have their own standalone analysis, such as the sea surface temperature, or to update a climatological field.

The data assimilation scheme is then run. This adjusts the model background field, which is a forecast from a previous model run, towards the new data received from the observations.

The main forecast is then run, the length of which varies according to the particular run of the model, more details are given below.

The forecast data are written into files known as fieldsfiles. Using these, various plotted charts and maps are produced which forecasters then use to produce the weather forecast. It is important that the charts are available at the earliest possible time and therefore fieldsfiles are produced that cover a 24 hour period only. This enables charts for say T+24 to be plotted and made available even though the forecast is continuing.

D.3 Lunar Power System

LUNAR SOLAR POWER SYSTEM FOR ENERGY PROSPERITY WITHIN THE 21ST CENTURY

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Houston, TXU.S.A.

1. Introduction

Approximately 6 kWt/person or, eventually, 2 kWe/person can enable energy prosperity. Note that "t" refers to thermal energy and "e" to electric energy. For a population of 10 billion people, anticipated by 2050, this implies 60,000 GWt or 20,000 GWe. For purposes of discussion, assume that power usage continues to be high to 2070. From 2000 to 2070 the world would consume approximately 3,000,000 GWt-Y or 1,000,000 GWe-Y of energy [1, 2, 3, 4]. It is highly unlikely that conventional fossil, nuclear, and terrestrial renewable power systems can provide the power needed by 2050 and the total energy consumed by 2070. They are restricted by limited supplies of fuels, pollution and wastes, irregular supplies of renewable energy, costs of creating and operating the global systems, and other factors.

It is technically and economically feasible to provide at least 100,000 GWe of solar electric energy from facilities on the Moon. The Lunar Solar Power (LSP) System can supply to Earth power that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere. Inexhaustible new net electrical energy provided by the LSP System enables the creation of new net material wealth on Earth that is decoupled from the biosphere. Given adequate clean electric power, humanity's material needs can be acquired from common resources and recycled without the use of depletable fuels [4, 5]. LSP power increases the ability of tomorrow's generations to meet tomorrow's needs, and enables humanity to move beyond simply attempting to sustain itself within the biosphere to nurturing the biosphere.

Fig. 1 illustrates the essential features of the LSP System: Sun, Moon, microwave power beam from a power base on the Moon, and a microwave receiver or rectenna on Earth. The LSP System uses bases on opposing limbs of the Moon. Each base transmits multiple microwave power beams directly to Earth rectennas when the rectennas can view the Moon. Each base is augmented by fields of photoconverters just across the limb of the Moon. Thus, one of the two bases in the pair can beam power toward Earth over the entire. cycle of the lunar day and night. This version of LSP supplies extra energy to a rectenna on Earth while the rectenna can view the Moon. The extra energy is stored and then released when the Moon is not in view.

The LSP System is an unconventional approach to supplying commercial power to Earth. However, the key operational technologies of the LSP have been demonstrated at a high technology readiness level (TRL = 7). TRL = 7 denotes technology demonstrated at an appropriate scale in the appropriate environment [6].

Power beams are considered esoteric and a technology of the distant future. However, Earth-to-Moon power beams of near-commercial intensity are an operational reality. Fig. 2 is picture of the South Pole of the Moon that was taken by the Arecibo radar in Puerto Rico. The Arecibo beam passes through the ionosphere with an intensity the order of 20 - 25 W/m^2. The LSP System is designed to provide power beams at Earth with intensities of less than 20% of noon-time sunlight (= 230 W/m^2). Lower intensity beams are economically reasonable. The intensity of microwaves scattered from the beam will be orders of magnitude less than allowed for continuous exposure of the general population.

Load-following electrical power, without expensive storage, is highly desirable. Earth orbiting satellites can redirect beams to rectennas that cannot view the Moon and thus enable load-following power to rectennas located anywhere on Earth. Rectennas on Earth and the lunar transmitters can be sized to permit the use of Earth orbiting redirectors that are 200 m to 1,000 m in diameter. Redirected satellites can be reflectors or retransmitters. The technology is much more mature than realized by the technical community at large.

Fig. 3 is an artist's concept of the new Trumpet satellite that employs a 100 m diameter reflector antenna. Trumpet is now in geosynchronous orbit. It is operated by the U.S. National Reconnaissance Office [7]. This reflector, only a few tons in mass, has a diameter within a factor of 1 to 3 of that necessary to redirect a power beam to a 1 km diameter or larger rectenna on Earth. Trumpet is reportedly similar in design to antennas planned for the Hughes commercial HS 601 AMPT satellites. Power beams and redirector satellites can minimize the need for long-distance power transmission lines and their associated systems.

Alternatively, a power beam from the Moon can be received by a receiver satellite. The relay satellite then retransmits new beams to several rectennas on Earth. The transmission of beams, with commercial level intensity in low Earth orbit, has been demonstrated by unmanned and manned spacecraft. Fig. 4 illustrates the NASA Shuttle with a phased array making a synthetic aperture radar picture of the Earth. Near the Shuttle the beam has an intensity the order of 150 W/ m^2. This is well within the range for commercial transmission of power [6, 8].

