

**Production and Operations Management Society (POMS)  
21st Annual Conference, Vancouver, Canada  
May 7 to May 10, 2010**

**Abstract number: 015-0113**

***Abstract title: Advanced Sensor Development to Monitor Aircraft Sub-Component Product  
Life-cycle***

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1. Introduction

When aircraft assemblies enter their life-cycle maintenance, service centers do not always have access to the most current as-built data to aid in the repair processes. This can result in additional inspections and engineering disposition time and potential complications in performing the repairs. One approach is for the parts to be tracked centrally where a database repository stores part history information. Another approach is to implement a distributed topology where the part-specific information such as flight hours and/or sensor technology that provides detailed information pertinent to the manufacturing process history on the part. Containers of spare parts and materials shipped from various vendors to their destination may endure extreme conditions during transportation impacting their integrity. This paper presents investigative research in utilizing sensor technologies to monitor shipment location and part health during transit. The approach includes temporary and enduring technologies for sensing as well as data recording capabilities. The same approach will be applied to the parts returned from the field for rework. There are three key areas under evaluation:

**1.1 Sensors for Shipping Container Adaptation**

Miniature wireless sensing capabilities added to containers are integral to the package itself. Sensing capabilities include acceleration, temperature, humidity, and orientation. The mode of shipment and shipping company capabilities is evaluated to enable location services during transportation. An important feature of the new sensor hardware is its wireless communication capabilities. The primary focus of this work is to integrate the hardware necessary for sensor data acquisition, analysis, and reporting. Subsequent analysis and predictions will be performed to demonstrate how reconstruction of shipping event history can be used to verify parts physical condition at their destination.

**1.2 Digital Part DNA**

The researchers are demonstrating “Digital Part DNA” using miniature wireless sensors to record data during fabrication, assembly, and life-cycle to maintain process traceability and accountability. Information types to be logged include total flight hours by tail number, service dates, useful life, and repair status. While part information is kept with the part/assembly at all times through its Digital Part DNA, this data can be synchronized with a central database for backup, offline processing, deployed inventory tracking, and data mining when necessary. Part DNA must have complete information about the component so that service events can be

analyzed quickly by having complete information about the component using its traceable details. Therefore, if Part DNA is standardized in XML type constructs, it will be beneficial for interfacing and programming standpoints. The architecture of the Part DNA should provide adequate security and access privileges to access the data. For example, some stakeholders will be able to access only the data as recorded at time of manufacture, while some other stakeholders will be able to access in-service data in addition to the baseline manufacturer supplied data.

### **1.3 Monitor Parts Returned for Rework**

The researchers are investigating the use of commercially available sensors in health monitoring (HM). This will interpret structural health with the intent to build a generic data analysis model to determine a part's condition and its potential replacement cycle. This part of the development includes sensor hardware design/miniaturization and strain gauge data analysis. Appropriate but concise repair and rework information will be kept in the associated sensors hardware.

## **2. Benefits**

### **2.1 Life-Cycle Performance Visibility**

NAVAIR benefits from increased visibility over the entire product life-cycle from fabrication facilities to depot centers and beyond. Shipments from vendors to the service centers will be protected to the highest standard. Through cooperation with the shipping companies and GPS based map services, container location can be determined and provide real-time visibility on the delivery status. This system can assist in prevention of lost, misplaced, or misrouted shipments.

### **2.1 Build Process Status Information**

The technologies created will also generate logs for factory and prognostic health management (PHM) methods. The factory logs will create process control visibility and feedback during the manufacturing process. Part location and inventory can be used to identify bottlenecks and to establish a lean process. This information can also be used by production schedulers, production control personnel, industrial engineers, and operations personnel during the manufacturing build process. Users can access data through a handheld wireless device to scan and retrieve specific part information. The benefits will be in the reduction of support labor to investigate and record part status before, during, and after delivery.

### **2.2 Inventory Management and Ordering Process**

Part history data will aid in scheduled maintenance and help reduce the stores inventory. The same solutions will be applied to aging aircraft and parts returned from the field to repair centers. On these parts, a networked system can be created to calculate service-life from the embedded sensor information and to support the back-end systems. The intent is to populate the sensor application throughout the product life cycle for complete visibility and inventory control.

