EVALUATING THE EFFECT OF INTEGRATED SYSTEM HEALTH MANAGEMENT ON MISSION EFFECTIVENESS

THESIS

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THESIS

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Abstract

This research used systems architecture to develop a model that determined the effect of Integrated System Health Management (ISHM) on mission success rates for unmanned aerial systems (UAS). To evaluate this effect, a simulation model was developed and used to analyze the difference between mission success rates for a theoretical UAS with and without ISHM. Design of Experiments analysis techniques were used to map a response surface that modeled the difference between mission success rates calculated for current health management technology and ISHM. Using representative data for a UAS, the analysis determined that the failure distribution parameters, sensor quality (which determines the relationship between probability of detection and probability of false alarm), and probability of an imminent fault during a mission were significant to the model. The result of the model determined that ISHM can result in a significant improvement on mission assurance, especially when implemented with higher quality sensors and on vehicles where the probability of imminent failure is higher relative to the mission times and time between preventative maintenance. This appears consistent with the premise that ISHM can support an extension of preventative maintenance intervals with an attendant reduction in sustainment cost.

Dedicated to my loving and patient husband, I could never have finished this without you! To my mother, who read endless drafts of this paper, thank you for assisting me through every challenge I throw myself into. And finally, to my son, thank you for being the light at the end of the tunnel.

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Sarah E. Storm

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EVALUATING THE EFFECT OF INTEGRATED SYSTEM HEALTH MANAGEMENT ON MISSION EFFECTIVENESS

I. Introduction

1.1 Background

In 2010, the United States Air Force (USAF) released the results of a year-long study highlighting the need for increasing autonomy in modern weapon systems, especially in the domain of unmanned aerial systems (UAS). The study identified the need for greater system autonomy as the *"single greatest theme"* for future USAF Science and Technology investments [Dahm, 2010]. Current technology advancements have brought the USAF to a state of *flexible autonomy*, which involves dynamically shifting command and control (C2) from autonomous to operator based on workload, system health, and the perceived intent of the operator.

One of the key attributes sustaining flexible autonomy is the ability of the UAS to self-detect, isolate, and diagnose system health problems. Current flight avionics architectures may include lower level sub-system health monitoring or may isolate health monitoring functions to a black box configuration, but a vehicle-wide health monitoring information system has seldom been implemented. A new area of research, Integrated System Health Management (ISHM), adds a centralized health management system that is responsible for collecting and processing vehicle health status information from across the vehicle during all mission phases. ISHM balances data flow from multiple sub-systems and produces the information necessary to identify current vehicle capabilities, provide situational awareness to mission and ground operations, and quickly identify contingencies for improved vehicle control and mission decisions.

1.2 Problem Statement

Although reliability has improved since the last official UAS reliability study, the *Unmanned Aerial Vehicle Reliability Study* commissioned by the Office of the Secretary of Defense in 2003, significant problems still plague the overall health of the systems. Current statistics on the loss rate per 100,000 flight hours of several unmanned systems are compared with various manned military aircraft in Table 1. The UAS loss rates are magnitudes above the manned aircraft, although some UAS platforms have not yet reached 100,000 lifetime flight hours.

Table 1 - Class A Mishap Rates per 100,000 Flight Hours [AF Safety Center, 2012]

UAS	Mishap Rate Per 100K Hours	Manned Aircraft	Mishap Rate Per 100K Hours
Predator	7.69	F-16	3.58
Global Hawk*	11.37	B-52	1.29
Reaper	6.37	C-5	1.04
* Has not reached 100k flight hours		C-130	0.83

The dominant causes of these UAS mishaps are presented in Table 2.

Table 2 - Causes of [UAS] Mishaps [OUSDATL, 2004]

[UAS] Mishap Cause	Percent
Power and Propulsion	37%
Flight Controls	25%
Human Error	17%
Communications	11%
Miscellaneous	10%

The two mishap causes where there can be an assumption made that the current health management or monitoring system did not adequately detect an imminent failure are

Power and Propulsion and Flight Controls, which amount to 62% of total mishap causes. Granted, even a theoretically ideal health management system cannot account for every fault or failure cause, but vast improvements need to be made in fault detection systems.

There is also cause for concern on the maintenance side of health management. Even when a fault is detected pervasive "Could Not Duplicate" (CND) and "No Defect Found" (NDF) maintenance results show that improvement in fault isolation is needed. In 1999, an average of nine CND and 47 NDF maintenance results were recorded per aircraft [Stoll, 2000].

ISHM may be one answer to these health management problems, both on the aircraft and in the maintenance and logistics side of operations. Previous research efforts have focused solely on quantifying the cost or performance benefits provided by ISHM, but few have looked into the effect of ISHM on operational effectiveness. This research effort intends to give decision makers a better understanding of the advantages and disadvantages of ISHM by adding the mission environment to previously built cost and performance analyses.

1.3 Research Objectives and Hypothesis

The focus of this research is to quantify the mission-related benefits of ISHM by constructing architecture for analysis to compare against current autonomous vehicle capabilities, and to provide a general baseline model that can be implemented over any current or future autonomous vehicle. The architecture will include the ability to analyze the causal relationship of ISHM performance metrics (to include the performance of the necessary algorithms, and the performance and reliability of the monitoring sensors) to mission performance. The research presented in this thesis is aimed at primarily answering the following questions using the architecture in a modeling and simulation context:

(1) What are the potential impacts to ground control stations and users?

(2) What are the potential impacts on current maintenance practices?

(3) What are the performance characteristics necessary for ISHM to effect mission success?

In order to answer these research questions and develop an appropriate model, a literature review should first be conducted to answer these questions:

(1) What is the current status of UAS health management?

(2) What are the essential elements of ISHM?

(3) What are the expected benefits of ISHM?

The architecture should also contribute to answering these secondary questions:

(1) How should ISHM data be presented to be effective? How will the presentation change in regards to the different users of ISHM (operators, maintenance, etc.)?

(2) Is ISHM cost effective?

1.4 Methodology

The development of the analytic architecture simulating ISHM over the lifetime of the UAS will follow the eight-step Architecture Based Evaluation Process and be in accordance with the Department of Defense Architecture Framework [DoD, 2012]. This process was developed by a group of AFIT graduate students in 2006 to bridge the gap between the system engineering architecture community and the modeling and simulation community [Dietrichs, 2006]. The analytic architecture will model expected mission success rates and maintenance actions for a UAS, both with and without ISHM for statistical comparison.

1.5 Assumptions and Limitations

In order to make a general baseline model, it is not possible to represent every possible aspect of ISHM; therefore, there are several limitations to this research:

(1) This architecture does not analyze ISHM past the system level; however, the architecture can be easily modified to include components and subsystems that are of value to the researcher.

(2) At this point in ISHM development, the ISHM system has no command or control over the autonomous vehicle. ISHM in its current technology state only provides recommended actions based on the type of fault it detects. The vehicle's autonomous management system will prioritize actions as necessary or, if there is time, a ground-based ISHM team can overrule or direct mitigation actions as necessary.

1.6 Implications

An ideal ISHM would have several major benefits over current maintenance and tasking practices. By having a real-time autonomous capability to detect, isolate, and diagnose problems, the largest direct benefits include a reduction in maintenance time, a larger operational flight envelope, and the ability to enable e collaborative mission re-planning based on current system capability and health. Overall, ISHM would improve mission decision making, enable condition-based maintenance and provide remaining life quantification while reducing current conservative design life margins and/or inspection intervals. Planned Near Term, Mid Term, and Far Term future capabilities of ISHM are illustrated in Figure 1.

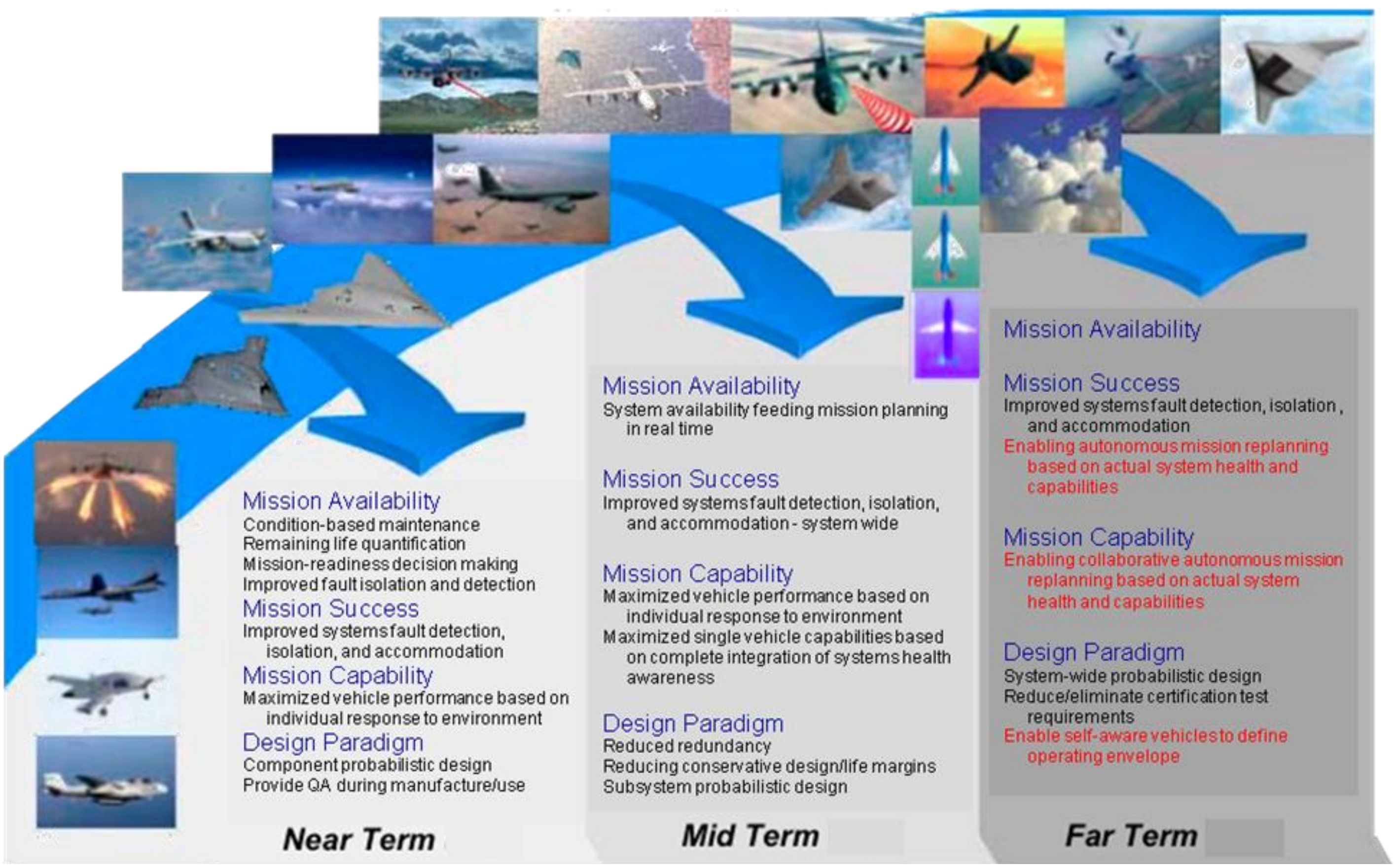


Figure 1 - Future ISHM Capabilities [Derriso, 2011]

1.7 Preview

This thesis is organized into five chapters. The introductory chapter discusses ISHM considerations in terms of technical standards and through the system architectural definition. The remaining chapters are as follows:

- Chapter II examines and classifies the current state of health management for unmanned aerial systems, provides an ISHM system taxonomy, and summarizes the major areas of research currently being performed.
- Chapter III describes the research methodology and introduces the architectural development process used to conduct the research.
- Chapter IV presents a proposed prototypical ISHM architecture and provides analysis of the analytic architecture.
- Chapter V draws conclusions regarding research objectives, answers the investigative questions and proposes future research.

II. Literature Review

2.1 Chapter Overview

The purpose of this chapter is to summarize the state of health management for unmanned aerial systems (UAS), provide an ISHM system taxonomy, and summarize the major areas of research currently being performed. The first section discusses current health management practices and describes key terminology. The second section provides a description of a typical ISHM system as described by literature and the third section lists expected benefits and applicable metrics of ISHM. The fourth section describes the main modeling approaches for analyzing the performance or cost-benefit tradeoffs of ISHM systems. The fifth section gives an overview of current analytic architectures. The last section summarizes the information provided.

2.2 Background

In order to quantify the effects of ISHM on a system, the current health management practices must be investigated for comparison; this section discusses current health management practices and describes key terminology.

2.2.1 Current State of UAS Health Management

The Air Force UAS programs currently use independent sensors incorporated into the vehicle's hardware to monitor for fault indicators on critical subsystems. The sensor data is continuously transmitted to ground operations where it is processed. If the data indicates a fault has occurred the ground operator executes pre-determined mitigation steps, dependent on which sensor indicated a fault, and sends a message to maintenance. Once the vehicle lands, maintenance personnel perform diagnostic tests to confirm the location and identify the type of fault, and then perform maintenance actions to restore the component. This is less a health management system than a health monitoring system, in terms of nomenclature. The algorithms used for these systems generally only indicate an off-nominal condition; they do not give any other information typical of a health management system.

2.2.2 Taxonomy

Understanding the ISHM system and the benefits it offers depends greatly on understanding several key terms: failures, errors, faults, novel events, fault detection, fault isolation, diagnostics, and prognostics.

Failure is defined as a "deviation in behavior between the system and its requirements. Since the system does not maintain a copy of its requirements, a failure is not observable by the system" [Buede, 2000].

Error is defined as "a subset of the system state, which may lead to failure. The system can monitor its own state, so errors are observable in principle. Failures are inferred when errors are observed. Since a system is usually not able to monitor its entire state continuously, not all errors are observable. As a result, not all failures are going to be detected (inferred)" [Buede, 2000].

A *fault* is a known "defect in the system that can cause an error. Faults can be permanent (e.g., a failure of system component that requires replacement) or temporary due to either an internal malfunction or external transient. Temporary faults may not cause a sufficiently noticeable error or may cause a permanent fault in addition to a temporary error" [Buede, 2000].

A *novel event* is another type of anomaly in the same class as a fault. The difference is that a fault is a known defect, where novel events are unknown. Prognostic algorithms are designed to respond to known events (faults), not novel events [Atlas, 2001].

Degradation involves a declining performance measure that changes with time, particularly to a lower condition, quality, or level. Generally, systems will continue to operate in a degraded mode, but not at a specified operating level. Whether the degradation has advanced to a fault or failure state will be determined as part of the reliability specification [Ebeling, 2010].

Fault detection is the "determination that the performance of a system or subsystem does not correspond to its expected behavior. In more general terms, it is determining that a failure has occurred" [Ross, 1999].

Fault isolation is the "determination of the specific cause of failure so corrective action can be taken… Ideally, systems are partitioned such that measurable functions can be implemented on the lowest repairable assembly" [Ross, 1999].

Diagnostics can be described as “the process of locating [a] fault at the level in which restoration may be accomplished” [Ebeling, 2010]. The process includes the utilization of monitoring hardware and/or software to detect and isolate faults in a given system [Clutz, 2003]. In some expanded definitions, diagnostics can even include determination of a failure cause [Cardona, 1999]. For the purpose of this thesis, diagnostics will be defined as “the utilization of monitoring hardware and/or software to determine the failure cause by detecting and isolating faults.”

Prognostics is defined as an assessment of likely future health (educated prediction) of a piece of equipment, based on current information [Cardona, 1999]. Prognostics builds on current diagnostic capabilities using automated procedures to calculate the Estimated Time to Failure of a system or component. A prognostics system is often associated with condition-based maintenance, since the results of a prognostic analysis indicates required maintenance actions, either real-time or predicted [Clutz, 2003].

All these definitions are brought together in Figure 2, which shows a typical component health trajectory. Diagnostics tells “what” fault curve the component is on and prognostics determines “where” on the overall health curve the component currently resides.

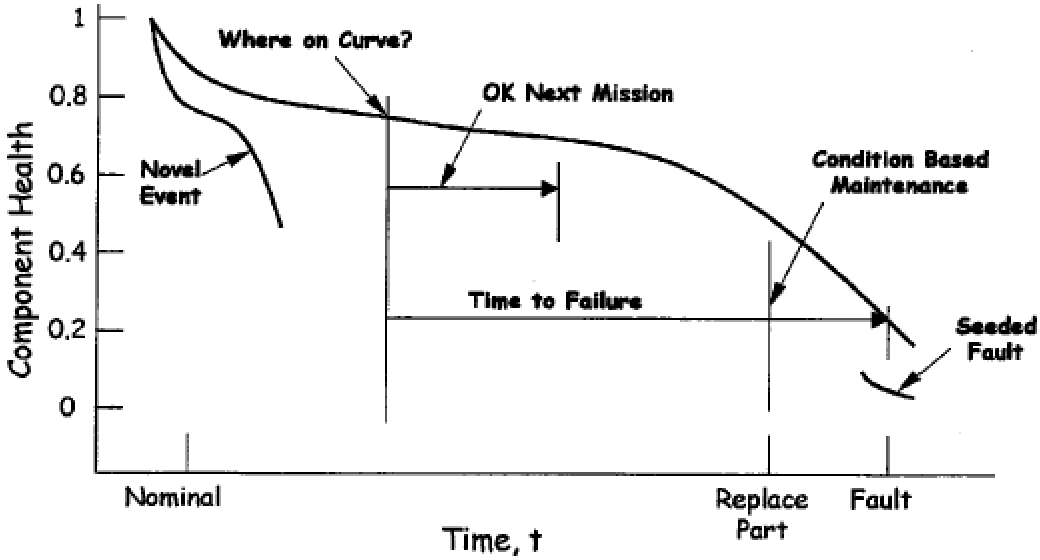


Figure 2 - Component Life: 100% Healthy to 100% Failed [Atlas, 2001]

2.3 Notional ISHM Configuration

An ISHM system is envisioned to serve two primary goals: to monitor the "functional health" of the system real-time; and to facilitate the maintenance and availability of the system by diagnosing the physical break-downs in the system that can be replaced off-line. These two goals are further explained below:

1. Real-time monitoring of the functional health of the system: ISHM must constantly monitor the functional health of the system to detect and isolate faults. From this standpoint, the system is regarded as a 'collection of functional units' (rather than physical units) that must perform flawlessly to constitute the overall function(s) of the mission. Depending on the level of autonomy, criticality, and authority, ISHM could either make 'real-time' decisions to reroute flows of information, energy, or material from the failed

unit to ensure continuous operability, or send appropriate information to a human-in-the-loop for decision making. The information ISHM provides to the decision maker should have integrity and be relayed within enough time to facilitate a good outcome.

2. Determining the physical health of the system: To help maintain the physical health of the system, ISHM must be able to determine which physical component has failed or is going to fail and the effect of the failed component on the system's capabilities. By continuously monitoring physical units, the information collected from ISHM should also be used to identify long-term degradation effects that could cause failures [Mehr, 2005].

Using these goals, this section describes a notional ISHM configuration.

A typical ISHM system consists of sensors placed at critical components within subsystems of the vehicle that stream data to a management system. The management system processes the sensor data, executes diagnostic and prognostic algorithms, and then feeds this information through a reasoner, as seen in Figure 3. This management system can either be on-board the vehicle in a hardware configuration or off-board enabling the ground command and control (C2) element.

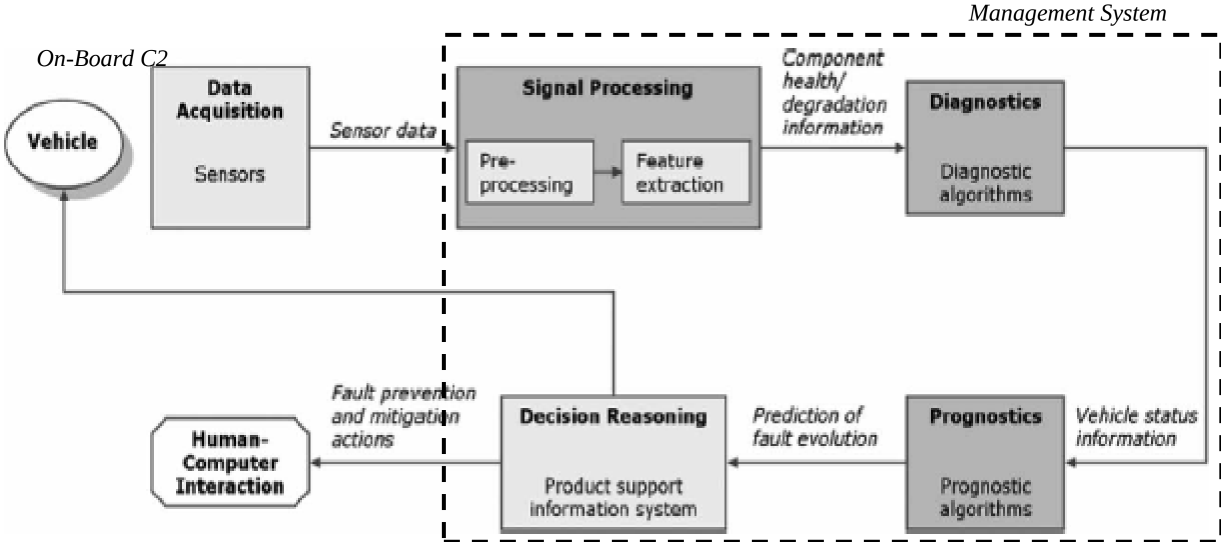


Figure 3 - Typical ISHM configuration [Benedettini, 2009]

Sensors can be conventional, measuring temperature, speed, and flow rate, or specifically tailored to health management applications, such as strain gauges, ultrasonic sensors, or proximity devices. The sensor data is then processed to remove any artifacts or noises and manipulated to extract fault features. The diagnostic module then analyzes the fault features to detect, identify, and isolate developing failure conditions. The diagnostic information will be combined with historical data in the prognostic module to generate an estimation of failure times. Algorithms developed for the diagnostic and prognostic modules are generally based on mathematical models (e.g., Hamilton dynamic, Lagrangian dynamic, approximation methods), or pattern recognition (e.g., fuzzy-logic, statistical/regression methods, neural network clustering). Finally, the diagnostic and prognostic information is turned over to the reasoner module which analyzes available resources, decides which hazard mitigation steps to execute, and then passes the selected decision to the on-board C2 module and relays appropriate information to the ground C2 operator and maintenance element [Benedettini, 2009].

2.4 Expected Benefits and Applicable Metrics

The overall desired effect of an ISHM system would be to continuously monitor the system, detect and isolate either a real-time fault or pre-cursers to a fault, determine the criticality of the fault, and then relay appropriate information to ground control, the on-board C2 module, and maintenance for action. Benefits of this capability are discussed in the remaining sub-sections.

2.4.1 Effect on Scheduled and Unscheduled Maintenance

The Air Force goal for prognostic systems such as ISHM is to completely eliminate traditional aircraft inspection and repair patterns [Ross, 1999]. Currently, a malfunctioning unit is either identified in-flight (based off an alert from an individual sensor) or identified through scheduled inspections. There is an inherent probability of a false alarm and a probability of fault detection, meaning that the aircraft could be incorrectly pulled from an on-going mission or could continue on a mission with an unknown fault that could lead to system failure. The integrated aspect of ISHM proposes to severely reduce the false alarm rate and increase the total probability of detection, as understanding the full health status of the vehicle can identify false positives and identify if a fault or failure has occurred down-stream. For example: a sensor falsely identifies a valve stuck closed, a sensor further down the stream indicates a normal flow rate and the system has not lost any performance aspects; ISHM would therefore not report this as a system fault, but as a sensor fault.

With the continuous monitoring provided by ISHM, pre-cursors to faults can also be identified and Estimated Time to Failures of the component or total system will be reported. Additionally, if multiple mission data is stored, every time a fault occurs, the data collected by ISHM can be used to identify new indicators or pre-cursors to a failure to be uploaded into the diagnostic and prognostic algorithms.

The overall result is that with ISHM implemented, the probability of unscheduled maintenance, currently inflated due to prevalent “Could Not Duplicate” and “No Defect Found” maintenance results, should decrease as unscheduled maintenance should become more fault driven. Scheduled maintenance intervals can also be investigated for potential relaxation or removal; current intervals may be conservatively small to counteract the current lack of health awareness. Ideally with ISHM, the aircraft would replace time-based or event-driven maintenance with a condition-based maintenance system, where maintenance is only performed based on objective evidence of actual or predictable failure of a system or its components [OSAIDD, 1999].

Metrics (unless stated otherwise, all formulas in this Chapter are from *An Introduction to Reliability and Maintainability Engineering* by Charles Ebeling, 2010):

T_{pm} – Mean Time between Performances of Preventative (Scheduled) Maintenance

MTBM – Mean Time between Maintenance (includes both scheduled and unscheduled maintenance). The equation for MTBM is shown in Equation 1.

$$MTBM = \frac{t_d}{m(t_d) + \frac{t_d}{T_{pm}}} \tag{1}$$

where t_d = system design or (economic) life
$m(t_d)$ = expected number of failures in the interval (0, t_d)

R_U - Rate of Unscheduled Maintenance. The equation for R_U is shown in Equation 2.

$$R_U = \frac{m(T_{pm})}{T_{pm}} \tag{2}$$

where $m(T_{pm})$ = expected number of failures in the interval (0, T_{pm})

MDT – Mean Downtime. The equation for MDT is shown in Equation 3.

$$MDT = \frac{m(t_d)MTTR + \left(\frac{t_d}{T_{pm}}\right)MPMT}{m(t_d) + \frac{t_d}{T_{pm}}} \tag{3}$$

where $MTTR$ = Mean Time to Repair
$MPMT$ = mean preventative maintenance time

P_D - Probability of Detection

$$P_D = P(Fault\ Indication | Fault\ \cap Operational\ Sensor) \tag{4}$$

P_{FA} - Probability of False Alarm

$$P_{FA} = P(Fault\ Indication | No\ Fault\ \cap Operational\ Sensor) \tag{5}$$

2.4.2 Decreased Mean Time to Repair

Current fault detection is limited to identifying the occurrence of a fault and an approximate location, meaning that fault isolation can only occur after the aircraft has landed. There is also a non-unity probability that the mechanic can even correctly identify the failure mode once it lands. With ISHM, both fault detection and isolation are performed in-flight, within a specified confidence level, and the appropriate information is relayed to the maintenance element. This gives the maintenance element time to pre-position the necessary maintenance equipment and personnel or order any necessary replacement parts, severely reducing the total Mean Time to Repair (MTTR) after an event.

As a result of its continuous monitoring, ISHM would also reduce maintenance time during scheduled inspections. Prognostics would, theoretically, calculate an Estimated Time to Failure (ETF) for each component, resulting in each inspection only focusing on those systems that had passed an ETF threshold in that time interval. Knowing that the specific systems to be inspected ahead of time would again allow the maintenance element time to pre-position the necessary maintenance equipment and personnel or order any necessary replacement parts. ISHM would also negate the current use of time-intensive Built-in Test (BIT) units, as each system would be continuously tested.

2.4.3 Operational Availability Improvement

Based on the decreased downtime in unscheduled maintenance and scheduled maintenance from ISHM, the Operational Availability for each aircraft should improve. Another factor affecting Operational Availability is mission turn-around time, or the time from when the aircraft lands to when it is ready for the next mission. Without ISHM, mission turn-around time can include lengthy BIT tests to check for failures. Since these tests are not needed with continuous monitoring and a higher confidence in fault detection, the mission turn-around time should decrease, increasing Operational

Availability. Whether measured in maintenance downtime or a reduction in hours required for testing and diagnostics, etc., the net result is that a system with ISHM will be available for use more of the time.

Metrics:

A_O - Operational Availability. The equation for A_O is shown in Equation 6.

$$A_O = \frac{MTBM}{MTBM + MDT} \tag{6}$$

2.4.4 Increased Mission Success

Having situational awareness of the entire health state of the vehicle assists ground operations in providing full mission coverage. If a UAS autonomously detects a fault and due to the fault criticality (for example, low fuel levels) decides to re-task to a closer trajectory, ground operations can re-task other UAS vehicles to ensure coverage of the priority targets. Without ISHM, a fault alert would generally give no indication of the remaining performance capability of the UAS, leaving ground operations to conservatively scrap that particular mission set.

An additional aspect of increased situational awareness is its affect on UAS flight limits. Modern autonomous flight control systems limit the vehicle to safe operating loads and environments; this operating envelope is pre-defined and conservative. With ISHM, the flight envelope can theoretically be expanded and defined by the design criteria for the vehicle. Health data would then be used to restrict the envelope to a prescribed level in the event of a detected fault. This would increase the operational capability of the vehicle, allowing for larger mission sets. Improved situational awareness combined with the theoretical improved Operational Availability would greatly improve the rate of mission success.

Metrics:

R_{MS} - Rate of Successful Completed Missions. The equation for R_{MS} is shown in Equation 7.

$$R_{MS} = \frac{\#\ Successful\ Missions}{Total\ Missions\ Attempted} \tag{7}$$

2.4.5 Cost Savings

The previous benefits all have some measure of cost savings attached to them. Having a lower total maintenance downtime, due to decreases in scheduled maintenance and a lower probability of unscheduled maintenance, leads to a lower personnel cost and even an option of having less maintenance personnel needed. Fewer maintenance actions also indicate a potential reduction in spares and supply costs. However, there is an inherent cost in implementing ISHM, not just to the vehicle but to the resulting operational infrastructure. The cost savings must be weighed against the implementation costs to truly investigate the financial aspect of ISHM.

Cost avoidance measures could also be applied as a benefit of ISHM. ISHM identifies components or subsystems that are near failure, replacing or repairing these parts before they fail and cause damage to other parts would avoid the cost of repairing the additional damage. The upfront cost may be higher in the short run, but the final life cycle cost would be lower.

2.5 Analytic Models

The majority of analytic models for ISHM have been created by NASA at Ames Research Center. On-going research is aimed at developing a robust methodology that can evaluate different ISHM architectures to optimize a set of pre-determined metrics. This process, known as ISHM Systems Analysis and Optimization (SA&O), consists of a set of models that can be easily customized for a specific system. Using this SA&O process offers two immediate advantages:

- The effects of ISHM on the overall safety, maintainability, and performance of the system can be calculated.
- During design, engineers can use the process to find the 'optimal ISHM architecture' for that specific system [Mehr, 2005].

