# Project: Prognostics System on a Military Wheeled Vehicle

**ENSE 622**
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# Introduction

## Problem Statement

This case study looks at the availability problem of fielded military wheeled vehicle systems.  Availability is the percentage of units capable of performing a mission out of the total number of units at a given time.  The basic problem is that military vehicles have components which fail due to fatigue damage from the severe usage in military applications.  If a component fails while the vehicle is in the field one or more things can occur: the vehicle is lost, mission will be unsuccessful, fatalities, or any combination of these.

The system chosen to attack the availability problem of fielded military vehicles is a prognostics system on board the vehicle that monitors the life remaining of chosen components.  The components are chosen based on whether or not they are a critical reliability concern and the ability to accurately predict fatigue damage of that component. The number of components to monitor is limited by the number of signals the prognostics system can handle, the number of components that failures can be accurately predicted for, and the feasibility of monitoring a component with a long life expectancy.

## System Overview

The current prognostics system monitors the life remaining of components and the vehicle's usage (i.e., driving the vehicle too hard).  The system calculates the life remaining based on sensor inputs from various sources and the engine data bus.  The system contains GPS as well as multiple input channels and an interface for downloading the engine data bus information.  The output data available from the GPS, engine data bus, suspension sensor system, and vehicle mounted sensors are: location, vehicle speed, pitch and roll, potential suspension problems, suspension response characteristics, engine and transmission data, sensor data (acceleration).  The system has the ability to obtain more information, but the aforementioned data is the only data needed at present time. Because mounting sensors on the exterior of the vehicle is not feasible for military applications; the only sensors available are accelerometers mounted at various locations inside the vehicle.  These sensors do not include the suspension sensor system input, which is not part of the prognostics system design.  The prognostics hardware currently under test is shown in Figure 1.  The device is approximately 7" x 5" x 4" in length, width, and height, although the device has the ability to add layers for additional inputs. Figure 2 shows an example of a wheeled vehicle that the system could be mounted to.


**Figure 1.** Prognostics Hardware

**Figure 2.** Military Wheeled Vehicle

## System Description

The prognostics system has numerous inputs from many areas to prognosticate the life remaining of critical components. Typically the components take one of the following forms: structural, drivetrain, or suspension. The system has sensor inputs (accelerometers) located at various locations in the vehicle as well as suspension sensor system input. The system also receives the engine data bus to correlate usage. This information encompasses the data that is used to calculate the damage. The physical makeup of the system is the sensors, message indicators, and the enclosure that contains the hardware for processing and data storage. The first step is filtering the sensor data and then digitizing the filtered output (acceleration and suspension input). The digitized data is then processed through a series of data quality checking algorithms. Once all the data is verified, the suspension, vehicle, and engine data is fused together. Then the usage profile is estimated. After the usage profile is estimated, damage algorithms calculate the amount of damage that has accumulated on the components. Next, the prognostics algorithms calculate the remaining life of the components based on their damage accumulation and usage profile. The prognostics algorithm uses driver or maintainer input (user input) to define the expected amount of usage over the next mission or time period. If the driver or maintainer did not input the mission profile, the profile is estimated based on past usage. This could be in the form of mileage or terrain type. Once the prognostics are performed, driver alerts are shown if a component is close to failure. The maintainer alerts are given when a component reaches a specified percentage of its life remaining. The maintainers are able to download the results of the damage and prognostics algorithms to examine in more detail. A basic overview of the system is given in Figure 3.

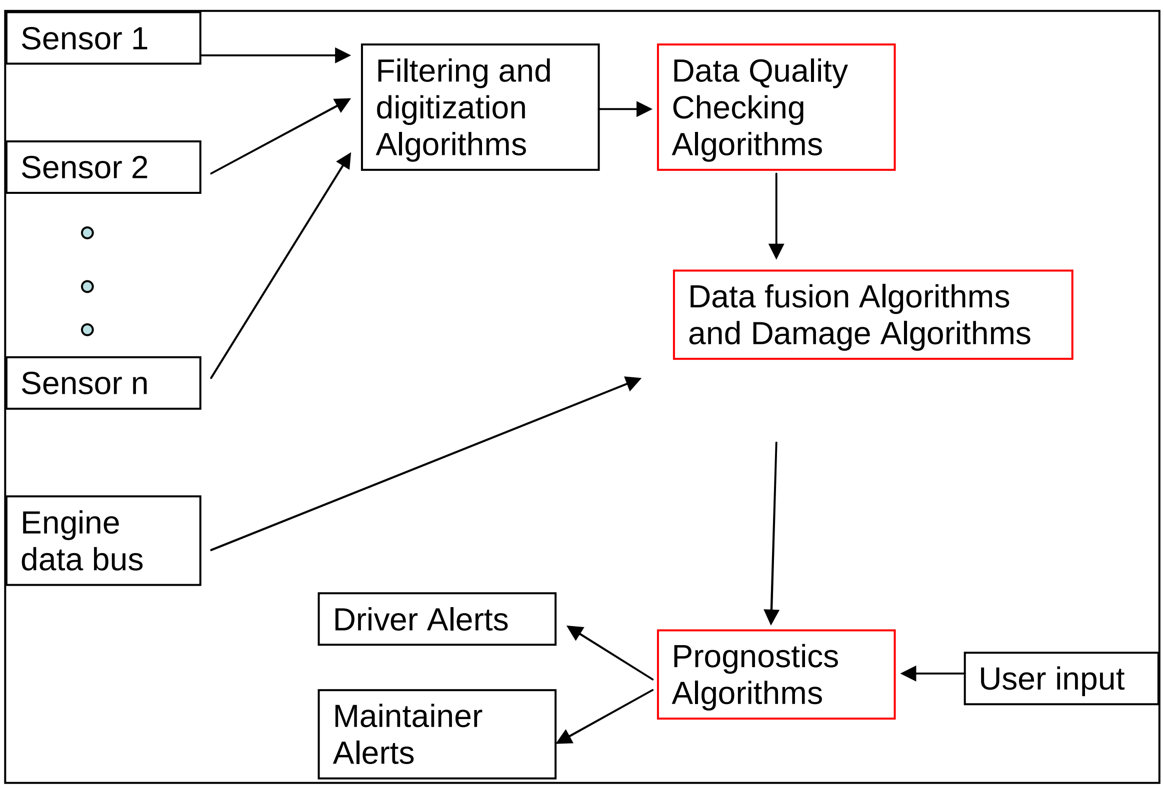


**Figure 3** Basic System Overview

## Anticipated Benefits

1. The system will increase availability of military wheeled vehicle systems.
2. The system will increase the logistics efficiency and accuracy for part replacement/maintenance.
3. The system will increase the probability that a vehicle will be able to complete its mission.
4. Cost savings will be realized in the areas of availability, maintenance, recovery, and non-recoverable vehicles.

## Scope and Objectives

The purpose of this analysis is to design a system that can increase the availability of military wheeled vehicles by replacing components before they fail. This analysis will use high-level systems engineering concepts and UML modeling to improve the system development and describe the functionality of this system. The case study given here describes the prognostics system, which is currently in the development phase. The following issues will be examined in this study:

1. What does the system do?
2. What are the system requirements?
3. How does this system work?
4. Can this system work effectively?
5. How do the subsystems interact?
6. How does the system behave?
7. What are the goals of the system?
8. How are responsibilities in system development assigned?
9. What is needed to verify the system?

## Long-term System Goals

Because I am involved with this system, the long-term goals and objectives will be discussed. The overall goal is to add prognostics systems on fielded wheeled vehicles and to incorporate more component monitoring such as electronics. This system could be applied to the following platforms: trucks, armored wheeled vehicles, wheeled tactical vehicles, and tracked vehicles. Having these systems installed on the vehicles will create a cost savings due to its increased availability, decreased loss of vehicles, decreased recovery costs, less stockpiles of parts, and decreased fatalities. The military may not have to perform recovery of vehicles and vehicles may not be lost. The system would allow for maintenance to be performed at the repair facility because damaged items can be sent to a repair facility instead of attempting repair in the field. Components can also be repaired at the repair facility's convenience, because it is known when the vehicle will fail and parts or vehicles can be replaced or ordered ahead of time. All of these factors will lead to an increase in logistics efficiency for part replacement and maintenance.

Note: The U.S. Army Materiel Systems Analysis Activity (AMSAA) is in the process of applying for a patent for this system. AMSAA is the organization in the Army that I am employed by.

## Possible Areas of Concern

As the system progresses through its design, test, and validation phases; concerns about the system are addressed. Some of the concerns at this point in the process are listed below.

- Cost of equipment
- Cost of installation
- Selecting incorrect components to monitor
- Creating too many false alarms, which could cause the maintainer to ignore the system
- Developing algorithms that are not correct due to some unforeseen loading cases
- Predicting dominant failure mechanism to monitor
- Whether the Return On Investment is high enough for the Program Manager to implement it
- Estimating loading from the sensor location (sensors are not mounted on the components)
- Is this the most effective way to monitor component life
- Ensuring quality data reaches the prognostics system
- Applying the proper statistical distribution to the component life

## Project Framework and Focus

The system has many teams working on the project as it moves along in the development phase. The main group involved in the design is the reliability engineering team. They perform the testing and oversee the contractors who help develop the system. Once the design team believes it is ready to move forward, more groups are brought in and gain responsibility. Their overall intended program responsibilities for system development at a high level of abstraction are listed below.

- **Program Manager (PM):** Integration of system, and working with prime contractors to put system on vehicles
- **Research and Development Command:** Design and test of system/units
- **Reliability Engineers:** Implementation and software development
- **Contractor 1:** Hardware and software development
- **Contractor 2:** Algorithm development (software)
- **Prime contractor:** Production of units

The high level abstraction of responsibility for the system, once it is fielded, is given in this list.

- **Maintainers:** Operation of system, maintenance of system
- **PM**: Buying units, spare parts
- **Reliability Engineers:** Fix major design flaws, add new algorithms, adjust current algorithms, find new components to monitor
- **Research and Development Command:** Add on solution for other platforms
- **Prime Contractor:** Production and maintaining a specified level of performance

## Goals, Scenarios and Use Cases

### Goals and Scenarios

**Goal 1.** System captures quality data for processing

1. Scenario 1.1. Sensors and system checked before mission begins.
2. Scenario 1.2. Sensors are sending quality data.
3. Scenario 1.3. Hardware receives sensor data.
4. Scenario 1.4. Software begins to process data.