### **2.3 Continuous Product Improvement**

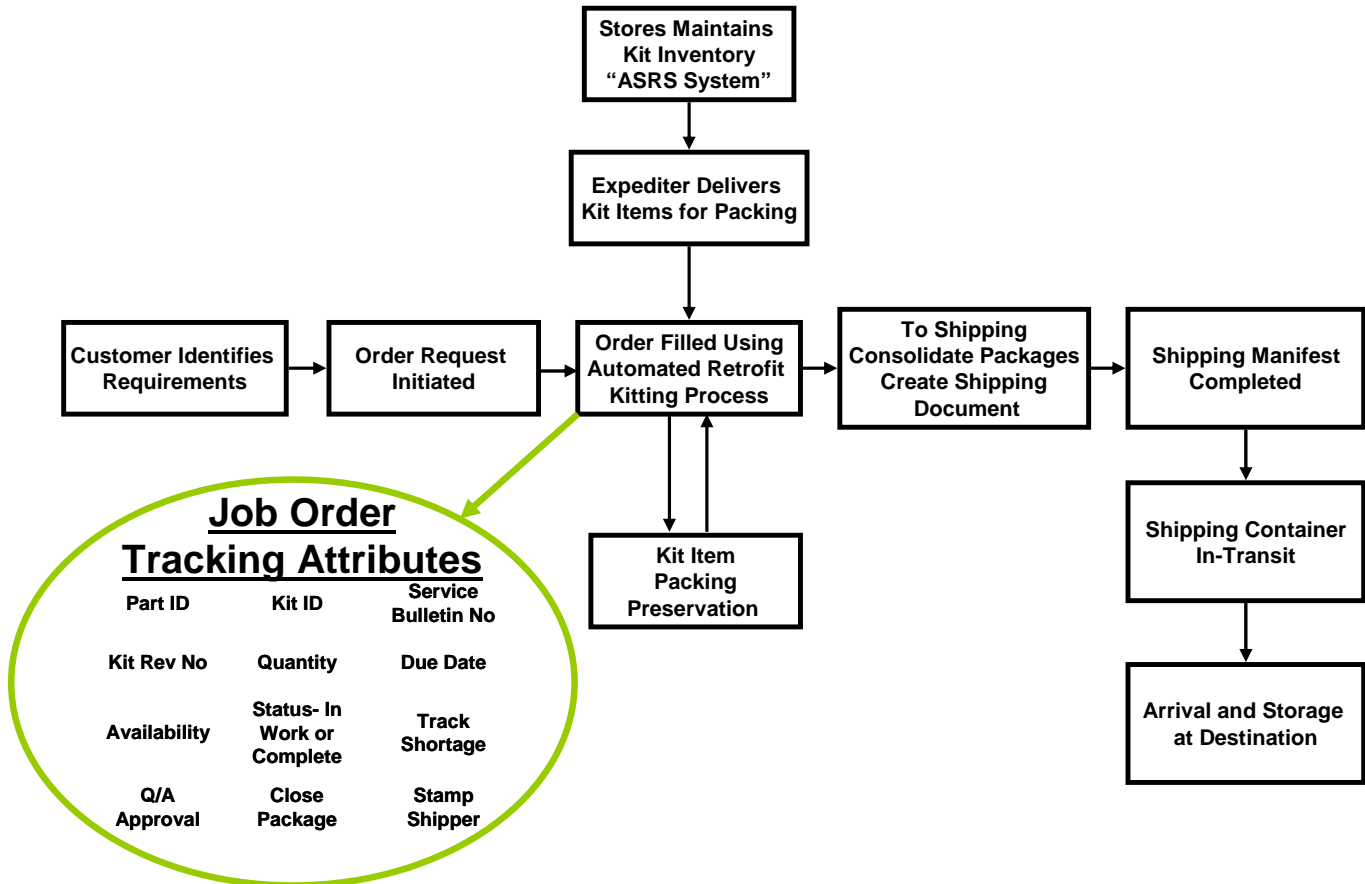
Capturing and integrating sensor feedback into the design community could help detect patterns in defects and reduce manufacturing problems.

## **3. Baseline research and objectives**

Aerospace firms provide spares, service bulletins, and kits to a wide range of customers on a daily basis. The process is tightly controlled from receiving and storage to packaging and preservation. The order system typically includes the contract number, item type, and part number, quantity available and packaging requirements. The tracking system goes through rigorous inspection steps to ensure no mistakes are made in completing a customer order with the exact quantities, and 100% quality inspections in an expeditious manner.

The following flow chart displays the standard process for completing a customer order:

## Kits, Service Bulletins, and Spares Packaging & Shipping Process



The majority of parts shipped are in cardboard containers that are bundled together and palletized. For additional protection, wooden crates are also built on-site and used for high value and large items. Spare parts such as control surfaces and empennage are placed in specially designed re-usable containers. Most aerospace firms do not commonly utilize sensors to monitor their container health during transit. However, packaging engineers conduct limited studies on some spare orders by randomly placing electronic hardware such as shock sensors inside some spares containers on new orders. This process is not sustained due to the cost and difficulty in performing this type of study. Based on interviews with the domain experts, when damage occurs in transit, it is very difficult to trace the root cause and the feedback is usually when repeated damages occur over time. Therefore, the researchers observe a real need for a solution that can be simple and affordable.



Photos represent typical service bulletins packaged and filled in the kitting area at Boeing



Typical containers strapped and positioned on pallets prior to shipment from Boeing – St. Louis

The wooden boxes are treated in the same manner as the tri-wall containers with slightly different strapping technique. These containers usually have provisions for fork lift truck handling and their lid is secured with reusable straps instead of nails.

