Rotary Wing Structural Life Tracking Architecture

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ABSTRACT

Technical Data Analysis (TDA) presents the architecture development of its rotary wing dynamic component structural life tracking system, HeloTrack.net, which was developed for the US Navy to meet Condition Based Maintenance (CBM) objectives. Methods of fatigue lifing are discussed in the context of improving accuracy for end of life predictions of rotary wing fleets. TDA improves on the current damage calculation process of hours based tracking with HUMS regime recognition and direct loads monitoring. This paper also presents methods for collection and reconciliation of aircraft configuration and fleet logistics data using both legacy paper-based tracking systems as well as advanced Radio Frequency Identification (RFID) tag networks. The union of configuration data and usage data allows for implementation of accurate life tracking techniques. Capabilities and design of the web-based user interface for HeloTrack.net are also discussed.

INTRODUCTION

In support of US Navy (USN) CBM+ objectives, TDA has developed a prototype architecture for tracking and lifing serialized, fatigue-critical rotorcraft dynamic components throughout their lives. The system, HeloTrack.net, will allow for more accurate tracking of individual component lives, as well as fleet-wide assessment of health to aid all program stakeholders in operations, logistics, and engineering.

Current lifing methods are based on information from three primary sources: component strength information developed during component qualification fatigue testing, flight loads data obtained in the aircraft flight test qualification program, and the definition of a mission spectrum to reflect fleet in-service usage [1]. These three pieces of information are used to produce component retirement times (CRT) for each fatigue-critical part. However, in the shift towards CBM, ideally each serialized component should be assessed individually, and inspected or replaced based on an accumulation of actual fatigue damage. The assumption of a fleet-wide usage spectrum conservatively necessitates that a part be retired after an accumulation of a set amount of flight hours, regardless of actual fatigue damage accrued. Advances in usage tracking technology such as HUMS and direct-loads sensing, and their implementation, have set the stage for the USN to incorporate CBM concepts to improve rotorcraft availability and readiness while reducing operating costs.

Still, a major barrier to the implementation of CBM is the ability to accurately indentify aircraft configuration. This is especially critical when components are swapped from one aircraft to another, or repair/refurbishments are carried out as part of maintenance actions in the fleet. The USN correctly identifies the significance of this in Ref. [2]: "…challenges with serialization and accurate tracking of dynamic components prevent us from taking full advantage of individual usage monitoring. Without a comprehensive system to identify and track specific parts over their life in the fleet, our ability to determine damage accrued at the component level is severely limited."

HeloTrack.net combines and reconciles logistics data from several sources to build a configuration history, identifying when and on which aircraft tracked parts are or have been installed. At the same time, the architecture processes aircraft flight-by-flight usage data, using one of three fatigue damage assessment methods: (1) hours-based lifing, (2) regime-based lifing, or (3) direct loads measurement-based lifing. The flight usage data collected from any or all of these methods are to be used to perform incremental fatigue damage calculations. Those damage assessments are then assigned to the appropriate serialized components, based on the aircraft configuration information that has been gathered.

The ability to match flight usage information with configuration information, and therefore assign incremental fatigue damage to individual serialized components is the innovation behind HeloTrack.net. System users will therefore have the ability to gage the current health of their aircraft, squadron, or fleet in near real-time. More importantly, specialized tools allow users to spot usage trends, predict supply needs, or plan maintenance actions. Figure 1 shows a high-level schematic of HeloTrack.net functions.

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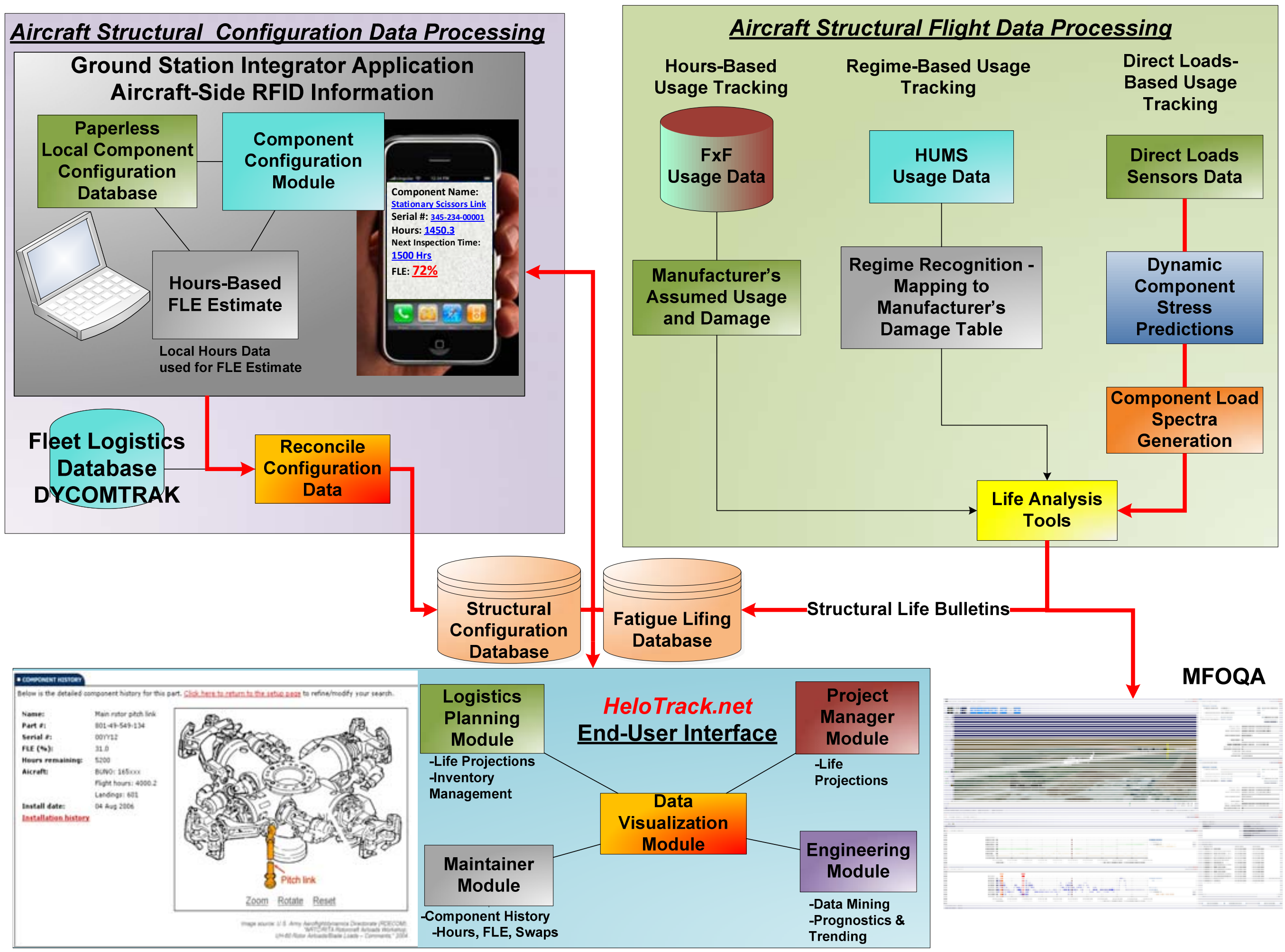

