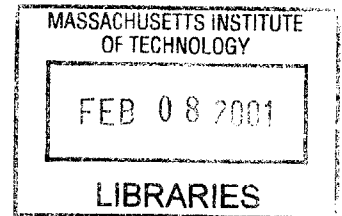


An Internet Based System to Monitor Aircraft's Health

By

BARKER

James M. Wang



Submitted to the System Design and management Program
in Partial Fulfillment of the Requirement for the Degree of
Master of Science in Engineering and Management
At the Massachusetts Institute of Technology
June 2001

© 2001 James M. Wang. All right reserved. The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part.

Signature of Author _____
System Design and Management Program

Certified by _____
Thesis Supervisor: Dr. Daniel Whitney
Senior Research Scientist
Center for Technology, Policy and Industrial Development

Certified by _____
LFM/SDM Co-Director: Dr. Paul A. Lagace
Professor of Aeronautics & Astronautics and Engineering Systems

Certified by _____
LFM/SDM Co-Director: Dr. Stephen C. Graves
Abraham Siegel Professor of Management

An Internet Based System to Monitor Aircraft's Health

By

James M. Wang

Submitted to the System Design and management Program
in Partial Fulfillment of the Requirement for the Degree of
Master of Science in Engineering and Management
At the Massachusetts Institute of Technology

Abstract

A new system concept is described that will reduce the operating cost of commercial aircraft for the operators, reduce inspection labor hours, cut down paper work, minimize down time, enhance safety, modernize aircraft manufacturers' supply chain management, and improve future aircraft designs' safety. The concept requires installing health and usage monitor (HUM) onboard aircraft. The critical components on the aircraft are recorded during flight and downloaded to the aircraft operator's computer when the aircraft returns to the hangar. The data are encrypted and sent to the aircraft manufacturer via the Internet. Or, during flight the data can be transmitted to the closest ground mobile cell phone station and relayed to the aircraft manufacturer's computer via the Internet. The aircraft manufacturer uses the information to track the health of the aircraft and send notice via the Internet to the aircraft operators to remind them when a particular aircraft needs scheduled or unscheduled maintenance. The aircraft manufacturer computer will compare the operational characteristics of one aircraft against other similar aircraft in the operator's fleet, and against other operators' aircraft to uncover unusual operational problems, manufacturing defects, or engineering short falls. This Internet based HUM system would permit the aircraft manufacturer to track aircraft parts' health, accurately

forecast when replacement parts are needed, and order replacement parts for the operators. The orders are transferred from the aircraft manufacturer to the OEM suppliers via EDI (electronic data interface), or B2B network, or through electronic auction. This centralized ordering scheme improves the economy of scale, and the early forecast helps suppliers plan their factory production schedule. Currently, most aircraft manufacturers only own a small market share of the after-sale maintenance and parts sale business. This system concept will increase the after-sale maintenance and parts sale business for the aircraft manufacturer and network the aircraft operators, aircraft manufacturer, and OEM parts suppliers closer together.

For aircraft operators, it means no more downtime, they will have the parts when they need them and at a lower cost. This Internet based HUM system also reduces mechanics' inspection hours and service manger's paper work. The operators still retain the responsibility of maintaining and fixing the fleet. However, the operators can access the entire health history of their own aircraft by going into a custom web site at the aircraft manufacturer. Aircraft operators can pass on the saving to paid passengers and cargo shippers.

This Internet based HUM system becomes more useful when it is used long enough to establish long-term trends in wear and tear of aircraft components. The manufacturers will possess a vast documentation of all their products in use which can help engineers better predict product life expectancy, solve existing problems, and improve future designs. This systematic collection of knowledge for aircraft in operation has never existed before. Air transportation will become safer and more economical. It is a win-win solution for aircraft operators, aircraft manufacturers, parts suppliers, and paid customers.

Thesis Supervisor:

Dr. Daniel Whitney

Senior Research Scientist

Center for Technology, Policy and Industrial Development
Massachusetts Institute of Technology

Acknowledgements

I am deeply indebted to many people for the work contained herein, especially my family who has encouraged me to attend the SDM program. I am grateful to Sikorsky Aircraft Corporation for sponsoring the MIT education. I sincerely appreciate the guidance and enlightening discussion provided by Dr. Daniel Whitney, the thesis advisor. In the two-year SDM program, I also have the fortuitous opportunity to work with Dr. Whitney in the Product Design and Development class and in the Underwater Unman Vehicle project. I am especially grateful to Jim Falco, the Sikorsky VP of e-commerce for giving me the inspiration to do a thesis in the growing area of HUM and e-commerce. To my company supervisors, and many years classmate and friends, Dr. Mike Torok and David Matuska, I deeply appreciate their patience with my sometimes crazy schedule. I wish to thank Richard Sewersky for educating me about the HUM technology, Vaughn Askue for the enlightening discussion on commercial helicopter operation cost, and all the pilots, and mechanics that I have interviewed with.

Table of Contents

ABTRACT.....	2
ACKNOWLEDGEMENTS.....	5
TABLE OF CONTENTS.....	6
LIST OF FIGURES.....	7
CHAPTER 1 – INTRODUCTION.....	8
CHAPTER 2 –EXISTING HUM SYSTEMS.....	18
CHAPTER 3 – A RECENT HUM EXPERIENCE.....	28
CHAPTER 4 – A NEW SYSTEM STRUCTURE.....	34
CHAPTER 5 –COST BENFIT ANALYSIS.....	45
CHAPTER 6 –NPV AND IRR CALCULATIONS.....	57
CHAPTER 7 – CONCLUSIONS.....	58
CHAPTER 8 – RECOMMENDATIONS.....	59
REFERENCES.....	61
APPENDIX A.....	62

List of Figures

Figure 1 – The Internet based aircraft health and usage monitor concept.....	34
Figure 2 – Operator X cost per year.....	47
Figure 3 – Cumulative cost for Operator X for using the Internet based HUM.....	47
Figure 4 – Operator X saving per year.....	52
Figure 5 – Cumulative saving for Operator X for using the Internet based HUM...	52
Figure 6 – Cumulative cost and saving for Operator X for using the Internet based HUM.....	53

Chapter 1 – Introduction

Commercial airline industry first started using aircraft recording and monitoring system 30 years ago, and that was an engine health monitoring device in the Hawker Siddeley Trident airliners. It sampled and recorded just 13 parameters that included temperatures, pressures, vibration and speed. On landing, the tape was taken to a ground-based facility for processing and analysis.

The system was simple by today's standards, but the foundations had been laid for the future. The crude system could only record information and could not determine the stress and strains being experienced in flight, nor could it interpret the wear on components. It could not analyze the amount of life used to calculate remaining safe life of the component.

Nowadays, aircraft monitoring systems do more than acquire and record aircraft signals. Today, information is monitored for accuracy and results calculated and recorded in real time to support rapid feedback, reduced data volume and immediate output to other systems. As described by Smith Industry, the company who designed the original engine health monitoring system for the Hawker Siddeley Trident airliners: “today's systems have grown much more capable, supporting multiple functions within a common chassis. This not only reduces acquisition, integration and support costs, but also allows for the sharing and correlation of data between functions. For example, flight parameters such as g force acceleration and angle of attack across the air intake will affect engine

performance and can be related to engine temperatures and performance. An increasing number of aircraft flight parameters can be directly correlated with airframe fatigue stresses and fatigue life, eliminating the need for costly dedicated strain gauges. The future of aircraft monitoring is further functional integration, expanded signal monitoring, greater recorded resolution and data fidelity and increased reliance for improved maintenance management, focused maintenance diagnostics, reduced life cycle support cost and aircraft service life extension.”

Both commercial and military operators are interested in lowering maintenance costs and improving safety. Military desires to equip all future production aircraft with prognostics and diagnostics computer chips that are linked to multiple sensors to detect airframe problems such as cracking and corrosion. They also monitor engine temperature, fuel purity, oil purity and exhaust fumes. These sensors send a signal to the cockpit or to a ground station, warning of any potential malfunction, ranging from routine maintenance problems to catastrophic failures.

As explained by Gregory J. Johnson, a research administrator at the Pennsylvania State University's Applied Research Laboratory and a former Marine helicopter pilot who flew combat missions in Vietnam, this technology is what enables “condition-based maintenance. Condition base maintenance (CBM) is a high-tech approach to vehicle maintenance that helps predict when aircraft components will reach the end of their useful lives.

Traditionally, the “phased” method is used, which means every so many hours of flight, technicians have to change the oil, torque bolts, or replace certain components. The downside to that maintenance philosophy, said Johnson, is that it often fixes things that don't need fixing. Johnson added, “Common sense says if it's working okay, leave it alone, but you can't do that under phased maintenance.”

As an example, the condition-based maintenance system will tell the operator whether it is necessary to remove the engine to replace a servo valve because the schedule says so, or the mechanics can decide whether to use it until it reaches the manufacturer recommended maximum tolerance. As a result of these capabilities, maintenance is performed only when needed in order to prevent operational deficiencies or failures, thus eliminating costly periodic maintenance. The Penn State University Applied Research Air Vehicles Technology Group believes condition-based maintenance represents a promising development in the evolution of maintenance practices. Both commercial and military aircraft operators are increasingly faced with demands to lower maintenance costs, increase product quality. The Penn State Group thinks CBM has emerged as a viable alternative to traditional planned maintenance, run-to-failure operation, and the various maintenance approaches between those two extremes. John Coyle, the professor of logistics at Penn State University's business school and executive director of the Center for Logistics Research says CBM falls under the category of "precision logistics."