**Goal 2.** Filtering and digitization perform their functions as intended

1. Scenario 2.1. Filtering process receives sensor data and suspension data.
2. Scenario 2.2. Filters do not eliminate pertinent data.
3. Scenario 2.3. Digitization does not eliminate pertinent data.

**Goal 3.** Only quality data is used to calculate the life

1. Scenario 3.1. The system performs a series of data quality checking algorithms.
2. Scenario 3.2. The system passes on quality data from the checking algorithms.
3. Scenario 3.3. The system replaces or ignores bad data from the quality checks.
4. Scenario 3.4. The system flags bad data that is found.

**Goal 4.** Damage accumulation calculations are accurate

1. Scenario 4.1. The system received good engine data.
2. Scenario 4.2. The system fused the engine, suspension, and vehicle sensor data correctly.
3. Scenario 4.3. The system estimated the usage profile accurately.
4. Scenario 4.4. The system did not over-predict or under-predict damage accumulation.

**Goal 5.** All alerts are sent in time to complete mission

1. Scenario 5.1. The mission profile is entered by the driver or maintainer.
2. Scenario 5.2. The expected mission profile is indicative of what the vehicle will experience.
3. Scenario 5.3. When a profile is not given, the estimated profile is accurate.
4. Scenario 5.4. The driver and maintainer receive the alerts.
5. Scenario 5.5. The driver and maintainer know what action is needed from an alert.

**Goal 6.** System alerts must be accurate

1. Scenario 6.1. Sensors are in tact and calibrated.
2. Scenario 6.2. Only quality sensor data is used.
3. Scenario 6.3. The data fusion algorithms do not eliminate important data.
4. Scenario 6.4. Damage is accurately predicted.
5. Scenario 6.5. The fatigue limit is known for selected components.
6. Scenario 6.6. The system accurately predicted life remaining for components.
7. Scenario 6.7. Mission profile is accurate.

## Identify Actors

An actor is anything that interfaces with the system externally and participates in use case modeling.  The actors in the prognostics system would be:

1. **Driver.** This actor enters the mission profile, receives alerts of impending failure and also determines the severity of the loading based on how they drive the vehicle.
2. **Maintainer.** This actor enters the mission profile and receives alerts of life remaining.  Maintainers also decide when to repair the vehicle and order parts. Maintainers may download the life of all the components.
3. **Vehicle Response.** This actor is the recorded sensor measurements (acceleration) at various locations in the vehicle.  This data is used to calculate the life remaining of components.
4. **Engine data bus.** This actor contains engine data, as well as other data used to calculate life remaining.
5. **Suspension Sensor System.**  This actor contains the suspension’s response to terrain.  The data collected by the system is used to calculate the life remaining of components.

**System Boundary**

The system boundary is defined by anything external to the prognostics system. Sensors, algorithms performed (processing and data storage hardware), and the alert messaging system (driver/maintainer indicators) comprise the system.  Their inputs or outputs mark the system boundary, such as: vehicle sensor measurements, mission profiles, engine data bus, suspension sensor system, message indicators, and downloadable prognostics results. The system does allow for sensor calibration and mission profile entry for internal control and adjustment.

## Initial Use Case Diagram

A use case describes a single goal and all the things that can happen as the user attempts to reach that goal. Although use cases are neither requirements nor functional specification, they imply requirements, objects and object interactions in the stories they tell. Use cases define the behavior of the system without revealing the system's internal structure. A use case focuses on only the features visible at the external interfaces. The use case diagram has four actors and four use cases. The use case diagram is given in Figure 4.

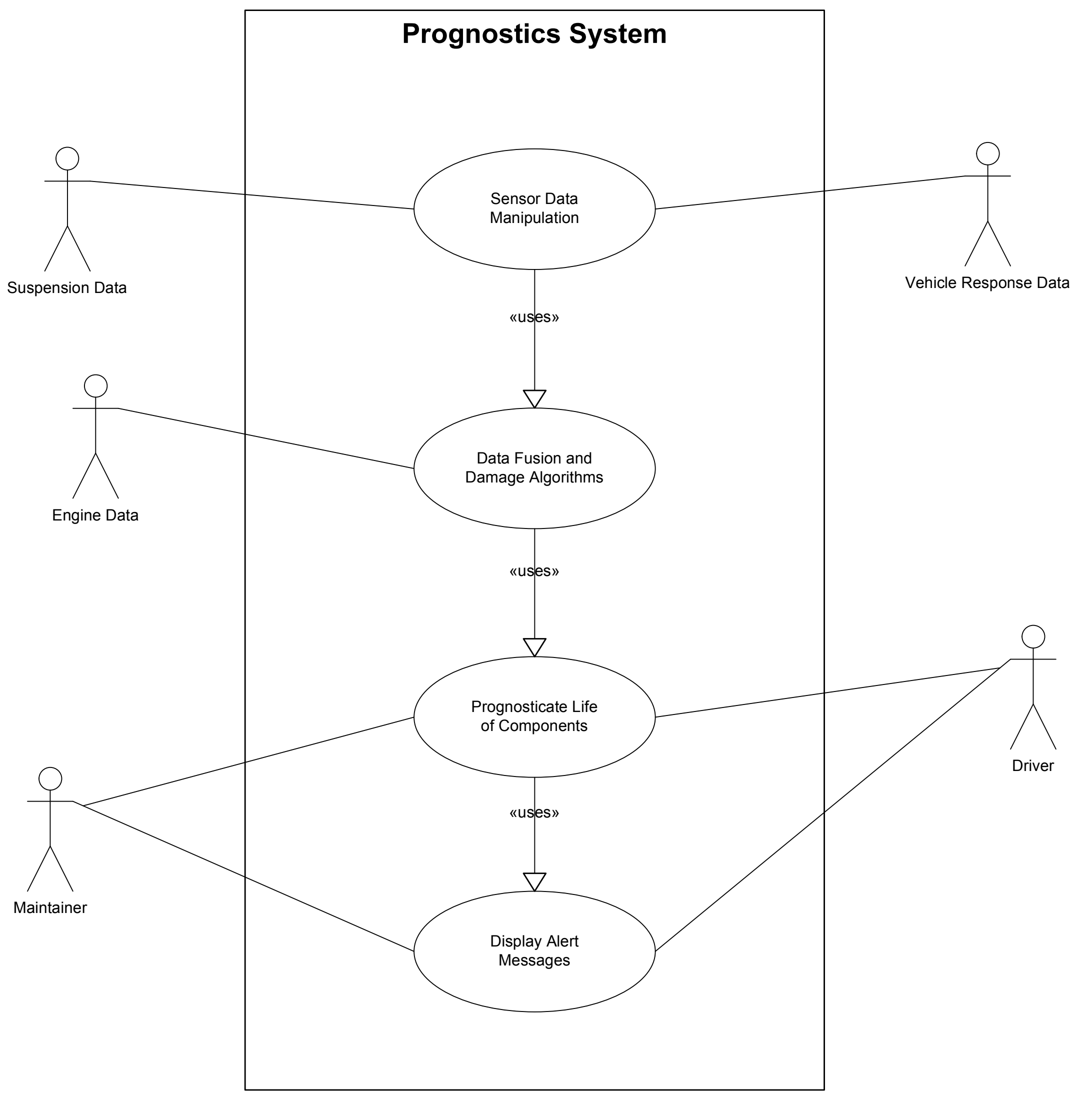


**Figure 4.** Use Case Diagram for Prognostics System

The figure depicts the suspension sensor data and the measured response of the vehicle interfacing with the system. This data sent to the prognostics system is used in the sensor data manipulation algorithms.  The data received is suspension sensor data and vehicle sensors.  The processes performed in sensor data manipulation include digitization, filtering, and data quality checking algorithms.  The data fusion and damage algorithms use the output of the sensor data manipulation and incorporate engine data to calculate damage.  The life remaining (prognostics) is calculated from the damage algorithms and the mission profile entered by the maintainer. The maintainer may also download the life of the components at this point.  The alert messages use the prognosticated life remaining to decide when to display messages to the driver and maintainer.  The use cases shown in Figure 4 are sequential tasks.  The output of the previous use case is needed before completion of the current use case.

## Use Cases with Activity Diagrams

Activity diagrams provide visual documentation of sequences of tasks. They especially are useful for activities governed by conditional logic, and the flow of events running concurrently.

**Use Case 1.** Sensor data manipulation (filtering, digitization, data quality checking)

**Primary Actor:** Vehicle Response & Suspension Sensor Data
**Description:** The measured vehicle response (interior vehicle sensors) and suspension sensor system data are filtered, digitized, and verified for data quality.

**Pre-conditions:** The sensors are calibrated, and the vehicle is ready for missions.
**Flow of Events:**

1. Vehicle is driven across terrain.
2. Sensors measure vehicle response created by vehicle usage.
3. Suspension sensor system sends data to prognostics system.
4. All data are filtered.
5. Filtered data is digitized.
6. Digitized data is sent through data quality algorithms.
7. Quality data is sent on.

**Alternative Flow of Events:**

7. Data did not pass quality checking algorithms.
8. Inaccurate data ignored or replaced with representative data.
9. "Flag" data that did not pass quality algorithm.
10. "Flag" and data are sent on.

**Post-condition:** Data are sent to data fusion algorithms.
**Assumption:**  The maintainer and driver are trained in appropriate action when an alert occurs. Data received are quality data.

The activity diagram for this use case is given in Figure 5.


**Figure 5.** Activity Diagram for Sensor Data Manipulation

**Use Case 2.** Data Fusion and Damage Algorithms

**Primary Actors:** Engine Data Bus
**Description:** Quality data is processed through the data fusion and damage

algorithms.
**Pre-condition:** The engine data bus and quality data are ready for processing.

**Flow of Events:**

1. Data from engine bus are received.
2. System fuses (incorporates) quality suspension, vehicle, and engine data.
3. Usage profile is estimated.
4. Damage is calculated for components.

**Alternative Flow of Events:** None

**Post-condition:** Damage accumulation is sent to prognostics algorithms.
**Assumption:** Data reduction and damage algorithms correctly reduce and calculate damage. Data reduction and damage algorithms are performed in parallel.