Approximately once a year the Earth will eclipse all the lunar power bases for up to 3 hours. This predictable outage can be accommodated by power storage of defined capacity or reserve generators on Earth. Alternatively, a fleet of solar mirrors in orbit about the Moon can reflect solar power to selected bases during eclipses and during sunrise and sunset. These solar reflectors, actually types of solar sails, will be less expensive to build and operate than the high precision reflectors such as in Fig. 3 [6, 7].

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2. LSP demonstration base

The lunar portion of an LSP System prototype Power Base is depicted in Fig. 5. A Power Base is a fully segmented, multi-beam, phased array radar powered by solar energy. This Power Base consists of tens to hundreds of thousands of independent power plots such as depicted in the middle to lower right portion of Fig. 5. Each power plot emits multiple sub-beams. Sets of correlated sub-beams from all the plots are phased electronically to produce one power beam. A given base can project tens to hundreds of independent power beams.

A power plot consists of four elements. There are arrays of solar converters, shown here as north-south aligned rows of photovoltaics. Solar electric power is collected by a buried network of wires and delivered to the microwave transmitters. Power plots can utilize many different types of solar converters and many different types of electric-to-microwave converters. In this example the microwave transmitters are buried under the mound of lunar soil at the Earthward end of the power plot. Each transmitter illuminates the microwave reflector located at the anti-Earthward end of its power plot. The reflectors overlap, when viewed from Earth, to form a filled lens that can direct very narrow and well defined power beams toward Earth. The Earth is fixed in the sky above the Power Base.

To achieve low unit cost of energy, the lunar portions of the LSP System are made primarily of lunar-derived components [2, 3, 9]. Factories, fixed and mobile, are transported from the Earth to the Moon. High output greatly reduces the impact of high transportation costs from the Earth to the Moon. On the Moon the factories produce 100s to 1,000s of times their own mass in LSP components. Construction and operation of the rectennas on Earth constitute greater than 90% of the engineering costs. Upfront costs can be reduced by using lunar materials to make significant fractions of the machines of production and support facilities. Most aspects of manufacturing and operations on the Moon can be controlled by personnel in virtual work places on Earth [9, 10].

An LSP demonstration Power Base, scaled to deliver the order of 10 to 100 GWe, can cost as little as 20 billion dollars over 10 years [2, 9, 11]. This assumes the establishment of a permanent base on the Moon, by one or more national governments, that is devoted to the industrial utilization of lunar resources for manufacturing and logistics. Such a base is the next logical step for the world space programs after completion of the International Space Station.

LSP is practical with 1980 s technology and a low overall efficiency of conversion of sunlight to Earth power of ~0.15%. Higher system efficiencies, = 35%, are possible by 2020, and greater production efficiencies sharply reduce the scale of production processes and up-front costs. An LSP System with 35% overall efficiency will occupy only 0.15% of the lunar surface and supply 20, 000 GWe to Earth.

There are no "magic" resources or technologies in Fig. 1 or Fig. 5. Any handful of lunar dust and rocks contains at least 20% silicon, 40% oxygen, and 10% metals (iron, aluminum, etc.). Lunar dust can be used directly as thermal, electrical, and radiation shields, converted into glass, fiberglass, and ceramics, and processed chemically into its elements. Solar cells, electric wiring, some micro-circuitry components, and the reflector screens can be made out of lunar materials. Soil handling and glass production are the primary industrial operations. Selected microcircuitry can be supplied from Earth.

Unlike Earth, the Moon is the ideal environment for large-area solar converters. The solar flux to the lunar surface is predicable and dependable. There is no air or water to degrade large-area thin film devices. The Moon is extremely quiet mechanically. It is devoid of weather, significant seismic activity, and biological processes that degrade terrestrial equipment. Solar collectors can be made that are unaffected by decades of exposure to solar cosmic rays and the solar wind. Sensitive circuitry and wiring can be buried under a few- to tens- of centimeters of lunar soil and completely protected against solar radiation, temperature extremes, and micrometeorites.

The United States has sponsored over 500 million dollars of research on the lunar samples and geophysical data since the first lunar landing in 1969. This knowledge is more than adequate to begin designing and demonstrating on Earth the key lunar components and production processes. Lunar exploration is continuing. The DoD Clementine probe and the new NASA Lunar Prospector (http://lunar.arc.nasa.gov) will extend the Apollo-era surveys to the entire Moon.

3. Rectennas and energy delivery on Earth

The Power Bases direct microwave power beams to rectennas on Earth as shown in Fig. 1. The intensity of each beam can be controlled to provide load following power. The beams pass through clouds, rain, and dust. There is no need for long-distance power transmission lines or indeterminately large systems to store power.

Power beams are assumed to have an intensity of about 20% that of sunlight just above the rectenna (~ 230 W/m^2). A few hundred meters from the edge of the rectenna the intensity will be 1% or less of the central intensity. Farther from the rectenna the stray power of a 20,000 GWe system will drop in intensity to that of the light from a full moon. LSP can be competitive with the conventional systems even if the beam is operated at intensities below those allowed for continuous exposure of the general population (10 W/m^2 at 1.5 GHz to 100 W/m^2 at 15 GHz). The energy received by the rectenna can be fully offset by reflecting back to space, from the area of the rectenna or elsewhere, an equal amount of lowquality solar energy. LSP energy can be environmentally neutral.