"Precision means having maintenance support only when needed and lowering inventory of parts.

The traditional, periodic approach to maintenance is very wasteful. Many items are good for several hundred more flight hours but get replaced anyway because the estimates are conservative. With the smart prognostics and health management, the sensor and software tells when an item begins to fail. This helps reduce logistics requirements because it reduces the items replaced. The argument for preplanned intervals is that it can be more economical from a setup point of view to do all the replacements at once. But that only works when the setup is time consuming and the items being replaced are cheap. For aircraft, the replacement items are usually quite expensive.

This condition based maintenance methodology has helped spur much research and development in a new technology called Health and Usage Monitoring (HUM). HUM system technology for aircraft has grown steadily in recent years. HUM now can provide fault detection for the drivetrain, engine, oil system, and electrical system. The detection mechanism incorporates chip detectors, vibration monitoring, and limit exceedence monitoring of temperature, pressure, torque and rpm on turning shafts, and deflection angle and strain on structures. A survey of what is the state-of-the-art in HUM is provided in Chapter 2.

Currently, health and usage monitoring technology is a process which assess the life consumption of critical components, systems, and structures by monitoring actual damage exposure. Information is extracted related to the mechanical or function condition of a system in order to detect incipient failure or degradation which could lead to failure [1].

The exceedence monitoring process is a procedure that involves checking all the in flight monitored parameters to see if any parameter has exceeded pre-determined threshold. The parametric values are automated recorded and used for post flight evaluation by ground crews. The HUM records the airspeed, altitude, ambient pressure, temperature, g-loading and other parameters that can help provide additional insight in the post flight analysis. The vibration monitoring portion uses accelerometers to record loading at strategic and critical places. The recorded signatures must be post-processed by the ground crew using time domain or frequency domain technique software. The engine inlet and electrostatic exhaust monitoring portion measures debris ingested through the jet engine intake. Foreign object injected or wear inside the engine generate metallic debris that will be combusted and released as negatively charged ions. The electrostatic gas path monitoring technology can classify the type of debris by analyzing the ionized gas flow. The acoustic signature can also be recorded and analyzed. Unusual acoustic emission can indicate cracks, delaminations, or loose parts.

In reference [1], an example was given that a particular aircraft operator has a fleet of twenty aircraft. Since the company started using the HUM, twenty faults were detected

and four of these could have led to catastrophic failure. Fortunately the HUM provided early warning and saved the day.

As pointed out in reference [2], currently, most structural maintenance portion for aircraft use off-line, ground based inspection methods, such as visual inspection, X-ray, ultrasonics, and eddy currents. These are applied at discrete intervals based on a pessimistic maintenance policy, involving factors such as flying hours, take off and landings and flight loads. Reference [2] says the pessimistic inspection method for checking aircraft structures normally results in no fault found reports, leading to significant cost penalties and no direct benefit.

Reference [2] describes a new European aircraft safety group has been formed called the MONITOR. The objective of MONITOR is to meet the challenges of reducing the operating costs of metallic and composite structures. Monitor has identified a twin track approach to this challenge. The first, is to develop and demonstrate in a flight test environment and operational load monitoring system based on optical Bragg Grating sensors [2]. This direct load monitoring technology will allow inspections to be based on actual damage loading.

The second technology thrust is to identify optimum on-line damage detection technologies. The goal is to detect the actual occurrence of damage without the need for ground support facilities. Technologies under consideration include: acoustic emission,

lamb waves, stress waves, optical fibre sensors, and optical crack gauges. These on-line techniques provide the potential to inspect normally un-inspectable areas such as sub-structure, allow a faster inspection to occur, allow more frequent inspection at minimal to no extra cost.

It is perceived that a continually monitored structure will reduce in-service maintenance costs whilst maintaining current safety standards. Studies have shown that a 20% reduction in damage related maintenance on civil airliners with a 20-year economic lifetime equates to approximately two million dollars per aircraft [2]. Continuous monitoring will not stop damage, however it will allow more cost-effective implementation of the maintenance policies.

A potentially more significant benefit for operators is the inherent usage, inspection and maintenance records that will be produced as a by product of the HUM technology. This thorough knowledge of the airframe state has the potential to lead to aircraft equipped with this technology having:

- A lower rate of depreciation.
- Reduced risk in the purchase of used aircraft.
- Lower insurance costs.

Currently, HUM is primarily a detection and diagnostic technology and has not developed into a “predictive” methodology. Reference [3] defines detective and diagnostic for a rotorcraft as follow:

Detective: The identification of the existence of an anomalous condition in a system. For instance, by performing a rotor track and balance (for rotorcraft) the maintainer may identify an abnormally high fuselage vibration in the vertical direction at the one-per-rev frequency. Detection includes active and passive sensing, signal processing and character extraction and data fusion.

Diagnostics: The identification of the cause of the anomalous condition. For instance, the cause of the previously mentioned one-per-rev vibration may be identified as a blade tab error. Diagnosis includes the mapping of macro observables to potential fault conditions. It also includes the interpretation of these conditions in the context of the current operating environment and history.

HUM is not perfect. For example in the Joint Strike Fighter Program, the military is struggling over many questions. Should HUM provide warning one hour or three days before a part fails? What is the rate of false alarms? What is the timeliness? In the commercial airliner sector, if a pilot were on a six-hour flight across the Pacific and, an hour into it, he received a warning of a catastrophic failure within minutes, that wouldn't help save his life.

To make the HUM really beneficial, the information obtained from flight should be processed automatically. Labor-intensive post processing by the ground crew should be minimized or eliminated. Ideally, the aircraft owner and operator should be informed exactly how much life is left in all critical parts, what components need service and how soon, where are the sources of the problem, and why there is a problem. This information should be recorded and tracked automatically. It should not require the ground crew to record them manually. This inadequacy is what motivated the author to develop an Internet based system to monitoring aircraft health.

This thesis offers a solution that can significantly enhance the potential benefit of existing HUM systems. The proposed concept will utilize the Internet to link the aircraft operators, aircraft manufacturers, and OEM parts suppliers together. This new integrated system will generate the following major contributions:

- (1) Make aircraft operation safer.
- (2) Reduce the operating cost for the aircraft operators. This includes lower replacements parts costs, reduced post flight inspection time, data entry time, flight logging time, parts identification time, ordering time, and aircraft downtime.
- (3) Saving for the paid passengers and cargo shippers.
- (4) Create a vast database for the aircraft manufacturer for the first time, which will improve technical understanding of existing production aircraft, and help design

better future aircraft. The database will improve market understanding and customer relationship.

(5) Pave the road for B2B and online auction between aircraft manufacturer and OEM parts suppliers.

Chapter 2 provides a technical survey of the state-of-the-art in HUM systems. Since HUM is an off the shelf technology, thus it is not the intention of this thesis to provide a complete technical treatise on HUM engineering. Chapter 3 presents an example that illustrates the short comings of current HUM systems and demonstrates how the proposed Internet based HUM system could have prevented a fatal helicopter crash in the North Sea. Chapter 4 shows the system architecture for the new concept. Finally, Chapter 5 provides a cost benefit analysis to demonstrate the financial reward of this concept.

Chapter 2 – Existing HUM Systems

Current HUM systems monitor various critical components to determine if a pilot exceeds any predetermined or manufacturer limitations. The device can log up to 1,000 events on 500 different flight. Because of the log-type way the HUMS records the information, HUM users describe it as the ultimate telltale.

If a pilot does exceed a certain manufacturer guideline, the HUM signals to the owner that maintenance may be needed. For example, if a pilot does an extreme maneuver that causes the rotor undue stress, it can cause the main rotor bearings to overheat, affecting their overall strength and reducing the fatigue life of the bearing. And if the bearings are not replaced, the rotor system could fail and cause the helicopter to crash. Another plus to the HUMS system is that it's tamper resistant. Any attempt to delete or change the data will be noted.

The on-board HUM system automatically monitors and records data, and executes diagnostics without pilot involvement, and saves data for later analysis on the ground station. The on-board monitor suite for both fixed wing aircraft and helicopters typically includes:

- Engine compressor speed

- Engine power turbine speed
- Oil chip detection in engine and gearboxes
- Engine oil temperature and pressure
- Squat switch position (weight-on-wheels)
- Bleed air valve position
- Hard landing detection
- External navigation data
- True and indicated air speed
- Pressure altitude
- Radar altitude
- Outside air temperature
- Hoist cycle count
- Total landings
- GPS positions and velocities
- Limit and exceedance monitoring
- Engine performance monitoring
- Automatic cycle counting
- Propulsion system, drivetrain and airframe usage monitoring
- Power assurance
- Regime recognition and time in regime
- Hydraulic pressure

- Control actuator load and motion

The following additional parameters are monitored for the helicopters:

- Rotor track and balance
- Main rotor speed, shaft torque
- Rotor brake engaged/disengaged
- Rotor, drive-train, and engine vibration
- Drive-train condition assessment

The system usually stores flight data on an industry standard PC card, and can display advisory messages on the cockpit display. Critical selective information is also stored in non-volatile RAM memory in the main processor unit. Additionally, the pilot may query the system to:

- Check power assurance
- Review exceedance data
- Observe the current value of parameters
- Check if sufficient data is available for rotor and track balance adjustments

Currently, the rotorcraft industry is leading the airplane industry in HUM technology. There are more R&D in HUM for helicopters than for airplanes, because helicopters are a lot more temperamental than airplanes said Fetherston [4]. One of the top suppliers of

high-end HUM today is the BFGoodrich (BFG) Company Aerospace Aircraft Integrated Systems, of Vergennes, Vt. The firm was selected by the Sikorsky Aircraft company to provide HUMS systems for all Sikorsky's S-92 and S-76 helicopters.