Activity diagram for this use case is given in Figure 6.

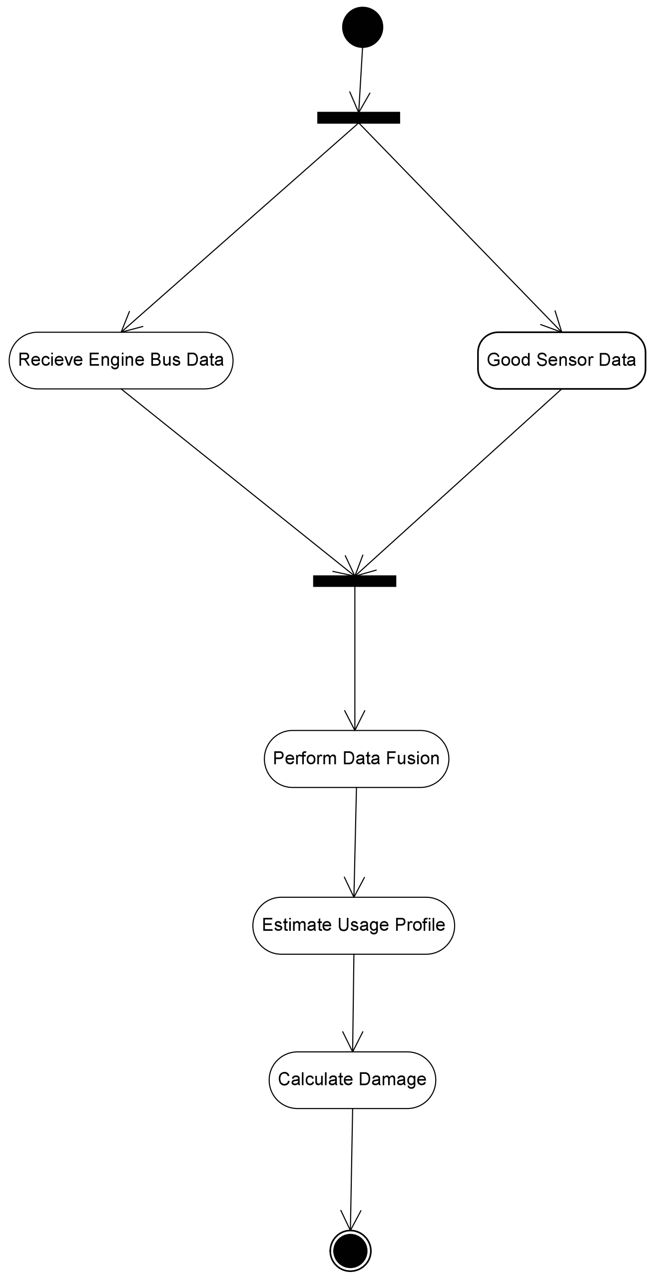


**Figure 6.** Activity Diagram for Data Fusion and Damage Algorithms

**Use Case 3.** Prognosticate Life Remaining

**Primary Actor:** Driver, Maintainer
**Description:** Accumulated damage is used to prognosticate the life remaining.

**Pre-condition:** Damage was calculated in damage algorithms. Maintainer entered expected usage profile.
**Flow of Events:**

1. Driver or maintainer enters expected usage profile.
2. System checks for mission profile.
3. Prognosticate life remaining based on the damage algorithms.

**Alternative Flow of Events:**

1. Mission profile is not entered by driver or maintainer.
2. System does not find mission profile.
3. System estimates mission profile based on past missions.
4. Prognosticate life remaining.

**Post-condition:** Prognostic results are used to determine which alerts to activate, if any.
**Assumption:** The predicted amount of damage required for component failure is correct. Mission profile entered by user is accurate of what vehicle will be exposed to. The estimated usage is indicative of what vehicle will see when mission profile is not entered.

The activity diagram for use case three and four are given in Figure 7.

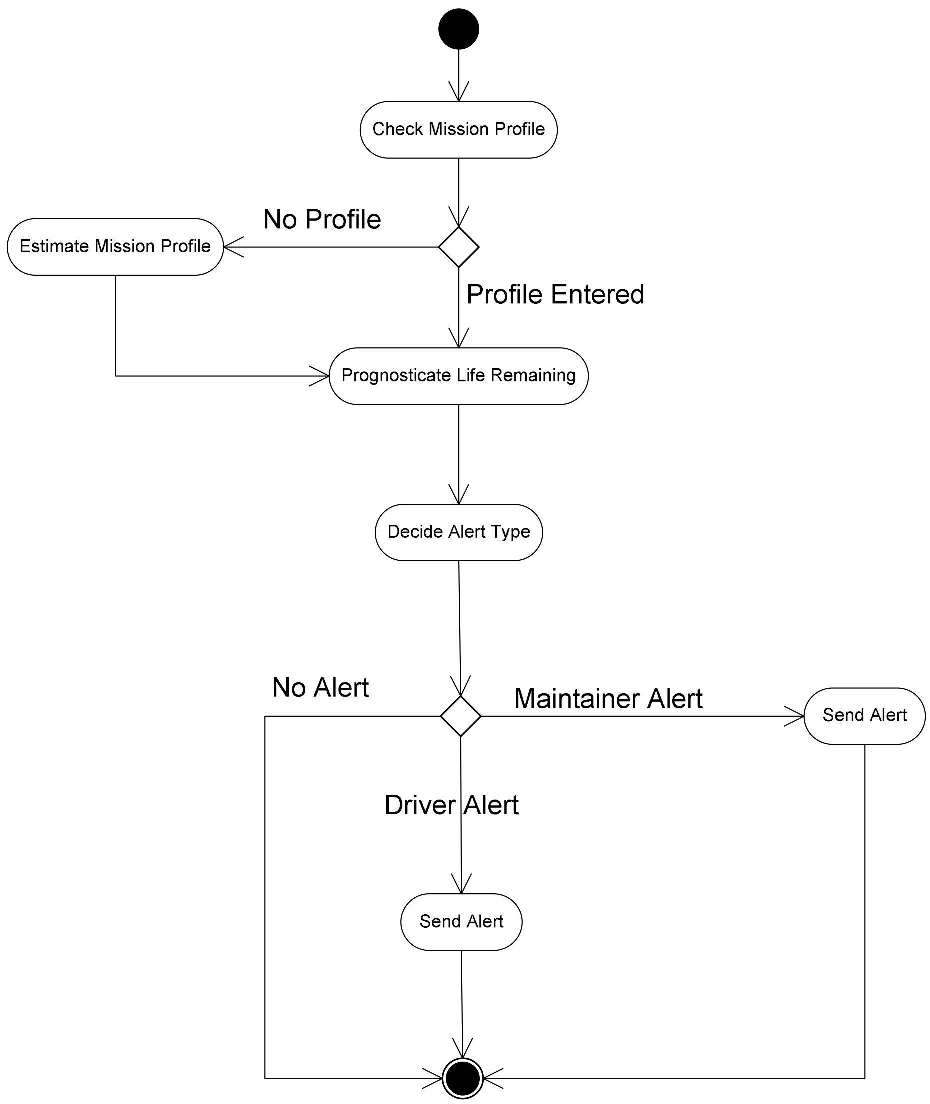


**Figure 7.** Activity Diagram for Prognostics Algorithms and Alert System

**Use Case 4.** Alert Messages Sent

**Primary Actors:** Driver, Maintainer

**Description:** The prognostics results determine when to display alerts to the driver and maintainer. Maintainer can download all components' life remaining.
**Pre-condition:** Prognostic algorithms were performed.
**Flow of Events:**

1. Prognostics algorithms determined life remaining.

2. Based on component life, determine where to send alerts.
3. Send alerts where needed.

**Alternative Flow of Events:**

2. Components have ample life remaining to complete mission.
3. No alerts are needed.

**Post-condition:** Driver and maintainer will adhere to alerts.
**Assumption:** Driver and maintainer have training on what to do when alert messages are sent.

Activity diagram is given in Figure 7.

## Requirements

Now that the goals, scenarios, and use cases are defined we can list the requirements. These are the high-level requirements that were determined at this stage in the development cycle. The system is also subject to a measure of effectiveness. The effectiveness for this type of system will be defined by how well the system meets its requirements and exceeds its goals and expectations. The customer in a military system is the PM, while the soldier is the end user. The PM will be satisfied as long as the system saves money and is accurate in predicting the failures. The soldier is satisfied if the system accurately predicts failures before the vehicle fails. Another smaller measure will be the ability of the soldier to understand and use the prognostics system without interfering in his normal duties. The high-level requirements that help achieve a satisfactory level of effectiveness are given in the following section.

### High-Level Requirements

The following lists are the high level requirements for the system. They reflect the user, performance, and function of the system. The analysis, test, and training requirements are used to verify that the system will perform properly. In other words they are used to verify the user, functional, and performance requirements.

**User Requirements (U#)**

1. Driver understands what alert message means.
2. Maintainer understands what alert message is for.
3. Driver or maintainer knows the expected mission profile.
4. Maintainer understands how to calibrate sensors.
5. Maintainer orders replacement part before failure.
6. Driver understands course of action when an alert occurs.

7. Maintainer understands course of action when an alert occurs.
8. Maintainer understands data downloading procedure from system.
9. Alerts must not impede driver's ability for mission success.
10. Maintainer resets life of component when that component is replaced.

**Performance Requirements (P#)**

1. Sensors and system are calibrated and operational.
2. Prognostics system is powered to proper level.
3. Component's fatigue limit is known.
4. Data fusion process leaves accurate data (meet a specified level).
5. Damage algorithms accurately predict damage accumulation (meet a specified level).
6. Sensor measurements are accurate (meet a specified level).
7. Prognostics algorithms accurately predict remaining life (meet a specified level).
8. Statistical distributions applied to components are accurate enough for the highest Return On Investment.
9. Data quality checking captures all anomalies.
10. Filtering process does not eliminate pertinent data and does not create false data.
11. Digitization process is accurately represents data for further processing.

