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Perspectives on the Commercial Development of Landing Gear Health Monitoring Systems

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Abstract

The development of health monitoring technologies for aerospace systems creates a number of challenges for the community of engineers and technical specialists as they seek to integrate the technology into well defined working practices. These challenges do not just extend to the technical, but require a number of commercial questions to be addressed. It is of vital importance, that there is a clearly identified need for aerospace health monitoring, both from a technological and commercial viewpoint. If these needs cannot be identified, then any attempt for marketing health monitoring as a necessary future technological requirement is doomed for failure. Health monitoring technology will need to either deliver significant cost saving benefits to the aircraft operator or demonstrated increases in aircraft safety. The objective of the paper is to provide an assessment of the commercial benefits and development of aircraft landing gear health monitoring. The commercial need and challenges for health monitoring systems are explored in this paper within the context of a changing aerospace maintenance industry and the role in which new systems technology will play. The key findings of the research study are that within the aerospace industry there is a desired paradigm shift within aircraft maintenance towards offering maintenance systems with predictive capabilities. This maintenance revolution will not just incorporate new technologies, but will result in aircraft maintenance packages tailored towards individual customer requirements. The study illustrates the state-of-the-art in health monitoring currently restricts aerospace integration and a number of key technical and commercial issues need to be addressed. Predictive health monitoring offers a variety of commercially benefits for maintenance providers, aircraft operators and manufacturers. However, in order for these benefits to be realised increased transparency in maintenance related information is required between these key players.

Keywords: Health monitoring, maintenance systems, landing gears, expert systems

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1. Introduction

The airline industry is considered as one of the most unique businesses in the world which suffers from a variety of complex operations associated with moving aircraft loaded with passengers or cargo over large distances and the scheduling of flights, crews and maintenance. These all lead up to substantial costs measured in time and money. Aircraft maintenance forms an essential part of an aircrafts airworthiness criteria, with its main objective being to ensure a fully serviced, operational and safe aircraft. If an aircraft is not maintained to the required level then this inevitably risks passenger and crew safety (Gramopadyhe and Drury 2000). There is a substantial risk that the aircraft may be unable to take-off leading to passenger dissatisfaction if maintenance is not correctly performed. Likewise it is plausible that the aircraft may be forced to land in undesirable locations, where spare parts or maintenance expertise is unavailable. Maintenance actions therefore have to be carried out at regular scheduled intervals, ideally with minimum cost to the operator, whilst maximising revenue to the maintenance providers. The current move within the aerospace maintenance market is looking at utilising new technologies, such as predictive maintenance systems based around health monitoring, for example in avionics systems (Kumar et al., 2008) to detect operational anomalies (Sotiris et al., 2010) in order to reduce the levels of scheduled/unscheduled maintenance activities, without compromising safety.

In this paper the commercial need and industry desire for health monitoring is explored in the context of the role in the modern changing aerospace maintenance industry. Focuses on the reasons behind changes to the maintenance market and the drive towards innovative maintenance support concepts is discussed at length. This discussion includes the key benefits and value potential of predictive maintenance and through life support of aerospace products. Challenges to integrating new monitoring technologies into existing products are identified as extending to not only technical challenges but also challenges to commercial integration. A number of pricing strategies are explored in the context of commercial integration, and finally a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the technology is provided along with recommendations on a commercial development strategy. The discussions are related to the authors work in developing health monitoring for novel electromechanically actuator systems for landing gears, but are also applicable to the generic case of aerospace health monitoring.

2. Landing Gear Actuator Health Monitoring Application

Landing gears are an essential part of any aircraft; even though they remain redundant for most of the flight. The main task of the landing gear is to absorb the horizontal and vertical energy of the aircraft as it touches down on the runway. During flight most aircraft have their landing gears retracted and stowed, only extending them during the approach to landing. Extension and retraction of aircraft landing gears is commonly achieved using either hydraulic or pneumatic drives. A standard landing gear contains three such actuator drives; the largest of which is the retraction actuator that generates a force about a pivotal axis in order to raise the gears against weight and aerodynamic loading. The other two actuators are the lock-stay actuator, which locks the landing gear in place once extended and the door actuator that ensure that the landing gear bay doors are successfully opened and closed for landing gear deployment. Figure (1) shows a standard landing gear arrangement undergoing a retraction cycle.

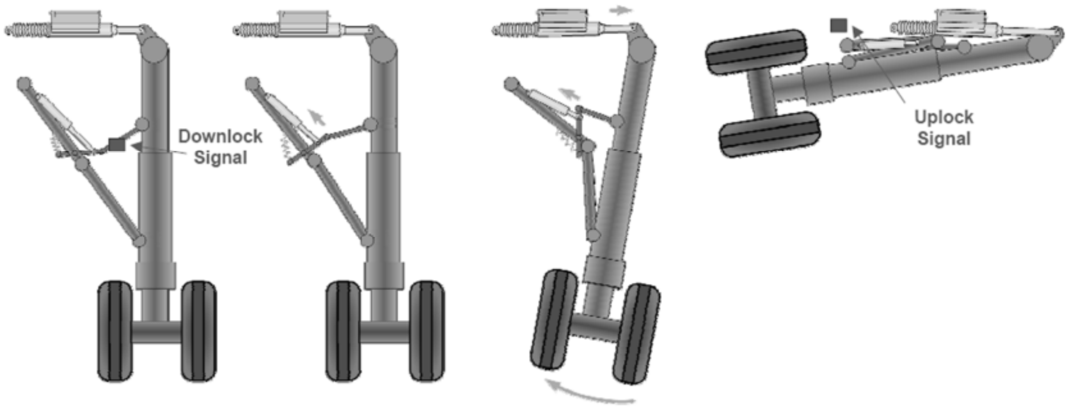

Figure 1: Retraction cycle for a standard landing gear

Hydraulic actuation systems have found popular use in aerospace as a whole due to their reliability, relative simplicity and their wide spread use has generated engineering experience and familiarity. They are ideally suited for a landing gear application as the hydraulic fluid provides a constant lubrication and natural damping. There are however disadvantages; when used in aircraft they are heavy, require large volumes of space; operate noisily and require the correct disposal of hydraulic fluid in accordance with environmental legislation. There is currently a move within the aerospace industry to move away from these hydraulic drives and to replace them with lighter, smaller, cleaner and more efficient electrically powered actuation as part of what is now commonly termed the More Electric Aircraft (Rosero et al., 2007).