BFG has developed a HUM system that reduces operation and support cost by automatically tracking usage and limit parameters, calculates flight regime spectra structural life usage, obtain rotor and track balance adjustment needed, monitor engine health and performance, and assesses drive-train component condition. The aircraft operator needs to buy the on board HUM equipment and the ground support computer from BF Goodrich. The ground computer evaluates the component usage and recommends replacing parts solely as a function of flight hours. In 1997, BFG was awarded by the Office of the Secretary of Defense (OSD) to provide an open architecture HUM system for evaluation on six Navy H-60 and six Marine CH-53E model helicopters in 1999, and deployment options for 600 systems. HUM systems are currently been developed for Army's Apache, Blackhawk and OH58 Kiowa Warrior helicopters. A cost benefit study showed that this system could reduce operating and support costs by 30% while improving readiness and safety. Sikorsky Aircraft Corporation will start offer the BFG IMD-COSI HUMS on all new commercial S-92 and S-76 helicopters. A BFG HUM system has already received FAA certification for installation in the Italian Agusta A109K2 helicopter and the Franco-German Eurocopter AS350B1, AS350B2, AS355N helicopters. The dual use IMD-HUMS system is currently in developmental flight test on the H-60 and H-53 platforms. Certification is expected by 2001.

HUM is good for inexpensive civil aircraft, too [4-6]. The system records these events in an inexpensive onboard data acquisition device. The information can then be downloaded into a home-based computer, or hooked up to a compatible printer for an on-the-spot report. The two-pound unit consists of a remotely mounted processor and sensors that monitor main rotor rpm, engine speed, rotor speed, and engine torque and temperature. Prices range between \$2,400 to \$6,000, depending on the model. Altair Avionics Corporation Avionics in Norwood in partnership with Honeywell, has designed an affordable HUM system piston and single turbine engine powered helicopters. The 1022 Piston Model (\$2395) and the 1122 Turbine Model (\$3795) have received supplemental type certification for use on the Robinson R22 and the Bell 206 series helicopters, respectively. This IntelliStart HUM features enhanced engine monitoring capability and a unique hot start protection feature when used in conjunction with Honeywell/Bendix fuel controls. It has been used on a Bell 206 with an Allison 250 engine. The system is also certified on the MD500. For example, during a flight over Boston Harbor, if a Robinson R22 helicopter was buffeted by wind shear from the financial district's tall buildings and had to overspeed its rotors to recover, the HUM device would record the mechanical stress.

These low cost HUM systems are designed to remain on the airframe throughout their service life. They monitor turbine outlet temperature, torque and main rotor speeds. The information collected by these systems are later downloaded into a laptop PC using a

Windows-based software application. Thresholds, cycle definitions and flight start definitions can be programmed by the operator to suit a personalized maintenance program. The HUM systems for piston engine helicopters monitor cylinder head temperature, engine RPM and main rotor RPM as well as recording the time and duration of autorotations.

The HUM unit, weighing two pounds can be fitted under the pilot's seat. They have their own back-up batteries in case of mechanical failure. Up to 1,000 events on 500 different flights can be held in a non-volatile memory. Upon landing and downloading the information to a PC, a spreadsheet will display data recorded in a tabular flight log complete with all exceedances listed and tabulated.

Peter Bransfield, president of Altair, says, "The Altair HUM system approach to aircraft monitoring is unique in that we look for the causal events that could potentially affect the structural integrity of the aircraft or its component parts. By monitoring in this manner we provide the operator with the earliest possible indication of system fatigue or abuse. The company aims to certify the HUM system on the McDonnell Douglas MD500, Eurocopter AS350 and BO105, Schweizer 330 and Enstrom 480 turbine aircraft as well as the Schweizer 300 and the Robinson R44 piston helicopters."

Scheduled maintenance of helicopters is usually determined by manufacturer's guidelines of normal usage, but certain situations stress a helicopter beyond those parameters. HUM

system essentially advocates condition-based maintenance. Larry Jacob, senior vice president for technology at Orincon Corporation, a research and development firm in San Diego, says the goal is to predict and replace parts when they need to be replaced, rather than wait until you reach 1,000 hours or 10,000 hours or whatever pre-established maintenance schedule. The technology is available today, he added. HUM can be used to create an automated system to monitor and decide, for example, whether an engine should be pulled out. In a HUMS-equipped helicopter critical points would be monitored, such as hangar bearing, parts within the transmission and other rotating parts. The system would gather data continuously on how the parts are performing and would help technicians decide whether or not they need attention. For example, the HUM from Orincon can monitor up to 30 different points in a helicopter. The information for all aircraft in an operator's fleet can put this into a central database and used to predict when something needs attention. If a component is degrading at a high rate, the particular aircraft type can be grounded before having a catastrophic failure.

There is a lot of interest by the Navy and Marine in HUM technology because of its implications in life-cycle cost savings. If the technology could be used to help reduce the vibration of an airframe, it can double or triple the life of the airframe. As aircraft get older, they require more maintenance. They develop leaks and they form cracks. HUM can help in condition-based maintenance. There is potential for expanding the application of HUM. The Army currently is also evaluating HUMS technology for

predictive maintenance of its Abrams and Bradley combat vehicle fleets. The Army calls this ADIP, or advanced diagnostic improvement program.

HUM can become very useful when it become used long enough to establish long-term trends in wear and tear of aircraft components. If the information could be systematically collected by the original aircraft manufacturer, then the knowledge can be used to extend the life of existing aircraft in service and to help design better aircraft for the future.

HUM may become a very important option in help selling aircraft in the future. With increasing global competition in the aerospace industry, both the Americans and the Europeans are investing in HUM technology. The European MONITOR group that was mentioned in Chapter 1 has received strong participation from all leading European aerospace firms. British Aerospace provide the overall project management of MONITOR. In addition they provide HUM technology expertise in optical sensors and processing system, design and manufacture and flight test and ground evaluation facilities. Aerospatiale provide knowledge and facilities for acoustic emission monitoring and expertise on the design and integration of the on-line systems. Alenia provide opto-electronic expertise, based on their experience in integrated optical chip technology. This is of particular importance for the interrogation and multiplexing of Bragg Gratings in the load monitoring tasks [2]. ARTT provide background expertise in the development of coating techniques for optical fibres to optimize load transfer, bonding and reliability issues. Institut D'electronique et de Microelectronique Du Nord (CNRS) provide

experience in the study of carbon-epoxy composite materials, from various propagation modes such as Lamb waves. Daimler Benz provide a wider view of the implementation potential of the technologies and provide direct management of the damage detection work programs. They also bring significant expertise in the use of piezo-electric sensing for damage detection. The British Defense Research Agency Structural Materials Center provide knowledge in optical damage detection and the integration of monitoring systems into real structure. They also provide a demonstration facility for composite structures. The FFA provide a comprehensive background in the validation and development of fiber optic sensing systems integrated in composite for application on primary aircraft structures. The Institute of Optical Research provide the management of the Operational Load Monitoring work package. In addition they provide the skills to develop the Bragg Grating sensor technologies specific for these applications.

The sensing technology for HUM is fairly mature. Besides the hardware research listed above, the software portion can benefit from more advancement. Software functions as a sophisticated data processing system, monitoring a number of critical points through vibration and pressure strain. The software processes the data during the flight. When the aircraft lands, the maintenance crews download the information from the onboard system to the ground based computer. The ground PC determines whether there are problems and direct the crew to the appropriate procedure. What is missing is the sophisticated software and trained expertise to evaluate these HUM data on the ground. Different technicians may decipher the same data very differently. In Chapter 3 a

recount will be given that illustrates how a recent crash could have been avoided if HUM data were examined by experienced engineers.

Chapter 3 – A Recent HUM Experience

Besides the traditional drivetrain and lubrication system monitoring, Innovative Dynamics in Ithaca, NY has developed an on board HUM system to monitor engine mounts and related structures. Experience has shown the structural area near the engine usually provide early warning of problems that will creep up elsewhere on the aircraft. One of the techniques of structure monitoring is to check the vibration signature.

The system relies on the fact that every rotating part of the transmission system in the aircraft has an associated vibration signature. Once the aircraft is established in a particular phase of flight, the HUM system automatically samples and logs the vibration signatures by sequencing through various sources and taking measurements. Up to ten separate phases of flight can be allocated; each with a particular selection of vibration sources to measure. On helicopters, the vibration monitor suite will include monitoring main rotor track and balance using an optical sensor and azimuth detector, and monitoring tail rotor imbalance in two orthogonal planes using two airframe mounted accelerometers.