**Functional Requirements (F#)**

1. System must be able to monitor components without requiring maintenance, downloading, or calibration for every mission.
2. System must meet all specifications that vehicle meets.
3. System must operate in all environmental conditions that vehicle experiences, including operational (shock and vibe).
4. Prognostics system must be unobtrusive to the crew.
5. System must be diverse enough to exist as an add-on system for certain vehicles.
6. System may not interfere with performance of vehicle.
7. System and sensors must not create additional signatures.
8. Statistical distribution applied to component life does not over-predict failure.
9. Alert must be seen by driver and maintainer, but not intrusive.
10. Failure of box does not interfere with any other vehicle systems.
11. System does not send false alert messages.
12. Calculated life can be reset when new components are installed.
13. System and sensors must not create EMI.

**Analysis & Test Requirements (A#)**

1. Instrumented test to validate estimated loading.
2. Test to validate statistical distribution applied to component.
3. User tests to validate human factors with alert system.
4. Test to validate system is receiving sensor data.
5. Endurance test to verify correct components are monitored.

6. Analysis to provide insight into component selection.
7. Materials testing to provide fatigue limits of components and to determine material properties.
8. FEA on components to know their fatigue limit.
9. Test signature of system for interference with vehicle signature.
10. Test system to verify engine data bus is not overwritten.
11. Test to verify system does not interfere with suspension sensor system.
12. Accelerated Life Testing to determine fatigue life of components.
13. Test to verify system and sensors do not create additional signatures.
14. Test to verify system does not create EMI.
15. Endurance test to verify fatigue limit of components and ensure accuracy and effectiveness of system.
16. Test and analysis to verify data quality algorithms do not eliminate important data (algorithms are working properly).
17. Test to verify system performs in all conditions vehicle experiences.
18. Test to verify filtering process.
19. Test to verify digitization process.

**Training Requirements (T#)**

1. Maintainer trained in proper course of action when alerts are given.
2. Driver trained in proper course of action when alerts are given.
3. Maintainer & driver trained to understand all aspects of alerts.
4. Maintainer trained how to reset prognostics system when a new component is installed.
5. Maintainer & driver trained how to enter expected mission profile.
6. Maintainer & driver trained how to estimate expected mission profile.
7. Maintainer trained in calibration of sensors and system.
8. Maintainer trained in part replacement ordering procedure.

## Requirements Traceability

### Traceability of Requirements to Use Cases/Scenarios

Traceability from requirements back to originating use cases/scenarios is given in Table 1.

**Table 1.** Traceability of Requirements to Use Cases/Scenarios

| Requirement | Description | Scenario | Use Case |
|---|---|---|---|
| U1 | Driver understands what alert message means. | 5.5 | Display Alert Message |
| U2 | Maintainer understands what alert message is for. | 5.5 | Display Alert Message |
| U3 | Driver or maintainer knows the expected mission profile. | 5.1 | Prognosticate Life Remaining |
| U4 | Maintainer understands how to calibrate sensors. | 1.1 | Sensor Data Manipulation |
| U5 | Maintainer orders replacement part before failure. | 5.5 | Display Alert Message |
| U6 | Driver understands course of action when an alert occurs. | 5.5 | Display Alert Message |
| U7 | Maintainer understands course of action when an alert occurs. | 5.5 | Display Alert Message |
| U8 | Maintainer understands data downloading procedure from system. | 5.1 | Display Alert Message |
| U9 | Alerts must not impede driver’s ability for mission success. | 5.4 | Display Alert Message |
| U10 | Maintainer resets life of component when that component is replaced. | 6.6 | Prognosticate Life Remaining |
| P1 | Sensors are calibrated and operational. | 6.1 | Sensor Data Manipulation |
| P2 | Prognostics system is powered to proper level. | 1.3 | Sensor Data Manipulation |
| P3 | Component’s fatigue limit is known. | 6.6 | Prognosticate Life Remaining |
| P4 | Data fusion process leaves accurate data (meet a specified level). | 4.2 | Data Fusion & Damage Algorithms |
| P5 | Damage algorithms accurately predict damage accumulation (meet a specified level). | 4.4 | Data Fusion & Damage Algorithms |
| P6 | Sensor measurements are accurate (meet a specified level). | 1.2 | Sensor Data Manipulation |
| P7 | Prognostics algorithms accurately predict remaining life (meet a specified level). | 6.6 | Prognosticate Life Remaining |

| | | | |
|---|---|---|---|
| P8 | Statistical distributions applied to components are accurate enough for the highest Return On Investment. | 6.6 | Prognosticate Life Remaining |
| P9 | Data quality checking captures all anomalies. | 3.2 | Sensor Data Manipulation |
| P10 | Filtering process does not eliminate pertinent data and does not create false data. | 2.2 | Sensor Data Manipulation |
| P11 | Digitization process is accurately represents data for further processing. | 2.3 | Sensor Data Manipulation |
| F1 | System must be able to monitor components without requiring maintenance, downloading, or calibration for every mission. | 1.1 | Sensor Data Manipulation |
| F2 | System must meet all specifications that vehicle meets. | 1.3 | Sensor Data Manipulation |
| F3 | System must operate in all environmental conditions that vehicle experiences, including operational (shock and vibe). | 1.3 | Sensor Data Manipulation |
| F4 | Prognostics system must be unobtrusive to the crew. | 5.4 | Display Alert Message |
| F5 | System must be diverse enough to exist as an add-on system for certain vehicles. | 6.6 | Prognosticate Life Remaining |
| F6 | System may not interfere with performance of vehicle. | 1.1 | Sensor Data Manipulation |
| F7 | System and sensors must not create additional signatures. | 1.1 | Sensor Data Manipulation |
| F8 | Statistical distribution applied to component life does not over-predict failure. | 6.6 | Prognosticate Life Remaining |
| F9 | Alert must be seen by driver and maintainer, but not intrusive. | 5.4 | Display Alert Message |
| F10 | Failure of box does not interfere with any other vehicle systems. | 5.5 | Display Alert Message |
| F11 | System does not send false alert messages. | 5.5 | Display Alert Message |
| F12 | Calculated life can be reset when new components are installed. | 6.6 | Prognosticate Life Remaining |
| F13 | System and sensors must not create EMI. | 1.1 | Sensor Data Manipulation |
| A1 | Instrumented test to validate estimated loading. | 4.4 | Data Fusion & Damage Algorithms |

| | | | |
|---|---|---|---|
| A2 | Test to validate statistical distribution applied to component. | 6.6 | Prognosticate Life Remaining |
| A3 | User tests to validate human factors with alert system. | 5.4 | Display Alert Message |
| A4 | Test to validate system is receiving sensor data. | 1.3 | Sensor Data Manipulation |
| A5 | Endurance test to verify correct components are monitored. | 6.5 | Prognosticate Life Remaining |
| A6 | Analysis to provide insight into component selection. | 6.5 | Prognosticate Life Remaining |
| A7 | Materials testing to provide fatigue limits of components and to determine material properties. | 6.5 | Prognosticate Life Remaining |
| A8 | FEA on components to know their fatigue limit. | 6.5 | Prognosticate Life Remaining |
| A9 | Test signature of system for interference with vehicle signature. | 1.1 | Sensor Data Manipulation |
| A10 | Test system to verify engine data bus is not overwritten. | 4.1 | Data Fusion & Damage Algorithms |
| A11 | Test to verify system does not interfere with suspension sensor system. | 1.3 | Sensor Data Manipulation |
| A12 | Accelerated Life Testing to determine fatigue life of components. | 6.5 | Prognosticate Life Remaining |
| A13 | Test to verify system and sensors do not create additional signatures. | 1.1 | Sensor Data Manipulation |
| A14 | Test to verify system does not create EMI. | 1.1 | Sensor Data Manipulation |
| A15 | Endurance test to verify fatigue limit of components and ensure accuracy of system. | 6.5 | Prognosticate Life Remaining |
| A16 | Test and analysis to verify data quality algorithms do not eliminate important data (algorithms are working properly). | 3.2 | Sensor Data Manipulation |
| A17 | Test to verify system performs in all conditions vehicle experiences. | 1.3 | Sensor Data Manipulation |
| A18 | Test to verify filtering process. | 2.2 | Sensor Data Manipulation |
| A19 | Test to verify digitization process. | 2.3 | Sensor Data Manipulation |
| T1 | Maintainer trained in proper course of action when alerts are given. | 5.5 | Display Alert Message |

| | | | |
|---|---|---|---|
| T2 | Driver trained in proper course of action when alerts are given. | 5.5 | Display Alert Message |
| T3 | Maintainer & driver trained to understand all aspects of alerts. | 5.5 | Display Alert Message |
| T4 | Maintainer trained how to reset prognostics system when a new component is installed. | 6.6 | Prognosticate Life Remaining |
| T5 | Maintainer & driver trained how to enter expected mission profile. | 5.1 | Prognosticate Life Remaining |
| T6 | Maintainer & driver trained how to estimate expected mission profile. | 5.3 | Prognosticate Life Remaining |
| T7 | Maintainer trained in calibration of sensors and system. | 6.1 | Sensor Data Manipulation |
| T8 | Maintainer trained in part replacement ordering procedure. | 5.5 | Display Alert Message |

The analysis, testing, and training requirements are traced back to the functional, performance, and user requirements for verification. The requirement verification table is given in Table 2.

