Design and Implementation of a Flight Deck Motion Monitoring System

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Abstract: *Shipboard launch and recovery of maritime helicopters is difficult and dangerous, particularly in elevated sea conditions. Typically, during the aircraft hover and landing phases, a Landing Signals Officer (LSO), among other responsibilities, monitors ship motions from a position close to the flight deck and communicates the state of deck quiescence to the pilot. This paper discusses the development of a Flight Deck Motion Display (FDMD) system that has been designed for use by navies to improve the safety and efficiency of helicopter/ship operations by displaying critical motion parameters to the LSO in an ergonomic fashion. After giving a short overview on the motivation for the project, and similar available systems, the FDMD's capabilities and design requirements are presented. A detailed breakdown of the system hardware and software architectures and implementations is given. Sample test results are presented along with a description of the environment under which the system is being tested and evaluated. Finally, some challenges associated with quiescence monitoring are discussed.*

Keywords: *Shipboard helicopter operation, ship motion, flight deck, motion display, Landing Signals Officer.*

1 Introduction

Launch and recovery of shipboard helicopters is a safety critical task which requires an accurate assessment of ship motions. Analysis of actual Canadian flight operations has suggested that landing opportunities are discriminated by a combination of deck roll angle and flight deck vertical acceleration [1].

While human detection of orientation is relatively accurate, judgement of vertical acceleration is not. The issue is further complicated due to the fact that flight decks on most non-flight-dedicated military vessels are located at the stern, which causes the flight deck's vertical acceleration to be strongly a function of both the vertical acceleration of the ship's centre of gravity and its pitch angular acceleration. Historically, the approach taken to allow vertical acceleration limits to be expressed as limits on pitch angle has been to impose a very narrow band on acceptable pitch angles. This results in not only a reduced motion envelope for operations, but can be misleading in cases where high flight deck vertical accelerations occur at low pitch angles.

The Applied Dynamics Research Group at Carleton University has developed a Flight Deck Motion Display (FDMD) system in order to increase operational safety and efficiency of helicopter operations in high sea states. This device delivers real-time ship motion information to a flight deck operator along with information on how those motions compare to predefined limits for specific flight deck operations. Specifically, it allows a flight deck operator to monitor flight deck pitch angle, roll angle, and vertical acceleration, or any other motion, and to a precision that is sufficient for supporting flight deck operations.

The overall goal of the FDMD is to present current and past motion information about a naval vessel's flight deck in a way that provides meaningful information to a Landing Signals Officer (LSO) or any other officer responsible for planning flight operations. The concept of displaying real-time information and defining real-time operational limits is not new. Colwell [1] introduces the concept of real-time ship motion criteria and how they compare to traditional ship/helicopter operating limits (SHOLs).

Traditional SHOLs are determined based on experience, and provide a description of the range of ship motions under which helicopter operations are expected to be successful. Alternatively, real-time motion limits are the maximum motions that can be safely tolerated at the time of performing an activity. To an operator, this difference means that instead of a motion display notifying the user that ship motions may soon become calm enough to land, it can clearly say whether or not deck motion limits are within predefined quiescence bounds at that particular moment in time.

The FDMD displays flight deck motion data and how it compares to real-time motion limits, both instantaneously and over an adjustable time history. In this way it allows an operator to observe when a lull in a ship's motions may soon occur or determine the exact moment when the dynamic state of the ship is within limits for a safe helicopter landing.

Currently there are few alternative products available. The ones that exist can be separated into two categories: systems designed for specifically monitoring ship helidecks and systems designed to monitor all ship motions as well as hull stresses and torsions. A Norwegian company, Fugro, has an extensive helideck motion monitoring system that provides real-time monitoring of ship motions and meteorological information [2]. In Sweden, SMC offers a similar helideck motion monitoring system [3]. Siri Marine, in the Netherlands, has a system capable of measuring, displaying and logging the motions of a vessel as well as monitoring ship hull stresses [4]. In France, Sirehna provides a system with the same functionality [5].