Rectennas are the major cost element of the LSP System. Rectennas will occupy as little as 5% of the land-area per unit of received energy as now devoted to the production and distribution of electricity. A rectenna can begin outputting commercial power after it reaches 0.5 km in diameter. Additional construction is paid for out of current revenue. A rectenna of one-square-kilometer area with an average output of 180 MWe produces every year the electric energy equivalent to burning 3.3 million barrels of oil or 650, 000 tons of coal in a fossil-fueled electric plant.

Rectennas can be placed virtually anywhere on Earth. It is reasonable to situate them over open land that is not used. It also appears reasonable to place them over agricultural land and industrially zoned property and facilities. They would provide additional revenue the order of 4 \$/m^2 -Y for power sold at 0.03 \$/kWe-h. Rectennas can be placed in countries or regions that do not have indigenous energy resources. Rectennas enable non-polluting solar electric power to efficiently support recycling, use of common mineral resources, and petrochemical processing of hydrocarbons into more valuable process chemicals and products. Rectennas provide both developed and developing countries equal access to electric power for economic development and the enhancement and preservation of the local environment.

Table 1 compares estimated life-cycle costs of five power systems scaled to provide 1,000,000 GWe-Y of energy. The costs are given in trillions (1 T = 1*10^{12}) of U.S. dollars. The estimates are based on studies of systems utilizing 1990s levels of technology [12, 13, 14]. The major cost categories are capital, labor, fuel, and waste handling and mitigation. Thirty percent of the costs of the coal and fission systems are for regional power distribution systems. The terrestrial solar photovoltaic system costs are scaled from studies of globally distributed photovoltaics linked by a global electrical transmission system. However, no power storage is included [15]. Both LSP Systems, power storage on Earth or load-following, offers enormous savings in the cost of production and distribution of electric power. The savings are the order of 1, 000 trillion dollars over coal to the order of 8, 000 trillion dollars for terrestrial solar photovoltaic.

Cost estimates for the LSP energy are derived from systems level analyses conducted by General Dynamics on the cost of building space solar power satellites (SSPS) from lunar materials [11, 16, 17]. For similar levels of manufacturing and operating technologies the LSP approach is approximately 50 times more cost effective than making SSPS from lunar materials or deploying SSPS from Earth. Lunar and space operations are a small fraction of the LSP System life-cycle cost. For the load-following LSP System the construction and operation of rectennas on Earth represents over 90% of the expenditures. For the LSP that uses power storage on Earth (deep pumped hydro is assumed). The terrestrial expenditures account for over 95% of total costs [18].

4. LSP System power and economic growth

The 70 year life-cycle costs of power for an energy-prosperous world are so enormous that it is difficult to understand their scale and significance. One method is to calculate the simple sum of gross world product (GWP) over that same period. Assume that GWP/person is 4,000 $/person-Y over that period. The sum is 2,400 trillion dollars. Alternatively, present economic growth of approximately 2%/Y-person sums to only 3,700 trillion dollars. Such "poor" worlds simply cannot afford to build and operate the coal, fission, and terrestrial photovoltaic systems. Approximately 10% of GWP is now expended on the production and consumption of commercial energy. This corresponds to 240 to 370 trillion dollars between 2000 and 2070. These sums are much smaller than the costs of conventional systems but larger than projected for the LSP System. A poor world must remain energy poor if it uses only conventional power systems. However, the less costly LSP System electricity can both save money and accelerate the generation of wealth.

Between 1960 and 1986, the total electric energy E_e (Y) used every year, measured in T kWe-h, was an excellent index of the annual GWP in trillions of dollars (T$e(Y)) in a given year "Y" [19, 12]. Equation 1 includes the annual increase in productivity of energy Eff(Y) of approximately 1%/Y. The cost of 1,000 TWe-Y of energy delivered between 2000 and 2070 is taken to be 200 T$.

$$T\$e\ (Y) = 4.3\ T\$ + [1.2\ T\$/TkWe\text{-}h]^*\ E_e(Y)\ *\ Eff(Y) - 200T\$/(70\ Y) \quad \text{Equation (1)}$$

Applying Equation (1) to the production of 1,000,000 GWe-Y of energy by 2070 predicts an integral net GWP ~ 14,700 T$ by 2070 or 12,300 T$ more than the 2,400 T$ predicted for a "poor" world. Equation 1 also implies an average annual income in 2070 of 36,000 $ per person. This is approximately 10 times present per capita world income.

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5. Conclusions

Enormous attention is directed to discovering and promoting "sustainable" sources of energy and seeking more efficient means of utilizing conventional commercial and renewable energy. However, there are clear limits to the conventional options. Over 4 billion of Earth's nearly 6 billion people are poor in both wealth and energy. Their existence depends primarily on new net energy taken from the biosphere. This energy is harvested as wood, grass, grain, live stock from the land, fish from the seas, and in many other direct and indirect products. The biosphere incorporates each year approximately 100,000 GWt-Y of solar energy in the form of new net plant mass (algae, trees, grass, etc.). It is estimated that humanity now directly extracts ~ 5% of that new energy and disturbs a much greater fraction of the natural cycles of power through the biosphere. People divert almost 50% of the new solar photosynthetic energy from its natural cycles through the biosphere [21. 22]. Humankind now collects and uses approximately 50% of all the rain water that falls on accessible regions of the continents. Given the continuing growth of human population, most of the fresh water used by humans will be obtained through desalination.