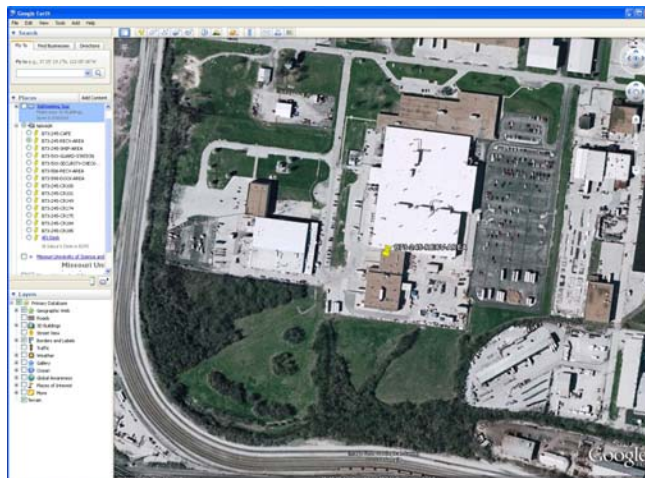


There are other modes for shipping materials such as molded plastic rotatable containers commonly used for wire bundles and avionics shown on the right hand side of the following picture:



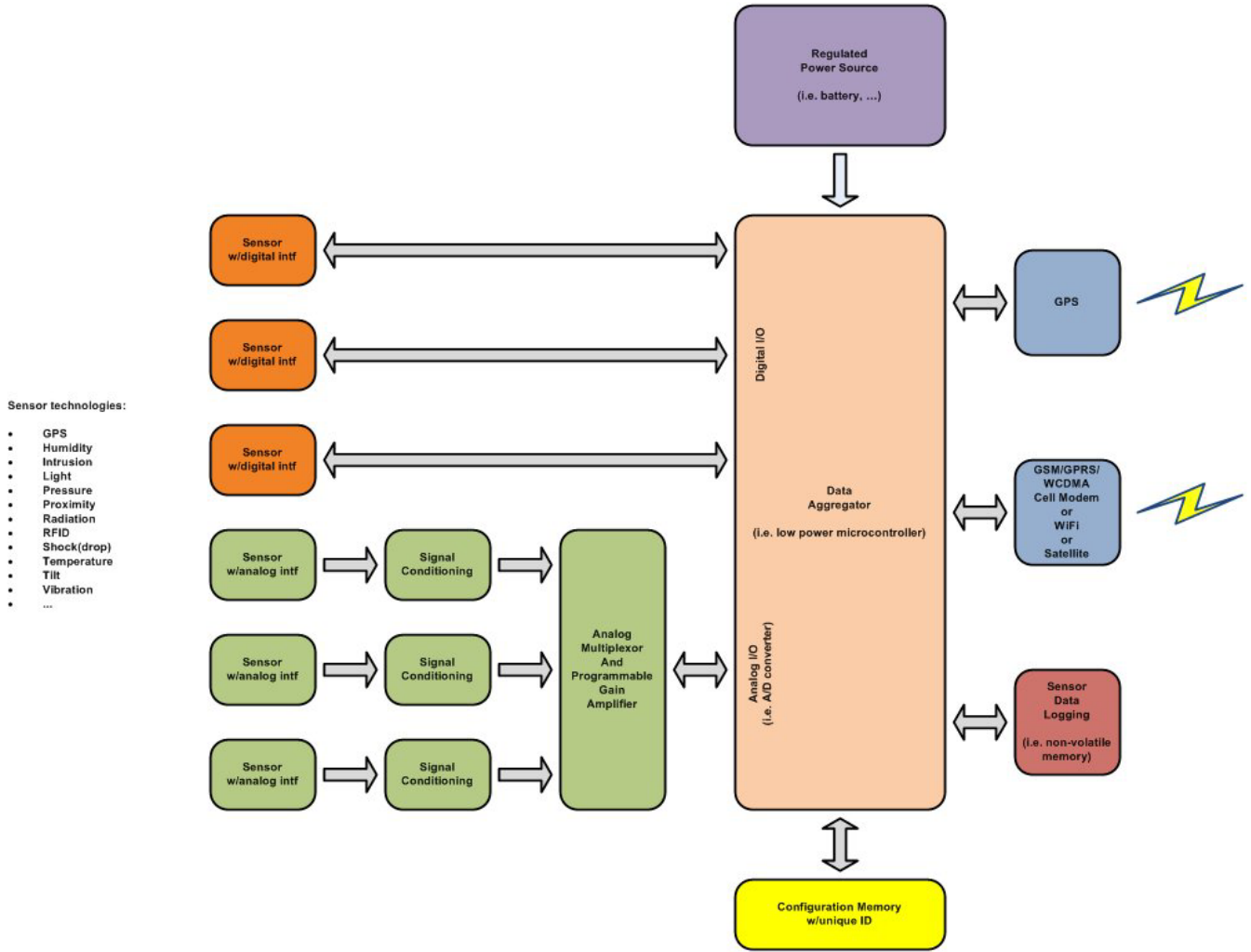
#### 4. Architecture & Design Diagrams

As part of the research and demonstration for the container tracking application, integration with 3<sup>rd</sup> part software such as Google Earth and other web based location services are being developed. Below is a screen shot image of the preliminary development effort. For internal tracking purposes several key “place-marks” have been located for container tracking and reporting.