**Table 2.** Requirement to Analysis/Test & Training requirement

| **Requirement Source** | | **Verification Requirements** |
|---|---|---|
| **Requirement** | **Description** | **Analysis/Testing & Training Requirements** |
| U1 | Driver understands what alert message means. | T3 |
| U2 | Maintainer understands what alert message is for. | T3 |
| U3 | Driver or maintainer knows the expected mission profile. | T5, T6 |
| U4 | Maintainer understands how to calibrate sensors. | T7 |
| U5 | Maintainer orders replacement part before failure. | T8 |
| U6 | Driver understands course of action when an alert occurs. | T2 |
| U7 | Maintainer understands course of action when an alert occurs. | T1 |

| | | |
|---|---|---|
| U8 | Maintainer understands data downloading procedure from system. | T7, T4 |
| U9 | Alerts must not impede driver's ability for mission success. | A3 |
| U10 | Maintainer resets life of component when that component is replaced. | T4 |
| P1 | Sensors and system are calibrated and operational. | A4,T3,T7 |
| P2 | Prognostics system is powered to proper level. | A15 |
| P3 | Component's fatigue limit is known. | A7,A8,A12,A15 |
| P4 | Data fusion process leaves accurate data (meet a specified level). | A1, A15 |
| P5 | Damage algorithms accurately predict damage accumulation (meet a specified level). | A1, A7, A15 |
| P6 | Sensor measurements are accurate (meet a specified level). | A4, A15 |
| P7 | Prognostics algorithms accurately predict remaining life (meet a specified level). | A2, A15 |
| P8 | Statistical distributions applied to components are accurate enough for the highest Return On Investment. | A2 |
| P9 | Data quality checking captures all anomalies. | A15, A16 |
| P10 | Filtering process does not eliminate pertinent data and does not create false data. | A18 |
| P11 | Digitization process accurately represents data for further processing. | A19 |
| F1 | System must be able to monitor components without requiring maintenance, downloading, or calibration for every mission. | A15, T2 |
| F2 | System must meet all specifications that vehicle meets. | A17 |
| F3 | System must operate in all environmental conditions that vehicle experiences, including operational (shock and vibe). | A17 |
| F4 | Prognostics system must be unobtrusive to the crew. | A3 |
| F5 | System must be diverse enough to exist as an add-on system for certain vehicles. | A15, A17 |

| | | |
|---|---|---|
| F6 | System may not interfere with performance of vehicle. | A17 |
| F7 | System and sensors must not create additional signatures. | A13 |
| F8 | Statistical distribution applied to component life does not over-predict failure. | A2 |
| F9 | Alert must be seen by driver and maintainer, but not intrusive. | A3 |
| F10 | Failure of box does not interfere with any other vehicle systems. | A17 |
| F11 | System does not send false alert messages. | A15 |
| F12 | Calculated life can be reset when new components are installed. | T4 |
| F13 | System and sensors must not create EMI. | A13 |

The Object to which the corresponding requirement is linked to is given in Table 3. The table depicts the object in the system for which the requirement is intended for.

**Table 3.** Requirements to Corresponding Object

| Requirement | Description | Object |
|---|---|---|
| U1 | Driver understands what alert message means. | Alert System |
| U2 | Maintainer understands what alert message is for. | Alert System |
| U3 | Driver or maintainer knows the expected mission profile. | Prognostics Algorithm |
| U4 | Maintainer understands how to calibrate sensors. | Sensors |
| U5 | Maintainer orders replacement part before failure. | Components |
| U6 | Driver understands course of action when an alert occurs. | Alert System |
| U7 | Maintainer understands course of action when an alert occurs. | Alert System |
| U8 | Maintainer understands data downloading procedure from system. | Prognostics Algorithm |
| U9 | Alerts must not impede driver’s ability for mission success. | Alert System |
| U10 | Maintainer resets life of component when that component is replaced. | Prognostics Algorithm |
| P1 | Sensors are calibrated and operational. | Sensors |
| P2 | Prognostics system is powered to proper level. | Prognostics System |
| P3 | Component’s fatigue limit is known. | Components |

| | | |
|---|---|---|
| P4 | Data fusion process leaves accurate data (meet a specified level). | Data Fusion Algorithms |
| P5 | Damage algorithms accurately predict damage accumulation (meet a specified level). | Damage Algorithms |
| P6 | Sensor measurements are accurate (meet a specified level). | Sensors |
| P7 | Prognostics algorithms accurately predict remaining life (meet a specified level). | Prognostics Algorithm |
| P8 | Statistical distributions applied to components are accurate enough for the highest Return On Investment. | Prognostics Algorithm |
| P9 | Data quality checking captures all anomalies. | Data Quality Algorithms |
| P10 | Filtering process does not eliminate pertinent data and does not create false data. | Filters |
| P11 | Digitization process accurately represents data for further processing. | Digitization Process |
| F1 | System must be able to monitor components without requiring maintenance, downloading, or calibration for every mission. | Prognostics System |
| F2 | System must meet all specifications that vehicle meets. | Prognostics System |
| F3 | System must operate in all environmental conditions that vehicle experiences, including operational (shock and vibe). | Prognostics System |
| F4 | Prognostics system must be unobtrusive to the crew. | Prognostics System |
| F5 | System must be diverse enough to exist as an add-on system for certain vehicles. | Prognostics System |
| F6 | System may not interfere with performance of vehicle. | Prognostics System |
| F7 | System and sensors must not create additional signatures. | Prognostics System, Sensors |
| F8 | Statistical distribution applied to component life does not over-predict failure. | Prognostics Algorithm, Components |
| F9 | Alert must be seen by driver and maintainer, but not intrusive. | Alert System |
| F10 | Failure of box does not interfere with any other vehicle systems. | Prognostics System |
| F11 | System does not send false alert messages. | Alert System |
| F12 | Calculated life can be reset when new components are installed. | Prognostics Algorithm |

| | | |
|---|---|---|
| F13 | System and sensors must not create EMI. | Prognostics System, Sensors |
| A1 | Instrumented test to validate estimated loading. | Damage Algorithms |
| A2 | Test to validate statistical distribution applied to component. | Prognostics Algorithm, Components |
| A3 | User tests to validate human factors with alert system. | Alert System |
| A4 | Test to validate system is receiving sensor data. | Prognostics System, Sensors |
| A5 | Endurance test to verify correct components are monitored. | Components |
| A6 | Analysis to provide insight into component selection. | Components |
| A7 | Materials testing to provide fatigue limits of components and to determine material properties. | Components |
| A8 | FEA on components to know their fatigue limit. | Components |
| A9 | Test signature of system for interference with vehicle signature. | Prognostics System |
| A10 | Test system to verify engine data bus is not overwritten. | Engine Bus Data, Prognostics System |
| A11 | Test to verify system does not interfere with suspension sensor system. | Suspension Sensor System, Prognostics System |
| A12 | Accelerated Life Testing to determine fatigue life of components. | Components |
| A13 | Test to verify system and sensors do not create additional signatures. | Prognostics System, Sensors |
| A14 | Test to verify system does not create EMI. | Prognostics System, Sensors |
| A15 | Endurance test to verify fatigue limit of components and ensure accuracy of system. | Prognostics System, Components |
| A16 | Test and analysis to verify data quality algorithms do not eliminate important data (algorithms are working properly). | Data Quality Algorithms |
| A17 | Test to verify system performs in all conditions vehicle experiences. | Prognostics System, Sensors |
| A18 | Test to verify filtering process. | Filters |
| A19 | Test to verify digitization process. | Digitization Process |
| T1 | Maintainer trained in proper course of action when alerts are given. | Alert System |
| T2 | Driver trained in proper course of action when alerts are given. | Alert System |

| | | |
|---|---|---|
| T3 | Maintainer & driver trained to understand all aspects of alerts. | Alert System |
| T4 | Maintainer trained how to reset prognostics system when a new component is installed. | Prognostics Algorithm |
| T5 | Maintainer & driver trained how to enter expected mission profile. | Prognostics Algorithm |
| T6 | Maintainer & driver trained how to estimate expected mission profile. | Prognostics Algorithm |
| T7 | Maintainer trained in calibration of sensors and system. | Prognostics System, Sensors |
| T8 | Maintainer trained in part replacement ordering procedure. | Components |

The high-level requirements layering is given in the figure 8.  This figure depicts the requirements broken into categories corresponding to classes.  The detailed requirements layering will be taken from the low level requirements due to the fact that there are many requirements and the tool used to develop them does not adequately display them.

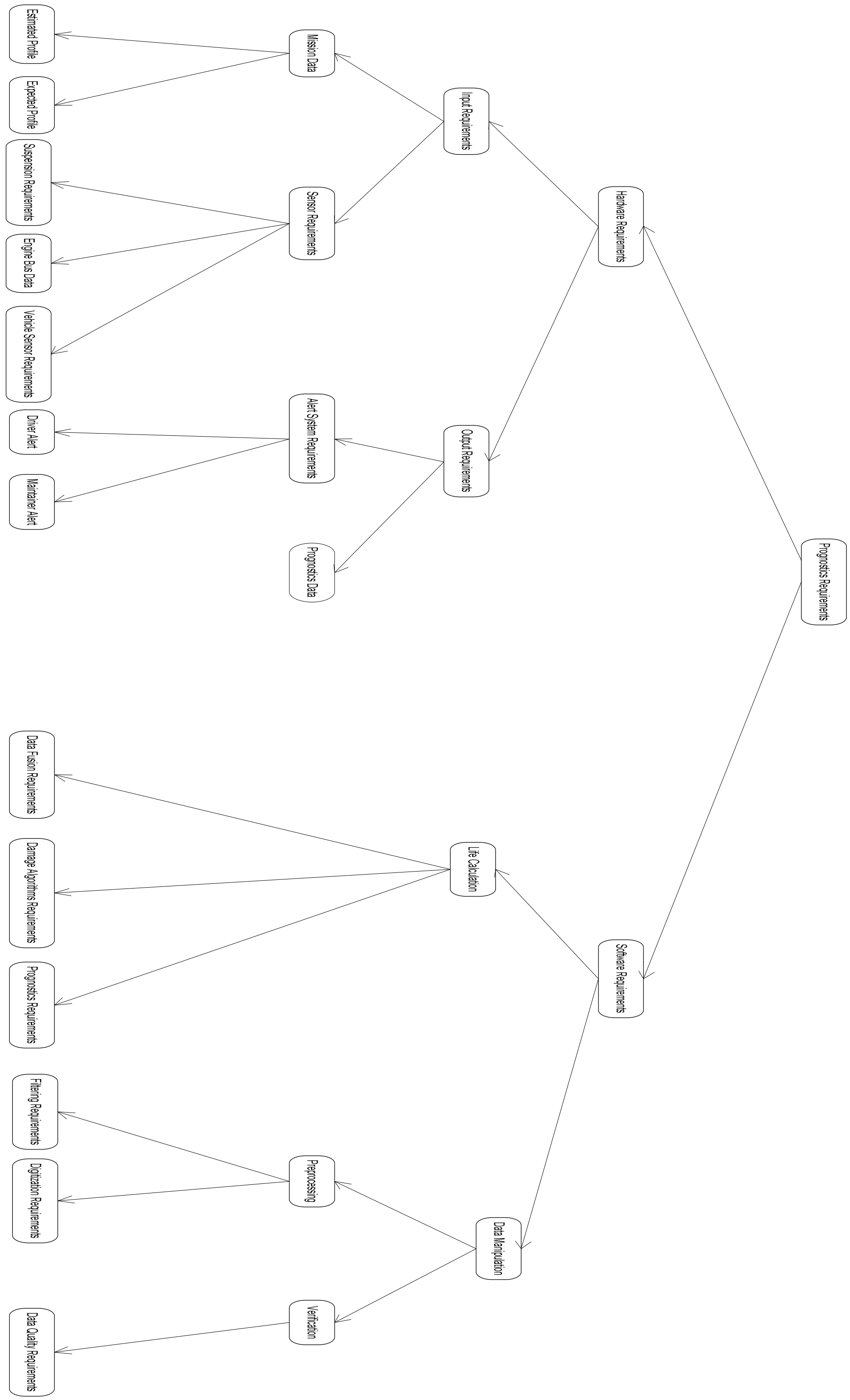


**Figure 8.** High-level Requirements Layering

Some of the internal system requirements were broken into their hierarchical requirements layering, they are given in figures 9-13.  Because Microsoft Visio was used to create the layering, it was not feasible to display all of the layering on one chart, therefore they are broken into systems.