A number of accelerometers are mounted on the aircraft in positions determined to best sense particular vibration sources. A signal processing technique is then used to extract the vibration signature. This processing requires information on the speed of rotation of the source and the sample rate of the accelerometer signal is governed by a master timing

signal, derived from the number one engine turbine. Signal averaging by acquiring a large number of samples is used to reduce data noise. This also helps reduce those vibration components that are not in synchronous with, and hence not relevant to, the vibration originating from the source being measured. Due to the short duration of some of the flight phases, such as hovering, the number of signal averages is reduced to enable time for more sources to be measured. In addition, the number of sources to be measured and the large number of averages used in the cruise condition mean that the time taken to complete a full cycle of measurements can be up to 12 minutes.

Once processed, the resulting vibration signatures are stored in the HUM system memory. At the end of a flight when the rotors have slowed to less than 100 RPM and the engines have run down to less than 10,000 RPM, the HUM memory is transferred to a non-volatile memory on a removable card. Upon landing the information can be transferred to a ground computer station for further analysis.

Due to the large number of individual vibration sources on the aircraft, considerable vibration data is accumulated during flights. The flight computer or the ground PC usually can not do justice to analyze the vast data thoroughly. It would be beneficial to involve the expertise of the aircraft manufacturer or have special factory trained technicians and special software to evaluate the data.

The ground station computer's duty is to automatically analyze the data and alert the operator if the vibration from any particular source exceeds a predetermined limit. This limit was set by the aircraft manufacturer during the designing phase of the aircraft. It is obtained after assessing each aircraft vibration source and its likely vibration level during normal operation. A report log is generated to detail areas of concern to aid aircraft maintenance. Currently, the ground-based HUMS system users can extract time histories of vibration signature levels for establishing trends in the data by manual analysis.

At the present, HUM data are only examined by aircraft operator mechanics. There are limitation in their expertise and equipment. As an example [7], an Aerospatiale AS332L Super Puma, G-PUMH that crashed over the North Sea on 27 September 1995 may have been avoided if its HUM data were more thoroughly examined. The source of that crash was a tail rotor failure.

The aircraft carried a complete suite of the latest HUM system previously described. A complete vibration record was recorded for each flight. Prior to that crash, the onboard HUM equipment generated a clear trend of progressive abnormality within its data over some 50 flight hours and exceedance of a predetermined threshold prior to the incident. Three data management issues arose that compromised its effectiveness in preventing this tail rotor failure:

1. The HUM system did not provide for data to be either manually or automatically examined for developing trends as a routine.
2. The specified alert threshold was, with hindsight, set too high.
3. Specific maintenance actions relating the alert to the potential failure modes and the most relevant inspection methods did not exist.

As a result, the associated alert was not responded despite the damage progression, and the engineer involved received no direct advice as to the location, or nature, of the defect. The operator was using the HUM system in the intended manner in which the primary function of the ground based software was to automatically highlight threshold exceedances. Although such a warning was generated five days before the incident, the importance of this was probably obscured by the very high number of false warnings which had previously been experienced. By manually initiating additional software functions, trend data was generated which showed that an unusual and divergent trend existed many hours before the incident. However, with so many parameters being recorded on each aircraft, and the possibility of generating many different types of output trace, it was impracticable for the ground based users of the system to routinely examine trend data. A sophisticated main frame computer should automate the procedure. This is one of the key deficiencies of current HUM systems.

In order to derive maximum benefit from the system, analysis of trend data is just as important as, or maybe even more than, deriving discrete data for each flight. In addition,

the discrete data trigger levels were, with hindsight, set too high. The following safety recommendations were therefore made by the accident review board after the incidence.

1. The air safety board, such as FAA (in the US) or CAA (in Europe) should review, with associated helicopter operators and manufacturers, the function and trigger thresholds of the ground based HUM software.

2. At the present, the individual HUM data across the operator fleet were being “manually” recorded and plotted on paper, and although this information was seen by the operator as valuable in identifying unusual parameters on a given aircraft, it was difficult and time-consuming to obtain. In view of the demonstrated usefulness of fleet-wide data to the operator, the incidence investigation team recommends that there should be a means by which ready access could be provided to fleetwide trend data which would identify abnormal trends on a particular aircraft against an operator's whole fleet. The expert involvement from the aircraft manufacturer would be advantageous.

3. A major limitation of existing HUM systems has been the lack of involvement of the airframe manufacturer in providing technical information for the design assessment. This has prevented the development of optimized systems for existing types and the development of formal maintenance instructions related to specific indications. Therefore the operator is able only to apply engineering judgement in the light of available data. These limitations are removed for later designs where the manufacturer

has been closely involved in the design assessment. In this incident the current standard of HUM was successful in providing an early warning of the incipient failure, but there were no specific and required associated maintenance actions.

Chapter 4 – A New System Structure

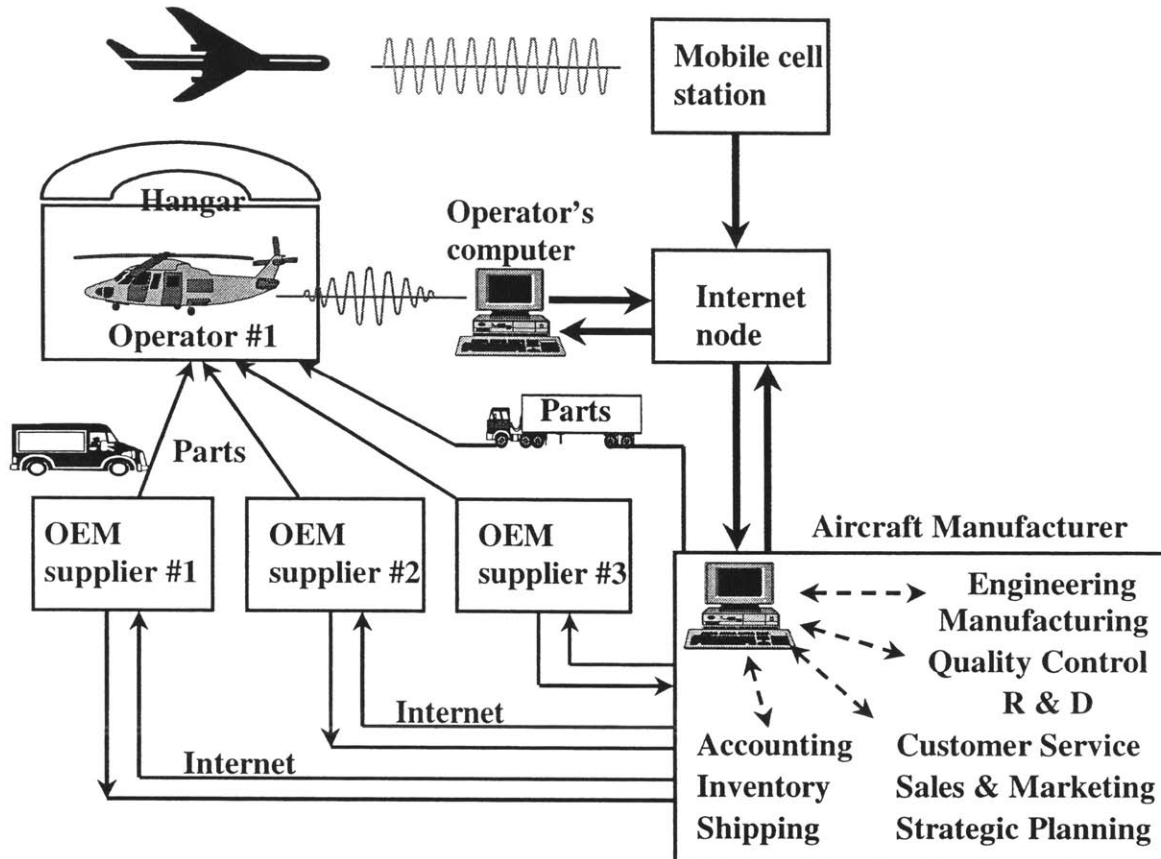


Figure 1 The Internet based aircraft health and usage monitor concept.

Figure 1 illustrates the system flow of a new concept proposed by the author. The onboard HUM system will be integrated with cockpit voice and flight data recorders and also calculates structural life usage, rotor track and balance adjustments, vibration trends and drivetrain diagnostics. HUM information are recorded on the aircraft computer. Upon landing and taxiing to the hangar, the recorded information are transmitted

wirelessly to the operator's ground computer. The information are stored in a compressed and encrypted format. The ground computer temporarily stores the data, and at the same time sends the data via the Internet to the aircraft manufacturer. The computer at the aircraft manufacturer confirms receiving the data accurately and echoes the information back to the operation ground computer again. Operator's computer does a one-to-one mapping to ensure the information echoed back are identical to that stored in the buffer, then it can chose to delete the HUM information from the buffer while sending a confirmation to the aircraft manufacturer's computer.

Alternatively, some commercial operators may prefer to transmit the encrypted HUM information to a ground cell station on a regular interval during the flight. The information are then relayed to the aircraft manufacturer's computer directly or via the Internet.