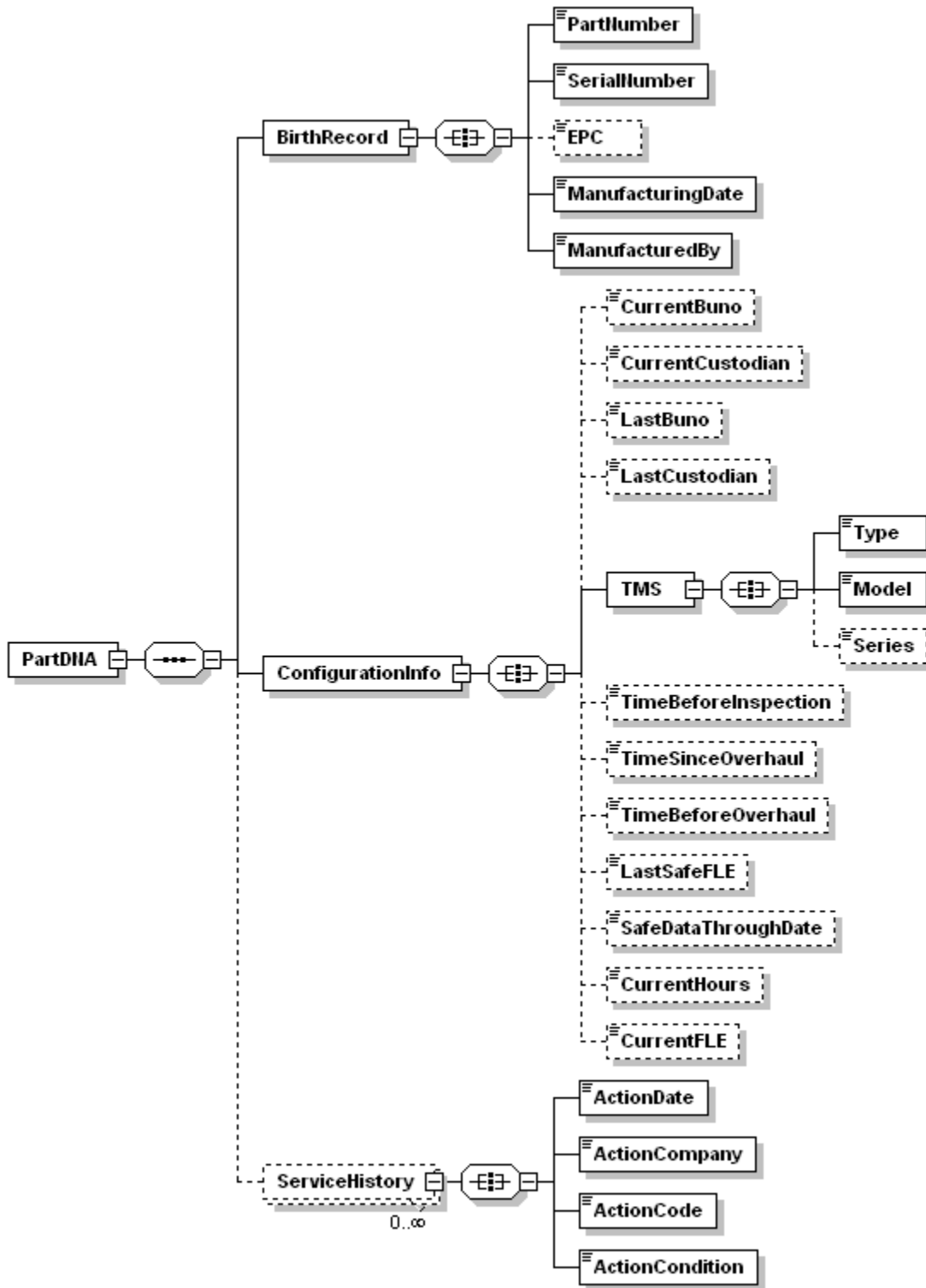
The following diagram illustrates the abstract hardware architecture for container health monitoring:

NAVAIR CONTAINER MONITORING



18-FEB-2010

The following diagram identifies data elements from the Digital Part DNA schema:

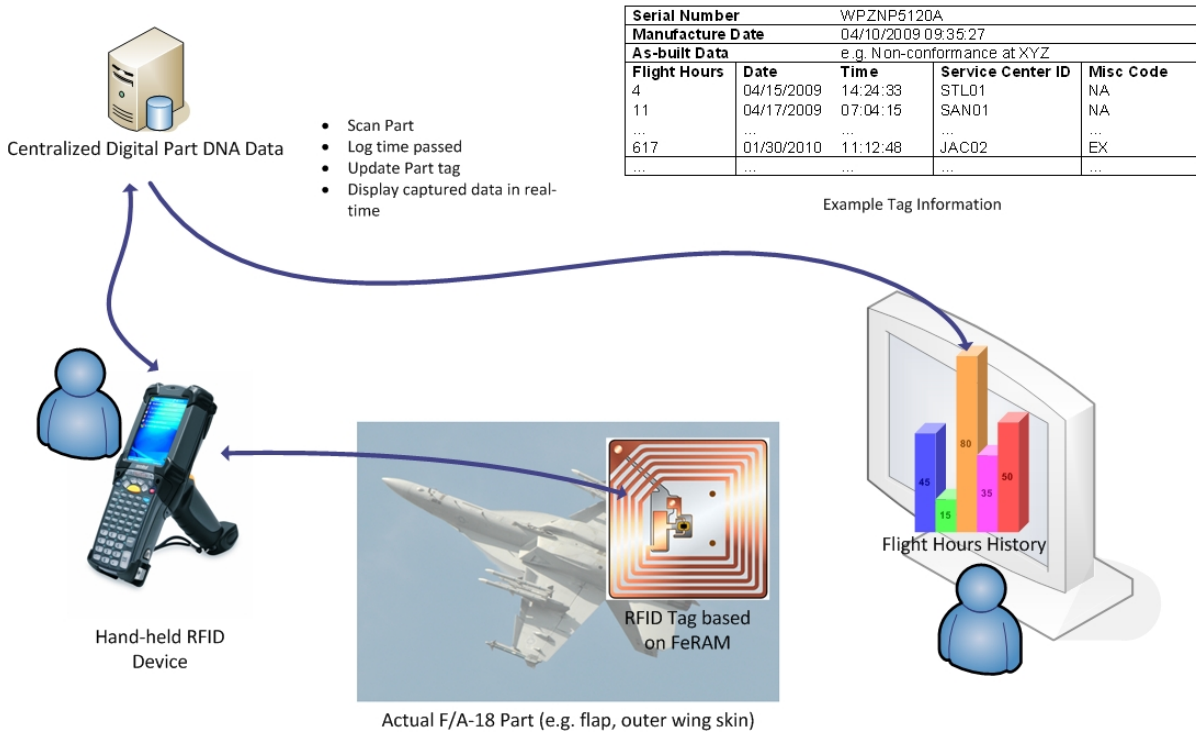


Generated by XMLSpy  
 Schema for data recording

www.altova.com

Part DNA XML describes information about a component. The XML is divided into three sections and is based on the following architecture design:

### Digital Part DNA



## 5. Health Monitoring and Management Using Advanced Sensors

Health management is defined in this paper as an umbrella term covering the range of benefits to be obtained by having access to a large range of data. Data availability starts from the manufacturing ‘birth’ of a part until it fails and is discarded (end of life-cycle). The benefits include:

**Forecasting:** The number of parts that will need replacement over various periods of time can be estimated allowing the correct number of spares to be ready at all times thereby increasing fleet readiness

**Condition Based Maintenance:** Certain parts can be maintained based on their condition rather than based on a fixed schedule. This means systems can be kept operational with less likelihood of failing in the field. Additionally, it means certain parts can be replaced only when needed and not based on a fixed schedule that could mean replacing perfectly good parts.

**Damage Detection:** Parts can become damaged from impact events that cannot be predicted from usage data such as flight hours. A damage detection system can provide alerts about damage and possibly characterize it without waiting for inspection. This increases safety as well as enabling timely repair before damage can grow.

Every health management system is highly dependent on data; it is by far the most important component of the system. Data, if it turns out to be too expensive and/or difficult to obtain can end up being the weak link in a chain. Taking data obtainability into consideration leads to designing a

modular system that can be made operational using readily available data while still providing value. Then, as more data sources become available, new nodes or modules can be added to the system further increasing its value.

## 6.1 Data levels

The availability of various data types range from easy-and-inexpensive-to-obtain to difficult-and-expensive-to-obtain. The complete range can be broken down into four levels of data obtainability.

### Level 1 Data:

Level 1 data is easily collected as part of the general concept for this program and is the least expensive to obtain. As a part is used over its life, various types of data can be collected and will be written to and from its RFID tag. Some of this data will be permanently stored on its RFID tag while some will be stored on a central database. This data is sufficient to perform basic health management.

