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Architecting Integrated System Health Management for Airworthiness

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ARCHITECTING INTEGRATED SYSTEM HEALTH MANAGEMENT FOR AIRWORTHINESS

THESIS

Kerwin Chun Seong Teong, Major (Military Expert 5), Republic of Singapore Air Force

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

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ARCHITECTING INTEGRATED SYSTEM HEALTH MANAGEMENT FOR AIRWORTHINESS

THESIS

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

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ARCHITECTING INTEGRATED SYSTEM HEALTH MANAGEMENT FOR AIRWORTHINESS

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Abstract

Integrated System Health Management (ISHM) for Unmanned Aerial Systems (UAS) has been a new area of research – seeking to provide situational awareness to mission and maintenance operations, and for improved decision-making with increased self-autonomy. This research effort developed an analytic architecture and an associated discrete-event simulation using Arena ® to investigate the potential benefits of ISHM implementation onboard an UAS. The objective of this research is two-fold: firstly, to achieve continued airworthiness by investigating the potential extension of UAS expected lifetime through ISHM implementation, and secondly, to reduce life cycle costs by implementing a Condition-Based Maintenance (CBM) policy with better failure predictions made possible with ISHM. Through a series of design experiments, it was shown that ISHM presented the most cost-effective improvement over baseline systems in situations where the reliability of the UAS is poor (relative to manned systems) and the baseline sensor exhibited poor qualities in terms of missed detection and false alarm rates. From the simulation results of the test scenarios, it was observed that failure occurrence rates, sensor quality characteristics and ISHM performance specifications were significant factors in determining the output responses of the model. The desired outcome of this research seeks to provide potential designers with top-level performance specifications of an ISHM system based on specified airworthiness and maintenance requirements for the envisaged ISHM-enabled UAS.

Dedicated to my beloved fiancée, for your unconditional love and patience. To my parents, thank you for being my lifelong role models and for always being supportive of my endeavors. And to my classmates and friends at AFIT, you all have made this an amazing journey.

Acknowledgments

I would like to express my deepest appreciation for my research advisor, Dr. David Jacques, for his mentorship and guidance. I would also like to thank my committee members, Dr. Michael Grimaila and LtCol. Kyle Oyama, for their support and feedback throughout this research effort. For your patience and kind words, I am sincerely grateful.

Kerwin Chun Seong Teong

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I. Introduction

1.1 Background

The challenges of tomorrow's battlefield involve time-critical decision making in a massive whirlpool of available information – and the *best* decision needs to be made every time, all the time. The Office of the Chief Scientist of the United States Air Force (AF/ST) released a report in May 2010 that advocated greater use of highly flexible autonomous systems; seeking to provide significant time-domain operational advantages over adversaries limited by human processing and decision speeds. In order to achieve these gains from the use of autonomous systems, new methods will need to be developed to establish "certifiable trust in autonomy" through verification and validation of the near-infinite state systems that result from high levels of adaptability [Dahm, 2010].

In the domain of unmanned aerial systems (UAS), *trust in autonomy* can be determined by airworthiness, the safety record, or the number of successful missions. Existing technology has not brought UAS to a state of complete autonomy with command and control (C2) still residing in the human operator during critical phases of flight or mission. Diagnostic and prognostic algorithms seek to improve the self-autonomy of UAS through detection and isolation of faults, and determination of the *best* course of action. Although in-flight fault-monitoring or detection protocols currently exist for specific flight critical sub-systems, a UAS-wide health monitoring and decision system has seldom been implemented.

For manned aircraft, Health and Usage Monitoring Systems (HUMS) technology had been developed since the 1980s in response to airworthiness concerns for helicopters. HUMS implementation normally involves a comprehensive suite of sensors measuring vital aircraft parameters (e.g. vibration and temperature) spanning over critical sub-systems such as the engine, rotor and gearbox. The HUMS will also include software to handle data processing (diagnostics) and prognostics to enhance overall aircraft safety and reliability through condition-based maintenance [Miller et al., 1991].

With the same motivation, Integrated System Health Management (ISHM) for UAS has been a new area of research – seeking to provide situational awareness to mission and maintenance operations, and for improved decision-making with increased self-autonomy. Through a centralized health management system, ISHM identifies necessary sources of input data from multiple sensors, generates the status of real-time UAS capabilities, and initiates the *best* course of action in relation to airworthiness and/or mission objectives. These objectives can be measured by an improvement in expected lifetime or an overall reduction in the maintenance costs.

1.2 Problem Statement

According to the Air Force Policy Directive 62-6, airworthiness is defined as “the verified and documented capability of an air system configuration to safely attain, sustain, and terminate flight in accordance with approved usage and limits" [Donley, 2010]. To this end, Failure Modes, Effects and Criticality Analysis (FMECA) has been a necessary process in most airworthiness type certification plans. FMECA is a procedure that identifies potential failure modes (and effects) of a system, and thereafter ranks these failure modes based on the combination of their severity and probability of occurrence. [DoD, 2005]. Although FMECA has been widely applied (or mandatory in some cases) during conceptual or preliminary design phases, its applications during the operational phase of a UAS has been limited. Furthermore, the integration of FMECA considerations within an ISHM architecture deserves deeper exploration.

Previous research on ISHM evaluated the effect of ISHM on mission effectiveness; and a *baseline model* had been implemented to quantify the mission-related benefits of ISHM by constructing architecture for analysis to compare against current autonomous vehicle capabilities [Storm, 2013]. The focus of this research extends beyond previous efforts through increased realism of the ISHM architecture by considering FMECA data for UAS airworthiness, sensor fusion of existing and ISHM sensors, and attempts to develop a business case for condition-based maintenance with improved diagnostics and prognostics provided by ISHM.

1.3 Research Objectives and Hypothesis

The objectives of this research are to quantify the continued airworthiness benefits of ISHM by developing an analytic architecture for comparison between an "as-is" UAS (without ISHM capabilities) and a "to-be" UAS (with ISHM capabilities). From an airworthiness certification perspective, this research aims to develop a method for establishing performance requirements for components of an ISHM-enabled UAS. An analysis of the architecture will examine the effects of ISHM decisions through stipulated algorithms, ISHM reliability through the performance and degradation of its sensors-diagnostics-prognostics suite, and the associated costs of maintenance.

Adopting a modeling and simulation approach, the research presented in this thesis shall attempt to answer the following questions:

(1) What are the performance characteristics of ISHM to ensure continued airworthiness of the UAS?

(2) How will ISHM provide a business case to improve the level of UAS self-autonomy?

(3) What are the potential impacts of ISHM to maintenance practices and life cycle costs?

Prior to the formal research work, a literature review was conducted to answer related questions in the research field:

(1) What is system health monitoring/management and what are some related applications?

(2) What are the essential elements of ISHM?

(3) What are the critical FMECA hazards associated with a typical UAS and their relation to airworthiness?

(4) What is Condition-Based Maintenance (CBM)?

1.4 Methodology

An analytical architecture shall be developed in accordance with the Department of Defense Architecture Framework [DoD, 2012], simulating ISHM over the lifetime of the UAS with the primary architectural goal to achieve cost-effective improvements to airworthiness. The architecture will attempt to model the typical failure modes of a generic UAS and derive its life expectancy as a proxy for continued airworthiness certification of a UAS, both with and without ISHM for statistical comparison. It is anticipated that there will be a system design paradigm shift with this architecture being able to establish performance requirements for components of an ISHM-enabled UAS; possibly with reduced redundancy and cost with information fusion enabled by ISHM – to achieve the same or higher airworthiness standards.

Implementation-wise, the architecture developed shall be generic enough to be applied across various UAS platforms with appropriate FMECA information. A discrete-event simulation approach shall be adopted to develop realistic models for (a) on-board ISHM implementation with diagnostics and/or prognostics algorithms, and (b) purely baseline sensors available in UAS hardware without ISHM. As a secondary objective, a life-cycle cost model of the ISHM suite can also be derived to account for possible degradation (made apparent through high false alarm or missed detection rates) that will require replacement – and provide a holistic picture of the maintenance costs of an ISHM-enabled UAS.

1.5 Assumptions and Limitations

The primary research objective is to investigate the potential benefits of ISHM onboard UAS – a relatively new knowledge domain with limited implementation data. As such, there need to be several assumptions providing boundaries of this research for it to be useful:

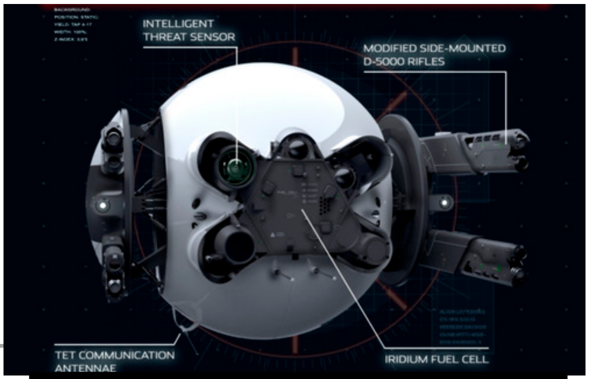
> (1) Without actual FMECA data, it will not be possible to model and/or evaluate all the failure modes for a typical UAS. As such, only selected critical sub-system failures affecting airworthiness of the UAS shall be evaluated using the model.
>
> (2) Without actual sensor performance data, theoretical/nominal thresholds will need to be assumed to model sensor degradation in terms of False Alarm Rate (FAR) and missed detections.

1.6 Implications

From an airworthiness perspective, the direct implication of this research lies in its ability to establish meaningful metrics and design-to requirements for an ISHM-enabled UAS. A validated ISHM can provide the desired level of UAS self-autonomy to detect, diagnose and implement corrective actions as necessary. This, in turn, drives future UAS designs that can operate with reduced redundancy (and maintenance demands) with diagnostic and prognostic capabilities provided by ISHM. In the longer term, sustained airworthiness records with onboard ISHM will be able to foster *greater trust in autonomy*.

With the improved intelligence behind airworthy UAS, complex mission tasks can then be entrusted upon UAS with greater collaborative capabilities (including mission re-planning based on system health) and wider operational envelopes [MacConnell, 2006]. On the other hand, drawing negative parallels from science fiction, the movie “Oblivion” featured fully autonomous drones controlled by an alien artificial intelligence that had invaded Earth [Kosinski, 2013]. These drones would operate collaboratively to dominate Earth and were programmed to kill humans on sight. Therefore, a delicate balance of autonomy and delegation of authority needs to be established with ISHM. See Figure 1.

Desired ISHM Capabilities
Sustained Airworthiness
Availability
Mission Success
Collaborative Capabilities
Reduced Redundancy
Lower Costs of Maintenance



Unknown Threats
Rules of Engagement
Delegation of Power/Authority

Figure 1 – Desired Capabilities of ISHM and Unknown Threats of Autonomy [Kosinski, 2013]

1.7 Preview

This thesis is organized into five chapters. The introductory chapter discusses the background, problem statement and objectives of the research. The descriptions of the ensuing chapters are as follow:

- Chapter II examines the current state of system health monitoring/management and its related applications, and provides an understanding of the main elements of ISHM. This chapter also highlights airworthiness and system safety concepts, presents a preliminary FMECA hazard assessment of a typical UAS, and discusses the benefits of the ideal ISHM system.
- Chapter III describes the research methodology through the proposed analytic architecture.
- Chapter IV presents the results and associated analysis of the discrete-event simulation model.
- Chapter V draws conclusions regarding the research objectives, and proposes potential areas for future research.

II. Literature Review

2.1 Chapter Overview

The objectives of this chapter are to examine the current state of system health monitoring/management and its related applications, provide an understanding of the main elements of ISHM, highlight airworthiness and system safety concepts, present a preliminary FMECA hazard assessment of a typical UAS, and discuss the benefits of the ideal ISHM system.

2.2 System Health Management

This section presents various definitions of system health monitoring/management in its various related applications.

2.2.1 Application in Health Care

There exist varied definitions and applications of system health management; with its most direct application in health care. In a recent technology 'disruption' to health care, IBM's Watson – the same machine that beat Ken Jennings at *Jeopardy* - was being 'tutored' at Memorial Sloan-Kettering, perusing through medical case histories and *learning* to make diagnoses and treatment recommendations [Cohn, 2013]. This innovation seeks intelligence beyond simple electronic look-ups of medical encyclopedia. Although the future of a robot seeing a patient in place of a human doctor remains to be seen, intelligence in the form of Watson provides consistency of decisions amongst available medical solutions, based on accurate clinical examinations and evidence. Another medical innovation exists in the form of a device called the Stealth Vest, wearable sensor technology that can continuously communicate data without the patient even being aware of it [Glen, 2012]. This was developed by a group of researchers based at Emory University and Georgia Tech primarily for teenagers, who are less likely to comply with physician instructions about taking readings or medications.

The technological breakthroughs in health care, in the areas of sensor data fusion and artificial intelligence, presented similarities to an ideal ISHM architecture that integrates processed sensor information and intelligence through diagnostics and prognostics algorithms.

2.2.2 Health and Usage Monitoring System (HUMS) in Helicopters

Increased demand for improved operational safety and reduced rotorcraft maintenance costs had paved the way for HUMS [Wiig, 2006]. These systems emerged in the 1980s as a response to the high accident rates experienced by offshore shuttle helicopters traversing the petrol installations in the North Sea. The UK Civil Aviation Authority (CAA) defined HUMS in two main subsystems: a Vibration Monitoring System (VMS), and a Usage Monitoring System (UMS). The latter included functions such as temperature and torque monitoring, magnetic plugs and chip detectors. The VMS addresses the Health aspect of HUMS and should monitor:

- engine to main gearbox input drive shafts,

- main gearbox shafts, gears and bearings,
- accessory gears, shafts and bearings,
- tail rotor drive shafts and bearings,
- intermediate and tail gearbox gears, shafts and bearings,
- oil cooler drive, and
- main and tail rotor track and balance.

In terms of process management, the typical processes of a HUMS program are depicted in Figure 2 [JHSIT, 2013]. Basic HUMS operation requires that data be displayed on a ground station after download, identifying any primary indicators exceeding their pre-defined thresholds. Recent history of primary and secondary data should also be available to maintenance personnel for comparison against past alerts (or false alarms) to ensure continued airworthiness of the aircraft. The ability to trend data and facilitate comparison with other aircraft, fleet average thresholds or other health indicators is also recommended.

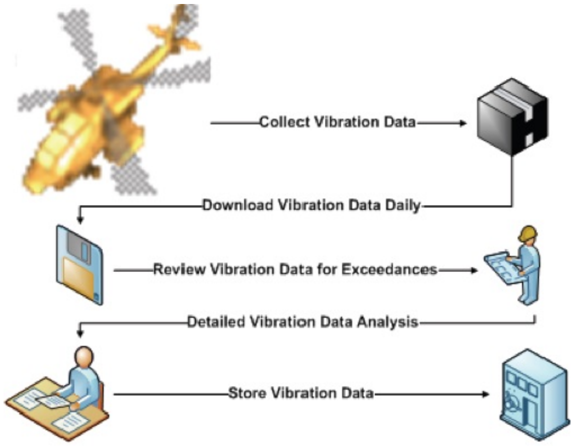


Figure 2 – HUMS Processes [JHSIT, 2013]

The following processes are defined for a HUMS program [JHSIT, 2013]:

- Data Acquisition and Transfer – The process of acquiring data from the various sensors and transferring it to a ground station. It is important to download HUMS data regularly to ensure currency of HUMS data.
- Data Analysis – This includes the review of HUMS data by a maintainer on the flight line for advisories or threshold exceedances, followed by a detailed analysis by a trained HUMS analyst or engineer. The latter is best accomplished by trending historical vibration data against the rest of the fleet – and this helps in the analysis for lesser known faults.
- Data Validation – Whenever a measurement is recorded, there is a chance for error. As such, whenever a HUMS generates an alert, an effort must be made to ensure that the alert is valid. A collaborative data exchange utilizing maintenance records, pilot and mechanic recorded discrepancies, vibration readings, oil analysis, visual inspection etc. will be essential in reducing such erroneous alerts or false alarms.
- Training – It is important that technicians or maintainers are adequately trained to deliver the first level of analysis on the flight line – critical for releasing an aircraft for subsequent flights. Thereafter, HUMS analysts or engineers will then need to be provided additional tools to deliver deeper analysis and trending information.

HUMS originated from an airworthiness concern, and its implementation drove extensive research in condition-based rotorcraft maintenance. Understanding the HUMS architecture and associated processes will provide alignment in this research in developing maintenance cost models.

2.2.3 Integrated Vehicle Health Management

Integrated vehicle health management (IVHM) is a collection of data relevant to the present and future performance of a vehicle system and its transformation into information can be used to support operational decisions. This design and operation concept embraces an integration of sensors, communication technologies, and artificial intelligence to provide vehicle-wide abilities to diagnose problems and recommend solutions [Benedettini *et al.*, 2009]. The author also presented various definitions of IVHM found in the literature, as presented in Table 1.

Table 1 – IHVM Definitions [Benedettini *et al.*, 2009]

Author	**Definition of IVHM**
NASA, 1992	'The capability to efficiently perform checkout, testing, and monitoring of space transportation vehicles, subsystems, and components before, during, and after operation.'…'must support fault-tolerant response including system/subsystem reconfiguration to prevent catastrophic failure; and IVHM must support the planning and scheduling of post-operational maintenance.'
Aaseng, 2001	'All the activities that are performed to understand the state of the vehicle and its components, to restore the vehicle to nominal system status when malfunctions occur, and to minimize safety risks and mission impacts that result from system failures'
Baroth *et al.*, 2001	An 'effort to coordinate, integrate, and apply advanced software, sensors, and design technologies to increase the level of intelligence, autonomy, and health state determination and response of future vehicles'
Roemer *et al.*, 2001	'Integrates component, subsystem, and system level health monitoring strategies, consisting of anomaly/diagnostic/prognostic technologies, with an integrated modelling architecture that addresses failure mode mitigation and lifecycle costs'
Price *et al.*, 2003	'An example of an intelligence sensing system. The purpose of such system is to detect and measure certain quantities, and to use the information and knowledge obtained from the measured data, and any prior knowledge, to make intelligent, forward-looking decisions, and initiate actions'
Wilmering, 2003	'The unified capability of an arbitrarily complex system of systems to accurately assess the current state of member system health, predict some future state of the health of member systems, and assess that state of health within the appropriate framework of available resources and operational demand'
Paris *et al.*, 2005	'The process of assessing, preserving, and restoring system functionality across flight and ground systems'
Jakovljevic and Artner, 2006	'Ensures the reliable capture of the "health status" of the overall aerospace system and helps to prevent its degradation or failure by providing reliable information about problems and faults'
Karsai *et al.*, 2006	'Its goal is to provide better ways for operating and maintaining aerospace vehicles using techniques, such as condition monitoring, anomaly detection, fault isolation, and managing the vehicle operations in the case of faults'

2.3 Architecture of ISHM

From the literature presented, Figure 3 depicts a suggested architecture for ISHM.

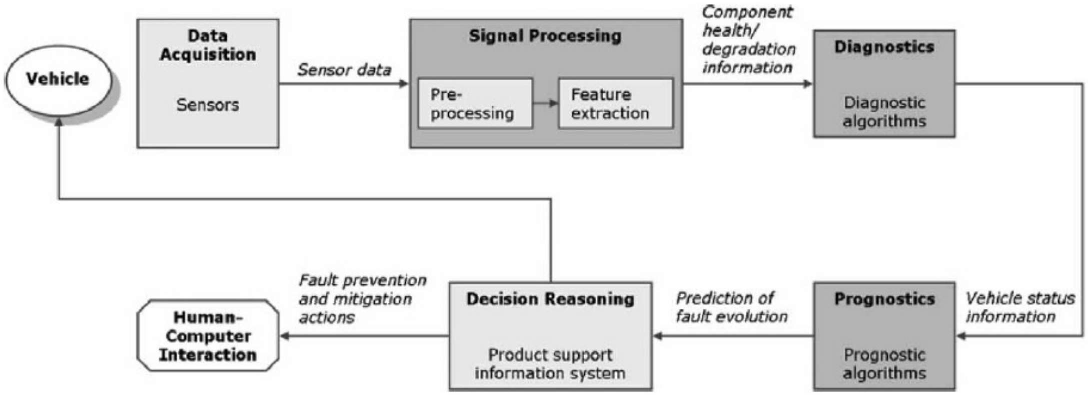


Figure 3 – Typical ISHM Architecture [Benedettini et al., 2009]

At the front end of the architecture is a *sensor suite* responsible for gathering state awareness variables that are indicative of potential failure modes. For an envisaged ISHM configuration, apart from conventional sensors that monitor and control sub-systems, system-level sensor suites are also being introduced in the form of smart embedded sensor systems with wireless communications transfer protocol in place for overall system health management. Upon filtering of sensor data to extract relevant fault features, the *diagnostics module* analyzes the fault features to detect, identify and isolate impending fault conditions. In addition, with health and usage data being fed to the *prognostic module*, the latter is able to combine historical data to generate an estimation of the time-to-failure of specific subsystems and components. Depending on the level of autonomy, such diagnostic and prognostic information can be processed on-board the vehicle through its auto-recovery systems or communicated to technical support managers on ground.

Although there exist various definitions of IHVM, they seem to align to this ideal ISHM configuration – that will provide a basis for the analytic architecture of this research.

2.4 Airworthiness and System Safety Framework

System safety is the application of engineering and management principles, criteria and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle. MIL-STD-882 is the primary reference for system safety program information for DoD weapon systems. A system safety program is crucial for the initial and continued airworthiness of all weapon systems; with the following objectives as listed in the Air Force System Safety Handbook [AFSC, 2000]:

a. Safety, consistent with mission requirements, is designed into the system in a timely, cost-effective manner;
b. Hazards are identified, evaluated, and eliminated, or the associated risk reduced to a level acceptable to the managing activity (MA) throughout the entire life cycle of a system;
c. Historical safety data, including lessons learned from other systems, are considered and used;
d. Minimum risk is sought in accepting and using new designs, materials, and production and test techniques;
e. Actions taken to eliminate hazards or reduce risk to a level acceptable to the MA are documented;
f. Retrofit actions are minimized;

g. Changes in design, configuration, or mission requirements are accomplished in a manner that maintains a risk level acceptable to the MA;

h. Consideration is given to safety, ease of disposal, and demilitarization of any hazardous materials associated with the system;

i. Significant safety data are documented as "lessons learned" and are submitted to data banks, design handbooks, or specifications;

j. Hazards identified after production are minimized consistent with program constraints.

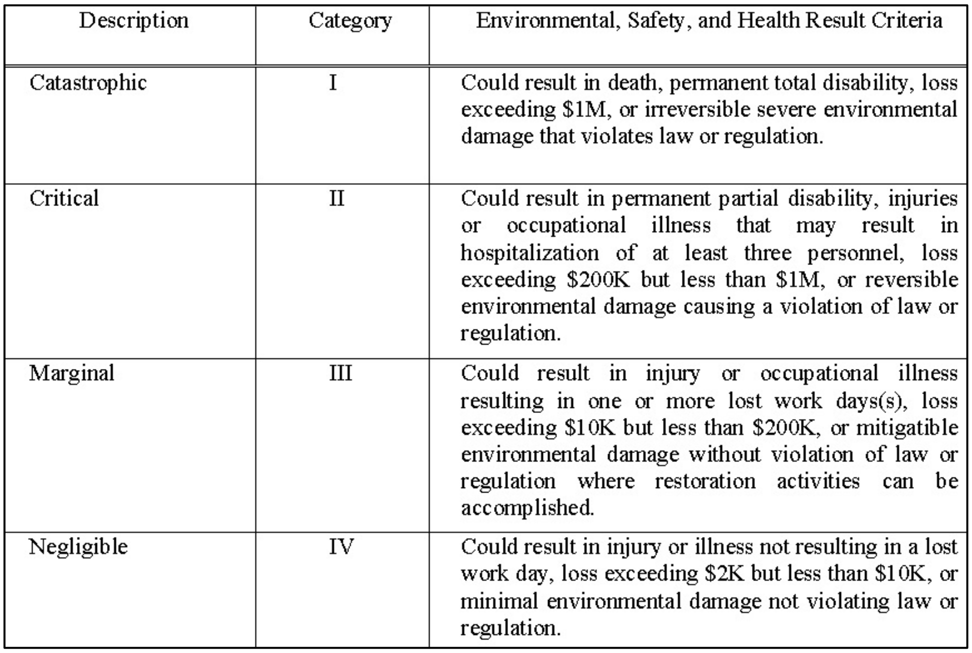
Understanding airworthiness requirements and the fundamental objectives of the System Safety Framework provides the impetus to this research.

2.4.1 Mishap Severity and Probabilities

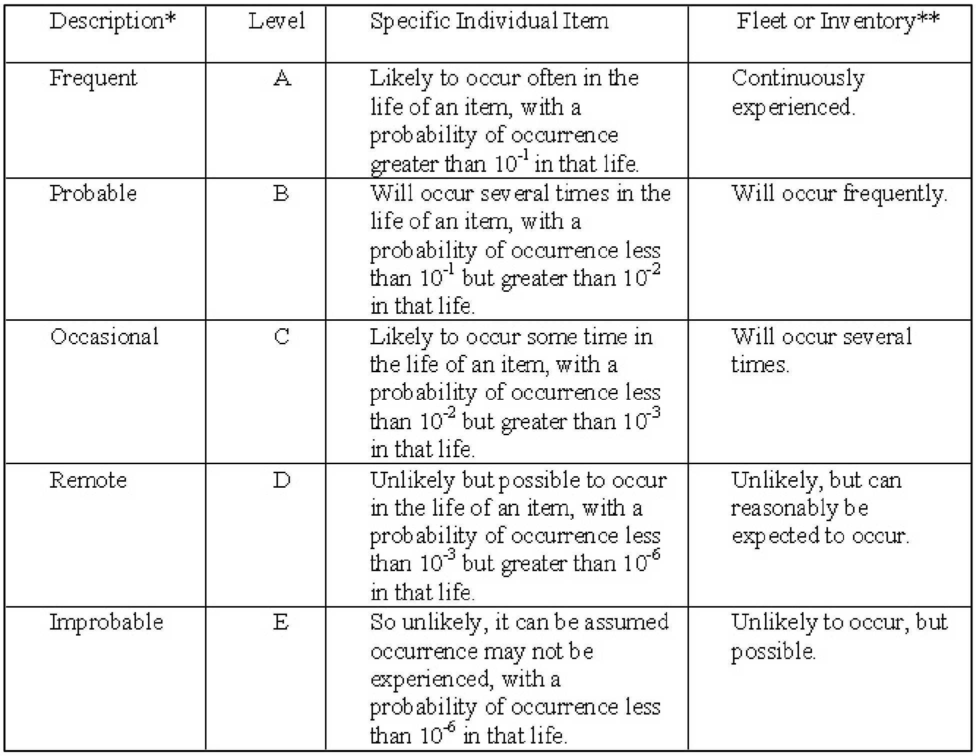
In accordance with the system safety framework and MIL-STD-882, hazard analyses based on failure modes are classified according to mishap severity categories and probabilities listed in Table 2. Appropriate risk mitigation measures are devised after the risk assessment has been made. The mishap assessment also serves as a guideline for the appropriate authorities to accept any residual risk after mitigation measures have been implemented.

For this research, different severity categories and probability levels of failure modes will initiate different courses of actions in the discrete-event simulation.

Table 2 – Suggested Mishap Severity Categories and Probability Levels [DoD, 2000]



Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work days(s), loss exceeding $10K but less than $200K, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.