Figure 1. Structural Life Tracking Roadmap.

COMPONENT LIFING TECHNIQUES

As mentioned above there are three basic methods for assessing fatigue life of components: (1) hours-based lifing, (2) regime-based lifing, or (3) direct loads measurement-based lifing. Each of these methodologies and their implementation into HeloTrack.net will be described below.

Hours-Based Lifing

Tracking the accumulation of flight hours of a serialized component is the current standard of fatigue life tracking. Once the CRT is reached, the component is removed and refurbished or discarded. In the HeloTrack.net system, accumulated flight hours are culled from Aviation Maintenance Material Management (AV3M) data from the Naval Aviation Flight Records (NAVFLIR) database. This data is based on pilot accounts after each flight. Information such as flight hours, number and type of landings, gross weight, and mission type are recorded. For the purposes of dynamic component life tracking, only flight hours are at issue. The aircraft component configuration information gathered by HeloTrack.net is then matched with the aircraft flight information, and accumulated hours are assigned to each serialized component.

The immediate benefit of HeloTrack.net for this type of legacy tracking method is the use of the end-user tools for data interrogation, visualization, and prognostics, which will be described later. As the USN implements more advanced usage tracking methods fleet-wide, this lifing technique will remain as a contingency in the case that flight usage data from other sources has been corrupted or gap-filling is required.

Additionally, the system automatically accounts for conversion factors between different Type-Model-Series (TMS). For example, the fatigue damage accumulated by a component on an SH-60B is different than that for the same component on an SH-60R. So if a component flies a certain amount of time on an SH-60B, and is then removed and installed on an SH-60R, the accumulated hours must be adjusted by the Life-Cycle Fatigue Component-Time Conversion factor (LCFCTC).

As mentioned previously, the CRT's are set based on assumed usage spectra. The types of missions and maneuvers actually flown, as well as environments, gust conditions, gross weights, and other factors, may not match the conditions assumed when the CRT's were calculated.

This uncertainty leads to significant factor of safety being applied, drastically reducing the useful lives of the dynamic components.

Regime-Based Lifing

With the widening implementation of Health and Usage Monitoring Systems (HUMS) throughout the fleet, the USN is developing methods to more accurately gage aircraft usage. TDA has developed regime recognition algorithms for H-60 and H-53 variants, based on the Vibration/Structural Life and Engine Diagnostics (VSLED) algorithms developed for the V-22. Using these codes, the regimes flown by a HUMS-equipped aircraft can be identified, giving a clear picture of the maneuvers performed throughout a particular flight.

Currently, every SH-60R/S being delivered to the USN is outfitted with HUMS, and existing airframes are being retrofitted with HUMS. Other H-60 variants, as well as H-1, H-47, and H-53 variants are also being equipped with the systems.

The collection of this data can lead toward more accurate life prediction in two distinct ways. Firstly, building a vast database of regimes flown by aircraft across the fleet, under all conditions and mission types, will allow a refinement or correction of the assumed usage spectra described above. As more information is accumulated indicating actual fleet usage, that can form the basis of more accurate CRT calculations.

Alternatively, actual regimes flown can be matched with flight loads data obtained in the aircraft flight test qualification program. Since loads and damage rates have already been associated with each regime during the aircraft flight test qualification program, the ability to calculate incremental damage, maneuver-by-maneuver, and flight-by-flight, is readily available. TDA sees this method is the preferable use of HUMS. Using HUMS data to refine assumed usage will be valuable as a contingency. However, it does not advance the USN toward its CBM goals. In assuming a usage across the entire fleet, statistical outliers must be accounted for by large factors of safety. Rather than basing a conservative CRT on an assumed usage, the actual regimes flown by each individual aircraft can be used, reducing the need for conservatism.