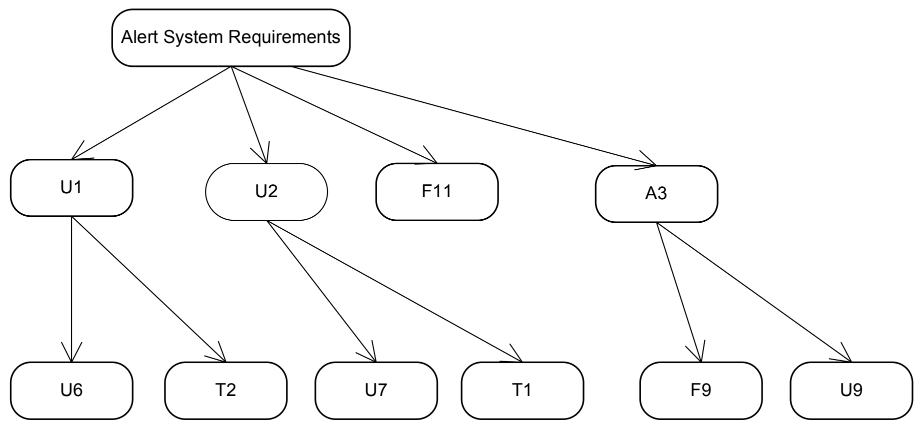


**Figure 9.** Alert System Requirements Layering

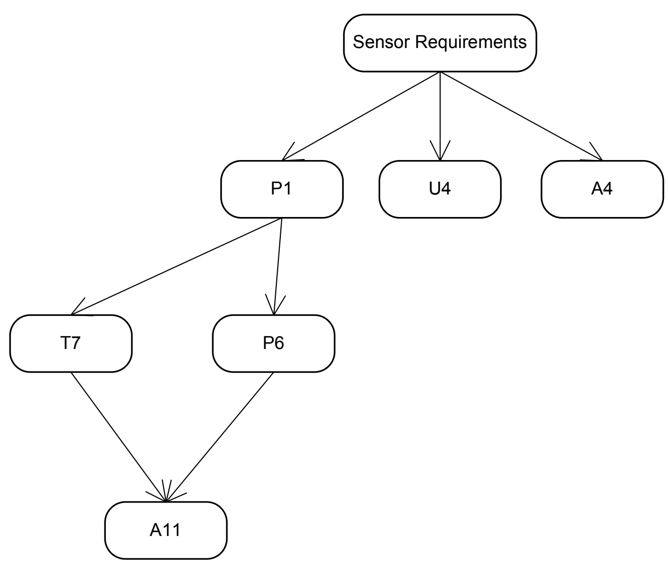


**Figure 10.** Sensor System Requirements Layering

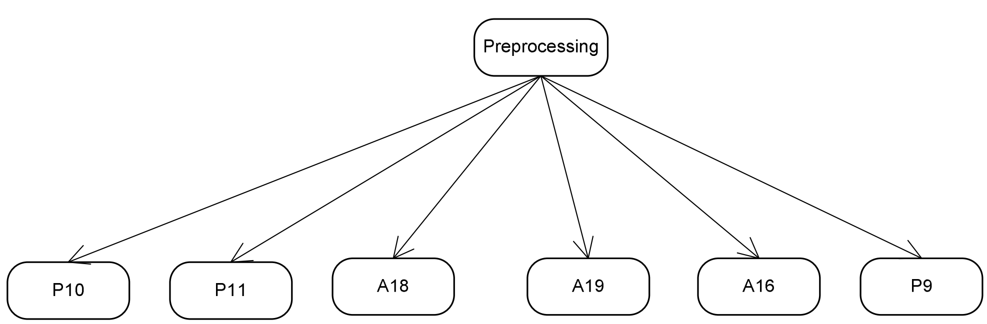

**Figure 11.** Preprocessing Requirements Layering

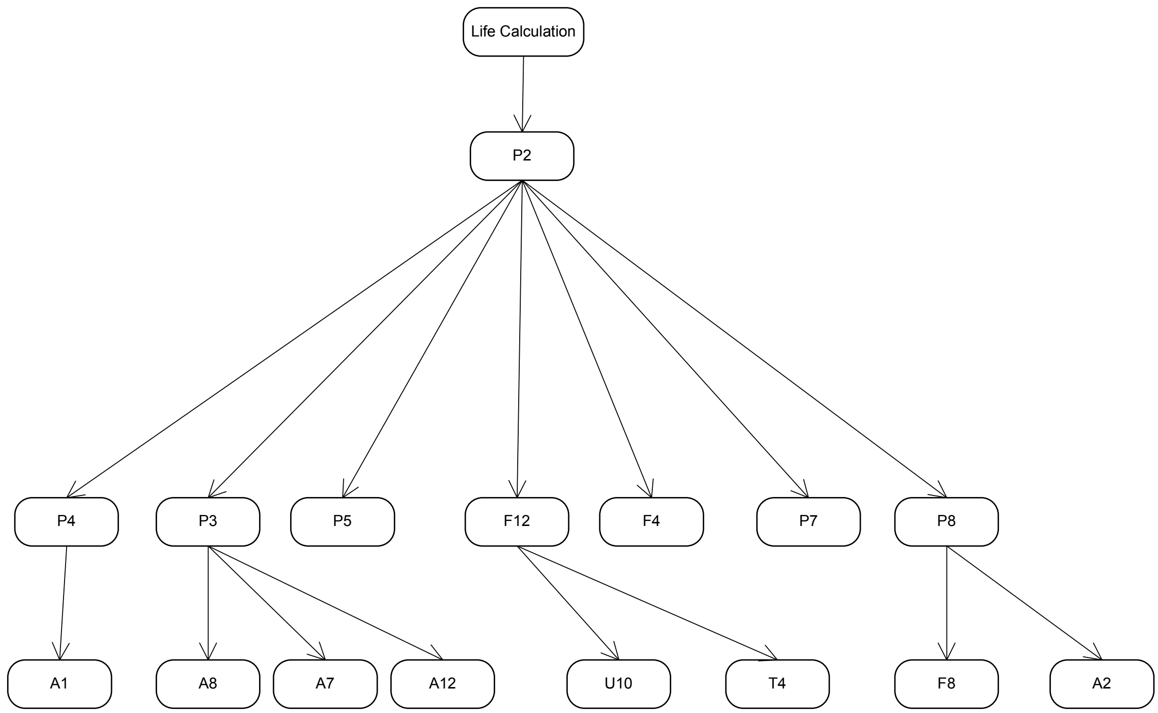


**Figure 12.** Life Calculation Algorithms Requirements Layering

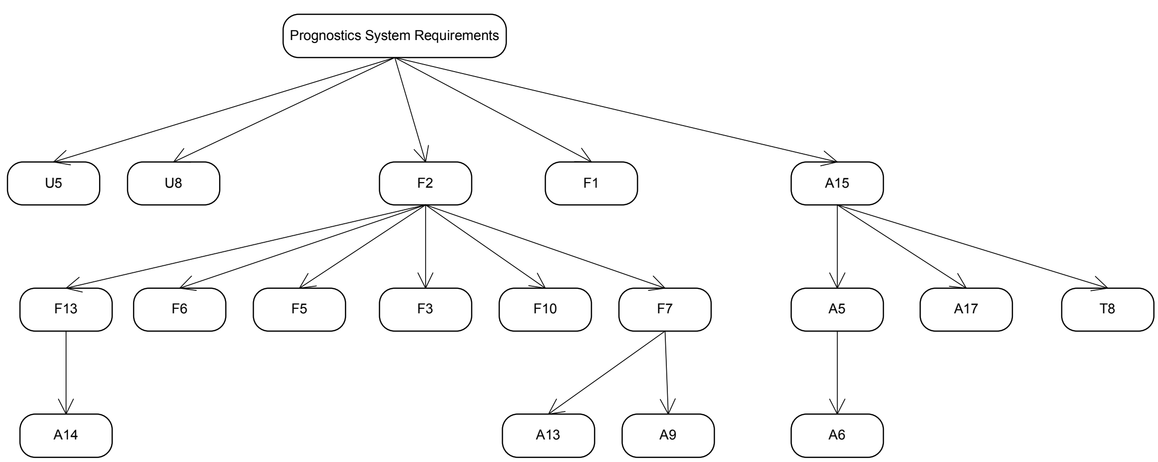


**Figure 13.** Prognostics System Level Requirements Layering

## System Behavior and Structure

### System Behavior

System behavior shows what a system does or appears to do. It is represented graphically by a model which integrates the functional model and the inputs and outputs.

A sequence diagram represents the interaction between objects to achieve a desired result. The sequence diagram for prognosticating the life remaining is given in Figure 14. The diagram shows that the process of prognosticating the life remaining is sequential using data from the previous process to perform the task at hand.