Description*	Level	Specific Individual Item	Fleet or Inventory**
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.	Continuously experienced.
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.	Will occur frequently.
Occasional	C	Likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.	Will occur several times.
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.	Unlikely to occur, but possible.

2.4.2 Hazard Reduction Precedence

In line with the system safety program objectives, the order of precedence for satisfying system safety requirements and resolving identified hazards is depicted in Figure 4 [AFSC, 2000].

Step 1. Design for Minimum Risk – Design to eliminate hazards. If an identified hazard cannot be eliminated, reduce the associated risk to an acceptable level, as defined by the MA, through design selection.

Step 2. Incorporate Safety Devices – If identified hazards cannot be eliminated or their associated risk adequately reduced through design selection, that risk shall be reduced to a level acceptable to the MA through the use of fixed, automatic, or other protective safety design features or devices.

Step 3. Provide Warning Devices – When neither design nor safety devices can effectively eliminate identified hazards or adequately reduce associated risk, device shall be used to detect the condition and to produce an adequate warning signal to alert personnel of the hazard.

Step 4. Develop Procedures and Training – Where it is impractical to eliminate hazards through design selection or adequately reduce the associated risk with safety and warning devices, procedures and training shall be used. Procedures may include the use of personal protective equipment.

With an ISHM-enabled UAS, it is anticipated that there may be a paradigm shift in UAS design in terms of hazard reduction precedence. Through better sensor data fusion, less effort may be focused on developing redundant designs (Step 1) or safety devices (Step 2). Instead, better diagnostics or prognostics algorithms may be developed to ensure that the UAS will always be able to detect (or even predict) a fault condition and execute safe recovery actions.

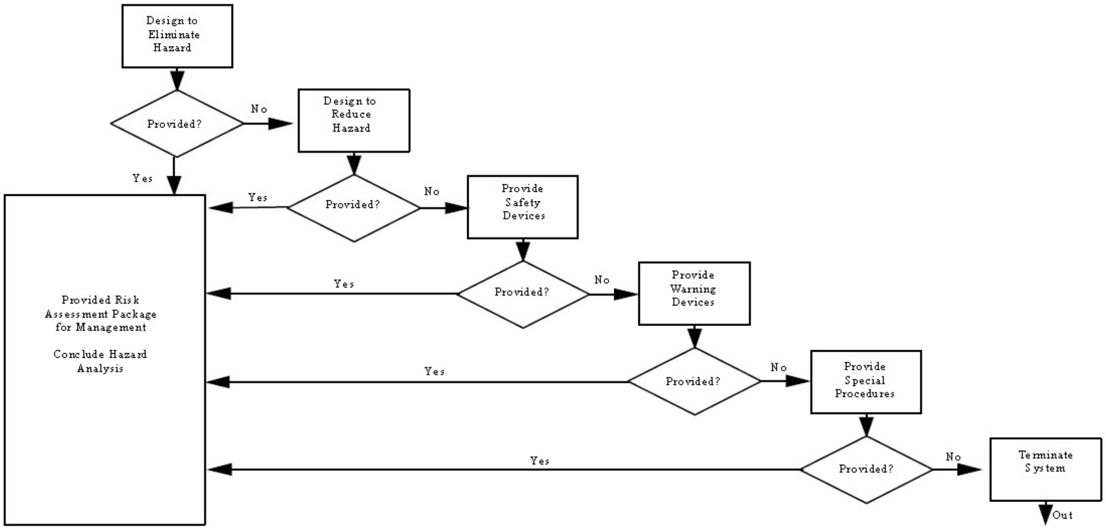


Figure 4 – Hazard Reduction Precedence [AFSC, 2000]

2.4.3 Unmanned Aerial Systems Safety by Mass Classification – Ground Impact Hazard Analysis

The severity definitions (refer to Table 2) related to occupants of the aircraft do not apply to an unmanned system. In UAS operation, the most severe possible outcomes are those that result in injury to the general public, either in other aircraft or on the ground. *Ground impact* can endanger the general public, and *midair collision* with a manned aircraft can threaten the safety of the passengers aboard that aircraft. Both effects are critical system design drivers that have implications for UAS operations and reliability requirement. In this section, a ground impact hazard analysis conducted by MIT is presented [Weibel and Hansman, 2005]. The ground impact model considers varying risk of ground impact across the entire CONUS area based on population density. An UAS accident 'exposes' the general public to potential harm, but does not necessarily directly result in a fatality. In simplified terms, the model considered an average area of exposure for which the accident has effects (which can be considered as the lethal debris area), estimated by the term A_{exp} – which is determined by the UAS class based on its frontal area. In addition, the UAS accident must also penetrate sheltering, such as houses and vehicles, before coming into contact with persons. The proportion of time that the debris will penetrate shelter given exposure is modeled by the penetration factor, P_{pen}. It is assumed that if debris penetrates sheltering, then a fatality has occurred. The ground impact model was applied to six UAS from the Heavy, HALE (High Altitude Long Endurance), MALE (Medium Altitude Long Endurance), Tactical, Mini and Micro classifications. Table 3 summarizes the parameters of the model.

Table 3 – UAS Classes for Ground Impact Analysis [Weibel and Hansman, 2005]

Representative Vehicles		Weight	A_{exp}	Estimated P_{Pen}
Heavy		602,500 lb	7700 ft^2	100%
HALE		25,600 lb	900 ft^2	90%
MALE		2,250 lb	360 ft^2	60%
Tactical		351 lb	30 ft^2	25%
Mini		9.6 lb	14 ft^2	10%
Micro		0.14 lb (2.16 oz)	0.26 ft^2	5%

The objective of the analysis was to calculate the target level of reliability for each UAV class in order to meet an assumed target level of safety of 10^{-7} fatalities per hour of UAS operation. The study concluded that there is an increase in required reliability of the UAS as vehicle mass increases. This implied that the inherent risk of operating a heavier UAS is higher when addressing ground impact hazards. Specifically for HALE UAVs, they would need to meet reliability levels of current manned military or general aviation aircraft, on the order of 100,000 hr between accidents, to overfly 20% of the country at the target level of safety.

This study established a direct relationship between the weight of a UAS and its inherent operating risk. In addition, it suggested a proxy for this research in terms of target reliability to define the airworthiness standard of an UAS.

2.5 Failure Mode, Effects and Criticality Analysis

FMECA is a procedure for identifying potential failure modes in a system and classifying them according to their severity. A FMECA is usually carried out progressively in two parts. The first part identifies failure modes and their effects (also known as failure modes and effects analysis). The second part ranks the failure modes according to the combination of their severity and the probability of occurrence (criticality analysis) [DoD, 2005]. A general approach for conducting a FMECA is shown in Figure 5. The steps listed are self-explanatory. However, a distinction needs to be made between determining the *severity* of a failure mode, and the failure mode *criticality*. The latter is a function of severity, the frequency of occurrence of a failure mode, and the probability that it will be detected in time to preclude its impact at the system level. This criticality analysis resulted in the determination of the *risk priority number (RPN)* as a metric for evaluation. RPN can be expressed as

RPN = (severity rating) x (frequency rating) x (probability of detection rating)

The RPN reflects failure-mode criticality; and on inspection, one can see that a failure mode with a high frequency of occurrence, with significant impact on system performance, and that is difficult to detect is likely to have a high RPN [Blanchard, 2004].

FMECA evaluations form the basis of the architecture – and the analysis results will determine the performance requirements of individual subsystems and components in achieving defined airworthiness standards.

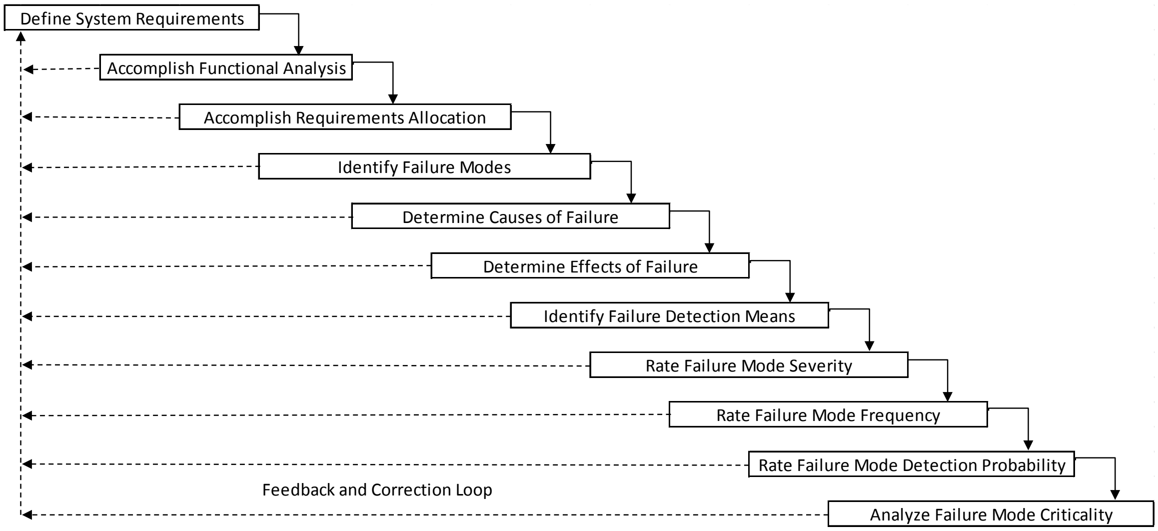


Figure 5 – General Approach to Conducting a FMECA [Blanchard, 2004]

2.5.1 Preliminary Hazard Assessment of Generic UAS

NASA published a report in 2007 that identified the typical failure conditions of a UAS based on functional decomposition of a generic UAS [Hayhurst *et al.*, 2007]. The full functional decomposition is relatively large, with 69 functions at the lowest level under the major functions of aviate, navigate, communicate and mitigate. Figure 6 shows the top-level view of these functions.

- *Aviate* includes not only actions involved in flying the aircraft, but also actions for moving the aircraft on the ground, providing command and control, and managing sub-systems.
- *Navigate* includes actions involved in the management and execution of a flight plan.
- *Communicate* provides functionality for the communication between the UAS, ATC and other aircraft. All actions associated with the command and control link to the vehicle are contained within the Aviate category.

- *Mitigate* includes actions such as avoiding traffic, avoiding ground objects, avoiding weather or other types of environmental effects, and handling contingencies.

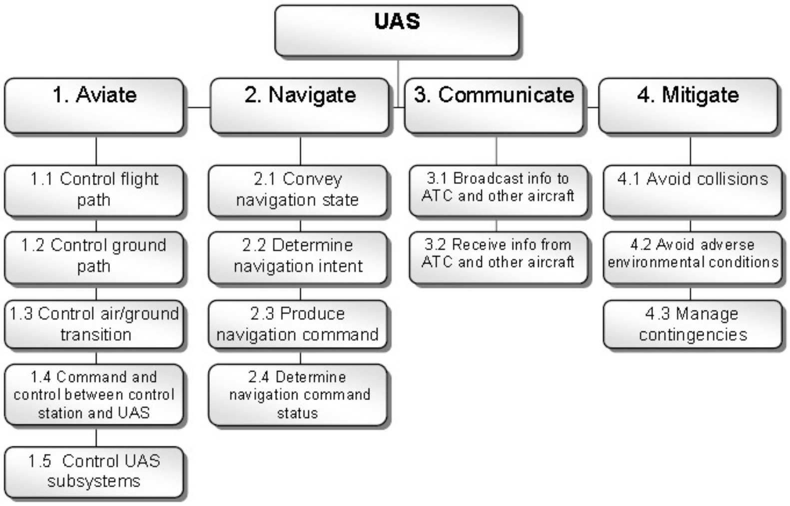


Figure 6 – Top-Level View of UAS Functional Decomposition [Hayhurst *et al.*, 2007]

The primary safety goal of the failure hazard assessment is to avoid any UAS-initiated decrease in the safety of the National Air Space (NAS). As a result, failure condition criticality is determined by its effect on people on ground or in other aircraft. The latter case includes stress or injury to occupants of other aircraft as a result of an evasive maneuver. Damage to material assets is out-of-scope, unless it affects human safety. The assessment was applied to 69 different functions (that equated to the 69 leaf nodes of the functional decomposition). Figure 7 shows the total number of failure conditions by the four major categories in the functional decomposition. The majority of potential failure conditions fall under the Aviate or Mitigate functions. Figure 8 presents the same data, with detail regarding the number of failure conditions per severity level.

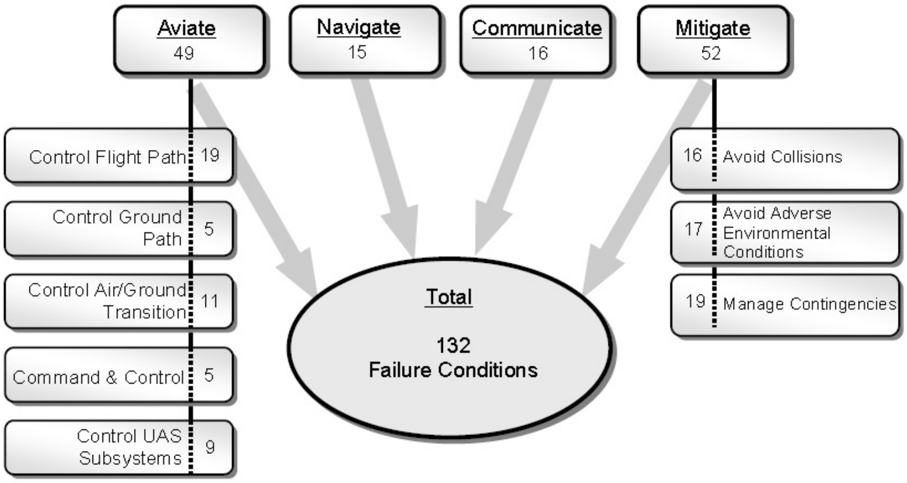


Figure 7 – Failure Condition Totals by Functional Category [Hayhurst *et al.,* 2007]

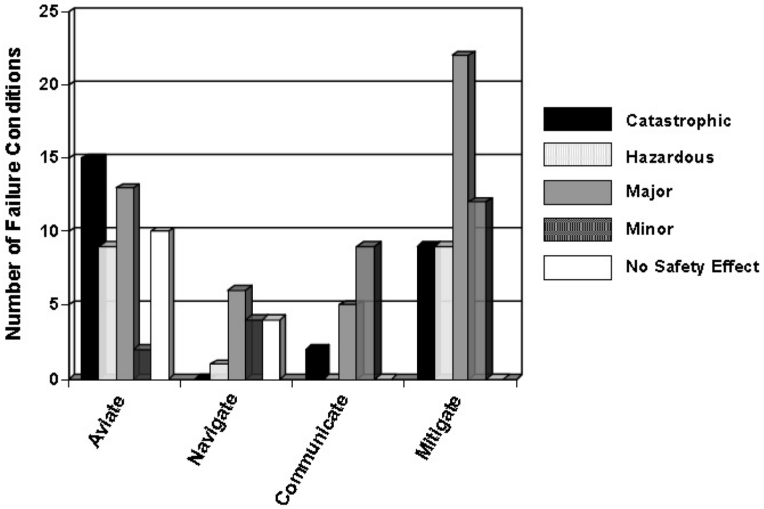


Figure 8 – Failure Condition Severities by Functional Category [Hayhurst *et al.,* 2007]

The majority of failure conditions with catastrophic and hazardous consequences are found in the Aviate and Mitigate functions. In the assessment by NASA, twenty-six potentially catastrophic failure conditions were identified, considering only single failures in the en-route phase of flight. An interesting observation to make at this point is how the number of catastrophic failure conditions for a generic UAS compares with those numbers assumed for commercial transport aircraft and for general aviation aircraft. According to AC 23.1309-1C[1], there are ten catastrophic failure conditions assumed for a general aviation aircraft (covering single and multiple failures over all phases of flight); and there are 100 catastrophic failure conditions assumed for a commercial transport aircraft according to AC 25.1309-1A[2]. While recognizing that these are broad generalizations, preliminary indications are that the number of potential catastrophic failure conditions for a generic UAS will be greater than the number for general aviation aircraft; and the relation of the estimate to commercial transport aircraft will have to depend on further assessment of failure conditions in all phases of flight.

Understanding the functional decomposition of a generic UAS and the potential failure conditions aids in this research by providing the top-level functional failure modes for analysis.

2.6 Benefits of the Ideal ISHM System

The preceding section discussed the development and applications of system health management in recent years. At present, health management is already part of the standard performance and maintenance paradigms in the propulsion and rotorcraft arenas. Although its influence is steadily growing, health management (or pure monitoring?) is

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[1] FAA Advisory Circular (AC) 23.1309-1C – Equipment, Systems, and Installations in Part 23 Airplanes. Date Issued: 12 Mar 1999. *Currently superseded by AC 23.1309-1E issued on 17 Nov 2011.*

[2] FAA Advisory Circular (AC) 25.1309-1A – System Design and Analysis. Date Issued: 21 Jun 1988.

still viewed primarily as a means for detecting damage and/or failures in support of maintenance activities; with health management systems being an ‘after-thought’ of system designs. This led to the development of health management systems focused on individual components of subsystems with data generated being typically viewed only within the context of that subsystem. Yet, it is a common belief that integrated system health management offers far more benefits than is being envisioned currently [MacConnell, 2006].

2.6.1 Benefit Classes

In a collaborative research effort with the Air Force, industry and academia, MacConnell categorized the benefits of ISHM in the following four classes [MacConnell, 2006]. *These classes presented potential areas within the ISHM architecture where Measures of Performance (MOP) or Measures of Effectiveness (MOE) can be defined.*

Mission Availability — These benefits encompass all aspects of ISHM that involve getting a system ready for mission launch from in-flight fault diagnostics triggering a maintenance action to ground check-out. Go/No-go decision making based on knowledge of remaining time to failure. This category includes conventional Condition Based Maintenance (CBM) and is geared towards making sure the vehicle is ready to perform its mission when assigned. These scenarios are heavily dependent on *diagnostics, remaining life assessments* and automation and communication.

Mission Success — This category encompasses all scenarios that result in a platform being able to accomplish its mission after "launch" regardless of in-flight faults, failures or damage sustained during the mission. This deals primarily with real-time vehicle state sensing and *autonomous decision-making during a mission in particular dealing with in-flight faults/events*.

Mission Capability — This category focuses on the potential of new capabilities to improve performance. This category in particular includes new approaches to integrating differing subsystems to generate new abilities. It also addresses the development and *exploitation of theater-wide ISHM based planning and execution*.

Design Paradigm — This category addresses the indirect benefits or those benefits which are enabled by ISHM; and these benefits are not necessarily reflected in the war-fighters experience of the platform but rather in the *process of the design and manufacture* of the system. This benefit class includes concepts such as dramatically reduced factors of safety for design and revolutionary certification processes.

2.6.2 The ISHM Business Case – Condition Based Maintenance

Though the benefits of ISHM are well recognized, the most quantifiable benefits in the current paradigm were almost exclusively reported in terms of maintenance related savings. Maintenance policies generally define two types of maintenance:

- Time Based Maintenance (TBM), also known as scheduled/preventive maintenance where components are replaced at specified intervals to preclude failures during operation. Due to design especially in cases where redundancy is absent, stringent and conservative replacement intervals are implemented way before a component's actual failure.

- Condition Based Maintenance (CBM), also known as unscheduled/corrective maintenance where components are replaced upon detection of an unsatisfactory condition – such as those detected (or even *predicted*) by an ISHM system.

Every component has a safe life or operating life, beyond which continued operation of the component could result in catastrophic failures. In a TBM maintenance policy, there is potential for wastage should a component be replaced way ahead of its life expiration. With the potential of increased health management and surveillance presented by ISHM, the useful life of a component can be extended until diagnostic or prognostic algorithms decide that an impending failure is imminent. The algorithms will have to consider the uncertainty and confidence levels regarding a component's useful life in order not to encroach upon the unsafe operating window. The concept of savings through a CBM philosophy can be illustrated by Figure 9.

A CBM life cycle cost model can be incorporated within the analytic architecture for a cost-benefit analysis of an ISHM-enabled UAS.

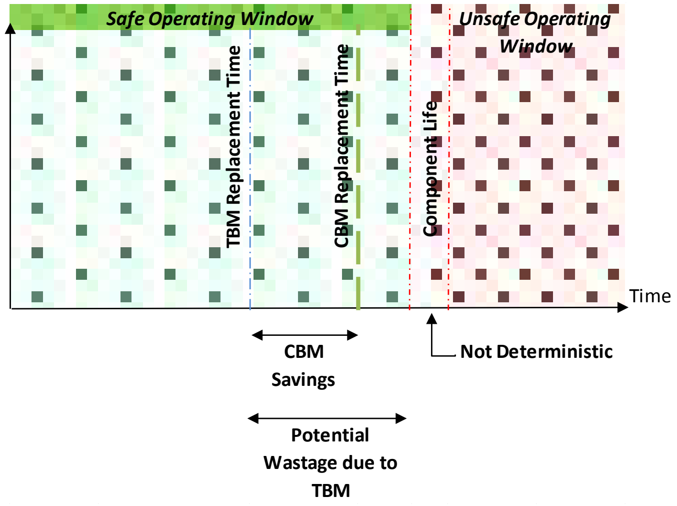

Figure 9 – Illustration of Savings from Condition Based Maintenance

The literature also presented potential benefits in the following areas that strengthen the business case of ISHM, as summarized in Table 4 [MacConnell, 2006].

Table 4 – The ISHM Business Case [MacConnell, 2006]

The ISHM Business Case of Today
Maintenance Time Savings
Direct cost/time savings due to proper diagnosis, reduction in scheduled maintenance and reduction in inspection time.
False Alarm Avoidance
Direct cost/time savings due to elimination of unnecessary maintenance; arising from Cannot Duplicate (CND) and Retest OK (RTOK) cases.
Availability Improvement
Direct benefit due to downtime elimination.
Spares and Supply Savings
Direct cost/time savings due to knowing what is needed and when it is needed.
Recurring Cost Savings
Strict cost savings due to health management.
The ISHM Business Case of Tomorrow
A fully ISHM enabled system will cost only 70% of a comparable conventional system for equivalent capability
50% reduction in support costs due to false alarm, CND and RTOK elimination, minimized diagnostic time and reduction of unnecessary maintenance.
10% reduction in Acquisition costs due to reduced conservatism in design due to relaxed safety margins with increased real-time status knowledge, and reduced redundancy resulting in reduced weight.
4% reduction in required fleet size based on ability to do more with less due to increased availability, reduced abort and cancellation rates, and increased endurance and range.
A fully ISHM enabled design will be able to produce at least 15% more completed missions over any given time period than a conventional system.
A fully ISHM enabled design will be able to reduce the system attrition rate by over 10% compared to a conventional system.
Fully integrated health management can lead to dramatic reductions in weight, cost, design and development flow time, certification and qualification time and cost. Not to mention changing the fundamental paradigm driving the way systems are designed.

2.6.3 The ISHM Technology Development Roadmap

The research conducted by MacConnell also proposed follow-on ISHM capability planning in the form of an ISHM Capabilities Roadmap. Refer to Figure 10. This serves as a foundation for which ISHM related research efforts can be focused and provided an impetus for this thesis effort. The architecture developed through this research aimed to validate the business case of ISHM through improved mission availability (with CBM) and improved mission success (with improved safety of UAS). In the longer term, the FMECA architecture proposed could also be utilized in UAS design paradigms.

This will be consistent with the objective of this research in deriving performance requirements for components of an ISHM-enabled UAS for airworthiness certification.

Figure 10 – ISHM Capabilities Roadmap [MacConnell, 2006]

2.7 Successful Practice of Simulation Experiments

Simulation is a powerful tool for evaluation and analysis of new system architecture and designs, modifications to existing designs and proposed changes to operational rules. Conducting a valid simulation experiment is both an art and a science. As a systems engineer, it is important to recognize that the success of simulations involved much more than the technical aspects that one has been trained in. This section presents the common pitfalls in performing simulation studies and identifies approaches for avoiding them [Sadowski and Grabau, 2004].

2.7.1 What is Success?

First and foremost, a successful simulation project is one that delivers useful *information* at the appropriate *time* to support a meaningful *decision*.

The Right Information – presenting information from the perspective of the decision makers, in the proper context of what they will be doing with this information to deliver value to the proposition.

The Right Timing – intuitively, a high-fidelity answer that is too late to influence a decision is not nearly as good as a rough estimate that is in time to help. In addition, preliminary insights always serve their purpose in a project for decision makers to steer their focus.

The Right Decision – this aspect may not be within your span of control, but on-time information needs to be delivered to the *right person* in the *right context* for the right decision to be made.

2.7.2 Pitfalls

Table 5 summarizes the potential pitfalls faced in simulation projects as presented by Sadowski and Garbau.

Table 5 – Common Pitfalls of Simulation Projects [Sadowski and Garbau, 2004]

Tackling the Wrong Problem
Step back and double check that simulation is the best tool for the problem
Ill-defined scope that might be too ambitious
Working on the Right Problem at the Wrong Time
Designers are still considering widely differing ideas
Fundamental systemic problems not resolved
Late request – panic call for information
Missing the Warning Signs of 'Data Woes'
More often, too little data is available for simulation – or getting the required data might be time consuming. Important to establish data needs early
Too much data – identifying valid and accurate data from multiple sources
Letting the Window of Opportunity Close
Getting lost in detail – adding too much details into the simulation just because you could
Leaving analysis till the end – unable to draw valuable conclusions from simulation results
Having too much fun with animation – distracted with the software tool itself
Testing only at the end of a project – validation and verification should be a continuous process throughout the project

2.7.3 Approach to Avoid Pitfalls

The final part of this section lists a few simple habits (applicable in all projects) that help to circumvent the above-mentioned pitfalls [Sadowski and Grabau, 2004]. These may seem intuitive to all readers but internalizing these habits amidst external demands, pressures and distractions may be challenging.

- Establish a clear focus;
- Plan carefully and thoroughly;
- Build a realistic timeline;
- Constantly review and reassess.

This research will employ a discrete-event simulation to implement the analytic architecture. Being aware of the potential pitfalls of a simulation project and the various approaches to mitigate them serve as constant beacons in ensuring a positive outcome for this research.

2.8 Literature Review Summary

This section presented the existing state of ISHM implementation through its various definitions and applications. Following which, a typical ISHM architecture was presented with the following elements: a sensor suite that detects/identifies critical system conditions, a management component that included sensor data processing, diagnostic and prognostic algorithms to identify current or incipient faults, and a reasoner to select the appropriate mitigation steps to execute. Key airworthiness and system safety concepts aligned to the Air Force's safety objectives were also presented; with specific focus on

UAS safety in terms of a ground impact analysis. The FMECA methodology was also introduced and a preliminary hazard assessment conducted by NASA on a generic UAS was also presented. The review proceeded to recognize the benefits of an ideal ISHM system and highlighted the business case and ISHM capabilities roadmap to substantiate follow-on ISHM research efforts. Finally, the last section of the literature review discussed the potential pitfalls and mitigating approach of a simulation experiment, which would be the methodology employed to validate the proposed architecture of this thesis.

III. Architecture Definition

3.1 Overview

This chapter describes the analytic architecture that provides the basis of the discrete event simulation model. The architecture is developed in accordance with the Department of Defense Architecture Framework (DoDAF). The chapter provides a preview through the concept of operations for the analytic architecture. Thereafter, specific architectural products that are of relevance to the simulation model are created. Finally, the architecture is translated to logical flows pertaining to the implementation of the simulation model.