Electric motor driven actuation is now very widespread within the transport industry. In automotive products, for example, electric windows, locks, aerials, seat/lamp/mirror adjustment are common. Drive-by-wire introduces motor-actuated steering and the starting circuit is a heavy motor-driven actuation system. Similar situations are encountered in railway point motor mechanisms, heavy electrical switch gear, and valve actuation. The motivation for the use of Electro-Mechanical Actuators (EMA) is driven by the desire to reduce aircraft weight arising from a combination of increasing fuel costs and environmental concerns. For example, environmental damage associated with air traffic has created the need to reduce aircraft fuel consumption and polluting emissions, a key factor in achieving this is the reduction of weight. Another key motivation for utilising electrically powered actuators is that there is a real possibility that with the move towards optimisation of engine efficiency, future aircraft engines will not be designed to produce hydraulic power. Another benefit of replacing landing gear hydraulics is to reduce aircraft turn-around times. Aircraft currently have the requirement that the brakes must be allowed to cool before the wheels can be stowed due to the fire risk associated with hot brakes coming into contact with leaked flammable hydraulic fluid. EMA would mean that these toxic hydraulic fluids which require significant maintenance efforts to maintain are no longer needed.

A key challenge associated with the introduction of EMA for the current range of civil aircraft in operation are currently design issues associated with space constraints (it has proven difficult to fit electrical motors into the available space designed for a hydraulic actuator). Aerospace requires high reliability, and these new drives must be proved robust and as reliable as the current drives in use. The aerospace industry has a long history of using hydraulic actuator drives, and customer confidence must also be gained in replacement technologies. The move towards electrical actuation in aircraft therefore will utilise the support of health monitoring to guarantee reliability and increase confidence (Phillips et al. 2008).

Development of automated health monitoring systems are also being encouraged for aerospace systems as a way of reducing unexpected failures and reducing over engineering of systems removing to some extent the amount of redundant (backup) mechanical elements and finally to aid in maintenance optimisation. EMA are complex mechanical systems and inspection of individual subsystems and components is not as straight forward as is the case with hydraulics and simple on-wing maintenance becomes more problematic. Most of the key components (i.e.

gears, bearings, wiring) are often sealed within housing units making access to them difficult. The use of traditional inspections for damage would require a larger degree of landing gear dismantling. There is the possibility therefore that the use of EMA could even increase the time an aircraft spends in the maintenance hanger, increasing aircraft down time costs. The use of automated systems to identify and/or predict component damage in the form of health monitoring systems would offer a reduced risk of this being the case.

3. Current Aerospace Maintenance Practice

Maintenance programmes for key systems such as the engines and landing gears are made up of several activities based around preventive (Nakagawa 2002) corrective and on-condition (Moubray 2002) and redesign maintenance (Knotts 1999). Preventive maintenance is the process of performing specific tests, measurements, adjustments or part replacements specifically aimed at preventing failures. Preventative actions are taken at pre-determined intervals based upon the number of operating hours, or often in the case of landing gears, the number of landings. This is supported by regularly scheduled inspections and tests in which on-condition maintenance is performed, where components are replaced based upon observations and test results. Each of these activities is supported by corrective maintenance which is conducted in response to discrepancies or failures within the aircraft during service and is the process of replacing or repairing a system or component which has failed to ensure full working order is restored. The final action type, redesign maintenance is the form of engineering modifications that are made in order to address arising safety or reliability issues, which were unanticipated in the original design.

Much of the major aircraft maintenance and repair work is provided through service providers who carry out Maintenance, Repair and Overhaul (MRO) operations for the aircraft operators. The landing gear is a critical assembly and a major key to maintaining the overall aircraft value. Operators cannot afford, or are not willing to risk compromising their landing gear MRO activities and will look for the best combination of affordability, expertise, flexibility and the ability to offer the best solutions when faced with the choice of MRO provider.

Landing gears are complex systems with a vast number of parts which need all need to be maintained and inspected, which results in costly maintenance operations. An example of how maintenance support of landing gears would be as follows. In the event of a series of incidents such as ‘hard landings’ reported by the operators, major repair operations, or complete gear overhauls will be conducted at a MRO provider's maintenance site. The operators themselves will also carry out, minor repairs and on-wing maintenance, also at pre-determined intervals. Once the aircraft has been received at the MRO maintenance facility, the landing gears will be dismantled and individual parts will be put through a serious of non-destructive tests. This testing would identify any developing failures, such as structural fatigues or internal corrosion. The results of which will determine if the parts are repaired, replaced, scrapped or recycled (Patkai et al. 2007).

In corrective maintenance much of the time is spent on locating a defect which often requires a sequence of disassembly and reassembly. Being able to predict fault location times is extremely difficult using traditional inspection techniques. The ability to automate this fault diagnosis, with advanced technologies and techniques, can help accurately predict the downtime and hence the operational availability of the aircraft. Operational availability is considered as the probability that the necessary systems will operate when required within a set of specified conditions (Macheret et al. 2005). The prediction of availability based upon known reliabilities and operational parameters can be relatively straightforward. However, the prediction of the set of events which can occur as a result of a certain availability requirement, or determining the system attributes which are required to meet a desired availability in a 'real world' situation is difficult. This difficulty have been addressed by Jazouli and Sandborn (2010), through the development of a "design for availability" model for predicting the required logistics, design and operational parameters for a specified availability requirement and is demonstrated for cases with and without a predictive maintenance capability.

4. Recent Factors affecting Aircraft Maintenance

The market for landing gear overhauls, new gear-sets, exchange gears and spare parts has become somewhat chaotic, with some new gear lead times running at up to four years and overhaul queues lengthening by the day. This has been somewhat unexpected by Original Equipment Manufacturers (OEM) and overhaul providers even though landing gear maintenance intervals are widely known and plans put into place. There is a growing feeling that current business models will eventually no longer cope and the following coinciding factors are forcing changes in maintenance strategy (Burchell 2007).

- The large number of aircraft sales between 1998 and 2000 which, given the typical 18,000-cycle or eight to ten years time between overhauls, has created an unprecedented demand for landing gear overhauls on both long- and short-haul aircraft.

- Record aircraft production following unprecedented sales in 2006 and 2007.

- Higher utilization of short-haul aircraft, which has shortened time between overhauls for some airlines by one or more years.

- The growing number of aircraft in service, including some older types returned from desert storage, bringing more and more landing gear into the market. This also has increased the number leakage or heavy corrosion findings in line maintenance which also drives early overhauls.

- A lack of landing gear overhauls capacity created by the high cost of setting up an overhaul facility. The number of service providers has not grown enough to meet the increasing demand.

- Seasonal cycles have overloaded winter overhaul slots, leaving some summer slots unfilled.