The manufacturer possesses the engineering expertise to best process the HUM information from flights. The aircraft manufacturer's computer calculates exceedences accrued, calculates the life consumed on all flight-critical parts, and when the next maintenance is require. The sophisticated computer hardware and software at the aircraft manufacturer can track the wear and tear of aircraft parts over a long period of time and benchmark the findings against other aircraft in operation at the operator site and around the globe. This technique will permit a reasonably accurate long leading time prediction of when a part will use up its life expectancy. This powerful capability is missing in the

current HUM systems used by individual operators. With current HUM system, the aircraft operator will not know when to change parts until a part is about to become defective. This means a short lead time for ordering replacement parts. If the needed parts are out of stock at the suppliers, then the aircraft downtime can cost valuable revenue. This is known as AOL (aircraft on the ground). HSI is one of the large aircraft parts distribution companies. John Chimini, a VP at HSI says usually an operator can always locate a replacement in urgency if it screams AOL to all the parts suppliers and warehouses, but it will cost extra to quickly dispatch the parts. This can still mean one or two day downtime just waiting for the parts to arrive. As discussed on Chapter 1, the current unconditional scheduled based replacement system also can be wasteful. The FAA knows it is expensive and wasteful, but until the a new system is in place that can truly monitor and track the aircraft health over a long period of time accurately, the FAA will continue to dictate the current scheduled parts replacement scheme.

With the proposed Internet based HUM system, every part that will eventually be replaced will be checked after each flight by the aircraft manufacturer's computer against a data table that shows how much lead time is required to order that spare part. After the Internet based aircraft health monitoring system is used for a period of time, the aircraft manufacturer sophisticated analysis and database can reasonably estimate the useful life left in each part. Then, based on the operator average usage of the aircraft, the component life consumed, and the lead time dictated by the OEM suppliers, the aircraft manufacturer can plan according when to place the next batch of order. Since the aircraft

manufacturer has now become the focal point for tracking and predicting the demand of the spare parts, the aircraft manufacturer can accurately control when and how much parts to produce each time.

This “conditional based” parts replacement method must receive approval from the FAA. For example, currently, a Sikorsky S-76 helicopter spindle/cuff assembly (approximately \$120,000 per ship set) must be retired at 5,000 flight hours, regardless of the part condition. The 5,000 hours are based on laboratory fatigue test results. With the new Internet based HUM system, the spindle will be monitored and in service for as long as it is deemed safe. This could well extend beyond the conservatively established 5,000 hours. Currently, aircraft manufacturers are seriously lacking valuable information on how much parts life is remaining in parts that are automatically retired due date. The proposed Internet based HUM system will network the aircraft operators closer together with the aircraft manufacturer. The aircraft manufacturer will have access to track the usage, wear pattern, and replacement history of the aircraft that it has produced. These information will help modify current FAA rule and extend the parts’ life.

At the present, aircraft manufacturers receive parts order randomly and can not predict the demand accurately. Furthermore, frequently the operators will buy parts directly from OEM suppliers or sometimes from third party suppliers to save money. With the proposed concept, most of the aircraft operators will have to buy parts from the aircraft

manufacturer. The new system will integrate the replacement parts supply chain and actually lead to lower replacement parts prices. The following paragraphs explain why.

Aircraft parts are either manufactured by the aircraft manufacturers themselves, or the aircraft manufacturers purchase them from OEM suppliers. Aircraft parts are usually very expensive because of stringent safety standard and low production quantity. With the proposed Internet based HUM system, the aircraft manufacturer is now responsible for ordering parts for all operators, hence the volume has increased. Secondly, with the Internet HUM system, the aircraft manufacturer can now predict when parts are needed by all operators. The aircraft manufacturer can optimize its manufacturing cycle or optimize its purchasing timing from the OEM suppliers, so parts can be produced in large batches just in time to meet the demand. This minimizes warehouse waste and prevents back orders.

The OEM suppliers and third party suppliers will also benefit. By setting up an Internet link between the parts suppliers and the aircraft manufacturer, the supplier can monitor the demand build up. Once the demand has reach a threshold, the parts will be made in a large batch to enhance the economy of scale. This permits small suppliers to plan its production schedule so they can take on orders for other industries. Improving production efficiency and economy of scale will reduce the aircraft parts unit-price and enhance production uniformity. As shown in Figure 1, parts that do not require additional finishing or inspection from the aircraft manufacturer can be delivered directly from the

OEM suppliers to the aircraft operators to cut cost and time. However, the aircraft manufacturer will become the central accountant for book keeping how many parts are manufactured, where they are stored, delivery received, and account payable and receivable. Aircraft operators pay an annual subscriber fee to the aircraft manufacturer for maintaining the Internet based HUM systems, and for providing technical support. The aircraft operators will also pay the aircraft manufacturers for replacement parts that are sent automatically to the operators either directly from the aircraft manufacturer or from the OEM suppliers. The aircraft manufacturer is responsible to pay the OEM suppliers for all the parts that are manufactured in each batch. This benefits the OEM suppliers by reducing their business risk and investment. They are guaranteed a payment by the aircraft manufacturer, and the aircraft manufacturer now owns all the manufactured parts. This new B2B system also opens up possibilities to setting up online auction between the aircraft manufacturers and the parts suppliers. The aircraft manufacturer can announce on the net when the next batch of parts will be needed and the suppliers can place their bid.

Based on the HUM record, the aircraft manufacturer will inform the operator via the Internet when their aircraft should be serviced and let the operator know what replacement parts have been ordered and when the parts will be delivered. If the manufacturer's computer detects anomalies, then the appropriate engineering department will be contacted automatically by email. Since the aircraft manufacturer designed the aircraft, therefore, it has the most qualified expertise to handle unusual problems. The

main computer will maintain a comprehensive database that contains current and historical data for each aircraft and its parts and assemblies, as well as a complete maintenance and configuration history.

The aircraft manufacturer's computer will monitor the aircraft health in multiple manners. After each flight, the computer will check whether the aircraft has any exceedence. Then, the computer will automatically trend the wear pattern of each aircraft. A sudden rise in wear rate of a particular component or a steady increase in the vibration signature over a period of time will raise a warning flag. Then all the aircraft owned by one operator are compared and correlated against each other to look for unusual wear rate or similar abnormalities. Then, the data for similar aircraft owned by different operators are benchmarked and compared to obtain standardized wear and usage pattern. The information can be decisively beneficial in detecting any wrong operating or maintenance procedure by a particular user, or for discovering a batch of defects components. The aircraft manufacturer can then recommend the corrective action.

With such a huge and comprehensive database, the aircraft manufacturer can cross correlate the data against different variables to thoroughly understand its own aircraft. For example, plotting the failure rate of turbine generator versus operator's geographic location mean temperature will help explain why the generator from a particular OEM supplier fails frequently in the cold climate. In the future the designer can avoid prescribing that brand and that model of generator for aircraft operating in frigid

temperature locations. As an another example, the aircraft manufacturer noticed that operator company X always file a warranty request on the nose gear spring absorber while none of the other operators do. Upon examining the HUM record, the vibration signature reveals that Operator X's pilots always land their airplane in a certain manner and their mechanics always set the spring rate too low.

This proposed Internet based HUM system will provide the airframe manufacturer with a comprehensive database that documents most, if not all, the aircraft that have been or will be manufactured. The database is invaluable when it comes to designing new aircraft, doing crash investigation, performing product improvement, or forecasting future sales and marketing. By tracking the operation profile, such as flight duration, airspeed, g-loading, component failure rate, the manufacture can learn what the customers need. The manufacturer can in turn generate modifications and enhancement to existing to improve performance and safety. The new aircraft will also be designed based on factual demands instead of anticipation. Both operators and the aircraft manufacturers will benefit in the long run.

The operators can access information regarding their own fleet by connecting to a confidential web site at the aircraft manufacturer. Operators can check the condition of their aircraft, query on maintenance schedule, track spare parts order status, etc. The web site also provides processed information, such as, average fuel consumption rate for any flight conducted by the operator, aircraft wear pattern, maintenance announcements, and

accounting information. The operator will learn how to utilize their aircraft more efficiently. The aircraft company will provide service for the entire fleet for the operator. For military, the size can be an entire wing.

This Internet based HUM system is designed to provide the following strategic benefits: (1) save money for the operator, (2) provide insightful database for the manufacturers, and (3) make air travel safer and cheaper.

The operational benefits include: enhanced readiness, decreased down-time, reduced logistics footprint for deployed units, improved safety, and improved awareness of current aircraft condition. This state-of-the-art system achieve these global benefits by possessing the ability to forecast, track and reduce maintenance actions by:

- Avoiding unnecessary inspections, removals, and overhauls.
- Offering longer part utilization with fewer manual inspections.
- Decreasing scheduled and unscheduled maintenance.
- Detecting transmission problems earlier, reducing time and cost for trouble shooting and repair.
- Reducing "power by the hour" cost of engines and transmissions for both user and repair activity.
- Supporting "Reliability Centered Maintenance" concepts to help the OEM and end user fully utilize the design life of many mechanical components.