3.2 Concept of Operations

3.2.1 Issue

A. Problem Statement

As presented in the literature review, health management at present is still viewed primarily as a means for detecting fault and/or failures in support of maintenance activities; with health management systems being an 'after-thought' of system designs. This led to the development of health management systems focused on individual components of subsystems with data generated being typically viewed only within the context of that subsystem. An ISHM architecture for analysis of UAS failure modes will provide a means for initial airworthiness certification of ISHM-enabled UAS designs – by determining performance requirements of subsystems or components.

B. Purpose of the CONOPS

The purpose of this CONOPS is to articulate how the architecture will enhance airworthiness (and other secondary benefits) through the analysis of failure modes of a generic UAV. Specifically, these are the research questions that the architecture aims to answer:

(1) What are the performance characteristics of ISHM to ensure continued airworthiness of the UAS?

(2) How will ISHM provide a business case to improve the level of UAS self-autonomy?

(3) What are the potential impacts of ISHM to maintenance practices and life cycle costs?

3.2.2 Overview

A. Synopsis

The proposed architecture shall optimize existing UAS designs through the incorporation of a typical ISHM configuration (i.e. sensors suite, diagnostic/prognostic algorithms and a decision reasoner). With available FMECA data in terms of possible failure conditions as input, the architecture will then evaluate the effectiveness of ISHM in terms of its resultant reliability over the lifetime of the UAS. The architecture will also consider the degradation of the ISHM suite in terms of missed detection and false alarm rates and their effects on maintenance policies. The implementation of the analytic architecture for ISHM-enabled UAS shall provide basis for:

(i) initial airworthiness certification during UAS induction,

(ii) continued airworthiness certification when field reliability data are available, and

(iii) change in maintenance policies and potential benefits in terms of increased availability and cost savings.

B. Description of Military Challenge

Besides quantitative benefits in terms of system availability, mission success and related cost savings, ISHM presents mid- and long-term benefits in the design paradigm through expansion of operational envelopes, reduced safety factors and revolutionary certification techniques. In seeking to improve the *trust in autonomy* of UAS, this analytic architecture shall examine the target reliability of an ISHM-enabled UAS over its lifetime.

C. Desired Effects

The architecture shall provide a baseline analytical model for a generic UAS. Various failure conditions, their failure probability distributions and assigned criticalities provide inputs for the analysis. ISHM effectiveness can be modeled through the strength of its diagnostics and prognostics algorithms, i.e. probability of an accurate ISHM deduction. On the other hand, ISHM degradation is compared against established thresholds of false alarms and missed detections. Output and sensitivity analysis on measures of performance, such as UAS life expectancy and cost of maintenance over its lifetime, can then be performed to determine ideal performance requirements and maintenance policies for specific UAS designs.

3.2.3 Context

A. Time Horizon

The architecture and preliminary analysis should be completed by end July 2013 with the research out-brief scheduled in end Aug 2013. The ISHM technology relevant to the implementation of this analytic model should be available in the next 5 to 15 years.

B. Assumptions

(i) Without actual FMECA data, it will not be possible to model and/or evaluate all the failure modes for a typical UAS. As such, only selected critical sub-system failures affecting airworthiness of the UAS shall be evaluated using the model.

(ii) Without actual sensor performance data, theoretical/nominal thresholds will need to be assumed to model sensor degradation in terms of False Alarm Rate (FAR) and missed detections.

C. Risks

Absence of real-world UAS design data may raise uncertainties on the accuracy of the output metrics. However, this research seeks to establish a sound analytical architecture that would serve its intended benefits through appropriate sensitivity analyses.

3.2.4 Employment Concept

A. Critical Capabilities

The critical capabilities needed to meet the desired end state of this architecture include:

(i) Flexibility – able to be further customized for specific UAS configurations with associated FMECA.

(ii) Analysis Support – regardless of evaluation/simulation tool, the architecture will be able to support the associated software analysis and evaluation to yield useful results.

B. Enabling Capabilities

In order to better implement the architecture, a formal Failure Mode, Effect, and Criticality Analysis (FMECA) must be performed on the UAS. This is an iterative process throughout the System Life Cycle that identifies failure modes, assesses their probabilities of occurrence, criticalities and their effects on the system. The results of the FMECA should identify critical sub-systems or components that ISHM needs to monitor and/or control; and guide the diagnostic and prognostic algorithms required for effective health management.

C. End State

A system-wide analytic architecture for an ISHM-enabled generic UAS – capable of delivering design decisions based on failure modes of UAS, which in turn ensures continued airworthiness of UAS operations.

3.3 Architecture Views

3.3.1 Operational Activity Decomposition Tree (OV-5a)

Figure 11: Describes the operational activities organized in a hierarchical structure.

There are two top-level operational activities for the architecture; namely "Perform Generic UAS Activities" and "Perform ISHM". The former is applicable to all UAS and decomposes into lower-level activities such as "Perform Top-Level UAS In-Flight

Functions" – *Aviate, Navigate, Communicate and Mitigate* [Hayhurst *et al.*, 2007], "Perform Failure Detection" and "Perform Failure Assessment". In addition, a generic UAS upon confirmation of failure, will "Perform Subsystem Maintenance" upon landing. The analytic architecture will also need to "Record UAS Operational Lifetime" to determine scheduled maintenance requirements and more importantly, the accumulated life expectancy of the UAS.

The top-level operational activity – "Perform ISHM" is only applicable for ISHM-enabled UAS. It decomposes into two lower-level activities – "Perform Diagnostics and Prognostics Assessment" determines the accuracy and effectiveness of ISHM algorithms, while "Perform ISHM Maintenance" repairs/replaces ISHM components when false alarm and missed detection thresholds are exceeded.

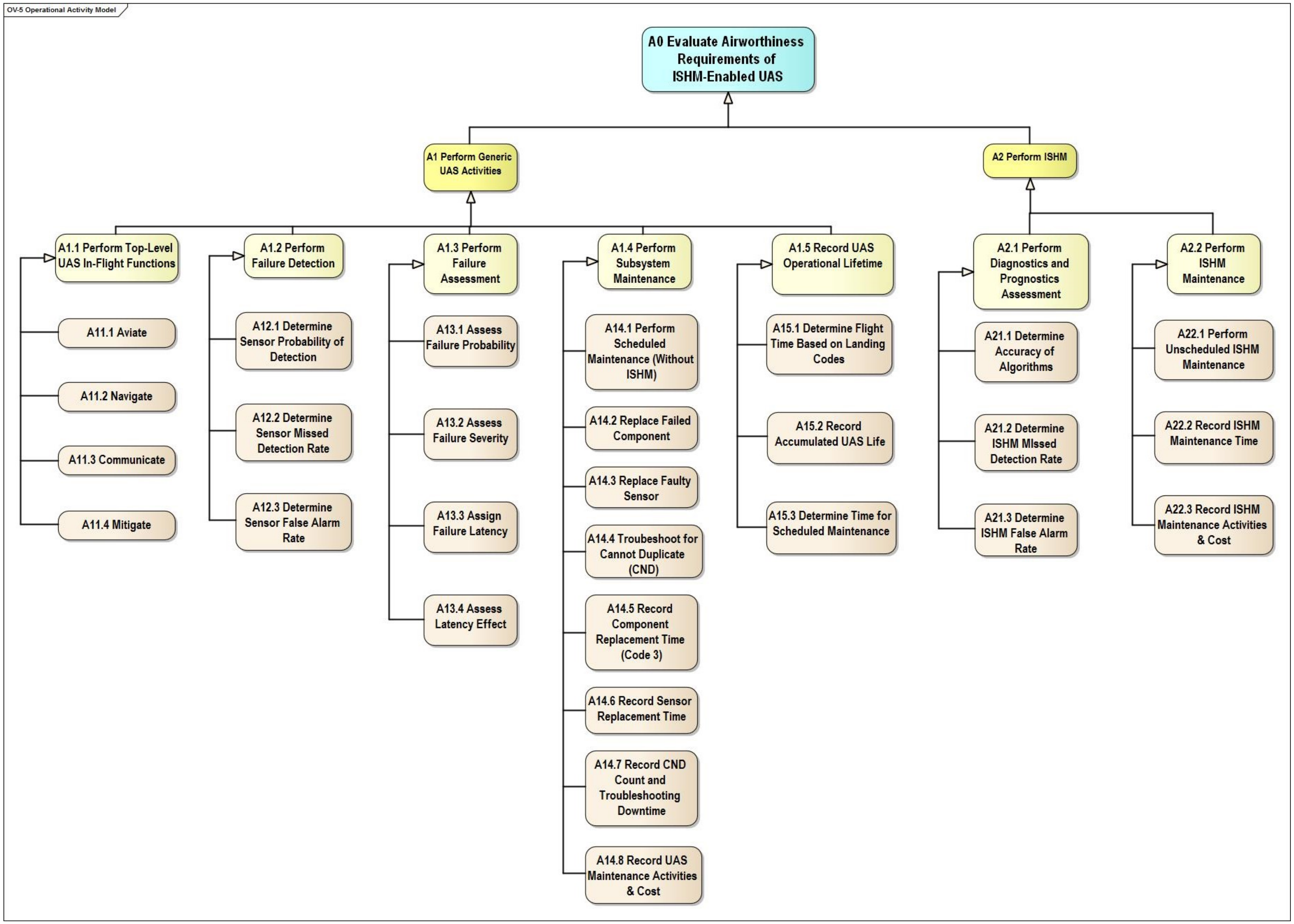

Figure 11 – OV-5a: Operational Activity Decomposition Tree

3.3.2 Operational Rules Model (OV-6a)

Table 6: Describes the business rules that constrain operations for an ISHM-enabled UAS.

Based on the results of the various conditions listed in the “Condition Stub”, each of the 19 operational rules determines a set of specific actions in the “Action Stub” to be executed by the simulation.

Table 6 – OV-6a: Operational Rules Model (ISHM-Enabled UAS)

Rules and Decision Analysis Table (ISHM-Enabled UAS)																			
Condition Stub	**Condition Matrix**																		
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19
Determine if Failure Condition is Present During Flight																			
Failure Occurred?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N
Determine if UAS is Aware of Present Failure Condition																			
Is Failure Detected by Isolated Subsystem Sensor?	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	N	N	N
Is Failure Ascertained by ISHM?	Y	N	N	N	N	Y	Y	N	N	N	Y	Y	Y	Y	N	N	Y	Y	N
Assess Failure Severity and Latency Effect																			
Is Failure Catastrophic?	-	Y	-	N	N	-	-	Y	-	N									
Is Failure Latent (occurred in previous flights but not detected/ascertained)?	-	-	Y	N	N	-	-	-	Y	N									
Determine Maintenance Requirements of Existing Sensors																			
Is Sensor Miss Rate Exceeded?	N	-	-	N	N	Y	N	-	-	N	-	-	-	-	-	-	-	-	-
Is Sensor False Alarm Rate Exceeded?	N	-	-	-	-	-	-	-	-	-	Y	Y	N	N	Y	N	N	N	N
Determine Maintenance Requirements of ISHM																			
Is ISHM Miss Rate Exceeded?	N	-	-	Y	N	N	N	-	-	N	-	-	-	-	-	-	-	-	-
Is ISHM False Alarm Rate Exceeded?	N	-	-	-	-	-	-	-	-	-	Y	N	Y	N	N	N	Y	N	N
Action Stub	**Action Matrix**																		
Perform Failure Assessment																			
A13.2 Assess Failure Severity	X	X	X	X	X	X	X	X	X	X									
A13.3 Assign Failure Latency										X									
A13.4 Assess Latency Effect	X	X	X	X	X	X	X	X	X	X									
Decide UAS Recovery State																			
UAS Recovering Code 1 [A11.1 Aviate - No Discrepancy Reported]										X									X
UAS Recovering Code 2 [A11.1 Aviate - Minor Discrepancy Reported But Does Not Affect Current Mission]				X	X										X	X			
UAS Recovering Code 3 [A11.4 Mitigate - Discrepancy Reported that Require Rectification Before Next Mission]	X					X	X				X	X	X	X			X	X	
UAS Mishap [A15.2 Record UAS Accumulated Life - Terminated]		X	X					X	X										
Degradation of Isolated Subsystem Sensors																			
A12.2 Determine Sensor Missed Detection Rate [After increasing count]						X	X	X	X										
A12.3 Determine Sensor False Alarm Rate [after increasing count]											X	X	X	X	X	X			
Degradation of ISHM Suite																			
A21.2 Determine ISHM Missed Detection Rate [after increasing count]		X	X	X	X			X	X										
A21.3 Determine ISHM False Alarm Rate [after increasing count]											X	X	X	X			X	X	
Perform Required Maintenance																			
A14.4 Troubeshoot for Cannot Duplicate (CND)											X	X	X	X	X	X	X	X	
A14.7 Record CND Count and Troubleshooting Downtime											X	X	X	X			X	X	
A14.2 Replace Failed Component	X			X	X	X	X												
A14.3 Replace Faulty Sensor						X					X	X			X				
A22.1 Perform Unscheduled ISHM Maintenance				X							X		X				X		
Record UAS Operational and Maintenance Life																			
A15.1 Determine Flight Time Based on Landing Codes [Normal Flight Time for Codes 1 and 2]				X	X					X					X	X			X
A15.1 Determine Flight Time Based on Landing Codes [Reduced Flight Time for Code 3 and Mishap]	X	X	X			X	X	X	X		X	X	X	X			X	X	

Notes:

1) '-' in Condition Matrix indicates condition *does not matter* for recommended set of actions.

2) 'X' in Action Matrix indicates *specified actions to be carried out or transition into pre-defined states based on conditions.*

Table 7: Describes the business rules that constrain operations for a non-ISHM UAS. Based on the results of the various conditions listed in the “Condition Stub”, each of the 12 operational rules determines a set of specific actions in the “Action Stub” to be executed by the simulation. With a non-ISHM UAS, fewer conditions and actions exist due to absence of an ISHM failure (or non-failure) declaration and the associated ISHM maintenance actions, therefore there will be fewer rules than an ISHM-enabled UAS.

Table 7 – OV-6a: Operational Rules Model (Non-ISHM UAS)

Rules and Decision Analysis Table (Non-ISHM UAS)												
Condition Stub	**Condition Matrix**											
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Determine if Failure Condition is Present During Flight												
Failure Occurred?	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N
Determine if UAS is Aware of Present Failure Condition												
Is Failure Detected by Isolated Subsystem Sensor?	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N
Assess Failure Severity and Latency Effect												
Is Failure Catastrophic?	-	-	Y	-	N	N						
Is Failure Latent (occurred in previous flights but not detected/ascertained)?	-	-	-	Y	N	N						
Determine Maintenance Requirements of Existing Sensors												
Is Sensor False Alarm Rate Exceeded?	-	-	-	-	-	-	Y	Y	N	N	N	N
Determine Scheduled Maintenance Requirements of UAS												
Is UAS Due for Scheduled Maintenance?	Y	N	-	-	Y	N	Y	N	Y	N	Y	N
Action Stub	**Action Matrix**											
Perform Failure Assessment												
A13.2 Assess Failure Severity	X	X	X	X	X	X						
A13.3 Assign Failure Latency						X						
A13.4 Assess Latency Effect	X	X	X	X	X	X						
Decide UAS Recovery State												
UAS Recovering Code 1 [A11.1 Aviate - No Discrepancy Reported]					X	X					X	X
UAS Recovering Code 3 [A11.4 Mitigate - Discrepancy Reported that Require Rectification Before Next Mission]	X	X					X	X	X	X		
UAS Mishap [A15.2 Record UAS Accumulated Life - Terminated]			X	X								
Degradation of Isolated Subsystem Sensors												
A12.3 Determine Sensor False Alarm Rate [after increasing count]							X	X	X	X		
Perform Required Maintenance												
A14.4 Troubeshoot for Cannot Duplicate (CND)							X	X	X	X		
A14.7 Record CND Count and Troubleshooting Downtime							X	X	X	X		
A14.1 Perform Scheduled Maintenance (Without ISHM) [Reset Maintenance Schedule]	X				X		X		X		X	
A14.2 Replace Failed Component	X	X										
A14.3 Replace Faulty Sensor							X	X				
Record UAS Operational and Maintenance Life												
A15.1 Determine Flight Time Based on Landing Codes [Normal Flight Time for Codes 1 and 2]					X	X					X	X
A15.1 Determine Flight Time Based on Landing Codes [Reduced Flight Time for Code 3 and Mishap]	X	X	X	X			X	X	X	X		
A15.3 Determine Time for Scheduled Maintenance [Add Flight Time to Maintenance Schedule]						X		X		X		X

Notes:

1) '-' in Condition Matrix indicates condition *does not matter* for recommended set of actions.

2) 'X' in Action Matrix indicates *specified actions to be carried out or transition into pre-defined states based on conditions.*

3.3.3 State Transition Description (OV-6b)

Figure 12: Describes the business process (activity) responses to *<u>presence</u>* *of failure condition.*

This state transition diagram provides a temporal view of the analytic architecture in the event of a failure condition. The left-hand side (LHS) of the diagram depicts the state transition of an ISHM-enabled UAS while the right-hand side (RHS) shows the corresponding state transition of a non-ISHM UAS. Consistent with the operational rules presented in the OV-6a, the architecture transits through the various states based on the presented conditions. These states include the UAS recovering with various landing codes based on failure detection by the subsystem sensors and failure determination by ISHM (LHS). In addition, based on the landing codes, appropriate maintenance actions on the subsystem and/or ISHM are executed. Specifically for a non-ISHM UAS, there is provision for scheduled maintenance. In the event that the failure condition is not detected (by both the subsystem sensor and ISHM), the model transits into a state to determine the latency effect of the missed failure condition. If a missed failure condition is catastrophic or latent (to the extent that it becomes critical), the model terminates with a UAS mishap.

Figure 13: Describes the business process (activity) responses to *<u>absence</u>* *of failure condition.*

This state transition diagram provides a temporal view of the analytic architecture in the absence of a failure condition. Without actual failures, this model does not result in a UAS mishap. However, this view will be more concerned with false alarms and Cannot-

Duplicate (CND) that generate unnecessary maintenance activities. Otherwise, the states presented in both state transition diagrams are similar.

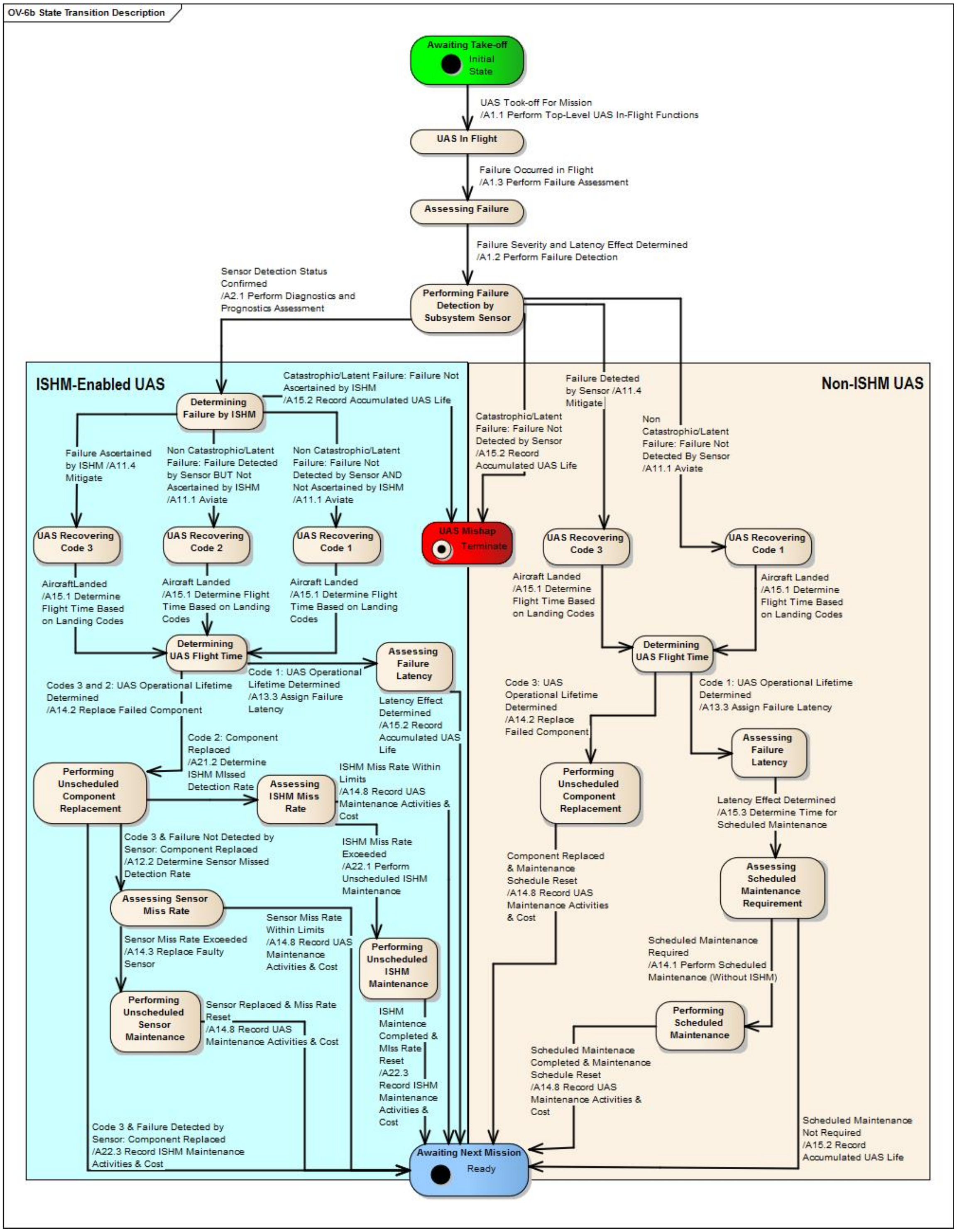

Figure 12 – OV-6b: State Transition Description (Failure Condition Present)

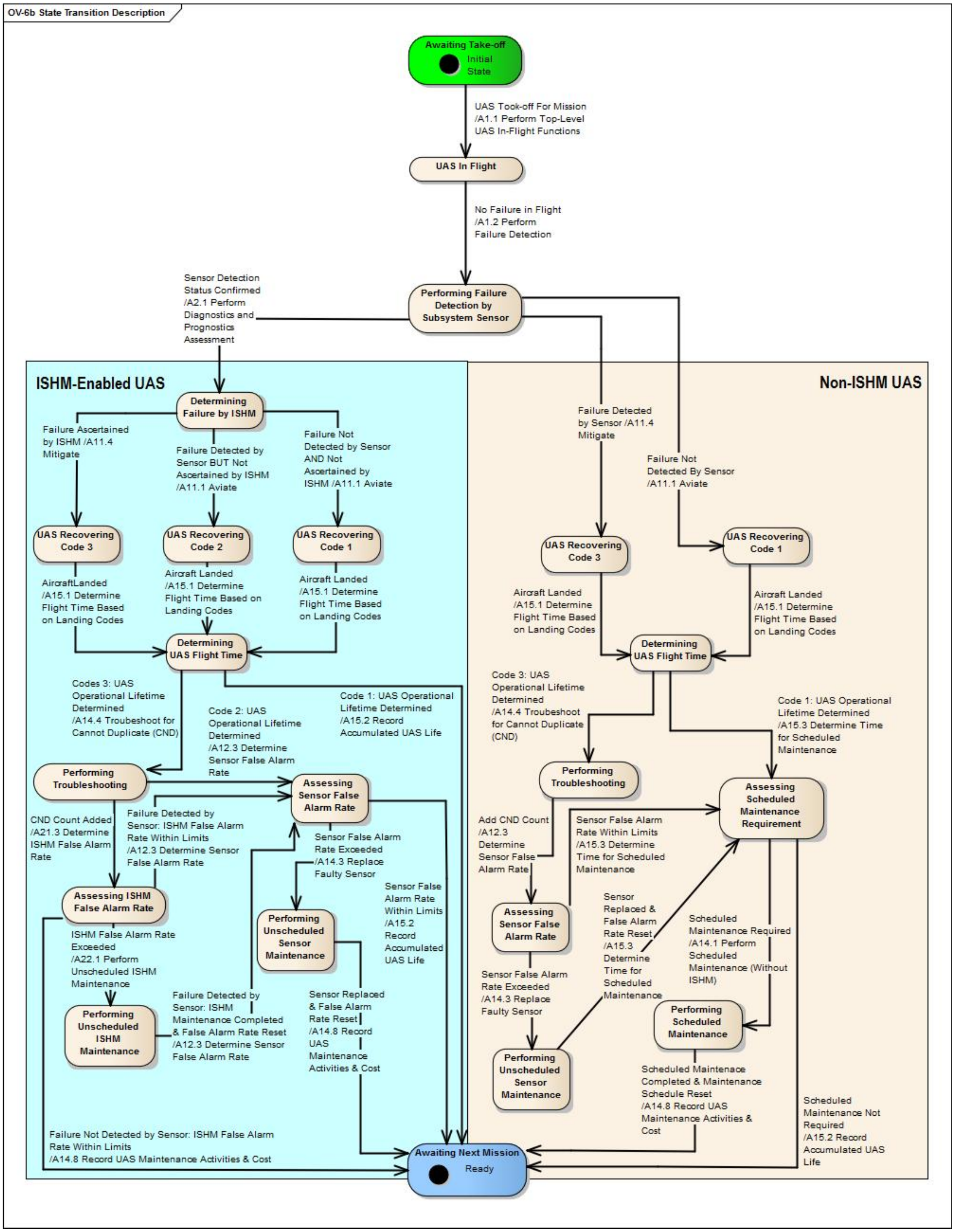

Figure 13 – OV-6b: State Transition Description (Failure Condition Absent)

3.4 Discrete Event Simulation Model

3.4.1 Logic Flow

Based on the analytic architecture, flowcharts are drawn up to present the logical sequence that guide the development of the simulation model. Four logical sequences are presented in the following figures.

- Failure Condition Present for an ISHM-Enabled UAS: *Refer to Figure 14*.
- Failure Condition Present for a Non-ISHM UAS: *Refer to Figure 15*.
- Failure Condition Absent for an ISHM-Enabled UAS: *Refer to Figure 16*.
- Failure Condition Absent for a Non-ISHM UAS: *Refer to Figure 17*.

3.4.2 Model Parameters

Input modeling and output analysis are two important phases of a simulation project. Based on the model logic, the required input parameters and desired output performance measures are defined in Table 8.

3.4.3 Sensitivity Analysis – Design of Experiments (DOE)

The benefits of this research effort will be based on the analysis of the simulation results. Representative data for a UAS will be fed into the model and DOE techniques will be employed to determine situations where the life expectancy of an ISHM-enabled UAS can be maximized based on the various UAS design factors. The secondary objective of the analysis will be to establish a business case for ISHM by minimizing the cost of a condition-based maintenance program with onboard ISHM.