- A worldwide shortage of raw materials like rubber, high strength steel and titanium, exacerbated by increasing demand from the burgeoning economies of China and India.

- The on-going conflicts in Iraq and Afghanistan, which make significant demands on spare-part production and material supply.

- Complacent operators who either ignored the "need-to-plan" warnings from the OEMs or simply have left landing gear overhauls to the last minute

5. Changing Maintenance Practice

Currently the European market holds a 26% share of the worldwide MRO business compared to 39% held by North America and is expected to experience further dramatic worldwide growth during the next 10 years (Jenson 2008). There are however several hurdles which must be overcome by these MRO providers in order to continue their leading global market shares (Fitzsimons 2007). Examples of which include:

- Growing competition from the Middle East.
- Greater competition from original equipment manufacturers.
- Continuing pressure from airlines to reduce costs.

These hurdles coupled with increased demand for airline MRO are forcing changes in the global aviation maintenance industries, including:

- MRO providers are expanding their geographical reach and capabilities in a bid to become regional and global full service providers.
- Spending on MRO is expected to universally increase.
- Airlines are now seeking how to make the next level of savings, which has raise the demand for more predictive maintenance strategies, with more reliability and material solutions to compliment outsourced maintenance repair work.
- To drive further cost reductions, airlines are seeking to incorporate sophisticated maintenance management solutions into their aircraft, reducing investments in inventory and to aid in improvements in airline operations and reliability (Jazouli and Sandborn 2010).

Such factors have begun to dictate a change in maintenance strategy for operators and the solutions in the services that the MRO suppliers can provide. These will aid in reducing the levels of scheduled maintenance and hence optimising maintenance on aircraft fleets and recommendations and techniques on selecting the best maintenance strategy are currently being developed (Labib 2010). In terms of landing gear, much of the current business offered to the customers is contracted in the form of ‘time and materials’, which can be an expensive option for operators. The changing face of the aviation industry requires that maintenance management become increasingly tailored towards individual customers needs with cost-effective solutions being found, offering compromises between customer involvement and the level of commitment required from the providers. Figure (2) shows a matrix with different maintenance solutions and the level of commitment and partnerships required by the operators and MRO providers (Phillips et al. 2009).

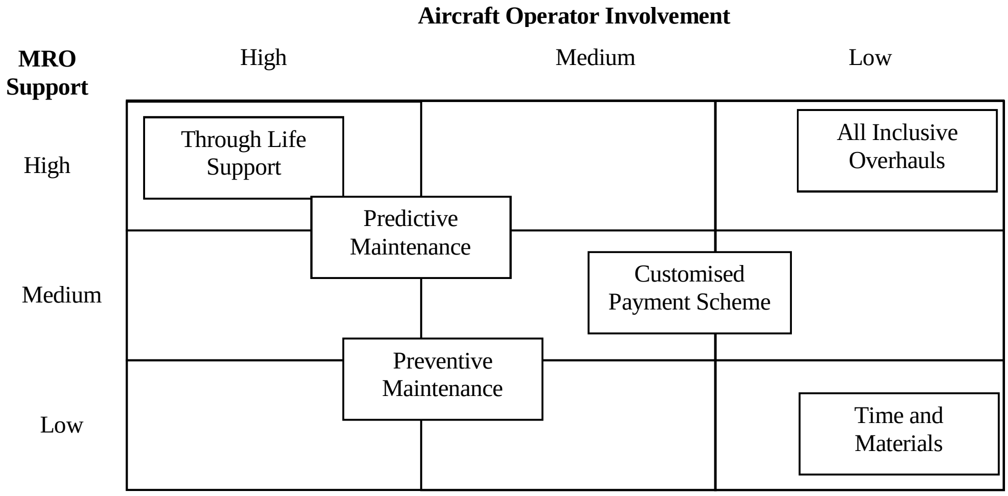

Figure 2: Maintenance support concepts.

6. Predictive Maintenance

The desire is such that in order to remain competitive and meet the demands and challenges facing operators and suppliers new maintenance support concepts should offer several gains. For the operators these should be reductions in unscheduled maintenance activity, lower total cost of ownership, reductions in administrative burdens and overall optimisation of maintenance activities. This can be achieved by moving away from the scheduled preventive maintenance actions by introducing new systems that can provide details on the in-service operation and condition of landing gear mechanisms, such as brakes, shock absorbers and actuators. Such systems known as health monitoring systems (Kothamasu et al. 2006) utilise a variety of data gained from on-board sensors in order to extract meaningful information. This information when combined with expert knowledge such as component reliabilities, failure mechanisms and service/maintenance history will provide a quantification of system/subsystem/component health. Based upon this information future corrective maintenance actions can be predicted and allow for the optimisation of aircraft maintenance. Figure (3) illustrates the concept of predictive maintenance.

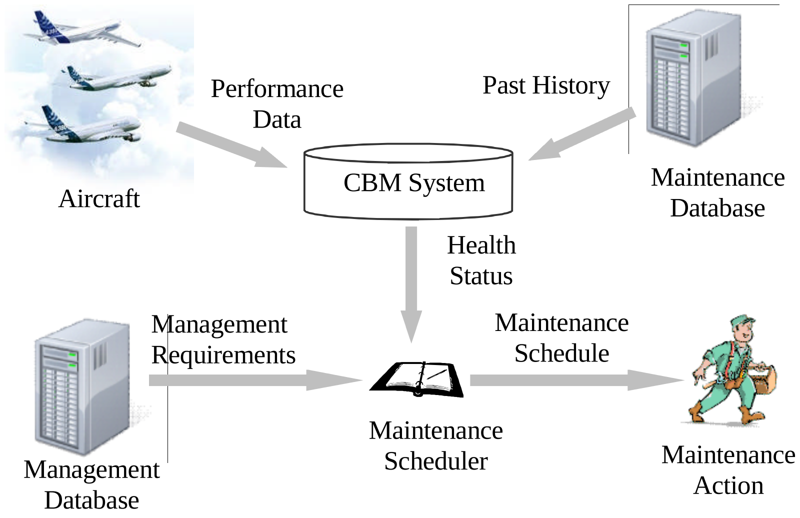

Figure 3: Predictive maintenance concept.

Incorporating health monitoring systems into aircraft landing gears in order to employ a predictive maintenance strategy (Mobley 2002) in place of preventive maintenance, offers benefits to both the operators, MRO providers and landing gear manufacturers as described in Table 1.

Table 1: Benefits of a predictive maintenance strategy.