There are two main features that set the FDMD apart from these systems. The first is that the FDMD is designed to be stand-alone and focused on efficient operator use, which makes it extremely cost-effective. The second is the implementation of an innovative quiescent period indicator, which allows the FDMD to provide comprehensive information on the ship's motions in a simple and compact form.

This paper discusses the design, implementation, and evaluation of the FDMD. The design requirements are presented in terms of the overall capabilities of the system as well as specific hardware and software requirements. The design of the hardware and software is described and the operation of each of the software components is presented in detail. Finally, the definition of flight deck quiescence is presented and how it relates to the implementation of the FDMD. One of the major challenges in the design of the FDMD is the creation of the best user interface for presenting real-time information. Some of the results from this work are presented.

2 System Requirements

The FDMD system requirements were generally based on developing a prototype system that addresses the requirements of many helicopter-operating navies and is equally suitable for laboratory and at-sea evaluation. Considerations of available project budget and schedule are also relevant but did not place significant bounds on system capabilities or performance.

A Capabilities

The FDMD's design includes the capabilities listed below.

- The system can receive data from multiple sources and forward data to additional computer terminals in order to provide a backup in case of failure, ensure data consistency, and provide data to multiple operators as needed.
- Continuous data for 6 dof flight deck motion, as measured by a high-quality inertial sensor, is recorded to disk and can be readily reviewed by an operator.
- The system provides real-time flight deck information, including the primary parameters display of flight deck roll angle, pitch angle, and vertical acceleration.
- Operational motion limits are displayed for each motion parameter.
- Multiple, reconfigurable motion limit sets can be toggled to allow the FDMD to be used in ship operations with a variety of motion limits. At the minimum this includes deck and flight operations, during day and night.
- A time history is available for each primary parameter to assist in identifying trends.
- A novel 'quiescence period indicator' is available to allow an operator to quickly assess ship motions.

The goal of the quiescent period indicator is to allow the operator, in a quick glance, to determine whether ship deck motions are within limits, which motions are beyond their limits if applicable, and whether ship motions are tending to move closer to or farther away from quiescence. It must do this without predicting future ship motions in any way.

B Hardware

Hardware requirements are defined based on the perceived requirements of operators and best established practices for systems of this general type.

In order to provide essential functionalities, the FDMD hardware must consist of at least an inertial sensor, a computer, and a display. The sensor needs to measure motions in six degrees of freedom, at a frequency of at least 20 Hz, and at a resolution of at least 12 bits. Accelerations need to be measured in a range of at least ± 1 times Earth's gravity, and to an accuracy of 0.002 times Earth's gravity or better. Angles need to be measured in a range of at least ± 30 degrees and to an accuracy of 0.6 degrees or better.

The computer system needs to be capable of logging, processing, and displaying ship motion data within a latency of 250 milliseconds. The computer display needs have an active viewing area of at least 8 inches (width) by 6 inches (height), and overall dimensions cannot be greater than 9 inches (height) by 12 inches (width) by 3 1/2 inches (depth) due to space restrictions in typical installations. The display's brightness needs to be controllable so that it can be used in day and night operations. The display needs to have software-configurable bezel keys for controlling the software instead of a touchscreen. This is because a touchscreen can be undesirable in a harsh outdoor environment.

C Software

The software needs to run under the Windows 2000 operating system and be written in C++. It should be reconfigurable through the use of input files and be designed such that it is modular and maintainable. The software needs to have dedicated display screens for connectivity status, real-time guidance, data playback, mission planning, and maintenance/testing, that address the requirements of many helicopter-operating navies.

D User Interface

Due to the evaluations and subsequent revisions of the user interface there are no specific constraints on the appearance of major user interface elements. However there are some requirements on the user interface elements that are common to all operating modes of the FDMD:

- overall system status needs to be displayed on every screen and in the same place;
- each operating mode needs to be directly accessible through the push of a button; and
- each operating mode needs to have unique characteristics that allow it to be clearly identified.