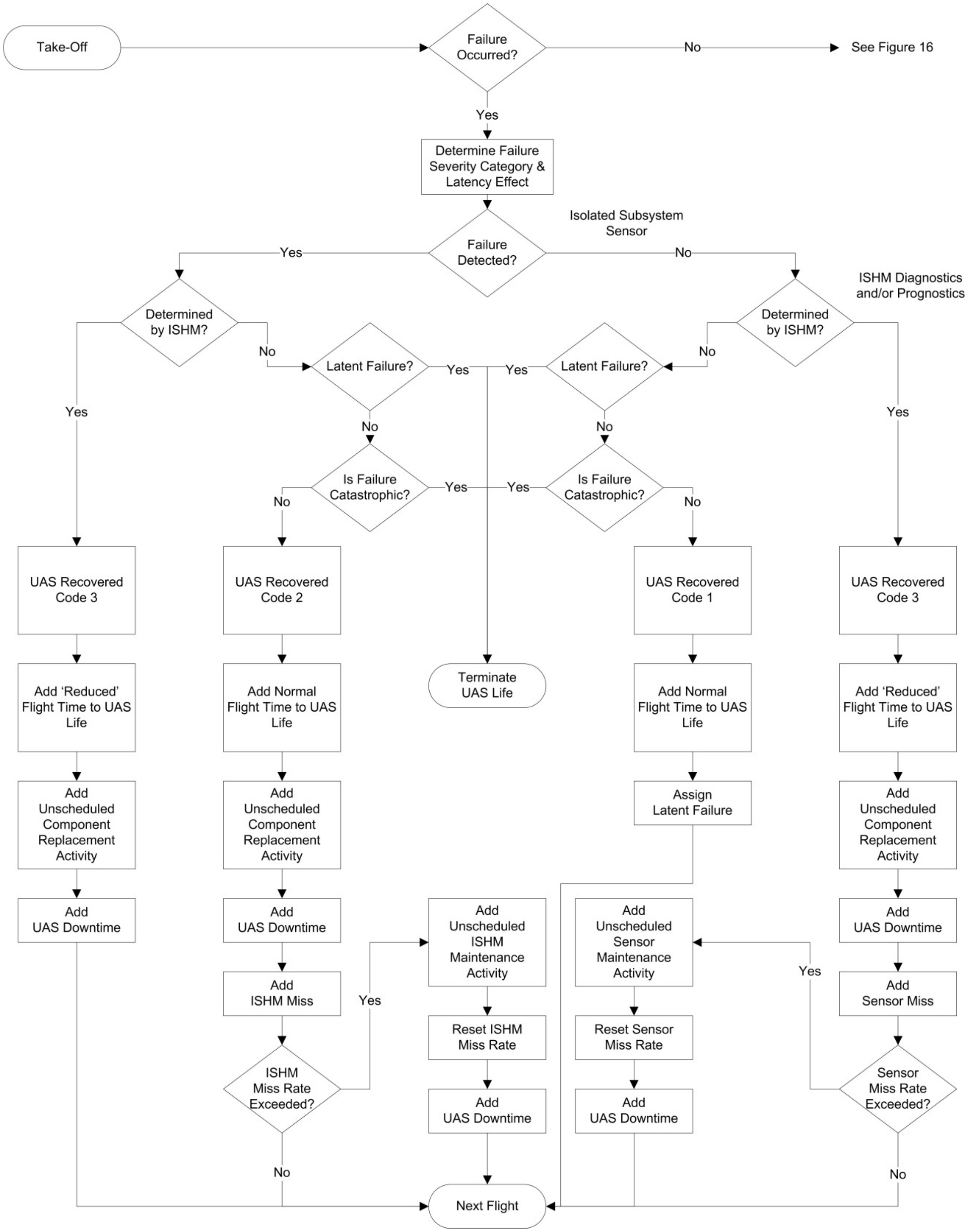

Figure 14 – Simulation Model Flowchart: Failure Condition Present for an ISHM-Enabled UAS

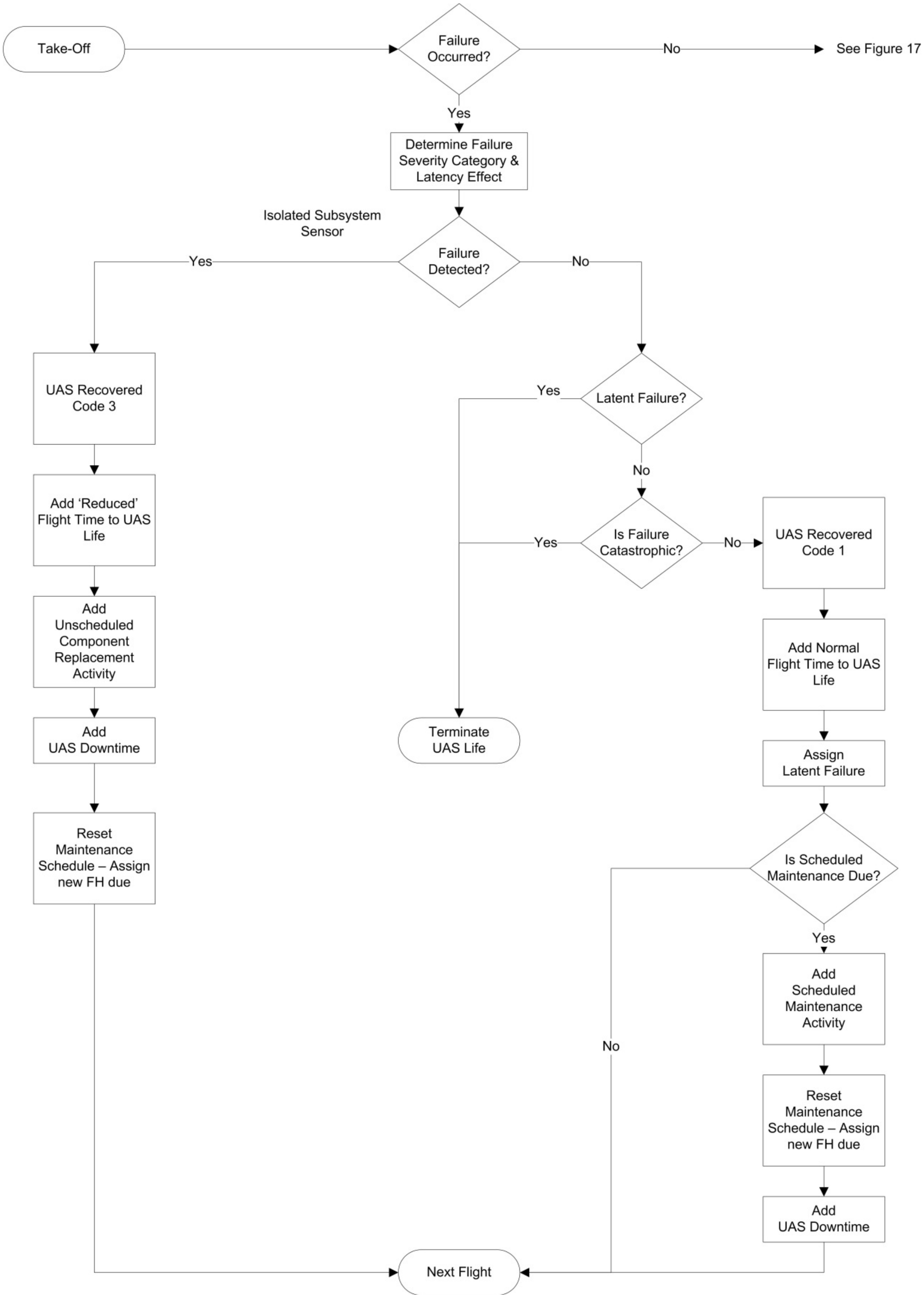

Figure 15 – Simulation Model Flowchart: Failure Condition Present for a Non-ISHM UAS

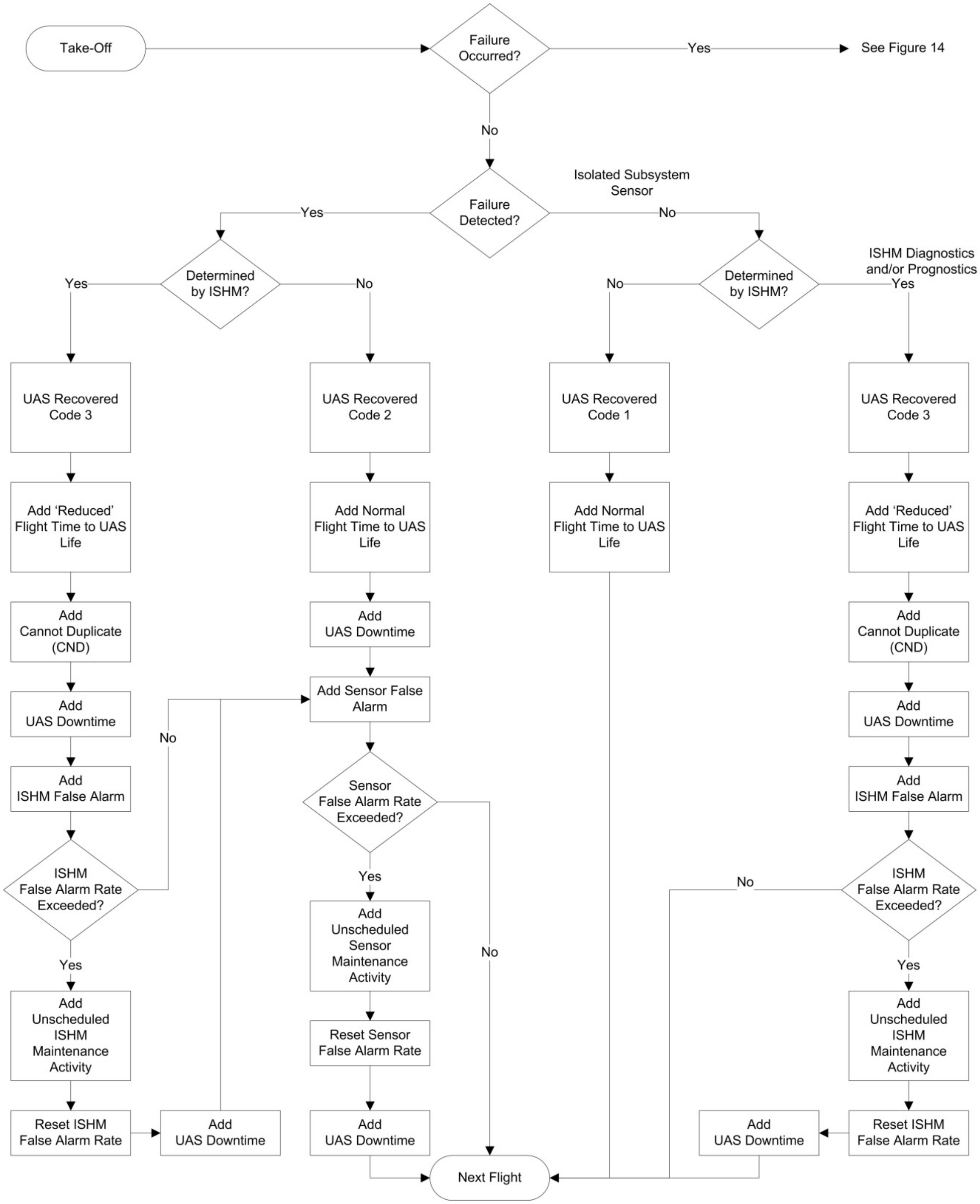

Figure 16 – Simulation Model Flowchart: Failure Condition Absent for an ISHM-Enabled UAS

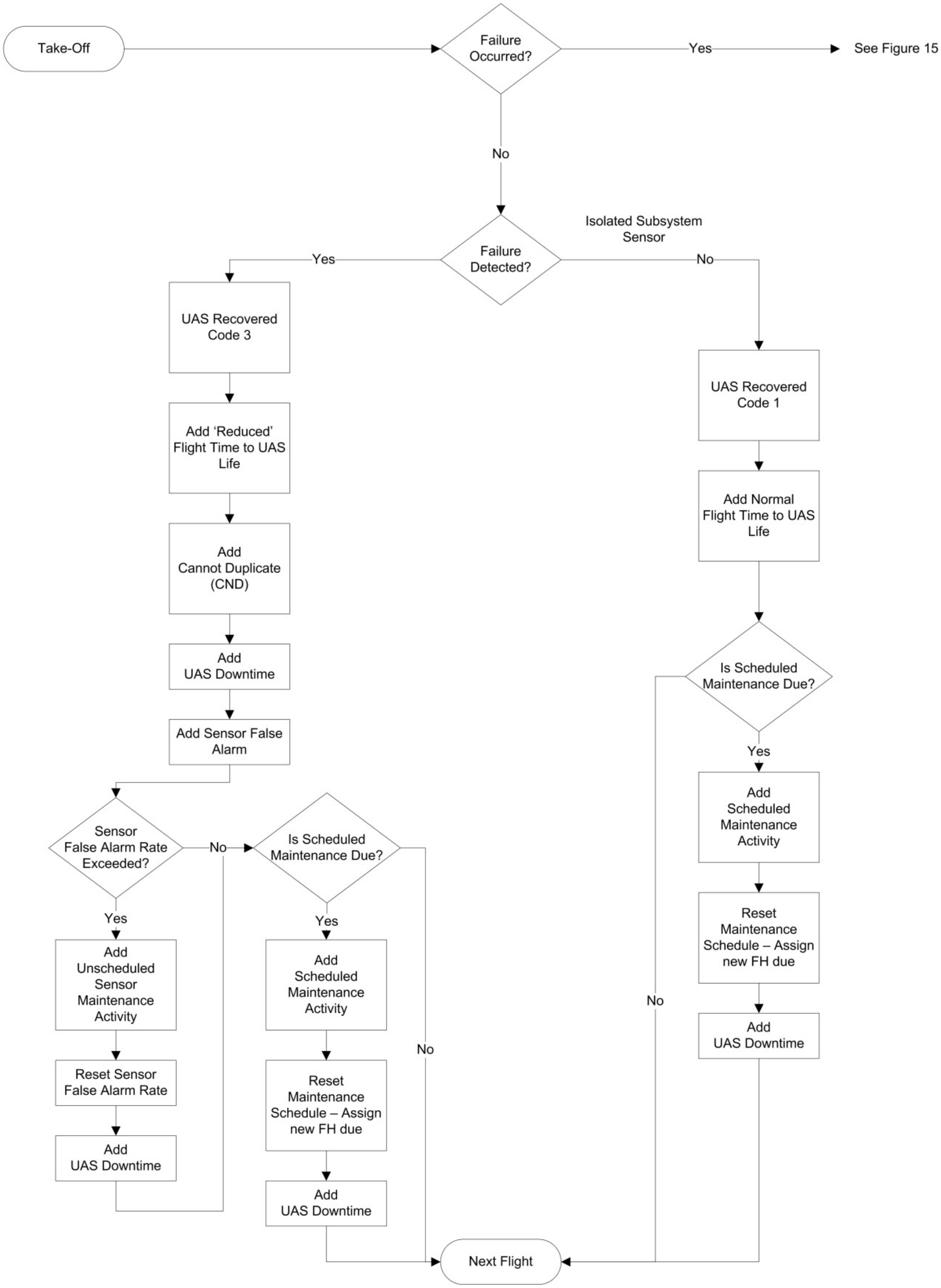

Figure 17 – Simulation Model Flowchart: Failure Condition Absent for a Non-ISHM UAS

Table 8 – Simulation Model Parameters

UAS Properties (Input Parameters)	**Definition**
P(Failure)	The probability of a failure occurring for a given sortie.
P(Failure is Catastrophic)	Given that a failure occurs, the probability of it being catastrophic, i.e. resulting in mishap if undetected.
Latency Threshold	The accumulated latency effect that determines criticality of a failure condition every time it is not detected in previous flights. A latent failure that reaches its pre-determined Latency Threshold due to prior missed detections will be upgraded to a catastrophic failure resulting in a mishap – *such as in the case of a crack propagating beyond its critical crack length*.
P(Sensor Detection)	The probability of the sensor detecting a failure given that a failure condition exists.
P(Sensor False Alarm)	The probability of the sensor detecting a failure given that there is no failure condition.
Sensor Missed Detection Threshold	The performance specification of the sensor in terms of missed detections; exceeding which sensor maintenance is to be carried out.
Sensor False Alarm Threshold	The performance specification of the sensor in terms of false alarms; exceeding which sensor maintenance is to be carried out.
Scheduled Maintenance Interval	For a non-ISHM UAS, the interval between scheduled maintenance (in hours).
Sortie Flight Time (Normal)	The duration of flight (in hours) for a UAS mission that recovered Code 1 or Code 2.
Sortie Flight Time (Reduced)	The truncated duration of flight (in hours) for a UAS mission that recovered Code 3.
ISHM Properties (Input Parameters)	**Definition**
P(ISHM Confidence)	The probability of ISHM declaring that a failure condition has occurred when an actual failure condition exists – an indication of the strength of the diagnostic and prognostic algorithms.
P(ISHM False Alarm)	The probability of ISHM declaring that a failure condition has occurred when there is no actual failure.
ISHM Missed Detection Threshold	The performance specification of ISHM in terms of missed detections; exceeding which ISHM maintenance is to be carried out.
ISHM False Alarm Threshold	The performance specification of ISHM in terms of false alarms; exceeding which ISHM maintenance is to be carried out.
Expected Model Output Measures	**Definition**
Expected System Lifetime	The expected lifetime of the UAS (in hours) based on accumulation of airworthy sorties.
Number of CND	The expected number of Cannot-Duplicate (CND) cases that contribute to unnecessary maintenance.

Scheduled Maintenance Actions	The expected number of scheduled maintenance actions for a non-ISHM UAS.
Unscheduled Maintenance Actions	The expected number of component replacements due to actual failures.
Sensor Maintenance Actions	The expected number of sensor maintenance actions due to exceedance of missed detection and false alarm thresholds.
ISHM Maintenance Actions	The expected number of ISHM maintenance actions due to exceedance of missed detection and false alarm thresholds.
UAS Downtime	This is a calculated parameter based on fixed maintenance times for the above categories of maintenance actions.
Model Properties	**Definition**
Number of Iterations	The number of iterations to execute the simulation model to achieve greater statistical accuracy.

3.5 Concordance and Consistency

The fundamental principle in architecting lies in ensuring concordance between architectural products – so that end-users (customers, builders, architects) looking at different products will have a common picture of the desired architecture. In this research effort, where the analytic architecture is applied to a simulation model, greater care must be taken to ensure consistency between the architecture and the translated logic flow that is to be implemented within the simulation model. In order to demonstrate the adherence of concordance and consistency principles in the research methodology, this section identified a specific logic path from Figure 14, and traced its relevance and consistency with the three architectural products presented (refer to Figure 18):

- OV-5a (Operational Activity Decomposition Tree) – The actions executed within the logic path are consistent with defined operational activities;
- OV-6a (Operational Rules Model) – The actions executed based on decisions within the logic path are consistent with the defined operational rule for the identified path;

- OV-6b (State Transition Description) – The logical sequence presented by the logic path is consistent with the defined states, conditions and associated operational activities.

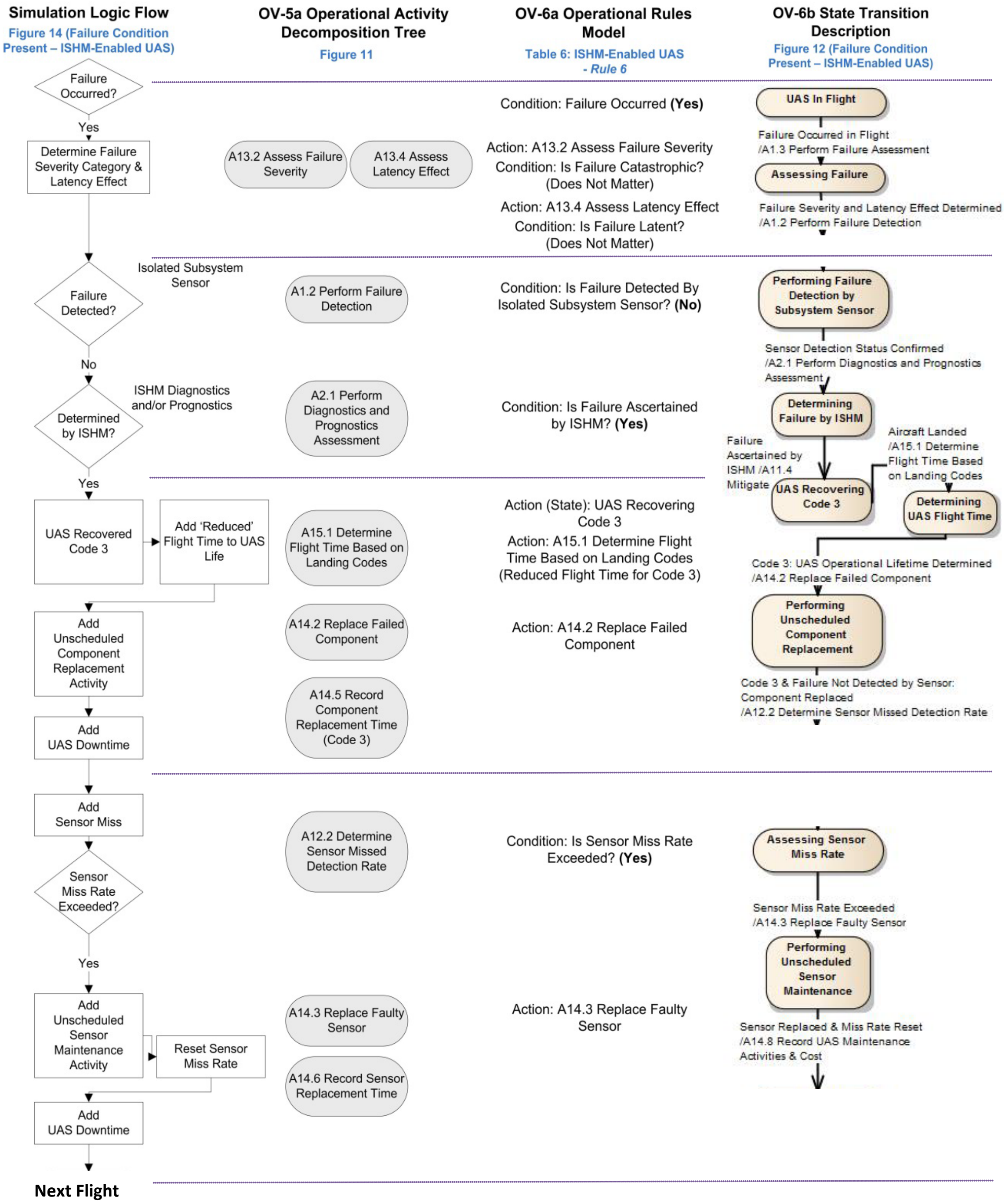

Figure 18 – Demonstrating Concordance and Consistency

3.6 Architecture Summary

This chapter defined the architecture for this research originating from the CONOPS that drove the relevant analytic architectural products, and subsequently translated into logical sequences for the implementation of the simulation model. While various heuristics guided the art of architecture, the principle of concordance between products was enforced throughout the architecting process – ensuring consistent representation in the development of the simulation model. Architecting for the purpose of sound analysis provided a well-grounded methodology for this research.

IV. Analysis and Results

4.1 Chapter Overview

This chapter will present the implementation of the analytic architecture using Arena ® Version 14.5 [3] and the analysis of the discrete event simulation model using representative UAS data for both ISHM-enabled and non-ISHM UAS models.

4.2 Input Modeling

Input analysis is the process of characterizing input variables – identifying their possible values and associated probabilities. Input models provide the driving force for a simulation, and identifying the right input variables will form the basis of sensitivity analysis at the end of a simulation project. Choosing the appropriate distributions for input data is a major task, as faulty models will lead to outputs whose interpretation could give rise to misleading recommendations (and follow-on decisions in the worst case) [Banks *et al.*, 2010]. The challenge in this research lies in the fact that real-world data were not available; from failure data and baseline sensor qualities of a generic UAS to characteristics of an envisioned ISHM suite, in terms of diagnostics and prognostics accuracy. Hence, various assumptions were made, in terms of the input parameters, in order to derive useful output measures within reasonable boundaries. Table 9 presents the input parameters for the discrete-event simulation model.

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[3] Accessed on 2 August 2013. Student Version 14.5 downloaded from Rockwell Automation, Inc. – Arena® website: http://www.arenasimulation.com/Private_Content.aspx?code=727I57H9K24&type=1

Table 9 – Simulation Model Input

UAS Properties (Input Parameters)	**Implementation Remarks**	**Typical Values for Analytic Considerations**
Failure Rate, λ	The failure rate is the rate at which failures occur in a specified time interval. $\lambda = \frac{number\ of\ failures}{total\ operating\ hours}$ Assumed to be relatively constant during normal UAS operation if system design is mature [Blanchard, 2004]. The failure rate is usually what is presented in FMECA reports, e.g. 1 failure in 10^3 hours (or $\lambda = 10^{-3}$ failure per hour).	** Based on suggested probability levels defined in Table 2 [DoD, 2000].* *Typical Values considered:* 10^{-1}, 10^{-2}, 10^{-3}*(baseline),* 10^{-4}*, and* 10^{-5} *Unit: failure per hour.*
P(Failure)	Probability of failure for a given sortie. Assumed to follow an exponential function with constant failure rate, λ – calculated by the following formula: $P(Failure) = 1 - e^{-\lambda * SortieFlightTime}$	*Dependent on failure rate.*
P(Failure is Catastrophic)	Based on NASA report in 2007, there are 26 potentially catastrophic failures out of 132 identified failure conditions for a generic UAS [Hayhurst *et al.*, 2007].	*Fixed Parameter* $= \frac{26}{132} = 0.197$
Latency Threshold	The accumulated latency effect that determines criticality of a failure condition every time it is not detected in previous flights. A latent failure that reaches its pre-determined Latency Threshold due to prior missed detections will be upgraded to a catastrophic failure resulting in a mishap.	*Fixed Parameter = 5 (Assumed that 5 prior missed detections of a non-catastrophic failure will escalate its severity and result in a catastrophic failure)*
P(Sensor Detection)	Assumed to be a baseline sensor characteristic for generic UAS. Has a positive correlation with expected UAS lifetime.	*Typical Values considered: 0.6, 0.7, 0.8 (baseline), and 0.9* *(Assumed to be constant over the lifetime of the UAS without sensor degradation)*
P(Sensor False Alarm)	Assumed to be a baseline sensor characteristic for generic UAS. Has a positive correlation with unscheduled sensor maintenance actions.	*Typical Values considered: 0.01, 0.02, 0.03 (baseline), 0.04 and 0.05* *(Assumed to be constant over the lifetime of the UAS without sensor degradation)*
Sensor Missed Detection Threshold	Assumed to be an arbitrary target threshold to carry out sensor maintenance when exceeded; should be lower than assumed accumulated latency effect to be meaningful.	*Fixed Parameter = 4*

Sensor False Alarm Threshold	Assumed to be an arbitrary target threshold to carry out sensor maintenance when exceeded; should be higher that missed detection threshold due to no safety of flight concern.	*Fixed Parameter = 10*
Scheduled Maintenance Interval	Only applicable for Non-ISHM UAS, assumed to be a fixed interval throughout the life of the UAS.	*Fixed Parameter = 1000 operating hours*
Sortie Flight Time (Normal)	Assumed to be constant.	*Fixed Parameter = 10 hours*
Sortie Flight Time (Reduced)	Assumed flight time to be reduced by 50% for a Code 3 mission.	*Fixed Parameter = 0.5 * Normal Sortie Flight Time = 5 hours*
ISHM Properties (Input Parameters)	**Implementation Remarks**	**Fixed Parameter / Variable?**
P(ISHM Confidence)	The probability of ISHM declaring that a failure condition has occurred when an actual failure condition exists – an indication of the strength of the diagnostic and prognostic algorithms. Performance specification of ISHM system. Has a positive correlation with the expected UAS lifetime.	*Typical Values considered: 0.6, 0.7, 0.8 (baseline), and 0.9* *(Assumed to be constant over the lifetime of the UAS without ISHM degradation)*
P(ISHM False Alarm)	The probability of ISHM declaring that a failure condition has occurred when there is no actual failure. Performance specification of ISHM system. Has a positive correlation with unscheduled ISHM maintenance actions.	*Typical Values considered: 0.01, 0.02, 0.03 (baseline), 0.04 and 0.05* *(Assumed to be constant over the lifetime of the UAS without ISHM degradation)*
ISHM Missed Detection Threshold	Assumed to be an arbitrary target threshold to carry out ISHM maintenance when exceeded; should be lower than assumed accumulated latency effect to be meaningful.	*Fixed Parameter = 4*
ISHM False Alarm Threshold	Assumed to be an arbitrary target threshold to carry out ISHM maintenance when exceeded; should be higher that missed detection threshold due to no safety of flight concern.	*Fixed Parameter = 10*

4.2.1 Assumptions

- For an ISHM-enabled UAS, the detection outcome by the baseline sensor and the eventual declaration by ISHM were assumed to be independent events, with the latter being the final authority in failure declaration. However, in a realistic ISHM implementation scenario, the declaration results of ISHM will be dependent upon, in part, the detection outcome of the baseline sensor(s). The present assumption was made due to modeling limitations in conflict resolution techniques between the baseline sensor and ISHM; relaxation of this assumption presents a potential area for future research.