Operator	**MRO provider**	**Landing gear manufacturer**
Optimised maintenance scheduling	Optimisation of spare parts stockpiling	Information available from on-board health monitoring sensors can be used as a marketing tool
Reductions in maintenance costs	Minimisation of scrap	Evaluation of in-service performance of landing gear systems
Reduced risk of in-service failures	Elimination of bottlenecks in machine usage during MRO operations	Extensive knowledge of in-service performance can be incorporated into re-designs.
Increased aircraft availability	Reduction in turnaround times	Aids in increasing operator confidence in incorporating new replacement technologies.

However it should be noted that innovative predictive maintenance solutions supported by health monitoring can only provide each of the key players the necessary benefits if the necessary commitments are made. A smooth flow of information is required between the operators, maintenance providers and the manufacturers. It could also be questionable if operators would really want to commit to a long term innovative maintenance solution, due to the added commitment requirements on their behalf. They may be hesitant to uptake the offer of health monitoring systems if the manufacturers have not listened to the specific requirements for their aircraft, most notably component reliability and minimal effects on weight and complexity. The operators will also be wary of the need for the probable handling of vast quantities of extra data and information generated from the health monitoring systems. Support with this should therefore be offered within any innovative maintenance service, or systems that can provide automatic health, related decisions are essential if health monitoring is to be accepted. Operators must also be willing to follow a long-term commitment as a support partner and be willing to exchange failure data with the manufacturers in order for increased reliability in future designs. This flow of information is illustrated in Figure (4)

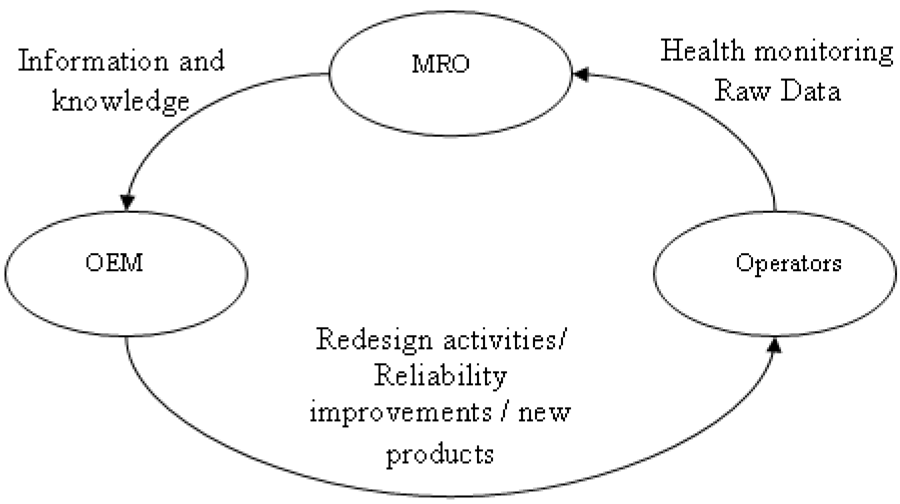

Figure 4: The process of information flow.

7. Value potential of Predictive Maintenance

The value of incorporating health monitoring systems is most likely to arise in savings in overall operating costs. The use of health monitoring systems for landing gear retraction mechanisms, or other aircraft systems, will offer a very competitive advantage in maintenance decision-making, which is crucial for both military and commercial aerospace users. This will help manufacturers retain customers and attract new business; these aspects will mean that health monitoring solutions will become a key part of formulating future maintenance strategies. The airline industry has seen a rapid increase in operators over the past decade, particularly in low cost short haul operators. The nature of the budget airlines business succeeds in the ability to operate large aircraft fleets, coupled with high aircraft availability and short turn-around times whilst keeping ticket costs low. For such factors to remain and for airlines to create a business winning advantage, then strategic maintenance management has to become one of the significant factors in their operations management. The adoption of health monitoring and overall predictive maintenance can help push an aircraft operators business forward as illustrated in Figure (5).

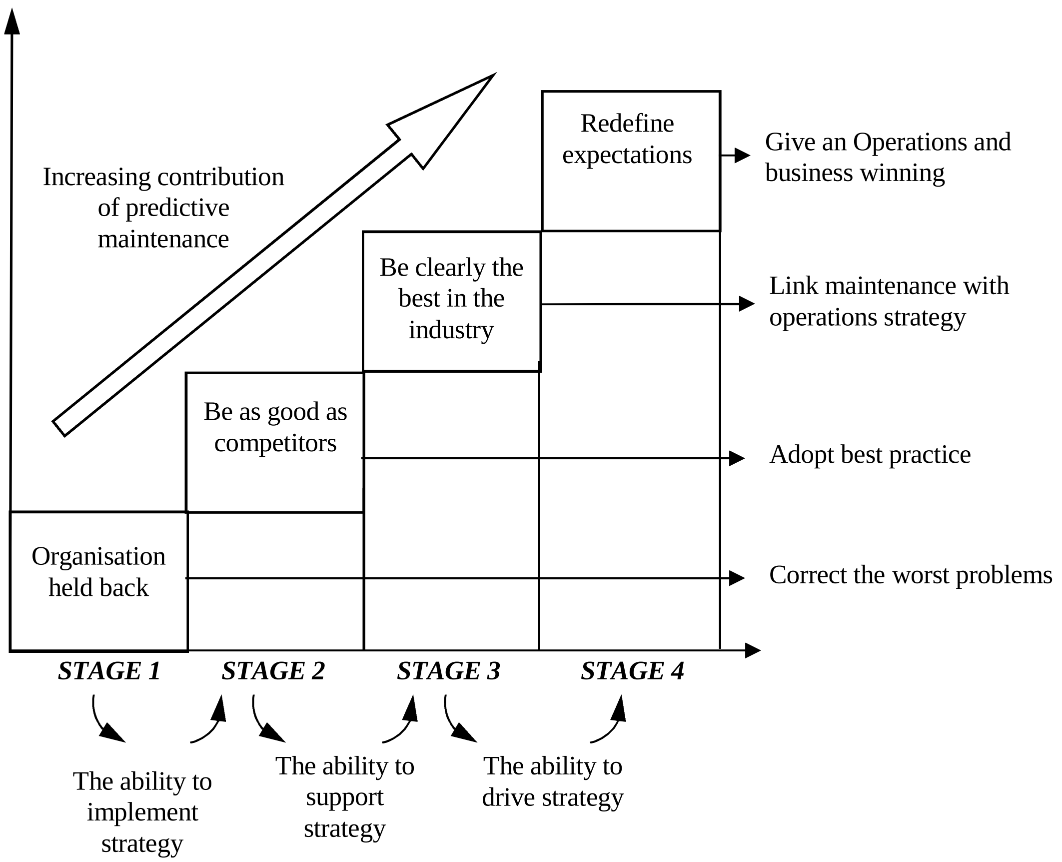

Figure 5: Potential effects of predictive maintenance on an aircraft operators business

