Vehicle Health and Sensors
Reusable Launch Vehicle (RLV)

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Overview

An increasing need is to make space transportation more cost effective and to move it to the commercial sector where it can become a profitable venture. The Avionics system is an essential element that incorporates health and sensors in order to have a successful program with outstanding performance and minimum cost.

One of the highest returns of investment is Vehicle Health and in the past it has been the most neglected. Our goal is to replace the armies of people that are required to maintain a space vehicle with significantly less workforce while increasing reliability and lowering total costs (Figure 1).

Vehicle sensors are like human senses; they provide the information that is interpreted by the Vehicle Health Management system. The essential aspect is to reduce operations replacement costs and lost time due to failure of sensors and their information.

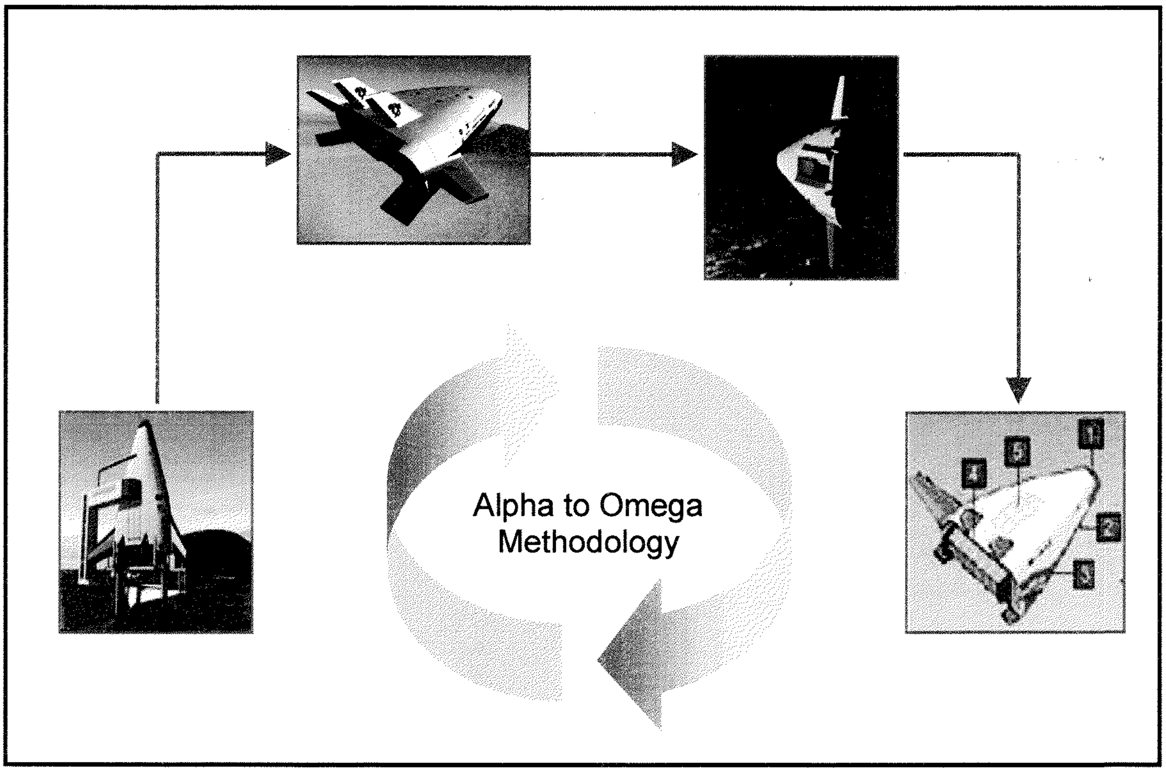

Figure 1: An Alpha to Omega Methodology for IVHM

1.0 Vehicle Health Management (VHM)

1.1 Prior Practice

Typically VHM systems have previously been nothing more than slightly intelligent flight recorders that collected data, possibly augmented with fixed alarm limits. If the ground crews were specifically looking for something, then upon landing the data was eventually analyzed; otherwise it was ignored. Obviously the VHM played a very insignificant role in assessing the health of the vehicle while in flight. Upon landing, the mounds of unstructured information that it generated could only then be interpreted and used by experts.