Human energy needs can be accommodated by approximately 6 kWt/person or in the next century by approximately 2 kWe/person [4, 23, 24, 25]. For a population of 10 billion people this corresponds to a minimum of 2,000,000 GWe-Y, or 2,000 TWe-Y, of electric energy per century. Much more energy might be desirable.

It is widely recognized that the lack of affordable and environmentally benign commercial energy limits the wealth available to the majority of the human population [20]. However, there is almost no discussion of how to provide the enormous quantities of quality commercial energy needed for an "energy-rich" world population. The dashed curve of Fig. 6 depicts the cumulative depletion of terrestrial fossil thermal energy by a prosperous human population in tera-Watt-Y (= 1,000 GW-Y) of thermal energy. There is approximately 4,000 to 6,000 TWt-Y of economically accessible fossil fuels. Thus, the "Fossil" energy use stops changing between 2050 and 2100 when the prosperous world consumes the fossil fuels. There are other severe fundamental problems with global prosperity based on fossil fuels. For example, burning the fossil carbon will increase atmospheric CO_2 by a factor of 15 or more. Economically available uranium and thorium can provide only the order of 250,000 GWt-Y of energy. The doubling rate for nuclear fuels is too long for the breeding of adequate fuels to meet the energy needs of a prosperous world by 2050 [26]. Breeder systems would provide only the order of 10,000,000 GWt-Y or 3,000,000 GWe-Y of energy before requiring the use of uranium and thorium from sea water and granite at a much higher cost of process energy.

Consideration of the LSP System is recommended by technical [27], national [28], and international panels [29, 30] and scientists active in lunar research [30, 31, 32]. An LSP System scaled to enable global energy prosperity by 2050 can, between 2050 and 2070, stop the depletion of terrestrial resources and bring net new non-polluting energy into the biosphere. Humanity can stop extracting resources from the biosphere, become independent of the biosphere for material needs, and have excess energy to nurture the biosphere. The boundaries of routine human activities will be extended beyond the Earth to the Moon and a two-planet economy will be established.

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Table 1: Power System cost and affordability

Type of Global Power System	Life-cycle cost (trillion = $1\bullet10^{12}$ \$)
Solar Photovoltaic	8,000
Advance Fission	3,300
Advanced Coal	1,500
LSP (With 16 hrs of storage)	200
LSP (Load following, no storage)	40
Σ GWP (2000-2070) @ 4,000 $/Y-person	2,400

Fig. 1 LSP System (Sun, Moon, Beam, Rectenna)