'Birth' records: Manufacturing date, Unique ID number, model number  
End of Life (Failure Date or 'Death' record)  
Aircraft tail number (one part can move between aircraft)  
Maintenance/Inspection dates (and other relevant maintenance data)  
Discrete Flight hours for each mission and running total  
Date and Time for each data entry  
Service Center ID  
GPS Coordinates – Useful for aircraft on carriers

Some level 1 data could be generated from a look-up table located in the central database:

Aircraft type (C/D or E/F) – Looked up from aircraft tail number  
Base location (indicates environmental factors: hot/sandy, cold/wet, hot/wet) – Looked up from Service center ID or from GPS data

### Level 2 Data:

Level 2 data requires integration with other existing centralized sources of data. Data is currently collected from various sources. Rather than duplicate effort obtaining this data, it makes sense to integrate the system proposed here with already existing and future data sources. This type of data would require coordination with the database owners and creation of a common format or other technique to enable remote sharing of the various data sources. The following list provides examples of this type of data.

Data from the Flight Data Recorder  
Proximity maintenance – Provides a record of what surrounding maintenance may have damaged this part (Example: Horizontal tail damaged during maintenance)  
Reliability/Lifetime information/specs on individual part  
Shipping Environment history (max g, max temp, etc.). It is possible that rough treatment of a part during shipping, receiving, and inventorying may have shortened its life.

Level 2 data could be integrated with level 1 data to improve health management calculations.

Level 3 data:

Level 3 data is dependent on installing one or more sensors specifically to monitor a part. These sensors will require mounting, maintaining, recording, and powering on an aircraft. This is considered very hard to do on a fleet wide basis.

- Strain gages
- Accelerometers
- Thermocouples
- Corrosion sensors
- ...

In addition to improving the health management system, Level 3 data could enable simple damage detection. It would be fused with lower data levels to increase the accuracy even further.

Level 4 Data:

Level 4 data is received from transducer arrays and stand-alone health management (HM) systems. This type of HM system is capable of detecting and characterizing damage with a press of a button or even as it occurs. These systems are typically very expensive to develop and require the use of an entire array of transducers in order to function.

System to detect and characterize composite part impact data damage

Level 4 data can diagnose and characterize problems with a part. It would be fused with lower data levels to increase the accuracy even further.

### RFID Data Flow Architecture

Health management using level 1 data requires that data flow architecture be put in place as shown in Figure 5.3. In operation, a given part type would be tagged at its time of manufacture with a RFID tag having read/write capability. This would be done for that part type fleet-wide. This tag would stay with the part for its entire lifetime to track its usage and service history.

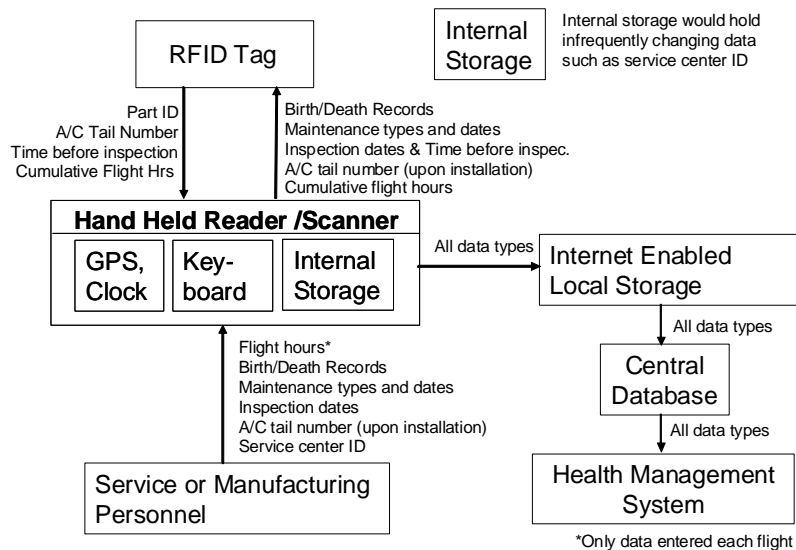


Figure 5.3 - RFID data flow architecture

## 6. Hardware Selection

When shipping routes include transit via truck, rail, or sea, cellular and satellite coverage may be intermittent, or simply the signals are blocked; therefore, an augmented solution using Assisted GPS (AGPS) appear to be a reasonable approach. AGPS utilizes cell tower location and satellite constellation information to get a quick fix on location. The AGPS methods would provide a method to get a rough fix on the asset to enable position reports through only cellular reception. Conventional GPS receivers that do not use AGPS have vulnerability that when sight of the sky is blocked by shipping containers or materials, buildings, or multipath interference that reception is limited or non-existent.

Integrated hardware solutions from several vendors have been studied, and a subset has been selected for a proof-of-concept demonstration. Data communication is facilitated by a GSM modem that is integrated with selected sensors.

The GSM-based sensor system uses a microcontroller as the data aggregator to manage collection and routing of data. Additionally, the microcontroller will also provide a data processing and buffering service and relay information through the cellular modem. Frequent updates to the database of container sensor status provide significant visibility into the product delivery and warehousing cycle.