Direct Loads Measurement-Based Lifing

The third life tracking methodology uses direct load measurements in flight to calculate the fatigue damage on individual components. Theoretically, this is the most accurate method of establishing usage. Load sensors on fatigue critical components would allow for an unambiguous determination of fatigue damage, regardless of regimes flown, aircraft weight, gust conditions, etc.

Clearly though, an exhaustive system, with load sensors on every fatigue critical component throughout the fleet, would be impossible to implement today. Designing, installing, calibrating, and maintaining an all-encompassing network if sensors would not save any money in operating costs.

However, a few key sensors in critical locations, combined with an analytical model, can provide an accurate picture of the loads throughout the rotor system. TDA is currently partnered with Georgia Tech [3] to calibrate and validate a dynamic model of the UH-60 rotor system using DYMORE, a finite element-based tool for nonlinear flexible multi-body system modeling. Using data from a joint NASA-Army UH-60A flight test program, the DYMORE model was calibrated such that known blade loads input into the model would result in matching expected loads on the dynamic components throughout the rotor system. See Figure 2 below. In the process, TDA has identified essential parameters for model accuracy, such as key sensor locations, critical modes, sampling rate, etc.

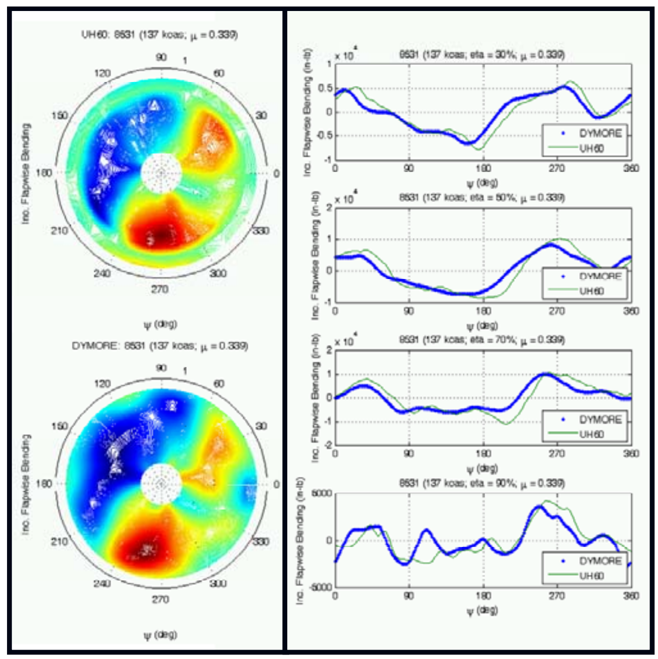

Figure 2. Results Comparing UH-60A DYMORE Model with Test Data.

Direct loads monitoring is a feasible method for determining incremental fatigue damage. When coupling the capability of wireless sensor networks with the reduced sensor count, system operation and maintenance become even more viable.

Practicalities of sensor design and fielding remain a barrier to implementation. Each sensor location presents unique requirements for power, electromagnetic effects, vibratory environment, data sampling rate, and wired or wireless transmission. KCF Technologies, of State College, PA, has already developed a "Smart Rodend" for an H-53 pitch link by integrating a wireless load sensor into the elastomeric rodend. See Figure 3 below. "The new load sensor addresses the need for low power, EMI robustness, and calibration free sensing. The energy harvester enables battery-free operation of the sensor system with a compact 0.3 cubic inch package size. The wireless RF communication uses recent advances in low-power wireless radio communication that have been released in 2010. The complete system is self-contained inside the threaded stem of the rodend, rendering a durable and maintenance-free sensor. The Smart Rodend has been demonstrated with realistic helicopter load spectrums to prove that the energy harvesting generates sufficient power to operate the load sensor and wireless communication." [4]

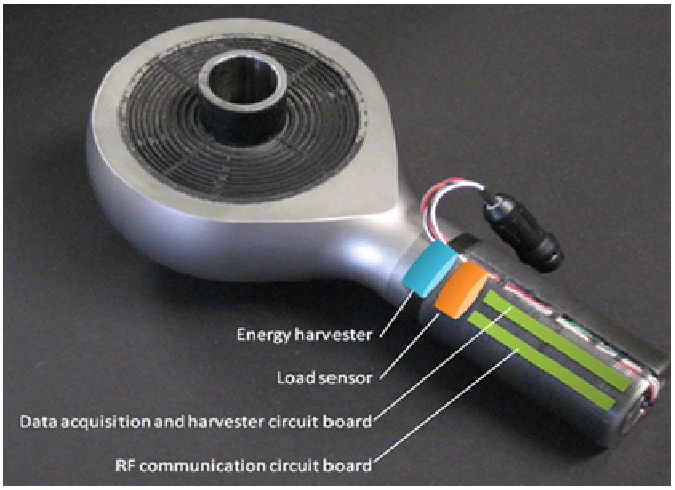

Figure 3. Smart Rodend Prototype from KCF Technologies.

KCF's sensor design presents many advantages. First and foremost, the sensor requires no calibration and no batteries, so it is maintenance-free. Secondly, by housing the sensor within a cavity inside the rodend, there is no danger of damaging the sensor, or interfering with normal operation of the pitch-link.