The present practice is to schedule vehicle maintenance based upon assumptions from prior models from engineers. These models "predict" expected performance based upon normal wear and tear. From these predictions maintenance schedules are formulated to replace the component prior to its "expected" failure.

One of the reasons that VHM systems have played such insignificant roles in the past is the complexity required to build a system to diagnose meaningful failures, let alone predict failures before they occur with nearly zero false alarms. Typically the best diagnostic models can only identify 10-30% of the faults that could actually occur while the prognostic models often produce many false alarms and waste time and money with unnecessary maintenance.

1.2 Present Practice

In the past Vehicle Health Management (VHM) was only something that was thought about after all the major components had already been designed. When VHM is present from the initial design of the vehicle, not only does it provide significant savings in maintaining the vehicle but also through the entire design and build cycle too.

The same tools provide VHM functions while in flight can be used to assist in the design of major flight components such as engines, tanks, structures, and avionics. This has already been clearly demonstrated by the work in progress at the Jet Propulsion Laboratory (JPL) by the analysis tools: Beacon-based Exception Analysis for Multimissions (BEAM) and Spacecraft Health Inference Engine (SHINE). They are being used for the analysis of the X-33 Powerpacks (Engines) and LOX tanks.

BEAM not only provides diagnostic information on the anomalies that it detects but it also tells you what information needs to be monitored. This provides a reliable design with the minimum amount of sensors to prevent a catastrophic failure from occurring because of a lack of a measurement or a failed sensor.

Integrated Health Management (IHM) is not limited to a box that is put on the vehicle to perform system and subsystem level detection, diagnostics and maintenance, but is a PHILOSOPHY that is used when designing the vehicle and the vehicle processing functions. Traditionally all systems/subsystems have been designed with some level of VHM, but to meet the operational requirements of a RLV a thorough and methodical implementation of IHM must be followed. IHM will be used during all phases: initial testing, prelaunch, flight and turnaround. IHM will also be performed both in real-time (as the systems and subsystems are being operated) and for post flight analysis.

1.3 IHM System Objectives

The three objectives of IHM are to increase the safety, mission reliability and reduce the operational costs for the RLV system. Each objective has importance to the success of the program. One safety objective of IHM is to increase the safety of the people, payload, and the vehicle system. The reliability objective requires to make the specified launch window and successfully complete the mission. The last objective is to reduce operational costs, which is achieved by reducing the required labor force, by reducing required maintenance, and by minimizing the required ground turn-around time (Figure 2).