- The probability of failure for the UAS was assumed to follow a constant failure rate. Likewise, the baseline sensor and ISHM were modeled to exhibit constant probabilities of missed detection and false alarm. Possible improvements to the model might consider failure distributions with increasing failure rate exhibiting component wear-out, and also sensor and ISHM degradation with time.

- In typical FMECA designs, failure conditions with greater severity will be mitigated with redundancy or better detection devices. However, this model assumed fixed probabilities of sensor detection and ISHM confidence regardless of the severity of the failure condition.

4.3 Model Implementation

Based on the analytic architecture presented in Chapter III, two separate Arena ® simulation models were set up; one for an ISHM-enabled UAS and another for a non-ISHM UAS. The sequenced actions for the two top-level models are described in the following sub-sections. The details of the sub-models implemented within Arena ® are also provided in Appendix A.

4.3.1 ISHM-Enabled UAS Simulation Model

Figure 19 depicts the simulation model path if a failure condition is present, while Figure 20 refers to the simulation model path if there is no failure.

4.3.1.1 Sequenced Actions for ISHM-Enabled UAS Simulation Model

- Sorties are generated as model entities – with pre-defined average sortie duration.
- Probability of failure is calculated based on occurrence rate.
- The simulation performs a random draw from the failure distribution to determine the occurrence of failure for a given sortie.
- IF failure condition is present (refer to Figure 19),
    - A1.3 Perform Failure Assessment – to determine if failure is catastrophic and its latency effect (based on missed detections of past failures).
    - A1.2 Perform Failure Detection – to determine if failure is detected by baseline sensor.
    - A2.1 Perform Diagnostics and Prognostics Assessment – to determine if failure is ascertained by ISHM.
    - IF failure is missed by ISHM, determine if it will result in a mishap based on prior failure assessment.
        - IF mishap results, terminate UAS life.

        - ELSE IF no mishap results, check status of sensor detection.
            - IF failure is detected by sensor, a Code 2 recovery results with an ISHM miss.
                - A22.1 Perform Unscheduled ISHM Maintenance based on comparison with ISHM Missed Detection Threshold.
            - ELSE IF failure is also not detected by sensor, a Code 1 recovery results with both ISHM and sensor misses.
                - A13.3 Assign Failure Latency – add latency effect to UAS due to missed detection.
    - ELSE IF failure is determined by ISHM, a Code 3 recovery results with an unscheduled component replacement action. Then, check status of sensor detection.
        - IF failure is missed by sensor, a Code 3 recovery results with a sensor miss.
            - A14.3 Perform Unscheduled Sensor Maintenance based on comparison with Sensor Missed Detection Threshold.
        - ELSE IF failure is not missed by sensor, a Code 3 recovery results with both ISHM and sensor confirmations.
- ELSE IF failure condition is absent (refer to Figure 20),
    - A1.2 Perform Failure Detection – to determine presence of false alarm by baseline sensor.
    - A2.1 Perform Diagnostics and Prognostics Assessment – to determine presence of false alarm by ISHM.
    - IF ISHM produces a false alarm, a Code 3 recovery results with a Cannot Duplicate (CND).
        - A22.1 Perform Unscheduled ISHM Maintenance based on comparison with ISHM False Alarm Threshold.
        - IF sensor produces a false alarm, a Code 3 recovery results with both ISHM and sensor false alarms.

      - A14.3 Perform Unscheduled Sensor Maintenance based on comparison with Sensor False Alarm Threshold.
    - ELSE IF sensor does not produce a false alarm, a Code 3 recovery results with ISHM false alarm only.
  - ELSE IF ISHM does not produce a false alarm, check status of sensor false alarm.
    - IF sensor produces a false alarm, a Code 2 recovery results with sensor false alarm only.
      - A14.3 Perform Unscheduled Sensor Maintenance based on comparison with Sensor False Alarm Threshold.
    - ELSE IF sensor does not produce a false alarm, a Code 1 recovery results – uneventful flight without false alarms.
- Statistics are collected at the end of each sortie recovery.
  - UAS Expected Lifetime is accumulated through every sortie based on sortie durations from different recovery codes.
  - The following categories of maintenance activities are added from respective sorties:
    - Unscheduled component replacement;
    - Unscheduled ISHM maintenance actions;
    - Unscheduled sensor maintenance actions.
- Simulation is terminated whenever a mishap occurs.

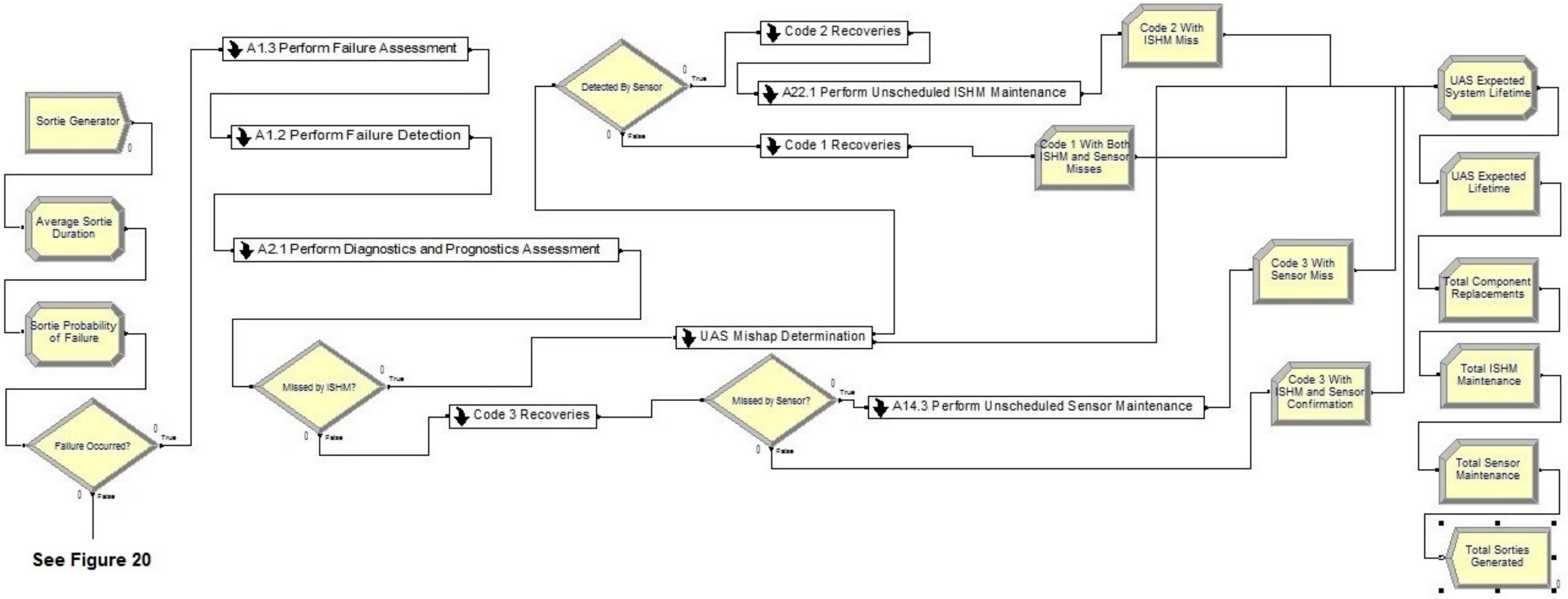
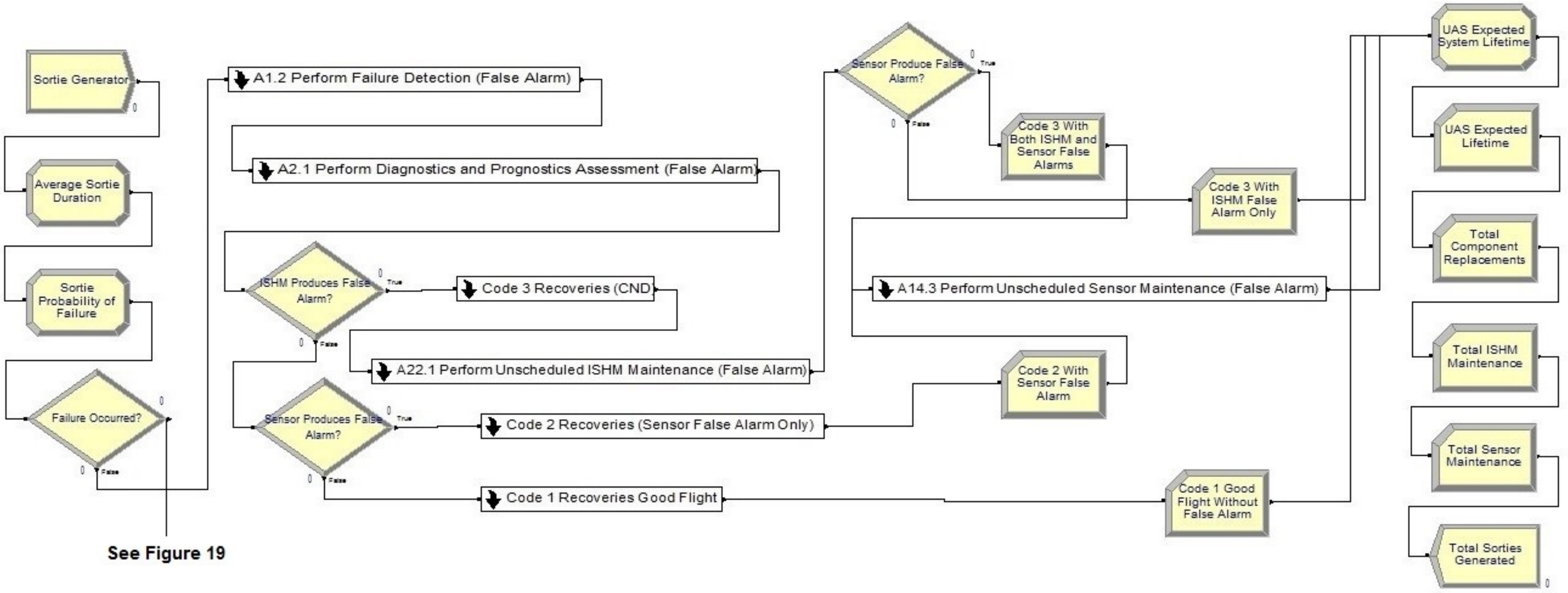


Figure 19 – Arena Model: ISHM-Enabled UAS (Failure Condition Present)



See Figure 19

Figure 20 – Arena Model: ISHM-Enabled UAS (Failure Condition Absent)

4.3.2 Non-ISHM UAS Simulation Model

Figure 21 depicts the simulation model path if a failure condition is present, while Figure 22 refers to the simulation model path if there is no failure.

4.3.2.1 Sequenced Actions for Non-ISHM UAS Simulation Model

- Sorties are generated as model entities – with pre-defined average sortie duration.
- Probability of failure is calculated based on occurrence rate.
- Define scheduled maintenance interval.
- The simulation performs a random draw from the failure distribution to determine the occurrence of failure for a given sortie.
- IF failure condition is present (refer to Figure 21),
  - A1.3 Perform Failure Assessment – to determine if failure is catastrophic and its latency effect (based on missed detections of past failures).
  - A1.2 Perform Failure Detection – to determine if failure is detected by baseline sensor.
  - IF failure is detected by sensor, a Code 3 recovery results with an unscheduled component replacement action.
    - Reset maintenance schedule whenever a component replacement has been carried out.
  - ELSE IF failure is not detected by sensor, determine if it will result in a mishap based on prior failure assessment.
    - IF mishap results, terminate UAS life.
    - ELSE IF no mishap results, a Code 1 recovery results with a sensor miss (but this is unknown to the UAS).
      - A13.3 Assign Failure Latency – add latency effect to UAS due to missed detection.
      - A14.1 Perform Scheduled Maintenance based on comparison with remaining time to scheduled maintenance.

- ELSE IF failure condition is absent (refer to Figure 22),
    - A1.2 Perform Failure Detection – to determine presence of false alarm by baseline sensor.
    - IF sensor produces a false alarm, a Code 3 recovery results with a Cannot Duplicate (CND).
        - A22.1 Perform Unscheduled Sensor Maintenance based on comparison with Sensor False Alarm Threshold.
        - A14.1 Perform Scheduled Maintenance based on comparison with remaining time to scheduled maintenance.
    - ELSE IF sensor does not produce a false alarm, a Code 1 recovery results – uneventful flight without false alarm.
        - A14.1 Perform Scheduled Maintenance based on comparison with remaining time to scheduled maintenance.
- Statistics are collected at the end of each sortie recovery.
    - UAS Expected Lifetime is accumulated through every sortie based on sortie durations from different recovery codes.
    - The following categories of maintenance activities are added from respective sorties:
        - Unscheduled component replacements;
        - Scheduled maintenance actions;
        - Unscheduled sensor maintenance actions due to false alarms only.
- Simulation is terminated whenever a mishap occurs.

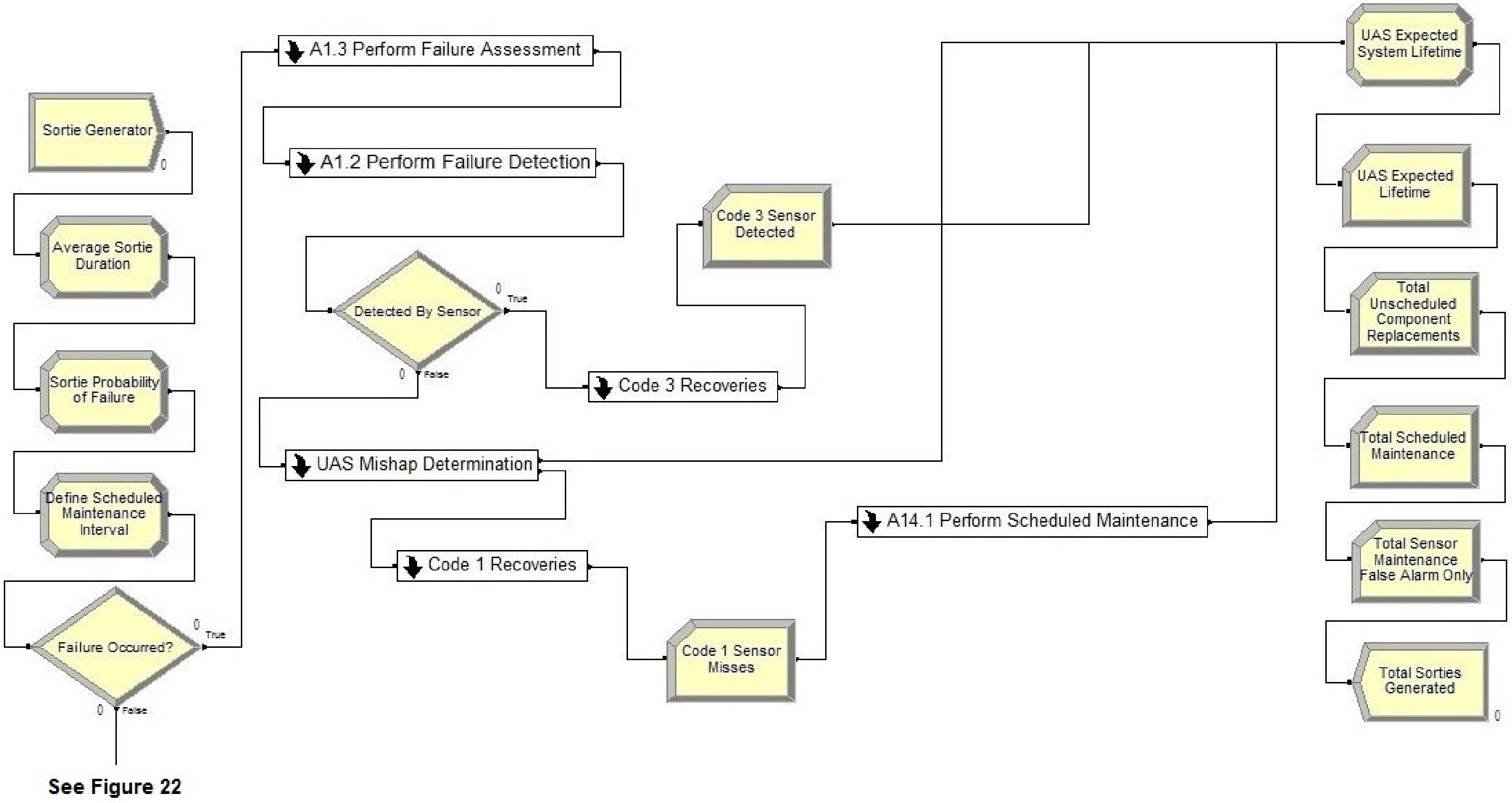


Figure 21 – Arena Model: Non-ISHM UAS (Failure Condition Present)

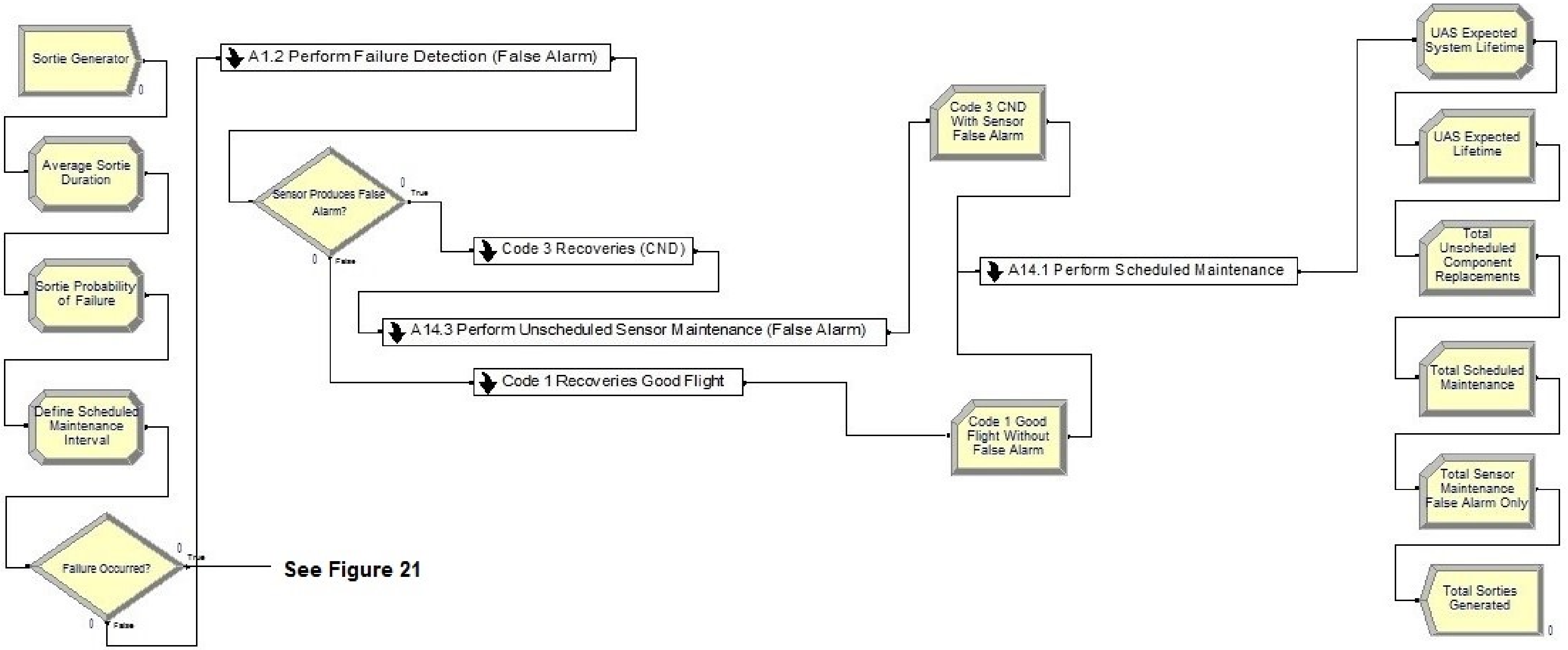


Figure 22 – Arena Model: Non-ISHM UAS (Failure Condition Absent)

4.3.3 Verification and Validation

4.3.3.1 Verification – Did I Build the Model Correctly?

Diligent effort was expended to *prove the model wrong*. Numerous iterations were tested until errors in design, coding logic, process flows, or concepts were found. The following analysis tools were used to test the models and deem them either adequate or incorrect:

a) *Software Debugging Function* – A first-cut verification was conducted by using the Arena ® debugger to ensure that no coding irregularities or warnings exist for the simulation model.

b) *Stress Testing* – There were multiple variables modeled with statistical distributions or percentage-based decisions within the model. These variables were varied using 'non-realistic' levels based on experience to ensure logical results would be generated.

c) *Animation* – This feature that is available within Arena ® was used to trace a UAS sortie through the model. Furthermore, animation was used to ensure entities did not enter infinite loops or proceed along '*illogical paths*'.

d) *Analytical Method Using Probability Theory* – Based on probability theory, analytical methods can be employed to verify certain output measures of the model. A close approximation of simulation results to analytical values provides confidence that the model is accurate.

The following parameters were defined for a test simulation run.

Table 10 – Test Values for Theoretical Calculation

Parameter	Formula or Label	Specified or Calculated Value
Normal Sortie Duration	ASD	10 hours
Failure Occurrence Rate	λ	10^{-6} failure per hour
Probability of Failure Occurring in a Given Sortie	$P_F = 1 - e^{-\lambda * ASD}$	$1 - e^{-0.000001 * 10} = 9.99995 * 10^{-6}$
Probability of Sensor Detection	P_{SD}	0.8
Probability of ISHM Confidence	P_{IC}	0.8

Assuming that the above decision processes are independent, probability of a failure occurring and being detected by both ISHM and baseline sensor

$= [P_F \cap P_{SD} \cap P_{IC}]$

$= 9.99995 * 10^{-6} * 0.8 * 0.8 =$ $\underline{\mathbf{6.400 * 10^{-6}}}$

The same test values from Table 10 were input for the ISHM-enabled UAS Arena® model. For the test simulation run, the above probability should be approximately equal to:

$$\frac{\text{Code 3 With Both ISHM and Sensor Confirmation}}{\text{Total Sorties Generated}}$$

From the results of the simulation run over three test replications, the average values obtained are:

Table 11 – Results for Test Simulation Run

Replication	Code 3 with ISHM & Sensor Confirmation	Total Sorties Generated	$\frac{\text{Code 3 with ISHM \& } Sensor\ Confirmatio}{\text{Total Sorties Generated}}$
#1	14	$2.4370 * 10^{6}$	$5.745 * 10^{-6}$
#2	3	$3.3350 * 10^{5}$	$8.996 * 10^{-6}$
#3	10	$1.5239 * 10^{6}$	$6.562 * 10^{-6}$
Average Value:			$\underline{\mathbf{7.101 * 10^{-6}}}$

e) It can be seen that the values of the theoretical calculation and the test simulation are in agreement within an 11% difference[4] – and the difference is expected to decrease with greater statistical accuracy achieved through more replications. Though not all outputs of the simulation can be verified through analytical methods, partial verification of such measures lends confidence and weight to the overall accuracy of the model.

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[4] The actual percentage difference of 10.95% between the theoretical and simulation results for the test case appeared to be magnified due to small fractions resulting from the large numbers of sorties generated (denominator) with an extremely low failure occurrence rate (10^{-6}). However, this provided an extreme case for our simulation boundaries. If we increase the failure occurrence rate to 10^{-3} (which will be more typical of existing UAS designs), the percentage difference between the simulation and analytical results is reduced to 2.51%.

4.3.3.2 Validation – Did I Build the Correct Model?

Upon verification of the model, the next step of validation posed certain challenges because no real-world or historical data was available to validate the output results of the model. Hence, external perspectives were an important source of validation. Consultation with my thesis advisor and other students involved in ISHM research provided valuable insights on process logic and modeling techniques. The final validation shall be provided by the research sponsors from AFRL who will be able to provide Subject Matter Expert (SME) advice on the applicability of this research model.

4.4 Sensitivity Analysis

This section discusses the test scenarios to achieve various ISHM implementation objectives. Although a large number of input variables and possible values exist, the design of the various experiments fixed certain parameters at reasonable baseline values as defined in Table 9. Thereafter, variables of interest (factors) were varied at defined levels and provided as inputs to the simulation models. Using Arena ® Process Analyzer, results (responses) from the simulation models were obtained and the various scenarios were ranked in terms of achievement of desired objectives. In order to improve the statistical accuracy for the simulation results, each test scenario was run for 10 replications for every experiment. In addition, a Common Random Number (CRN) strategy was employed to reduce random variance ("noise") between the ISHM-Enabled UAS and Non-UAS models, i.e. assigning the same random number streams to failure occurrence and detection decisions within the two simulation models [Banks *et al.*, 2010].

The first experiment demonstrates the dependence of UAS expected lifetime on failure occurrence rate. With the boundaries provided by the first experiment, in terms of failure occurrence rates, the second experiment investigates those relevant scenarios with the greatest percentage extension of UAS life expectancy. The third and fourth experiments seek to establish a business case for ISHM implementation through reduction of Cannot-Duplicate (CND) cases and maintenance activities.

4.4.1 Dependence of UAS Expected Lifetime on Failure Occurrence Rate, λ

This experiment seeks to identify those parameters that have an influence on UAS expected lifetime. Table 12 lists the various factors and levels considered for this experiment. Based on the three factors and their associated levels, a total of 80 scenarios are being tested for the desired response. Appendix B: Table B1 shows the results of this experiment in terms of the relative ranking of the 80 scenarios in achieving the longest UAS expected lifetime of an ISHM-enabled UAS.

Table 12 – Experiment 1: Design Factors and Levels

Input/Control Variables *Factors*	**Defined Values** *Levels*
Failure Rate, λ	10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} *Unit: failure per hour.*
P(Sensor Detection)	*0.6, 0.7, 0.8, 0.9*
P(ISHM Confidence)	*0.6, 0.7, 0.8, 0.9*
Output Performance Measure *(Response)*	
UAS Expected Lifetime *Unit: Hours*	

Results: The experiment showed that the failure occurrence rate has the greatest effect on the UAS expected lifetime. Figure 23 illustrates the range of UAS lifetimes associated with the various levels of failure occurrence rates defined for the experiment. For an extremely low failure occurrence rate of 10^{-5}, it is possible to achieve over a million flight hours for an UAS with or without ISHM implementation. However, UAS are not typically designed for such extended lifetimes, as age-related issues such as structural health will outweigh the benefits provided by ISHM. On the other hand, a high failure occurrence rate of 10^{-1} will reduce the expected lifetime to a few hundred flying hours – and such a low-reliability UAS will not be cost-effective for ISHM consideration. Hence, this experiment tightened the bounds for failure occurrence rates in subsequent experiments. Thus, only failure rates between 10^{-4} and 10^{-2} per flying hour will be considered in the remaining experiments.