The original quantification process identified 24 metrics, listed in Table 3, to be used across four domains: Design for Testability (DFT) Model, Loss of Mission (LOM) Model, Turnaround Model, and Maintenance Model.

Table 3 - ISHM SA&O Process Metrics [Datta, 2004]

1. Loss of Mission	13. [UAS]/Subsystem Mean Time Between Failure
2. Loss of Vehicle	14. Subsystem Availability
3. Loss of Crew	15. [UAS] Turnaround Time
4. Launch Availability	16. Cost of Spares
5. Development Cost	17. [ISHM] Weight
6. Production Cost	18. Subsystem Weight
7. Annual Operational Cost	19. Fault Detection Coverage
8. $/lb (Mission Price/lb)	20. Fault Isolation Coverage
9. Inherent [ISHM] Reliability	21. [ISHM] False Alarm Rate
10. Subsystem Reliability	22. Subsystem False Alarm Rate
11. Subsystem Failure Probability	23. Net Present Value and IRR of [UAS] program
12. [UAS]/Subsystem Mean Time To Repair	24. Probability of unscheduled maintenance

The DFT Model assesses the ability of a given instrumentation suite to detect and isolate the faults for a proposed design, the size of ambiguity groups, and test point selection; fault detection and fault isolation metrics are derived for the ISHM system from the DFT Model. The LOM Model assesses the probability of failures that result in an inability to complete a given mission; the primary output for the LOM Model is the probability of loss of mission (as a metric). The Turnaround Model predicts the cost, time and resources required to prepare the UAS for the next mission; it models scheduled and unscheduled maintenance and the repair process. Typically this model uses discrete simulation to output the new (ideally, lower) UAS turnaround times and costs of operations. The Maintenance Model is used to provide maintenance-related input on a subsystem-by-subsystem basis as required by the turnaround and mission models. Figure 4 maps each of the metrics to each other and to the relevant model [Datta, 2004].

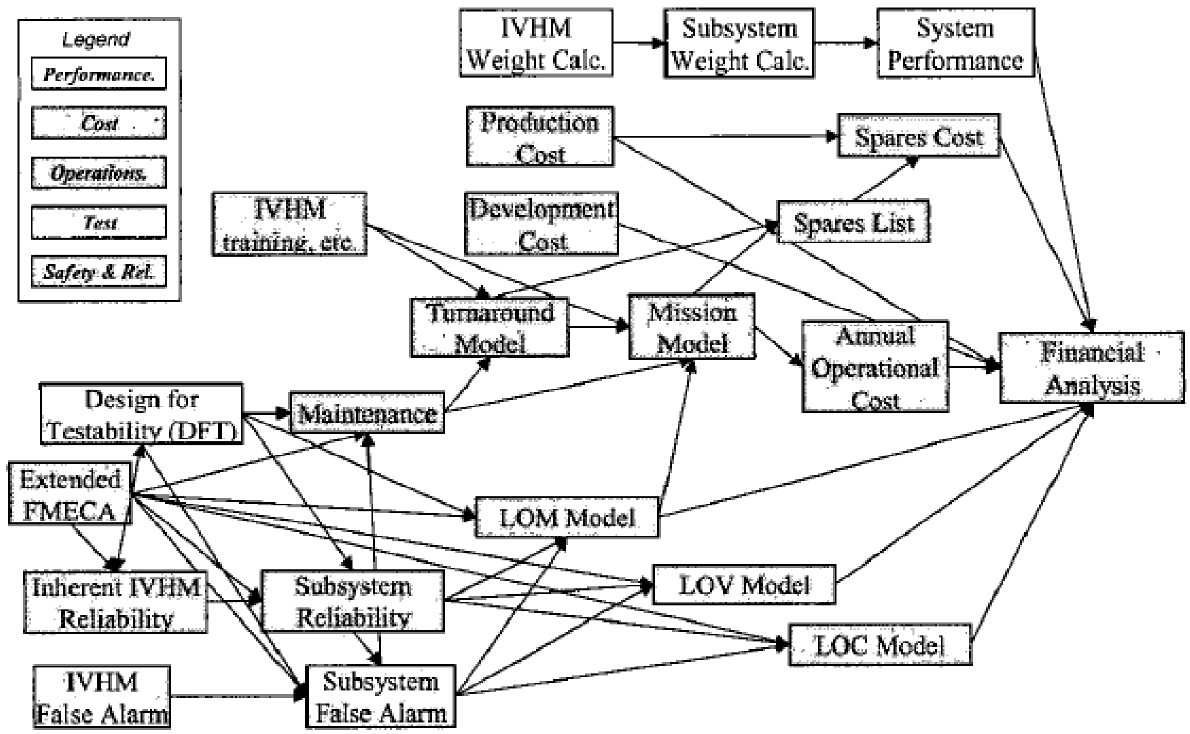


Figure 4 - The ISHM SA&O Quantification Process Map [Datta, 2004]

The SA&O process was found to have several shortcomings that hindered its application and generalization to larger and more complex systems: it was only capable of producing a 'point-design' instead of a suite of design alternatives, and it did not take into account that there are global (shared) as well as local design parameters for each subsystem. Building from the SA&O process and focusing on closing these gaps, the next approach to ISHM analysis is known as ISHM Multidisciplinary Multi-objective Systems Analysis and Optimization (MMSA&O). MMSA&O structures the design problem into a two-level hierarchical architecture; an example can be seen in Figure 5.

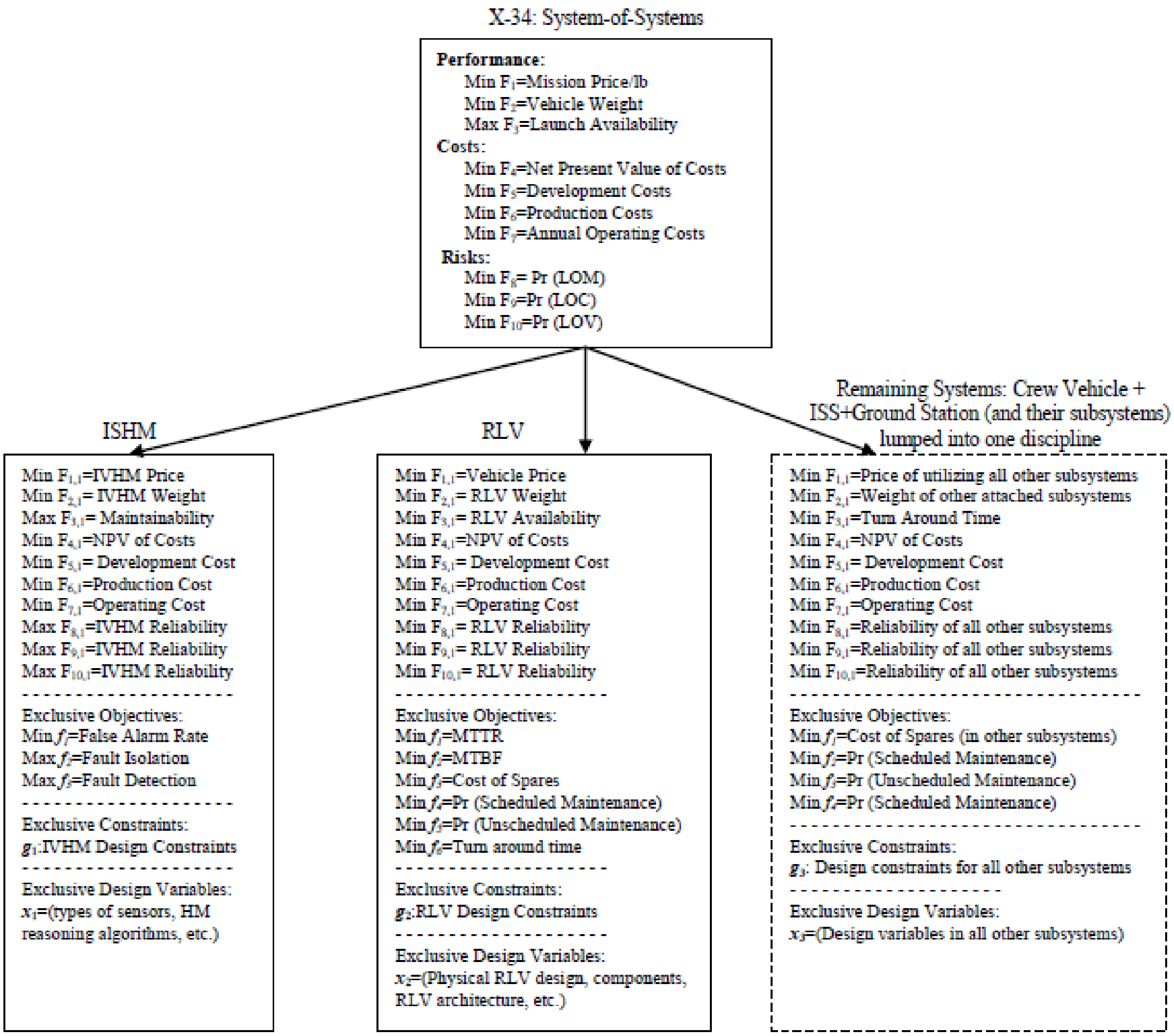


Figure 5 - Example Two-Tier Formulation of an ISHM Design Problem for a Reusable Launch Vehicle (RLV) [Mehr, 2005]

In this process, ISHM is decomposed into a hierarchy of several sub-problems, each of which may contain multiple objectives. In its multi-disciplinary form (as seen in Figure 6), the optimization problem can be organized into two levels: one sub-problem at the system level, and *J* sub-problems at the sub-system level.

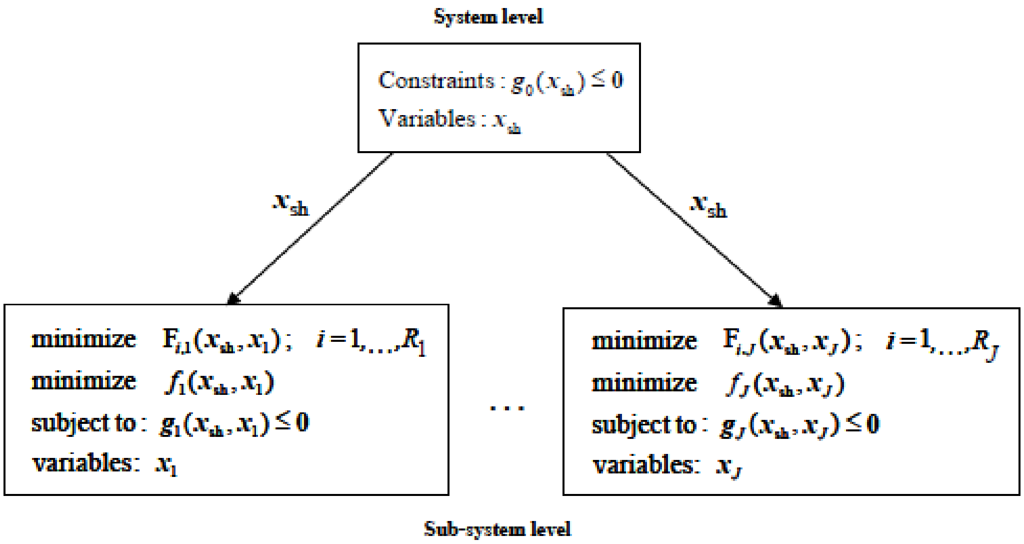


Figure 6 - Multi-Disciplinary Form of a Multi-Objective Optimization Problem [Mehr, 2005]

The goal of this optimization approach is to obtain a set of solutions $(\boldsymbol{x}_{SH}, x_1, \ldots, x_J)$ that minimizes a weighted sum of *R* objectives while satisfying the constraints in all *J* sub-problems. The equivalent single-level form of the multi-disciplinary problem is seen in Equation 8.

$$\begin{aligned} &\text{minimize} \quad F_{i,j}(x_{sh}, x_j); \quad i = 1, \ldots, R_j \\ &\text{minimize} \quad f_j(x_{sh}, x_j) \\ &\text{subject to:} \begin{Bmatrix} g_0(x_{sh}) \\ g_j(x_{sh}, x_j) \end{Bmatrix} \le 0 \end{aligned} \tag{8}$$

where:

$\boldsymbol{F}_{i,j}$ **=** functionally-separable objectives
$\boldsymbol{f}_j$ = exclusive objectives
$\boldsymbol{x}_{SH}$ = shared variable vector
$\boldsymbol{x}_j$ = variable vector exclusive to the sub-system
$\boldsymbol{g}_0$ = system constraint vector
$\boldsymbol{g}_j$ = constraint vector exclusive to the sub-system

The solutions from each sub-problem are then rolled up to the top-level for integration; however, since each sub-problem is solved independently, convergence matrices must be used to guide the full system optimization [Mehr, 2005].

The SA&O process was proven to significantly improve the efficiency of ISHM architecture, in one case study the percentage of total faults detected from the optimized ISHM increased to 75% from 12% in the original design [Mehr, 2005]. Likewise, the improved MMSA&O has seen percentages of total faults detected between 76 and 98% [Hoyle, 2007].

Both of these models only focus on the safety, maintainability, and performance of the new ISHM-enabled system. These models are missing a key environment that is necessary when truly evaluating the full effect of ISHM: the mission environment. What is the effect of higher availability and increased situational awareness on mission success rates over the lifetime of the vehicle? The effect on mission effectiveness must be quantified to help fully understand the cost/benefit tradeoff of ISHM.

2.6 Analytic Architecture

Historically, architecture and modeling had been performed relatively separately:

> "On one side of the fence, systems engineers … [develop] the in-depth integrated architectures to define system concepts for development and production. On the other side, often times those evaluating the concepts for decision makers develop simulations and models from information obtained by performing their own research and interpretation of the system concept. The result of this disconnect is often times an inaccurate evaluation of the system that is actually developed and produced" [Dietrichs, 2006].

In 2006, a group of AFIT graduate students bridged this gap by combining the Department of Defense Architecture Framework (DoDAF) [DoD, 2012] and modeling techniques into an analytic architecture, resulting in the development of the Architecture Based Evaluation Process (ABEP) [Dietrichs, 2006].

The ABEP is made up of the following eight steps (see Appendix A: Architecture-Based Evaluation Process (ABEP) for the process assumptions and further breakdown):

1. **Design Operations Concept of System to be evaluated.**
   The Ops Concept provides the system operations which the architecture will model.
2. **Identify Measures of Effectiveness (MOEs) relevant to the decision/evaluation.**
   Identify the mission level metrics that represent the effectiveness of the system.

3. **Identify required level of abstraction for architecture to show traceability to MOEs.**
   Analyze the Ops Concept to determine if MOEs are measured at the output of a system, within a system, or at the output of activities external to the system.

4. **Identify architecture views necessary to capture structure/relationships.**
   a. Structure (OV-1, OV-2, and OV-5 mandatory)
   b. Decision Logic (OV-6a mandatory)
   c. As Required: SV-2, SV-4, SV-7, OV-6b, OV-6c

5. **Develop architecture views.**
   Develop or acquire the architecture views identified in Step 4 IAW DoDAF to include all relevant activities and entities.

6. **Develop Modeling and Simulation to replicate architecture.**
   a. Select modeling or analytical tools best suited to meet evaluation requirements
   b. Model structure of simulation or analytical solution to match architecture
   c. Model decision logic of simulation or analytical solution to match OV-6a
   d. Choose input parameters consistent with SV products

e. Calculate MOEs at output of activities as functions of design parameters

7. **Evaluate Model Completeness.**
   Determine whether model considers all relevant aspects of the system/concept.

8. **Evaluate model for MOE results, requirements, and key parameters.**
   a. Once the model is complete, evaluate the system's ability to meet target metrics
   b. Vary design parameters and perform sensitivity analysis to identify key parameters
   c. Compare sensitivity analysis to target MOEs to help establish/refine requirements and KPPs
   d. If not already accomplished, develop SV-7 Systems Performance Parameters Matrix and identify critical performance parameters
   e. Vary system design and design parameters to evaluate the system's robustness and its rate of degradation

2.7 Design of Experiments

Design of Experiments (DOE) is a type of statistical design in which

> "purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response… [These experiments are planned] so that appropriate data will be collected and analyzed by statistical methods, resulting in valid and objective conclusions" [Montgomery, 2009].

For this research effort, DOE techniques will be used to supplement the ABEP when evaluating models. The DOE techniques used will follow the seven guidelines provided in *Design and Analysis of Experiments* by Dr. Douglas Montgomery [2009]:

1. Recognition of and Statement of the Problem

A clear statement of the problem provides a better understanding of the phenomenon being studied and the final solution of the problem. It is important to keep the overall objective in mind to avoid wasting time, materials, and other resources.

2. Selection of the Response Variable

The response variable or variables "provides useful information about the process under study." This is often the output of a process, or a measurable characteristic of a system. There may be one or more response variables.

3. Choice of Factors, Levels, and Range

Design factors are "those [variables] that the experimenter may wish to vary in the experiment." These factors are expected to have a large effect on the response variable. Once the experimenter has selected the factors, they "must choose the ranges over which these factors will be varied and the specific levels at which runs will be made." A very common method of choosing levels is to select a high and a low point that covers a range that the experimenter deems is appropriate for operating conditions or is of interest to the experiment.

4. Choice of Experimental Design

Choosing the design involves consideration of sample size, selection of an appropriate run order, and determination of any restrictions in the design. The three basic principles of experimental design are randomization, where both the allocation of resources and the order in which the individual trials are performed are randomly determined; replication, or independent repeats of each factor combination; and blocking, a design technique used to improve the precision with this comparisons among the factors of interest are made.

A common experimental design that combines these three principles is a *factorial experiment*, in which factors are varied together instead of one at a time. This particular experiment enables the experimenter to easily investigate the individual effects of each factor and to determine where the factors interact. If there were *k* factors, each at two levels (high and low), the factorial design requires 2^k runs. Generally if there are more than five factors, it becomes cumbersome to run all possible combinations of factor levels.

Another experimental design, a *fractional factorial experiment*, is a variation of the factorial experiment in which only a subset of the runs are used. These designs rely on the experimenter assuming that certain high-order interactions are negligible, and that the important information is found in the main factors and low-order interactions. This is also known as the *sparsity of effects principle.* A major use of this experiment is for screening factors to identify those factors (if any) that have large effects on the response.

5. Performing the Experiment

It is vital to monitor the process carefully to ensure that the procedure is executed according to plan. Errors in procedure will usually destroy experimental validity.

6. Statistical Analysis of the Data

If the experiment has been designed correctly and performed according to the design, the statistical methods required can be simple. The output of the experiment should be a model that describes the response surface of the process or system being investigated.

The most commonly used statistical inference procedure to validate this model is the *Analysis of Variance*, which relies on portioning the total variability into its component parts: variance due to the model, and variance due to random error. Certain assumptions have to be satisfied for this procedure to be implemented, specifically that the errors are normally and independently distributed with mean zero and constant but unknown variance σ^2. Violations of these assumptions can be investigated by examination of the residuals, or the difference between the observed value and the predicted value. If the model is valid the residuals should be structureless, or containing no obvious patterns.

7. Conclusions and Recommendations

Once the data has been statistically analyzed, the experimenter can draw practical conclusions about the results and recommend a course of action. Confirmation testing can be performed to validate the conclusions, if necessary. Often, full investigation of the response surface involves iterative experimentation, as each new experiment builds on the conclusions found in the last.

2.8 Literature Review Summary

This section discussed and identified several key terms, such as faults, failures, prognostics and diagnostics, that are necessary for understanding an ISHM system and identified current health management practices for Unmanned Aerial Systems. A typical ISHM configuration was introduced and had the following components: a sensor suite placed along critical system elements, and 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. The expected performance, maintenance, and mission benefits of adding a typical ISHM configuration to a UAS were identified and discussed.

Prior analytic models were also investigated. Most published research concerning analytic modeling of Integrated System Health Management were found to be generally concerned with quantifying the effects of ISHM on the performance and scheduled maintenance of the intended recipient system. Few, if any, addressed the effect of ISHM on mission success rates; most that did addressed this aspect at a mission level and did not address the system degradation that would occur over the lifetime of the vehicle. Finally, this chapter discussed the analytic architecture process model that will be used in Chapter III to help quantify the effect of ISHM on mission success rates.

III. Methodology

3.1 Overview

The purpose of this chapter is to describe the process of developing an analytic architecture to be used to evaluate the advantages and disadvantages of installing an ISHM system on a UAS. The development will follow the eight-step Architecture Based Evaluation Process (ABEP) described in Section 2.6, and will be IAW the Department of Defense Architecture Framework (DoDAF).

3.2 Design ISHM Concept of Operations

Per Step 1 of the ABEP, Concept of Operations (CONOPs) will be developed based upon discussions with the users. To help organize the competing objectives of ISHM and ISHM's analysis, two CONOPs will be built: the first detailing the ISHM system to be implemented, the second focusing on the analytic architecture model. The CONOPs will adhere to Air Force Policy Directive 10-28 and will outline basic Measures of Effectiveness (MOEs), sequences of events, command relationships, and the expected output data from the model.

The ISHM CONOPs is meant to be as general as possible and will take a system-level view of the technology. Capabilities and characteristics will be taken mostly from the research completed in the literature review with implementation directed at an Unmanned Aerial System.

The purpose of the Analytic Architecture CONOPs is to primarily answer the research questions posed in Chapter I. For the purpose of this research effort, the architecture created will provide a general baseline model that can be implemented over any autonomous vehicle. The architecture will be built using the characteristics and capabilities detailed in the ISHM CONOPs and will be used to design an analytic model that quantifies the effect of ISHM on the operational availability and mission success rate.

3.3 Identify Measures of Effectiveness

The next two steps, Step 2 and 3, continue development with the creation and analysis of a list of MOEs to be used to evaluate ISHM. MOEs should primarily be derived from the expected benefits of ISHM. Section 2.4, Table 3 and the ISHM CONOPs built in the previous section list several metrics that have already been identified as pertaining to the performance of ISHM. The MOEs chosen should reflect the purpose and desired output of the analytic model, as they will ultimately guide the development of the model; leaving out key evaluation metrics would cause an inappropriate output from the model.

Once the MOEs are chosen, they should be analyzed against the CONOPs to determine where in the system (within, at the output, through an external system) they are measured. The MOEs will also be used to identify within the overall system's architecture those products that specifically addressed ISHM. From these products, a

Rules Model can be built that will abstract activities and will serve as the basis for the ISHM simulation.

For this research effort, the analytic architecture will have the capability to ingest system failure characteristics, in this case an appropriate failure distribution that models the total system as well as probabilities of occurrence for the fault categories listed in Table 4, and ISHM performance characteristics, such as the probability of detection, the probability of a false alarm, and the diagnostic algorithm confidence level (a probability that the diagnostic subsystem will correctly identify the fault). These categories are not exclusive to degradation effects; the Estimated Time to Failure could be calculated for a component experiencing long-term system degradation due to normal wear and tear or for a component operating at a high level of stress. The analytic architecture will then have the capability to use those input variables to calculate these metrics for a UAS with ISHM and without ISHM for comparison: number of unscheduled maintenance actions, and the rate of mission success.

Table 4 - Fault Categories

Fault Category	Category Definition
I	The calculated Expected Time to Failure is much greater than mission length. Maintenance can wait until the next scheduled Preventative Maintenance activity.
II	The calculated Expected Time to Failure is greater than mission length. Unscheduled Maintenance must occur after the current mission is completed.
III	The calculated Expected Time to Failure is less than mission length, but mission can still be completed with reduced capability. Unscheduled Maintenance must occur after the current mission is completed.
IV	The calculated Expected Time to Failure is less than mission length and the UAS must abort the mission and return to base immediately. Unscheduled Maintenance must occur as soon as possible.
V	Catastrophic Damage expected from fault. Loss of vehicle occurs

3.4 Identify and Develop Architecture Views

Step 4 and 5 identifies and then develops the architecture views necessary to capture all the inter-relationships. The ABEP offers several mandatory and recommended products that should be developed to cover the overall structure and decision logic. Using the previously developed CONOPs as the basis, nearly all evaluations will require an OV-1 (High Level Operations Concept) and OV-2 (Operational Node Connectivity Description), and all will require an OV-5b (Operational Activity Model). The level of abstraction for the OV-5 will have been identified in the previous section. For the decision logic, an OV-6a (Rules Model) will be developed to match the level of abstraction used for the OV-5.

Additional necessary views will be identified through the CONOPs and the selected MOEs. Some additional views called out by the ABEP that have been used in the past include the SV-2 (Systems Resource Flow Description), SV-4 (Systems Functionality Description), SV-7 (Systems Measures Matrix), OV-6b (State Transition Diagram), and OV-6c (Event-Trace Description). All identified views will then be developed IAW DoDAF guidelines.

Current views planned for this research effort are displayed in Table 5 along with their purpose.

Table 5 - Planned Architecture Views

Operational Views	Purpose
OV-1 High Level Operations Concept	Provides a graphical depiction of what the architecture is about and an idea of the players and operations involved
OV-2 Operational Node Connectivity Description	Depicts Operational Needlines (flows of funding, personnel and materiel in addition to information) that indicate a need to exchange resources
OV-5a Operational Activity Decomposition Tree	Decomposes the operational activities that are normally conducted in the course of achieving a mission
OV-5b Operational Activity Model	Describes input/output flows, dependencies and relationships, and external interchanges between operational activities
OV-6a Rules Model	Describes the rules under which the architecture behave under specified conditions
System Views	**Purpose**
SV-1 Systems Interface Model	Depicts all System Resource Flows between Systems that are of interest
All Views	**Purpose**
AV-1 Overview and Summary Information	Provides executive-level summary information in a consistent form that allows quick reference and comparison between views.

3.5 Develop Analytic Modeling and Simulation

Selecting the modeling or analytical tools best suited to meet the purpose of the analysis is Step 6 of the ABEP. The model should be consistent with the architecture: the structure should match the OV-2 and OV-5b products, the decision logic should be based off of the OV-6a, and the parameters should be consistent with the systems described in the SV-1. The additional views will not be directly involved with the analytic model but are required to ensure the architecture products are consistent with each other: the OV-1 and CV-1 provide general overviews for each viewpoint, the SV-5b ensures that the operational activities in the OV's are matched to the ISHM systems described in the SV-1, and the AV-1 ties all the views together.

For this evaluation of the effect of ISHM on mission effectiveness, a spreadsheet model will be built in Microsoft Excel. The model will run over the lifetime of a UAS, whose failure characteristics serve as an input to the model, and will output unscheduled maintenance actions and mission success rates using ISHM performance characteristics. Each lifetime will be considered a Monte Carlo event, with each scheduled maintenance interval or unscheduled maintenance repair acting as a renewal process for the UAS (a process that restores the vehicle to "its original or 'as good as new' condition") [Ebeling, 2010].

The full list of parameters needed for the model and their definitions are displayed in Table 6; the inputs are divided between characteristics of the UAS and performance measures of the proposed ISHM addition, the outputs are divided between expected maintenance actions and a calculated rate of mission success as defined by Equation 7. The user can also select how many Monte Carlo simulations to execute, up to 500 iterations of the lifetime of the UAS.

Table 6 - ISHM Analytic Model Parameters

UAS Properties (Input)	Definitions
P(Failure)	Probability of a failure occurring; a failure distribution
P(Fault Categories)	If a fault occurs, the probability of it falling into each of the five fault categories; a number between 0 and 1 for each fault category
Average Mission Length	The average mission length for the UAS; in hours
Scheduled Maintenance Interval	The interval between scheduled maintenance; in hours
Expected System Lifetime	The expected lifetime of the UAS; in hours
ISHM Properties (Input)	**Definitions**
P_D	Probability of detecting a fault; between 0 and 1 $P(Fault\ Indication \mid Fault\ \cap Operational\ Sensor)$
P_{FA}	Probability of the sensor reading a false alarm; between 0 and 1 $P(Fault\ Indication \mid No\ Fault\ \cap Operational\ Sensor)$
D_{CL}	ISHM's Diagnostic Confidence Level, or the strength of the prognostic and diagnostic algorithms; between 0 and 1
Expected Model Output	**Definitions**
Baseline Maintenance Actions	Expected number of maintenance actions for a UAS using current health management practices
Baseline Rate of Mission Success	Expected rate of mission success for a UAS using current health management practices
ISHM Maintenance Actions	Expected number of maintenance actions for the baseline UAS with the addition of ISHM
ISHM Rate of Mission Success	Expected rate of mission success for the baseline UAS with the addition of ISHM
Model Properties	**Definitions**
Number of Simulations	Number of lifetime simulations to execute; from 1 to 500

3.6 Evaluate Model

The model will then be evaluated for completeness and ability to meet the target metrics in the final Steps 7 and 8. In Step 7, the model is evaluated solely on its ability to consider all relevant aspects (processes, assumptions, input variables, output data and MOEs) of the concept. If the model is determined to not be complete, the process will return to Step 3 with some additional considerations (listed in Appendix A: Architecture-Based Evaluation Process (ABEP)). If the model is considered complete, the process will proceed to Step 8.

The final step deals with the results of the model. Representative data for a UAS will be fed into the model and Design of Experiments (DOE) techniques will be used to determine situations where ISHM can be effectively used. The response for this analysis is the difference between the number of successful missions calculated for a system without ISHM (i.e. using current health management techniques) and a system with ISHM. The intent is to explore the response surface where this difference is maximized, which coincides with the operational area where ISHM would be most beneficial. Representative data can be found in Table 7.

Table 7 - Representative UAS Data

UAS Properties	Values
P(Failure) - Distribution	Weibull Distribution
Average Mission Length	10 hours
Scheduled Maintenance Interval	1,000 hours
Expected System Lifetime	10,000 hours

Without actual UAS failure data, a Weibull failure distribution for P(Failure) was chosen because of its ability to model the minimum of a large number of independent positive random variables from several classes of distributions (i.e., the distribution is great at modeling a system of systems where a failure in one component causes a system-level failure) [Meeker, 1998]. The scale and shape parameters will be left up to DOE analysis to determine the region where the response is maximized.

The average mission length, scheduled maintenance interval, and expected lifetime were chosen by the researcher to represent a typical UAS. They do not reflect any specific aircraft in the USAF inventory.