KCF worked closely with LORD, the manufacturers of the elastomeric rodend, to tailor the design for this application. Novel sensor design, in close concert with the component manufacturers, will be required for each desired sensor location on the rotor system. Additionally, retrofitting active aircraft with these sensors may not be practical. The most logical solution would be to incorporate the sensor construction into the component manufacturing process, and introduce these new parts into the logistics stream. As will be discussed below, TDA is developing an infrastructure to collect aircraft-side configuration and usage data, including loads information, after each flight.

MicroStrain, of Williston, VT, has also developed and tested a proof-of-concept pitch link load sensor on an M412 aircraft [5]. They are currently advancing towards creation of a larger network of energy harvesting, wireless load sensors linked with data aggregators that will sample at the required rate, and will test on a USN test aircraft.

A Note on Factors of Safety

The conservancy of manufacturer -determined CRTs is the result of a stack-up of assumptions made throughout the fatigue analysis process. There are three layers of conservatism in a component CRT: (1) S-N curve scatter, (2) assumed flight usage spectrum, (3) load levels associated with that assumed usage spectrum.

Scatter in component fatigue test results lead to an Xσ statistical reduction in S-N curves. In addition to this, the assumed usage of the aircraft over its lifetime is typically conservative, as mentioned previously. Finally, to calculate a component CRT, damage rates for each regime in the assumed usage spectrum must be calculated. These rates are usually large enough to encompass Xσ statistical outliers in vibratory load associated with each regime.

With the advent of the HUMS regime recognition system, conservative assumption #2 can be eliminated. There is no longer any need assume a flight usage for every aircraft across an entire fleet. The actual flight usage of each individual aircraft and component can be used to determine the retirement time of that component.

Going one step further, regime recognition still relies on assumed load levels induced by a given maneuver. The vibratory content of loading varies from aircraft to aircraft, depending on how the aircraft is loaded, outfitted, flown, etc. Since, in reality, no maneuver is ever the same, the level assumed must be Xσ of the statistical distribution of vibratory loading. However, by directly measuring loads in the rotor system, the uncertainty of conservative assumption #3 can be reduced or eliminated.

While the USN is not prepared to accept component life extension in place of manufacturer specified CRTs at this time, the implementation of direct loads monitoring and regime recognition methods can lead to refined condition-based inspection intervals at throughout the life of the part. Gathering data from these refined inspections can help manufacturers understand and revise fatigue analyses and CRTs. Acceptance of condition-based inspections may then lead to life extensions by operators and manufacturers.

Quantitative Comparison of Lifing Methodologies

TDA has conducted a study quantifying the advantages of using regime recognition and direct loads monitoring over standard safe-life estimations [6]. To carry out this study, data was used from four USN H-60 aircraft which are equipped with HUMS systems. Additionally, TDA was able to simulate a stream of direct loads monitoring data based on a USN flight loads survey aircraft of the same model and series.

Three sample rotor system components were studied: the Pitch Control Horn, Rotating Swashplate, and the Main Rotor Shaft. S-N curves developed by Sikorsky for the pitch control horn and swashplate are given in terms of pitch link load, which was instrumented with a load sensor. A load sensor was also present on the main rotor shaft. Accumulated fatigue damage was calculated using HUMS regime recognition based on nearly 3000 hours of data, as well as direct stress-life methods based on over 3400 records of flight test data.

The fatigue lives of the two calculation methods for the rotating swashplate are shown below, in Figure 4. The dashed line indicates the manufacturer's mandated component retirement time. Note that the HUMS regime recognition approach identified, by a detailed accounting of aircraft usages, slower accumulation of damage in aircraft number 3 of the test and faster accumulation of damage in aircraft number 4.

Results for the main rotor shaft and pitch control horn are similar. See Ref. [6] for a detailed analysis and description of the simulated direct loads data.

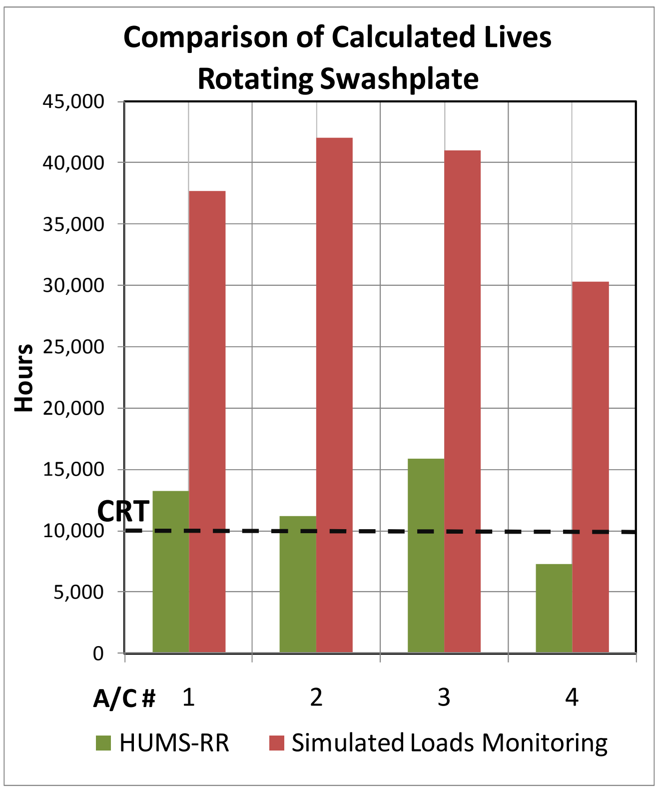

Figure 4. Comparison of Lifing Methods: CRT, HUMS, and Loads Monitoring.