3 System Design

A Hardware

A.1 Configuration

The full hardware architecture design, as it has been implemented, consists of a primary system and secondary system, and is shown in Figure 1. The primary system consists of an inertial sensor located as close to the helicopter landing point as possible and a smart computer display. The ship's motions are measured by the inertial sensor and forwarded to the smart display. The smart display performs the calculations necessary to display the data on the screen and forwards the data over a network connection to the secondary system.

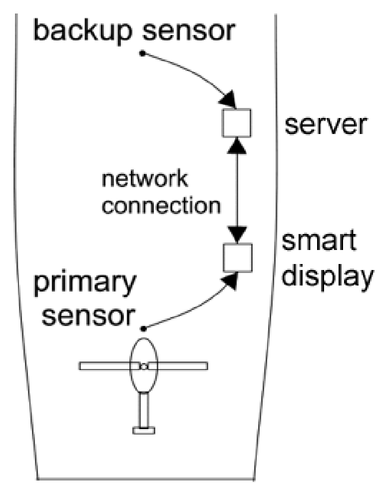

Figure 1: FDMD hardware architecture with backup and error checking functionality.

The secondary system consists of a second computer system and a backup sensor. The secondary computer system compares the primary and secondary motion data sources to ensure that the system is measuring data properly. If any discrepancy is detected then the operators of both computer systems are notified. In the case of a hardware failure of the primary sensor, the system can automatically reconfigure itself to display data to the LSO from the backup sensor, with appropriate kinematic calculations to account for the relative placement of the two sensors. The secondary system records all of the data from all sensors to disk. The backup sensor can be located anywhere on the ship as long as the software is aware of its location. If a third sensor were added to the system it could also be determined which sensor is faulty in the case of sensor malfunction. In the interests of keeping the system as simple and economical as possible, this has been excluded from the current hardware design. Alternative methods for identifying which sensor is faulty can be explored.

B Software

B.1 Components

The software design consists of four major components, each having its own functionality and interactive user interface. They consist of communications, data management, operations, and mission planning. Figure 2 shows the flow of information between these software components.

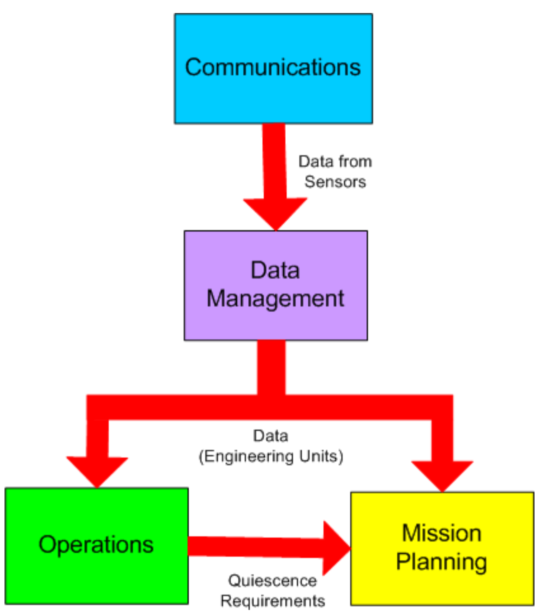

Figure 2: FDMD software modules and information flow.

The first, communications, manages all of the hardware in the system, monitors connectivity status, and manages the receiving/redirecting of sensor data. It is fully configurable through ASCII input files and can manage multiple data sources. These data sources can be TCP servers, TCP clients, or hardware that is connected by a serial connection. Typically serial connections are used for sensors, and TCP connections are used to transfer data over a network connection between computers. The communications module treats incoming data equally regardless of its source. If a data source does not keep track of time, then a time stamp is assigned to the data packets as they arrive. If the data the communications module receives needs to be processed locally it is passed onto the data management module.