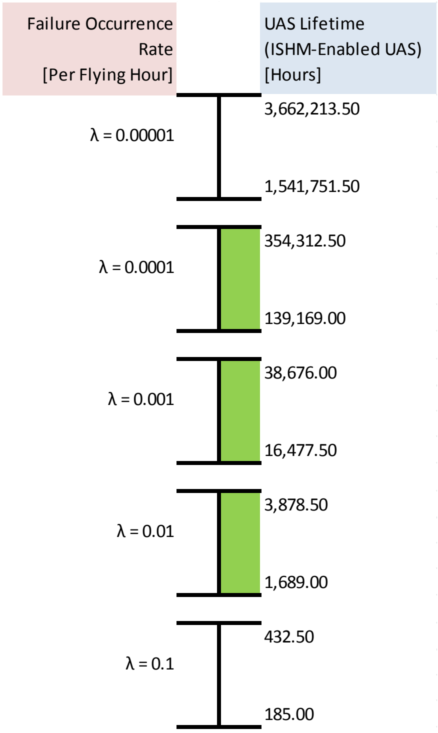


Figure 23 – Experiment 1: Dependence of UAS Expected Lifetime on Failure Occurrence Rate

4.4.2 Maximizing Percentage of Lifetime Extension

This experiment seeks to identify those scenarios that will yield the greatest benefit in terms of operational lifetime extension through ISHM implementation. With the revised bounds for failure occurrence rates, the input factors/levels are shown in to Table 13, with 48 scenarios being tested for the desired response. Appendix B: Table B-2 shows the results of this experiment in terms of the relative ranking of the 48 scenarios in achieving the greatest percentage of lifetime extension through ISHM implementation.

Table 13 – Experiment 2: Design Factors and Levels

Input/Control Variables ***Factors***	**Defined Values** ***Levels***
Failure Rate, λ	*10^{-2}, 10^{-3}, 10^{-4}* *Unit: failure per hour.*
P(Sensor Detection)	*0.6, 0.7, 0.8, 0.9*
P(ISHM Confidence)	*0.6, 0.7, 0.8, 0.9*
Output Performance Measure ***(Response)***	
Percentage Gain in Lifetime Extension (%)	

Results: From the simulation results, it was observed that, for a non-ISHM UAS, the expected lifetime is highly sensitive to its baseline sensor probability of detection. However, for an ISHM-enabled UAS, in scenarios where the probability of ISHM confidence is higher than the baseline sensor probability of detection, the expected lifetime is relatively insensitive to the latter, but highly sensitive to the former. The reason for the latter is because in the ISHM-enabled UAS model, the eventual declaration by ISHM of a failure will override the detection result of the baseline sensor.

Therefore, to achieve the most benefit through ISHM implementation, in terms of lifetime extension, the probability of ISHM confidence must be much higher than the probability of baseline sensor detection.

For scenarios with the same probabilities of baseline sensor detection and ISHM confidence, the deciding factor appeared to be on the former. Refer to Table 14. With the baseline sensor having a probability of detection above 0.8, the experiment showed that implementing ISHM does not improve the UAS expected lifetime.

Table 14 – Experiment 2: Scenarios with Same Probabilities of Baseline Sensor Detection and ISHM Confidence

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of Detection (Baseline Sensor)	Probability of ISHM Confidence	UAS Lifetime (ISHM-Enabled UAS) [Hours] (a)	UAS Lifetime (Non-ISHM UAS) [Hours] (b)	Increase in UAS Lifetime (c) = (a)-(b)	% Lifetime Gain (d) = (c)/(b)
1	0.001	0.6	0.6	16477.5	10755.5	5722	53.20%
2	0.01	0.6	0.6	1689	1105	584	52.85%
3	0.0001	0.6	0.6	139169	103479.5	35689.5	34.49%
4	0.001	0.7	0.7	18828	15623	3205	20.51%
5	0.01	0.7	0.7	1914.5	1687.5	227	13.45%
6	0.0001	0.7	0.7	158851.5	154323.5	4528	2.93%
7	0.001	0.8	0.8	22096.5	24979.5	-2883	-11.54%
8	0.01	0.8	0.8	2266	2634.5	-368.5	-13.99%
9	0.0001	0.8	0.8	191844.5	253859	-62014.5	-24.43%
10	0.001	0.9	0.9	38676	74975.5	-36299.5	-48.42%
11	0.01	0.9	0.9	3878.5	7679.5	-3801	-49.50%
12	0.0001	0.9	0.9	354312.5	731245.5	-376933	-51.55%

4.4.3 Minimizing Number of Cannot-Duplicate (CND) Cases

This experiment seeks to identify those scenarios that will reduce troubleshooting times for maintainers in dealing with Cannot-Duplicate (CND) defect reports. The benefits of reduced CND cases can be further quantified in terms of reduced maintenance time leading to better availability of the UAS. In addition, conservative maintenance policies that dictate the replacement of component for precautionary measures in the event of CND will increase maintenance costs significantly. In the absence of a failure condition, the design specifications of baseline sensors and ISHM (in terms of probabilities of false alarm) will determine the number of CND cases. Table 15 lists the various factors and levels considered for this experiment and a total of 75 scenarios are being tested for the desired response. Appendix B: Table B3 shows the results of this experiment in terms of the relative ranking of the 75 scenarios in achieving the maximum reduction in terms of CND cases.

Table 15 – Experiment 3: Design Factors and Levels

Input/Control Variables ***Factors***	**Defined Values** ***Levels***
Failure Rate, λ	*10^{-2}, 10^{-3}, 10^{-4}* *Unit: failure per hour.*
P(Sensor False Alarm)	*0.01, 0.02, 0.03, 0.04, 0.05*
P(ISHM False Alarm)	*0.01, 0.02, 0.03, 0.04, 0.05*
Output Performance Measure ***(Response)***	
Reduction in CND Cases	

Results: From the simulation results, it was observed that for a non-ISHM UAS, the number of CND cases is highly sensitive to its baseline sensor probability of false alarm. However, for an ISHM-enabled UAS, in scenarios where the probability of ISHM false alarm is lower than the baseline sensor probability of false alarm, the number of CND cases is relatively insensitive to the latter, but highly sensitive to the former. The reason for the latter is because in the ISHM-enabled UAS model, the eventual declaration by ISHM of a non-failure will override the detection result of the baseline sensor. This result can be illustrated by Figure 24. Considering the specific case when the failure rate is 0.001 per flying hour, the surface plot showed that there is positive reduction in CND cases only when the probability of the baseline sensor false alarm is higher than or equals to the probability of ISHM false alarm (as represented by the upper light blue area).

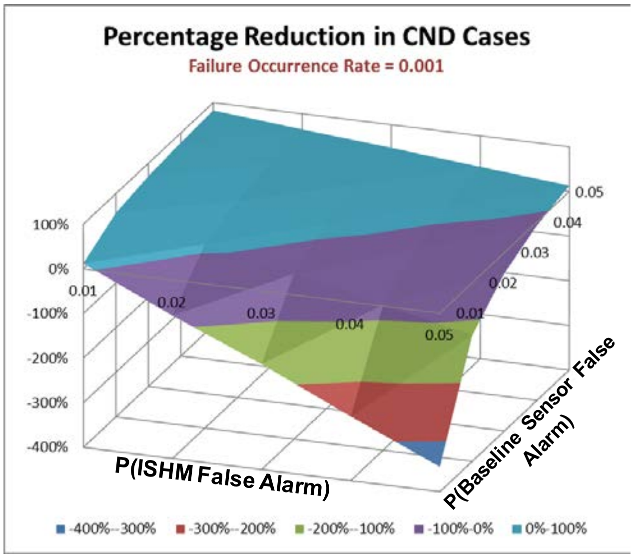


Figure 24 – Experiment 3: Minimizing Number of CND Cases

From the analytic model, higher CND counts (over an UAS' lifetime) are expected for more reliable UAS. To achieve a greater reduction in the number of CND cases, the probability of ISHM false alarm must be much lower than the probability of false alarm for the baseline sensor.

Refer to Table 16. For scenarios where the probabilities of false alarm are the same for the baseline sensor and ISHM, the simulation results suggested that ISHM implementation is only effective in reducing CND cases when the failure occurrence rate is less than 10^{-3}.

Table 16 – Experiment 3: Scenarios with Same Probabilities of Baseline Sensor False Alarm and ISHM False Alarm

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of False Alarm (Baseline Sensor)	Probability of ISHM False Alarm	Total Cases of CND (ISHM-Enabled UAS) [a]	Total Cases of CND (Non-ISHM UAS) [b]	Reduction in CND [c]=[b]-[a]	% Reduction in CND [d]=[c]/[b]
1	0.0001	0.05	0.05	977	1286	309	24.03%
2	0.0001	0.04	0.04	778	1023	245	23.95%
3	0.0001	0.03	0.03	584	768	184	23.96%
4	0.0001	0.02	0.02	390	515	125	24.27%
5	0.0001	0.01	0.01	193	252	59	23.41%
6	0.001	0.05	0.05	111	128	17	13.28%
7	0.001	0.04	0.04	89	103	14	13.59%
8	0.001	0.03	0.03	66	76	10	13.16%
9	0.001	0.02	0.02	45	51	6	11.76%
10	0.001	0.01	0.01	22	25	3	12.00%
11	0.01	0.05	0.05	11	13	2	15.38%
12	0.01	0.03	0.03	7	8	1	12.50%
13	0.01	0.04	0.04	9	10	1	10.00%
14	0.01	0.01	0.01	2	2	0	0.00%
15	0.01	0.02	0.02	5	5	0	0.00%

4.4.4 Minimizing Number of Maintenance Actions

This experiment seeks to identify those scenarios that will reduce the overall maintenance actions. It is assumed in the analytic model that an ISHM-enabled UAS will not require scheduled maintenance due to its added onboard diagnostics and prognostics capabilities. However, additional maintenance for an ISHM-enabled UAS will be driven by generated ISHM false alarms. The benefits of reduced maintenance actions can be further quantified by assigning a cost factor to each of the maintenance actions. This will provide justifications in relaxing maintenance schedule intervals and eventually a condition-based maintenance program through ISHM. Table 17 lists the various factors and levels considered for this experiment. Similar to the previous experiment, a total of 75 scenarios are being tested for the desired response. Appendix B: Table B4 shows the results of this experiment in terms of the relative ranking of the 75 scenarios in achieving the maximum reduction in terms of maintenance actions.

For ISHM-Enabled UAS, total maintenance actions include:

- Total Number of CND Cases (troubleshooting required)
- *Total Number of Unscheduled ISHM Maintenance (due to ISHM missed detections and false alarms)*
- Total Number of Unscheduled Sensor Maintenance (due to baseline sensor missed detections and false alarms)

For Non-ISHM UAS, total maintenance actions include:

- Total Number of CND Cases (troubleshooting required)
- *Total Number of Scheduled Maintenance (with maintenance interval of 1000 flying hours)*
- Total Number of Unscheduled Sensor Maintenance (due to baseline sensor false alarms only)

Table 17 – Experiment 4: Design Factors and Levels

Input/Control Variables ***Factors***	**Defined Values** ***Levels***
Failure Rate, λ	*10^{-2}, 10^{-3}, 10^{-4}* *Unit: failure per hour.*
P(Sensor False Alarm)	*0.01, 0.02, 0.03, 0.04, 0.05*
P(ISHM False Alarm)	*0.01, 0.02, 0.03, 0.04, 0.05*
Output Performance Measure ***(Response)***	
Reduction in Maintenance Actions	

Results: Of the 75 tested scenarios, a total of 46 scenarios showed a reduction in overall maintenance activities with ISHM implementation. As an illustration, refer to Figure 25 for the specific case when the failure occurrence rate is 0.01 per flying hour. If we consider the effects of probabilities of false alarm on the number of maintenance actions, it was observed from this surface plot that there is positive reduction in maintenance actions only when the probability of the baseline sensor false alarm is higher than the probability of ISHM false alarm (as represented by the upper light blue area).

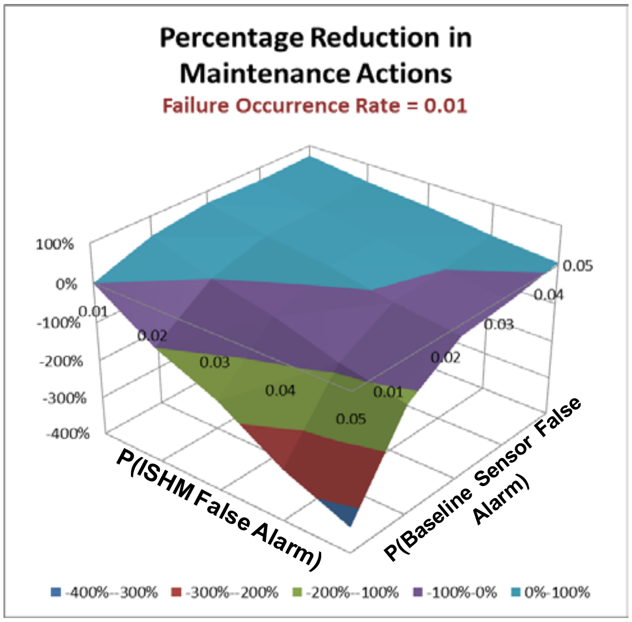


Figure 25 – Experiment 4: Minimizing Number of Maintenance Actions

From a system engineer's perspective, a cost-benefit analysis can be derived from the results of this experiment. Each response value in terms of reduction in maintenance actions can be assigned a cost value. The expected cost savings can then be weighed against the design budget or the expected cost of the ISHM system (with specified performance requirements) to evaluate its cost-effectiveness.

4.5 Analysis Summary

This chapter provided details of the Arena ® simulation and highlighted the assumptions in input modeling due to data inadequacies. Thereafter, four experiments were set-up to test full-factorial scenarios in achieving desired ISHM performance measures. The desired outcome of the validated scenarios is to provide future UAS designers with an analytical tool to identify performance specifications of baseline UAS and complementing ISHM systems to achieve a desired UAS lifetime extension or reduction in maintenance costs.

V. Conclusions and Recommendations

5.1 Chapter Overview

This chapter will discuss the answers to the research objectives and recommend areas for future research.

5.2 Research Questions Answered

The focus of this research was to quantify the continued airworthiness benefits of ISHM by developing an analytic architecture for comparison between an "as-is" UAS (without ISHM capabilities) and a "to-be" UAS (with ISHM capabilities). From an airworthiness certification perspective, this research sought to develop a method for establishing performance requirements for components of an ISHM-enabled UAS.

Prior to developing the architecture, a literature review was conducted to gain a better understanding of the research arena. The following questions were posed in Chapter I for literature review:

(1) What is system health monitoring/management and what are some related applications?

There are many different terms and associated definitions on system health management available in the literature and this research chose the term, *Integrated System Health Management (ISHM)* – aligned to previous research in the department [Storm, 2013].

Benedettini *et al.* [2009] termed system health management as *integrated vehicle health management (IVHM)* and defined it as "a collection of data relevant to the present and future performance of a vehicle system and its transformation into information can be used to support operational decisions". The authors also presented various definitions found in the literature that sought to provide a top-level perspective of ISHM.

In terms of related ISHM applications, Health and Usage Monitoring Systems (HUMS) surfaced as one of the more matured applications related to airworthiness of helicopters. These systems emerged in the 1980s as a response to the high accident rates experienced by offshore shuttle helicopters traversing the petrol installations in the North Sea, and increased demand for improved operational safety and reduced rotorcraft maintenance costs had paved the way for HUMS [Wiig, 2006]. In terms of process management, the typical processes of a HUMS program are previously depicted in Figure 2 [JHSIT, 2013]. Basic HUMS operations include real-time data collection and download, defining thresholds based on trending information, and comparison of health indicators against these thresholds to ensure continued airworthiness of the aircraft. This concept of operations is definitely in agreement with that of a typical ISHM implementation. *HUMS originated from an airworthiness concern, and its implementation drove extensive research in condition-based rotorcraft maintenance. Understanding the HUMS architecture and associated processes provided alignment in this research in developing the analytic architecture and associated maintenance cost models.*

Apart from aerospace applications, the literature review also cited a technological breakthrough from the health care industry – to draw parallel inferences of ISHM from another systems thinking perspective. Artificial intelligence in the form of IBM's Watson provides consistency of decisions amongst available medical solutions, based on accurate clinical examinations and evidence [Cohn, 2013]. *Such technological breakthroughs in health care, in the areas of sensor data fusion and artificial intelligence, presented similarities to an ideal ISHM architecture that integrates processed sensor information and intelligence through diagnostics and prognostics algorithms.*

(2) What are the essential elements of ISHM?

The ISHM design and operation concept embraces an integration of sensors, communication technologies, and artificial intelligence to provide vehicle-wide abilities to diagnose problems and recommend solutions [Benedettini *et al.*, 2009]. At the front end of a typical ISHM architecture is a *sensor suite* responsible for gathering state awareness variables that are indicative of potential failure modes. For an envisaged ISHM configuration, apart from conventional sensors that monitor and control sub-systems, *system-level sensor suites* are also being introduced in the form of smart embedded sensor systems with wireless communications transfer protocol in place for overall system health management. Upon filtering of sensor data to extract relevant fault features, the *diagnostics module* analyzes the fault features to detect, identify and isolate impending fault conditions. In addition, with health and usage data being fed to the *prognostic module*, the latter is able to combine historical data to generate an estimation of the time-to-failure of specific subsystems and components. Depending on the level of autonomy, such diagnostic and prognostic information can be processed on-board the vehicle through its auto-recovery systems or communicated to technical support managers on ground. In order to highlight the similarities in considerations between the analytic architecture developed in this research and the typical ISHM architecture described in the literature review, the relevant operational activities from the OV-5a were superimposed on Figure 3 that previously depicted the suggested architecture for ISHM.

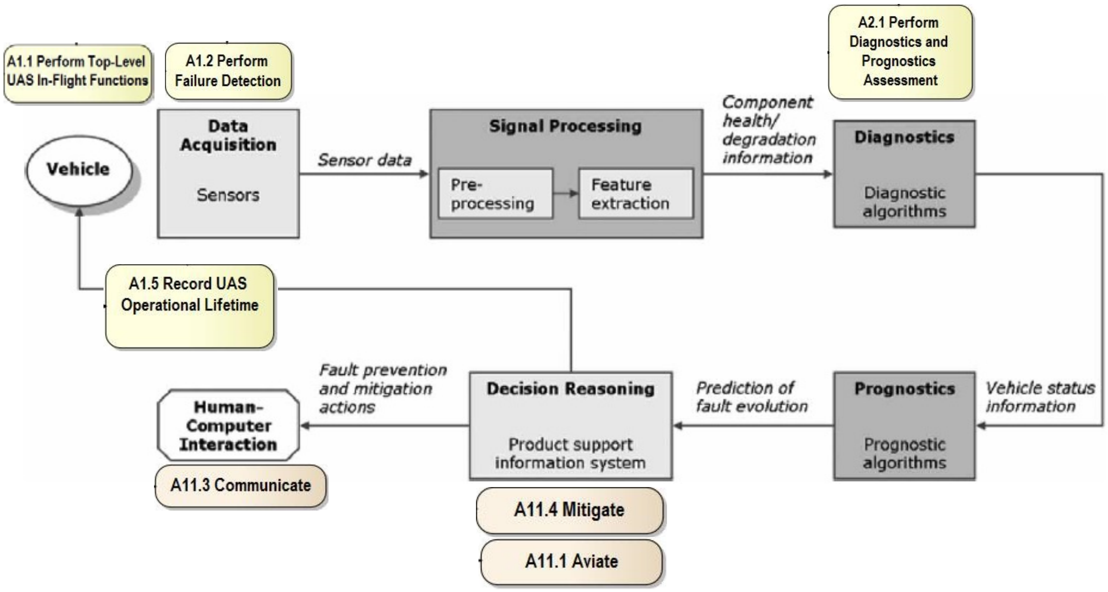


Figure 3 – Typical ISHM Architecture [Benedettini et al., 2009]
(** Superimposed with operational activities of developed analytic architecture*)

(3) What are the critical FMECA hazards associated with a typical UAS and their relation to airworthiness?

NASA published a report in 2007 that identified the typical failure conditions of a UAS based on functional decomposition of a generic UAS [Hayhurst *et al.*, 2007]. The full functional decomposition is relatively large, with 69 functions at the lowest level under the major functions of *aviate, navigate, communicate* and *mitigate*. The primary safety goal of the failure hazard assessment is to avoid any UAS-initiated decrease in the safety of the National Air Space (NAS). As a result, failure condition criticality is determined by its effect on people on ground or in other aircraft. Damage to material assets is out-of-scope, unless it affects human safety. The majority of potential failure conditions fall under the *Aviate* or *Mitigate* functions. In the assessment by NASA, twenty-six potentially catastrophic failure conditions out of 132 were identified, considering only single failures in the en-route phase of flight.

Although severity effects related to the occupants of an aircraft do not apply to unmanned systems, other severe outcomes are possible that will result in human casualties, either in other aircraft or on the ground. *Ground impact* can endanger the general public, and *midair collision* with a manned aircraft can threaten the safety of the passengers aboard that aircraft. Both effects are critical system design drivers that have implications for UAS operations and reliability requirement. As the size of an UAS grow from *Micro → Mini → Tactical → MALE (Medium Altitude Long Endurance) → HALE (High Altitude Long Endurance) → Heavy* classifications in terms of weight, there will be an increased level of hazard risk involved in the operation of UAS [Weibel and Hansman, 2005].

Airworthiness requirements and certification for UAS are hence crucial in assessing its inherent operating risk. System safety is the application of engineering and management principles (such as FMECA), criteria and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle. A system safety program is crucial for the initial and continued airworthiness of all weapon systems, both manned and unmanned. *Understanding the functional decomposition of a generic UAS and the potential failure conditions and effects provided an appreciation of the top-level functional failure modes in architecting ISHM for initial and continued airworthiness.*

(4) What is Condition-Based Maintenance (CBM)?

Though the benefits of ISHM are well recognized, the most quantifiable benefits in the current paradigm were almost exclusively reported in terms of maintenance related savings. Specifically, HUMS and CBM are almost *synonymous* in the rotorcraft world. CBM, also known as unscheduled/corrective maintenance, defines a maintenance policy where components are replaced upon detection of an unsatisfactory condition – such as those detected (or even *predicted*) by an ISHM system. Every component has a safe life or operating life, beyond which continued operation of the component could result in catastrophic failures. In a scheduled maintenance policy, there is potential for wastage should a component be replaced way ahead of its life expiration. With the potential of increased health management and surveillance presented by ISHM, the useful life of a component can be extended until diagnostic or prognostic algorithms decide that an impending failure is imminent. To implement a safe and effective CBM program, it should be cautioned that the algorithms will have to consider the uncertainty and confidence levels regarding a component's useful life in order not to encroach upon the unsafe operating window. *A CBM life cycle model was incorporated within the analytic architecture for a cost-benefit analysis of an ISHM-enabled UAS as compared to a non-ISHM UAS requiring scheduled (or time-based) maintenance.*

The answers to the literature review provided the foundation in the development of the analytic architecture and the discrete-event simulation model. Thereafter, the results from the simulation model serve to answer the following research questions:

(1) What are the performance characteristics of ISHM to ensure continued airworthiness of the UAS?

The Arena ® discrete-simulation model made provision for investigation of various UAS parameters for ISHM implementation based on the analytic architecture. The simulation model defines the airworthiness of an ISHM-enabled UAS through the output parameter of ***UAS Expected Lifetime***. Within the limits of defined boundary conditions, it was observed that the failure occurrence rate has the greatest effect on the UAS expected lifetime. For an extremely low failure occurrence rate of 10^{-5}, it is possible to achieve over a million flight hours for an UAS with or without ISHM implementation. This result made possible the tightening of experimental boundaries to only consider scenarios with typical UAS lifetimes within reasonable failure occurrence rates.

The secondary observation from the simulation model is that for a non-ISHM UAS, the expected lifetime is highly sensitive to its baseline sensor probability of detection. However, for an ISHM-enabled UAS, in scenarios where the probability of ISHM confidence is higher than the baseline sensor probability of detection, the expected lifetime is relatively insensitive to the latter, but highly sensitive to the former. This is explained by the fact that for an ISHM-enabled UAS, the eventual declaration of a failure (or non-failure) from its diagnostics and prognostics algorithms will override the detection results by the baseline sensor.

Establishing Performance Requirements for an ISHM-Enabled UAS

Initial Airworthiness – In the preliminary or conceptual design stage of an UAS, the designer should be aware of the design requirements, i.e. in terms of the desired UAS expected operational lifetime (output performance). From the results of the simulation, an associated reliability requirement of the UAS in terms of failure rate can be obtained as a performance specification. This overall reliability requirement can then be cascaded through the subsystems of the UAS based on reliability allocation design. Secondly, performance specifications in terms of baseline sensor qualities and ISHM diagnostics/prognostics capabilities can be specified by the parameters of *Probability of Sensor Detection* and *Probability of ISHM Confidence* respectively.

Continued Airworthiness – For a non-ISHM UAS in the operational phase of its life cycle considering an ISHM upgrade, existing performance data on failure occurrence rates and baseline sensor detection rates would have been available. Comparing the available field information with the simulation results will assist the designer in defining performance specifications in terms of ISHM diagnostics/prognostics capabilities to achieve a desired reduction in maintenance costs.

(2) How will ISHM provide a business case to improve the level of UAS self-autonomy?

This research effort developed two separate Arena ® simulation models for an ISHM-enabled UAS and non-ISHM UAS. Among the 48 scenarios tested, only 26 scenarios showed an expected gain in UAS life expectancy with ISHM implementation. Hence, ISHM does not necessarily improve the life expectancy of a UAS, especially in conditions where the baseline sensors have shown excellent performance in detection of failure conditions. Therefore, implementing an ISHM system with poor diagnostics and/or prognostics capabilities will only do more harm than good. We conclude that in order to achieve lifetime extension with ISHM implementation, the probability of ISHM confidence must be greater than the probability of detection for the baseline sensor.

The simulation models were set-up to investigate the cost-effectiveness of a CBM policy for an ISHM-enabled UAS that was assumed not to require scheduled maintenance unlike the non-ISHM UAS. Among the 75 scenarios tested for reduction in maintenance actions, only 46 scenarios showed a reduction in the total number of maintenance actions after ISHM implementation. This result cautioned that it will be important to define ISHM performance specifications in terms of missed detection and false alarm rates so that implementing ISHM onboard a UAS will not induce unnecessary maintenance actions. In addition, different costs components attributed to the various types of maintenance actions will need to be considered to weigh against the implementation cost of ISHM. In summary, the simulation results from the test scenarios will be able to determine the performance specifications of the envisaged ISHM system, by considering the desired benefits of ISHM implementation based on the existing reliability of the UAS and the baseline sensor quality.

(3) What are the potential impacts of ISHM to maintenance practices and life cycle costs?