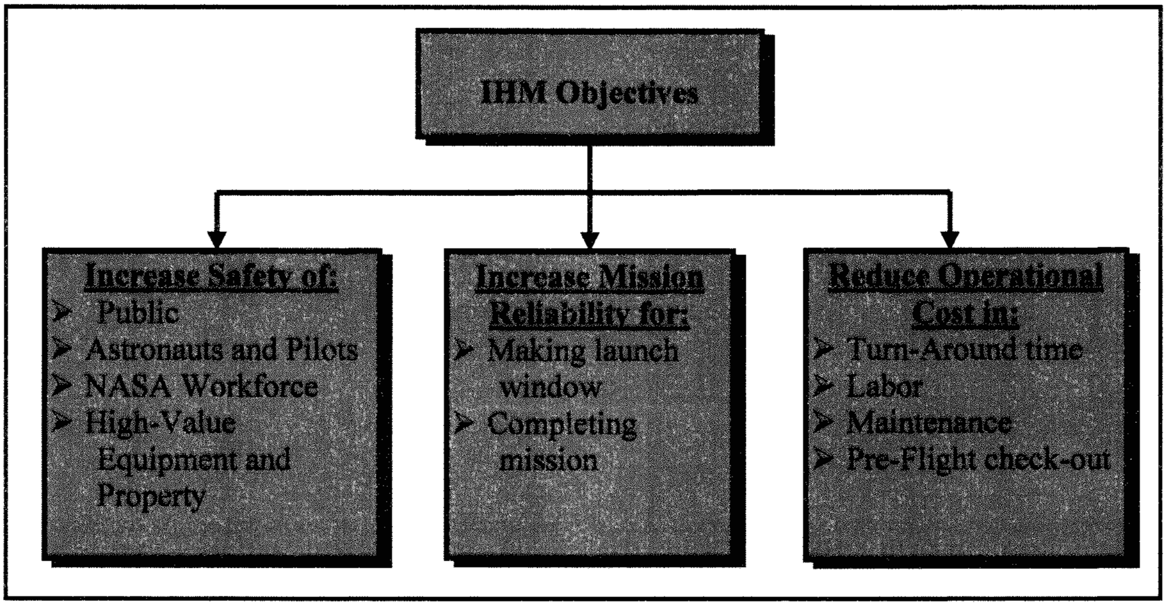

Figure 2: IHM Objectives

There is no priority assigned or assumed to these three objectives of the IHM system. All three are important and will greatly benefit the RLV program. They are all related; therefore, improvements in any area result in an overall benefit to the program. These objectives should not be separated due to their relationships with other objectives and the goals of the program. The significant reduction in operations cost alone will make the IHM an essential addition to the RLV program.

1.4 What Can Be Done

JPL is in the process of demonstrating its advanced vehicle health technologies (Technology Readiness Levels [TRL] 6 and 7) on the X-33, using test results from various components and end-to-end simulations. These technologies include BEAM, a highly advanced state estimator/predictor and SHINE, a state-of-the-art real-time expert reasoner. These systems provide significant advantages over existing systems in that they identify 90% (and more) of system failures and predict early maintenance before a failure develops with nearly zero false alarms.

These novel technologies have a proven track record in JPL missions and commercial applications, including the Voyager II, Galileo, Magellan, Cassini and EUVE (Exreme Ultraviolet Explorer) missions, NASA Deep Space Network communication facilities and advanced fighter aircraft efforts. In all cases, JPL has proven its ability to out perform all competing diagnostic techniques (and frequently the human operators as well), to react decisively and appropriately in the face of previously unknown fault modes and to provide a true prognostic capability. This makes the goal of near zero false alarms and 100% detection attainable. Applied to RLV, this technology will significantly reduce mission costs and launch turnaround times and greatly enhance mission safety.

These systems provide new insight into system visibility that were not previously possible using channel-based diagnostics techniques thereby making near zero false alarms attainable. Sensor data, results from software and commands are simultaneously fused in real-time to automatically abstract system physics and information invariants (constants). This makes it ultra-sensitive to system degradation and change so anomalies can be isolated in both time and space to specific sensors. These techniques are highly scalable and have been efficiently used on systems involving 10 to 10,000 sensors.

Our key focus area for IHM is the composite tank structure of the RLV. This is a high-risk item with poorly understood lifecycle and fault behavior. While BEAM is ideally suited for this component, it is important that we consider the implementation path. In order to win the support of the RLV program, the process starts with test demonstration through validation.

JPL proposes to continue our maturation efforts with this firmly in mind. Adding to our successful demonstrations on other programs, we shall continue our close work with the X-33 test program. This includes continuing results on the propulsion system and the Avionics Flight Experiment. We are currently examining LOX structures data in cooperation with Marshall Space Flight Center and we are in the loop for the composite tank tests soon to come. These results are very important, because with them we will directly address a key concern of the RLV.