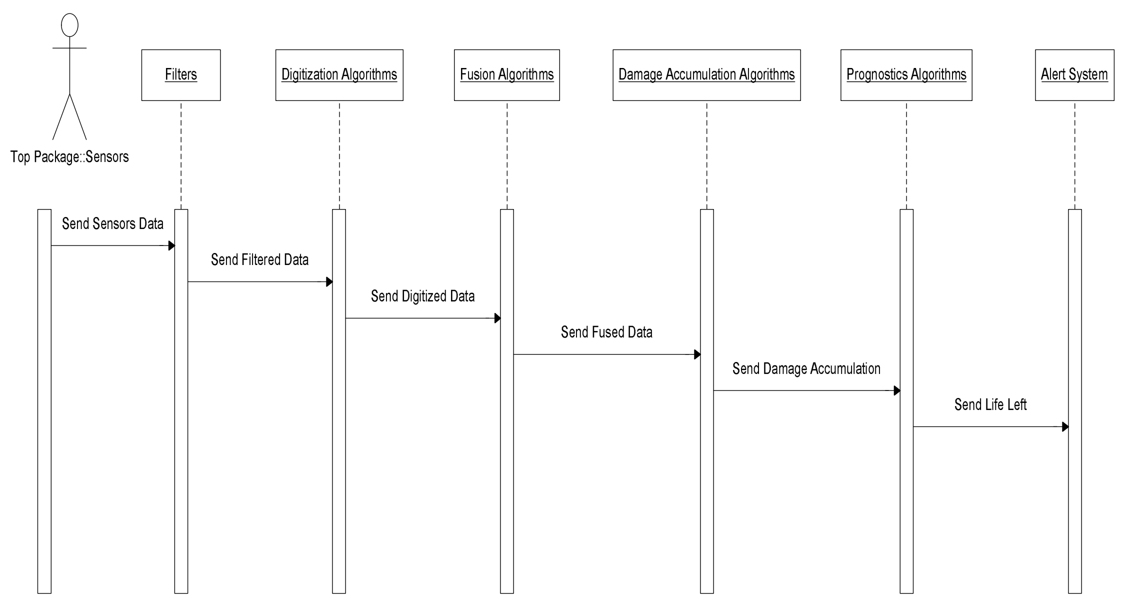


**Figure 14.** Sequence Diagram

A statechart diagram describes the possible states of a class and the interaction between states. The high-level state chart diagram for prognosticating the life remaining and sending the appropriate alert is given in Figure 15. The transitions between the states are sequential. The prognostics system is a real-time system, in which the sensor outputs are constantly being filtered and digitized and the subsequent algorithms are performed.

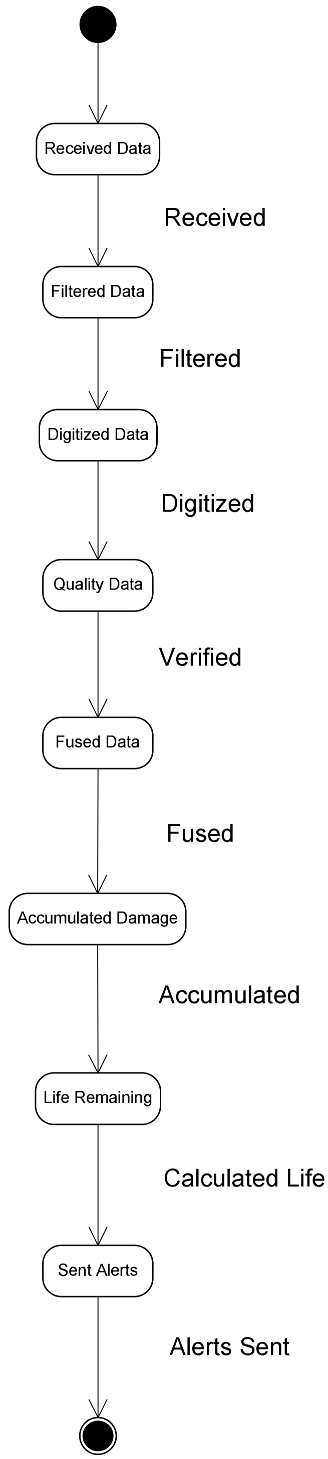


**Figure 15.** Statechart diagram

## System Structure

One of the ways to represent system structure is through a class diagram.  In a class diagram, classes describe the structure and behavior of objects.  The class diagram shows the operations and attributes of each class and their hierarchy.  The class diagram is given in Figure 16.

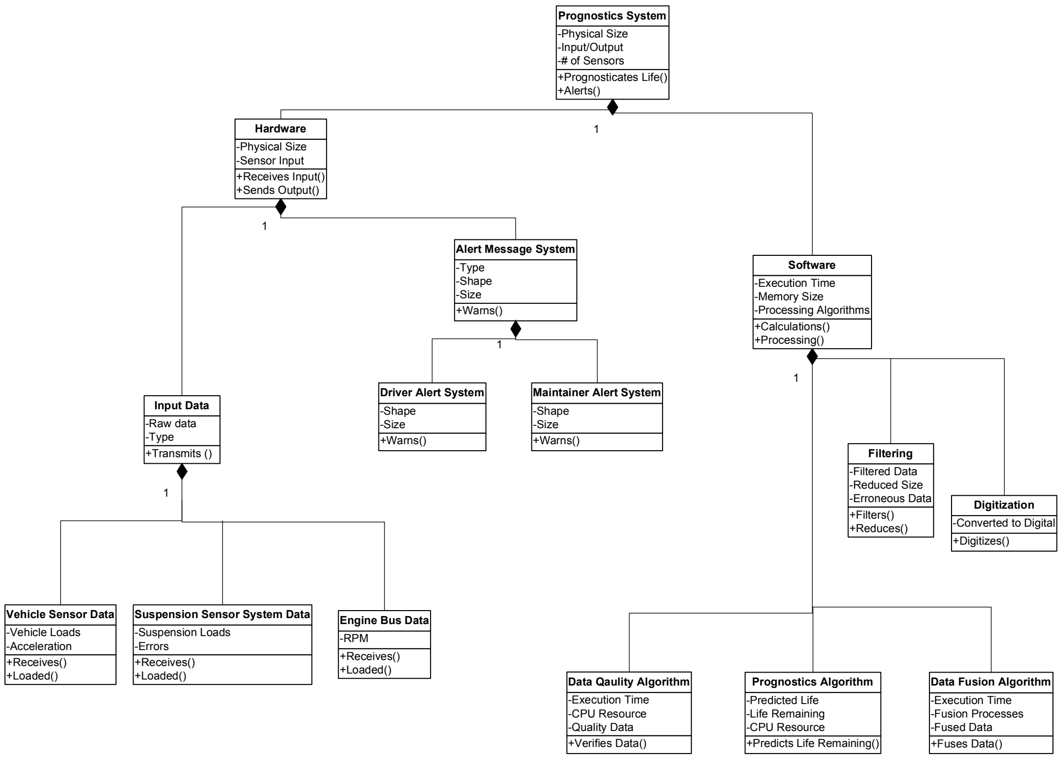


**Figure 16**: Class Diagram

## System Trade-Off Analysis

Performing a trade-off analysis will be discussed in the following section.  Because the system is designed to save cost the actual cost of just the hardware will not be a major factor.  But other costs associated with the system will be analyzed and optimized.  The costs chosen to optimize in the system are: the effect of cost on repair, parts, and logistics.  Also, an increase in cost may not increase the performance.  There may be a point in which the increase in cost and performance does not benefit the overall system performance.

### System Optimization Problems

1. Wasted Life vs. Cost of Failure
2. Accuracy vs. Total Cost

**1. Wasted Life vs. Cost of Failure**

This possible optimization problem deals with the cost of replacing a part before it fails versus the cost of the failure occurring. A representation of the possible distribution for component failure and replacement is given in Figure 17. The figure depicts the failure time and when the part was actually replaced. The figure also depicts the section of the curve for which the part would not have failed, but was replaced before it did. This was known as the "wasted life" of the component. The possible optimization problem will deal with choosing a failure distribution that would maximize the most cost savings and also ensure the component would not fail before it is replaced. A cost is associated with replacing the part before failure as well as waiting till failure. The factors to consider in the wasted life are: spare part cost, repair cost at motor pool, and the cost of the wasted life that was in the component replaced. The factors to consider for the cost of failure are: cost of recovery of vehicle, repairman cost for unscheduled maintenance, cost of system availability, and cost of repairing vehicle in the field. This optimization will deal with the cost tradeoff of replacing components early versus replacing parts after they fail. This tradeoff is intended to be a justification for replacing components before they fail. Because of the information that is available at this time, this optimization cannot be performed. The intent is to perform this optimization when the needed data is available.

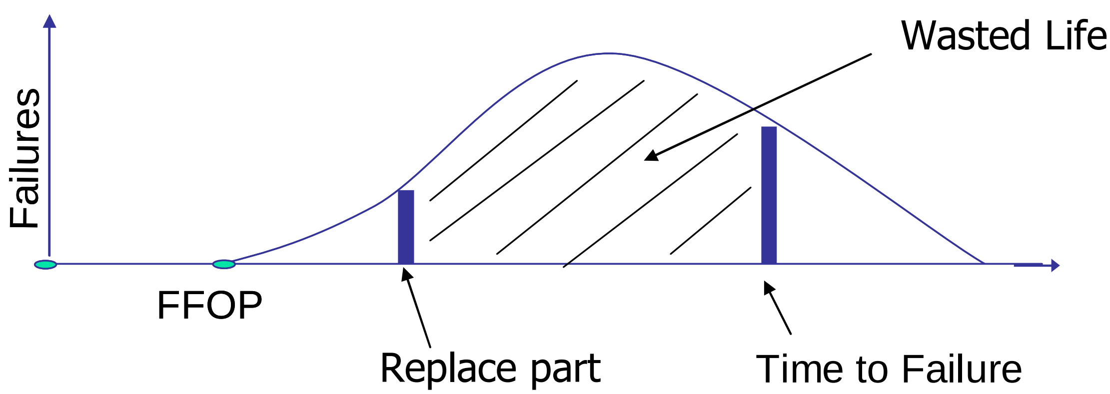


**Figure 17.** Wasted Life Distribution For a Component

**2. Accuracy vs. Total Cost**

The optimization for the prognostics system is the tradeoff of the accuracy of the system versus the total cost of the prognostics system and repair cost. All of the following costs were based on current estimated data. The costs associated with the prognostics system were the cost of having an accurate prognostics system, hardware costs, engineering refinement, and other associated costs. The costs associated with the repair were part cost, repair cost, and the cost of the failure occurring. The relationship between the accuracy of the prognostics system and the failure probabilities were estimated from experience. Figures 18-21 show the estimated relationships. Equations were fit to the estimated data and the equations were used in the non-linear generalized reduced gradient method optimization. The total system cost versus accuracy is given in Figure 21. This plot is the relationship of the previous three plots. The constraint applied in the optimization was that the accuracy of the prognostics system must be greater than 0.3. If this was not applied there would be a tendency among the maintainers to discount the credibility of the prognostics predictions. The actual optimization found a local minimum at accuracy of 0.51 corresponding to a system cost of $35,000.