- Smoothing the rotor system on rotorcrafts without dedicated flights.
- Enhancing smoothness decreases the vibratory loads on the flight control system components, cockpit displays, and electronic systems - maximizing usable service life of mechanical and electronic components.
- Supporting interactive electronic technical manuals through an open interface
- Detecting and annunciating exceedances
- Displaying Strip-chart analysis.
- Archiving mission data.
- Creating electronic pilot logs.
- Tracking serialized parts by part number.
- Tracking parts by Federal code.
- Tracking component usage (as determined by cycles, flight time, and other relevant parameter).
- Managing component and assembly history.
- Tracking engine performance. Diagnose gear, bearing and shaft assembly and wear features requiring maintenance.
- Generating rotor smoothing instructions for maintenance
- Tracking mission exceedances.
- Logging mission summary.
- Posting mission report.
- Generating "Maintenance Due" report.
- Generating maintenance work order.

- Generating flight and engine data strip-chart.
- Trending of data.
- Tracking engine performance over lifespan.
- Tracking structural usage and fatigue.
- Generating aircraft configuration management tracking.
- Generating assembly tracking.
- Tracking aircraft inventory.
- Generating pilot log.
- Doing automatic replacement parts ordering.
- Tracking ordered parts.
- Tracking global parts inventory.
- Tracking the accounting.
- Verify completed repairs.
- Indicating that repaired aircraft is ready to go.
- Participating in training repair technicians.

Chapter 5 – Cost Benefit Analysis

This Chapter will provide a cost benefit calculation for installing Internet based HUM systems for a medium sized helicopter operator. The purpose is to illustrate the saving that can be obtained by the operator. The same procedure can be applied for calculating the cost benefit for airplane operators or for a military outfit. The numerical values used are author's best estimation based on many anonymous interviews with pilots, engineers and service managers.

Cost Calculation:

A complete onboard HUM system for a rotorcraft ranges from \$3,000 to \$80,000 [4-9]. The low end HUMs are like the Altair units discussed in Chapter 2, which are designed for piston engines. The high end HUMs are like the units designed by BFG for the twin turbine engine powered Sikorsky S76 and S92 helicopters. The current technology ground processing unit is a PC located at the operator's hangar that is configured to run custom software. The Internet based HUM system will use the aircraft manufacturer's main frame computer as the HUM data processor.

Here is an example that illustrates the cost structure proposed by the author. Assume a commercial Operator X has eight S-76C+ helicopters (designed to carry 12 passengers and a pilot and a copilot) that are used for utility and offshore ferry services. The

operator has to purchase the hardware for the onboard HUM system and subscribes to the Internet based health monitor service plan provided by the aircraft manufacturer. A modern 12-passenger turbine powered helicopter has a acquisition cost between four and eight million dollars each. The S-76C+ is priced at \$7 million each. The acquisition cost for a modern HUM system, such as that made by BF Goodrich, is approximately \$80,000. As an assumption for this analysis, let the aircraft manufacturer charge a flat \$12,000 service fee per year, plus another \$30 per flight hour when an aircraft is used. Operator X accumulates an average of 1,000 flight hours per aircraft per year. (That is a typical industry usage for a utility/offshore operator. Military operators usually operate 300 hours per aircraft per year, corporate users average around 500 flight hours per year, and commercial users can go up to 1000 hours per aircraft per year.) The total cost of employing the HUM system for on the first year will be \$976,000. The calculation is shown in Figure 2. The cost of adding an Internet line is not included because it is negligible as compared to the total cost and most operators already possess a PC and Internet hookup. The cumulative cost of employing the HUM for more than 1 year is shown in Figure 3. Figure 3 shows the cumulative cost after the first year is \$976,000, then it increases by a delta of \$336,000 per year.

	Acquisition cost per aircraft	Number of aircraft	Total cost
Onboard HUM hardware (one time cost)	\$80,000	8	\$640,000
Fixed contract fee per year	\$12,000	8	\$96,000
Additional contract charge per flight hour	\$30/hour \$30,000 for 1000 flight hours per year	8	\$240,000
		Total for first year	\$976,000
		Total for each succeeding year	\$336,000

Figure 2 Operator X cost per year.

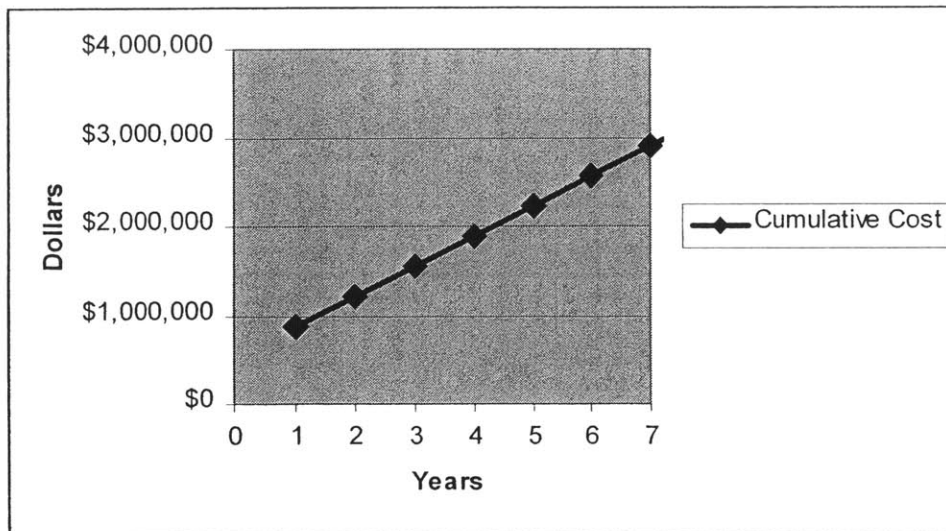


Figure 3 Cumulative cost for Operator X for using the Internet based HUM.

Saving Calculation:

The direct operating cost of the S-76C+ utility/offshore aircraft is approximately \$1,000 per hour [10]. This dollar value is derived based on 1,000 flight hours of usage per year. If the aircraft is used less than 1,000 hours, the directly operating cost can become higher. Appendix A provides the itemized breakdown for the direct operating costs. The direct operating cost includes two parts: “fixed cost” and “variable cost.” The “fixed cost” includes crew cost (pilot salary) and annual cost (aircraft insurance and depreciation). The crew cost will not be affected by the addition of the Internet based health monitor system. Insurance companies may agree to reduce the insurance rate because of safer operation. Let us assume a base insurance rate of \$100 per hour and a 5% discount is given to the operator for installing the Internet HUM system. In one year, the insurance saving is \$40,000.

The “variable cost” is sometimes called the “direct material cost.” It includes three major components: fuel cost per flight hour, maintenance labor hour cost, and replacement parts cost. The dollar values of the variable cost for the S-76C+ aircraft are documented in Appendix A. For 1,000 flight hour per year, the average fuel and lubricant cost per flight hour is \$176.75. The total labor cost based on the December 1998 Rotor and Wing International survey is only \$92.90. It must be pointed out this is based on a very low salary for the mechanics and service manager at only \$25.81 per hour. The salary is low because most offshore rotorcraft operators are located in the Gulf states where the pay

scale is lower. Furthermore, it is assume the mechanics are employees of the operator. The mechanics hourly rate for operators in other geographic location can be as high as \$40 per hour. If the mechanics works are contracted outside, then the hourly rate can go up to \$60 an hour. The parts replacement cost is separated into four categories in Appendix A. “Reserve for retirement items” are parts that will automatically be replaced when the life limit hour is up. For example, the main rotor spindle/cuff assembly for all four rotor blades are unconditionally replaced every 5,000 flight hours. The average per flight hour usage cost for the reserve for retirement items is \$34.01. The average per flight hour cost for the transmission is \$68.56. The average per flight hour cost for the “reserve for overhaul and unscheduled repairs” is \$68.56. For example, the landing gear is in this category. The estimated \$11.88 per flight hour cost for the landing gear is an average based on experience of how much an operator would spend on scheduled maintenance or unscheduled repair of the landing gear in one year based on 1,000 flight hour usage per year. The “reserve for engine overhaul and spares cost” is \$156.00 per hour. The total replacement parts cost per flight hour is \$410.61.

By using an Internet based health monitoring system, Company X with eight aircraft can eliminate the service manager’s workload by approximately 60%. The service manager is no longer needed to do the paper work for tracking maintenance schedule, part ordering, and accounting. This is labeled as indirect maintenance MH/FH, man hour per flight hour, in Appendix A. The mechanics hours that are needed are expected to be reduced by 10% because the aircraft manufacturer’s computer will take over the after-flight HUM

analysis. The mechanics need to link to the web site and download the HUM diagnostic report from the manufacturer. This will simplify the inspection routine.

The yearly salary of a moderately experienced service manager is \$60,000. A 60% reduction of his time needed means a saving of \$36,000. A certified aircraft mechanics gets between \$25 to \$45 an hour. For offshore operators, the salaries are lower, and both the direct and indirect labor man hours are charged at \$25.81 in Appendix A. So, the conservative value of \$25.81 shall be used in the cost benefit calculation. Each S-76C+ flight hour requires 3.6 hours or \$92.90 of labor service. Let us assume adding the Internet based health monitor system will reduce the indirect labor hours by 60% and the reduce the direct labor hours by 10%, then the total labor hour becomes 2.24 man hours per flight hours. The direct labor hours are not reduced significantly because this represents mechanics' time that is still need to work on the aircraft with tools. Reducing the total labor hours from 3.6 hours to 2.24 hours will reduce the labor cost from \$92.90 to \$57.81 per flight hour. Operator X with eight aircraft each operating 1,000 flight hours per year will reduce the maintenance labor cost from \$743,200 to \$462,515. The Internet based HUM represents a saving of \$280,685 in labor cost per year.