The data management module first records the raw data to disk if required. The data is stored in a simple binary format in order to maximize storage throughput speed and capacity. The data in memory is then converted into engineering units and passed into the operations module. Conversion factors for each motion parameter from each data source are stored in ASCII input files. The data management module can also be used to browse all of the data that has been recorded in the past. The data can then be replayed in real time if an operator wishes to review a particular event.

The operations module is the main operating mode of the software. For each monitored motion parameter, it displays a two minute time history with motion limits information, an indicator that displays the current value of each motion, and a quiescent status indicator. An example of this time history and instantaneous value indicator is shown for roll motion in Figure 3. The quiescence status indicator will be discussed in Section C.

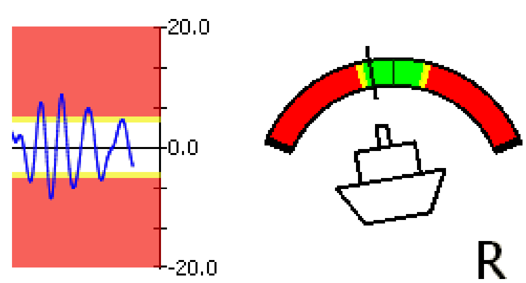

Figure 3: Roll motion history and value indicator in the operations user interface.

The final module of the FDMD is called mission planning. Its purpose is to use mathematical algorithms and statistical results based on historical data in order to aid in helicopter mission planning. For example, it could be used to aid in selection of ship course and speed that would minimize ship motions and/or maximize the average length of quiescent periods.

B.2 Test Environment

A parallel project being developed by the Applied Dynamics Research Group is the creation of a Real Time Virtual Flight Deck (VFD-RT) simulation environment. It is designed to execute small scale real-time helicopter-ship simulation for a variety of engineering purposes.

The VFD-RT simulation environment is composed of three layers: a core application that manages the passage of time and coordinates communication between parts of the simulation, a set of data input applications called "providers" that contain the mathematical models of the simulated entities, and a set of simulation data output applications called "clients". Figure 4 shows the three layers and the data flow between layers. The entities in the top row are providers, the middle row is the VFD-RT core application, and the bottom row are the clients.

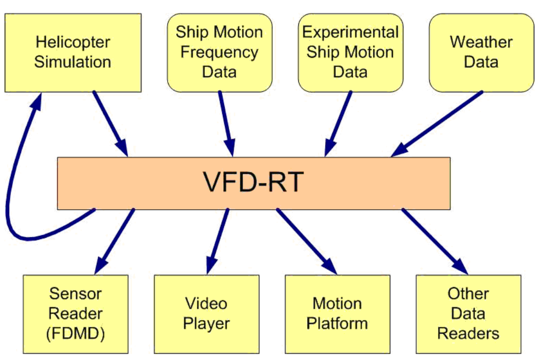

Figure 4: The three layers of the VFD-RT simulation environment.

One of the clients that has been developed simulates an inertial sensor placed anywhere on the ship. This simulated data is transfered to the FDMD over a TCP connection. The FDMD treats the data as if it is simply sensor data received from another computer, and in this way it provides a convenient method for debugging the FDMD. In the future, there are four main additions to the VFD-RT that will be used to further the FDMD's testing and evaluation.

- The VFD-RT will be used to drive a small scale motion platform that the FDMD's motion sensor will be placed on to evaluate its correct operation.
- A three-dimensional view of the simulation will be generated which will allow a user to monitor it from any location, including inside the LSO's compartment.
- A helicopter approach, hover, and landing simulation will be developed and incorporated into the VFD-RT to support an immersive simulation environment.
- The VFD-RT will be used to drive a 6 dof stewart platform and LSO compartment emulator to provide an immersive evaluation and training environment.

These additions to the VFD-RT will allow a user who is testing or evaluating the FDMD to observe actual sensor data, watch a simulated flight deck with helicopter approach, hover, and landing, and allow the user to physically experience the ship's motions as they complement reading of the FDMD display.