3.7 Summary

This section went into detail as to how the ABEP is used to create an analytic model for the purpose of evaluating ISHM. The architecture that will be built for the purposes of this research effort will represent a general ISHM, as researched in Chapter II. The analytic model based off this architecture will be focused primarily on analyzing mission effectiveness using generated unscheduled maintenance actions and mission success rates. The architecture, model, and model results are described in detail in Chapter IV.

IV. Analysis and Results

4.1 Chapter Overview

This chapter will present the completed architecture, resulting analytic model, and an analysis of representative UAS failure data.

4.2 ISHM Architecture

This section details the architecture developed using the methodology in Chapter III. Since the focus of this research effort is on the analytic nature of the architecture, only views directly relevant to the analytic model will be discussed in detail in this section. The full system architecture can be found in Appendix B: ISHM Architecture.

4.2.1 Integrated Systems Health Management Concept of Operations

The architecture relies heavily on a robust concept of operations, especially when designing the systems and operations viewpoints. The full concept of operations for a typical ISHM system can be found in Appendix B.1 Integrated System Health Management Concept of Operations, but for the purposes of understanding the resulting viewpoints in this chapter, critical portions of the necessary capabilities, enabling capabilities, sequenced actions, and command relationships are described below.

Necessary Capabilities – Data Management

The ISHM system must provide continuous monitoring over the entirety of the vehicle. Sensors are placed in critical locations in order to feed information on the state of the system. Sensors can be conventional, measuring temperature, speed, and flow rate, or specifically tailored to health management applications, such as strain gauges, ultrasonic sensors, or proximity devices.

Data Management also includes parameter sets, vehicle configuration, and a data store with a list of safe states associated with known fault events and mitigation steps. Current mission sensor data and event recording can either be kept in an on-board data storage system sent to ground as required, or continuously streamed to ground control.

Necessary Capabilities – Fault Detection

The sensor data is then processed to remove any artifacts or noises and manipulated to extract fault features (either current or pre-cursers) and provide a comprehensive system picture. Fault Detection combines diagnostic information with historical data (prognostic reasoning) to generate an estimation of failure times. These fault indications are then sorted, prioritized, and distributed to insure action within time to criticality. Algorithms developed for diagnostic and prognostic calculations are generally based on mathematical models (e.g. Hamilton dynamic, Lagrangian dynamic, approximation methods), or pattern recognition (e.g. fuzzy-logic, statistical/regression methods, neural network clustering).

Necessary Capabilities – Fault Isolation

After identifying that a fault has occurred, ISHM must pinpoint the fault mechanism (i.e. the specific cause of failure) and its location. If not identifiable through prognostic or diagnostic reasoning, common fault mechanisms for that location can be identified using historical failure data.

Necessary Capabilities – Health State Assessment

ISHM must have the capability to assess and assign levels of health to the vehicle. This is achieved by calculating the remaining vehicle capabilities based on a capability model and the current fault state of the system. A notional capability model is hierarchically based, where the higher-level capability is computed using the values of the lower-level capabilities and a mathematical expression. Faults are quantified at the lowest level with system-level capability computations that orient this data with mission requirements to determine effects on the vehicle.

Necessary Capabilities – Select Mitigation Procedures

The ISHM system will provide mitigation procedures in the event of a known fault for the on-board flight control to act on if necessary. In order to perform this capability, ISHM will a) examine the available resources to determine any performance limitations and to estimate the time to criticality; b) confirm the diagnosed event and declare it to be a valid vehicle event with a high confidence level; c) access the fault data store for the appropriate safe state and the feasible step alternatives; before d) selecting the action steps that allow completion within the criticality time and performance limitations. These action procedures will then be sent to the on-board flight control and to ground control. Since ISHM operates only on known faults and known mitigations, any unknown fault will immediately be assigned a critical level of health and the aircraft will automatically return to base.

Enabling Capabilities

A formal Failure Mode, Effect, and Criticality Analysis (FMECA) must be performed on the vehicle prior to ISHM being implemented [Ebeling, 2010]. This is an iterative process that identifies failure modes, assesses their probabilities of occurrence and their effects on the system, isolating their causes, and determining corrective action or preventative measures. The results of the FMECA should identify critical sub-systems or components where sensors need to be applied, guide the diagnostic and prognostic algorithm creation, and assign criticality to failure modes for health assessment purposes.

Sequenced Actions - Nominal Operations

The ISHM system will be continuously monitoring the health state of the UAS and will communicate either continuously or on set intervals (barring a fault event) the health status of the UAS. ISHM will also be continuously calculating an Estimated Time to Failures for every monitored component.

Sequenced Actions - Real-Time Fault Event

Once a failure occurs, the following actions should take place:

(1) ISHM locates the fault and identifies the failure mode

(2) ISHM assigns a criticality to the fault mode and adjusts the vehicle's health status to the appropriate level

(3) ISHM evaluates the new capability of the vehicle

(4) ISHM selects appropriate, deterministic, mitigation action procedures, correlating them with mission and vehicle inhibits.

(5) ISHM sends the action procedures to the on-board flight control, and alerts the Ground Operator and the Maintenance element

a. The on-board flight control can:

   (i) Continue on current trajectory (ignore ISHM)

   (ii) Use recommendations to autonomously reconfigure and/or reshape the current trajectory

b. The Ground Operator, as appropriate and in accordance with the criticality of the event, can:

   (i) Override the on-board flight control decision and re-task within its new capability

   (ii) Defer to the autonomous on-board flight control decision

c. The Maintenance element executes maintenance actions as appropriate

Sequenced Actions - Pre-Cursor to Fault is Detected

When a pre-cursor to a fault is detected, the following actions should take place:

(1) ISHM locates the affected component and identifies the impending failure mode

(2) ISHM calculates an Estimated Time to System (or Component) Failure

(3) ISHM assigns a criticality to the fault mode and adjusts the vehicle's health status to the appropriate level

(4) ISHM evaluates the new capability of the vehicle

(5) ISHM selects appropriate, deterministic, mitigation action procedures, correlating them with mission and vehicle inhibits.

(6) ISHM sends the action procedures to the on-board flight control, and alerts the Ground Operator and the Maintenance element

   a. The on-board flight control can:

      (i) Continue on current trajectory (ignore ISHM)

      (ii) Use recommendations to autonomously reconfigure and/or reshape the current trajectory

   b. The Ground Operator, as appropriate and in accordance with the criticality of the event, can:

      (i) Override the on-board flight control decision and re-task within its new capability

      (ii) Defer to the autonomous on-board flight control decision

   c. The Maintenance element executes maintenance actions as appropriate

Command Relationships - Ground Control

Ground systems are normally treated as separate systems, and their relationship to the vehicle has typically been one of controller and operator; in this case, ground is hierarchically superior to the vehicle and commands it for some mission phases but is reactionary for others. Vehicle control transitions between ground and on-board depending on mission phase and particular event conditions:

- Before Launch
  - Ground is master
  - Control transitions to vehicle during launch sequence
- During Flight
  - Vehicle is master (autonomous)
  - Ground monitors via downlink telemetry
  - Ground takes control when appropriate
- Post Landing
  - Ground is master (after auto-safing)

Command Relationships - Maintenance and Logistics

Maintenance and Logistics can be considered part of ground control (under the overarching domain of "Operations Control Center") or a separate system entirely. Their relationship to the vehicle is either reactionary or scheduled and does not consist of a hierarchical relationship.

Interactions:

- Scheduled Maintenance: Based on flight hours and is performed at either the base-level or at a depot. Collected historical data from ISHM monitoring can be used to highlight components that need to be inspected.

- Unscheduled Maintenance: Initiated when a fault has been discovered. Once the ISHM has detected an anomaly, the appropriate data is sent to Maintenance and Logistic for action.
- Post Mission: Degradation and non-critical fault information are sent to Maintenance and Logistics to improve vehicle turn-around time.

Command Relationships - On-Board Flight Control

The on-board flight control receives command to execute an action from ISHM generated by either ISHM and/or ground C2. The autonomous on-board flight control will decompose these decisions and action lists into a set of commands and send them to the appropriate systems for execution. On-board flight control schedules these tasks accordingly in order to complete in the prescribed time.

As a vehicle system, on-board flight control health status, events, time, and mission information are continuously sent to ISHM. ISHM in turn continuously provides the vehicle system health assessments, vehicle capability, and mitigation actions predetermined for particular anomalies.

4.2.2 OV-5b Operational Activity Models

The OV-5b "Operational Activity Model" shows the activity flow needed for the operation of a typical ISHM system. For graphical simplicity, ISHM has been divided into three main activity models: the first (Figure 7) being the activities performed under nominal mission operations; the second (Figure 8) concerning the actions performed when a fault is detected during a mission; and the third (Figure 9) the activities involved over the lifetime of the UAS.

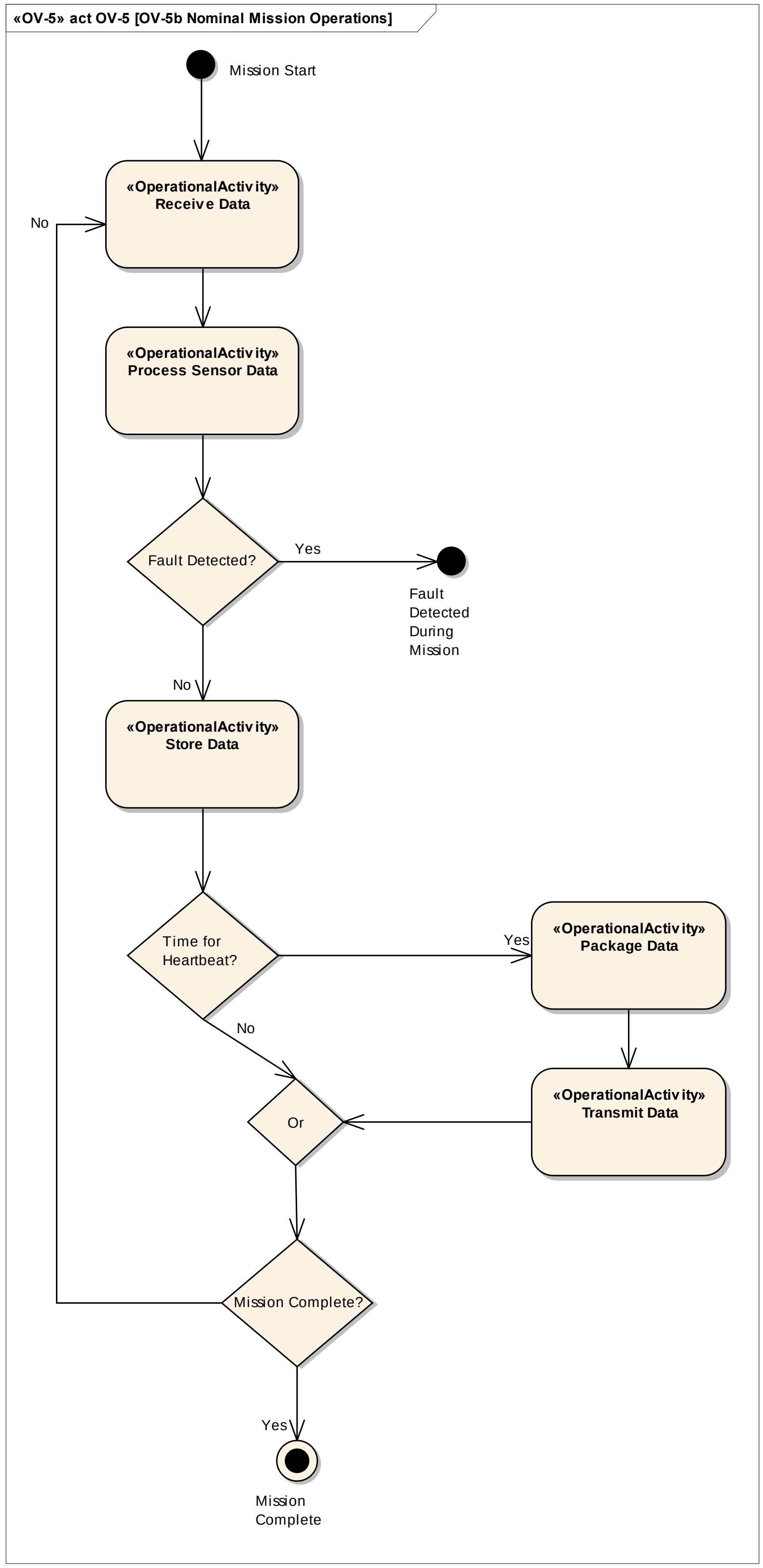


Figure 7 - OV-5b "Nominal Mission Operations"

Since current health management or monitoring technologies also use sensors, the activity flow through the diagram in Figure 7 is generally the same between a UAS with ISHM and one without. The difference occurs when a fault is detected, without ISHM there is no certainty as to what is actually occurring on the UAS and aside from a few prevalent and simplistic fault conditions the UAS will be recalled to base, ending the mission. With ISHM, greater system awareness is achieved and alternative mitigation actions can be found other than immediately recalling the vehicle.

The OV-5b diagram "Fault During a Mission", as seen in Figure 8, is where the bulk of ISHM activities are performed. Once a fault (or multiple faults) is confirmed, ISHM loops through the diagnostic and prognostic algorithms, determining the type and location of the fault as well as calculating the estimated time to failure. This data is then pushed to the decision reasoning system, where the faults are prioritized and the remaining capability of the vehicle compared to the current mission tasking. Mitigation actions are then selected from the data store and recommended for the vehicle's autonomous command and control system to evaluate. Ideally, the command and control system would accept the mitigation actions, execute them, and the UAS would be re-tasked or would continue on the mission as appropriate. A situation where the command and control system would not accept the mitigation actions would be if ISHM recommended actions that would cause the UAS to depart flight; although this is unlikely, the hierarchy must be maintained as the autonomous command and control system is flight-critical and ISHM is not.

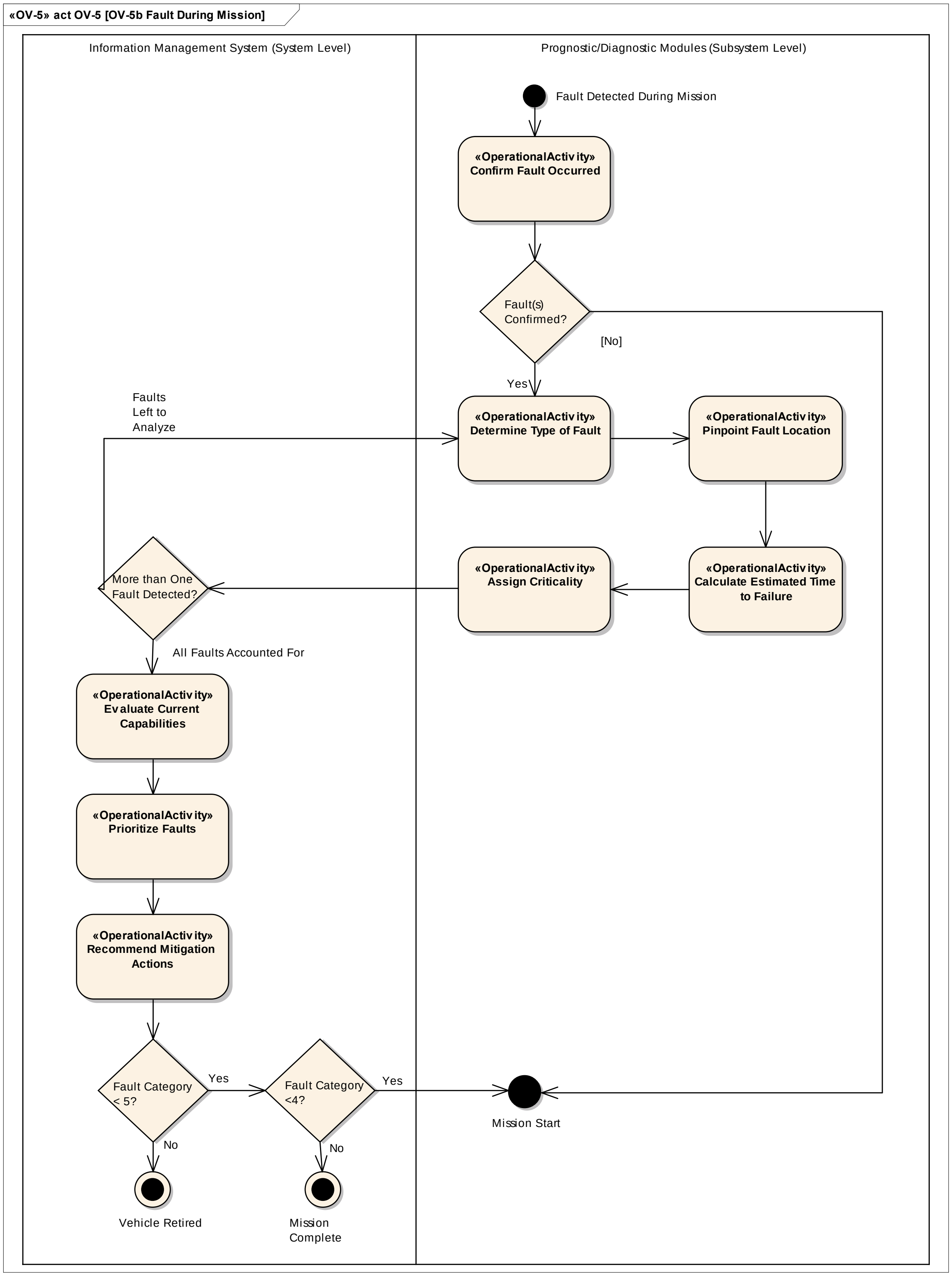


Figure 8 - OV-5b "Fault During Mission"

The activity flow through the OV-5b diagram "Lifetime Operations", as seen in Figure 9, also parallels UAS without ISHM activities. The difference would be found in the quantity of activities performed, ideally a system with ISHM would have fewer scheduled and unscheduled maintenance actions.

Theoretically, a system with ISHM would approach condition-based maintenance, where all maintenance actions are driven by the prognostic and diagnostic modules, eliminating scheduled maintenance. However, current ISHM technologies have not yet reached a level of confidence where scheduled maintenance can be entirely removed from maintenance operations. To represent how ISHM would be introduced to Air Force operations in the current generation of technology, scheduled maintenance remains in the architecture as a health management action.

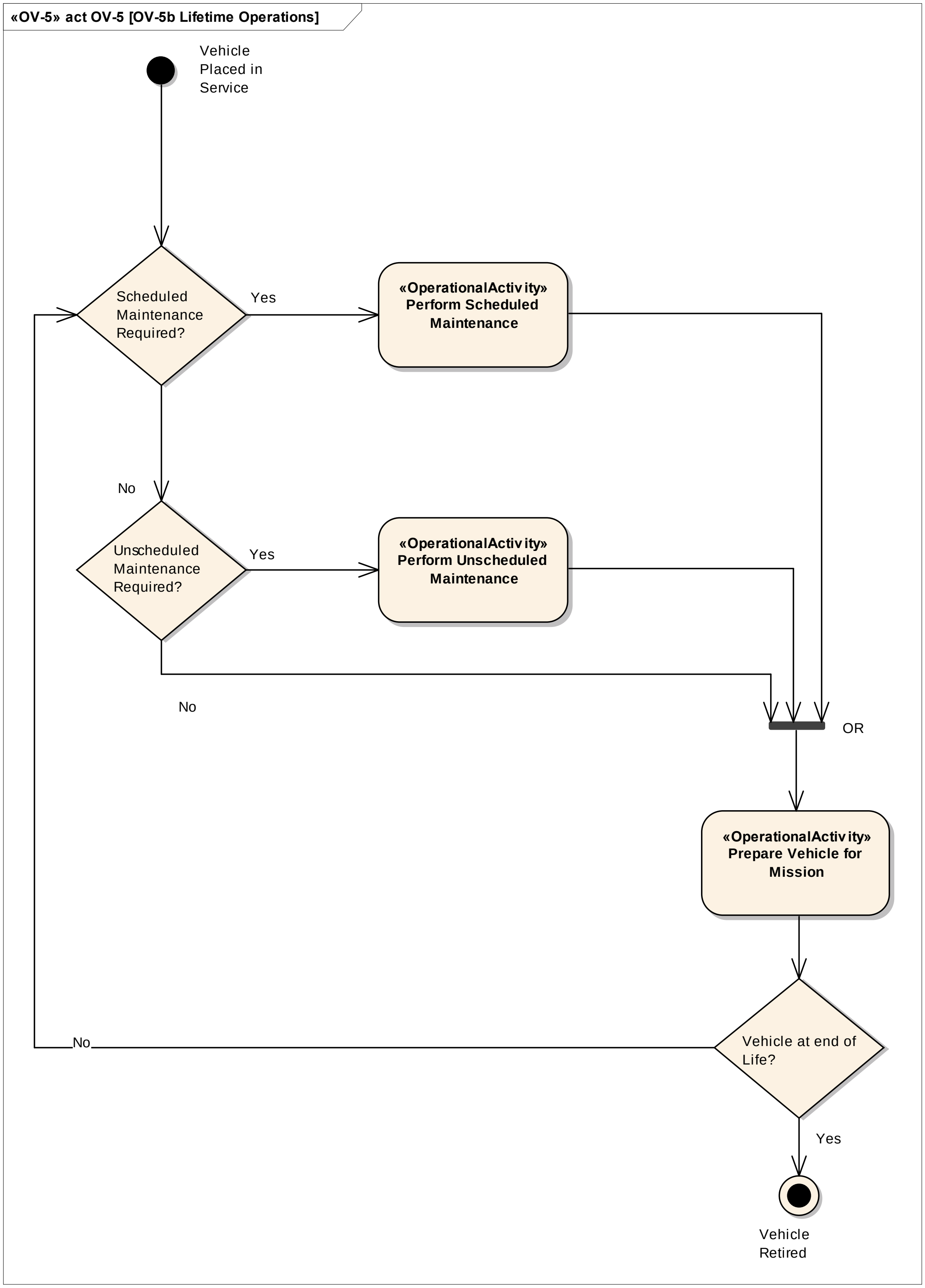


Figure 9 – OV-5b "Lifetime Operations"

4.2.3 OV-6a Rules Model

Development of the OV-6a Rules Model closely followed the development of the OV-5b diagrams. The OV-6a model, seen in Figure 10, represents the decisions made by ISHM over a single mission. The ISHM metrics that drive the model are the Probability of Detection (P_D), the Probability of a False Alarm (P_{FA}), and the Diagnostic Confidence Level (D_{CL}). The Probability of Detection and Probability of a False Alarm are dependent on the sensor quality. Generally, a higher Probability of Detection also equates to a higher Probability of False Alarm. The Diagnostic Confidence Level represents the quality of the diagnostic and prognostics algorithms. Better algorithms would give a higher Diagnostic Confidence Level and therefore a better probability of assigning the correct fault category for a detected fault. The Rules Model logic is discussed further in Section 4.3.

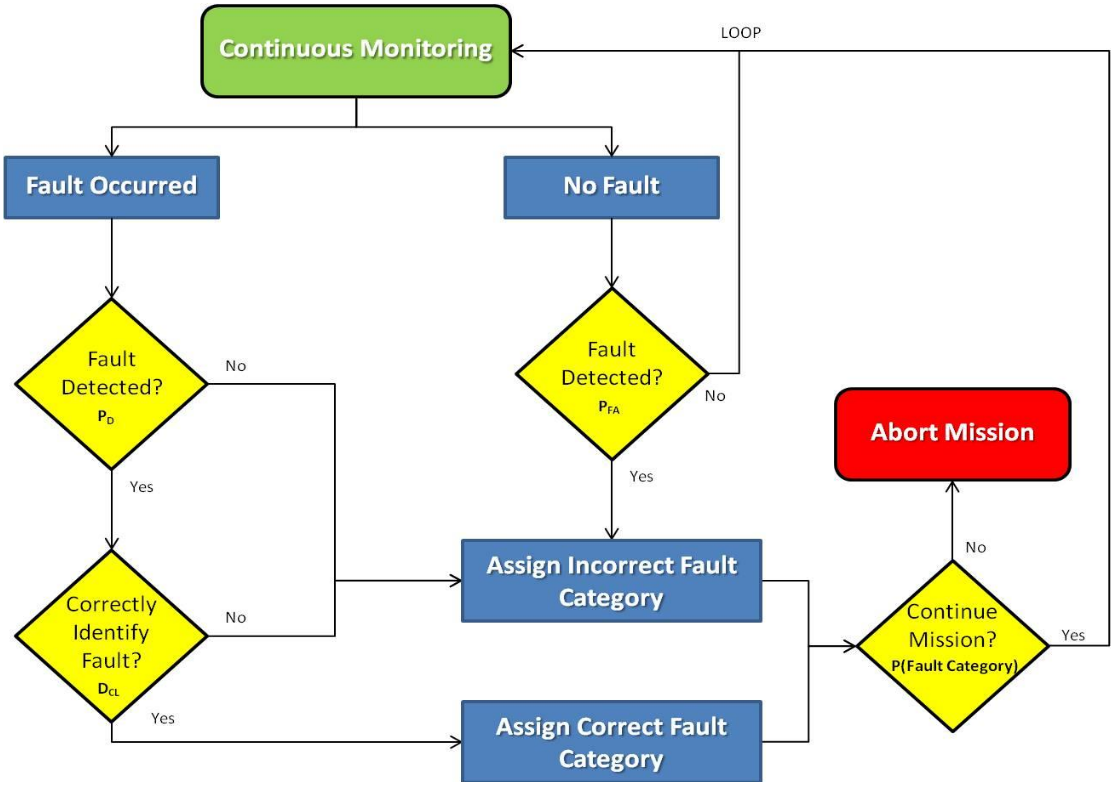


Figure 10 - OV-6a "Rules Model"

4.2.4 SV-1 Systems Interface Model

The SV-1 Systems Interface Model depicted in Figure 11 is for a UAS with ISHM using current ISHM technology. In this architecture ISHM starts at the subsystem and component level, with each critical subsystem having its own prognostic/diagnostic module. Having the prognostic and diagnostic module at this lower level allows each module to be individually configured to best interpret the health of that particular subsystem. The prognostic and diagnostic module ingests data from the sensors (or sensor suites, depending on the complexity of the subsystem), and can command system effectors when investigating off-nominal conditions. An example of when effectors for a subsystem would be utilized is when detecting structural cracks; the module would excite a piezoelectric transducer (i.e. an effector), which would send out an elastic wave from the transducer, the wave would then be measured by sensors further down the component and the module would evaluate the data for any deviations.

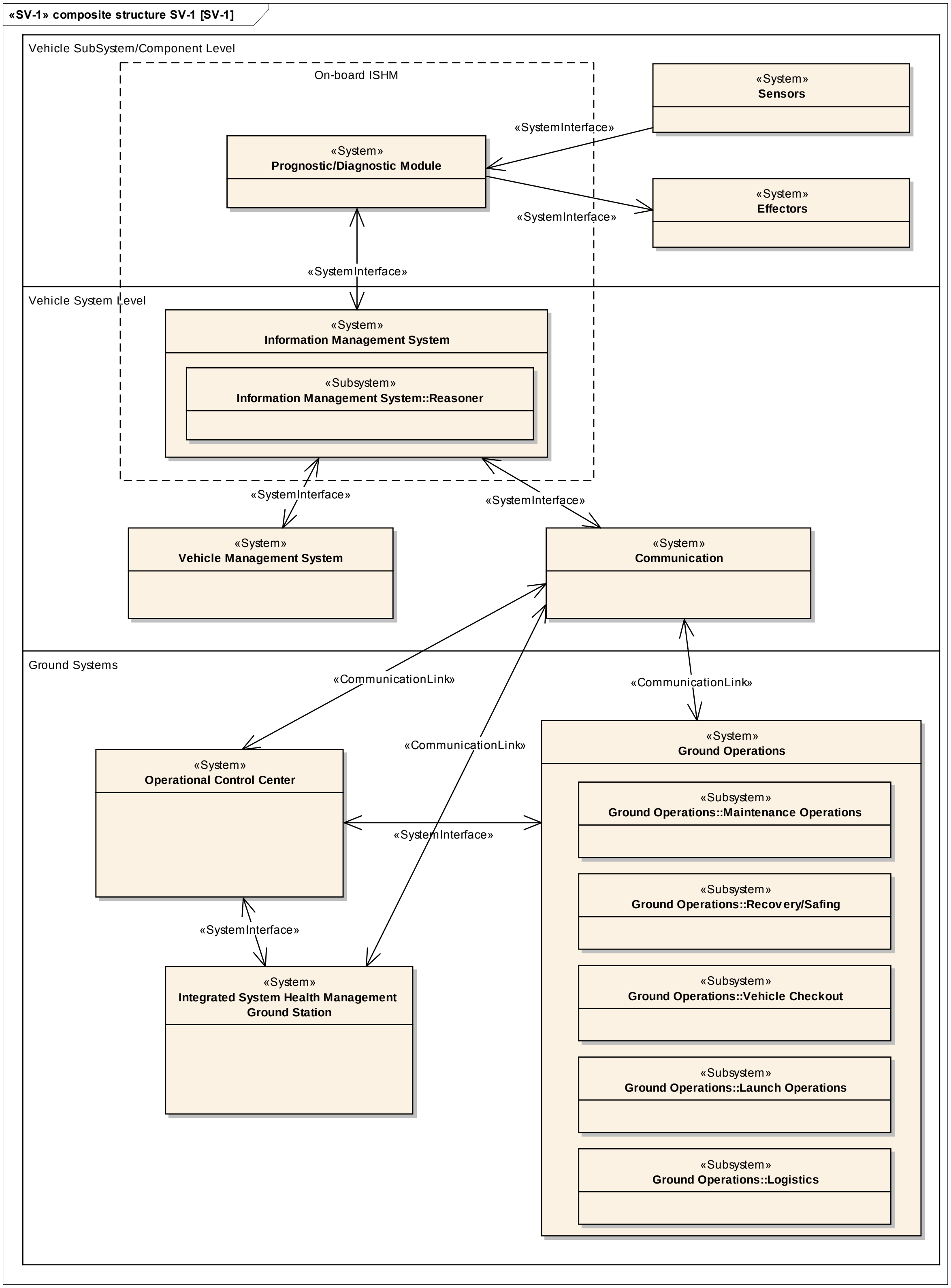


Figure 11 - SV-1 "Systems Interface Model"

The information from the subsystem and component level is then fed up to the system level to an Information Management System. This system includes the decision reasoner, a data store with a list of safe states associated with known fault events and mitigation steps, and another data collection module to store health-related data and to process information to be sent out as heartbeats (i.e. periodic health state assessments to ground-based operations) or maintenance actions, as appropriate. In the case of a fault, the Information Management System assesses the new health of the vehicles (based on the estimated time to failure and current UAS capabilities) and selects the mitigation steps to be recommended the on-board command and control unit. This on-board command and control unit is represented by the Vehicle Management System in the diagram.