As pointed out in Chapter 4, another advantage of the Internet based HUM is it streamline the spare parts ordering process. The process may reduce the spare parts cost by 5 to 15%. The aircraft manufacture can share the saving with the operators. For Operator X, The reserve for overhaul and replacement cost per flight hour is \$410.61. Replacement

part cost. Assume an average of 10% saving in overhaul and replacement parts cost, then the yearly saving for all eight aircraft operating at 1,000 hours each is \$328,488.

By tracking the wear rate of the aircraft parts, and monitoring the aircraft usage pattern, and automating the spare parts ordering process, the aircraft manufacturer can anticipate when the operators will need parts. The manufacturer will be able to pre-order the parts and deliver them to the operators before needed. This arrangement eliminates potential AOL (aircraft on the ground) time. It is estimated a commercial operator loses 1 % of its business because the aircraft is not operable due to waiting for parts to arrive. Assuming a 20% profit margin and the operating cost per flight hour is \$1,000, then the profit is \$200 per hour. Operator X operates 8,000 flight hours each year, hence the profit is \$1,600,000. A 1% lost in revenue translates to losing \$16,000 in potential profit. Figure 4 sums up the total cash saving per year. Figure 5 shows the cumulative saving versus time. The saving grows at a linear rate.

	saving
Insurance saving	\$40,000
Eliminate 10% of direct labor man hours and 60% of indirect labor hours.	\$280,685
Reduce overhaul and parts cost by 10%	\$328,488
Eliminate 1% downtime	\$16,000
Total saving per year	\$665,173

Figure 4 Operator X saving per year.

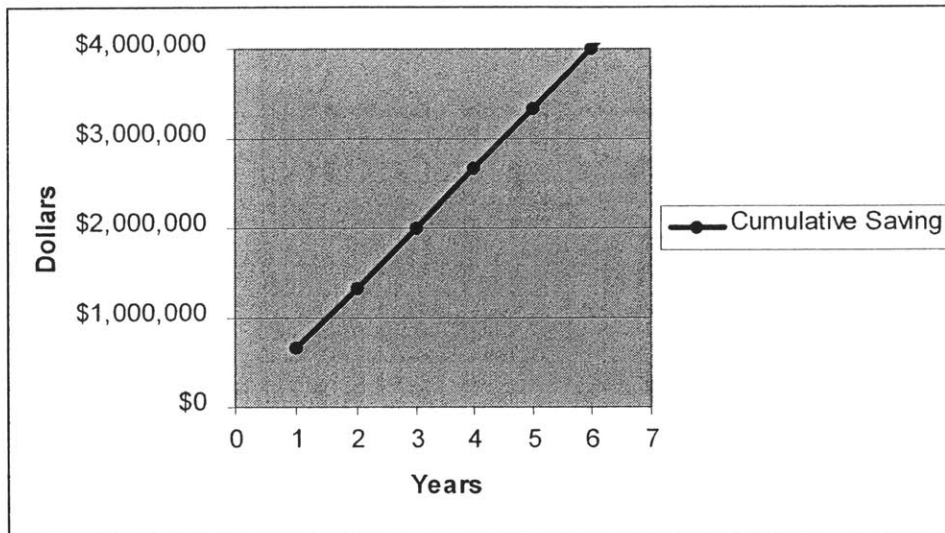


Figure 5. Cumulative saving for Operator X for using the Internet based HUM.

Figure 6 shows the cumulative expenditure and cost saving curves versus time. Figure 6 clearly shows after two and half years, the Internet based HUM system will start to generate more saving than what has been spent.

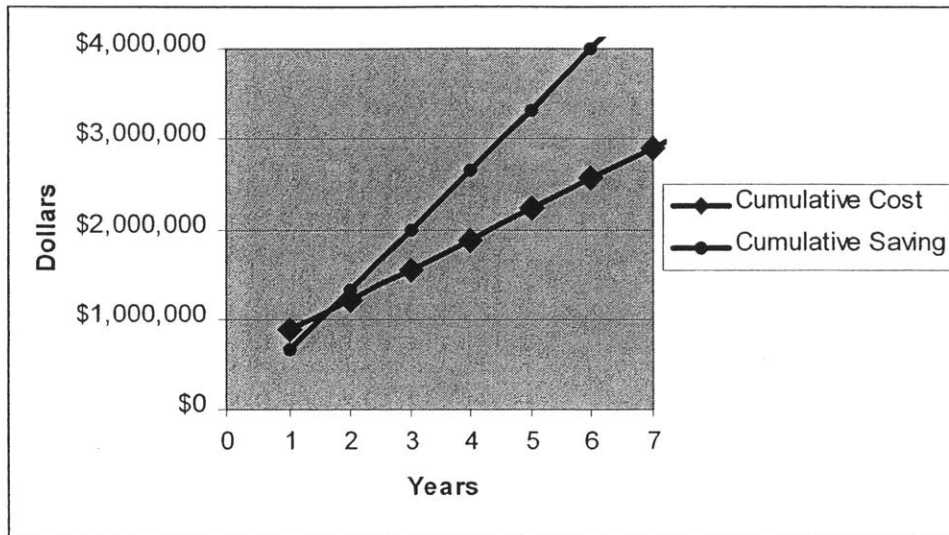


Figure 6. Cumulative cost and saving for Operator X for using the Internet based HUM.

Benefits for the Aircraft Manufacturers:

As for the aircraft manufacturer, it initially sells the onboard HUM unit to the operators at cost, which is \$80,000 per unit. However, it will collect \$240,000 from Operator X each year. This yearly earning is used to pay for the ground processing computer hardware and maintenance cost, repay the non-recurring engineering cost, and engineers' salary. The \$30 per flight hour charge will break even on the engineer salary and computer expense. It is estimated that on the average up to 0.5 hours of engineer time is need per aircraft flight hour. This is an average of a wide spectrum of engineering demand that are

needed from the aircraft manufacturer. When an aircraft operates smoothly, very little engineer time is required, but when there are anomalies, the engineering demand will rise dramatically. Engineer hours are used to examine HUM data, investigate peculiar aircraft problems, track down production errors, and trending global usage. The 0.5 hour engineer time is an estimated average need between benign aircraft users and aircraft abusers. Benign aircraft users generate fewer incidences, and aircraft operated by harsh users require more monitoring.

The \$12,000 fixed charge covers the overhead cost of operating the Internet based HUM system. The overhead cost includes floor space, electricity, water, telephone, system update, etc. The net profit from the \$12,000 is at most 50%. It may seem that \$6,000 profit before tax is miniscule and not worth the effort. But if an aircraft manufacturer tracks 1,000 aircraft, then the annual profit before tax is \$6,000,000.

The real financial gain for the aircraft manufacturer is not the \$240,000 service fee collected from Operator X. The true benefit is the manufacturer can acquire a larger market share of the after-sale maintenance business and parts sale business. After-sale maintenance includes light to medium duty works, such as repairing landing gears, and engine tuning. Smaller operators usually contract the work to an independent aircraft servicing company. Larger aircraft operators (usually with more than 10 aircraft) can perform the light to medium work themselves. Some mechanical works that are usually too complex for aircraft operators to conduct themselves are transmission over-hauls,

rotor head rebuilds and structural modifications. The work can be performed by the aircraft manufacturer or independent service contractors. A typical helicopter manufacturer may only occupy 15 to 25% of the after-sale maintenance and parts business. With the Internet based HUM concept, the aircraft manufacturer may conservatively increase the share to 40% or higher by cooperating with the aircraft operators, OEM parts suppliers, third party parts suppliers, and independent contractors. By signing on to the Internet based HUM system, the aircraft operator will automatically receive every replacement part from the aircraft manufacturer. The aircraft operators are also more likely to send the heavy-duty maintenance jobs to the aircraft manufacturer. At the present, a large helicopter company, such as Bell Helicopter or Sikorsky Aircraft, is probably bringing in 250 million dollars annually in after market maintenance and parts sale business (exact value is not available). This Internet based HUM system could double the annual revenue from \$250 million to \$500 million. This is the financial driver that motivates the aircraft manufacturer to adopt the Internet based HUM concept.

The strategic benefit for an aircraft manufacturer to adapt the Internet based HUM concept is to collect valuable technical and market information. The benefits have been cited in Chapter 4. The passengers will also enjoy a safer and lower cost ride. It is a win-win situation for the aircraft operators, manufacturers, OEM suppliers, and passengers.

Chapter 6 – NPV AND IRR CALCULATIONS

In order for aircraft operators to invest in the Internet based health monitor system, there must be a return down stream. The cost benefit analysis in the previous Chapter did not take into concern the interest rate cost. It was a straight payback rule with a zero discount rate. As shown in Figure 6, the payback period is just under two years. An NPV (net present value) calculation is used in this Chapter to show whether the Internet based health monitor system is still a viable investment when a 7% discount rate is applied.