Fig. 2 Arecibo Radar Picture of the Moon

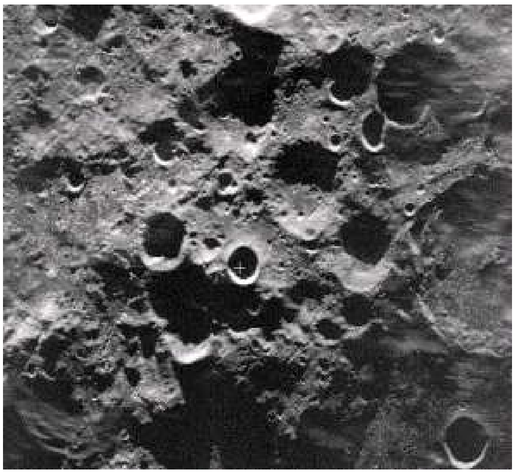


Fig. 3 Concept of NRO Trumpet Satellite

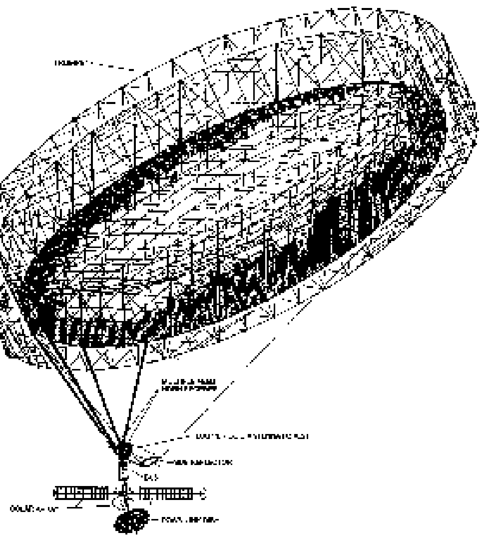


Fig. 4 Shuttle Synthetic Aperture Radar

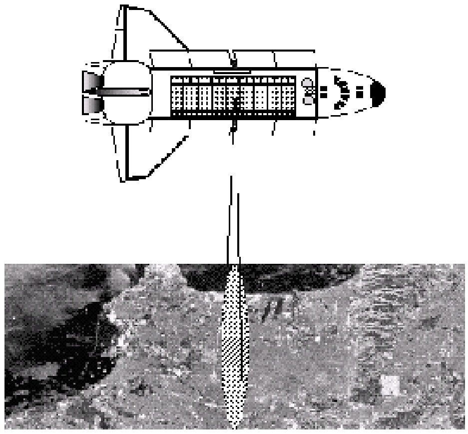


Fig. 5 LSP System Prototype Power Base

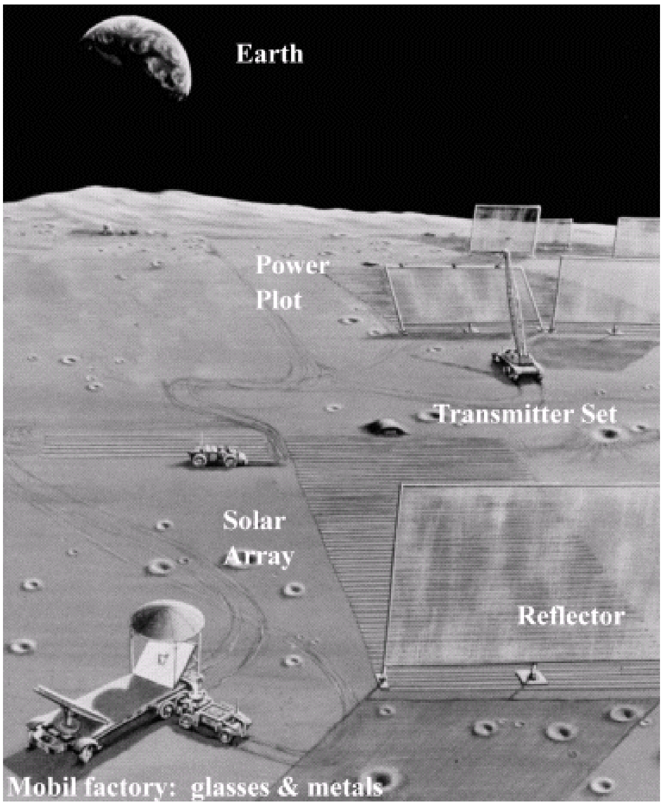
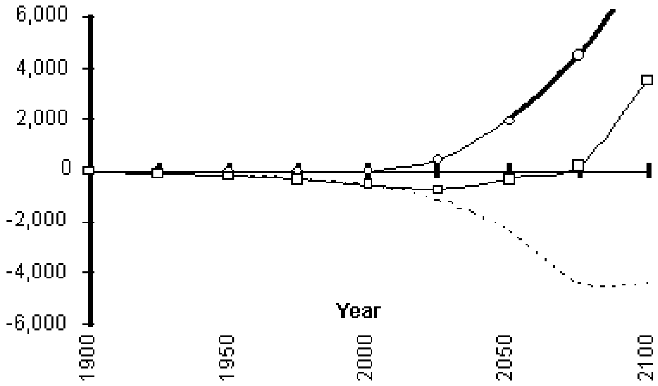


Fig. 6 Energy Use By Prosperous World: 1900 to 2100

------ FOSSIL —o—LSP —□—TOTAL



Summary

It is technically and environmentally feasible to provide commercial solar electric power to Earth from solar power facilities on the Moon. The Lunar Solar Power (LSP) System can supply electric energy to Earth at less than 0.01 $/kWe-h that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere. The LSP System uses bases on opposing limbs of the Moon as seen from Earth. Each base transmits multiple microwave power beams directly to Earth receivers called rectennas when a given rectenna can view the Moon. Also, satellites in orbit about Earth can be used to redirect beams to rectennas that cannot view the Moon and thus enable load-following power to rectennas located anywhere on Earth. The LSP System is an unconventional approach to supplying commercial power to Earth. However, the key operational technologies have been demonstrated at a high technology readiness level.

To achieve low unit cost of energy the lunar portions of the LSP System are made primarily of lunar-derived components. Factories, fixed and mobile, are transported from the Earth to the Moon. On the Moon the factories produce 100s to 1,000s of times their own mass in LSP components. Construction and operation of the power receivers on Earth constitute greater than 90% of the engineering costs. An LSP demonstration Power Base, scaled to deliver the order of 10 to 100 GWe, can cost as little as 20 billion dollars in incremental costs over 10 years when completed as part of a large permanent base on the Moon. Capacity can grow to 20,000 GWe within the 21st century and eventually to greater than 100,000 GWe.