The last level in the diagram includes the systems found at the ground level, to include the Operations Control Center; Ground Operations such as maintenance and logistics; and a ground component of ISHM. As with leaving scheduled maintenance as an activity in the OV-5b, the current state of ISHM technology does not allow for full autonomy in its decision making. Given time to review (some failures will be too imminent to allow time for review), a ground-based operator will be reviewing the activities controlled by ISHM, separate from the ground control center, and has the authority to override ISHM commands when appropriate.

4.3 ISHM Analytic Model

Using the Rules Model created in Figure 10, a model was developed to simulate the lifetime of a UAS and the effects of ISHM on the mission success rate and expected number of unscheduled maintenance actions. The model parameters were displayed previously in Table 6.

The model begins by generating a random fault time (in hours) from the failure distribution provided by the user, t_{Fault}, and four random numbers between 0 and 1: $RAND_{Detect}$, $RAND_{FA}$, $RAND_{Category}$, and $RAND_{CM}$. The model then determines if a fault is detected, whether or not a fault has occurred, or if a fault was not detected, whether or not a fault has occurred, for an average mission length (t_M), Probability of Detection (P_D), and Probability of False Alarm (P_{FA}) using Equation 9.

$$\begin{gathered} If(t_{Fault} \leq t_M)\ Then\ Fault = 1, Else\ Fault = 0 \\ If(Fault = 1 \cap RAND_{Detect} \leq P_D)\ Then\ Detect = 1 \\ If(Fault = 1 \cap RAND_{Detect} > P_D)\ Then\ Detect = 0 \\ If(Fault = 0 \cap RAND_{FA} \leq P_{FA})\ Then\ Detect = 1 \\ If(Fault = 0 \cap RAND_{FA} > P_{FA})\ Then\ Detect = 0 \end{gathered} \tag{9}$$

A fault category is then assigned using $RAND_{Category}$ and the P(Fault Categories) distribution provided by the user. Equation 10 displays how this category is assigned:

$$\begin{gathered} If(RAND_{Category} \leq P(Fault\ Cat\ I))\ Then\ Category_{TRUE}\ =\ 1 * Fault \\ ElseIf(RAND_{Category} \leq P(Fault\ Cat\ II))\ Then\ Category_{TRUE}\ =\ 2 * Fault \\ ElseIf(RAND_{Category} \leq P(Fault\ Cat\ III))\ Then\ Category_{True}\ =\ 3 * Fault \\ ElseIf(RAND_{Category} \leq P(Fault\ Cat\ IV))\ Then\ Category_{True}\ =\ 4 * Fault \\ Else\ Category_{True}\ =\ 5 * Fault \end{gathered} \tag{10}$$

A confusion matrix, displayed in Table 8, is used to determine the declared fault category based upon $Category_{True}$. The confusion matrix initiates using the diagnostic confidence level, D_{CL}, as the basis, but the model al lows the user to input values manually if necessary.

Table 8 - Confusion Matrix

Confusion Matrix	True Fault Category					
Declared Fault Category	**Nominal**	**I**	**II**	**III**	**IV**	**V**
Nominal	D_{CL}	$(1-D_{CL})/2$	0	0	0	0
I	$1-D_{CL}$	D_{CL}	$(1-D_{CL})/2$	0	0	0
II	0	$(1-D_{CL})/2$	D_{CL}	$(1-D_{CL})/2$	0	0
III	0	0	$(1-D_{CL})/2$	D_{CL}	$(1-D_{CL})/2$	0
IV	0	0	0	$(1-D_{CL})/2$	D_{CL}	$1-D_{CL}$
V	0	0	0	0	$(1-D_{CL})/2$	D_{CL}

An example of using the confusion matrix given $Category_{True}$ = II can be seen in Equation 11:

$$
\begin{gathered}
If \left(RAND_{CM} \leq \frac{1-D_{CL}}{2}\right) Then\ Category_{Detect} = I * Detect \\
ElseIf (RAND_{CM} \leq D_{CL}) Then\ Category_{Detect} = II * Detect \\
Else\ Category_{Detect} = III * Detect
\end{gathered} \tag{11}
$$

$\text{Category}_{\text{True}}$ and $\text{Category}_{\text{Detect}}$ are then used to calculate mission success rates and maintenance actions using the formulas found in Table 9. For this research effort, partially completed missions are considered successful missions.

Table 9 - Mission Success and Maintenance Rates Formulas

System without ISHM	**Formula**
Mission Success?	$\begin{cases} 1, \text{ if Category}_{\text{Detect}} = 0 \text{ AND Category}_{\text{True}} \leq 2 \\ 0, \text{ otherwise} \end{cases}$
Maintenance Required?	$\begin{cases} 1, \text{ if Category}_{\text{Detect}} = 1, 2, 3, 4 \\ 0, \text{ otherwise} \end{cases}$
System with ISHM	**Formula**
Mission Success?	$\begin{cases} 1, \text{ otherwise} \\ 0, \text{ if Category}_{\text{Detect}} \geq 4 \\ \quad \text{OR Category}_{\text{True}} \geq 3 \text{ when Category}_{\text{Detect}} \leq 2 \\ \quad \text{OR Category}_{\text{True}} \geq 4 \text{ when Category}_{\text{Detect}} = 3 \\ \quad \text{OR Category}_{\text{True}} = 5 \end{cases}$
Maintenance Required?	$\begin{cases} 1, \text{ if Category}_{\text{Detect}} = 2, 3, 4 \\ 0, \text{ otherwise} \end{cases}$

The model then outputs the number of missions attempted, number of missions completed successfully, and number of unscheduled maintenance actions initiated for both a UAS with ISHM and without.

This model has several assumptions and limitations that need to be weighed to fully understand how the results can be used by decision makers.

- Each simulation is independent; a simulation being a lifetime of the UAS
- Sensor and system degradation effects are not taken into account in this model

- The addition of ISHM causes negligible performance degradation of the UAS
- The Probability of Detection (P_D) and the Probability of False Alarm (P_{FA}) are the same for a UAS without ISHM (using current health management practices) and with ISHM. In reality, ISHM would have additional sensors and effectors based on the results of the FMECA, resulting in a different P_D and P_{FA}.
- Any fault detected will result in a cancelled mission under current detection/health management capabilities
- The scheduled maintenance intervals act as a renewal process – that is, if the UAS reaches a scheduled maintenance interval, the vehicle is returned to a "like new" state.
- P_D and P_{FA} are representative of the entire suite of sensors on the UAS. In reality, each sensor would have its own individual performance characteristics.

The model was coded in Microsoft Excel© using Visual Basic Applications (VBA) for Excel; the full code can be found in Appendix C: Analytic Model Code.

4.4 Model Analysis

As stated in Chapter III, the model will be analyzed using Design of Experiments (DOE) techniques to determine the region where ISHM is most effective. As the model assumes that the sensor characteristics are the same for the baseline UAS and the UAS with ISHM, the model is best used to evaluate the situation where ISHM prognostic/diagnostic modules and the information management system would be attached to the existing sensors on the baseline UAS. The DOE techniques used in the section are taken from *Design and Analysis of Experiments* by Douglas C. Montgomery and were described in detail in Section 2.7 Design of Experiments [2009].

4.4.1 Design of Experiments Test Design

The first two guidelines, defining the problem and selecting the response variable, have been discussed in depth previously in this section. The next step is to identify the design factors and their appropriate levels. For this analytic model, there are 14 separate inputs that can be used as design factors, as shown in Table 10.

Table 10 - Model Input

UAS Properties	Model Input
P(Failure)	Failure Distribution (i.e. Normal); two parameters (i.e. μ and σ)
P(Fault Categories)	P(Fault Category 1) P(Fault Category 2) P(Fault Category 3) P(Fault Category 4) P(Fault Category 5) *sum of these probabilities must add to 1
Average Mission Length	t_m
Scheduled Maintenance Interval	t_{pm}
Expected System Lifetime	T
ISHM Properties	**Model Input**
Probability of detecting a fault	P_D
Probability of the sensor reading a false alarm	P_{FA}
Diagnostic Confidence Level	D_{CL}

As discussed in Chapter III, several of these factors will be fixed and will be used to approximate a typical UAS: failure distribution, t_M, t_{PM}, and T. The remaining factors then become the design factors and will be varied to investigate their effect on ISHM effectiveness.

A key factor in DOE is independence in the factors being investigated. This is not possible for two groups of the factors: P(Fault Categories), which must sum to one; and the sensor characteristics P_D and P_{FA}, which are dependent on each other. Instead of using all five P(Fault Categories), two will be selected to represent this group. P(Fault Category II) and P(Fault Category III) best reflect the difference in how mission success is calculated in the model for a UAS with ISHM and for one using current health management practices (see Table 9).

The sensor performance characteristics, P_D and P_{FA} are determined by Receiver Operating Characteristic (ROC) curves, which relate true positive fraction to false positive fraction. The ROC curve model used in this research is shown in Equation 12 and is derived from [Moses, 1993]:

$$(1 - P_{FA}) = \frac{P_D}{(1 - c)P_D + c} \tag{12}$$

where the parameter c ϵ [1,∞] represents the quality of the sensor; as c increases, the ROC improves, as $c \to \infty$, the area under the curve approaches unity indicating perfect classification. There are many ways to calculate c but for the purposes of this model no specific equation will be provided, c will instead represent a general quality. A family of ROC curves is presented in Figure 12.

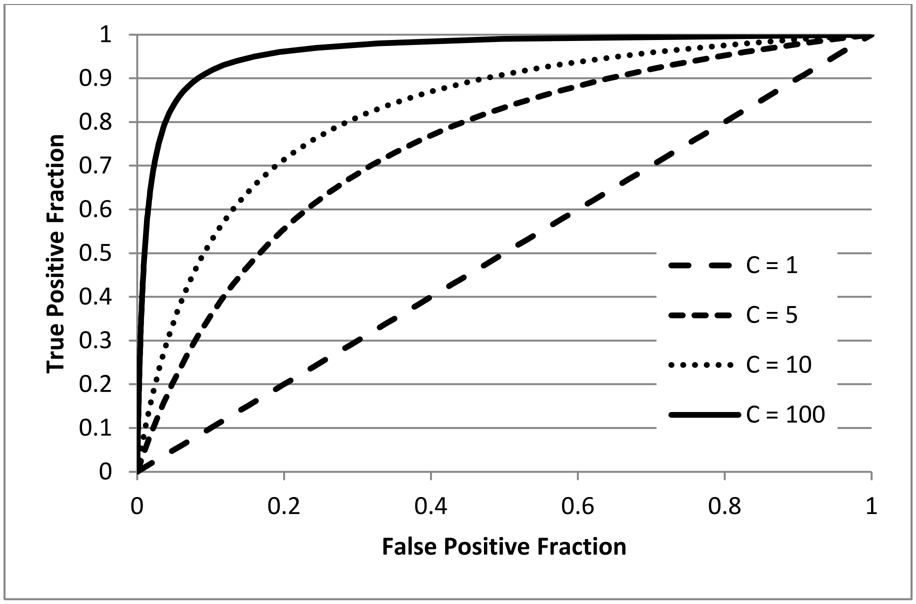


Figure 12 - Family of ROC Curves

To break the dependence on each other, only P_D and sensor quality (c) will be evaluated for the analysis.

The initial high (+1) and low (-1) discrete settings for each of the seven factors were chosen with input from health management Subject Matter Experts at AFRL/RQ and are displayed in Table 11. Center points are also included, as they are necessary to check for curvature in the response surface.

Table 11 - DOE Factor Levels

Factor	Discrete Settings		
	-1	Center	+1
Weibull - Theta	700	850	1000
Weibull - Beta	2.5	2.75	3
Sensor Quality	100	300	500
P_D	0.3	0.6	0.9
P(Fault Category II)	0.1	0.25	0.4
P(Fault Category III)	0.1	0.25	0.4
D_{CL}	0.6	0.75	0.9
Factor	**Fixed Settings**		
Distribution	Weibull		
T	10,000 hrs		
t_M	10 hrs		
t_{PM}	1,000 hrs		

To test every combination of high/low factors in a factorial design, a 2^7 design would require at least 128 runs, not including the additional center points and any replications. With this in mind, a fractional factorial 2^{7-4} Resolution III design with two replicates and four center points was chosen, for a total of 28 runs. Each run would also include four repeated measurements (i.e., four Monte Carlo trials) for a total of 12 measurements for each test point selected. The high number of measurements for each test point was chosen due to Excel's inadequacies at random number generation. Previous research into Excel has shown that Excel's random number generation does not fulfill the basic requirements for a random number generator to be used for scientific purposes [McCullough, 2008]. Since the model relies on primarily on the random number generator, a large number of measurements for each test point will hopefully assuage the number generation problems.

The defining relationship for this experiment was chosen to alias higher order effects and focus on the main factors and low-order interactions, following the *sparsity of effects* *principle* as discussed in Section 2.7: I = ABD = ACE = BCF = ABCG. For this relationship A = Weibull-Theta, B = Weibull-Beta, C = Sensor Quality, D = Probability of Detection, E = P(Fault Category II), F = P(Fault Category III) and G = the Diagnostic Confidence Level. The full alias structure can be found in Appendix D: Design of Experiments Results and Models.

4.4.2 Design of Experiments Results and Conclusions

The full experiment with test design, results, and statistical analysis can be found in Appendix D: Design of Experiments Results and Models. A summary of the results and the corresponding conclusions are detailed in this section. The statistical analysis in this section was performed using JMP® Version 9.0.1.

One of the main results is that not all of the design factors are significant. Using an F-test, only four main factors - Weibull-ϴ, P_D, P(Fault Category III), and sensor quality - and some low-order interactions were found to significantly affect the response. The remaining factors can essentially be ignored when using the model to compare a UAS with ISHM and without. Effect tests on the significant factors and interactions can be found in Figure 13, the alpha level for the significance tests was 0.05. The model was also found to include quadratic terms, in this case Weibull-ϴ * Weibull-ϴ and P(Fault Category III)* P(Fault Category III), which indicated a second-order response surface model and that some curvature would be seen in the response surface.

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Prob Detection	1	1	976.8580	48.8474	<.0001*
Prob Fault Category III	1	1	383.4336	19.1734	<.0001*
Weibull - theta	1	1	225.5012	11.2761	0.0018*
Sensor Quality	1	1	91.5769	4.5793	0.0390*
Prob Fault Category III*Prob Fault Category III	1	1	238.7926	11.9407	0.0014*
Prob Detection*Weibull - theta	1	1	954.2876	47.7187	<.0001*
Weibull - theta*Weibull - theta	1	1	108.6350	5.4322	0.0253*
Prob Fault Category III*Sensor Quality	1	1	1482.2742	74.1205	<.0001*

Figure 13 - Effect Tests on Significant Factors and Interactions

The final model equation, displayed in Equation 13, mapping the response surface was determined to be:

$$\begin{aligned} y = (&-5.861 + 0.015\theta + 17.322P_D - 67.369P(Fault\ Cat\ III) + \\ &0.007c + 501.715(P(Fault\ Cat\ III) - 0.191)^2 - \\ &0.237(\theta - 850)(P_D - 0.652) - 0.0001(\theta - 850)^2 + \\ &0.391) - 0.415(P(Fault\ Cat\ III) - 0.191)(c - 300))^2 \end{aligned} \tag{13}$$

where y is the difference between the number of successful missions calculated for a system with ISHM and the same system without ISHM (i.e. using current health management techniques)

From this equation the stationary point is a region of minimum response, clearly visible in Figure 14.

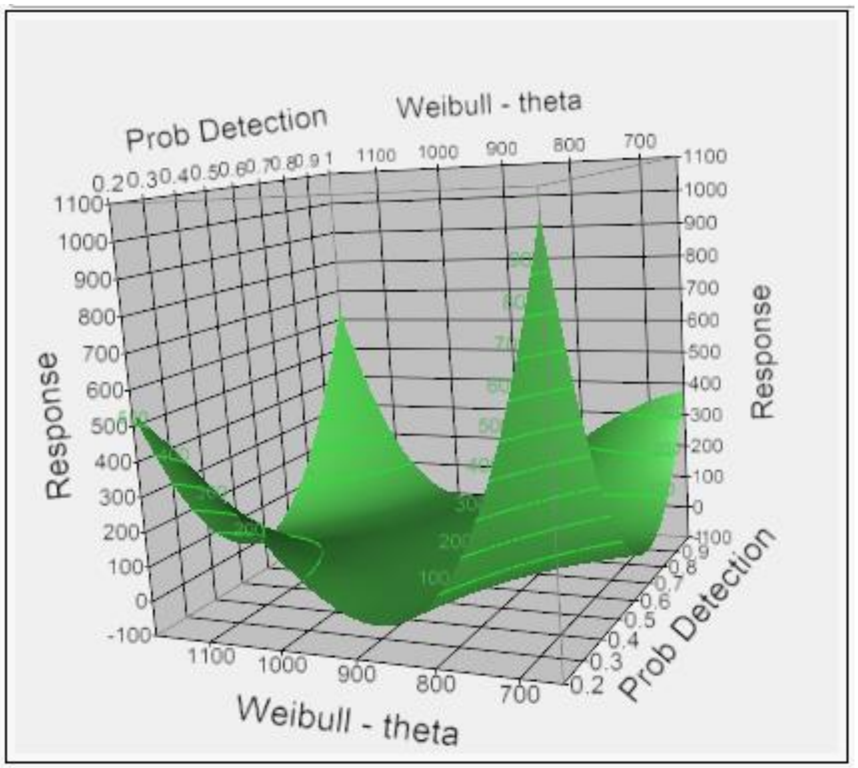


Figure 14 - Response Surface for Analytic Model

While this response surface best illustrates the region were the response is at its minimum, or the region where adding ISHM to the UAS baseline would not significantly affect mission success rates, there can be some inferences made about the regions that maximize the response. By not determining the ISHM performance characteristic (the Diagnostic Confidence Level) significant, this evaluation implies that the benefits or disadvantages of adding ISHM rely primarily on the performance of the baseline health management system. Specifically, that ISHM becomes more beneficial as the baseline health management system performs worse.

Another useful result of this analysis is that the model equation can be used to test if adding ISHM to a UAS will statistically affect the mission success rates. This can be done using a two-sample t-test, because we can assume that the variance is equal between mission success rates calculated for the UAS with ISHM and the UAS without. The t-test uses the statistic found in Equation 14 [Montgomery, 2009]:

$$t_0 = \frac{\overline{y_1} - \overline{y_2}}{S_p\sqrt{\frac{2}{n}}} \quad (14)$$

where $\overline{y_1} - \overline{y_2}$ = the output of the model equation, the difference between the number of successful missions calculated for a system without ISHM and the same system with ISHM

S_p = sample variance.

n = population size.

The Mean Square Error (MS_E) calculated for the model can be used as an estimate of sample variance. The sample size used to create the model, in this case 46 trials with four repeated measurements for each trial, can be used as the population size. The addition of ISHM would be considered statistically significant if $|t_0| > t_{\frac{\alpha}{2},2n-2}$ where α is the level of significance. Using the model results detailed in Appendix D and an alpha of 0.05, the updated Equation 15 becomes:

$$t_0 = \frac{\overline{y_1} - \overline{y_2}}{23.045\sqrt{\frac{2}{184}}} = \frac{\overline{y_1} - \overline{y_2}}{2.4026} \quad (15)$$

$$t_{\frac{\alpha}{2},2n-2} = t_{0.025,366} = 1.967$$

Using Equation 12 it can be inferred that if the difference between the expected number of successful missions calculated for a system without ISHM and the same system with ISHM is greater than 4.726, then the addition of ISHM to the baseline UAS will result in a statistically significant difference in mission success rates. Since the mission success rate difference is always positive, the addition of ISHM can be considered a beneficial addition in terms of mission success rates.

4.5 Summary

This chapter covered the final products and results from the methodology presented in Chapter III. An analytic architecture was created using the Architecture Based Evaluation Process and then evaluated using Design of Experiments techniques. Results from the evaluation indicated that installing ISHM in existing UAS platforms is only worthwhile, in terms of mission effectiveness, when the existing UAS's health management system has significant detection and false alarm problems. The products and model results will form the basis of this research effort's conclusions and recommendations discussed in Chapter V.

V. Conclusions and Recommendations

5.1 Chapter Overview

This chapter will answer the research objectives and discuss areas for future research.

5.2 Research Questions Answered

The focus of this research effort was to quantify the mission-related benefits of ISHM by constructing architecture for analysis to compare against current autonomous vehicle capabilities, and to provide a general baseline model that can be implemented over any current or future autonomous vehicle. To do this, a literature review was conducted to answer the following questions, posed initially in Chapter I:

What is the current status of UAS health management?

The Air Force UAS programs currently use independent sensors incorporated into the vehicle's hardware to monitor for fault indicators on critical subsystems. The sensor data is continuously transmitted to ground operations where it is then processed to detect anomalies. If the data indicates a fault has occurred the ground operator will execute pre-determined mitigation steps, dependent on which sensor indicated a fault, and relay a message to the maintenance and logistics element. Once the vehicle lands, maintenance personnel perform diagnostic tests to confirm the location and identify the type of fault, and then perform maintenance actions to restore the component. This is less health management than health monitoring, in terms of nomenclature.

What are the essential elements of ISHM?

A typical ISHM system consists of sensors placed at critical components within subsystems of the vehicle that stream data to a management system. The management system processes the sensor data, executes diagnostic and prognostic algorithms, and then feeds this information through a reasoner, as previously displayed in Figure 3. This management system can either be on-board the vehicle in a hardware configuration or off-board enabling the ground command and control (C2) element.

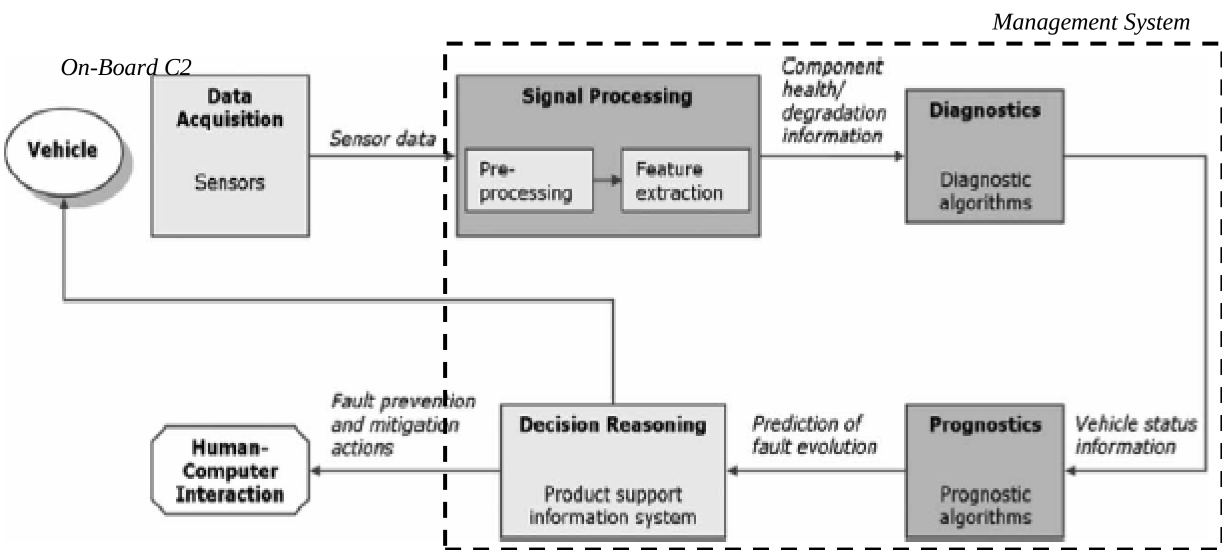


Figure 3 - Typical ISHM configuration [Benedettini, 2009]

Sensors can be conventional or specifically tailored to health management applications. The sensor data is then processed to remove any artifacts or noises and manipulated to extract fault features. The diagnostic module then analyzes the fault features to detect, identify, and isolate developing failure conditions. The diagnostic information will be combined with historical data in the prognostic module to generate an estimation of failure times. Finally, the diagnostic and prognostic information is turned over to the reasoner module which analyzes available resources, decides which hazard mitigation steps to execute, and then passes the selected decision to the on-board C2 module and relays appropriate information to the ground C2 operator and maintenance element [Benedettini, 2009].

What are the expected benefits of ISHM?

There were five areas that were determined to benefit the most from adding ISHM to UAS platforms: rate of scheduled and unscheduled maintenance, repair times, operational availability, mission success, and cost. With ISHM implemented, the probability of unscheduled maintenance should decrease as unscheduled maintenance becomes more fault driven and scheduled maintenance intervals can also be investigated for potential relaxation or removal. Ideally, the aircraft would replace time-based or event-driven maintenance with a condition-based maintenance system, where maintenance is only performed based on objective evidence of actual or predictable failure of a system or its components [OSAIDD, 1999]. Repair times would decrease as adding prognostic technology would result in each subsystem or component having an estimated time to failure. Knowing which systems are near failure ahead of time would again allow the maintenance element time to pre-position the necessary maintenance equipment and personnel or order any necessary replacement parts.

Based on the decreased downtime in unscheduled maintenance and scheduled maintenance from ISHM, the operational availability for each aircraft should improve. Another factor affecting operational availability is mission turn-around time, or the time from when the aircraft lands to when it is ready for the next mission. Without ISHM, mission turn-around time can include lengthy inspection tests to check for failures. Since these tests are not needed with continuous monitoring and a higher confidence in fault detection, the mission turn-around time should decrease, increasing operational availability. Mission success rates would also theoretically increase as having situational awareness of the entire health state of the vehicle assists ground operations in providing full mission coverage. If a UAS autonomously detects a fault and due to the fault criticality (for example, low fuel levels) decides to re-task to a closer trajectory, ground operations can re-task other UAS vehicles to ensure coverage of the priority targets. Without ISHM, a fault alert would generally give no indication of the remaining performance capability of the UAS, leaving ground operations to conservatively scrap that particular mission set. ISHM can also theoretically expand the flight envelope of the aircraft, which could allow for larger mission sets.

The previous benefits all have some measure of cost savings attached to them. Having a lower total maintenance downtime, due to decreases in scheduled maintenance and a lower probability of unscheduled maintenance, leads to a lower personnel cost and even an option of having less maintenance personnel needed. Fewer maintenance actions also indicate a potential reduction in spares and supply costs. However, there is an inherent cost in implementing ISHM, not just to the vehicle but to the resulting operational infrastructure. The cost savings must be weighed against the implementation costs to truly investigate the financial aspect of ISHM.

The answers to the literature review questions were then used to develop an analytic architecture that would answer these primary research questions:

What are the potential impacts to ground control stations and users?

With the addition of ISHM, unmanned aerial systems (UAS) move closer to a state of true autonomy and less reliance is placed on ground control stations. As with any new technology, a phased approach would be appropriate when integrating this technology with current practices.

The architecture built for this effort is designed for the initial phase and resembles a state of flexible autonomy, where command and control (C2) of the UAS shifts from autonomous to operator based on mission phase and particular event conditions. In general, ground C2 (as represented by the Operations Control Center in the SV-1) commands the vehicle before launch and post landing, and the autonomous C2 takes over during the launch sequence and releases command during auto-safing. Currently, the ground C2 still maintains significant control through the whole flight, even though the autonomous capability is there. ISHM should help to increase the level of autonomy within future UAS since ISHM would provide an estimation of the system's current abilities to enable real-time decision making by the vehicles C2. If designed for some UAS platforms, such as the RQ-4 Global Hawk, ground C2 would consist of separate Launch and Recovery (LRE) and Mission Control Elements (MCE). Also depending on the UAS, ground C2 can have the ability to control multiple vehicles at a single time. So far, this is not structurally any different from current UAS operations as performed by the

United States Air Force. Implementing ISHM into the UAS concept of operations would not eliminate any of the current ground C2 infrastructure but would instead require the addition of another element, the ISHM Ground Station, whose sole purpose is to monitor and verify the decisions made by ISHM. This element would not have personnel attached to it, it is instead another computer or set of computers with the more complex algorithms that would not be able to stored on the aircraft due to the processing speed limitations. ISHM would also affect current users on the ground by potentially increasing the number of vehicles that can be controlled at once; with health management handed over to the vehicle, ground C2 has the ability to potentially manage more UAS. Additional human factors analysis would be completed to determine the maximum amount of vehicles that ground C2 can safely control.

Ideally in the next phase (as confidence in ISHM and autonomous technology increases), the entire mission from launch to recovery would become fully automated, with ground C2 only managing the mission taskings or re-taskings. Ground operations, previously managed by multiple elements, such as the LRE, MCE, and ISHM Ground Station, can potentially be combined into one center. This could significantly lower the amount of personnel needed to operate a UAS.

What are the potential impacts on current maintenance practices?

The end-goal of ISHM is a state of condition-based maintenance, where maintenance is only performed based on objective evidence of actual or predictable failure of a system or its components [OSAIDD, 1999]. Mirroring the impact on ground control stations, the changes to maintenance practices should take a phased approach.

The initial phase of ISHM implementation, as built in the architecture, closely resembles current practices. There are still scheduled maintenance intervals; however, by providing continuous monitoring and knowing the Estimated Time to Failure for the critical components, these intervals have the potential to be relaxed. The other main impact would be in the response to faults. Before, time-intensive Built-in Test (BIT) units would be used to verify that the fault exists and to pinpoint which component to repair. ISHM verifies the fault in flight and provides reams of data to the maintenance element for their own verification, negating the use of the BIT unit. Also, by knowing the specific systems to be inspected or repaired ahead of time, the maintenance element has time to pre-position the necessary equipment and personnel or order any necessary replacement parts before the UAS has completed its mission.

The next phase would involve upgrading to condition-based maintenance. Scheduled maintenance intervals would no longer exist and the entire concept of operations for maintenance would become reactionary.