JPL is also conducting a validation experiment using the Integration and Test Facility (ITF) simulation facility as input. During the flight tests of X-33, we intend to operate from the ground, giving test engineers critical information about the health of the spacecraft. Throughout these tests, our primary goal is to provide value to the X-33 program. This will show the usefulness of VHM technologies, which is essential to make RLV a successful program.

1.5 Technology Objective

Our objective is to provide a core fundamental technology for providing an automated capability for reducing or eliminating unnecessary maintenance through long-term wear detection augmented with failure forecasts with nearly zero false alarms. This capability optimizes the performance of the RLV in determining its ability to meet mission objectives thereby reducing reoccurring operational maintenance costs. This means that maintenance is only performed when it is needed as opposed to hours in use replacement philosophies.

Long-term wear detection provides a capability that optimizes and strengthens the present costly and inefficient maintenance practice making it applicable to a broad range of future space transportation needs that ultimately must be cost effective.

These tools provide a far-reaching capability for future reusable space transportation systems to maintain and service them in a cost-effective manner for the life of the program. This enables the tractability of the technology to future space transportation needs by providing a high potential for payoff to future systems by its direct application. This brings us one step further by providing a strong core technological capability to enable U.S. leadership in low cost reusable space transportation.

1.5.1 Integrated Vehicle Health Management (IVHM) Components

The IVHM is composed of two basic building blocks that are the Remote Health Nodes (RHN) and the VHM. Combined they become an Integrated Vehicle Health System. The architecture for the IVHM is shown in figure 3.