One of the areas which have to be considered in the adoption of health monitoring is the different levels of scale and complexity of its implementation. This will be directly influenced by the maturity, robustness and applicability of the underlying algorithms and their impact upon an organizations enterprise. The value of health monitoring can take a variety of forms as presented in Table 1. However before any proposals to adopt health monitoring is taken, it must be articulated in the form of an economic justification which is often gauged by a Return on Investment (ROI) metric. This metric measures the cost saving, profit or cost avoidance that arises as a direct result of any given monies spent, in this case on the introduction, upkeep and support of health monitoring. Over a systems life cycle the ROI is defined as

$$ROI = \frac{\text{Return - Investement}}{\text{Investement}} = \frac{\text{Avoided Cost}}{\text{Investement}} - 1 \quad (1)$$

A positive value for the ROI replies that there is a cost benefit in monetary terms. However a negative ROI may also return a cost benefit which is not directly quantifiable. For example, in the use of EMA in landing gears where it is envisioned that health monitoring will be essential to meet reliability guarantees and ensure customer confidence in the replacement actuator technology. Many authors have investigated the potential cost benefits to implementing health monitoring in a variety of industries and applications including power systems (Vohnout et al. 2008) where prognostic approaches to EMA are assessed against analyses of the potential ROI. In the telecommunications industry the business case for the use of health monitoring prognostics on telecom power systems has been explored (Wood and Goodman 2006). In the aviation sector cost avoidance resulting from the possible implementation of health monitoring prognostics has been evaluated for military aircraft engines (Ashby & Byer 2002) and civil aircraft subsystems (Lea et al. 2008). A comprehensive review of previous work in these areas is given in the paper (Fieldman et al. 2008) which also provides an analysis of the ROI for aerospace electronics in civil aircraft.

Many of the published models used for analysing the ROI of health monitoring contain cost factors associated with maintenance. These cost factors however often fail to actually incorporate the maintenance processes into these models, which is essential for dealing with uncertainties. This issue is addressed by Feldman et al. (2009) where a maintenance planning cost tool is developed which use a detailed treatment of the maintenance process. This tool, which addresses uncertainties in estimates through monte-carlo simulation techniques, is applied to a case study focused on aircraft avionics in order to illustrate a positive business case for implementing health monitoring as compared against an unscheduled maintenance policy. One of the areas which have been highlighted as needing further consideration is the developments of models which are not just comparable to unscheduled maintenance but also have the ability to incorporate costs associated with other practices. For example, earlier in the paper it has been discussed that aircraft maintenance is often made up of a variety of practices (preventative, corrective, and on-condition etc) which lead to a mix of scheduled and unscheduled maintenance. Often preventative actions, arising from legislation and air worthiness directives lead to over scheduling of maintenance, indeed one of the key reasoning's behind predictive maintenance is to optimise maintenance both scheduled and unscheduled maintenance (Phillips et al. 2009). ROI models must therefore be adapted to incorporate all cost associated with the entire maintenance operations as a whole.

Much of the work in the areas demonstrating ROI for health monitoring are aimed at demonstrating the business case for health monitoring to be implemented into existing systems. In such contemporary or older systems uncertainties in costing estimates, such as life cycle costs, unscheduled maintenance costs and inventory costs (before health monitoring) may be better known due to years of familiarisation. The estimation on the ROI for a new technology such as novel landing gear EMA, which are still in the development phase and yet to enter service, would provide difficulties in terms of large uncertainties, some of which may or may not be quantifiable. A non-exhaustive list of uncertainties includes aircraft availability changes, false alarms generated by the health monitoring, variability in the operational profile and random events (Feldman et al. 2009). If the ROI was to be used as a justification for the value potential of EMA health monitoring then appropriate cost models are developed which can deal with uncertainties are developed before a realistic business case can be put forward.

8. Technical Challenges to Integrating Health Monitoring

Large-scale integration of health monitoring will cause disruptive changes within well defined and established maintenance related practices, such as logistics, parts management, and manufacturing and information management. If the integration of health monitoring technology is efficiently managed with the necessary support and infrastructure requirements in place then the technology will become firmly established, becoming a fully performance/business competitive innovation. Health monitoring systems are aimed at improving the performance of the aircraft, which will be achieved on the lines of 'evolutionary' changes whilst demonstrating reliability, validated cost benefits (Banks and Merenich 2005) and reduces operational risks. It is also necessary to ensure that appropriate parameters are selected for monitoring (Kumar et al. 2010) and that there is robustness in the modelling of the health management process (Kumar and Pecht, 2010).The integration of new technologies inevitably face difficulties and a number of challenges face the community of engineers and technical specialists as they seek to utilise health monitoring for aerospace usage, a non-exhaustive list of these difficulties include:.

1. The technology and frameworks are available but underutilised.

2. Performance characteristics are usually untested, leading to a lack of confidence

3. There is often a wealth of data available from the end users, but access to this data can be limited and much is yet to be converted to 'meaningful information'

Health monitoring systems for aerospace applications differ from those for other applications such as industrial machine monitoring or the monitoring of civil structures due to hardware restrictions and the difficulties associated with certification. Also, in many areas of aerospace health monitoring system development, often the state-of-the-art monitoring technique being developed are restricted by a variety of limitations. This affects their use in a real operational situation', for example, many of the sensor based methods under development for the monitoring of fuselage structures, based upon such methods as acoustics or vibration patterns require vast sensor arrays. Much of the information gained requires high levels of signal processing with the results being very subjective and consequently they may not be applicable for an on-line real time aerospace monitoring system, even though the fundamentals of the techniques work well in other applications. This will potentially lead to a case where the state of the art has difficulties in matching the necessary requirements for aerospace integration. This is possibly the reason for the current slow integration of health monitoring on civil aircraft, despite the vast wealth of academic research detailing monitoring methods, industry drive and potential areas for application.

Figure (6) illustrates this hypothesis it demonstrates how the current health monitoring state-of-the-art trend is progressing with respect to the capability requirements for health monitoring for aerospace usage (Phillips et al 2009). The hypothesis indicates that the current state-of-the-art is advanced enough for most industry uses; offering leaps in performance and capabilities. But is far below what is required for aerospace applications, and will require further innovations, amongst others, in terms of hardware minimisation, data reduction techniques and the use of fusion to merge multiple techniques to reduce individual limitations and maximise advantages.