One of the performance measures recorded from the simulation models was the number of Cannot-Duplicate (CND) cases, where a failure was reported in flight but the condition was unable to be duplicated on ground. Not only does CND drive additional maintenance effort in terms of extended troubleshooting along all possible paths of a fault tree analysis, it also reduces confidence in the UAS being able to perform subsequent missions – and in many instances, confidence drives changes in maintenance policies. A good ISHM system should reduce both the number of missed detections and false alarms of a UAS, and minimizing the latter will mean less CND cases. It is expected that with increased sophistication of future UAS, its cost will also increase substantially. This may dictate conservative approaches in maintenance of such high-value assets. In releasing UAS for flight with a CND, replacement of components for precautionary measure could be mandatory – inducing higher costs for UAS maintenance. A desired ISHM system should hence act as a safeguard for missed detections, while being a filter for false alarms. With added confidence in onboard autonomy through ISHM, it will then be possible to relax scheduled maintenance requirements and, in the long-term, adopt a condition-based maintenance (CBM) program with potential life cycle cost savings. It should be cautioned, though, that CBM drives *undesired* changes to maintenance policies in terms of maintenance scheduling. CBM will be more difficult to forecast and plan for as compared to time-based maintenance, and may result in inefficiencies with regard to resource allocation.

5.3 Recommendations for Future Research

This research effort provides potential designers with a top-level reference in determining performance specifications for an ISHM-enabled UAS to achieve desired airworthiness and maintenance outcomes, and there exists potential areas of future research. The Arena® simulation models were based upon the analytic architecture and it would be advisable to review the architecture for relevance of applications in future research. An important emphasis of this research lie in the accurate documentation of model input parameters, assumptions, implementation and results. Documentation is important to caveat the research conclusions within tested boundary conditions, and provide easy reference for potential researchers interested in this work.

Although the model provides provision for variation in many parameters (such as latency threshold, defined scheduled maintenance interval, etc.), not all of them were assigned as input/design variables in the analysis. One area of future research can be in terms of an extensive Design of Experiment (DOE) effort, to investigate the interactions among the various variables considered together to achieve a desired response. Thereafter, statistical regression techniques can be used to derive a model equation considering the input variables with significant effects.

All of this research effort used theoretical values when evaluating the simulation model. The levels considered for the test scenarios were arbitrary and may not be representative of real-world systems. Instead of the constant failure rate model that is currently assumed, realistic failure sub-models exhibiting wear-out conditions can be developed if failure data for existing UAS are made available. Similarly, sensor degradation can be incorporated in future research to model increased sensor maintenance in accordance to actual degradation patterns of a fielded sensor. In addition, when information on ISHM system prototypes are available, actual performance data can then be input into the simulation model to yield more realistic results.

An important assumption of the existing architecture and discrete-event simulation model is that in an ISHM-enabled UAS, the detection outcome by the baseline sensor and the eventual declaration by ISHM were assumed to be independent events, with the latter being the final authority in failure declaration. This effectively rendered the baseline sensor as a *'non-factor'* in the ISHM-enabled UAS simulation model in determining the expected lifetime of the UAS. This research does not investigate dependency of detection events, or different diagnostics or prognostics algorithms in resolving conflicts of baseline sensor and ISHM decisions, and future research could expound on developing ISHM algorithms to investigate dependency between them in order to define ISHM performance characteristics.

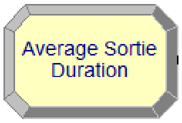
5.4 Summary

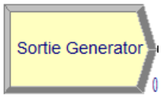
This research effort developed an analytic architecture and an associated discrete-event simulation to investigate the potential benefits of ISHM implementation onboard an UAS. From the results of the simulation, it was shown that ISHM presented the most cost-effective improvement over baseline systems in situations where the reliability of the UAS is poor (relative to manned systems) and the baseline sensor exhibited poor qualities in terms of missed detection and false alarm rates. Through simulation experiments involving defined test scenarios, it was observed that failure occurrence rates, sensor quality characteristics and ISHM performance specifications were significant factors in determining the output responses of the model. Although ISHM presented benefits in its envisioned implementation, the test scenarios exhibited instances whereby poor performance specifications of ISHM systems would lead to a reduced life expectancy, or increased maintenance actions, especially in the case of a highly reliable UAS.

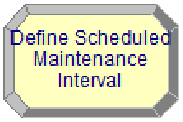
It is important to note that the results of this research seek to provide potential designers with top-level performance specifications of an ISHM implementation. However, the results of the analysis are only bounded by the defined assumptions of the simulation model. The analytic architecture is only a piece of the ISHM puzzle, and should be considered with other analyses to achieve the desired outcome of Integrated System Health Management for autonomous UAS.

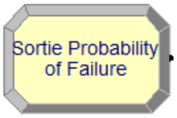
Appendix A: Description of Arena ® Modules and Sub-Models

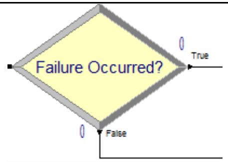
Initialization Modules

Title:	Average Sortie Duration
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Assign Module
Diagram:	
Purpose:	Assigns average sortie duration as a parameter to the simulation model.
Parameter:	NormalASD = 10 (hours)
Assumption/ Additional Information:	Assumed that an UAS mission that recovers Code 1 or Code 2 will fly an average mission length of 10 hours.

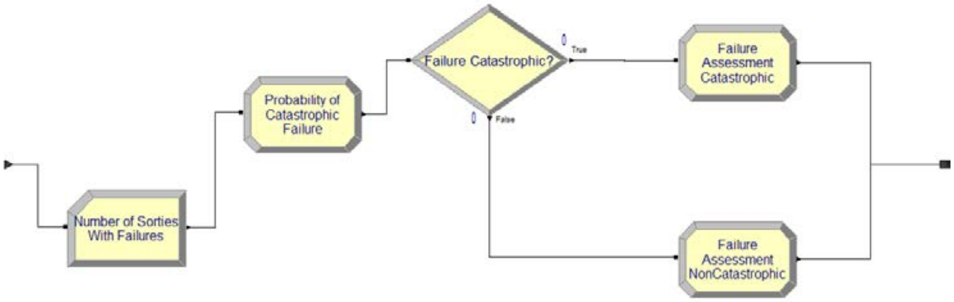
Title:	Sortie Generator
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Create Module
Diagram:	
Purpose:	Creates arrival entities (generate sorties) to simulation model at a specified rate.
Parameter:	Constant inter-arrival time of 12 hours, i.e. one sortie generated every 12 hours.
Assumption/ Additional Information:	Assumed that only 2 sorties planned in a 24-hour cycle for each UAS.

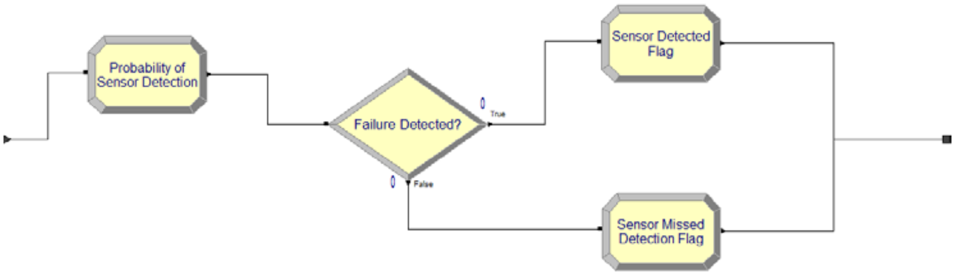
Title:	Define Scheduled Maintenance Interval
Applicable To:	Non-ISHM UAS Model Only
Type:	Assign Module
Diagram:	
Purpose:	Assigns the scheduled maintenance requirement to the Non-ISHM UAS model.
Parameter:	DefinedMaintenanceInterval = 1000 (hours)
Assumption:	Assumed to be a fixed interval throughout the life of the UAS.

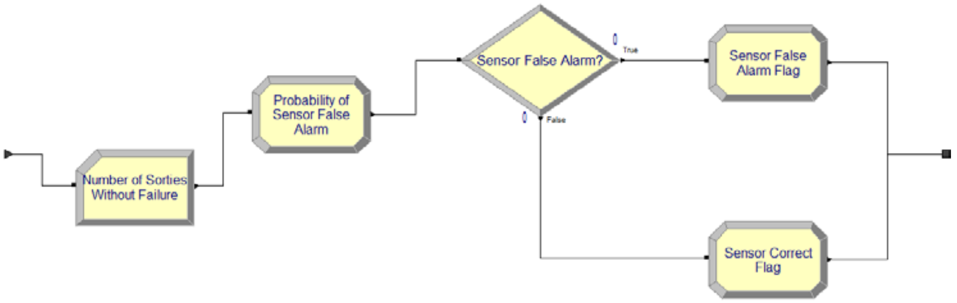
Title:	Sortie Probability of Failure
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Assign Module
Diagram:	
Purpose:	Calculates probability of failure for particular sortie based on occurrence rate.
Parameter:	FailureOccurrenceRate: *Typical Values considered:* 10^{-1}, 10^{-2}, 10^{-3}*(baseline),* 10^{-4}, *and* 10^{-5} *Unit: failure per hour.* ** Based on suggested probability levels defined in Table 2 [DoD, 2000].* ProbFailure = $1 - e^{-\text{FailureOccurrenceRate} * \text{NormalASD}}$ *Variable based on occurrence rate.* RandomFailureFlag: UNIF(0,1,*1*) *Assigns the first common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.*
Assumption/ Additional Information:	Failure rate assumed to be relatively constant during normal UAS operation if system design is mature [Blanchard, 2004]. The failure rate is usually what is presented in FMECA reports, e.g. 1 failure in 10^6 hours (or $\lambda = 10^{-6}$ failure per hour). Probability of failure is assumed to follow an exponential function with constant failure rate.

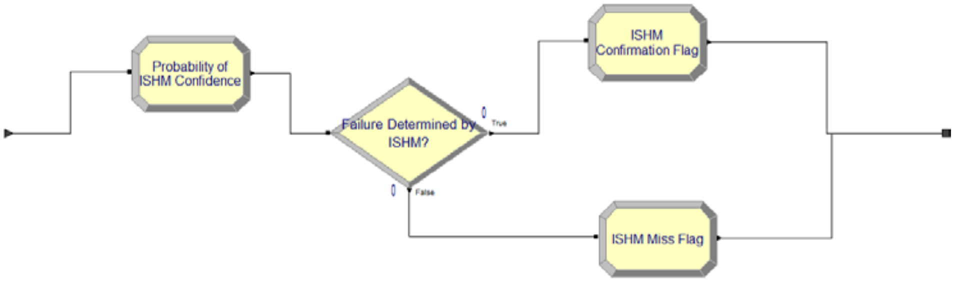
Title:	Failure Occurred?
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Decide Module
Diagram:	
Purpose:	Determines if a failure condition exists for each sortie.
Parameter:	True if RandomFailureFlag <= ProbFailure
Logic:	Based on presence (or absence) of failure condition within particular sortie, decides on the two major logic flows within each simulation model.
Assumption/ Additional Information:	For each of the two simulation models, there exist two similar major logic flows that include the *a) failure condition present*, and *b) failure condition absent* flows.

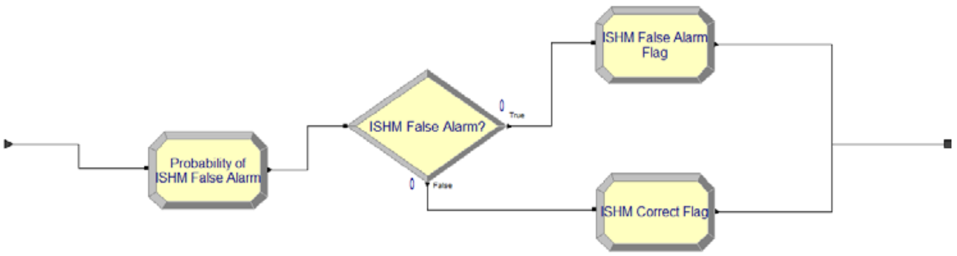
Failure Assessment and Detection Sub-Models

Title:	A1.3 Perform Failure Assessment
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Determines if a present failure condition is catastrophic or has a significant accumulated latent effect from prior missed detections.
Parameter:	Number of Sorties With Failures: *Record Module* ProbCatastrophicFailure = 26/132 = 0.197 LatencyFactor (range from 0 to 5) – attribute of current sortie AccumulatedLatencyEffect – system variable of UAS RandomCatastrophicFlag: UNIF(0,1,*2*) *Assigns the second common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.*
Logic:	Based on probability of a failure being catastrophic, assigns a status flag to a sortie. Also checks the accumulated latency effect from missed detections of past sorties against the LatencyThreshold (*fixed at 5)* to ascertain latency factor of current sortie.
Assumption/ Additional Information:	Based on NASA report in Feb 2007, there are 26 potentially catastrophic failures out of 132 identified failure conditions for a generic UAS [Hayhurst *et al.*, 2007]. Assumed that a maximum of 5 prior missed detections will result in the upgrade in severity of a current defect that will result in a mishap if undetected.

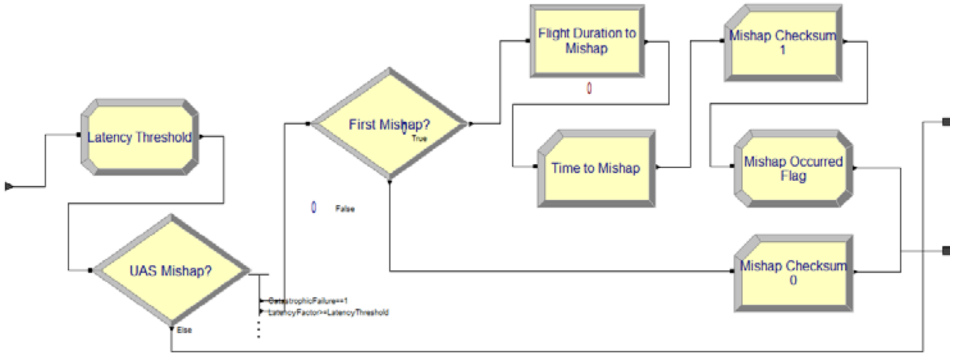
Title:	A1.2 Perform Failure Detection
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Determines if a present failure condition is detected by baseline sensor.
Parameter:	ProbSensorDetection: *Typical Values considered: 0.6, 0.7, 0.8 (baseline), and 0.9* RandomSensorDetectionFlag: UNIF(0,1,*3*) *Assigns the third common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.* IF RandomSensorDetectionFlag <= ProbSensorDetection, SensorDetected (status flag) = 1, ELSE SensorDetected (status flag) = 0.
Logic:	Based on probability of sensor detection, assigns a status flag to a sortie.
Assumption/ Additional Information:	Assumed to be a baseline sensor characteristic for generic UAS. Has a positive correlation with expected UAS lifetime.

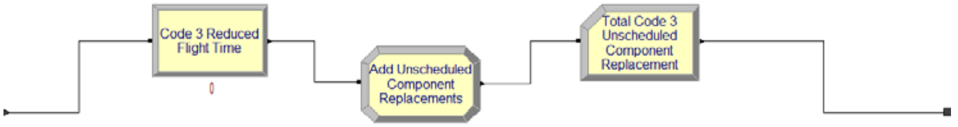
Title:	A1.2 Perform Failure Detection (False Alarm)
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Determines if baseline sensor produces a false alarm when no failure condition exists.
Parameter:	Number of Sorties Without Failure: *Record Module* ProbSensorFalseAlarm: *Typical Values considered: 0.01, 0.02, 0.03 (baseline), 0.04 and 0.05* RandomSensorFAFlag: UNIF(0,1,*4*) *Assigns the fourth common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.* IF RandomSensorFAFlag <= ProbSensorFalseAlarm, SensorFalseAlarm (status flag) = 1, ELSE SensorFalseAlarm (status flag) = 0.
Logic:	Based on probability of sensor false alarm, assigns a status flag to a sortie.
Assumption/ Additional Information:	Assumed to be a baseline sensor characteristic for generic UAS. Has a positive correlation with unscheduled sensor maintenance actions.

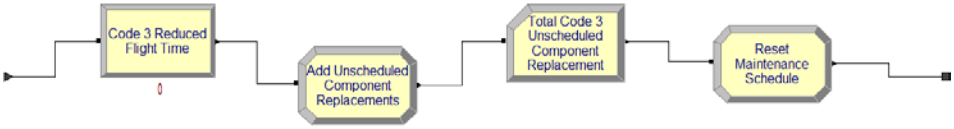
Title:	A2.1 Perform Diagnostics and Prognostics Assessment
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if a present failure condition is ascertained by ISHM.
Parameter:	ProbISHMConfidence: *Typical Values considered: 0.6, 0.7, 0.8 (baseline), and 0.9* RandomISHMDetectionFlag: UNIF(0,1,5) *Assigns the fifth common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.* IF RandomISHMDetectionFlag <= ProbISHMConfidence, ISHMConfirmed (status flag) = 1, ELSE ISHMConfirmed (status flag) = 0.
Logic:	Based on probability of ISHM confidence (representing strength of ISHM diagnostics and prognostics algorithms), assigns a status flag to a sortie.
Assumption/ Additional Information:	Desired performance specification of ISHM system. Has a positive correlation with the expected UAS lifetime.

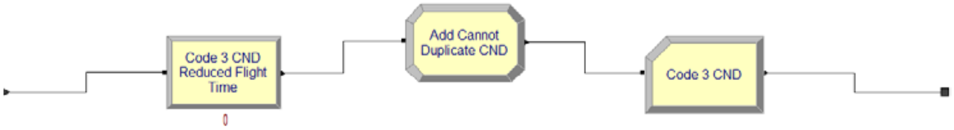
Title:	A2.1 Perform Diagnostics and Prognostics Assessment (False Alarm)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if ISHM produces a false alarm when no failure condition exists.
Parameter:	ProbISHMFalseAlarm *Typical Values considered: 0.01, 0.02, 0.03 (baseline), 0.04 and 0.05* RandomISHMFAFlag: UNIF(0,1,*6*) *Assigns the sixth common random number stream to this variable as a means of variance reduction between the ISHM-enabled UAS model and the Non-ISHM UAS model.* IF RandomISHMFAFlag <= ProbISHMFalseAlarm, ISHMFalseAlarm (status flag) = 1, ELSE ISHMFalseAlarm (status flag) = 0.
Logic:	Based on probability of ISHM false alarm (representing strength of ISHM diagnostics and prognostics algorithms), assigns a status flag to a sortie.
Assumption/ Additional Information:	Desired performance specification of ISHM system. Has a positive correlation with unscheduled ISHM maintenance actions.

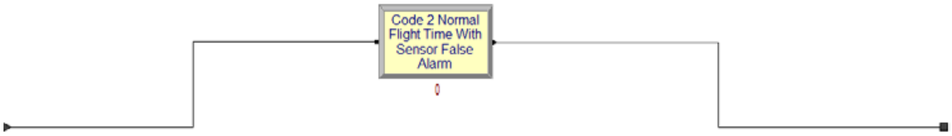
UAS Recovery States Sub-Models

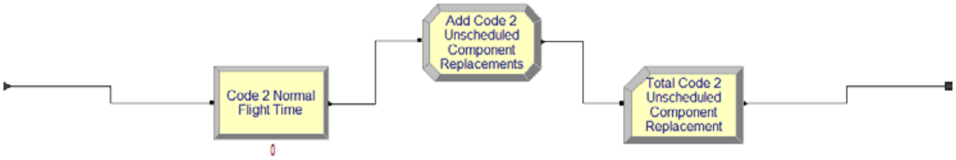
Title:	UAS Mishap Determination
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Determines if a present failure condition will result in a mishap if undetected. Terminate UAS flight upon detection of first mishap.
Parameter:	LatencyThreshold = 5 UASCrashed (1 or 0, status flag) Flight Duration to Mishap = 0.3 * NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS.
Logic:	Given that an existing failure is undetected, an UAS mishap will occur if the failure is catastrophic, or if the UAS had 5 previous missed detections of existing failure condition.
Assumption/ Additional Information:	Assumed that a maximum of 5 prior missed detections will result in the upgrade in severity of a current defect that will result in a mishap if undetected. In the event of a mishap, it is assumed that the UAS will fly for only 30% of its normal sortie duration.

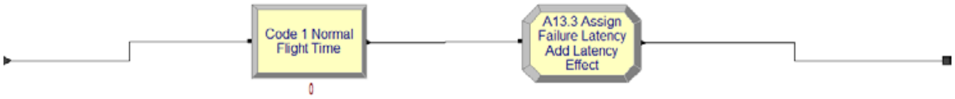
Title:	Code 3 Recoveries
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Calculates the flight time of a Code 3 mission. Also add an unscheduled component replacement action.
Parameter:	Code 3 Flight Duration = 0.5 * NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS. ComponentReplacement – Counter for number of component replacements being carried out.
Logic:	Process the flight duration and required maintenance activities for a Code 3 recovery.
Assumption/ Additional Information:	In the event of a Code 3, it is assumed that the UAS will fly for only 50% of its normal sortie duration.

Title:	Code 3 Recoveries
Applicable To:	Non-ISHM UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Calculates the flight time of a Code 3 mission. Also adds an unscheduled component replacement action and resets the maintenance interval.
Parameter:	Code 3 Flight Duration = 0.5 * NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS. ComponentReplacement – Counter for number of component replacements being carried out. TimeToScheduledMaintenance = DefinedMaintenanceInterval
Logic:	Process the flight duration and required maintenance activities for a Code 3 recovery. Resets the scheduled maintenance interval upon completion of component replacement.
Assumption/ Additional Information:	In the event of a Code 3, it is assumed that the UAS will fly for only 50% of its normal sortie duration.

Title:	Code 3 Recoveries (CND)
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Calculates the flight time of a Code 3 mission due to ISHM false alarm (for the ISHM-Enabled UAS model) and due to sensor false alarm (for the Non-ISHM UAS model). Also add a Cannot Duplicate (CND) incident.
Parameter:	Code 3 Flight Duration = 0.5 * NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS. CND – Counter for number of CND incidents.
Logic:	Process the flight duration and increment the number of CND incidents for a Code 3 CND recovery.
Assumption/ Additional Information:	In the event of a reported Code 3 (although it is a false alarm), it is assumed that the UAS will fly for only 50% of its normal sortie duration.

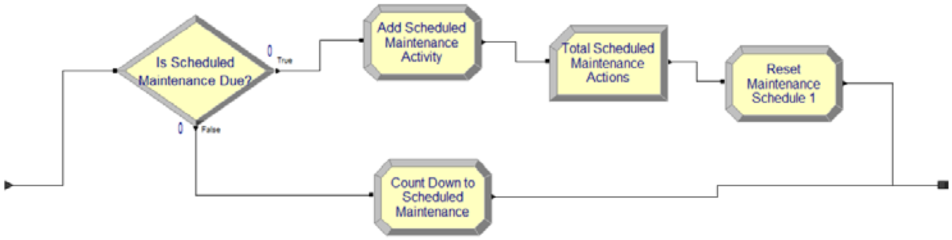
Title:	Code 2 Recoveries (Sensor False Alarm Only)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model with Single Process Module Only
Diagram:	
Purpose:	Calculates the flight time of a Code 2 mission. For this case, this sub-model only applies to a sortie without a failure condition; correctly diagnosed by ISHM but sensor produces a false alarm.
Parameter:	Code 2 Flight Duration = NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS.
Logic:	Process the flight duration Code 2 recovery. Requirement for sensor maintenance due to false alarm is being processed by the proceeding sub-model.
Assumption/ Additional Information:	In the event of a Code 2, it is assumed that the UAS will still complete its planned mission flying its normal sortie duration.

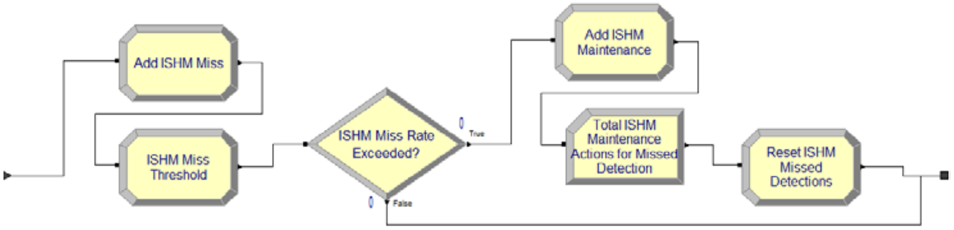
Title:	Code 2 Recoveries (ISHM Missed Detection Only)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Calculates the flight time of a Code 2 mission. For this case, there is a failure condition that is correctly detected by the baseline sensor but ISHM denies the failure condition. Hence, also add an unscheduled component replacement action as a failure condition exists.
Parameter:	Code 2 Flight Duration = NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS. ComponentReplacement – Counter for number of component replacements being carried out.
Logic:	Process the flight duration and required maintenance activities for a Code 2 recovery. Requirement for ISHM maintenance due to missed detection is being processed by the proceeding sub-model.
Assumption/ Additional Information:	In the event of a Code 2, it is assumed that the UAS will still complete its planned mission flying its normal sortie duration.

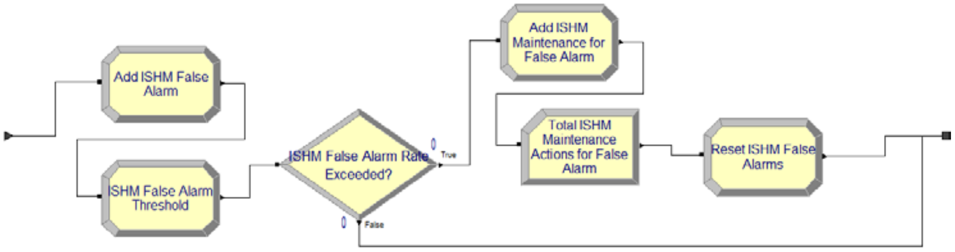
Title:	Code 1 Recoveries
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Calculates the flight time of a Code 1 mission. Also assigns failure latency to UAS system due to a missed detection (by both ISHM and sensor for an ISHM-Enabled UAS model, and by sensor for a Non-ISHM UAS model).
Parameter:	Code 1 Flight Duration = NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS. AccumulatedLatencyEffect – system variable of UAS (increase by 1)
Logic:	Process the flight duration and assign failure latency for a Code 1 recovery with missed detections by both ISHM and baseline sensor.
Assumption/ Additional Information:	In the event of a Code 1 recovery with a missed detection of a failure condition, it is assumed that the UAS will still complete its planned mission flying its normal sortie duration.

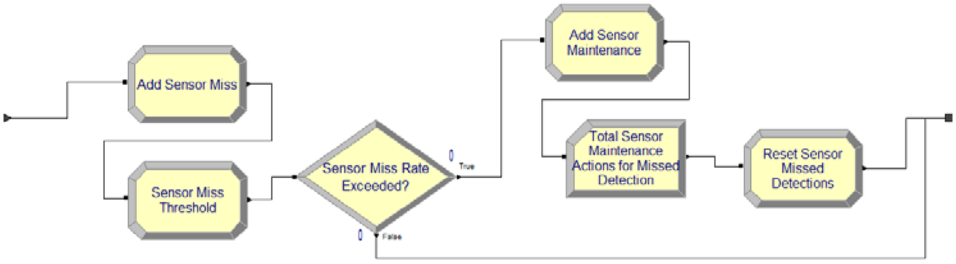
Title:	Code 1 Recoveries (Good Flight)
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model with Single Process Module Only
Diagram:	
Purpose:	Calculates the flight time of an uneventful Code 1 mission.
Parameter:	Code 1 Flight Duration = NormalASD – Implemented as a process delay to calculate the accumulated flight time of a UAS.
Logic:	Process the flight duration for an uneventful Code 1 recovery.