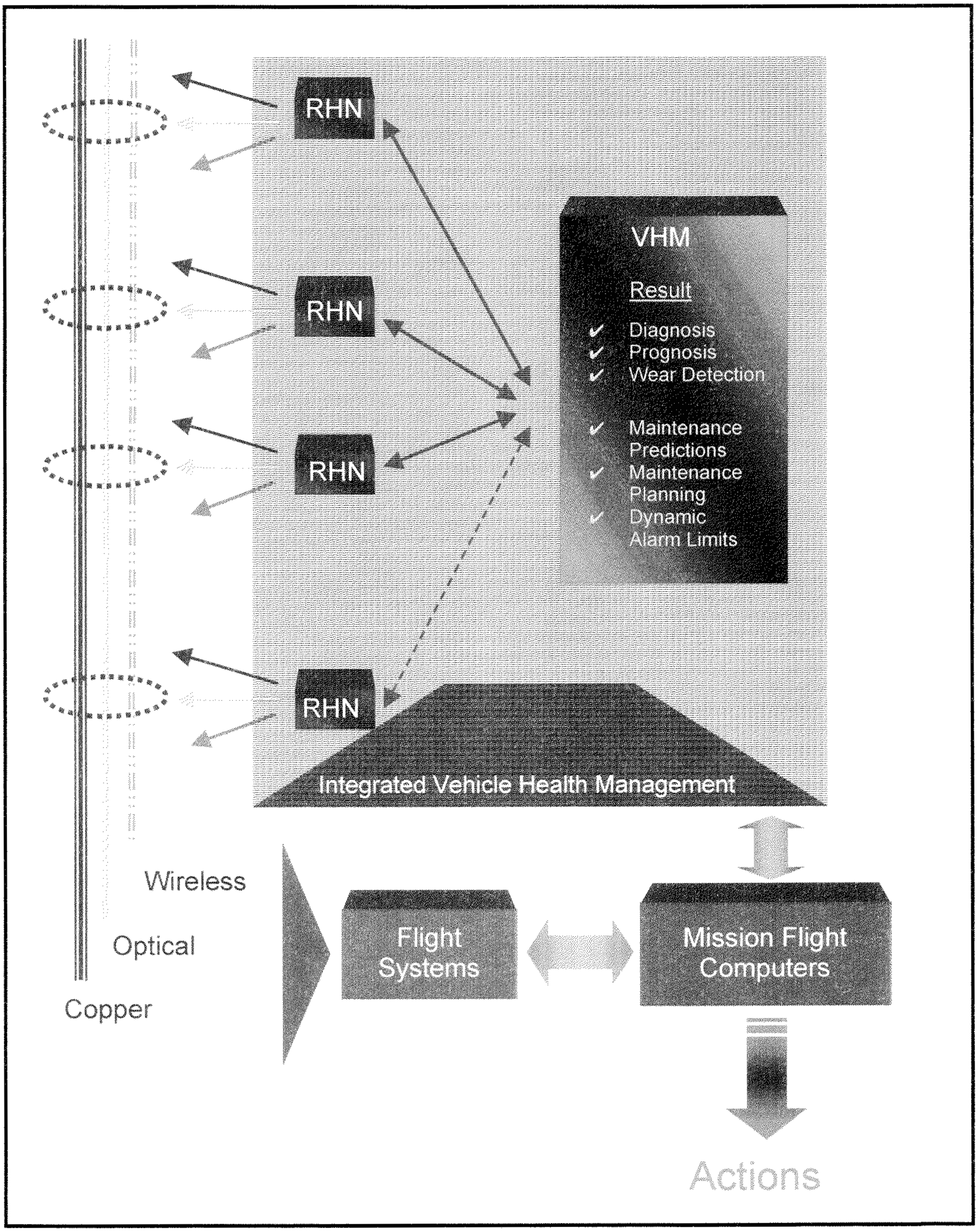

Figure 3: IVHM Architecture

RHNs are used to directly interface to sensors, flight systems and all flight buses. Any number of RHNs may be present depending upon the complexity of the vehicle. They convert raw sensor values from data into information and its corresponding interpretation. Their purpose is to distribute the computational requirements for processing of sensor values from the VHM to remote processing units. The RHNs can be located within close proximity to the sensors to significantly reduce cabling requirements.

BEAM and SHINE perform data analysis locally within each RHN. BEAM performs dynamic alarm limits and unmodeled event detection with SHINE performing diagnosis, prognosis and interpretation of BEAM results. These results are sent to the VHM for interpretation and integration.

All RHNs are copies of the same hardware running VxWorks with each RHN using the same hardware built from a common library set of interface cards. Because all RHNs are built from the same hardware, manufacturing and maintenance costs are significantly reduced.

The VHM Integrates and interprets results from all RHNs to robustly and compactly provide complete health and status information of the vehicle. The VHM contains an onboard computational core for smart summarization and source signaling providing for beacon-based health monitoring, diagnosis and prognosis with wear detection and prediction.

BEAM is used to analyze non-intuitive relationships between sensors and subsystems and detect unmodeled events. SHINE is used for rule-based inference and interpretation of BEAM results. The difference in analysis functions performed by the RHNs and the VHM is that the VHM performs its analysis functions across all RHNs while the RHNs only analyze data locally. This means that the VHM can detect non-intuitive relationships between all flight systems which a traditional system (or even person) would be unable to perform.

2.0 Advanced Sensors

2.1 Prior Practice

In the past, the sensors themselves were seen as the weak link in each subsystem. Overload readings were more likely to be the result of a bad sensor than a subsystem failure. Sensors were not 'smart' (did not convert data to information or perform analysis) and often left to fail as it was too expensive to replace them. They were a subsystem tool, not at all part of an integrated system.

2.2 Present Practice

The condition discussed as the past still exists in the present: the sensors themselves are the problem. They are simply not considered as reliable and maintenance-free as the rest of the subsystem they monitor. The information they transmit is suspect all too often.

In an attempt to address the problem of sensors, NASA requested that JPL conduct a Workshop focused on identifying the contributions that advanced sensors could make as part of an Integrated Health Management (IHM) system across aerospace transportation programs. That Workshop was held on November 17-19, 1998 in Pasadena. Over 115 people attended from NASA Centers, industry and academia.