The NPV is defined as the expenditure and return converted to today's dollar using the prescribed discount rate. Assume Operator X from Chapter 5 will keep the aircraft for five years, then the NPV is:

$$\begin{aligned} \text{NPV} = & -\$640,000 - \$336,000/(1+.07) - \$336,000/(1+.07)^2 - \$336,000/(1+.07)^3 - \\ & \$336,000/(1+.07)^4 - \$336,000/(1+.07)^5 + \$665,173/(1+.07) + \$665,173/(1+.07)^2 + \\ & \$665,173/(1+.07)^3 + \$665,173/(1+.07)^4 + \$665,173/(1+.07)^5 \end{aligned}$$

$$\begin{aligned} \text{NPV} = & -\$640,000 - \$314,019 - \$293,475 - \$274,276 - \$256,333 - \$239,563 \\ & +\$621,657 +\$580,988 + \$542,979 + \$507,457 + \$474,259 \end{aligned}$$

$$\text{NPV} = \$709,674$$

For Operator X with eight S-76C+ helicopters, the NPV is a positive values of \$709,674 which represent money saved for using the Internet based HUM system for five years. Therefore, it is advantageous for the operator to subscribe to the new concept.

A third method that is frequently used to determine whether it is worthwhile to accept a new proposal is to use the IRR (internal rate of return) method. The IRR method performs a NPV calculation but the discount rate is left as an unknown. The objective is to determine the discount rate (IRR) that will make the NPV equal to zero. If operator X keeps the fleet for five years, then the discount rate must be as high 42.7% in order to get a zero NPV for using this new concept. 42.7% is an unlikely high rate, therefore, operator X should adapt the Internet based aircraft health monitor system.

Chapter 7 – Conclusions

A new system idea has been proposed by the author to integrate the aircraft onboard health and usage monitoring system with the maintenance process and spare parts supply chain. The goal is to use an Internet based system to integrate the aircraft manufacturers with the aircraft operators and the OEM parts suppliers to reduce operating cost for the operators. The study shows it will also provide strategic benefit for the aircraft manufacturer. The vast data collected by the aircraft manufacturer will improve aircraft operational safety and improve the performance and safety of future designs. The improved parts demand forecast will also help the OEM parts suppliers to better control its manufacturing schedule. A cost-benefit analysis shows a medium size commercial aircraft operator with eight 12-passenger aircraft can expect to see a large cost saving two years after it invests in an Internet based health monitoring system. The passengers will enjoy safer and less expensive travel. The proposed concept is a win-win solution for aircraft operators, aircraft manufacturers, OEM parts suppliers, and passengers.

Chapter 8 – Recommendations

This study has provided a new system concept. This Internet based health monitor concept can be transferred to other industries. Any manufacturer planning on adapting or promoting this integrated concept must conduct a detailed cost benefit analysis for its own product and for a diverse spectrum of customers. The obstacle will be on convincing the operators to buy-in into the system. The operators have to put out an initial fixed cost. The analysis must demonstrate the operators will recover their investment and achieve long-term benefit. Furthermore, the manufacturer, operators, and the OEM suppliers will not obtain the full benefit if the manufacturer can not get enough subscribers because the database will be incomplete. The concept of condition based parts replacement introduced in the thesis will only work if aircraft manufacturer can obtain a complete health history of the aircraft. It will take time and thorough preparation to persuade the FAA to adopt a condition based parts replacement methodology. The HUM technology is also an art in itself. It still requires more time to discover exactly how accurately that HUM combined with a ground based usage tracking system can predict the failure time of a critical part. The manufacturer must take the lead in setting up this Internet based health monitoring system. Initially, the aircraft manufacturer may have to give away the onboard HUM system as part of the standard equipment on every aircraft and enforce the operators to download the aircraft health data back to the aircraft manufacturer. Otherwise, it will void the warranty. If the aircraft manufacturer decide to sell the HUM system, then the manufacturer has to set the pricing structure with a comprehensive

survey and feedback from its customers. It is a delicate balancing act to make it a win-win situation for all participants.

References

1. Land, J. and Weitzman, C., "How HUMS systems have the potential of significantly reducing the direct operating cost for modern helicopters through monitoring," American Helicopter Society 51st Annual Forum, Fort Worth, TX, May 9-11, 1995.
2. The newsletter of the MONITOR Consortium issue 1, Autumn/Winter 1996.
3. Stevens, P. W., Hall, D. L., Smith, E. C., "A multidisciplinary research approach to rotorcraft health and usage monitoring," American Helicopter Society 52nd Annual Forum, Washington D.C., June 4-6, 1996.
4. Fahy, C., "Altair Keeps an Eye On Copters," Mass High Tech Magazine, Oct. 30, 1995.
5. Parker, I., "Low cost HUM from Altair," Helicopter World Magazine, April 1996.
6. Jenkins, A., "Spy pilot: Device keeps tabs on pilots," Boston Business Journal, May 31, 1996.
7. Report on the incident to Aerospatiale AS332L Super Puma, G-PUMH over North Sea on 27 September 1995 <http://www.open.gov.uk/aaib/gpumh/gpumh.htm#Health>
8. Sewersky, R. A., "System design assessment for a helicopter structure usage monitor," thesis for master of science degree in engineering and management at MIT, June 1999.
9. Erwin, S. I., "Digital network monitors chopper health," National Defense 2000 Directory, 2000.
10. Technical Information brochure published for the Sikorsky S-76C+ helicopter, Sikorsky Aircraft, Stratford, CT, USA, January 1999.

APPENDIX A

Cost of Operation Information for Sikorsky S-76C+

Helicopter

Cost of Operation - Utility/Offshore Oil Service

The following information is supplied to aid in the preparation of cost estimates for the operation of the S-76C+ helicopter in utility/offshore oil service. Costs have been calculated in general accordance with the practices described in *Guide for Presentation of Helicopter Operating Cost Estimates*, published by the Committee on Helicopter Operations Costs. This estimate presumes a mature operation in which there has been opportunity for costs to stabilize and assumes no benefit for warranties.

Direct operating costs are calculated for an S-76C+ flying 1,000 hours per year for 12 years using 1999 component prices, average overhaul costs, and 1999 power-by-the-hour rates. Unscheduled removals are based on historical fleet-wide data.

Variable Costs

	<i>Sikorsky Estimate</i>	<i>Operator Estimate</i>
<i>Fuel and lubricants</i>		
Average fuel consumption (gallons/hour)	88	
Fuel cost per gallon (\$)	1.95	
Cost for fuel (\$/hour)	171.60	
Cost for lubricants (\$) (3% of fuel)	5.15	
Total cost for fuel and lubricants (\$/hour)	176.75	
<i>Labor</i>		
Salary (\$/year)*	39,700	
Salary with benefits (\$) (x 1.3)	51,610	
Labor rate (\$/hour)	25.81	
Direct maintenance (MH/FH)	1.6	
Indirect maintenance (MH/FH)	2.0	
Total maintenance (MH/FH)	3.6	
Total labor cost (\$/FH)	92.90	

*Rotor and Wing International - December 1998

Cost of Operation - Utility/Offshore Oil Service (continued)

Reserve for retirement items	Life limit (hours)	Sikorsky Estimate	Operator Estimate
Main rotor spindle/cuff assembly	5,000	31.79	
Main rotor spindle bearing outer race	1,250	1.02	
Tail rotor retaining plate	7,000	1.20	
Total retirement item cost (\$/hour)		34.01	
Transmissions*	TBO (hours)		
Main transmission (\$/hour)	3,250	57.76	
Intermediate gear box (\$/hour)	4,000	3.60	
Tail gear box (\$/hour)	3,500	7.20	
Total transmission cost (\$)		68.56	
Reserve for overhaul and unscheduled repairs			
Instruments		5.32	
Electrical		7.75	
Fuel system		2.20	
Hydraulic system		2.66	
Landing gear		11.88	
Lighting		1.25	
Heating/cooling		3.68	
Airframe		13.90	
Rotors		34.40	
Power train		5.82	
Flight controls		49.76	
Avionics		14.22	
Total overhaul and unscheduled repair cost (\$/hour)		152.04	
Reserve for engine overhaul and spares cost			
Overhaul reserve **		118.00	
Spares and unscheduled maintenance		38.00	
Total engine overhaul and spares cost (\$/hour)		156.00	
Total direct cost (\$)		680.26	

* Transmission costs based on power-by-the-hour cost distributed over the TBO.

** Engine costs based on one cycle per hour.

Cost of Operation - Utility/Offshore Oil Service (continued)

Fixed Costs

Crew costs	Sikorsky Estimate	Operator Estimate
Salary (\$/year)*	44,800	
Salary with benefits (\$) (x 1.3)	58,240	
Pilot hours per year	800	
Crew cost per hour (\$)	72.80	
Total crew cost for two pilots (\$/hour)	145.60	
Annual costs		
Assumed price (\$)		
Hull insurance, assumed rate (%)	2.50	
Hull insurance, annual cost (\$)		
Depreciation, assumed rate per year (%)	7.5	
Depreciation, annual cost (\$)		
Total annual cost (\$)		
Assumed flight hours per year (hours)	1,000	
Annual costs (\$/hour)		

Total Operating Cost Summary

	Sikorsky Estimate	Operator Estimate
Total direct cost (\$/hour)	680.26	
Total crew cost (\$/hour)	145.60	
Annual cost (\$/hour)		
Total operating cost (\$/hour)		

**Rotor and Wing International - December 1998*