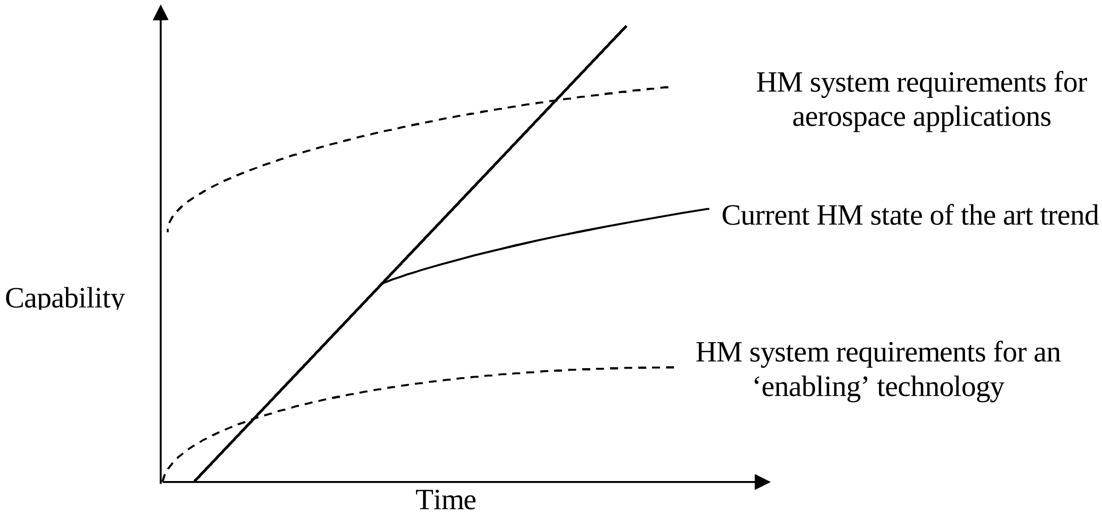

Figure 6: Aerospace health monitoring requirements as compared to the state-of-the-art.

9. Commercial Integration Challenges

Aerospace OEM will have well defined business models and practices. For example, this will usually follow two integrated paths which can be regarded as the product lifecycle, which begins with product innovation, design and development, manufacture, production and finally through life support. The second path is the business supply chain which begins with forecasts of landing gear sales, received orders, scheduling procurement, production and finally distribution and after sales support. For a OEM which has no history of supplying health monitoring systems the integration into these processes, which are illustrated in Figure (7) will not be an easy task. Integration of health monitoring for instance will directly affect how after sales service and through life support is conducted. For successful commercial integration it is very probable that a whole new structure to the suppliers' business model will be required.

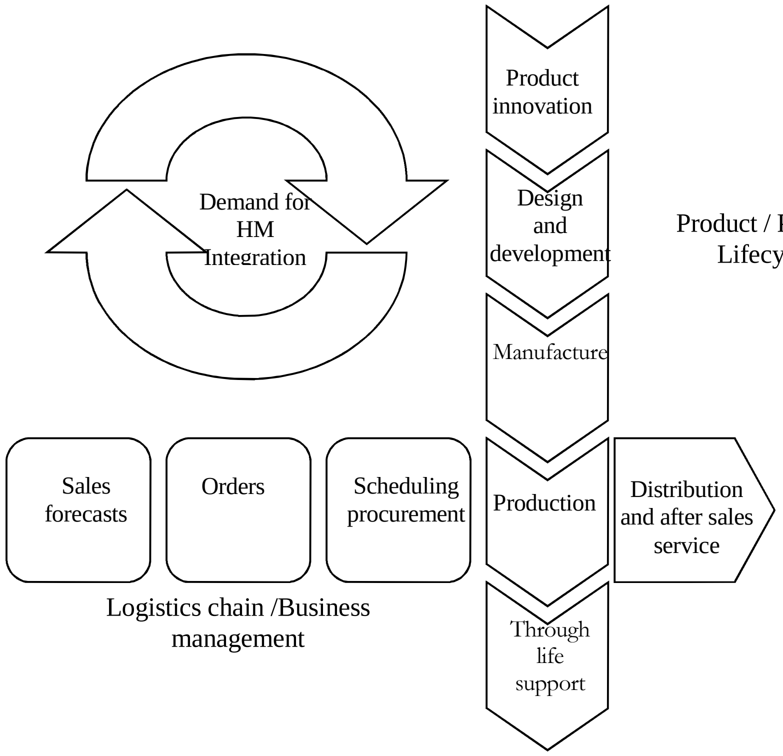

Figure 7: Logistics chain and business management.

Some of the more general issues (Raheja et al. 2006) relate to the conceptualisation of strategies for decision making and goal setting across multiple 'component or system' levels and time periods. A unique business methodology for incorporating cost as a factor to be considered in setting up these decision making strategies is a fundamental requirement for the successful integration of health monitoring technologies. Other considerations involve the linking of the maintenance system with Enterprise and Materials Resource Planning (ERP/MRP) to enable optimisation of spare parts ordering, and therefore ensuring the after sales and through life support elements of the business remain at their optimal capabilities.

10. Pricing Deployment Strategies

One of the commercial issues which a landing gear manufacturer/service provider will face once the decision to develop and provide health monitoring systems to support their products is how maximum revenue can be best achieved? There are two possible models which have relevance in for the development of landing gear health monitoring pricing strategies. The first is known as Product Service Systems (PSS), which engage the customers, manufacturer and suppliers in order to provide a product and a service that match the products specifications (i.e. manufacturing, product support, and supply chain and parts management) to the individual customer's needs (Bankole et al. 2009). In a PSS model the ownership of the tangible product is transferred to the customer and additional services such as a maintenance contract are offered by the provider. The second model is known as lease contracting (Yeh and Chang 2007) where the ownership of the product is held by the supplier, and a contract between the customer and service provider is created which will provide the customer with services which include the product installation, hardware/software updates and all other associated service tasks. The lease would also provide definitions of the operational constraints, failure rates and product availability.

There are very few published works which detail proposed pricing models for health monitoring technology. The reasons for this are generally due to the secretive nature of organisations have over their business models, one example however with direct relevance to this current work is provided in (Kidd 2007). This Engineering Doctorate thesis provides an extensive discussion on business and pricing models for health monitoring for automotive vehicles as seen from the vehicle OEM perspective. The nature of the automotive and aerospace commercial business operate on very different principles, but the models in this work provide a framework in developing pricing models for aerospace actuator health monitoring solutions.

A number of pricing proposals are therefore proposed in order to generate revenue for the provider of the health monitoring system, which is aimed at adding significant added value to their landing gear products. As has been identified there are several key players in aircraft maintenance, which all must be included in any future deployment/pricing models, if health monitoring on landing gears are to be successful.