2.3 Objectives

The overall conclusion of the workshop identified that the approach required for the advancement of sensor systems development for aerospace transportation is both better management and better technical awareness of the total program. This implementation includes comprehension of the total concept from the top down, and the specific implementation of useful sensors from the bottom up. This systems approach is cost-effective because it requires understanding of the total life-cycle costs, from the start of the design until operational completeness (Figure 4).

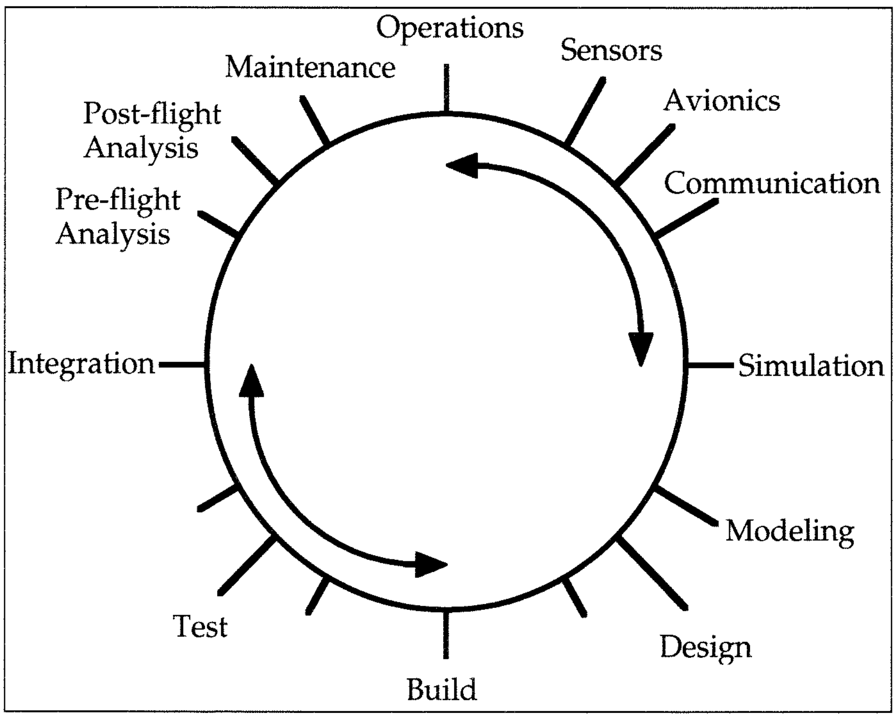

Figure 4. Relation of Sensors to an Integrated Vehicle Health Management System and Life-Cycle Costs.

IHM will be a necessity for future aerospace activities and it cannot be added afterwards; therefore, the timing is critical for the integration of vehicle health management to coincide with the system design process.

2.4 What Can Be Done

The following specific recommendations were proposed at the Workshop:

- Create a NASA-wide team to interface between those Program Managers and Centers performing IVHM activities, facilitating better communication and coordination and acting as an 'information broker'.

- Leverage existing Testbeds at Centers to prove IHM technologies and capabilities and so raise their Technology Readiness Level (TRL) from 'development' to 'flight ready,' where they may be integrated into flight project.

- Create Cost/Benefit tools and economic models to better demonstrate how IHM activities can contribute to reducing Life-Cycle Costs and integrate with the Intelligent Synthesis Environment (ISE) technology area's objectives.

What needs to be done regarding sensors is that they need to be fully integrated into an IVHM system. This integrated system will require advanced sensors and new ways and ideas of thinking about what sensors really are. Sensors will have to be considered as part of the subsystems they monitor. They must be self-contained to the point that they can diagnose and correct their own faults locally, yet pass relevant information to other subsystems and eventually, to the ground. This echoes the concept of the RHN mentioned previously.

Advanced sensors need to shorten the time and distance to go from signals to information. That includes on-board processing and analysis as close as possible to the sensors themselves. JPL is working on new types of sensors and sensor networks including 'wireless' and fully-contained systems-on-a-chip, including physical measurements, memory, power and communications.