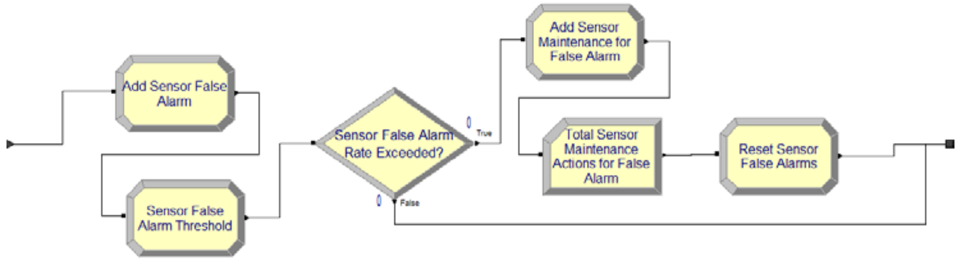
Maintenance Activities Sub-Models

Title:	A14.1 Perform Scheduled Maintenance
Applicable To:	Non-ISHM UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if scheduled maintenance is due.
Parameter:	TimeToScheduledMaintenance – Time counter that counts down towards due time for scheduled maintenance. ScheduledMaintenance – Counter for number of scheduled maintenance actions being carried out.
Logic:	Performs scheduled maintenance action if TimeToScheduledMaintenance is less than or equals to 0. Resets the scheduled maintenance interval upon completion of scheduled maintenance action.
Assumption/ Additional Information:	Even though scheduled maintenance actions are being carried out, it is assumed that the failure rate of the UAS does not change, i.e. system is mature in its operational phase with constant failure rate.

Title:	A22.1 Perform Unscheduled ISHM Maintenance (ISHM Missed Detection)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if unscheduled ISHM maintenance is required.
Parameter:	ISHMMissThreshold = 4 ISHMMaintenance – Counter for number of unscheduled ISHM maintenance actions being carried out.
Logic:	Performs unscheduled ISHM maintenance action if ISHM missed detection threshold is exceeded. Resets ISHM missed detection count upon completion of ISHM maintenance.
Assumption/ Additional Information:	Assumed to be an arbitrary target threshold to carry out ISHM maintenance when exceeded; should be lower than assumed accumulated latency effect to be meaningful.

Title:	A22.1 Perform Unscheduled ISHM Maintenance (ISHM False Alarm)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if unscheduled ISHM maintenance is required.
Parameter:	ISHMFalseAlarmThreshold = 10 ISHMMaintenance – Counter for number of unscheduled ISHM maintenance actions being carried out.
Logic:	Performs unscheduled ISHM maintenance action if ISHM false alarm threshold is exceeded. Resets ISHM false alarm count upon completion of ISHM maintenance.
Assumption/ Additional Information:	Assumed to be an arbitrary target threshold to carry out ISHM maintenance when exceeded; should be higher that missed detection threshold due to no safety of flight concern.

Title:	A14.3 Perform Unscheduled Sensor Maintenance (Sensor Missed Detection)
Applicable To:	ISHM-Enabled UAS Model Only
Type:	Sub-Model
Diagram:	
Purpose:	Determines if unscheduled sensor maintenance is required.
Parameter:	SensorMissThreshold = 4 SensorMaintenance – Counter for number of unscheduled sensor maintenance actions being carried out.
Logic:	Performs unscheduled sensor maintenance action if sensor missed detection threshold is exceeded. Resets sensor missed detection count upon completion of sensor maintenance.
Assumption/ Additional Information:	Assumed to be an arbitrary target threshold to carry out sensor maintenance when exceeded; should be lower than assumed accumulated latency effect to be meaningful. Only applicable for an ISHM-Enabled UAS model since for the isolated baseline sensor of a non-ISHM UAS, the latter would not know that it has missed a detection without secondary detection mechanisms (such as onboard ISHM).

Title:	A14.3 Perform Unscheduled Sensor Maintenance (Sensor False Alarm)
Applicable To:	Both ISHM-Enabled UAS and Non-ISHM UAS Models
Type:	Sub-Model
Diagram:	
Purpose:	Determines if unscheduled sensor maintenance is required.
Parameter:	SensorFalseAlarmThreshold = 10 SensorMaintenance – Counter for number of unscheduled sensor maintenance actions being carried out.
Logic:	Performs unscheduled sensor maintenance action if sensor false alarm threshold is exceeded. Resets sensor false alarm count upon completion of sensor maintenance.
Assumption/ Additional Information:	Assumed to be an arbitrary target threshold to carry out sensor maintenance when exceeded; should be higher that missed detection threshold due to no safety of flight concern.

Statistics Record Modules

Title:	Statistics Collection
Type:	Record Modules
Purpose:	Records parameters of interest for verification and analysis.
Module Names:	For Both Simulation Models UAS Expected Lifetime Total Unscheduled Component Replacements Total Sensor Maintenance Number of Sorties With Failures Number of Sorties Without Failures For ISHM-Enabled UAS Model Only Code 2 With ISHM Miss Code 1 With Both ISHM and Sensor Misses Code 3 With Sensor Miss Code 3 With Both ISHM and Sensor Confirmation Code 3 With Both ISHM and Sensor False Alarms Code 3 With ISHM False Alarm Only Code 2 With Sensor False Alarm Code 1 Good Flight Without False Alarm Total ISHM Maintenance For Non-ISHM UAS Only Code 3 Sensor Detected Code 1 Sensor Miss Code 3 CND With Sensor False Alarm Code 1 Good Flight Without False Alarm Total Scheduled Maintenance

Appendix B: Analysis Results – Experimental Objectives and Ranking Results

Objective 1: Investigate Dependence of UAS Expected Lifetime on Failure Rate, λ

Table B-1 – Dependence of UAS Expected Lifetime on Failure Rate, λ

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of Detection (Baseline Sensor)	Probability of ISHM Confidence	UAS Lifetime (ISHM-Enabled UAS) [Hours]	UAS Lifetime (Non-ISHM UAS) [Hours]
1	0.00001	0.6	0.9	3,662,213.50	1,025,301.50
2	0.00001	0.7	0.9	3,662,213.50	1,490,861.00
3	0.00001	0.8	0.9	3,662,213.50	2,423,547.00
4	0.00001	0.9	0.9	3,662,213.50	7,199,106.50
5	0.00001	0.6	0.8	2,029,693.00	1,025,301.50
6	0.00001	0.7	0.8	2,029,693.00	1,490,861.00
7	0.00001	0.8	0.8	2,029,693.00	2,423,547.00
8	0.00001	0.9	0.8	2,029,693.00	7,199,106.50
9	0.00001	0.6	0.7	1,722,959.50	1,025,301.50
10	0.00001	0.7	0.7	1,722,959.50	1,490,861.00
11	0.00001	0.8	0.7	1,722,959.50	2,423,547.00
12	0.00001	0.9	0.7	1,722,959.50	7,199,106.50
13	0.00001	0.6	0.6	1,541,751.50	1,025,301.50
14	0.00001	0.7	0.6	1,541,751.50	1,490,861.00
15	0.00001	0.8	0.6	1,541,751.50	2,423,547.00
16	0.00001	0.9	0.6	1,541,751.50	7,199,106.50
17	0.0001	0.6	0.9	354,312.50	103,479.50
18	0.0001	0.7	0.9	354,312.50	154,323.50
19	0.0001	0.8	0.9	354,312.50	253,859.00
20	0.0001	0.9	0.9	354,312.50	731,245.50
21	0.0001	0.6	0.8	191,844.50	103,479.50
22	0.0001	0.7	0.8	191,844.50	154,323.50
23	0.0001	0.8	0.8	191,844.50	253,859.00
24	0.0001	0.9	0.8	191,844.50	731,245.50
25	0.0001	0.6	0.7	158,851.50	103,479.50
26	0.0001	0.7	0.7	158,851.50	154,323.50
27	0.0001	0.8	0.7	158,851.50	253,859.00
28	0.0001	0.9	0.7	158,851.50	731,245.50
29	0.0001	0.6	0.6	139,169.00	103,479.50
30	0.0001	0.7	0.6	139,169.00	154,323.50
31	0.0001	0.8	0.6	139,169.00	253,859.00
32	0.0001	0.9	0.6	139,169.00	731,245.50
33	0.001	0.6	0.9	38,676.00	10,755.50
34	0.001	0.7	0.9	38,676.00	15,623.00
35	0.001	0.8	0.9	38,676.00	24,979.50
36	0.001	0.9	0.9	38,676.00	74,975.50
37	0.001	0.6	0.8	22,096.50	10,755.50
38	0.001	0.7	0.8	22,096.50	15,623.00
39	0.001	0.8	0.8	22,096.50	24,979.50
40	0.001	0.9	0.8	22,096.50	74,975.50

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of Detection (Baseline Sensor)	Probability of ISHM Confidence	UAS Lifetime (ISHM-Enabled UAS) [Hours]	UAS Lifetime (Non-ISHM UAS) [Hours]
41	0.001	0.6	0.7	18,828.00	10,755.50
42	0.001	0.7	0.7	18,828.00	15,623.00
43	0.001	0.8	0.7	18,828.00	24,979.50
44	0.001	0.9	0.7	18,828.00	74,975.50
45	0.001	0.6	0.6	16,477.50	10,755.50
46	0.001	0.7	0.6	16,477.50	15,623.00
47	0.001	0.8	0.6	16,477.50	24,979.50
48	0.001	0.9	0.6	16,477.50	74,975.50
49	0.01	0.6	0.9	3,878.50	1,105.00
50	0.01	0.7	0.9	3,878.50	1,687.50
51	0.01	0.8	0.9	3,878.50	2,634.50
52	0.01	0.9	0.9	3,878.50	7,679.50
53	0.01	0.6	0.8	2,266.00	1,105.00
54	0.01	0.7	0.8	2,266.00	1,687.50
55	0.01	0.8	0.8	2,266.00	2,634.50
56	0.01	0.9	0.8	2,266.00	7,679.50
57	0.01	0.6	0.7	1,914.50	1,105.00
58	0.01	0.7	0.7	1,914.50	1,687.50
59	0.01	0.8	0.7	1,914.50	2,634.50
60	0.01	0.9	0.7	1,914.50	7,679.50
61	0.01	0.6	0.6	1,689.00	1,105.00
62	0.01	0.7	0.6	1,689.00	1,687.50
63	0.01	0.8	0.6	1,689.00	2,634.50
64	0.01	0.9	0.6	1,689.00	7,679.50
65	0.1	0.6	0.9	432.50	121.00
66	0.1	0.7	0.9	432.50	189.00
67	0.1	0.8	0.9	432.50	307.50
68	0.1	0.9	0.9	432.50	865.50
69	0.1	0.6	0.8	246.50	121.00
70	0.1	0.7	0.8	246.50	189.00
71	0.1	0.8	0.8	246.50	307.50
72	0.1	0.9	0.8	246.50	865.50
73	0.1	0.6	0.7	208.00	121.00
74	0.1	0.7	0.7	208.00	189.00
75	0.1	0.8	0.7	208.00	307.50
76	0.1	0.9	0.7	208.00	865.50
77	0.1	0.6	0.6	185.00	121.00
78	0.1	0.7	0.6	185.00	189.00
79	0.1	0.8	0.6	185.00	307.50
80	0.1	0.9	0.6	185.00	865.50

Objective 2: Maximize Percentage of Lifetime Extension through ISHM Implementation

Table B-2 – Maximize Percentage of Lifetime Extension through ISHM Implementation

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of Detection (Baseline Sensor)	Probability of ISHM Confidence	UAS Lifetime (ISHM-Enabled UAS) [Hours] (a)	UAS Lifetime (Non-ISHM UAS) [Hours] (b)	Increase in UAS Lifetime (c) = (a)-(b)	% Lifetime Gain (d) = (c)/(b)
1	0.001	0.6	0.9	38676	10755.5	27920.5	259.59%
2	0.01	0.6	0.9	3878.5	1105	2773.5	251.00%
3	0.0001	0.6	0.9	354312.5	103479.5	250833	242.40%
4	0.001	0.7	0.9	38676	15623	23053	147.56%
5	0.01	0.7	0.9	3878.5	1687.5	2191	129.84%
6	0.0001	0.7	0.9	354312.5	154323.5	199989	129.59%
7	0.001	0.6	0.8	22096.5	10755.5	11341	105.44%
8	0.01	0.6	0.8	2266	1105	1161	105.07%
9	0.0001	0.6	0.8	191844.5	103479.5	88365	85.39%
10	0.001	0.6	0.7	18828	10755.5	8072.5	75.05%
11	0.01	0.6	0.7	1914.5	1105	809.5	73.26%
12	0.001	0.8	0.9	38676	24979.5	13696.5	54.83%
13	0.0001	0.6	0.7	158851.5	103479.5	55372	53.51%
14	0.001	0.6	0.6	16477.5	10755.5	5722	53.20%
15	0.01	0.6	0.6	1689	1105	584	52.85%
16	0.01	0.8	0.9	3878.5	2634.5	1244	47.22%
17	0.001	0.7	0.8	22096.5	15623	6473.5	41.44%
18	0.0001	0.8	0.9	354312.5	253859	100453.5	39.57%
19	0.0001	0.6	0.6	139169	103479.5	35689.5	34.49%
20	0.01	0.7	0.8	2266	1687.5	578.5	34.28%
21	0.0001	0.7	0.8	191844.5	154323.5	37521	24.31%
22	0.001	0.7	0.7	18828	15623	3205	20.51%
23	0.01	0.7	0.7	1914.5	1687.5	227	13.45%
24	0.001	0.7	0.6	16477.5	15623	854.5	5.47%
25	0.0001	0.7	0.7	158851.5	154323.5	4528	2.93%
26	0.01	0.7	0.6	1689	1687.5	1.5	0.09%
27	0.0001	0.7	0.6	139169	154323.5	-15154.5	-9.82%
28	0.001	0.8	0.8	22096.5	24979.5	-2883	-11.54%
29	0.01	0.8	0.8	2266	2634.5	-368.5	-13.99%
30	0.0001	0.8	0.8	191844.5	253859	-62014.5	-24.43%
31	0.001	0.8	0.7	18828	24979.5	-6151.5	-24.63%
32	0.01	0.8	0.7	1914.5	2634.5	-720	-27.33%
33	0.001	0.8	0.6	16477.5	24979.5	-8502	-34.04%
34	0.01	0.8	0.6	1689	2634.5	-945.5	-35.89%
35	0.0001	0.8	0.7	158851.5	253859	-95007.5	-37.43%
36	0.0001	0.8	0.6	139169	253859	-114690	-45.18%
37	0.001	0.9	0.9	38676	74975.5	-36299.5	-48.42%
38	0.01	0.9	0.9	3878.5	7679.5	-3801	-49.50%
39	0.0001	0.9	0.9	354312.5	731245.5	-376933	-51.55%
40	0.01	0.9	0.8	2266	7679.5	-5413.5	-70.49%
41	0.001	0.9	0.8	22096.5	74975.5	-52879	-70.53%
42	0.0001	0.9	0.8	191844.5	731245.5	-539401	-73.76%
43	0.001	0.9	0.7	18828	74975.5	-56147.5	-74.89%
44	0.01	0.9	0.7	1914.5	7679.5	-5765	-75.07%
45	0.01	0.9	0.6	1689	7679.5	-5990.5	-78.01%
46	0.001	0.9	0.6	16477.5	74975.5	-58498	-78.02%
47	0.0001	0.9	0.7	158851.5	731245.5	-572394	-78.28%
48	0.0001	0.9	0.6	139169	731245.5	-592076.5	-80.97%

Objective 3: Minimize Number of Cannot Duplicate (CND) Cases through ISHM Implementation

Table B-3 – Minimize Number of Cannot Duplicate (CND) Cases through ISHM Implementation

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of False Alarm (Baseline Sensor)	Probability of ISHM False Alarm	Total Cases of CND (ISHM-Enabled UAS) [a]	Total Cases of CND (Non-ISHM UAS) [b]	Reduction in CND [c]=[b]-[a]	% Reduction in CND [d]=[c]/[b]
1	0.0001	0.05	0.01	193	1286	1093	84.99%
2	0.0001	0.05	0.02	390	1286	896	69.67%
3	0.0001	0.04	0.01	193	1023	830	81.13%
4	0.0001	0.05	0.03	584	1286	702	54.59%
5	0.0001	0.04	0.02	390	1023	633	61.88%
6	0.0001	0.03	0.01	193	768	575	74.87%
7	0.0001	0.05	0.04	778	1286	508	39.50%
8	0.0001	0.04	0.03	584	1023	439	42.91%
9	0.0001	0.03	0.02	390	768	378	49.22%
10	0.0001	0.02	0.01	193	515	322	62.52%
11	0.0001	0.05	0.05	977	1286	309	24.03%
12	0.0001	0.04	0.04	778	1023	245	23.95%
13	0.0001	0.03	0.03	584	768	184	23.96%
14	0.0001	0.02	0.02	390	515	125	24.27%
15	0.001	0.05	0.01	22	128	106	82.81%
16	0.001	0.05	0.02	45	128	83	64.84%
17	0.001	0.04	0.01	22	103	81	78.64%
18	0.001	0.05	0.03	66	128	62	48.44%
19	0.0001	0.01	0.01	193	252	59	23.41%
20	0.001	0.04	0.02	45	103	58	56.31%
21	0.001	0.03	0.01	22	76	54	71.05%
22	0.0001	0.04	0.05	977	1023	46	4.50%
23	0.001	0.05	0.04	89	128	39	30.47%
24	0.001	0.04	0.03	66	103	37	35.92%
25	0.001	0.03	0.02	45	76	31	40.79%
26	0.001	0.02	0.01	22	51	29	56.86%
27	0.001	0.05	0.05	111	128	17	13.28%
28	0.001	0.04	0.04	89	103	14	13.59%
29	0.01	0.05	0.01	2	13	11	84.62%
30	0.001	0.03	0.03	66	76	10	13.16%
31	0.01	0.04	0.01	2	10	8	80.00%
32	0.01	0.05	0.02	5	13	8	61.54%
33	0.01	0.03	0.01	2	8	6	75.00%
34	0.01	0.05	0.03	7	13	6	46.15%
35	0.001	0.02	0.02	45	51	6	11.76%
36	0.01	0.04	0.02	5	10	5	50.00%
37	0.01	0.05	0.04	9	13	4	30.77%
38	0.01	0.02	0.01	2	5	3	60.00%
39	0.01	0.03	0.02	5	8	3	37.50%
40	0.01	0.04	0.03	7	10	3	30.00%
41	0.001	0.01	0.01	22	25	3	12.00%
42	0.01	0.05	0.05	11	13	2	15.38%
43	0.01	0.03	0.03	7	8	1	12.50%
44	0.01	0.04	0.04	9	10	1	10.00%
45	0.01	0.01	0.01	2	2	0	0.00%
46	0.01	0.02	0.02	5	5	0	0.00%
47	0.01	0.04	0.05	11	10	-1	-10.00%
48	0.01	0.03	0.04	9	8	-1	-12.50%
49	0.01	0.02	0.03	7	5	-2	-40.00%
50	0.01	0.03	0.05	11	8	-3	-37.50%

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of False Alarm (Baseline Sensor)	Probability of ISHM False Alarm	Total Cases of CND (ISHM-Enabled UAS) [a]	Total Cases of CND (Non-ISHM UAS) [b]	Reduction in CND [c]=[b]-[a]	% Reduction in CND [d]=[c]/[b]
51	0.01	0.01	0.02	5	2	-3	-150.00%
52	0.01	0.02	0.04	9	5	-4	-80.00%
53	0.01	0.01	0.03	7	2	-5	-250.00%
54	0.01	0.02	0.05	11	5	-6	-120.00%
55	0.01	0.01	0.04	9	2	-7	-350.00%
56	0.001	0.04	0.05	111	103	-8	-7.77%
57	0.01	0.01	0.05	11	2	-9	-450.00%
58	0.0001	0.03	0.04	778	768	-10	-1.30%
59	0.001	0.03	0.04	89	76	-13	-17.11%
60	0.001	0.02	0.03	66	51	-15	-29.41%
61	0.001	0.01	0.02	45	25	-20	-80.00%
62	0.001	0.03	0.05	111	76	-35	-46.05%
63	0.001	0.02	0.04	89	51	-38	-74.51%
64	0.001	0.01	0.03	66	25	-41	-164.00%
65	0.001	0.02	0.05	111	51	-60	-117.65%
66	0.001	0.01	0.04	89	25	-64	-256.00%
67	0.0001	0.02	0.03	584	515	-69	-13.40%
68	0.001	0.01	0.05	111	25	-86	-344.00%
69	0.0001	0.01	0.02	390	252	-138	-54.76%
70	0.0001	0.03	0.05	977	768	-209	-27.21%
71	0.0001	0.02	0.04	778	515	-263	-51.07%
72	0.0001	0.01	0.03	584	252	-332	-131.75%
73	0.0001	0.02	0.05	977	515	-462	-89.71%
74	0.0001	0.01	0.04	778	252	-526	-208.73%
75	0.0001	0.01	0.05	977	252	-725	-287.70%

Objective 4: Minimize Number of Maintenance Actions through ISHM Implementation

Table B-4 – Minimize Number of Maintenance Actions through ISHM Implementation

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of False Alarm (Baseline Sensor)	Probability of ISHM False Alarm	Total Maintenance Actions (ISHM-Enabled UAS) [a]	Total Maintenance Actions (Non-ISHM UAS) [b]	Reduction of Maintenance Actions [c]=[b]-[a]	% Reduction in Maintenance Actions [d]=[c]/[b]
1	0.0001	0.05	0.01	309	1655	1346	81.33%
2	0.0001	0.05	0.02	526	1655	1129	68.22%
3	0.0001	0.04	0.01	289	1367	1078	78.86%
4	0.0001	0.05	0.03	739	1655	916	55.35%
5	0.0001	0.04	0.02	506	1367	861	62.98%
6	0.0001	0.03	0.01	270	1088	818	75.18%
7	0.0001	0.05	0.04	952	1655	703	42.48%
8	0.0001	0.04	0.03	719	1367	648	47.40%
9	0.0001	0.03	0.02	487	1088	601	55.24%
10	0.0001	0.02	0.01	252	811	559	68.93%
11	0.0001	0.05	0.05	1171	1655	484	29.24%
12	0.0001	0.04	0.04	932	1367	435	31.82%
13	0.0001	0.03	0.03	700	1088	388	35.66%
14	0.0001	0.02	0.02	469	811	342	42.17%
15	0.0001	0.01	0.01	232	523	291	55.64%
16	0.0001	0.04	0.05	1151	1367	216	15.80%
17	0.0001	0.03	0.04	913	1088	175	16.08%
18	0.0001	0.02	0.03	682	811	129	15.91%
19	0.001	0.05	0.01	36	157	121	77.13%
20	0.001	0.05	0.02	61	157	96	61.25%
21	0.001	0.04	0.01	34	130	96	73.85%
22	0.0001	0.01	0.02	449	523	74	14.15%
23	0.001	0.05	0.03	84	157	73	46.63%
24	0.001	0.04	0.02	59	130	71	54.62%
25	0.001	0.03	0.01	32	100	68	68.00%
26	0.001	0.05	0.04	109	157	48	30.75%
27	0.001	0.04	0.03	82	130	48	36.92%
28	0.001	0.02	0.01	29	73	44	60.27%
29	0.001	0.03	0.02	57	100	43	43.00%
30	0.001	0.05	0.05	134	157	23	14.87%
31	0.001	0.04	0.04	107	130	23	17.69%
32	0.001	0.03	0.03	80	100	20	20.00%
33	0.001	0.02	0.02	54	73	19	26.03%
34	0.001	0.01	0.01	27	44	17	38.64%
35	0.01	0.05	0.01	4	15	11	73.15%
36	0.01	0.04	0.01	4	12	8	66.67%
37	0.01	0.05	0.02	7	15	8	53.02%
38	0.01	0.03	0.01	3	10	7	70.00%
39	0.01	0.05	0.03	9	15	6	39.60%
40	0.01	0.04	0.02	7	12	5	41.67%
41	0.01	0.03	0.02	6	10	4	40.00%
42	0.01	0.02	0.01	3	6	3	50.00%
43	0.01	0.04	0.03	9	12	3	25.00%
44	0.01	0.05	0.04	12	15	3	19.46%
45	0.01	0.03	0.03	8	10	2	20.00%
46	0.01	0.05	0.05	14	15	1	6.04%
47	0.01	0.01	0.01	3	3	0	0.00%
48	0.01	0.02	0.02	6	6	0	0.00%
49	0.01	0.04	0.04	12	12	0	0.00%
50	0.01	0.03	0.04	11	10	-1	-10.00%

Ranking	Failure Occurrence Rate [Per Flying Hour]	Probability of False Alarm (Baseline Sensor)	Probability of ISHM False Alarm	Total Maintenance Actions (ISHM-Enabled UAS) [a]	Total Maintenance Actions (Non-ISHM UAS) [b]	Reduction of Maintenance Actions [c]=[b]-[a]	% Reduction in Maintenance Actions [d]=[c]/[b]
51	0.001	0.04	0.05	132	130	-2	-1.54%
52	0.01	0.04	0.05	14	12	-2	-16.67%
53	0.01	0.02	0.03	8	6	-2	-33.33%
54	0.01	0.03	0.05	13	10	-3	-30.00%
55	0.01	0.01	0.02	6	3	-3	-100.00%
56	0.001	0.02	0.03	77	73	-4	-5.48%
57	0.001	0.03	0.04	105	100	-5	-5.00%
58	0.01	0.02	0.04	11	6	-5	-83.33%
59	0.01	0.01	0.03	8	3	-5	-166.67%
60	0.01	0.02	0.05	13	6	-7	-116.67%
61	0.001	0.01	0.02	52	44	-8	-18.18%
62	0.01	0.01	0.04	11	3	-8	-266.67%
63	0.01	0.01	0.05	13	3	-10	-333.33%
64	0.001	0.02	0.04	102	73	-29	-39.73%
65	0.001	0.03	0.05	130	100	-30	-30.00%
66	0.001	0.01	0.03	75	44	-31	-70.45%
67	0.0001	0.03	0.05	1132	1088	-44	-4.04%
68	0.001	0.02	0.05	127	73	-54	-73.97%
69	0.001	0.01	0.04	100	44	-56	-127.27%
70	0.001	0.01	0.05	125	44	-81	-184.09%
71	0.0001	0.02	0.04	895	811	-84	-10.36%
72	0.0001	0.01	0.03	662	523	-139	-26.58%
73	0.0001	0.02	0.05	1114	811	-303	-37.36%
74	0.0001	0.01	0.04	875	523	-352	-67.30%
75	0.0001	0.01	0.05	1094	523	-571	-109.18%

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14. ABSTRACT

Integrated System Health Management (ISHM) for Unmanned Aerial Systems (UAS) has been a new area of research – seeking to provide situational awareness to mission and maintenance operations, and for improved decision-making with increased self-autonomy. This research effort developed an analytic architecture and an associated discrete-event simulation using Arena ® to investigate the potential benefits of ISHM implementation onboard an UAS. The objective of this research is two-fold: firstly, to achieve continued airworthiness by investigating the potential extension of UAS expected lifetime through ISHM implementation, and secondly, to reduce life cycle costs by implementing a Condition-Based Maintenance (CBM) policy with better failure predictions made possible with ISHM. Through a series of design experiments, it was shown that ISHM presented the most cost-effective improvement over baseline systems in situations where the reliability of the UAS is poor (relative to manned systems) and the baseline sensor exhibited poor qualities in terms of missed detection and false alarm rates. From the simulation results of the test scenarios, it was observed that failure occurrence rates, sensor quality characteristics and ISHM performance specifications were significant factors in determining the output responses of the model. The desired outcome of this research seeks to provide potential designers with top-level performance specifications of an ISHM system based on specified airworthiness and maintenance requirements for the envisaged ISHM-enabled UAS.

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ISHM, Health Management, UAS

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