B.3 Quality Assurance

Once integrated into operational service, the FDMD will be safety-critical equipment. Therefore, its software must be designed to meet applicable development, verification, validation, and reliability standards. While the prototype system will be used for evaluation and supported by existing practices, final coding standards will only be required in the ruggedized, commercial version of the system. Despite this, the prototype system is being developed to facilitate software ruggedization during the FDMD commercialization process.

4 Motion Monitoring

A Flight Deck Operations

In shipboard helicopter landings, standard operational procedures are followed. These involve the use of trafficator lights for visual communication between the deck crew and the pilot, a hauldown system to aid helicopter fine positioning during landing, and securing device to stabilize the helicopter once it is on deck. The primary steps of Canadian landing procedures are outlined below [6].

Hauldown landings are used during moderate to high sea states and are much more demanding than landings in calm conditions. It is for this type of landing that the FDMD's use is targeted. In general, the following steps are followed:

1. When the helicopter receives clearance it approaches the flight deck and enters a high hover of 15 to 17 feet above the deck.

2. The helicopter positions itself to the side of the Rapid Securing Device (RSD) and lowers a messenger cable. As soon as it is safely possible, flight deck personnel ground the messenger cable and attach a hauldown cable.

3. The hauldown cable retracts to apply a constant tension, but does not prevent the distance between the helicopter and ship deck from changing.

4. The helicopter descends to a lower hover of approximately 5 feet and the pilot notifies the deck crew when ready to land.

5. The LSO gives instructions for the helicopter to position itself over the RSD, and when the deck is steady, orders the helicopter to land.

6. Once the helicopter is on deck the hauldown cable tension is increased and the helicopter is mechanically secured to the ship by the RSD and helicopter securing probe(s). Flight deck personnel may install additional securing restraints to the aircraft.

In the procedure outlined above, the LSO must wait until the deck is steady or 'quiescent' before ordering the helicopter to land. If it appears that it will be some time before a quiescent period occurs the helicopter may return to high hover or in some cases be waved off and the landing process repeated.

B Definition of Quiescence

A quiescent period is defined as a time when all monitored motion parameters are within limits for performing a specific activity. Two rules for changing quiescence status are defined in [1] and [7].

1. The state is not quiescent when at least one limit is exceeded; and,

2. In order to change state from non-quiescent to quiescent, each motion which has exceeded its limit must experience a subsequent motion peak below its limit.

This definition has been incorporated into the FDMD software that computes quiescent status. Three discrete states are used to define quiescent status.

- Red - the flight deck motion is out of limits.

- Yellow - the flight deck motion is within limits but close to the limit.

- Green - the flight deck motion is well within limits.

Quiescent status is calculated separately for each motion parameter and then the results are summed together, with yellow taking precedence over green and red taking precedence over both green and yellow.

A demonstration of quiescence calculations is shown in Figure 5. This figure displays a graph with the yellow and red limits marked, and a bar at the bottom which displays the colour corresponding to the quiescent status at that time. On the left, the status starts as green and the graph rises and peaks in the yellow area. On the following peak it passes the motion limit and enters the red area. As soon as a limit is exceeded the quiescent status colour changes. The data continues back through zero and peaks again in the red. The entire time the quiescent status remains red. Finally at the next peak, the data is in the yellow area and the quiescent status is downgraded to yellow. Shortly thereafter the data peaks below the yellow limit and the quiescent status changes to green.

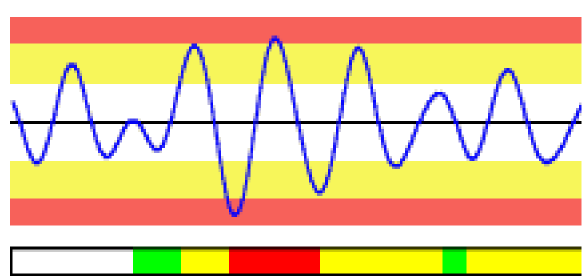

Figure 5: An example data graph and quiescent status bar.