Figure 4 demonstrates the large factors of safety inherent in both CRT, as well as HUMS regime recognition. When compared to the direct loads measurement, component CRT is in this study was as much as four times more conservative.

COMPONENT TRACKING TECHNIQUES

HeloTrack.net will be constructed to interface with several different types of configuration and logistics tracking systems. Gathering data from several different sources provides a more stable platform for quality control and contingency gap filling.

Legacy Paper-Based Systems

The current USN system for rotary wing component life tracking is called DYCOMTRAK, which is a part of the Configuration Management Information System (CMIS). DYCOMTRAK relies on hand-entry of information collected from paper records throughout the fleet. Every aircraft has an aircraft logbook, which contains the Scheduled Removal of Components (SRC) card or Assembly Service Record (ASR) of each serialized component currently installed on the aircraft. When a maintenance action is performed, the SRC card is annotated with pertinent information, such as airframe/bureau number (BUNO), time and date, time since new (TSN), etc. When a part is removed or swapped, the ASR or SRC card is removed from the logbook and attached to the component. At that time, a photocopy of the card is made, and mailed to the DYCOMTRAK processing center at MCAS Cherry Point, in North Carolina.

Upon receipt of the mailed-in cards, the data written on the ASR/SRC card is entered into the COMTRAK database. Participation in the COMTRAK program by the squadrons is mandated in the Periodic Maintenance Information Card (PMIC) deck. Unfortunately, that is not always the case. Exact data about mail-in participation rates are not available. However, semi-annual field audits of squadron logbooks are conducted to verify the database ensure each component is tracked. Mail-in rates average about once every 2-4 weeks, but that number can vary depending on the squadron's deployment status.

This type of system works well enough for the hours-based type of life tracking. If an aircraft logbook or individual SRC card is lost, the central DYCOMTRAK database can be consulted to reestablish component life times. However, this method is also prone to mistakes. Maintainers and/or data entry personnel can misread or mistype key data, data can be entered in the wrong field, etc. Additionally, LCFCTC hours could be improperly calculated, interpreted, or entered. There are many opportunities to mishandle data in this system, but due to the highly conservative CRT's, the level of risk is acceptable.

RFID-Based System

As mentioned previously, one barrier to extending part lives is being able to accurately match a flight usage history to the aircraft component configuration. By removing the human element from configuration record keeping, the opportunity for data loss is reduced. TDA is currently in Phase II of a USN SBIR project to develop component tracking system based on Radio Frequency Identification (RFID) technology. See Ref. [7] for a detailed description of the proposed RFID network.

TDA envisions using miniaturized active RFID tags with advanced power management capabilities track part movement across the squadron or throughout the fleet. Similar to the direct load sensors, each component and RFID tag location are unique, and present unique challenges for energy harvesting (if necessary), EM environment, physical attachment, etc. The RFID tags must be small enough to be bonded and not interfere with normal aircraft operation. Additionally, the RF signal must not cause or be susceptible to local interference. Figure 5 below shows the conceptual RFID network.

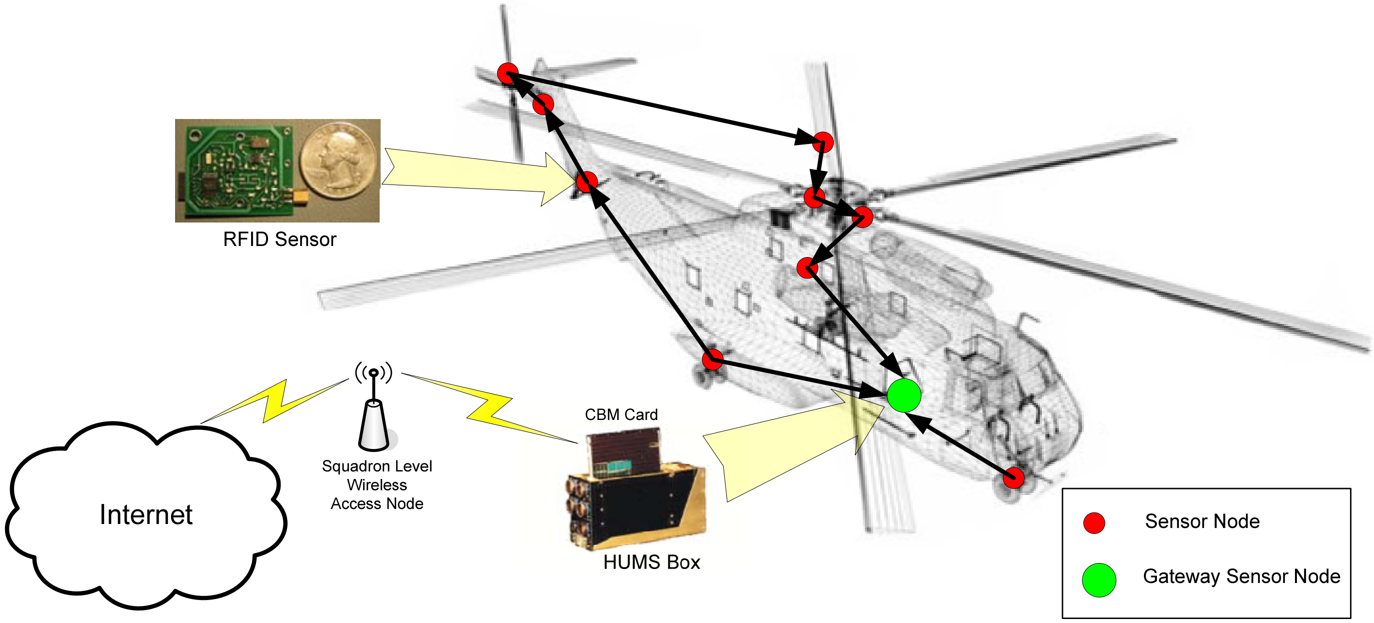

Figure 5. Notional RFID Tracking Network.