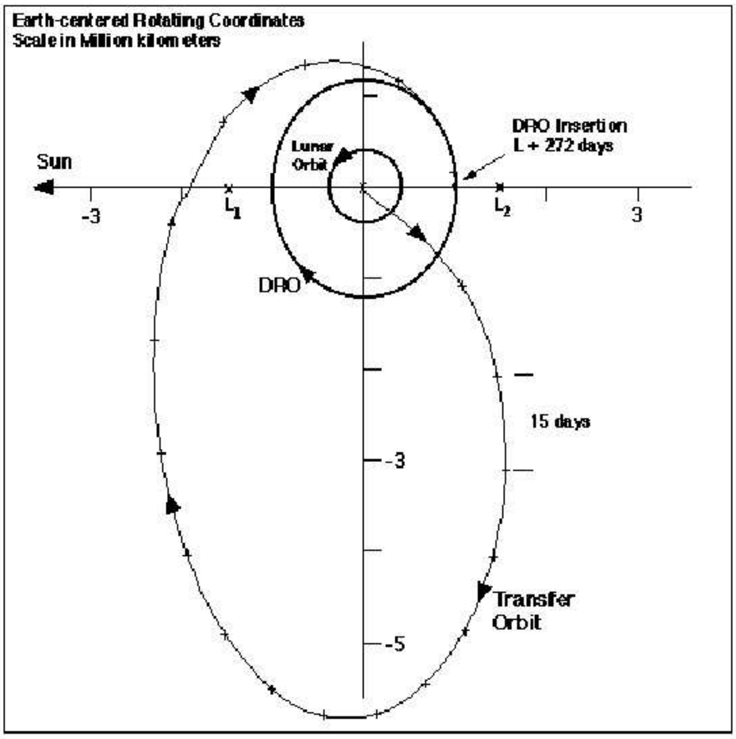
Global energy prosperity requires commercial systems that supply at least 2 kWe/person by approximately 2050 and approximately 1,000,000 GWe-Y of energy by 2070. Conventional renewable and non-renewable systems cannot achieve these goals. An LSP System can enable global energy prosperity by 2050, stop the depletion of terrestrial resources, bring new non-polluting net energy into the biosphere, and greatly accelerate the creation of new net wealth on Earth.

D.4 The ALFA Mission

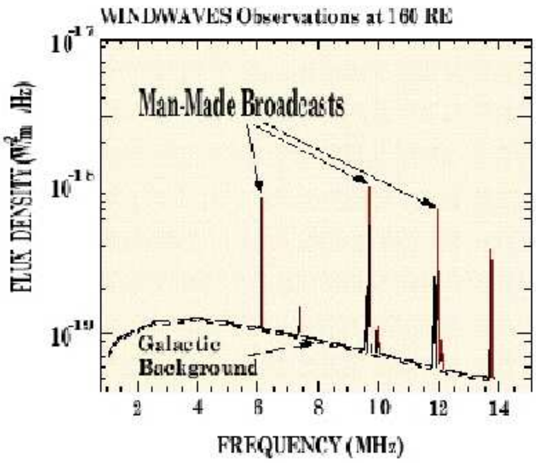
ALFA Mission Concept

The Astronomical Low-Frequency Array will be deployed in a distant retrograde orbit approximately 1 million km from Earth. This orbit allows the array to remain far from Earth's noisy radio environment and yet close enough to transmit data to small, inexpensive tracking antennas on the ground. The array will be composed of 16 identical small satellites in a loosely controlled, three-dimensional cluster occupying a volume about 100 km in diameter. The array will operate at frequencies between 0.03 and 30 MHz and will provide arcminute imaging at 10 MHz, consistent with the limits imposed by interstellar and interplanetary scattering. Each small satellite carries a pair of low frequency receivers and orthogonal dipole antennas.

The figure below shows the Moon's orbit, the distant retrograde orbit (DRO) of the ALFA satellites, and the transfer orbit used to go from Earth to the DRO. The DRO has an orbital period of about 3 months, and is inclined slightly with respect to the ecliptic plane to avoid eclipses by Earth.



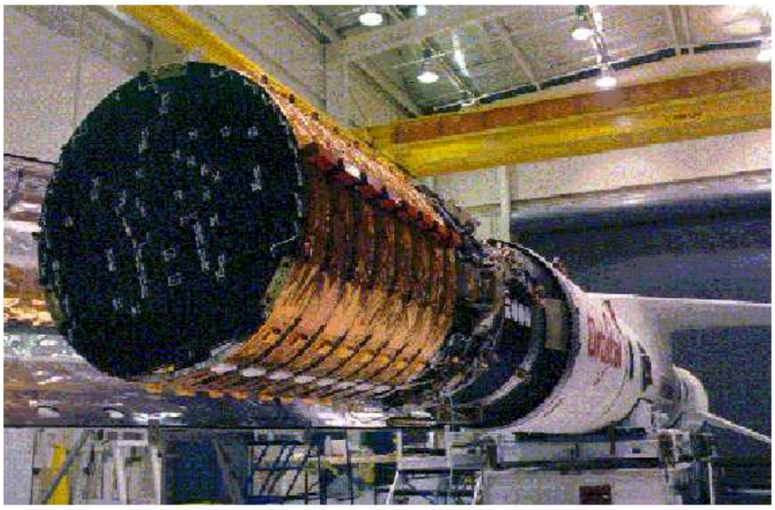
The distance of the DRO was chosen to avoid radio frequency interference (RFI) from terrestial transmitters. The figure below shows actual data from the Wind spacecraft when it was at the same distance from Earth as ALFA will be. Note that most of the frequency range is devoid of detectable interfering signals.



The 16 small satellites will be carried into space attached to a carrier bus on a Delta 7425 launch vehicle. The carrier bus deploys the array satellies after capture into the DRO, and also images Earth (and the Moon) with a small on-board camera, producing pictures like the simulated one shown below.