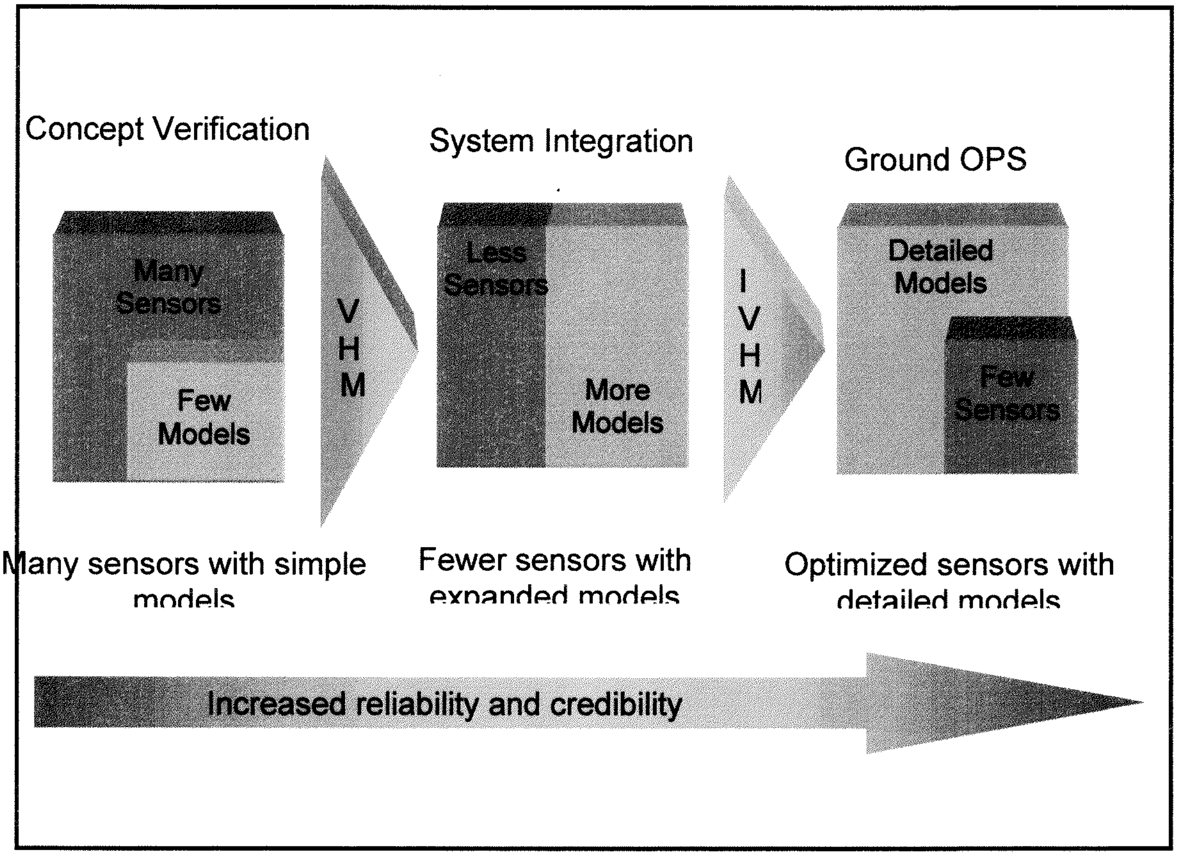

Figure 5: Improvements from VHM being introduced early

Figure 5 shows the relation of instrumentation (including sensors) and IVHM throughout the design, development and operations phases of a vehicle. In the concept verification phase, the model of the behavior has been developed, but the database to support the model does not yet exist. To provide verification, the subsystem is heavily instrumented with many sensors.

As data is converted to information and the database is expanded, reliability in the model improves. The IVHM software can convert data to information and show which sensors provide the most important information. This provides the mechanism to reduce instrumentation on the flight articles to reduce ground operations and maintenance. As the process proceeds through integration and ground operations, confidence in the model increases so instrumentation can be optimized.