What are the performance characteristics necessary for ISHM to effect mission success?

A response surface was modeled for a UAS with an expected lifetime of 10,000 hours, maintenance interval of 1,000 hours, and average mission length of 10 hours. The final model equation, initially shown in Equation 13, mapping this surface was determined to be:

$$y = (-5.861 + 0.015\theta + 17.322P_D - 67.369P(Fault\ Cat\ III) + 0.007c + 501.715(P(Fault\ Cat\ III) - 0.191)^2 - 0.237(\theta - 850)(P_D - 0.652) - 0.0001(\theta - 850)^2 + 0.391) - 0.415(P(Fault\ Cat\ III) - 0.191)(c - 300))^2 \quad (13)$$

where y is the difference between the number of successful missions calculated for a system with ISHM and the same system without ISHM (i.e. using current health management techniques)

Contour plots for the response surface near this point are provided in Figure 15. The statistical analysis performed in Section 4.4.2 determined that a response greater than 4.726 indicated a statistically significant difference in mission success rates. The shaded regions on the contour plots indicate areas where ISHM is not beneficial. If the factors fall anywhere outside of this region, ISHM should be investigated as a beneficial addition to the existing UAS in terms of mission success rates.

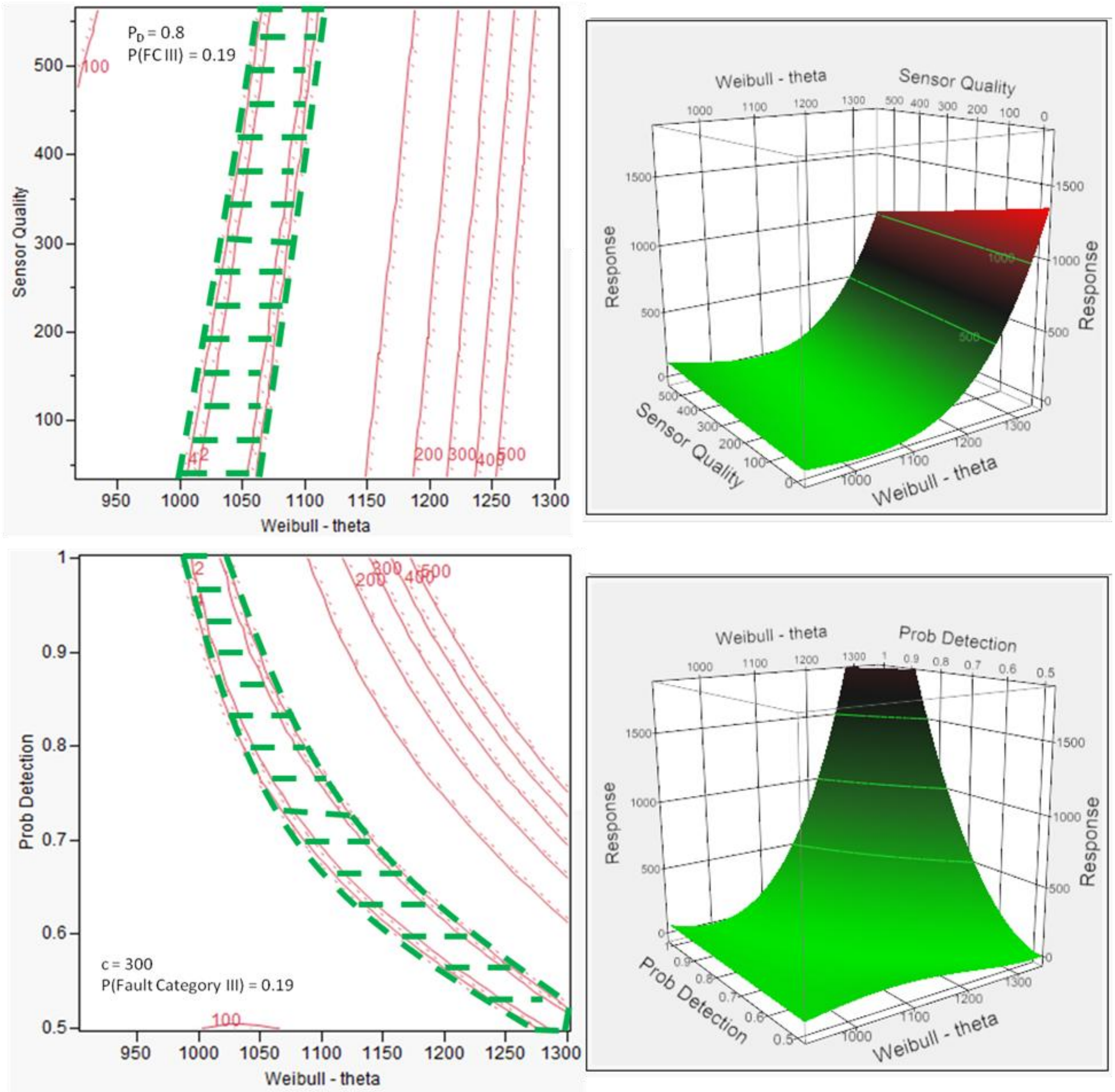


Figure 15 - Contour Plots for Response Surface

The architecture also contributed to answering these secondary questions:

How should ISHM data be presented to be effective? How will the presentation change in regards to the different users of ISHM (operators, maintenance, etc.)?

As seen in the OV-2, displayed in Figure 16, there are several types of information that are passed from ISHM to ground-level operations: vehicle status, vehicle capabilities, and maintenance reports. Additional human factors research will be needed to determine how this information is presented to the users; in this architecture there are three main users of the data: the Operations Control Center (OCC), the ISHM Ground Station (in the OV-2, the OCC and ISHM Ground Station are combined under "Ground Command and Control"), and Ground Recovery Operations consisting of maintenance and other launch and recovery operations. While maintenance reports are unique to Ground Recovery Operations, the OCC and the ISHM Ground Station exploit the vehicle status and capabilities differently; consideration of this point must be taken when researching the best way to present the data to the personnel of each element.

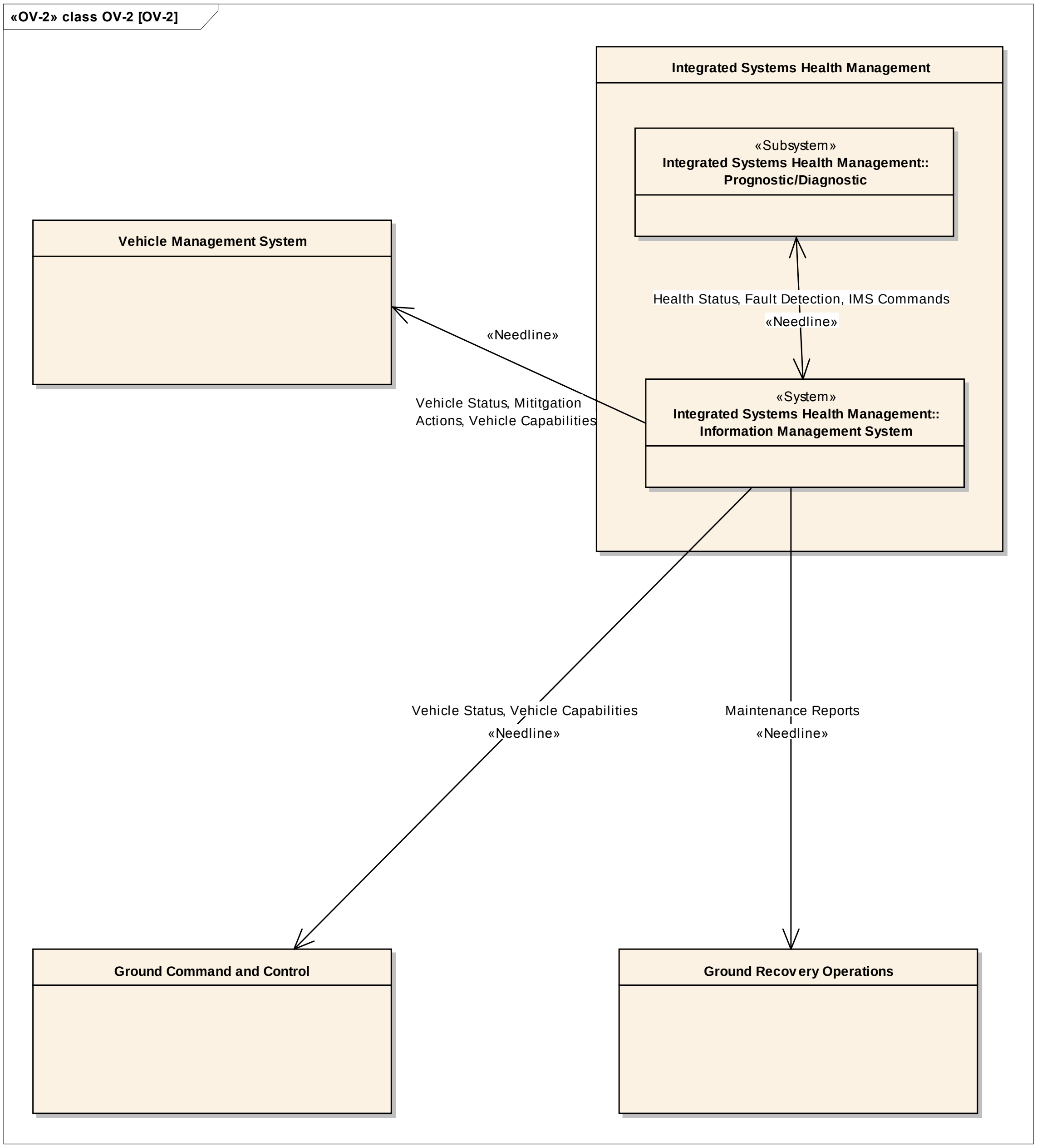


Figure 16 - OV-2 "Operational Node Connectivity Description"

Is ISHM cost effective?

The main result of the model evaluation indicated that the quality of sensors will affect the cost and mission benefits relative to the degree of ISHM implemented on a system. A cursory interpretation of this analysis result infers that decision makers should compare the cost and mission benefits of upgrading the sensors with the cost and benefits of implementing ISHM; however, a complete cost and mission benefit analysis should be completed before making any conclusions and will require a more in-depth ISHM model than that presented in this paper. The model presented in this research effort lays the foundation to develop the more in-depth model.

While no cost data was included in the model, the output from the model can be also used when evaluating the total financial benefit of ISHM. By putting a cost on an average unscheduled maintenance action, the expected number of maintenance actions, as output by the model, for a UAS without ISHM and one with ISHM can be compared. The model can also be used to determine the effect of longer scheduled maintenance intervals on expected unscheduled maintenance actions for a UAS with ISHM. The cost saved by having longer scheduled maintenance intervals can be added to the financial evaluation for decision makers.

The expected mission success rate can also be used to decide whether ISHM is cost effective. There is a cost associated with preparing a UAS for launch and with the recovery actions once the UAS has landed. If a UAS would have to curtail its mission or cancel it entirely because of health management issues, another UAS would be tasked to complete the mission, and could incur additional launch and recovery costs if it had to be launched from scratch. The expected mission success rate for a UAS with ISHM and for one without ISHM could be quantified as an expected cost per mission and then compared for evaluation by decision makers.

5.3 Recommendations for Future Research

There are numerous opportunities for further research into this aspect of Integrated System Health Management. A large benefit to the research would be lifting some of the assumptions under which the analytic model operates. One large assumption is that the scheduled maintenance intervals act as a renewal process; this is not close to reality, as the system will degrade over time, even with adequate maintenance intervals. A second model assumption follows along the same lines, only in this case assuming that there are no sensor degradation effects over the lifetime of the vehicle. Over time, the probability of detection for the sensor will decrease and/or the probability of a false alarm will increase. Another large assumption is that ISHM uses the same sensor suite that is currently in the baseline UAS; following the results of the FMECA, ISHM would actually supplement the original health management or monitoring system with additional sensors and effectors. The model should be updated to reflect these changes; this will give a more accurate representation of the reliability and health management aspects of the baseline UAS.

Much of this research effort used theoretical values when evaluating the model and mapping the response surface. If actual failure data for current UAS platforms or information becomes available for commercially-implemented ISHM systems, this information can be fed into the model and the response surface can be re-evaluated. Large ranges were used for the theoretical values to try and cover a variety of potential UAS platforms and ISHM systems; this leads to potential model inadequacy because local maximum and minimum ridges may not have been discovered. Actual ISHM performance data will hopefully give much smaller ranges and a more robust response surface can be determined.

5.4 Summary

In this research effort, an analytic architecture was created to help determine the effect ISHM had on mission success rates for a UAS. The final products revealed that, for mission success rates only, ISHM is beneficial in situations where the theoretical UAS has serious problems with detection and false alarm rates. Using representative data for a UAS, the analysis determined that the failure distribution parameters, sensor quality (which determines the relationship between probability of detection and probability of false alarm), and probability of an imminent fault during a mission were significant to the model. The result of the model determined that ISHM can result in a significant improvement on mission assurance, especially when implemented with higher quality sensors and on vehicles where the probability of imminent failure is higher relative to the mission times and time between preventative maintenance. This appears consistent with the premise that ISHM can support an extension of preventative maintenance intervals with an attendant reduction in sustainment cost.

It is important to note that the analytic model had several broad assumptions that affect these conclusions: (1) the model assumed that ISHM would use the same sensor suite that is currently in the baseline UAS – this does not reflect reality, ISHM would have additional sensors and effectors based on the results of the FMECA, resulting in a different P_D and P_{FA}; (2) the model is limited to detecting faults that the current system is looking for – theoretically, ISHM would gather data over the lifetime of the vehicle to supplement these fault states as new information becomes available; (3) the model does not allow for system or sensor degradation – this negates a lot of the benefits provided by prognostics. Additional analysis is needed to further study the effect of ISHM on mission effectiveness. These results should also be taken as just one part of the “big picture” of ISHM, and should be weighed against the other benefits that ISHM provides.

Appendix A: Architecture-Based Evaluation Process (ABEP)

1. Design Operations Concept of system to be evaluated.

Ops concept provides the system description which the architecture will model, and the models will simulate/evaluate.

2. Identify Measures of Effectiveness (MOE) relevant to the decision/evaluation

Identify the metrics that represent the effectiveness of the system.

3. Identify required level of abstraction for architecture to show traceability to MOE's

Analyze the Ops Concept to determine if MOE's are measured at the output of the system, within the system (requiring 'drilling' into the system activities), or at the output of activities external to the system (requiring external systems diagram)

4. Identify architecture views necessary to capture structure/relationships

a. Structure (OV-1, OV-2, and OV-5) In order to first develop the structure of the analysis, nearly all evaluations will require the OV-1 (High Level Operations Concept), OV-2 (Operational Node Connectivity Description), and OV-5 Operational Activity Model views. The level of abstraction (A-1, A-0, AO etc.) of the OV-5 is initially identified in the previous step.

b. Decision Logic (OV-6a) to capture the logic of the system, nearly all evaluations will require the OV-6a Rules Model, developed to match the level of abstraction used for the OV-5's.

c. As Required: SV-2, SV-4, SV-7,OV-6b, OV-6c Depending on the complexity, consideration for time and dependency on internal performance inputs, some or all of the listed views may be required.

5. Develop architecture views

Develop architecture views in accordance with DODAF to include all relevant activities and entities. If an integrated architecture already exists, then acquire the required architecture views.

6. Develop Modeling Simulation to replicate architecture

a. Select Modeling tool best suited to meet evaluation requirements (i.e. Excel spreadsheet vs. discrete model simulation program)

b. Model structure to match architecture (OV-2, OV-5)
c. Model decision logic to match OV-6a.
d. Calculate MOE"s at output of activities as functions of design parameters

7. Evaluate Model Completeness

Does model consider all relevant aspects (processes, assumptions, input variables and outputs, MOE"s) of the system/concept?

a. If so, continue to step 8.
b. If model not complete, return to step 3 with the following considerations.
    i. Determine additional architecture view and/or level of abstraction required to achieve traceability between system and the missing aspect.
    ii. Develop required additional architecture
    iii. Modify model to include additional architecture view.
    iv. Re-evaluate Step 7 until model captures all relevant aspects of the concept.

8. Evaluate model for MOE results, requirements and key parameters

a. Once the model is complete, evaluate the system's ability to meet target metrics.
b. Vary design parameters and perform sensitivity analysis to identify key parameters.
c. Compare sensitivity analysis to target MOE's to establish requirements and KPPs.
d. Identify critical performance parameters in the SV-7 Systems Performance Parameters Matrix.
e. Vary system design and design parameters to evaluate the system's robustness and its rate of degradation.

Appendix B: ISHM Architecture

B.1 Integrated System Health Management Concept of Operations

1.0 Purpose

Integrated System Health Management (ISHM) adds a centralized health management system that is responsible for collecting and processing health status information from across a system during all mission phases. ISHM balances data flow from multiple sub-systems and produces the information necessary to identify current system capabilities, provide situational awareness to mission and ground operations, and quickly identify contingencies for improved vehicle control and mission decisions. In order to be effective, ISHM must have the capability to: assess vehicle state; reliably detect, diagnose, and predict failures and degraded conditions; derive and relay accurate vehicle health status to the ground operations crew, maintainers, and the on-flight vehicle command and control module. These capabilities would allow the operator or vehicle to re-plan the mission, reconfigure flight control and continue, or abort as necessary in real-time.

2.0 Time Horizon, Assumptions, and Risks

This section discusses the time horizon for the future of ISHM, and the assumptions and risks overlaying the use of ISHM.

2.1 Time Horizon

In the near term (0-10 yrs), ISHM is envisioned to provide condition-based maintenance, remaining life-quantification, mission-readiness decision making, and improved fault isolation and detection to the operator.

In the far term (10+ yrs), as systems reach for true autonomy, ISHM will enable an autonomous vehicle to re-plan its own mission based on actual system health and capabilities, collaborate with other autonomous vehicles to ensure mission and capability coverage, and define its own operating envelope.

2.2 Assumptions

(1) The ISHM system will currently have no command or control over the autonomous vehicle; it only provides recommended actions for flight control and ground control.

2.3 Risks

(1) If ISHM lacks integrity, the false alarm rate will increase the probability of unscheduled maintenance over current health monitoring systems.
(2) The added weight of an ISHM system will decrease the capability of the system.
(3) The added cost of an ISHM could outweigh the benefits of the system.

(4) If ISHM is less reliable than the vehicle, the probability of unscheduled maintenance will increase over current health monitoring systems.

3.0 Description of the Military Challenge

In 2010, the United States Air Force (USAF) released the results of a year-long study highlighting the need for increasing autonomy in modern weapon systems, especially in the domain of unmanned aerial systems (UAS). The study identified the need for greater system autonomy as the *"single greatest theme"* for future USAF Science and Technology investments. [Technology Horizons, 2010] Current technology advancements have brought the USAF to a state of flexible autonomy, which involves dynamically shifting command and control (C2) from autonomous to operator based on workload, system health, and the perceived intent of the operator.

One of the key attributes sustaining flexible autonomy is the ability of the UAS to detect, isolate, and diagnose system health problems to relay back to ground C2, the on-board flight control module, and maintainers for appropriate action. Current flight avionics architectures may include lower level sub-system health monitoring or may isolate health monitoring functions to a black box configuration, but a vehicle-wide health monitoring information system has seldom been implemented.

4.0 Synopsis

ISHM provides the basis for integrating all the individual system's health management inputs and outputs (I/O) on a particular vehicle and determines, in real-time, the vehicle's health status and mission capabilities. The overall desired effect of an ISHM system would be an increase in mission success rates, driven by improved operational availability, increased health awareness, faster turnaround times, and false alarm avoidance. In order to perform this capability, ISHM must provide continuous monitoring over the entirety of the vehicle, identify that a fault has occurred, pinpoint the fault mechanism and its location, assess and assign a level of health to the vehicle, and relay selected fault data to the ground operator for action.

5.0 Desired Effects

The overall desired effect of an ISHM system would be to detect and isolate either a real-time fault or pre-cursers to a fault, determine the criticality of the fault, and then relay the appropriate information back to ground control for action. Benefits of this capability are discussed in the remaining sub-sections.

5.1 Effect on Scheduled and Unscheduled Maintenance

The Air Force goal for prognostic systems such as ISHM is to completely eliminate traditional aircraft inspection and repair patterns. [Ross, 1999] Currently, a malfunctioning unit is either identified in-flight (based off an alert from an individual sensor) or identified through scheduled inspections. There are an inherent probability of a false alarm and a probability of fault detection, meaning that the aircraft could be incorrectly pulled from an on-going mission or could continue on a mission with an unknown fault that could lead to system failure. The integrated aspect of ISHM proposes to severely reduce the false alarm rate and increase the total probability of detection, as understanding the full health status of the vehicle can identify false positives and identify if a fault or failure has occurred down-stream. For example: a sensor falsely identifies a valve stuck closed, a sensor further down the stream indicates a normal flow rate and the system has not lost any performance aspects; ISHM would therefore not report this as a fault.

With the continuous monitoring provided by ISHM, pre-cursors to faults can also be identified and an Estimated Time to Failures of the component or total system will be reported. Additionally, if multiple mission data is stored, every time a fault occurs, the data collected by ISHM can be used to identify new indicators or pre-cursors to a failure to be uploaded into the diagnostic and prognostic algorithms.

The overall result is that with ISHM implemented, the probability of unscheduled maintenance should be minimized and scheduled maintenance intervals can be relaxed or removed. Ideally with ISHM, the aircraft would replace time-based or event-driven maintenance with a condition-based maintenance system, where maintenance is only performed based on objective evidence of actual or predictable failure of a system or its components. [OSAIDD, 1999]

5.2 Decreased Mean Time to Repair

Current fault detection is limited to identifying the occurrence of a fault and an approximate location, meaning that fault isolation can only occur after the aircraft has landed. There is also a probability that the mechanic can even correctly identify the failure mode once it lands. With ISHM, both fault detection and isolation are performed in-flight, within a specified confidence level, and the appropriate information is relayed to the maintenance element. This gives the maintenance element time to pre-position the necessary maintenance equipment and personnel or order any necessary replacement parts, severely reducing the total Mean Time to Repair (MTTR) after an event.

As a result of its continuous monitoring, ISHM would also reduce maintenance time during scheduled inspections. Prognostics would, theoretically, calculate an Estimated Time to Failure (ETF) for each component, resulting in each inspection only focusing on those systems that had passed an ETF threshold in that time interval. Knowing that the specific systems to be inspected ahead of time would again allow the maintenance element time to pre-position the necessary maintenance equipment and personnel or order any necessary replacement parts. ISHM would also negate the current use of time-intensive Built-in Test (BIT) units, as each system would be continuously tested.

5.3 Operational Availability Improvement

Based on the decreased downtime in unscheduled maintenance and scheduled maintenance from ISHM, the Operational Availability for each aircraft should improve. Another factor affecting Operational Availability is mission turn-around time, or the time from when the aircraft lands to when it is ready for the next mission. Without ISHM, mission turn-around time can include lengthy BIT tests to check for failures, since these tests are not needed with continuous monitoring and a higher confidence in fault detection the mission turn-around time should decrease, increasing Operational Availability. Whether measured in maintenance downtime or a reduction in hours required for testing and diagnostics, etc., the net result is that a system with ISHM will be available for use more of the time.

5.4 Increased Mission Success

Having situational awareness of the entire health state of the vehicle assists ground operations in providing full mission coverage. If a UAS autonomously detects a fault and due to the fault criticality (for example, low fuel levels) decides to re-task to a closer trajectory, ground operations can re-task other UAS vehicles to ensure coverage of the priority targets. Without ISHM, a fault alert would generally give no indication of the remaining performance capability of the UAS, leaving ground operations to conservatively scrap that particular mission set.

An additional aspect of increased situational awareness is its affect on UAS flight limits. Modern autonomous flight control systems limit the vehicle to safe operating loads and environments; this operating envelope is pre-defined and very conservative. With ISHM, the flight envelope can theoretically be expanded and defined by the design criteria for the vehicle. Health data would then be used to restrict the envelope to a prescribed level in the event of a detected fault. This would increase the operational capability of the vehicle, allowing for larger mission sets. Improved situational awareness combined with the theoretical improved Operational Availability would greatly improve the rate of mission success.

5.5 Cost Savings

The previous benefits all have some measure of cost savings attached to them. Having a lower total maintenance downtime, due to decreases in scheduled maintenance and a lower probability of unscheduled maintenance, leads to a lower personnel cost and even an option of having less maintenance personnel needed. Fewer maintenance actions also indicate a potential reduction in spares and supply costs. The on-board test diagnostics provided by ISHM would also theoretically replace some ground test equipment, as it would become redundant.

6.0 Necessary Capabilities

The capabilities necessary for ISHM to be effective are appropriate data and information management, fault detection and isolation, the ability to assess the health status of the UAS, and communication, both internal and external to the system.

6.1 Data Management

The ISHM system must provide continuous monitoring over the entirety of the vehicle. Sensors are placed in critical locations in order to feed information on the state of the system. Sensors can be conventional, measuring temperature, speed, and flow rate, or specifically tailored to health management applications, such as strain gauges, ultrasonic sensors, or proximity devices.

Data Management also includes parameter sets, vehicle configuration, and a data store with a list of safe states associated with known fault events and mitigation steps. Current mission sensor data and event recording can either be kept in an on-board data storage system sent to ground as required, or continuously streamed to ground control.

6.2 Fault Detection

The sensor data is then processed to remove any artifacts or noises and manipulated to extract fault features (either current or pre-cursers) and provide a comprehensive system picture. Fault Detection combines diagnostic information with historical data (prognostic reasoning) to generate an estimation of failure times. These fault indications are then sorted, prioritized, and distributed to insure action within time to criticality. Algorithms developed for diagnostic and prognostic calculations are generally based on mathematical models (e.g. Hamilton dynamic, Lagrangian dynamic, approximation methods), or pattern recognition (e.g. fuzzy-logic, statistical/regression methods, neural network clustering).

6.3 Fault Isolation

After identifying that a fault has occurred, ISHM must pinpoint the fault mechanism (i.e. the specific cause of failure) and its location. If not identifiable through prognostic reasoning, common fault mechanisms for that location can be identified using historical failure data.

6.4 Health State Assessment

ISHM must have the capability to assess and assign levels of health to the vehicle. This is achieved by calculating the remaining vehicle capabilities based on a capability model and the current fault state of the system. A notional capability model is hierarchically based, where the higher-level capability is computed using the values of the lower-level capabilities and a mathematical expression. Faults are quantified at the lowest level with system-level capability computations that orient this data with mission requirements to determine effects on the vehicle.

6.5 Select Mitigation Procedures

The ISHM system will provide mitigation procedures in the event of a known fault for the on-board flight control to act on if necessary. In order perform this capability, ISHM will a) examine the available resources to determine any performance limitations and to estimate the time to criticality; b) confirm the diagnosed event and declare it to be a valid vehicle event with a high confidence level; c) access the fault data store for the appropriate safe state and the feasible step alternatives; before d) selecting the action steps that allow completion within the criticality time and performance limitations. These action procedures will then be sent to the on-board flight control and to ground control. Since ISHM is deterministic and operates only on known faults and known mitigations, any unknown fault will immediately be assigned a critical level of health and the aircraft will automatically return to base.

6.6 Communication

The ISHM must be able to send and receive messages internally and externally to the vehicle.

7.0 Enabling Capabilities

A formal Failure Mode, Effect, and Criticality Analysis (FMECA) must be performed on the vehicle prior to ISHM being implemented. This is an iterative process that identifies failure modes, assesses their probabilities of occurrence and their effects on the system, isolating their causes, and determining corrective action or preventative measures. The results of the FMECA should identify critical sub-systems or components where sensors need to be applied, guide the diagnostic and prognostic algorithm creation, and assign criticality to failure modes for health assessment purposes.

8.0 Sequenced Actions

There are three main use cases for ISHM: no faults occur, a fault event occurs real-time, and pre-cursors to a fault are identified. See Appendix 11.1 for key nomenclature definitions.

8.1 Nominal Operations

The ISHM system will be continuously monitoring the health state of the UAS and will communicate either continuously or on set intervals (barring a fault event) the health status of the UAS. ISHM will also be continuously calculating an Estimated Time to Failures for every monitored component.

8.2 Real-Time Fault Event

Once a failure occurs, the following actions should take place:

(1) ISHM locates the fault and identifies the failure mode
(2) ISHM assigns a criticality to the fault mode and adjusts the vehicle’s health status to the appropriate level
(3) ISHM evaluates the new capability of the vehicle
(4) ISHM selects appropriate, deterministic, mitigation action procedures, correlating them with mission and vehicle inhibits.

(5) ISHM sends the action procedures to the on-board flight control, and alerts the Ground Operator and the Maintenance element
  a. The on-board flight control can:
    (i) Continue on current trajectory (ignore ISHM)
    (ii) Use recommendations to autonomously reconfigure and/or reshape the current trajectory
  b. The Ground Operator, as appropriate and in accordance with the criticality of the event, can:
    (i) Override the on-board flight control decision and re-task within its new capability
    (ii) Defer to the autonomous on-board flight control decision
  c. The Maintenance element executes maintenance actions as appropriate

8.3 Pre-Cursor to Fault is Detected

When a pre-cursor to a fault is detected, the following actions should take place:

(1) ISHM locates the affected component and identifies the impending failure mode
(2) ISHM calculates an Estimated Time to System (or Component) Failure
(3) ISHM assigns a criticality to the fault mode and adjusts the vehicle's health status to the appropriate level
(4) ISHM evaluates the new capability of the vehicle
(5) ISHM selects appropriate, deterministic, mitigation action procedures, correlating them with mission and vehicle inhibits.
(6) ISHM sends the action procedures to the on-board flight control, and alerts the Ground Operator and the Maintenance element
  a. The on-board flight control can:
    (i) Continue on current trajectory (ignore ISHM)
    (ii) Use recommendations to autonomously reconfigure and/or reshape the current trajectory
  b. The Ground Operator, as appropriate and in accordance with the criticality of the event, can:
    (i) Override the on-board flight control decision and re-task within its new capability
    (ii) Defer to the autonomous on-board flight control decision
  c. The Maintenance element executes maintenance actions as appropriate

9.0 Command Relationships

ISHM will have no command and control over the UAS at this time. The ISHM system will need to communicate with the following systems/subsystems:

9.1 Ground Control

Ground systems are normally treated as separate systems, and their relationship to the vehicle has typically been one of controller and operator; in this case, ground is hierarchically superior to the vehicle and commands it. For events that happen during a mission, the ground will take control to determine the needed actions and then send the commands to the vehicle for execution. The vehicle interfaces with ground control to capture, analyze, and preserve vehicle health data.