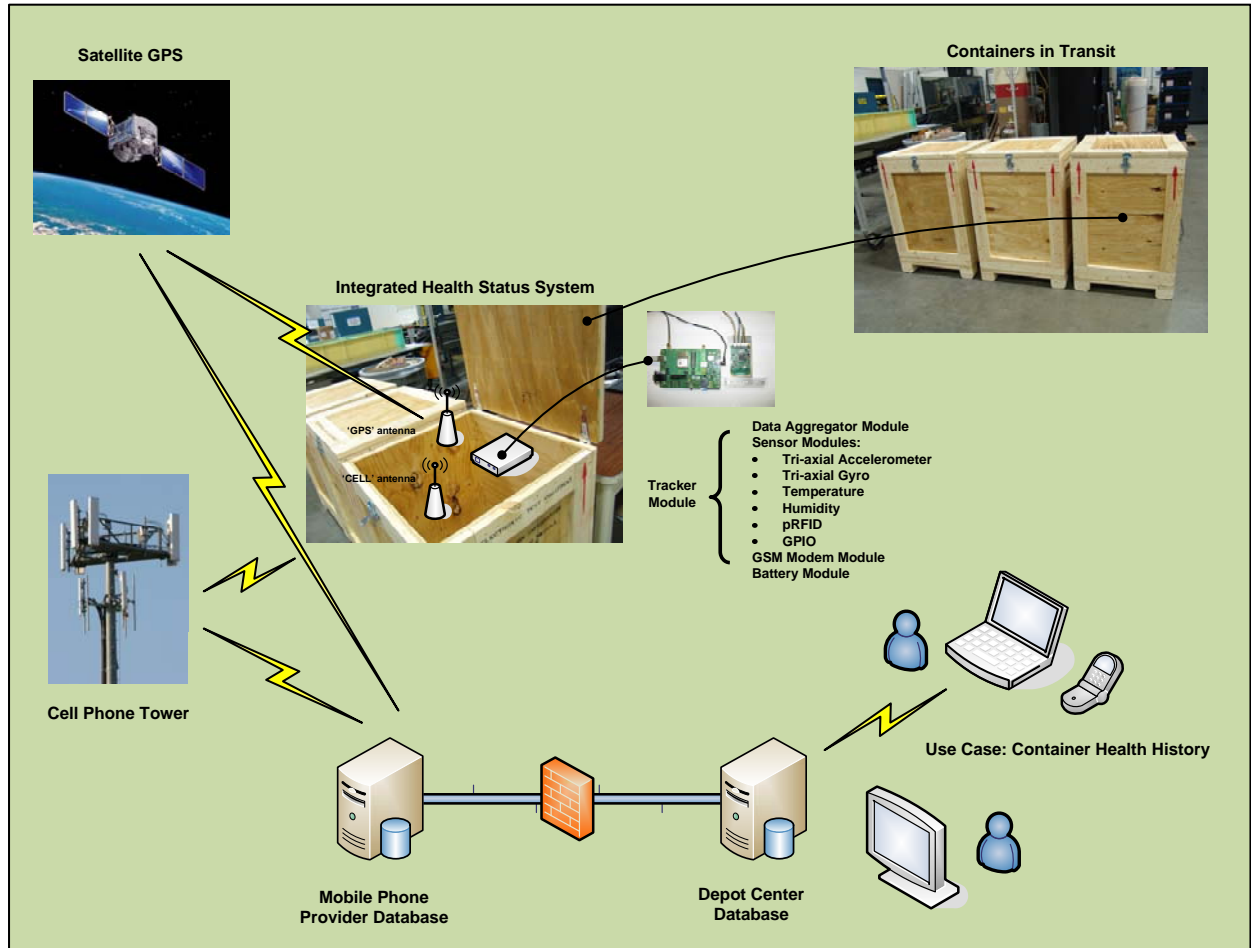
Communication from the container is achieved with a low-power GSM modem. Additional capabilities are created when considering communication to the container. Remote diagnostics are possible with the ability to administrate or probe the container through the GSM phone. Testing has yielded successful use of the modem and currently the shock and orientation sensors are operational.

With respect to small containers that hold replacement parts, retrofit kits, and spares, the researchers have designed identical small containers that are representative of the kitting processes. Land-based tracking will demonstrate the feasibility of container location at as many points possible in the kit life-cycle.

The following photo depicts a microcontroller development board (bottom-left) integrated with shock, orientation, and commercially available temperature sensor (bottom right). The cellular modem (top) provides GPS positioning to report location, speed, and heading with the other listed sensors.



The following diagram illustrate the integrated prototype solution for sensing, collecting, and reporting container data using Inertia-link Sensor, Data Aggregator, GSM Modem with Assisted-GPS capability. The integrated electronics solution needs a low-power analog front-end to process the raw sensor data.



## 6.1 Power supply and consumption

Powering the advanced sensor suite for aircraft sub-component life-cycle monitoring must balance size and weight with the power required by the integrated electronics package. Battery life plays a major role in design when one considers that a container of parts may sit un-opened in a warehouse for months before it is pulled for consumption.

Power control will enable long-term reliability of the container sensing hardware and include but is not limited to extreme low-power modes with drastically reduced CPU clock rates and sleep modes where specialized circuitry can awaken the sensor processing hardware on unique events. Power-harvesting techniques will be researched and integrated in subsequent phases.