1. The first pricing model generates revenue based upon sales volumes (variable costs).The health monitoring equipment is implemented onto the landing gear as standard equipment. A subscription is then paid by the landing gear customer to the health monitoring system provider for every landing gear set using the monitoring technology.

2. A second pricing model is based upon per landing gear unit (fixed cost). A one off payment is made to the health monitoring provider for any given monitoring solution per landing gear set. This ensures that the customer retains the ownership for the life of that product which is tailored towards their specific requirements that also remain

responsible for additional software/hardware updating of their systems. The necessary services such as parts management, logistics and data handling are offered as additional services by the provider.

3. The third model is based upon the health monitoring technology being incorporated into the landing gear as standard equipment (consolidated costs) by the OEM. No direct costs associated with the additional system equipment costs are passed onto the customer. But the customer will remain fully responsible for the systems upkeep and will remain free to seek alternative maintenance service providers. In this case indirect revenue for the OEM can be generated through product differentiation.

In order to assess the attributes of these three pricing deployment opportunities, it is necessary to understand the investment cost associated with a health monitoring programme. The investment cost is calculated as:

$$I_{PHM} = C_{NRE} + C_{REC} + C_{INF} \tag{2}$$

Non-recurring costs C_{NRE} are associated with one-time only activities that are typical at the beginning of a maintenance strategy based upon health monitoring. Specific non-recurring costs are given as hardware and software costs, personnel training, qualification and testing, documentation and the costs of integration. Recurring costsC_{REC}, are usually associated with the activities that continuously occur regularly throughout the life of the product implementing a health monitoring programme. These costs include additional hardware, assembly, recurring functional testing and re-installation costs. The costsC_{INF}, are those associated with supporting the programmes infrastructure. Infrastructure costs are characterised as a ratio of money to a given period of activity and includes the cost of data management (i.e. data collection, archiving, analysis and reporting), the costs of maintaining the actual health monitoring system devices, decision support costs and the cost or retraining necessary personnel in the use of the health monitoring systems (Fieldman et al. 2008).

It is then necessary to consider where along the supply chain these costs will be met. For example in the first proposal the non-recurring costs would be met by the system provider, but the recurring and infrastructural costs would to a large extent be met by the customer's subscription charges. In the second proposal costs associated with the additional systems hardware and integration would also be met by the customer in purchasing the product. Through the customers retained ownership of the product it would be their responsibility for much of the recurring costs such as additional hardware/installations/testing. In this proposal the infrastructure costs would be met by the service provider who provides the data management and maintenance decision support services as part of the products sale. The final proposal sees all costs associated with the addition of health monitoring met by the provider, but they have no direct responsibility for providing additional support services. The responsibility for recurring and infrastructure costs would then be dependent upon the customer's decision regarding their choice of service provider.

It should be noted that in all cases the health monitoring tools would be sold under licence, with the health monitoring system providers maintaining control over the background intellectual property. A first glance it may seem more appropriate that the providers may wish to pass off as many of the costs onto the customer. However we have to remember that for the customer to accept HM then the customers ROI must also be adequate. The pricing propositions discussed in this paper make no generalisation of the specific cost values, or whether the introduction of EMA with health monitoring would alter the sale value of the landing gear product. What the pricing propositions have however highlighted is that, if new landing gear products are to be supported by additional health monitoring systems, it is likely that new business models will need to be incorporated into the organization. The structure of these models will need to reflect maximised ROI for the customer and the providers.

11. SWOT Analysis: Actuator Health Monitoring Technology

The SWOT analysis is a useful tool for understanding the decision-making process for a multitude of situations in businesses and organisations. SWOT is an acronym for Strengths, Weaknesses, Opportunities and Threats. These headings provide a good framework for reviewing strategy, position and direction of a company or product idea. It is an assessment of data which when put into the SWOT format enables understanding, presentation, discussion and decision making. In this paper a SWOT analysis is presented for the actuator health monitoring technology aimed at providing a qualitative assessment of the technologies enabling the proposition of a commercial development strategy.

11.1 **Strength Analysis**

- Aerospace manufactures, maintenance providers and aircraft operators have expressed interests in aerospace health monitoring technologies. With cost saving and business winning advantages offered to each of these.

- Combining information generated from the actuator health monitoring system with other aerospace monitoring systems as part of a Integrated vehicle Health Monitoring (IVHM) system will increase overall aircraft safety, reliability and operational lifespan

- Health monitoring will aid in increasing customer confidence in new replacement all electric actuator technology.

- Extensive use of in-service performance data generated from a monitoring system can be used by manufacturer for re-design improvements, offering increasingly cost efficient and reliable products.

- Electromechanical actuators used in different applications all share the same common component types and general operating procedure. This means that an actuator monitoring system could be packaged and sold off-the-shelf. With customers only required performing simple tuning for their individual application.

11.2 **Weakness Analysis**

- Aerospace certification procedures for new hardware/software coupled with the requirements for aircraft weight reduction may restrict the addition of health monitoring systems.

- There may be a reluctance to accept the monitoring technology by operators as a new decision-making tool, until the system has proven itself as an in-service reliable technology.

- In general the incorporation of health monitoring would allow serviceable components to remain in service for longer periods. This may result in manufacturers, and third party suppliers loosing revenue generated by periodic maintenance operations.

- Once health monitoring systems are in place they must be reliable. Unreliable monitoring will result in reductions in customer confidence. This would lead to reluctance for future customers to invest in the technology.

11.3 **Opportunities Analysis**

- If new all electric actuation technology is accepted then a market for health monitoring systems will open up to support their reliability and gain customer confidence in replacement technologies.

- Electromechanical actuation is not just confined to aerospace applications. The rail, automotive, shipping and power processing industries all make use of them. More often than not in mission or safety critical applications. This offers the potential for a cross-market business.

- Health monitoring offers the potential to improve current maintenance operations. Allowing the provider to supply the customers with a range of innovative maintenance packages. These could be tailored to individual customer requirements, offering a competitive business winning advantage over competitors.

11.4 **Threats Analysis**

- Customers may see the introduction of health monitoring to enhance product reliability as an admittance of inherent product unreliability.

- There are currently several key European aerospace companies investigating the potential use of electromechanical actuation for landing gears. It is highly unlikely that these are oblivious to the potential advantages posed by health monitoring. There is also a more advanced drive for similar actuators for other aerospace applications such as control surfaces. There is a risk therefore that a competitor could be the first to the market.