Vehicle control transitions between ground and on-board depending on mission phase and particular event conditions:

- Before Launch
    - Ground is master
    - Control transitions to vehicle during launch sequence
- During Flight
    - Vehicle is master (autonomous)
    - Ground monitors via downlink telemetry
    - Ground takes control when appropriate
- Post Landing
    - Ground is master (after auto-safing)

9.2 Maintenance and Logistics

Maintenance and Logistics can be considered part of ground control (under the overarching domain of "Operations Control Center") or a separate system entirely. Their relationship to the vehicle is either reactionary or scheduled and does not consist of a hierarchical relationship.

Interactions:

- Scheduled Maintenance: Based on flight hours and is performed at either the base-level or at a depot. Collected historical data from ISHM monitoring can be used to highlight components that need to be inspected.
- Unscheduled Maintenance: Initiated when a fault has been discovered. Once the ISHM has detected an anomaly, the appropriate data is sent to Maintenance and Logistic for action.
- Post Mission: Degradation and non-critical fault information are sent to Maintenance and Logistics to improve vehicle turn-around time.

9.3 Vehicle Systems

ISHM collects status and event snapshots from the vehicle subsystems and processes the information using various health algorithms and reasoning capabilities.

9.4 On-Board Flight Control

The on-board flight control receives command to execute an action from ISHM generated by either ISHM and/or ground C2. The autonomous on-board flight control will decompose these decisions and action lists into a set of commands and send them to the appropriate systems for execution. On-board flight control schedules these tasks accordingly in order to complete in the prescribed time.

As a vehicle system, on-board flight control health status, events, time, and mission information are continuously sent to ISHM. ISHM in turn continuously provides the vehicle system health assessments, vehicle capability, and mitigation actions predetermined for particular anomalies.

B.2 Architecture Concept of Operations

1.0 Purpose

The focus of this research is to quantify the mission-related benefits of ISHM by constructing architecture for analysis to compare against current autonomous vehicle capabilities, and to provide a general baseline model that can be implemented over any current or future autonomous vehicle. The architecture capabilities will include the ability to analyze the causal relationship of ISHM performance metrics (to include the performance of the processor, and the performance and reliability of the monitoring sensors) to mission performance. The architecture is aimed at primarily answering the following questions:

(1) What are the potential impacts to ground control stations and users?
(2) What are the potential impacts on current maintenance practices?
(3) What are the performance characteristics necessary for ISHM to effect mission success?

The architecture should also contribute to answering these secondary questions:

(1) How should the ISHM data be presented?
(2) Is ISHM cost effective?

2.0 Time Horizon, Assumptions, and Risks

This section discusses the time horizon for the architecture, the assumptions overlaying the architecture, and the risks inherent in using this architecture and analysis tool.

2.1 Time Horizon

The architecture and preliminary analysis should be built and completed by December of 2012 with the project out-brief scheduled for March of 2013. Additional interim gates will be established as the project progresses.

2.2 Assumptions

At this point in ISHM development:

(1) This architecture does not analyze ISHM past the system level; however, the architecture can be easily modified to include components and subsystems that are of value to the researcher.
(2) At this point in ISHM development, the ISHM system has no command or control over the autonomous vehicle. ISHM in its current technology state only provides recommended actions based on the type of fault it detects. The vehicle's autonomous management system will prioritize actions as necessary or, if there is time, a ground-based ISHM team can overrule or direct mitigation actions as necessary.

2.3 Risks

(1) If the selected metrics for analysis either do not accurately describe ISHM or are not independent of each other, the optimization process will give an analysis that does not appropriately model the system.

3.0 Description of the Military Challenge

ISHM is currently being considered for implementation in unmanned aerial systems (UAS) for the United States Air Force. Before the USAF can move forward, the effects of ISHM both on-ground and in-flight need to be understood and evaluated. This project intends to perform an in-depth analysis on the advantages and disadvantages of adding an ISHM system to general or specific UAS through the use of DODAF architecture and optimization processes.

4.0 Synopsis

This concept intends to perform an in-depth analysis on the advantages and disadvantages of adding an ISHM system to a general or specific UAS through the use of architecture. The architecture will have the capability to optimize a given ISHM's fault detection rate, fault isolation coverage rate, false alarm rate, and calculate the mean time to repair, mean time between failure, probability of scheduled maintenance, probability of unscheduled maintenance, and turn-around time for a UAS with ISHM. To use the architecture and analysis tool, the user will select desired metrics, modify the system's objectives and constraints, input the results of the Failure Mode, Effect, and Criticality Analysis, integrate the ISHM architecture into the overall system architecture, execute the analysis, and then perform sensitivity analysis on the results.

5.0 Desired Effects

This architecture should provide a general baseline model that can be implemented over any autonomous vehicle and to quantify the effect of ISHM on the operational availability and mission success rate by comparing them to current autonomous vehicle capabilities. The architecture should have the capability to optimize the ISHM fault detection rate, fault isolation coverage rate, false alarm rate, and the expected weight of the ISHM. The architecture should have the capability to use those optimized rates to calculate these metrics for a UAS with ISHM: mean time between failures (MTBF), probability of scheduled maintenance, probability of unscheduled maintenance, operational availability, and the probability of mission success.

6.0 Necessary Capabilities

The capabilities necessary to use the ISHM architecture are that the architecture is flexible, supports analysis and optimization, and is easy to use.

6.1 Flexible

The architecture should have the capability to be modified to fit any UAS baseline architecture. This architecture should also have the capability to be expanded on for future generations of UAS and ISHM technologies.

6.2 Analysis and Optimization

This architecture should have the capability to support an evaluation model. The particular modeling or analytical tools (such as spreadsheets or discrete event simulation, or through a simulation software product such as ARENA) can be chosen by the user.

6.3 Ease of Use

The architecture and analysis process should be straightforward and clear. Any user that has some prior knowledge of ISHM and DoDAF architecture should have the ability to understand the architecture and perform some level of modification as appropriate and appreciate its use as an analysis tool.

7.0 Enabling Capabilities

In order to operate the architecture, a Failure Mode, Effect, and Criticality Analysis must be performed, and the overall architecture of the system must be built.

7.1 Failure Mode, Effect, and Criticality Analysis

A formal Failure Mode, Effect, and Criticality Analysis (FMECA) must be performed on the UAS prior to using this ISHM architecture. This is an iterative process that identifies failure modes, assesses their probabilities of occurrence and their effects on the system, isolating their causes, and determining corrective action or preventative measures. The results of the FMECA should identify critical sub-systems or components where sensors need to be applied, guide the diagnostic and prognostic algorithm creation, and assign criticality to failure modes for health assessment purposes.

7.2 UAS Architecture

The architecture for the overall system for which ISHM is going to be analyzed should be should be built prior to using this lower level ISHM architecture; the intent of the lower level ISHM architecture is to be integrated into the overall system architecture. The following metrics from the baseline vehicle should be collected for use in the architecture: Mean Time to Repair (MTTR), MTBF, rate of scheduled maintenance, probability of unscheduled maintenance, operational availability, and the probability of mission success.

8.0 Sequenced Actions

To execute the architecture, take the following steps:

(1) Select Metrics: Select the metrics that the user is interested in for analysis.
(2) Modify Objectives and Constraints: Modify the selected objectives and constraints to reflect the metrics that the user is interested in.
(3) Input results of FMECA: Enter in the failure data for each subsystem as a parametric distribution. Assign criticality to identified failure modes.
(4) Modify the Architecture: Integrate the ISHM architecture into the overall system architecture. Use the results of the FMECA to highlight the critical systems that need to be monitored and determine the number of sensors to be implemented in each system.
(5) Execute Analysis
(6) Perform Sensitivity Analysis.

B.3 AV-1

1.0 Architectural Description

Previous generation health monitoring technology was typically local to a given subsystem; the next generation, Integrated System Health Management (ISHM), adds a centralized health management system to a typical flight avionics configuration. It is responsible for collecting and processing vehicle health status information from across the vehicle during all mission phases. As a consequence it will enhance the ability to make on-board decisions, thus migrating strict ground control to shared vehicle autonomy. ISHM performs health management at the vehicle- and mission-level from events and diagnostics gathered at the subsystem level.

ISHM is currently being considered for implementation in unmanned aerial systems (UAS) for the United States Air Force (USAF). Before the USAF can move forward, the effects of ISHM both on-ground and in-flight need to be understood and evaluated. The focus of this architecture is to quantify the mission-related benefits of ISHM by constructing architecture for analysis to compare against current autonomous vehicle capabilities, and to provide a general baseline model that can be implemented over any current or future autonomous vehicle. The architecture capabilities will include the ability to analyze the causal relationship of ISHM performance metrics (to include the performance of the processor, and the performance and reliability of the monitoring sensors) to mission performance.

2.0 Scope

The architecture is aimed at primarily answering the following questions:

(1) What are the potential impacts to ground control stations and users?
(2) What are the potential impacts on current maintenance practices?
(3) What are the performance characteristics necessary for ISHM to effect mission success?

The architecture should also contribute to answering these secondary questions:

(1) How should ISHM data be presented to be effective? How will the presentation change in regards to the different users of ISHM (operators, maintenance, etc.)?
(2) Is ISHM cost effective?

2.1 Architectural Views and Products Contained

This architecture contains Operational and System views.

The Operational views include a High Level Operational Concept Graphic (OV-1) to graphically describe the operational concept, an Operational Resource Flow Description (OV-2) to describe the resource flows exchanged between operational activities, and Operational Activity Models (OV-5a and OV-5b) to describe the relationships, inputs, and outputs between operational activities. These Operational views model the static structure of the architectural elements and their relationships. An additional Operational view that describes dynamic behavior is the Operational Rules Model (OV-6a), which defines operational procedures and constraints.

The planned system view is the Systems Interface Description (SV-1), which identifies systems, system items, and their interconnections.

2.2 Project Timeline

The architecture and preliminary analysis should be built and completed by December of 2012 with the project out-brief scheduled for March of 2013. Additional interim gates will be established as the project progresses.

3.0 Purpose and Perspective

The purpose of the architecture is to provide a general baseline model that can be implemented over any autonomous vehicle and to quantify the effect of ISHM on the operational availability and mission success rate by comparing them to current autonomous vehicle capabilities. The architecture should have the capability to optimize the ISHM fault detection rate, fault isolation coverage rate, false alarm rate, and the expected weight of the ISHM. The architecture should have the capability to use those optimized rates to calculate these metrics for a UAS with ISHM: mean time between failures (MTBF), probability of scheduled maintenance, probability of unscheduled maintenance, operational availability, and the probability of mission success.

4.0 Tools and File Formats Used

The architecture will be built in Enterprise Architect v8.0 (student) and presented in three formats: Word documents, HTML reports, and XML data files.

5.0 Assumptions and Constraints

This section includes assumptions and constraints needed to understand the architecture and its intended usage.

5.1 Assumptions

(1) Cost will not be evaluated

(2) At this point in ISHM development, the ISHM system has no command or control over the autonomous vehicle. ISHM in its current technology state only provides recommended actions based on the type of fault it detects. The vehicle's autonomous management system will prioritize actions as necessary or, if there is time, a ground-based ISHM team can overrule or direct mitigation actions as necessary.

5.2 Constraints

In order to make a general baseline model, it is not possible to represent every possible aspect of ISHM. Therefore this architecture will not analyze ISHM past the system level; however, the architecture can be easily modified to include components and subsystems that are of value to the researcher.

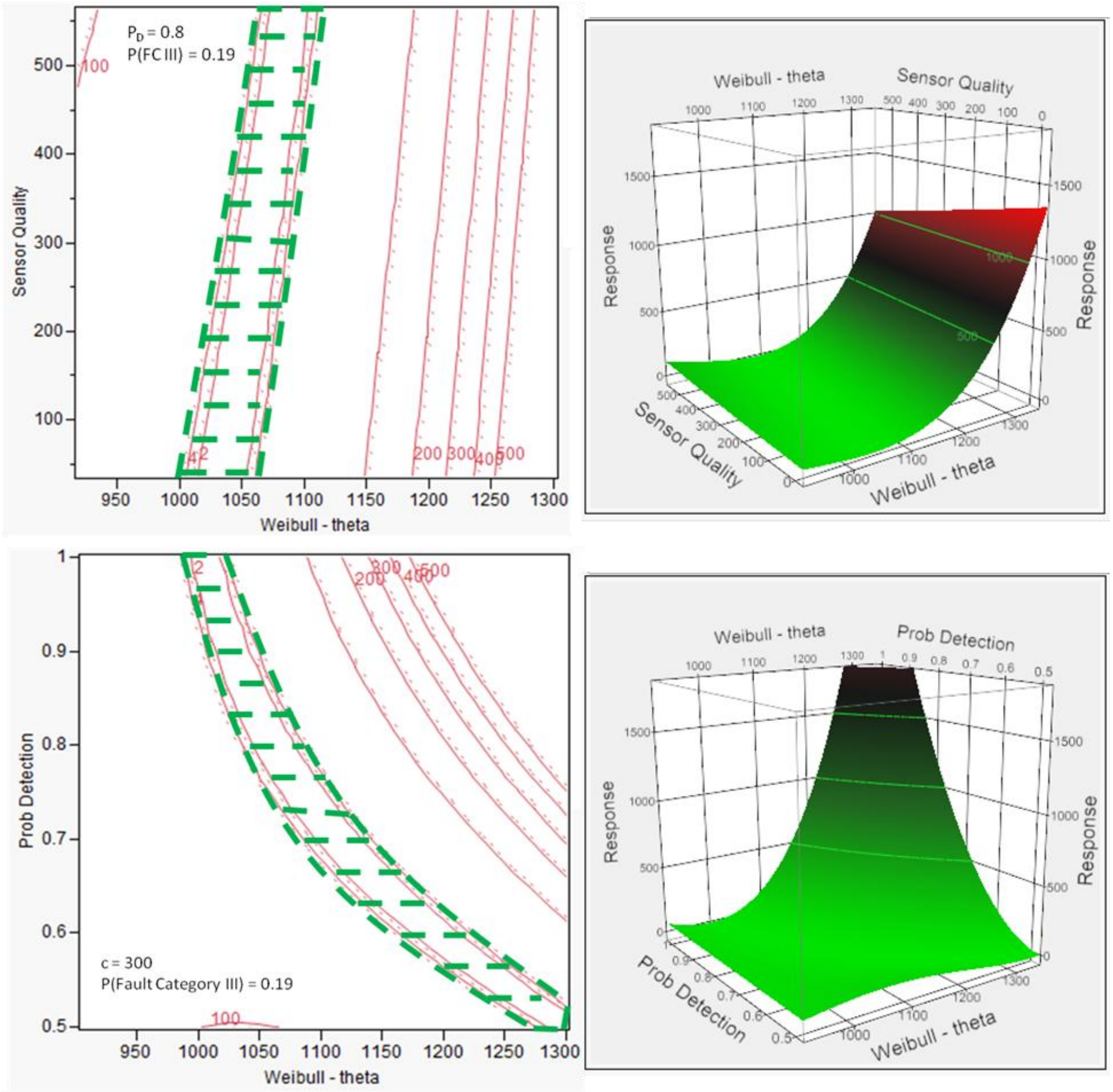
6.0 Supporting Analysis
Representative data for a UAS will be fed into the model and Design of Experiments (DOE) techniques will be used to determine situations where ISHM can be effectively used. The response for this analysis is the difference between the number of successful missions calculated for a system without ISHM (i.e. using current health management techniques) and a system with ISHM. The intent is to explore the response surface where this difference is maximized, which coincides with the operational area where ISHM would be most beneficial.

7.0 Findings
A response surface was modeled for a UAS with an expected lifetime of 10,000 hours, maintenance interval of 1,000 hours, and average mission length of 10 hours. The final model equation mapping this surface was determined to be:

$$y = (-5.861 + 0.015\theta + 17.322P_D - 67.369P(Fault\ Cat\ III) + 0.007c + 501.715(P(Fault\ Cat\ III) - 0.191)^2 - 0.237(\theta - 850)(P_D - 0.652) - 0.0001(\theta - 850)^2 + 0.391) - 0.415(P(Fault\ Cat\ III) - 0.191)(c - 300))^2$$

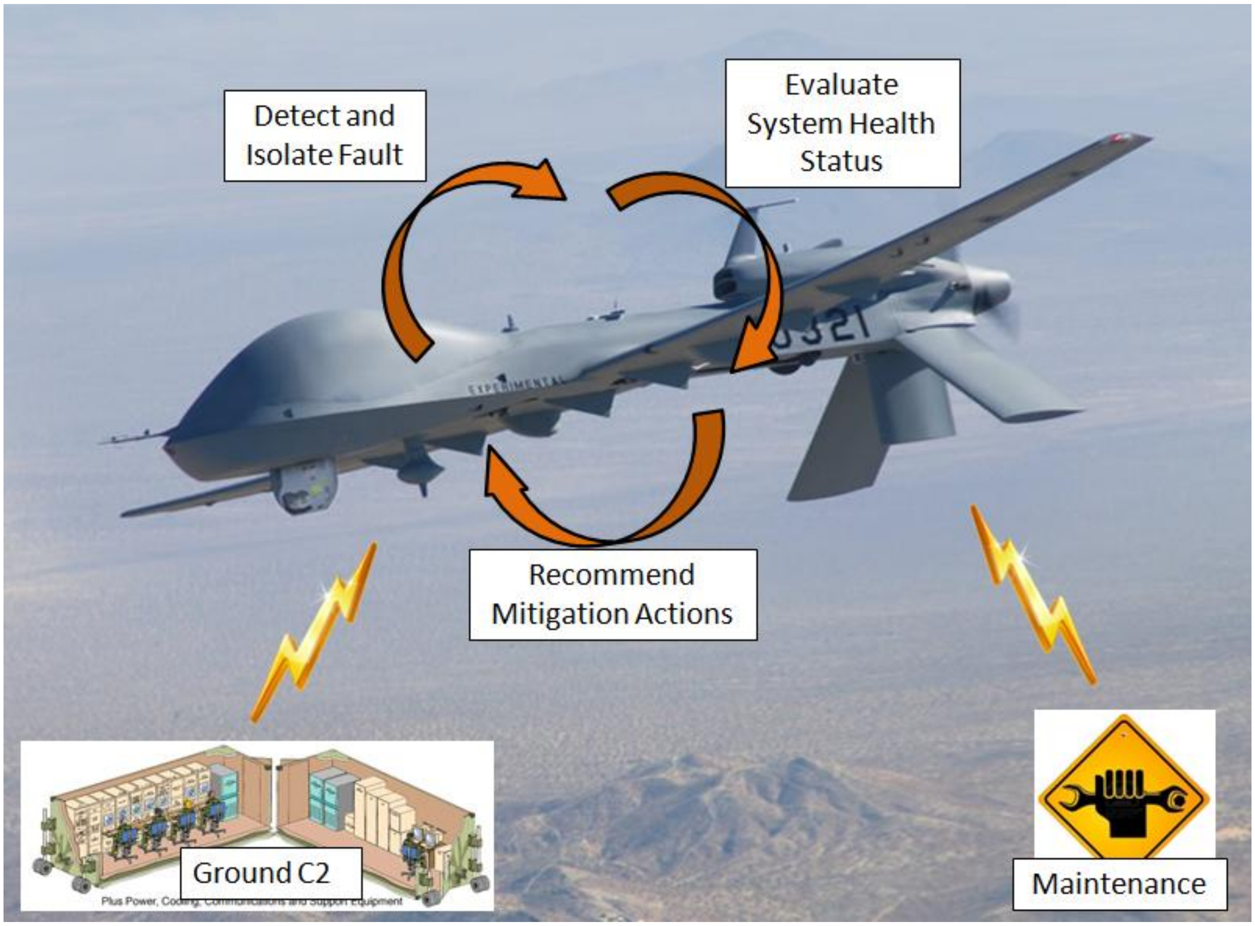
where y is the difference between the number of successful missions calculated for a system with ISHM and the same system without ISHM (i.e. using current health management techniques)

Contour plots for the response surface near this point are provided in the figures below. The statistical analysis determined that a response greater than 4.726 indicated a statistically significant difference in mission success rates. The shaded regions on the contour plots indicate areas where ISHM is not beneficial. If the factors fall anywhere outside of this region, ISHM should be investigated as a beneficial addition to the existing UAS in terms of mission success rates.

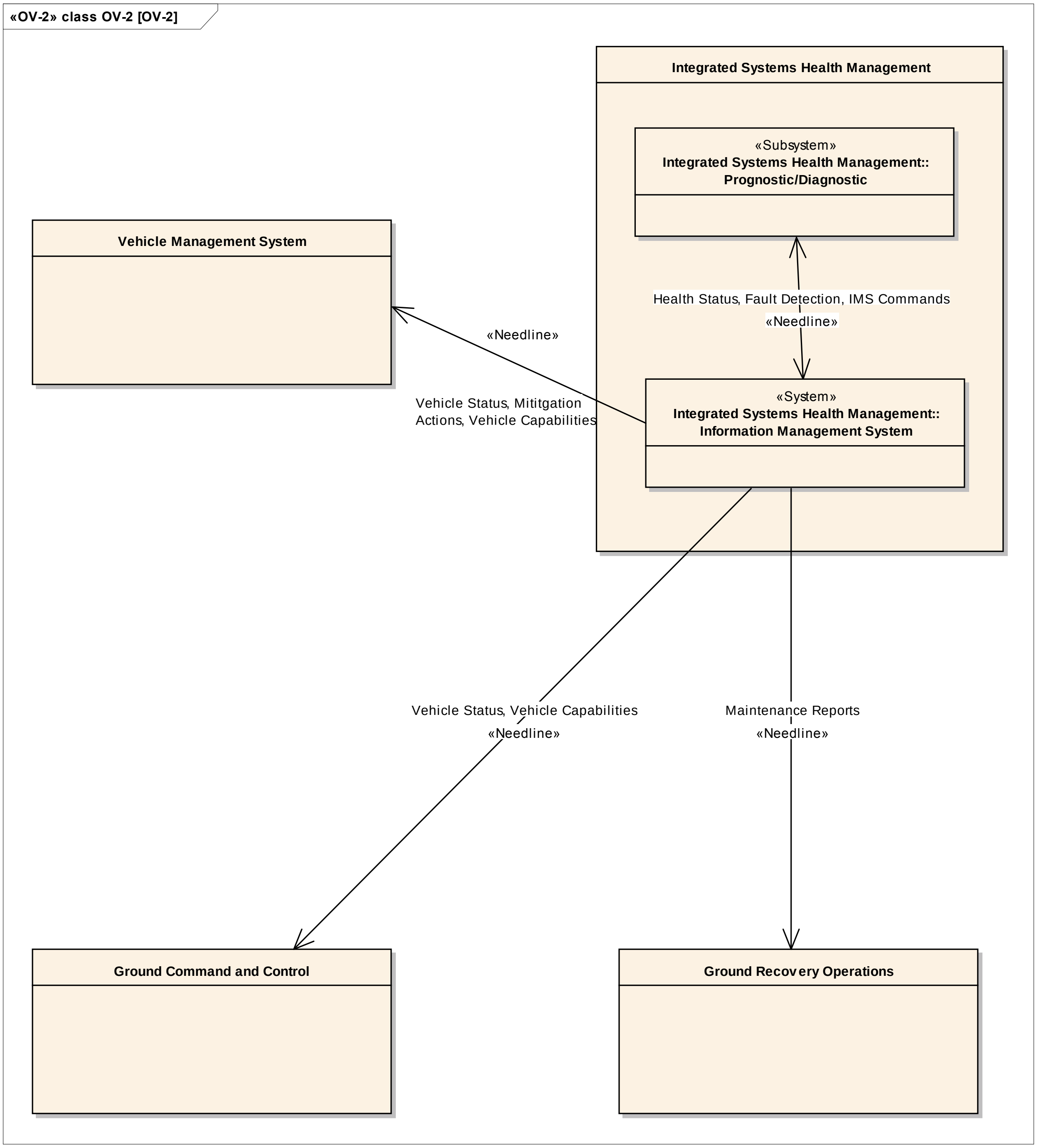


P_D = 0.8
P(FC III) = 0.19
Sensor Quality
Weibull - theta
Response
c = 300
P(Fault Category III) = 0.19
Prob Detection

B.4 OV-1

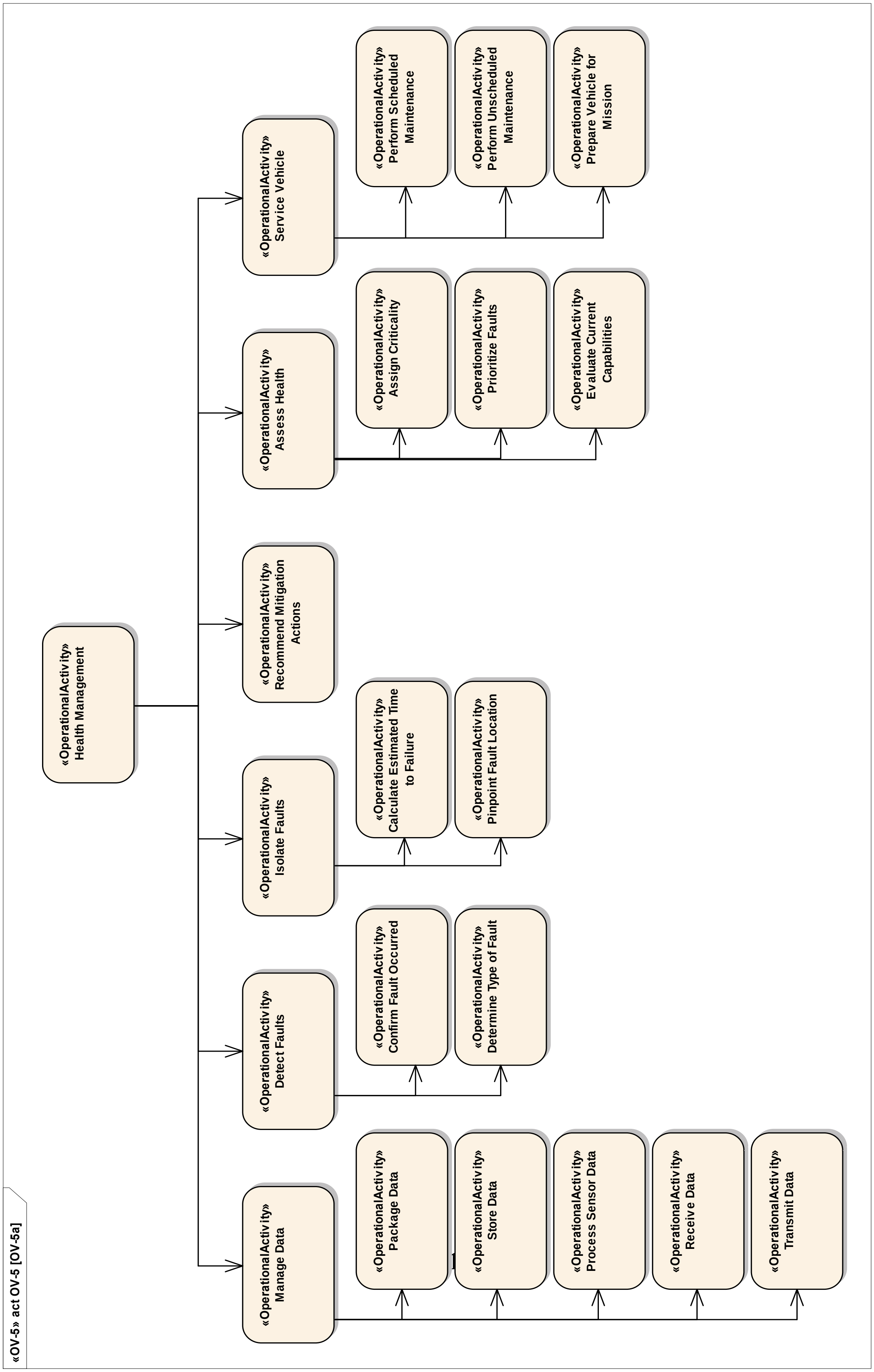

Detect and Isolate Fault
Evaluate System Health Status
Recommend Mitigation Actions
Ground C2
Maintenance