Currently, active tags, such as those from Orizin Technologies, can have adequately small physical profiles for most dynamic component tracking applications. Similarly, power saving techniques are available which enable battery life on the order of 5-10 years. Active tags are currently in use in the DOD supply chain for tracking assets. Acceptance of active tag operation is based on ISO 18000-7 protocols. However, this standard specifies use of the 433 MHz frequency band. For this tracking application, higher frequencies, above the 2 GHz range, would be most beneficial. Additionally, the communications protocols of ISO 18000-7 compliant tags, such as the necessity and timing of wake-up signals, are not suitable for this application. For those reasons, applications for variation from this standard must be made to certify the system.

In the proposed concept, the RFID network will be in "sleep" mode for power savings, and awaken only when interrogated by a properly encoded and validated signal. Also, in order to prevent local interference with other systems, these active tags will not be "pinging" during flight. The system can be tied to a kill switch, such as the weight on wheels sensor. Once the aircraft lifts off, the RFID network will shut down. The proposed data acquisition card located in the IMDS HUMS expansion slot can be used to set the triggers for status checks and data download.

Fatigue critical components tend to be clustered near the main and tail rotors. Therefore, two aircraft-side RFID readers will be installed to poll tags present during pre-flight. Both of these readers can wirelessly communicate with the proposed data acquisition card located in the IMDS HUMS expansion slot. This will allow HUMS and configuration information to be gathered simultaneously during post-flight. The CBM card will also be capable of receiving direct loads information from any loads sensors that may be in operation during the flight.

At the end of the flight, the readers download and send RFID tag data to the data acquisition card after a trigger signal is sent. This trigger signal source can come directly from the HUMS unit, as commanded by the ground station or by an external source.

Active tags also have the advantage of having larger memory storage than passive tags. At a minimum, the active tags on tracked components will contain standard logistics tracking information (identification codes, such as Part Number, Work Unit Code (WUC), National Item Identification Number (NIIN), Unique Identifier (UID), Part Serial Number), as well as history and usage data (Current Host Aircraft, time before overhaul, TSN, TSO, TBI, estimated FLE).

To pull and process the data off the aircraft, TDA will develop a local database and software, known as the integrator application. The architecture for the integrator application at the ground station will include the modules necessary to process and update the RFID, HUMS, and direct load sensors data from the data acquisition card. The integrator application database can be accessed by any squadron level computer with defined access privileges for reports on the status of different components. As shown in Figure 6, the same information can also be accessed from a 3G mobile device, using internet with proper security protocols and access privileges.

Figure 6. Remotely Accessible Updates.

HELOTRACK.NET SYSTEM ARCHITECTURE

As described previously, the HeloTrack.net user interface is designed to present information in a manner useful to all stakeholders. Component tracking, life prediction, and prognostics are just some of the tools to which users have access. Data is presented in both tabular and graphical form to aid data mining, and allow users to spot trends.

Implementation of this application follows the widely popular Model-View-Controller architectural pattern. It uses Java as the core programming language, as well as and other open source frameworks such as Struts 2.0 and Spring. The presentation layer is mainly designed using JSP. The application also makes use of Web 2.0 technologies like Ajax and JavaScript. The backend database used is Oracle.

Flight usage data (AV3M, HUMS, or loads sensors) is collected and processed separately from configuration data (ASR/SRC cards, RFID tags). Within the HeloTrack.net system, usage and configuration data is quality controlled and matched based on date of flight and aircraft number.

For the engineer stakeholder, fatigue damage analysis is carried out automatically. The modular architecture of the system design allows for interchangeable and simultaneous damage calculations based on preferred methods. HeloTrack.net is currently being designed with modules for Stress-Life, Local Strain, and Flaw Tolerant fatigue damage calculation methods. The engineer stakeholder will have the ability to select the most appropriate method based on the data available.

Authorized users of HeloTrack.net will have the ability to adjust damage rates and transfer functions based on new information or design changes. Additionally, by employing data mining techniques and visualization, engineers would be able to spot atypical usage and damage trends. This in turn would allow the engineer to adjust assumptions or models used in forming damage rates or transfer functions.

Once the fatigue damage accumulated has been calculated in the central system, an incremental FLE, expressed as a percentage, will be assigned to the appropriate component serial number(s) in the database. This new damage information will be subject to further quality control procedures, and then updated across the global tracking system. Each squadron ground station, when connectivity is available, will update its own local database of components in its inventory. At that time, maintainers, operators, and logisticians will have access to the current life of components on hand. If connectivity from the local ground station to the central database is not available, the ground station will estimate fatigue lives based on hours accumulated. Once a connection to the central database is re-established, and the usage data is processed, the component FLE's will be updated.

At the squadron level, maintainers with access to the local ground station database will have the ability to assess individual aircraft and component health, as well as the health of their inventory. Figures 7 and 8 below show the HeloTrack.net component tracking capability. The module will have the ability to forecast usage based on historical rates, and provide alerts when maintenance actions are pending. Maintainers and logisticians will also have the ability to project inventory over a future period based on an assumed future usage, and therefore be able to prepare for a deployment. Figure 9 below shows some of the HeloTrack.net data visualization capability.