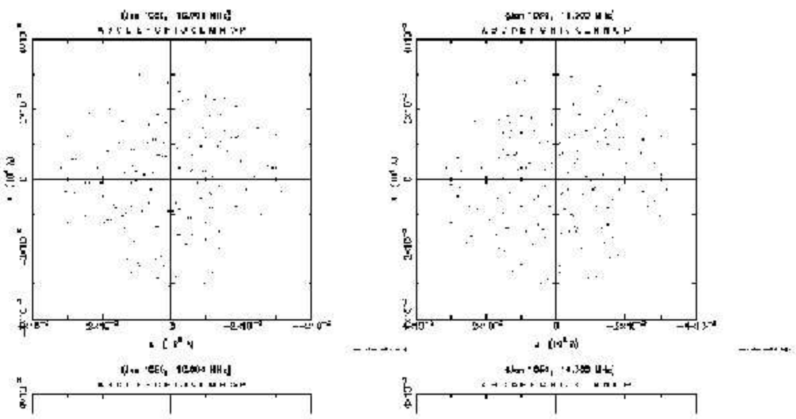
Precise control of the cluster geometry is not required because of the very long wavelengths being observed. The small satellites will be allowed to drift loosely about an assigned position with, typically, several days between shepherding maneuvers.

The ALFA satellites are based on the commercial Orbcomm bus, although the ALFA satellites are actually quite a bit simpler in design. The ALFA production run of 16 identical satellites will follow the production of 32 Orbcomm satellites, and will benefit for the production and test facilities developed for the Orbcomm program as well as from a heritage of flight-proven subsystems. The design reliability of Orbcomm satellites is 85% after 5 years. Using this value and assuming that failures are independent, the probability of at least 12 out of 16 ALFA satellites operating after 2 and 3 years is 99 and 95%, respectively. Because each ALFA satellite communicates independently with the ground, the failure on any individual satellite has no effect on the operation of the rest of the array. The figure below shows a stack of 8 Orbcomm satellites being prepared for launch on a Pegasus.



The ALFA mission proposal to NASA includes large reserves in launch mass and mission cost, made possible by using the flight-proven design and subsystems from the commercial Orbcomm satellites.

By using 16 satellites, ALFA is very resilient to the failure of a small number of satellites during the mission. In addition, the large number of baselines (120) allows good aperture plane sampling in all directions simultaneously. This is essential for all-sky imaging at low frequencies, where the directivity of individual antennas is very low. The figure below shows the aperture (u,v) plane sampling provided in six directions covering 0 to 90 degrees of ecliptic latitute at the same time. In each direction, the instantaneous coverage is dense and uniform - ideal for snapshot imaging.



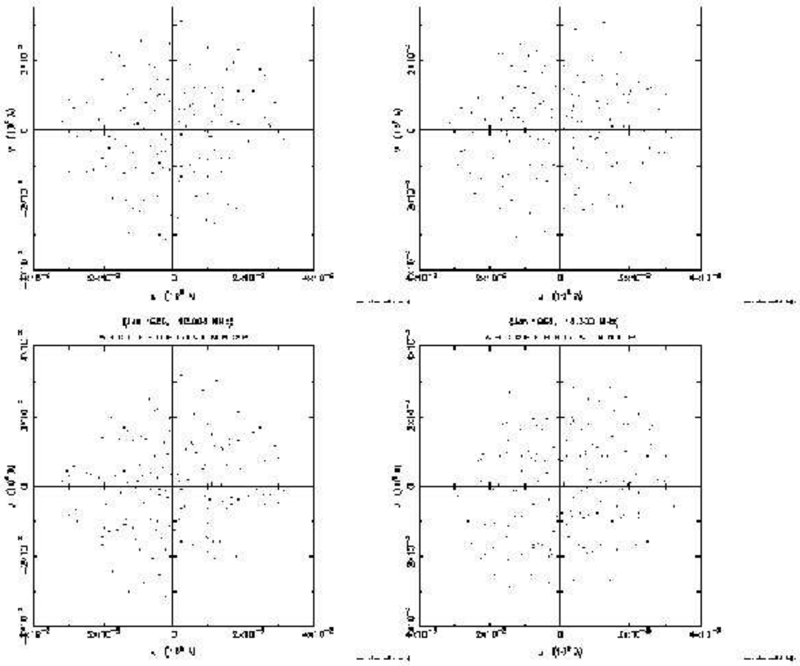


Figure 1: Array 15-m — (u,v) coverage for [illegible] ecliptic latitude.

Imaging simulations made with realistic data have shown that all-sky imaging is feasible with the type of omnidirectional coverage illustrated above.

Next (ALFA team)

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D.5 MEMS in Smart Structures

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A New Approach May Finally Make "Smart Structures" Scalable

by David F. Salisbury
Pittsburgh - June 4, 2002

Ken Frampton testing MEMs - photo by Neil Brake

The early promise of smart structures — equipping spacecraft, aircraft, automobiles and ships with networks of sensors and actuators that allow them TO respond actively to changing environmental forces, an approach predicted to revolutionize their design, construction and performance — has never materialized.