B.5 OV-2

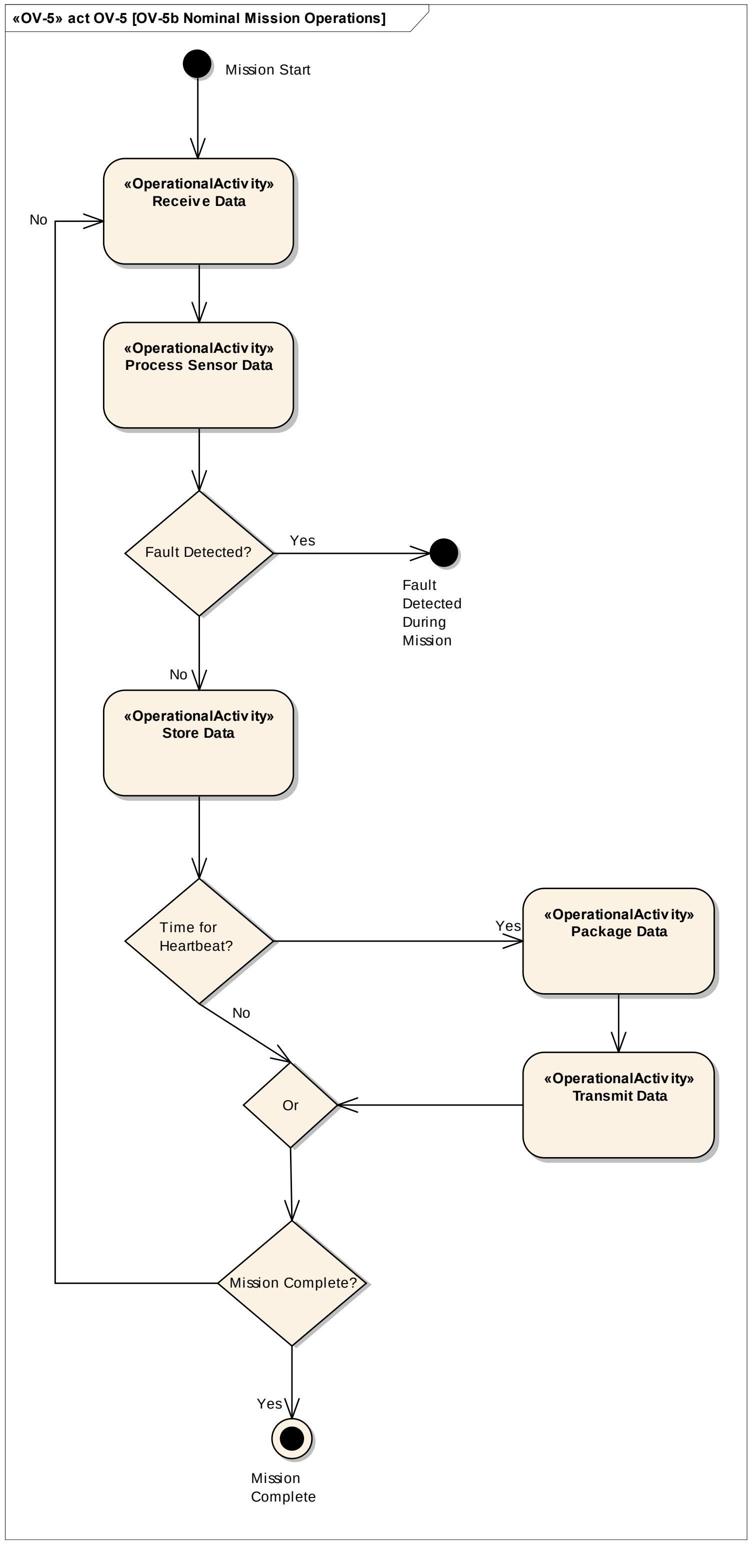


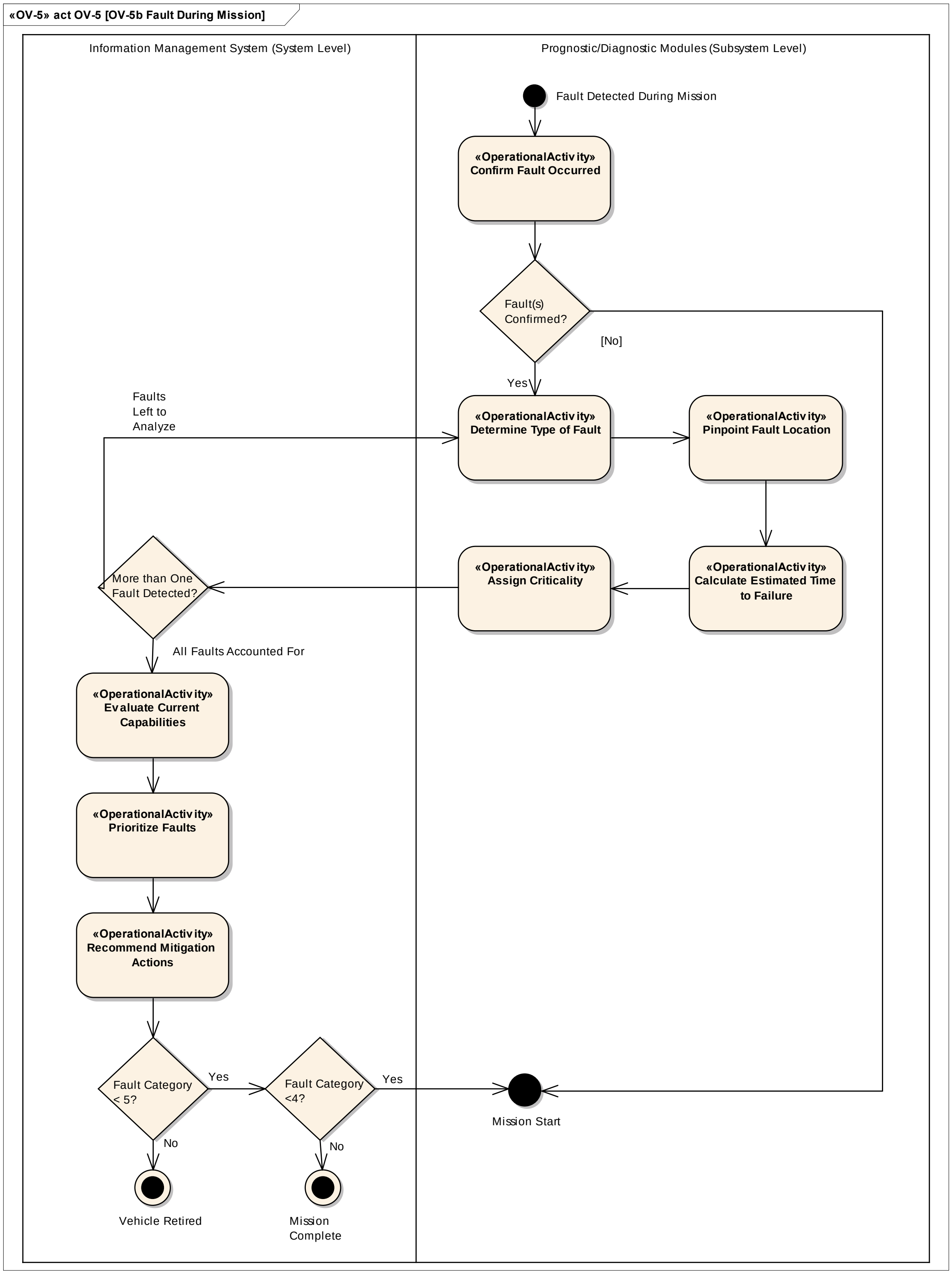
«OV-2» class OV-2 [OV-2]
Integrated Systems Health Management
«Subsystem»
Integrated Systems Health Management::
Prognostic/Diagnostic
Vehicle Management System
Health Status, Fault Detection, IMS Commands
«Needline»
«Needline»
«System»
Integrated Systems Health Management::
Information Management System
Vehicle Status, Mititgation
Actions, Vehicle Capabilities
Vehicle Status, Vehicle Capabilities
«Needline»
Maintenance Reports
«Needline»
Ground Command and Control
Ground Recovery Operations

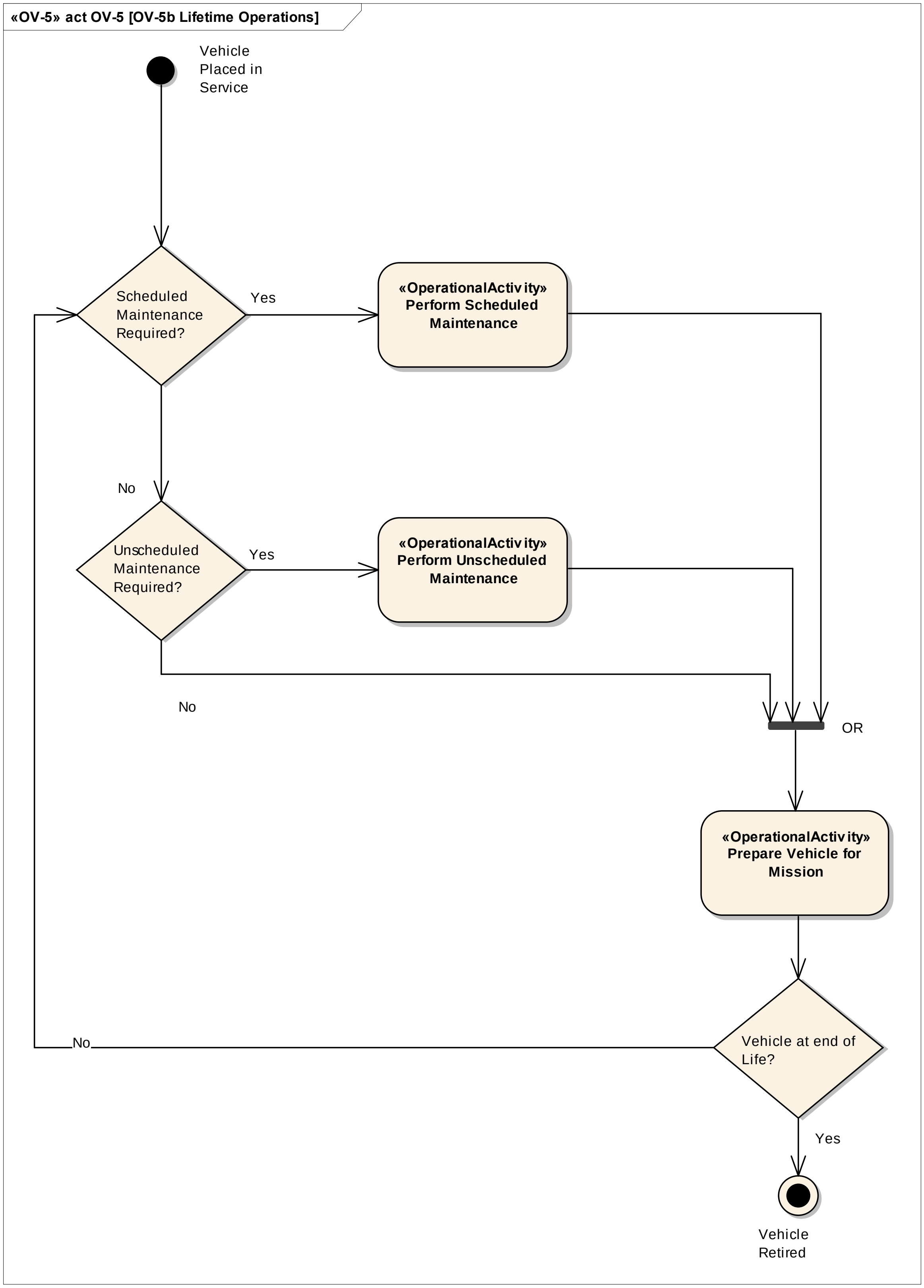
B.6 OV-5a


«OV-5» act OV-5 [OV-5a]
«OperationalActivity» Health Management
«OperationalActivity» Service Vehicle
«OperationalActivity» Perform Scheduled Maintenance
«OperationalActivity» Perform Unscheduled Maintenance
«OperationalActivity» Prepare Vehicle for Mission
«OperationalActivity» Assess Health
«OperationalActivity» Assign Criticality
«OperationalActivity» Prioritize Faults
«OperationalActivity» Evaluate Current Capabilities
«OperationalActivity» Recommend Mitigation Actions
«OperationalActivity» Isolate Faults
«OperationalActivity» Calculate Estimated Time to Failure
«OperationalActivity» Pinpoint Fault Location
«OperationalActivity» Detect Faults
«OperationalActivity» Confirm Fault Occurred
«OperationalActivity» Determine Type of Fault
«OperationalActivity» Manage Data
«OperationalActivity» Package Data
«OperationalActivity» Store Data
«OperationalActivity» Process Sensor Data
«OperationalActivity» Receive Data
«OperationalActivity» Transmit Data

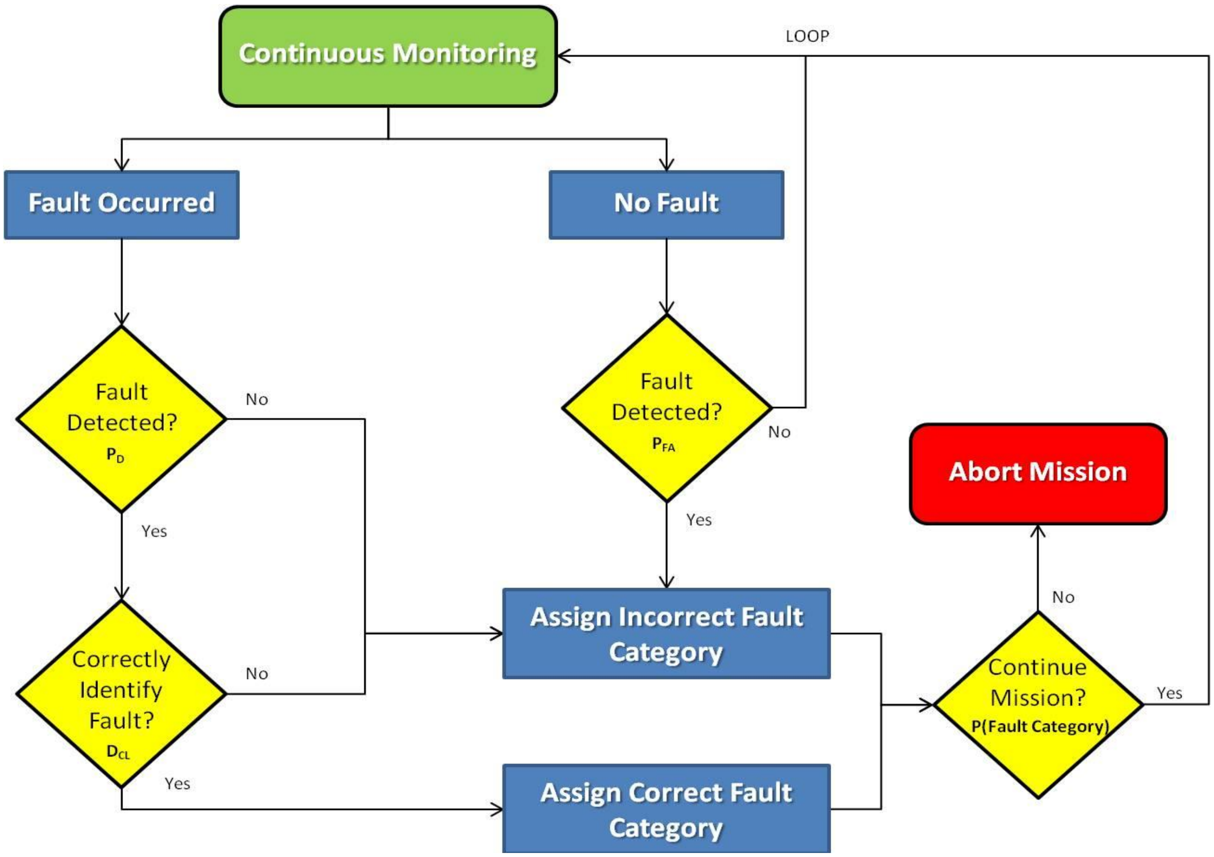
B.7 OV-5b


«OV-5» act OV-5 [OV-5b Nominal Mission Operations]
Mission Start
«OperationalActivity»
Receive Data
No
«OperationalActivity»
Process Sensor Data
Fault Detected?
Yes
Fault
Detected
During
Mission
No
«OperationalActivity»
Store Data
Time for
Heartbeat?
Yes
«OperationalActivity»
Package Data
No
«OperationalActivity»
Transmit Data
Or
Mission Complete?
Yes
Mission
Complete


«OV-5» act OV-5 [OV-5b Fault During Mission]
Information Management System (System Level)
Prognostic/Diagnostic Modules (Subsystem Level)
Fault Detected During Mission
«OperationalActivity» Confirm Fault Occurred
Fault(s) Confirmed?
[No]
Yes
Faults Left to Analyze
«OperationalActivity» Determine Type of Fault
«OperationalActivity» Pinpoint Fault Location
More than One Fault Detected?
«OperationalActivity» Assign Criticality
«OperationalActivity» Calculate Estimated Time to Failure
All Faults Accounted For
«OperationalActivity» Evaluate Current Capabilities
«OperationalActivity» Prioritize Faults
«OperationalActivity» Recommend Mitigation Actions
Fault Category < 5?
Yes
Fault Category <4?
Yes
Mission Start
No
No
Vehicle Retired
Mission Complete

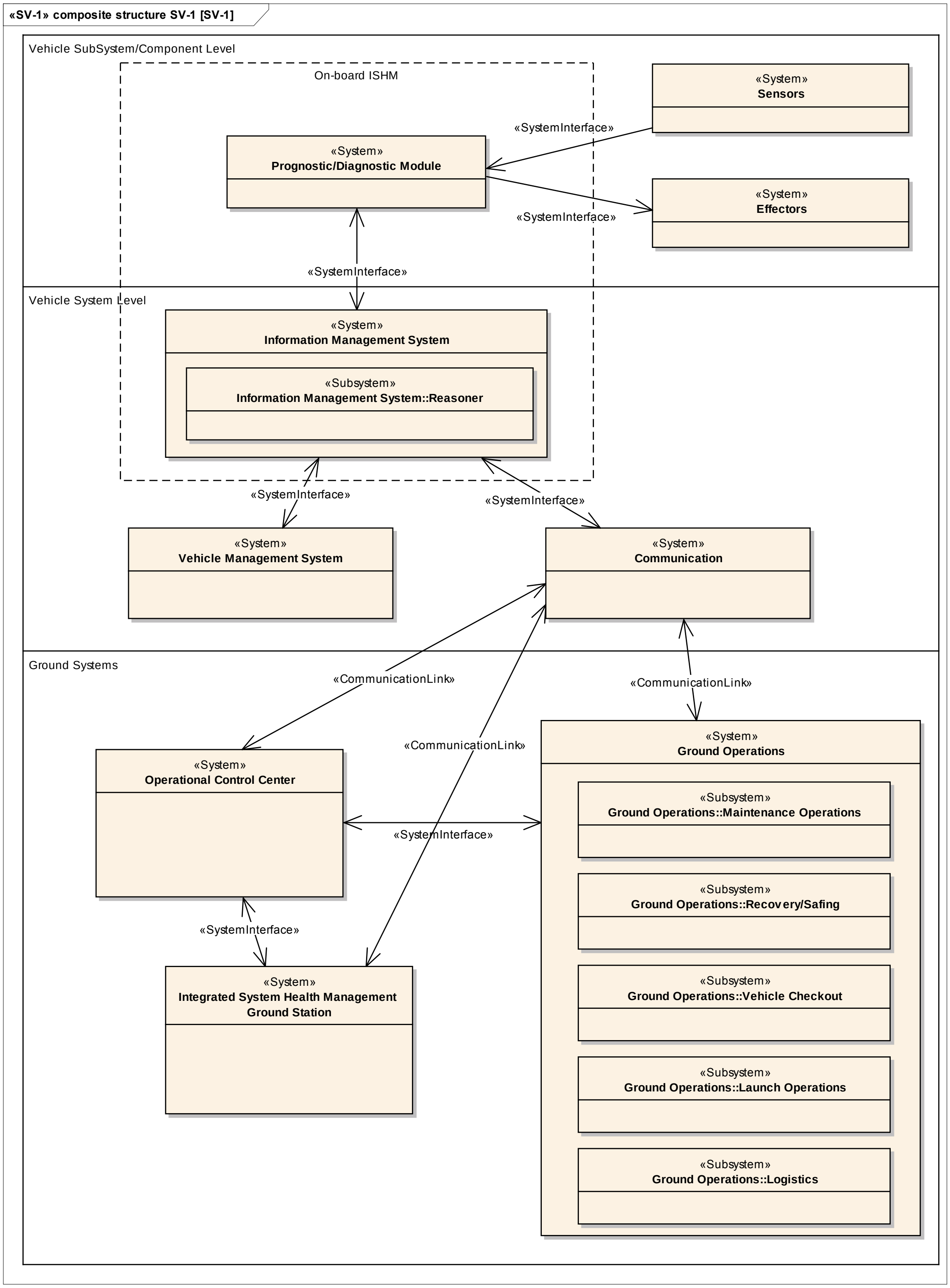

«OV-5» act OV-5 [OV-5b Lifetime Operations]
Vehicle Placed in Service
Scheduled Maintenance Required?
Yes
«OperationalActivity» Perform Scheduled Maintenance
No
Unscheduled Maintenance Required?
Yes
«OperationalActivity» Perform Unscheduled Maintenance
No
OR
«OperationalActivity» Prepare Vehicle for Mission
Vehicle at end of Life?
No
Yes
Vehicle Retired

B.8 OV-6a



Continuous Monitoring
LOOP
Fault Occurred
No Fault
Fault
Detected?
P_D
No
Yes
Fault
Detected?
P_{FA}
No
Yes
Abort Mission
No
Assign Incorrect Fault
Category
Correctly
Identify
Fault?
D_{CL}
No
Yes
Continue
Mission?
P(Fault Category)
Yes
Assign Correct Fault
Category

B.9 SV-1



«SV-1» composite structure SV-1 [SV-1]
Vehicle SubSystem/Component Level
On-board ISHM
«System»
Sensors
«SystemInterface»
«System»
Prognostic/Diagnostic Module
«System»
Effectors
«SystemInterface»
«SystemInterface»
Vehicle System Level
«System»
Information Management System
«Subsystem»
Information Management System::Reasoner
«SystemInterface»
«SystemInterface»
«System»
Vehicle Management System
«System»
Communication
Ground Systems
«CommunicationLink»
«CommunicationLink»
«CommunicationLink»
«System»
Ground Operations
«System»
Operational Control Center
«Subsystem»
Ground Operations::Maintenance Operations
«SystemInterface»
«Subsystem»
Ground Operations::Recovery/Safing
«SystemInterface»
«System»
Integrated System Health Management Ground Station
«Subsystem»
Ground Operations::Vehicle Checkout
«Subsystem»
Ground Operations::Launch Operations
«Subsystem»
Ground Operations::Logistics