At a higher level, logisticians will be able to project usage and inventory across the fleet, and ensure supply chain availability of tracked components. Figure 10 below shows the HeloTrack.net inventory status view.

Damage information from HeloTrack.net will also be used to enhance Military Flight Operations Quality Assurance (MFOQA) programs. During post-flight briefs, pilots can be alerted to damaging maneuvers that were performed, and receive a quantitative assessment of fatigue damage. Additionally, squadron- and fleet-wide data can be analyzed to find operational trends and their impact on the health of the aircraft.

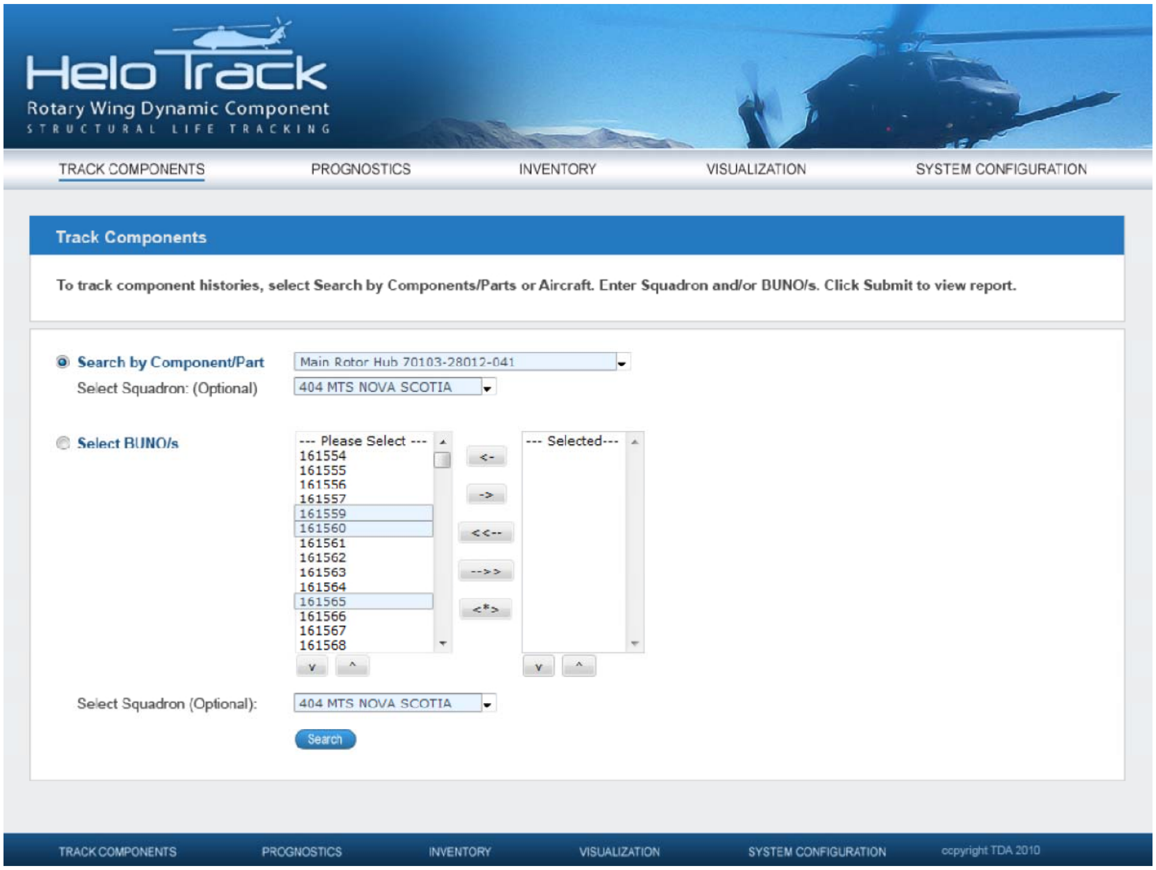

Figure 7. HeloTrack.net Component Tracking.