C Quiescence Monitoring

As stated in Section A, one of the major goals of this system is to provide the LSO with a graphical user interface that in one glance, can be used to determine whether ship motions are within limits or not, and some sort of indication on whether they are moving closer to or farther away from a lull in the motion.

In [7], Colwell proposes that each motion parameter should be displayed as a bar graph with its limit marked on the bar. An overall bar should then be displayed which shows the value of the largest bar. During development of the FDMD, it was found that while such a user interface is a visually appealing method for presenting the ship's status, it does not always convey required information efficiently. An example of this is the case where the quiescence status is dominated by one motion. In this case, even if the motions are very dramatic, the motions will still cycle through zero, and thus give an improper impression of the current quiescent status of the ship.

In order to avoid this problem the FDMD has been designed so that the most recent peak value of each motion parameter relative to its respective limit value is displayed. This allows the LSO in a quick glance to see whether any of the ship's motions are above their limits and how all of the ship's motions compare to each other. An example of this quiescent status indicator can be see in Figure 6. In this figure the user can clearly see that the ship's roll motion is the limiting motion, with vertical acceleration also a factor; pitch angle is not a limiting factor at the instant shown.

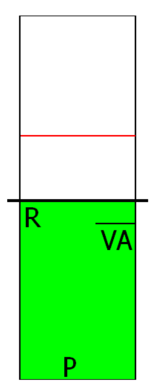

Figure 6: Quiescent status indicator.

5 Sample Results and Discussion

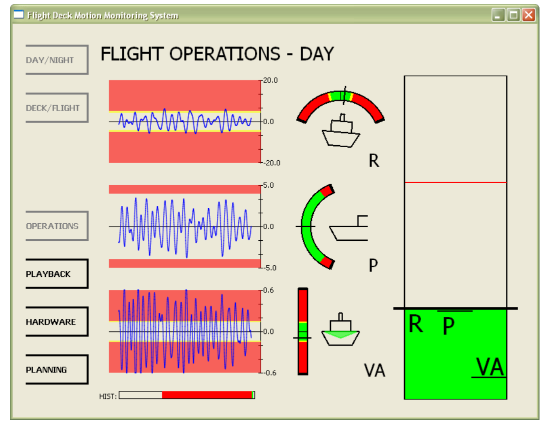

Figure 7: FDMD operations user interface.

A screenshot of the operations user interface is shown in in Figure 7. It contains data histories and instantaneous value indicators for roll angle (R), pitch angle (P) and vertical acceleration (VA) along with a quiescent period indicator on the right. This interface arrangement is the result of an iterative design process that has been refined with input from the user community.

One issue that has arisen with this interface is that displaying pitch information is redundant when deck vertical acceleration is shown. While this is true, measurement of vertical acceleration is not as intuitive as measurement of pitch angle and it is important that operators are aware that these are distinct measurements.

A carefully considered and deliberate decision in implementing the operations user interface was to make all critical information available to the user on a single screen. While this necessitates a relatively busy display, LSOs are proficient at scanning a portion of available instrumentation to extract information of interest. The current version of the display avoids redundant information and places vital information where it can be identified and extracted with a fleeting glance.

6 Conclusion

In order to improve operational safety and efficiency in helicopter/ship operations, the Flight Deck Motion Display has been developed. This device provides real-time accurate motion information to an operator as well as historical data to aid in identifying trends.

The FDMD is designed to help an operator predict when a lull will occur in a ship's motion, but without performing any type of predictive calculation. It does this through the use of a quiescent status indicator, which allows the operator in a quick glance to determine (a) whether the ship's motions are within operational limits or not, (b) which motions are beyond their limits if they are, and (c) how many of the ship's motions are close to or beyond their limits. In the common situation where landings must be completed in very short quiescent periods, the ability with the FDMD to identify the onset of quiescence quickly and accurately can offer significant benefits in the challenging and critical task of shipboard helicopter recovery.

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