Figure 6 shows the flow of information to and from sensors. The left-hand side shows signals converted into data, then information, and finally wisdom. It demonstrates the 'bottoms-up approach' mentioned previously. The right hand side demonstrates the 'top-down' approach. It shows the flow of requirements required for decisions. It is these two directions working in concert that is required to create an IHM architecture that can reduce costs of operation.

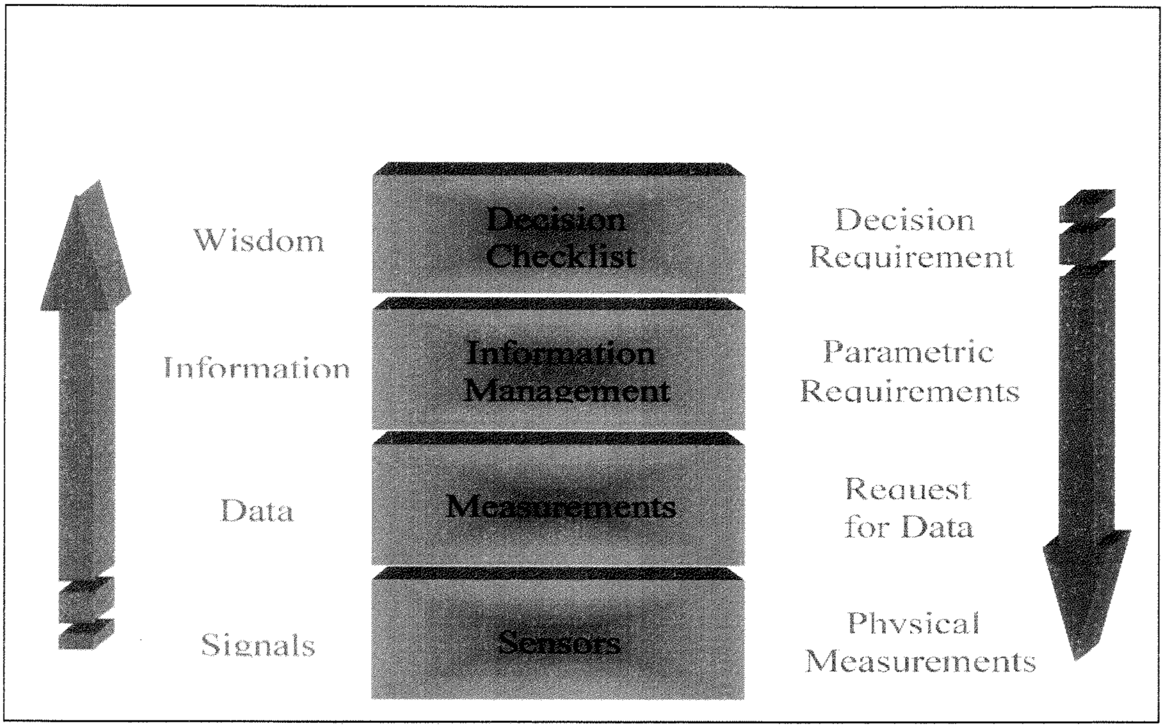

Figure 6: How sensors fit into the IVHM Architecture

Information and wisdom on test systems will lead to decision requirements for the actual (flight) systems. All of the work described cannot occur if sensors do not provide information that can be believed and trusted.

Advanced sensors and the analysis behind them (all part of an IVHM system) needs to be specifically tailored to suit the requirements of a future space transportation vehicle, much as a suit needs to be specifically tailored to its wearer. This includes 'wearable' computers, which has applications for tanks and surfaces, microminiaturization of components, with applications everywhere, but especially the concepts concerning how information is obtained, processed and dispersed. These concepts include new ideas regarding advanced sensors that rely on their being an integral part of the vehicle, not an add-on. Again, think of a human being attempting to process information without senses to obtain it.

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