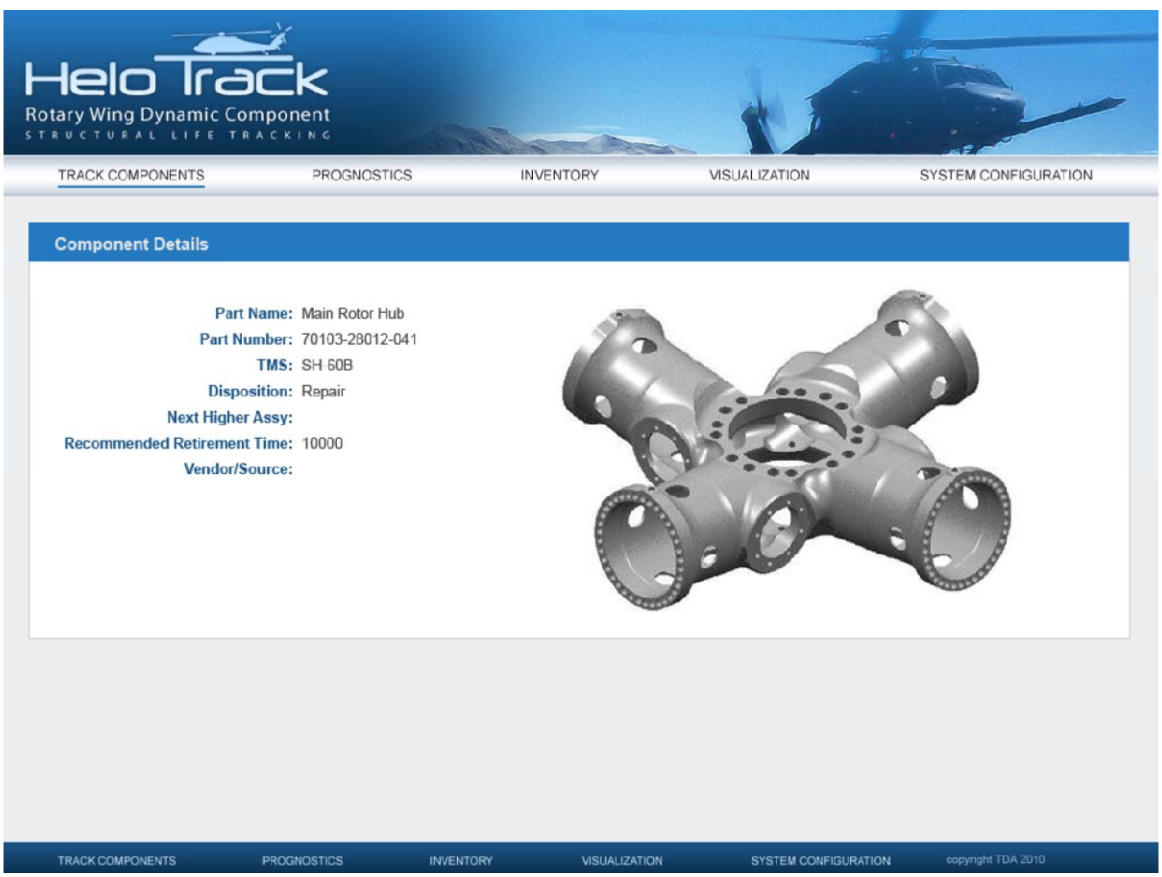

Figure 8. HeloTrack.net Component Tracking.

Figure 9. HeloTrack.net Data Visualization.

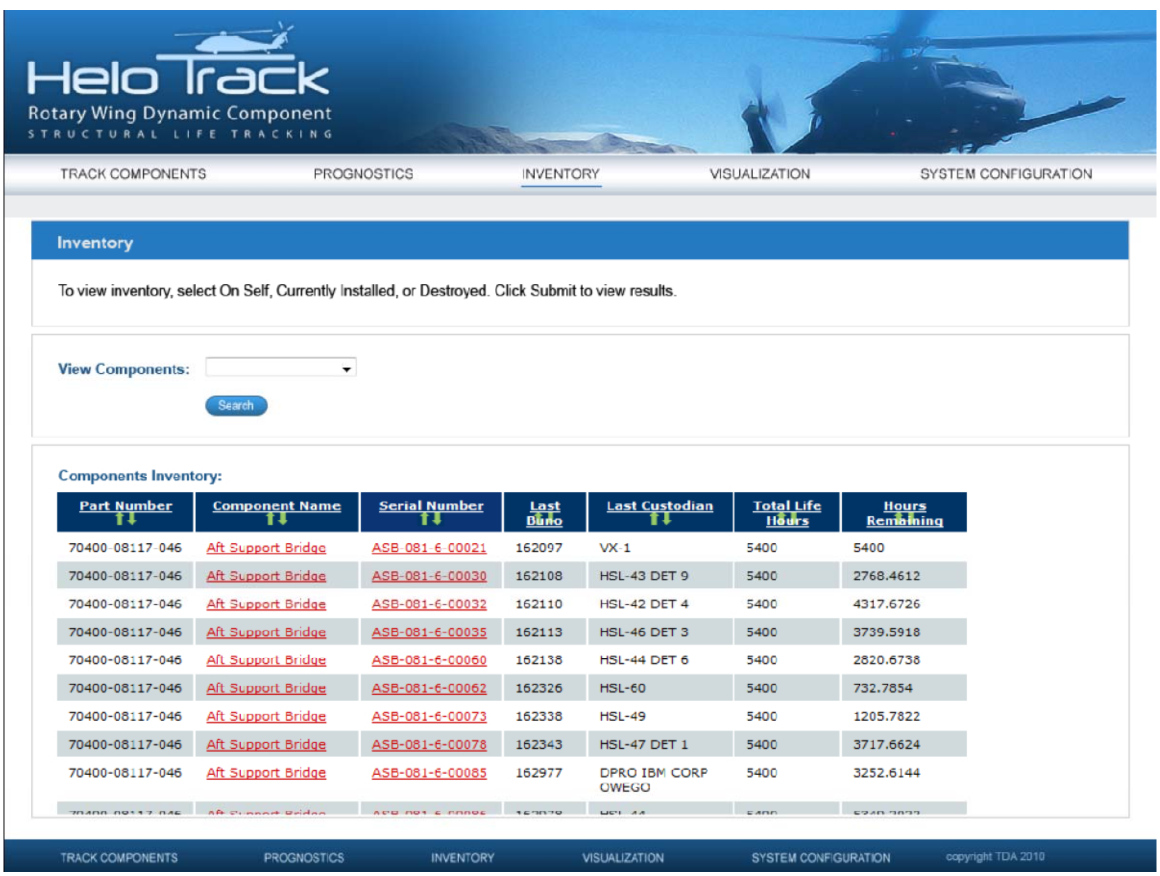

Figure 10. HeloTrack.net Inventory Viewer.

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