Appendix C: Analytic Model Code

```
Dim ConfMatrix(6, 6) As Double
Dim RandCat As Double, TrueCat As Single, Detect As Single
Dim SysCat1, SysCat2, SysCat3, SysCat4, SysCat5, SysParam1, SysParam2
Dim NumFalseAlarms, NumFaults, NumFaultsDetected, NumIncorrectDeclared
Dim ProbAlarm, ProbDetect, ProbDiagnostic, MissionSuccessOld, MissionSuccessNew
Dim MissionLength, MaintLength, MonteCarloNum, Lifetime, NumMissions
Dim Results() As Integer, SumTotal(8) As Integer

Sub UserForm_Start()

        UserForm1.Show

End Sub

Sub MonteCarloSim(flag As Boolean)

        If flag = False Then
           With Worksheets("HiddenCM")
              For i = 1 To 6
                 For j = 1 To 6
                    ConfMatrix(i, j) = .Cells(7 + i, 2 + j).Value
                 Next j
              Next i
           End With
        End If

        Worksheets("Calculations").Activate

        ReDim Results(MonteCarloNum, 8)
        For i = 1 To 8
           SumTotal(i) = 0
        Next i

        'Run simulation
        With Worksheets("Calculations")

           Application.Goto .Range("A1:P38")
           ActiveWindow.Zoom = True
           .Cells(5, 13).Select

           'Populate Calculation page
```

```
    .Cells(4, 2).Value = ProbDetect
    .Cells(5, 2).Value = ProbAlarm
    .Cells(6, 2).Value = ProbDiagnostic
    .Cells(4, 5).Value = SysCat1
    .Cells(5, 5).Value = SysCat2
    .Cells(6, 5).Value = SysCat3
    .Cells(7, 5).Value = SysCat4
    .Cells(8, 5).Value = SysCat5
    .Cells(3, 11).Value = MissionLength
    .Cells(4, 11).Value = NumMissions
    .Cells(5, 11).Value = MaintLength
    .Cells(6, 11).Value = Lifetime
    .Cells(7, 11).Value = MonteCarloNum

    MaintNum = Int(Lifetime / MaintLength)

    For i = 1 To MonteCarloNum

        NumFalseAlarms = 0
        NumFaultsDetected = 0
        NumFaults = 0
        NumIncorrectDeclared = 0
        NumSuccessMsns_Old = 0
        NumMaint_Old = 0
        NumSuccessMsns_New = 0
        NumMaint_New = 0

        For j = 1 To MaintNum

            'System Distribution
            If UserForm1.SystemDist = "Normal" Then
                temp1 = Application.WorksheetFunction.NormInv(Rnd(), SysParam1,
SysParam2)
            ElseIf UserForm1.SystemDist = "Lognormal" Then
                temp1 = Application.WorksheetFunction.LogInv(Rnd(), SysParam1,
SysParam2)
            ElseIf UserForm1.SystemDist = "Weibull" Then
                temp1 = SysParam1 * (-Log(1 - Rnd())) ^ (1 / SysParam2)
            Else 'Gamma'
                temp1 = Application.WorksheetFunction.GammaInv(Rnd(),
SysParam1, SysParam2)
            End If
            tempHours = 0
            NumFaults_temp = 0
            NumFalseAlarms_temp = 0
```

```
NumFaultsDetected_temp = 0
NumIncDecl_temp = 0
NumSuccessMsns_Old_temp = 0
NumMaint_Old_temp = 0
NumSuccessMsns_New_temp = 0
NumMaint_New_temp = 0
flagX = False
flagY = False

 For k = 1 To NumMissions

   tempHours = tempHours + MissionLength
   tempRow = Range("A13").End(xlDown).Offset(1).Row
   .Cells(tempRow, 1) = tempHours

   'Fault Occured
   If temp1 < tempHours Then
      Fail = 1
      NumFaults_temp = NumFaults_temp + 1
   Else
      Fail = 0
   End If
   .Cells(tempRow, 2) = Fail

   Rand1 = Rnd()
   Rand2 = Rnd()
   'Detection Prob
   If Fail = 1 Then
      If Rand1 < ProbDetect Then
         Detect = 1
      Else
         Detect = 0
      End If
   Else
      If Rand2 < ProbAlarm Then
         Detect = 1
      Else
         Detect = 0
      End If
   End If
   .Cells(tempRow, 3) = Detect

   'False Alarms? Detected Failure?
   If Fail = 0 And Detect = 1 Then
      NumFalseAlarms_temp = NumFalseAlarms_temp + 1
```

```
End If
If Fail = 1 And Detect = 1 Then
   NumFaultsDetected_temp = NumFaultsDetected_temp + 1
End If

RandCat = Rnd()

'True Fault Category
If RandCat < SysCat1 Then
   TrueCat = 1 * Fail
ElseIf RandCat < SysCat2 Then
   TrueCat = 2 * Fail
ElseIf RandCat < SysCat3 Then
   TrueCat = 3 * Fail
ElseIf RandCat < SysCat4 Then
   TrueCat = 4 * Fail
Else
   TrueCat = 5 * Fail
End If
.Cells(tempRow, 4) = TrueCat

'Declared Fault Category
DetectCat = DeclareMatrix(RandCat, TrueCat, Detect)

.Cells(tempRow, 4) = TrueCat
.Cells(tempRow, 5) = DetectCat

'Incorrectly Declared?
If TrueCat <> DetectCat Then
   NumIncDecl_temp = NumIncDecl_temp + 1
End If

'Mission Success Calculations
If DetectCat >= 1 Or TrueCat >= 3 Or flagX = True Then
   SuccessMsn = 0
Else
   SuccessMsn = 1
   NumSuccessMsns_Old_temp = NumSuccessMsns_Old_temp + 1
End If
.Cells(tempRow, 7) = SuccessMsn

If DetectCat >= 4 Or (TrueCat >= 3 And DetectCat <= 2) Or _
      (TrueCat >= 4 And DetectCat = 3) Or TrueCat = 5 _
      Or flagY = True Then
   SuccessMsn2 = 0
```

```
    Else
        SuccessMsn2 = 1
        NumSuccessMsns_New_temp = NumSuccessMsns_New_temp + 1
    End If
    .Cells(tempRow, 9) = SuccessMsn2

    'Maintenance Required?
    If DetectCat >= 1 And DetectCat < 5 Then
        MaintRx_Old = 1
        NumMaint_Old_temp = NumMaint_Old_temp + 1
    Else
        MaintRx_Old = 0
    End If
    .Cells(tempRow, 8) = MaintRx_Old

    If DetectCat >= 2 And DetectCat < 5 Then
        MaintRx_New = 1
        NumMaint_New_temp = NumMaint_New_temp + 1
    Else
        MaintRx_New = 0
    End If
    .Cells(tempRow, 10) = MaintRx_New

    'Continue on to next mission?
    If SuccessMsn = 0 Then
        .Cells(tempRow, 11) = "Baseline Offline until PM"
        flagX = True
    End If
    If SuccessMsn2 = 0 Then
        .Cells(tempRow, 11) = "Sys w/ISHM Offline until PM"
        flagY = True
    End If
    If flagX = True And flagY = True Then
        k = NumMissions + 1
    End If
    If DetectCat = 5 Or TrueCat = 5 Then
        k = NumMissions + 1
        j = MaintNum + 1
        .Cells(tempRow, 11) = "Catastrophic Failure"
    End If

Next k
tempRow2 = Range("A13").End(xlDown).Offset(1).Row
.Cells(tempRow2, 1) = "End of Preventative Maintenance Cycle"
```

```
            'Update Metrics
            NumFalseAlarms = NumFalseAlarms + NumFalseAlarms_temp
            NumFaultsDetected = NumFaultsDetected + NumFaultsDetected_temp
            NumFaults = NumFaults + NumFaults_temp
            NumIncorrectDeclared = NumIncDecl_temp + NumIncorrectDeclared
            NumSuccessMsns_Old = NumSuccessMsns_Old +
NumSuccessMsns_Old_temp
            NumMaint_Old = NumMaint_Old + NumMaint_Old_temp
            NumSuccessMsns_New = NumSuccessMsns_New +
NumSuccessMsns_New_temp
            NumMaint_New = NumMaint_New + NumMaint_New_temp

        Next j
        tempRow3 = Range("A13").End(xlDown).Offset(1).Row
        .Cells(tempRow3, 1) = "End of Vehicle Lifetime"

        Results(i, 1) = NumSuccessMsns_Old
        Results(i, 2) = NumMaint_Old
        Results(i, 3) = NumSuccessMsns_New
        Results(i, 4) = NumMaint_New
        Results(i, 5) = NumFaults
        Results(i, 6) = NumFaultsDetected
        Results(i, 7) = NumFalseAlarms
        Results(i, 8) = NumIncorrectDeclared

    Next i

End With

'Output Results
Worksheets("Results").Activate

With Worksheets("Results")
    Application.Goto .Range("A1:J30")
    For i = 1 To MonteCarloNum
        .Cells(11 + i, 2) = i
        .Cells(11 + i, 3) = NumMissions * MaintNum
        For j = 1 To 8
            .Cells(11 + i, 3 + j) = Results(i, j)
            SumTotal(j) = SumTotal(j) + Results(i, j)
        Next j
    Next i
    .Cells(2, 5) = MonteCarloNum * NumMissions * MaintNum
    .Cells(3, 5) = SumTotal(1)
    .Cells(4, 5) = SumTotal(2)
```

```
        .Cells(5, 5) = SumTotal(3)
        .Cells(6, 5) = SumTotal(4)
    End With

End Sub

Function InputCheck() As Boolean

    flagInput = True

    'Check combobox has selections
    If UserForm1.SystemDist.Value = "" Then
    MsgBox "You have not selected a distribution. Please select a distribution and "
    & _
            "run the Monte Carlo simulation again", , "Error"
        flagInput = False
        Exit Function
    End If

    'Check Parameter inputs are valid numbers
    If IsNumeric(UserForm1.SysParam1.Value) = False Or
    IsNumeric(UserForm1.SysParam2.Value) = False Then
        MsgBox "You have either entered a non-numeric value for the system
    parameters" & _
            " or left a field blank. Please enter a numeric value and run the Monte Carlo
    simulation again", , "Error"
        flagInput = False
        Exit Function
    End If

    'Turn parameter inputs into numbers
    SysParam1 = CDec(UserForm1.SysParam1)
    SysParam2 = CDec(UserForm1.SysParam2)

    'Check that all numbers are positive
    If SysParam1 < 0 Or SysParam2 < 0 Then
        MsgBox "You have entered in a negative number, all numbers should be
    positive", , "Error"
        flagInput = False
        Exit Function
    End If

    'Check Failure Properities are valid numbers
    If IsNumeric(UserForm1.SysCat1.Value) = False Or
    IsNumeric(UserForm1.SysCat2.Value) = False _
```

```
      Or IsNumeric(UserForm1.SysCat3.Value) = False Or
IsNumeric(UserForm1.SysCat4.Value) = False _
      Or IsNumeric(UserForm1.SysCat5.Value) = False Then
   MsgBox "You have entered a non-numeric value for a probability of a failure
mode occurance or have" & _
      " left a field blank. Please enter a numeric value and run the Monte Carlo
simulation again", , "Error"
   flagInput = False
   Exit Function
End If

'Turn failure inputs into numbers
SysCat1 = CDec(UserForm1.SysCat1)
SysCat2 = CDec(UserForm1.SysCat2) + SysCat1
SysCat3 = CDec(UserForm1.SysCat3) + SysCat2
SysCat4 = CDec(UserForm1.SysCat4) + SysCat3
SysCat5 = CDec(UserForm1.SysCat5) + SysCat4

'Check Failure Properties are between 0 and 1
If UserForm1.SysCat1.Value < 0 Or UserForm1.SysCat1.Value > 1 Or
UserForm1.SysCat2.Value < 0 Or UserForm1.SysCat2.Value > 1 _
      Or UserForm1.SysCat3.Value < 0 Or UserForm1.SysCat3.Value > 1 Or
UserForm1.SysCat4.Value < 0 Or UserForm1.SysCat4.Value > 1 _
      Or UserForm1.SysCat5.Value < 0 Or UserForm1.SysCat5.Value > 1 Then
   MsgBox "You have entered a failure propability greater than 1 or less than 0."
& _
      " Please enter a correct probability and run the Monte Carlo simulation
again", , "Error"
   flagInput = False
   Exit Function
End If

'Check Failure Properties sum to 1 for each system
If SysCat5 <> 1 Then
   MsgBox "The failure properties do not total 1. Please enter a correct probability
and run the Monte Carlo simulation again", , "Error"
   flagInput = False
   Exit Function
End If

'Check ISHM Properities are valid numbers
If IsNumeric(UserForm1.ProbDetect.Value) = False Or
IsNumeric(UserForm1.ProbFalseAlarm.Value) = False Or
IsNumeric(UserForm1.ProbDiagnostic.Value) = False Then
```

```
   MsgBox "You have entered a non-numeric value for an ISHM property or left a
field blank. Please enter a numeric value and run the Monte Carlo simulation
again", , "Error"
   flagInput = False
   Exit Function
End If

'Check ISHM Properties are between 0 and 1
If UserForm1.ProbDetect.Value < 0 Or UserForm1.ProbFalseAlarm.Value < 0 Or
UserForm1.ProbDiagnostic.Value < 0 _
      Or UserForm1.ProbDetect.Value > 1 Or UserForm1.ProbFalseAlarm.Value
> 1 Or UserForm1.ProbDiagnostic.Value > 1 Then
   MsgBox "You have entered a failure propability greater than 1 or less than 0
for an ISHM property" & _
   " or left a field blank. Please enter a correct probability and run the Monte
Carlo simulation again", , "Error"
   flagInput = False
   Exit Function
End If

'Turn ISHM inputs into numbers
ProbDetect = CDec(UserForm1.ProbDetect)
ProbAlarm = CDec(UserForm1.ProbFalseAlarm)
ProbDiagnostic = CDec(UserForm1.ProbDiagnostic)

'Check Monte Carlo inputs are numerical
If IsNumeric(UserForm1.MonteCarloNum.Value) = False Or
IsNumeric(UserForm1.AverageMissionLength.Value) = False _
      Or IsNumeric(UserForm1.MaintLength.Value) = False Or
IsNumeric(UserForm1.Lifetime.Value) = False Then
   MsgBox "You have either entered a non-numeric value or left a field blank in
the Monte Carlo frame. " & _
      "Please enter a numeric value.", , "Error"
   flagInput = False
   Exit Function
End If

'Check that inputs are within max and min or positive
If UserForm1.MonteCarloNum.Value < 0 Or
UserForm1.AverageMissionLength.Value < 0 Or UserForm1.Lifetime.Value < 0
_
      Or UserForm1.MonteCarloNum.Value > 500 Or
UserForm1.MaintLength.Value < 0 Then
   MsgBox "You have entered a negative number or a number out of range for
Monte Carlo Simulations. " & _
```

```
        "Please enter a valid number.", , "Error"
      flagInput = False
      Exit Function
    End If

    'Turn Monte Carlo Inputs into numbers
    MonteCarloNum = CDec(UserForm1.MonteCarloNum)
    MissionLength = CDec(UserForm1.AverageMissionLength)
    MaintLength = CDec(UserForm1.MaintLength)
    Lifetime = CDec(UserForm1.Lifetime)
    NumMissions = Int(MaintLength / MissionLength) 'Rounds down

    InputCheck = flagInput

End Function

Sub ActivateStartPage()

    Worksheets("Intro").Activate

End Sub

Sub ViewAssumptions()

    Worksheets("Assumptions").Activate
    Application.Goto Worksheets("Assumptions").Range("A1:N30")
    ActiveWindow.Zoom = True
    Worksheets("Assumptions").Cells(1, 1).Select

End Sub

Sub SetUpConfusionMatrix()

    'Assumption that any ISHM diagnostic algorithm will be within one category of
    the true category

    With Worksheets("ConfusionMatrix")
      .Cells(2, 6) = ProbDiagnostic
      'Nominal Column
      .Cells(8, 3) = ProbDiagnostic
      .Cells(9, 3) = 1 - ProbDiagnostic
      .Cells(10, 3) = 0
      .Cells(11, 3) = 0
      .Cells(12, 3) = 0
      .Cells(13, 3) = 0
```

```
        'Cat 1 Column
        .Cells(8, 4) = (1 - ProbDiagnostic) / 2
        .Cells(9, 4) = ProbDiagnostic
        .Cells(10, 4) = (1 - ProbDiagnostic) / 2
        .Cells(11, 4) = 0
        .Cells(12, 4) = 0
        .Cells(13, 4) = 0
        'Cat 2 Column
        .Cells(8, 5) = 0
        .Cells(9, 5) = (1 - ProbDiagnostic) / 2
        .Cells(10, 5) = ProbDiagnostic
        .Cells(11, 5) = (1 - ProbDiagnostic) / 2
        .Cells(12, 5) = 0
        .Cells(13, 5) = 0
        'Cat 3 Column
        .Cells(8, 6) = 0
        .Cells(9, 6) = 0
        .Cells(10, 6) = (1 - ProbDiagnostic) / 2
        .Cells(11, 6) = ProbDiagnostic
        .Cells(12, 6) = (1 - ProbDiagnostic) / 2
        .Cells(13, 6) = 0
        'Cat 4 Column
        .Cells(8, 7) = 0
        .Cells(9, 7) = 0
        .Cells(10, 7) = 0
        .Cells(11, 7) = (1 - ProbDiagnostic) / 2
        .Cells(12, 7) = ProbDiagnostic
        .Cells(13, 7) = (1 - ProbDiagnostic) / 2
        'Cat 5 Column
        .Cells(8, 8) = 0
        .Cells(9, 8) = 0
        .Cells(10, 8) = 0
        .Cells(11, 8) = 0
        .Cells(12, 8) = 1 - ProbDiagnostic
        .Cells(13, 8) = ProbDiagnostic

    End With

End Sub

Sub ReadConfusionMatrix()

    Dim Temp(6) As Double
    flag = True
```

```
        With Worksheets("ConfusionMatrix")
            'Input Check
            For j = 1 To 6
                Temp(j) = .Cells(15, 2 + j).Value
                If Temp(j) <> 1 Then
                    MsgBox "The columns need to add to 1, please reset this matrix", , "Error"
                    flag = False
                    j = 7
                End If
            Next j
        End With

        If flag = False Then
            Exit Sub
        Else
            With Worksheets("HiddenCM")
                For i = 1 To 6
                    For j = 1 To 6
                        ConfMatrix(i, j) = .Cells(7 + i, 2 + j).Value
                    Next j
                Next i
            End With

            Call MonteCarloSim(True)
        End If

End Sub

Function DeclareMatrix(RandCat As Double, TrueCat As Single, Detect As Single)

        If Detect = 0 Then
            DeclareMatrix = 0
            Exit Function
        End If

        If TrueCat = 0 Then
            For i = 0 To 5
                If RandCat < ConfMatrix(i + 1, 1) Then
                    DeclareMatrix = i
                    i = 6
                End If
            Next i
        ElseIf TrueCat = 1 Then
            For i = 0 To 5
                If RandCat < ConfMatrix(i + 1, 2) Then
```

```
                DeclareMatrix = i
                i = 6
            End If
        Next i
    ElseIf TrueCat = 2 Then
        For i = 0 To 5
            If RandCat < ConfMatrix(i + 1, 3) Then
                DeclareMatrix = i
                i = 6
            End If
        Next i
    ElseIf TrueCat = 3 Then
        For i = 0 To 5
            If RandCat < ConfMatrix(i + 1, 4) Then
                DeclareMatrix = i
                i = 6
            End If
        Next i
    ElseIf TrueCat = 4 Then
        For i = 0 To 5
            If RandCat < ConfMatrix(i + 1, 5) Then
                DeclareMatrix = i
                i = 6
            End If
        Next i
    Else
        For i = 0 To 5
            If RandCat < ConfMatrix(i + 1, 6) Then
                DeclareMatrix = i
                i = 6
            End If
        Next i
    End If

End Function

Sub ClearWorkbook()

    With Worksheets("Calculations")
        .Cells(4, 2).ClearContents
        .Cells(5, 2).ClearContents
        .Cells(6, 2).ClearContents
        .Cells(4, 5).ClearContents
        .Cells(5, 5).ClearContents
        .Cells(6, 5).ClearContents
```

```
    .Cells(7, 5).ClearContents
    .Cells(8, 5).ClearContents
    .Cells(3, 11).ClearContents
    .Cells(4, 11).ClearContents
    .Cells(5, 11).ClearContents
    .Cells(6, 11).ClearContents
    .Cells(7, 11).ClearContents
    .Cells(3, 14).ClearContents
    .Cells(4, 14).ClearContents
    .Cells(5, 14).ClearContents
    .Cells(6, 14).ClearContents
    .Cells(4, 16).ClearContents
    .Cells(4, 17).ClearContents
    .Cells(8, 16).ClearContents
    .Cells(8, 17).ClearContents
    .Range("a15:" &
.Range("a15").End(xlDown).End(xlToRight).Address).ClearContents
    .Range("g15:" &
.Range("g15").End(xlDown).End(xlToRight).Address).ClearContents
End With

With Worksheets("ConfusionMatrix")
    .Cells(2, 6).ClearContents
    .Range("c8:" &
.Range("c8").End(xlDown).End(xlToRight).Address).ClearContents
End With

With Worksheets("Results")
    .Range("E2:" & .Range("E2").End(xlDown).Address).ClearContents
    .Range("b12:" &
.Range("b12").End(xlDown).End(xlToRight).Address).ClearContents
End With

Unload UserForm1
Worksheets("Intro").Activate

End Sub

Sub ViewCalcPage()

        Worksheets("Calculations").Activate

End Sub

Sub ViewResults()
```

```
    Worksheets("Results").Activate
End Sub
```

Appendix D: Design of Experiments Results and Models

Alias Structure with Main Effects and Low Order Interactions

A = Weibull-Theta
B = Weibull-Beta
C = Sensor Quality (c)
D = Probability of Detection (P_D)
E = P(Fault Category II)
F = P(Fault Category III)
G = ISHM Diagnostic Confidence Level (D_{CL})

I = ABD = ACE = BCF = ABCG

A = A + BD + CE + FG
B = B + AD + CF + EG
C = C +AE + BF + DG

D = D + AB + CG + EF
E = E + AC + BG + DF
F = F + BC + AG + DE
G = G + CD + BE + AF

Initial Experiment Results

The initial experiment results can be found below. The original run order was random; however, this data has been sorted to place the center points at the bottom for easier analysis.

Run	Response	Weibull - theta	Weibull - beta	Sensor Quality	Prob Detection	Prob Fault Category II	Prob Fault Category III	Diagnostic CL
1	33	-1	-1	1	1	-1	1	-1
2	21	-1	1	1	-1	-1	-1	1
3	514	-1	-1	-1	1	1	-1	1
4	368	1	1	1	1	1	-1	-1
5	526	1	1	-1	1	-1	1	1
6	97	-1	1	-1	-1	1	1	-1
7	22	1	-1	1	-1	1	1	1
8	613	1	-1	-1	-1	-1	-1	-1
9	82	-1	-1	1	1	-1	1	-1
10	98	-1	1	1	-1	-1	-1	1
11	382	-1	-1	-1	1	1	-1	1
12	487	1	1	1	1	1	-1	-1
13	414	1	1	-1	1	-1	1	1
14	144	-1	1	-1	-1	1	1	-1
15	30	1	-1	1	-1	1	1	1
16	166	1	-1	-1	-1	-1	-1	-1
17	85	-1	-1	1	1	-1	1	-1
18	23	-1	1	1	-1	-1	-1	1
19	195	-1	-1	-1	1	1	-1	1
20	330	1	1	1	1	1	-1	-1
21	821	1	1	-1	1	-1	1	1
22	50	-1	1	-1	-1	1	1	-1
23	25	1	-1	1	-1	1	1	1
24	309	1	-1	-1	-1	-1	-1	-1
25	109	0	0	0	0	0	0	0
26	126	0	0	0	0	0	0	0
27	21	0	0	0	0	0	0	0
28	11	0	0	0	0	0	0	0

The response for each run is the total of the four repeated measurements, as seen below:

RM - 1	RM - 2	RM - 3	RM - 4	Response
2	6	0	25	33
0	2	15	4	21
13	324	53	124	514
0	49	148	171	368
213	169	100	44	526
10	3	1	83	97
15	5	2	0	22
242	10	69	292	613
21	60	1	0	82
3	23	1	71	98
92	124	11	155	382
45	1	344	97	487
44	163	51	156	414
1	27	108	8	144
5	9	13	3	30
29	0	17	120	166
10	26	2	47	85
2	8	4	9	23
0	50	106	39	195
213	109	2	6	330
149	222	94	356	821
36	6	2	6	50
13	4	7	1	25
45	91	90	83	309
6	3	4	96	109
48	16	8	54	126
13	1	0	7	21
3	3	1	4	11

Initial Model Analysis

Using these results, the sum of squares for the factors and their interactions were calculated and it was found that Weibull-Theta, Sensor Quality, and P_D were significant. Due to aliasing, the sum of squares for P_D also includes the interaction between Weibull-Theta and Weibull-Beta; however, since Weibull-Beta is not significant to the model, it can be assumed that P_D is the true significant factor.

Regressing these factors against the test data gave a fairly high coefficient of determination (R^2) value of 0.704 and an F_0 value of 13.67 (p-value of less than 0.0001), as seen below. These values signified that the model explained most of the variability in the data, and further exploration of the individual factors confirmed that they all still significantly contributed to the model.

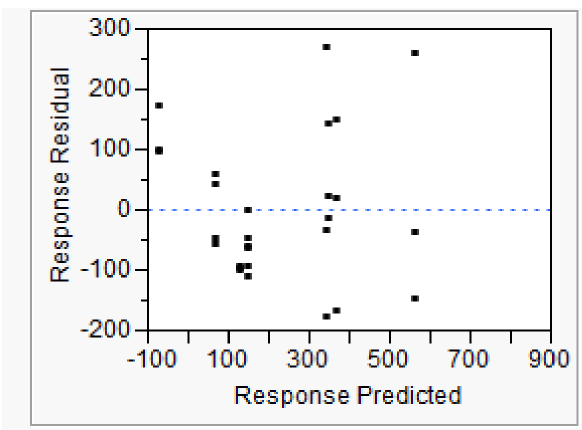
Analysis of Variance

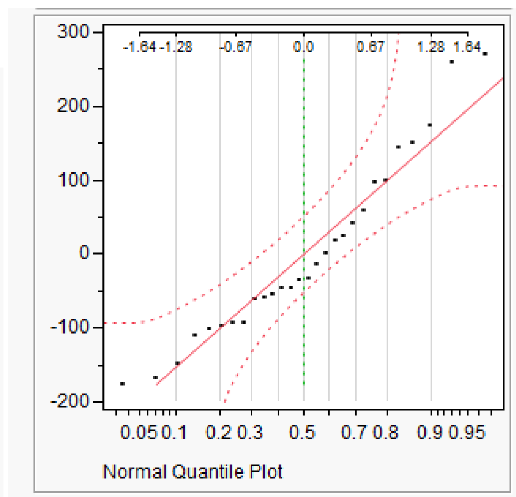
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	921790.6	230448	13.6764
Error	23	387551.2	16850	**Prob > F**
C. Total	27	1309341.9		<.0001*

Summary of Fit

RSquare	0.704011
RSquare Adj	0.652534
Root Mean Square Error	129.8078
Mean of Response	217.9286
Observations (or Sum Wgts)	28

Examination of the model residuals did not indicate any normality assumptions were violated (no apparent pattern or significant tailing in the variance checks). The Residual by Predicted Plot and the Normal Quantile Plot can be seen below.





Variability of the non-significant factors was also investigated, with the following settings to be determined as causing less variance in the results.

Factor	Best Setting for Variability
Weibull - Beta	Either
P(Fault Category II)	High – 0.4
P(Fault Category III)	Either
D_{CL}	Either

The Center Points that were chosen indicated that curvature is present, as seen by a p-value under 0.05 below. This means the assumption of linearity in the factor effects cannot be maintained and axial points need to be added for further analysis. Curvature can be investigated through a central composite design.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	243.125	26.4969	9.18	<.0001*
Weibull - theta	99.458333	26.4969	3.75	0.0010*
Sensor Quality	-109.4583	26.4969	-4.13	0.0004*
Prob Detection	109.95833	26.4969	4.15	0.0004*
Curvature	-176.375	70.1042	-2.52	0.0193*

Central Composite Model

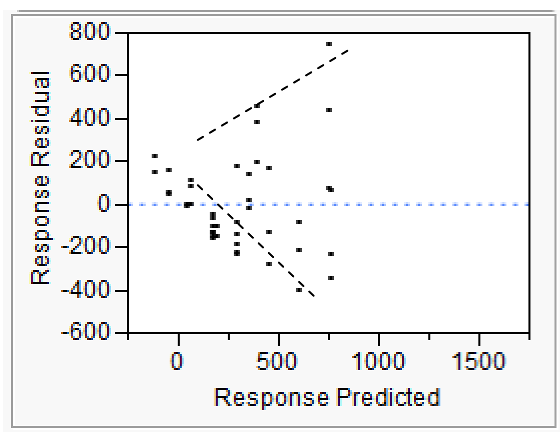
Axial points were then added to the test design to further explore the response surface. For a 3-factor experiment, an axial point of $3^{0.25}$ (0.316) will be used to ensure the design is fully rotatable. The new test design settings in natural units can be seen in the table below. The remaining test factors will be kept at their low settings except for P(Fault Category II), which will be kept high. The axial points will be tested in random order with two replications for a total of 18 additional test points and will be added the previous test results for re-analysis.

Factor	Axial (-1.316)	Axial (1.316)
Weibull-Theta	652	1047
Sensor Quality	36.8	563
P_D	0.21	0.99

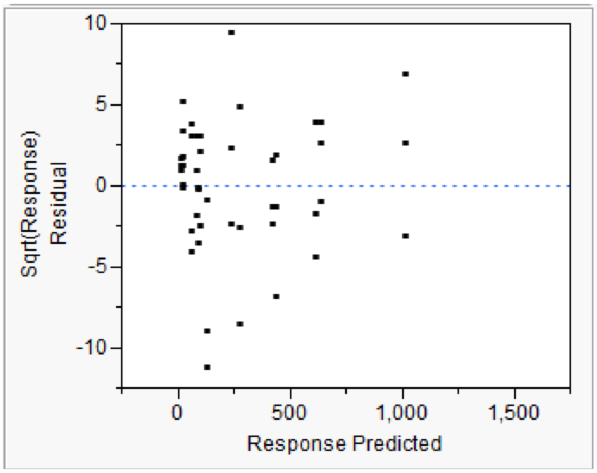
The second experiment results can be seen below:

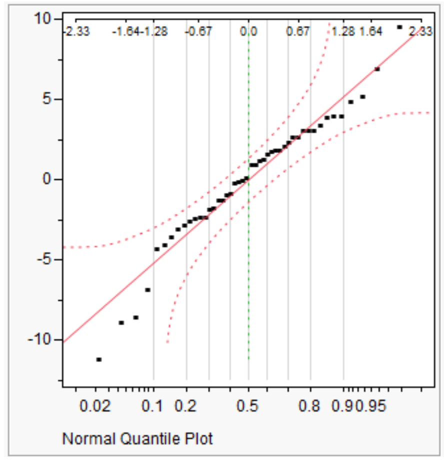
Response	Weibull - theta	Weibull - beta	Sensor Quality	Prob Detection	Prob Fault Category II	Prob Fault Category III	Diagnostic CL
460	1.316	-1	0	0	1	-1	-1
143	-1.316	-1	0	0	1	-1	-1
847	0	-1	0	1.316	1	-1	-1
106	0	-1	0	-1.316	1	-1	-1
1186	0	-1	1.316	0	1	-1	-1
63	0	-1	-1.316	0	1	-1	-1
197	1.316	-1	0	0	1	-1	-1
55	-1.316	-1	0	0	1	-1	-1
586	0	-1	0	1.316	1	-1	-1
0	0	-1	0	-1.316	1	-1	-1
824	0	-1	1.316	0	1	-1	-1
33	0	-1	-1.316	0	1	-1	-1
64	1.316	-1	0	0	1	-1	-1
167	-1.316	-1	0	0	1	-1	-1
776	0	-1	0	1.316	1	-1	-1
5	0	-1	0	-1.316	1	-1	-1
1498	0	-1	1.316	0	1	-1	-1
40	0	-1	-1.316	0	1	-1	-1

As expected from the results of the curvature analysis, a second-order response surface was discovered. There were also some low-order interactions and a main effect (P(Fault Category III)) that were found to be newly significant. However, there is clear funneling in the residuals, indicating that a transformation of the response variable is necessary.



Since the funneling is consistent with a Poisson random variable (the variance of y is proportional to the regressor), a transformation of y to $\sqrt{y}$ is appropriate. With this transformation, the residuals retained a scatter pattern and did not indicate any normality assumptions were violated. The new Residual by Predicted Plot and the Normal Quantile Plot can be seen below.





The final coded parameter estimates and significant factors and interactions can be seen below:

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6.0184269	2.586194	2.33	0.0255*
Prob Detection	5.3295735	0.762556	6.99	<.0001*
Prob Fault Category III	-8.842107	2.019323	-4.38	<.0001*
Weibull - theta	2.5606553	0.762556	3.36	0.0018*
Sensor Quality	1.6622854	0.776798	2.14	0.0390*
(Prob Fault Category III+0.3913)*(Prob Fault Category III+0.3913)	8.9648706	2.594351	3.46	0.0014*
Prob Detection*Weibull - theta	-13.09048	1.895008	-6.91	<.0001*
Weibull - theta*Weibull - theta	-2.859716	1.226968	-2.33	0.0253*
(Prob Fault Category III+0.3913)*Sensor Quality	-14.29718	1.660662	-8.61	<.0001*

Regressing these factors against the test data gave a higher coefficient of determination (R^2) value of 0.81 and an F_0 value of 16.73 (p-value of less than 0.0001) than the initial model, as seen below. This new model also gives a significantly smaller Mean Square Error, another indication that this model is a better fit to the data than the initial model.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	3085.2201	385.653	16.7349
Error	37	852.6568	23.045	**Prob > F**
C. Total	45	3937.8769		<.0001*

Summary of Fit

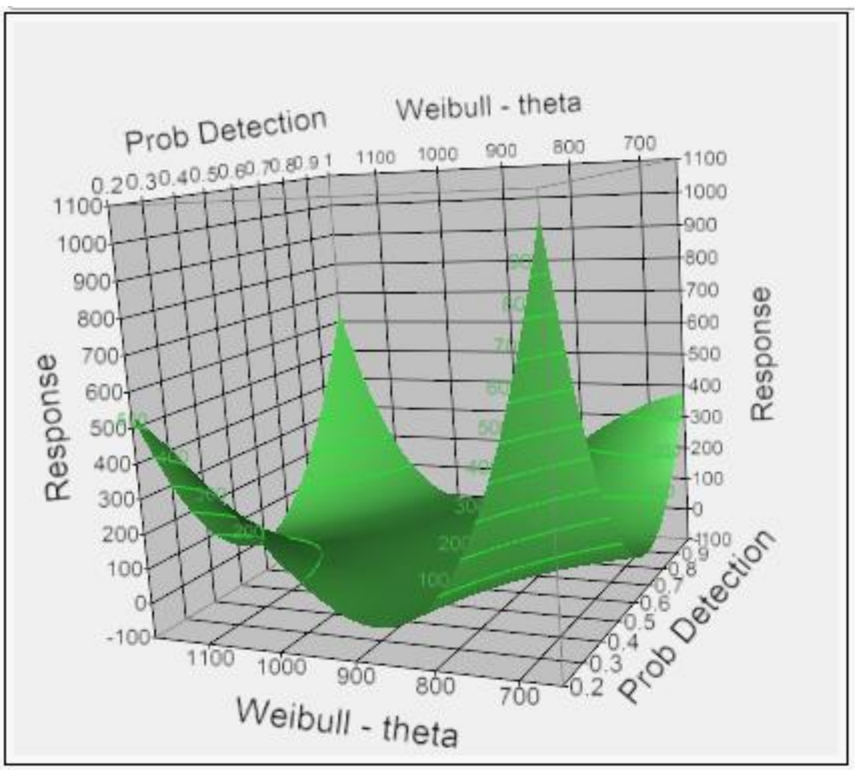
RSquare	0.812099
RSquare Adj	0.771471
Root Mean Square Error	4.471932
Mean of Response	14.15299
Observations (or Sum Wgts)	46

The final model equation mapping the response surface in natural values is seen below:

Prediction Expression

$$\begin{aligned}\Big(&-5.8606757513194\\
&+0.01544469484738*\text{Weibull - theta}\\
&+0.00748647127854*\text{Sensor Quality}\\
&+17.3222863745496*\text{Prob Detection}\\
&+-67.369395787959*\text{Prob Fault Category III}\\
&+(\text{Prob Fault Category III}-0.19130434782609)*\big((\text{Prob Fault Category III}-0.19130434782609)*501.71480745745\big)\\
&+(\text{Weibull - theta}-849.999990217391)*\big((\text{Prob Detection}-0.65217391304348)*-0.237351067408\big)\\
&+(\text{Weibull - theta}-849.999990217391)*\big((\text{Weibull - theta}-849.999990217391)*-0.0001395707596\big)\\
&+(\text{Prob Fault Category III}-0.19130434782609)*\big((\text{Sensor Quality}-300.000013043478)*-0.4148878097853\big)\Big)^2\end{aligned}$$

From this equation the stationary point is a point of minimum response, clearly visible in the figure below.



While this response surface best illustrates the region were the response is at its minimum, or the region where adding ISHM to the UAS baseline would not significantly affect mission success rates, there can be some inferences made about the regions that maximize the response. By determining the sensor properties significant and not the only ISHM performance characteristic (the Diagnostic Confidence Level), this evaluation implies that the benefits or disadvantages of adding ISHM rely primarily on the performance of the baseline health management system. Specifically, that ISHM becomes more beneficial as the baseline health management system performs worse.

Based on these results, when evaluating whether to add ISHM to a vehicle, decision makers should compare the cost and mission benefits of upgrading just the sensors with the cost and mission benefits of adding ISHM. The two options have roughly equivalent installation labor costs, as each would have to be implemented at the subsystem level (the difference being replacing the sensors versus adding a module to an existing sensor), so the main comparison would be the cost of the new sensors versus the cost of the ISHM technology weighed against the difference in expected mission success rates.

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14. ABSTRACT

This research used systems architecture to develop a model that determined the effect of Integrated System Health Management (ISHM) on mission success rates for unmanned aerial systems (UAS). To evaluate this effect, a simulation model was developed and used to analyze the difference between mission success rates for a theoretical UAS with and without ISHM. Design of Experiments analysis techniques were used to map a response surface that modeled the difference between mission success rates calculated for current health management technology and ISHM. Using representative data for a UAS, the analysis determined that the failure distribution parameters, sensor quality (which determines the relationship between probability of detection and probability of false alarm), and probability of an imminent fault during a mission were significant to the model. The result of the model determined that ISHM can result in a significant improvement on mission assurance, especially when implemented with higher quality sensors and on vehicles where the probability of imminent failure is higher relative to the mission times and time between preventative maintenance. This appears consistent with the premise that ISHM can support an extension of preventative maintenance intervals with an attendant reduction in sustainment cost.

15. SUBJECT TERMS

ISHM, Health Management, UAS

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