## 6.2 Size

Advanced sensor development should account for limited space in shipping containers. Weight should also be insignificant to the container payload to minimize shipping and handling costs.

Packaging of the sensor suite needs to be robust enough to survive many cycles of product and container monitoring.

### 6.3 Depot and Service Center Networking

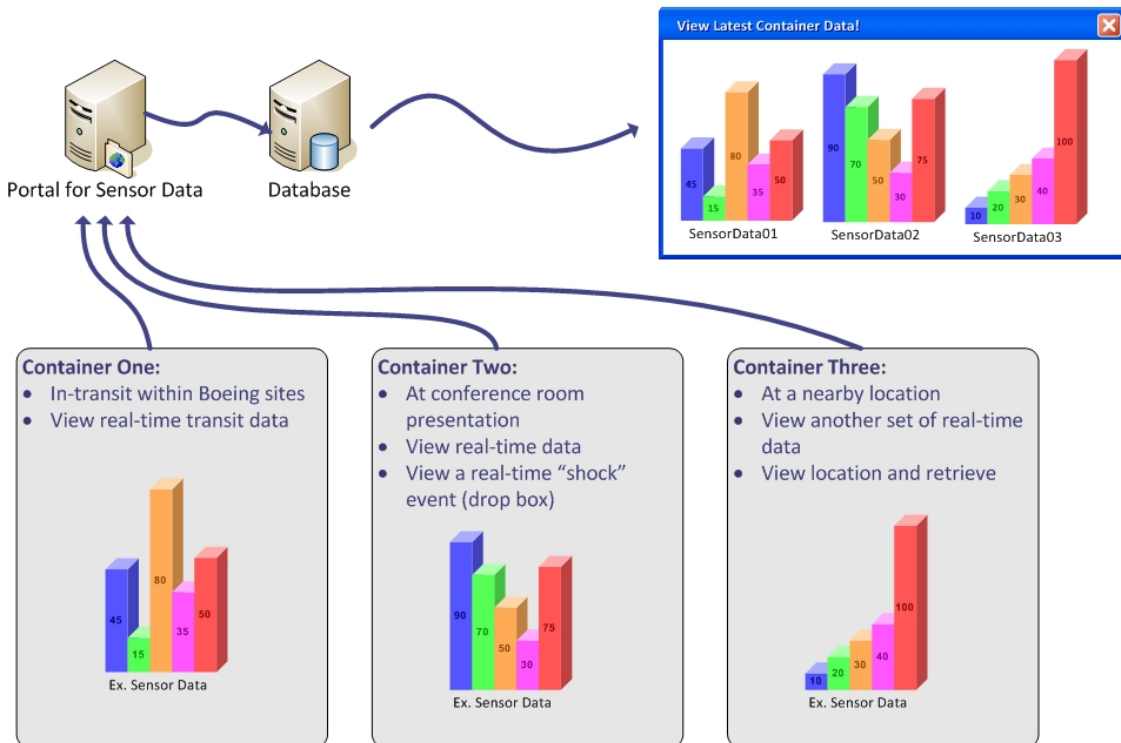
Depots and service centers will be required to handle communication from the monitored containers and products. Service centers may provide communication uplinks in parallel to GSM and satellite capabilities to offset the power requirements of stored containers and parts. For example, a network gateway within the warehouse is organized to report container status to a nearby gateway rather than communicating with a GSM phone tower that is miles away. This gateway at the service center will route container status data, alerts, and messages to the same back-end inventory system that contains data on all tracked and monitored containers and parts. Then common platform web applications can be used to browse and search for specific part information or, for example, send email alerts when database triggers detect urgent, critical data.

Boeing and other service center suppliers will network their back-end systems to provide full visibility of inventory level and delivery status. This networked approach will be studied in a future phase.

## 7. Testing and Demonstration

Wireless sensing nodes with embedded RFID capability will be placed on test boxes scheduled for shipment within a shipping container from an aerospace facility. During shipment, environmental parameters (EPs), such as: door open/closed, temperature, humidity, shock, vibration, and inclination will be monitored with wireless sensing nodes. Each wireless sensing node will include a precision timekeeper and will periodically log environmental parameter data to its on-board memory. Each wireless sensing node will also be pre-programmed to send periodic updates to a wireless base station, this base station to be placed at the ceiling of the shipping container.

### Sensors for Shipping Container Adaptation



## **8. Conclusion**

The researchers will be demonstrating live and recorded conditions and will continue their development into full scale in the next 3 years. The ultimate goal of this research is to prove the concept and encourage the container industry, shipping companies; GPS map services, sensor industry, and other related industries to recognize the value and interest by the aerospace firms and DOD service centers and initiate solution kits from the developed model for tracking containers in transit. Part DNA has many uses and it can be best promoted as a new standard through a collaborative effort by the aerospace airframe manufacturers.