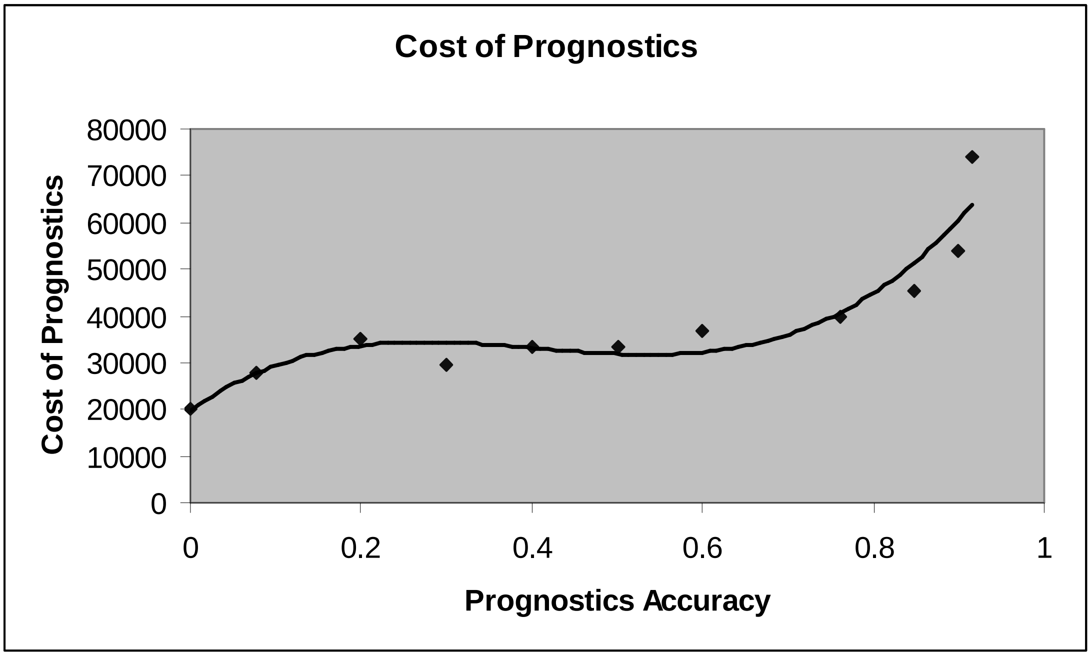


**Figure 18.** Cost of Prognostics

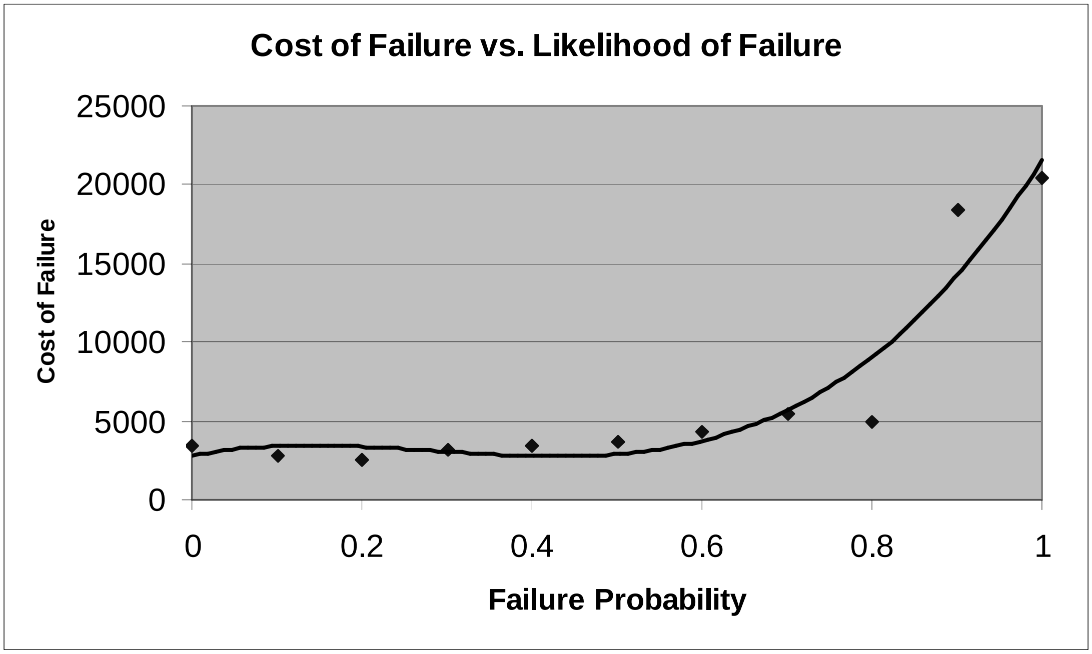


**Figure 19.** Cost of Failure vs. Likelihood of Failure

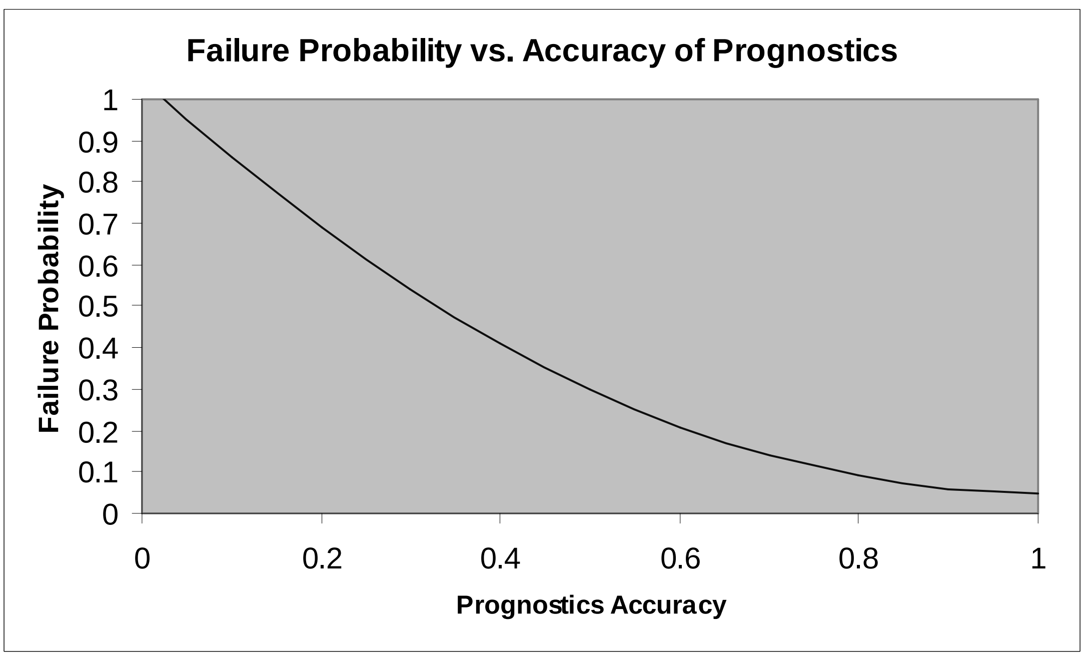


**Figure 20.** Failure Probability vs. Accuracy

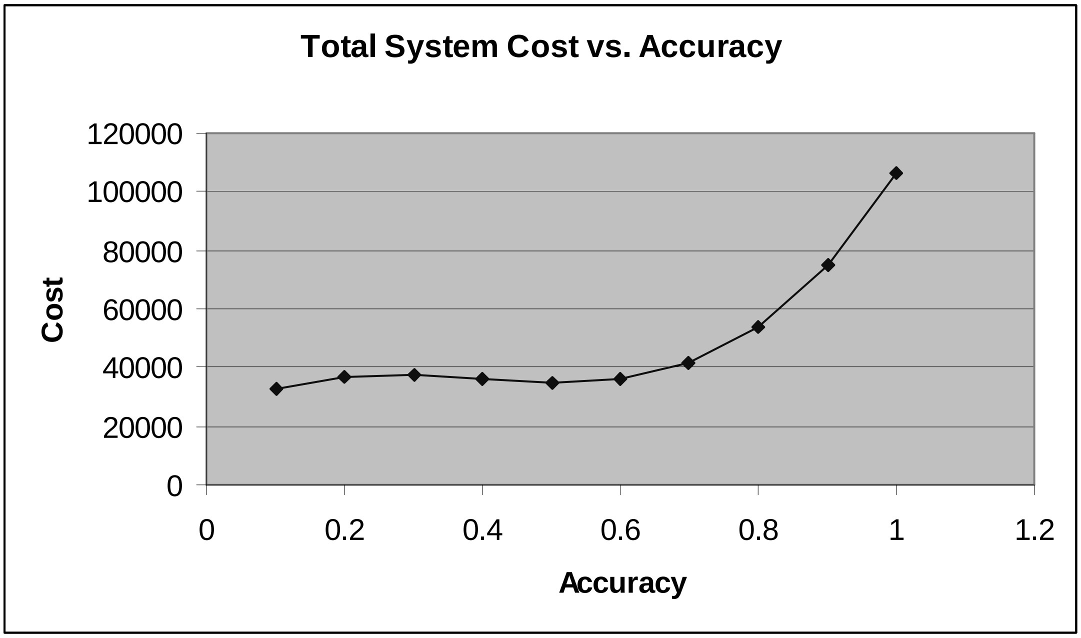


**Figure 21.** Total System Cost vs. Accuracy

## References


1. ENSE 621: Systems Modeling and Analysis, Lecture Notes. 2004
2. Relevant AMSAA briefings (U.S. Army internal briefings on the prognostics system).