- It is difficult to evaluate the cost of manufacture, implementation and upkeep of a health monitoring system in development. It may be the case that aircraft operators will not see health monitoring as an economically viable option they may therefore seek other maintenance solutions.

- Aerospace certification procedures may lead to the technologies which health monitoring is aimed at supporting not being accepted for incorporation into aircraft. This would make the designed monitoring system instantly redundant.

- Landing gear actuator health monitoring is just one monitoring system that is likely to see introduction onto aircraft in the future. For all of these systems to be optimally effective it would be desirable for them to work together. However this will be unlikely the case due to each supplier using incompatible hardware and software. This would make the case for a fully IVHM system unlikely, with operators choosing to optimise their selection of monitoring systems, leaving some key items on the aircraft as unmonitored. Landing gear actuation may be one of these items.

12. Development Strategy

Based upon the SWOT assessment it is possible to draw several conclusions on the key factors which must be addressed as part of a commercial development strategy. The purpose of this is to provide recommendations on the future direction of landing gear actuator health monitoring technology development.

The development a health monitoring system for an industrial application such as this is very multidisciplinary and a holistic viewpoint must be taken. There is therefore a number of opportunities and areas, both from a technical and business perspective which must be investigated and developed before landing gear health monitoring can be developed into a market ready system.

12.1 Reliable Fault Diagnostics

One of the major limitations of implementing health monitoring into a landing gear electrical actuator will be the lack of data from the new actuators such as operational performance, historical maintenance data and failure rates. Extensive testing will be required prior to any in service implementation and a set of generic fault cases will need to be developed. Data from fault case testing will enable the classification of faults enabling the diagnostics approach to be validated experimentally on a landing gear testing rig. Fault classification would enable robust and reliable diagnostic algorithms to be developed, fault testing on a landing gear rig, under representative operating conditions would aid in aircraft operators and relevant certification bodies to accept health monitoring as a reliable decision-making tool, where its reliance will not compromise aircraft safety.

12.2 System Uncertainty and Performance Metrics

Health monitoring systems will suffer from a variety of uncertainties which will need to be quantified, to ensure reliable diagnostics. Future research and development focus should be on understanding and dealing with the various sources of uncertainties including system and failure modelling errors, signal errors and strategies to deal with the initial lack of information at the start of the actuators introduction as an operational aircraft system. Techniques and the necessary infrastructure are also required in order to handle historical and service data as it becomes available throughout the actuators service life. Difficulties with dealing with such information are usually associated with incomplete or missing records.

It is essential that the performance of a monitoring system is known. Dialogue with designers and experimental testing is required to quantify individual component failure probabilities would allow specific component level objectives to be set for the monitoring system. Performance metrics, for the health monitoring system, would then be developed based upon a measure of accuracy in the diagnosis, for example probability of false/missed/correct alarms. If a monitoring system cannot meet specified objectives then reliance upon it would have an adverse effect upon the aircraft safety. So these areas of development are key to ensure safety and for the introduction of health monitoring to meet the objective of improving maintenance operations.

12.3 New Sensor Technology and Systems Integration

This research has put a strong emphasis on the need to keep a health monitoring systems affects on the actuators weight and complexity to a minimum. This instantly begins to restrict the health monitoring approach away from more popular sensor intensive techniques. Future research should focus on monitoring solutions using wireless smart sensors with inbuilt signal processing that can perform all monitoring tasks onboard the sensor itself (Pietruszkiewicz et al. 2006). The benefits of these are that they are lightweight; do not require additional cabling and they can create a reduction in the demand for aircraft computing resources (Starr et al. 2007). These advantages will open new doors for the investigation of monitoring techniques which have been deemed inapplicable with conventional sensor technology.

Systems integration research would need to be undertaken to ensure that any future monitoring system can not only integrate into the landing gear subsystems, but can also integrate seamlessly into the aircraft systems as a whole and if necessary work alongside aircraft BIT and any other local monitoring systems. This is essential if the concept of an aircraft IVHM is ever to be realised.

12.4 **Cost Modelling**

The introduction of a health monitoring based maintenance system would have a direct impact upon the through life support costs and processes of the landing gear equipment. The research into potential novel approaches to predict the through-life manufacture and repair costs for long life actuator products would be fundamental for decision making. Information from a monitoring diagnostics system incorporated into a novel costing model would be aimed at enabling the supply chain to predict, evaluate and optimise their operations for repair and maintenance. Costing research would require a focus on developing risk and uncertainty service metrics, assessments of organisational relationships and the identification and quantification of the various cost factors associated with all maintenance procedures including scheduled, unscheduled and predictive. Without such a model it will be a challenge to convince aircraft operators that a maintenance service based upon health monitoring will be economically beneficial for them over their current service.

12.5 **Remaining Life Models**

In the realm of health monitoring it is the ability to develop algorithms which can provide fault prognosis, returning a measure of a system/components remaining useful life (Jardine et al. 2006) which will see predictive maintenance reach its full potential. Development of actuator fault prognostics will require case based empirical studies in order to produce data sets observed from in service reports. The empirical data would then be used to generate an in service benchmark model the value of which would be to establish the remaining useful life of the system, or individual components. Remaining useful life models typically use measures such as operating hours, however for the landing gear application a remaining useful life measured in terms of 'number of cycles' would be more appropriate. Such a remaining useful life model would offer invaluable information in regards to generating an aircraft maintenance strategy. Deploying a prognostics system for a brand new technology however will be difficult without a wealth of failure data, the emphasis should therefore be to deploy diagnostics systems to the actuators in the first instance. With future improvements based upon prognosis being included once sufficient data has been gathered to ensure that remaining useful life models are reliable.

13. Conclusion

Health monitoring technology is intractably tied up with aerospace maintenance activities as a whole. The aerospace maintenance industry is currently facing a time of unprecedented demand for spare parts, complete overhauls and general servicing. This is due to, amongst other reasons, a sudden increase in aircraft numbers in the last decade or so which now have key systems such as landing gears reaching the end of their life. This is therefore putting a strain on overhaul providers and manufacturers. This has begun to force these key players to begin seeking new innovative maintenance solutions, to meet rising demands and costs.

It is envisioned that health monitoring systems technology will play a crucial role in revolutionising aircraft maintenance practice. This it will be proposed will not come about entirely as a direct result of the implementation of the technology. But rather by a set of unique customised solutions and support packages offered as a result of mature health monitoring technology. It has long been the tradition that operators are secretive when it comes to information regarding the maintenance of their fleets, information that suppliers often have to purchase in order to optimise their spare parts inventories. It is also proposed that for customised maintenance support packages to be successful, there must be a beneficial trade off for all players involved, and this will require changes to the way the key players share information.

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