That is because researchers found that when such networks grew beyond a modest size of about 100 nodes, they became too complex for central computers to handle. In addition, the weight, power consumption and cost quickly became prohibitive. In other words, they could not be scaled up to large sizes.

Today, however, recent advances in MEMS (micro-electromechanical systems) and distributed computing appear to be overcoming these limitations, reported Kenneth Frampton, assistant professor of mechanical engineering at Vanderbilt, speaking at the Acoustical Society of America meeting in Pittsburgh on June 6.

Frampton, who is an expert in vibration and acoustics, and his colleagues have incorporated these advances using a new approach, called embedded systems, to design a smart vibration-reduction system for a 15-foot-long rocket payload faring. Currently, the high noise and vibration levels inside rockets when they are launched significantly increase the cost of manufacturing satellites and other equipment boosted into space. So a system that reduces these levels by even a small amount would cut payload development costs substantially.

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In the first phase of the project, Frampton's group prepared and ran a detailed computer simulation of the system that showed it should provide a degree of vibration-reduction comparable to that of a centrally controlled smart system.

"The most important result of the simulation is that it shows that the embedded system is scalable," says Frampton. "That means we should be able to build it as big as we need to and it should continue to function."

In the older approach, all the sensors and actuators are connected to a central computer. It receives information from all the sensors, processes it and then sends instructions to all the actuators on how they should respond. As the size of the structure and the number of sensors and actuators increase, the amount of wiring required increases dramatically. Difference in arrival times of information from the nearest and farthest sensors also increases, as does the time it takes the farthest sensors to receive their orders. The bigger the system, the greater these and other problems become.

In an embedded system, on the other hand, each node contains a PC-strength microprocessor with a relatively simple program and modest amount of memory that allows it to directly control the sensors and actuators wired to its node. The microprocessor also communicates with its nearest neighbors so they can work together. Depending on how the system is set up, the processor also receives data from a certain number of its nearest neighbors so that it can coordinate the actions of its actuators with those of the other nodes. Although each processor has considerably less capability than that of a central computer, it has far less information to handle, and its workload does not increase as the system gets bigger.

"Embedded systems are also far more 'fault tolerant' than centrally controlled systems," Frampton points out. If the central processor breaks down, the entire system shuts down. But a decentralized system will continue to work even when several microprocessors fail, although probably with slightly diminished capability.

The second step in Frampton's project is to put a 100-node system into an actual rocket faring comparable to the simulated system. Then he will test how well in it performs in the laboratory. This information will allow the engineers to get better

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Collaborators on the project include Research Assistant Professor Akos Ledeczi, Associate Professor Gabor Karsai and Associate Professor Gautam Biswas from the Vanderbilt Department of Electrical Engineering and Computer Science.

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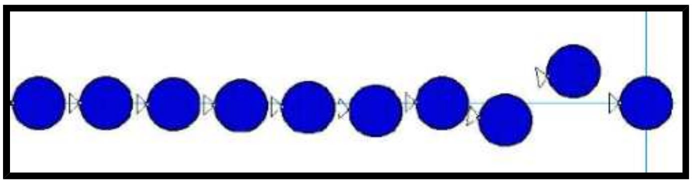
D.6 Distributed control of interconnected systems

A Linear Matrix Inequality Approach to Decentralized Control of Distributed Parameter Systems

ABSTRACT

In this paper preliminary results in the use of linear matrix inequalities for the decentralized control of distributed parameter systems is presented. The class of systems being considered are those that can be expressed as multidimensional systems. It is shown that linear matrix inequalities can be used to provide tractable solutions to this problem; the conditions are in general conservative, but are computationally attractive and lead to controllers which have a decentralized structure.

Postscript (372 KB), PDF (207 KB)



EXAMPLE: The example consists of a platoon of disks drafting each other in order to reduce drag. Click here for an open loop simulation of the system (AVI, 399 KB). Each disk can translate in the x-y plane and rotate about the z-axis (out of the page). A very simple model for the fluid forces is assumed: the vertical fluid force on a disk (the lift) is a function of the vertical position of the upstream disks (with the influence of the upstream disks diminishing as the separation is increased). The horizontal fluid force on a disk (the drag) is a constant plus a function of the vertical position of the upstream disks; the net torque on a disk is also a function of the vertical position of the upstream disks. The sensing capability is translational position, translational velocity, rotational position, and rotational velocity for each of the disks, while the actuation capability is direction and magnitude of a thruster situated downstream of each disk. As can be seen from the open loop simulation, the equilibrium condition is unstable; a small displacement of one of the disks away from equilibrium (the second one in the simulation), destabilizes the system.

The next simulation (AVI, 658 KB) is for a fully decentralized control strategy, where each controller was designed and implemented with the objective of returning each disk to the equilibrium position. H-infinity optimization was used, and due to the assumption of full state feedback, the optimal controller is static. As can be seen, the overall system is unstable, due to the coupling between systems (string instability).

The next simulation (AVI, 554 KB) is again a fully decentralized control strategy, designed using H-2 optimization. Again, the overall system is unstable.

The final simulation (AVI, 349 KB) is an implementation of the scheme proposed in the paper, which guarantees overall stability. The same constant weights used in the H-infinity and H-2 designs were used.