DEVELOPMENT AND EVALUATION OF A REMOTE CONDITION MONITORING SYSTEM

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ABSTRACT

This paper suggests a means for the design of a remote monitoring system for stationary engines, and then proceeds to evaluate that design. Our team employed axiomatic design to suggest an ideal system; the designed system is then divided into communications, monitoring, and user interface subsystems. The system is decomposed using IDEF0, and user interactions with the system are depicted with Use Case diagrams. This ideal design is then compared to currently fielded systems and shown to be superior to its competitors.

1 INTRODUCTION

In the last few years, several industries, among them power generation and petroleum production, have seen the introduction of more complex turbine and reciprocating engine systems. The resulting increase in complexity has necessitated the use of exotic materials in construction and required the employment of more elaborate cooling schemes, for example. These, in concert, have increased operating risk, as 'abnormal' behavior is now more likely [1].

As for the business relationship, customers are implementing projects in more remote locations and are pressing the manufacturers to increase operating hours and reduce the operating and maintenance cost [2].

One method to help in mitigating risk, improving quality, and reducing cost is through remote monitoring. This tool has come to the forefront with the ability to access vast amounts of information in real time over high speed internet connections over large distances. Through remote condition monitoring, operators can better plan for maintenance, accurately diagnose the condition of units, and generate cost savings by placing a lesser burden on service personnel/systems.

By improving the diagnostic capabilities, increasing the amount of information and the rate at which it is delivered, remote monitoring gives the manufacturers the ability to deliver a better service product to a larger number of customers while reducing service team costs.

2 KEY CONCEPTS AND TERMS

In order to fully understand the topics and analysis reviewed in this paper, one must first have a basic understanding of the following terms and concepts.

Axiomatic Design: A method of design that utilizes four state spaces to define the design of a device. Consumer Attributes (CAs) are characteristics that are defined by the customer space. Functional Requirements (FRs) are variables developed using CAs but define the actual functionality of the design. Design Parameters (DPs) are developed using FRs and define the physical properties of the device. Last, Process Variables (PVs) are developed using DPs and characterize the manufacturing processes required to develop the design. This method of design is utilized to develop a fully functional remote monitoring system [7].

Functional Decomposition (IDEF0): A method in which a given design is broken down into the many simple individual tasks required by the device. Specifically IDEF0 is the standardized format in which function blocks are created for each simple task. These blocks are connected and defined further by adding inputs, outputs, controls and mechanisms. The fully develop IDEF0 model becomes an entwined system of small functions that define the overall design. This method is used throughout the design to provide a better understanding of the requirements of a remote monitor system in stationary engine applications

Use Cases: Use cases are used in design to understand how a design will operate in multiple possibly environments. In this method, designs are applied to common customers in the stationary power industry and analyzed to the possible success in that sector.

3 CURRENT STATE-OF-THE-ART

A remote monitoring system integrates onsite condition monitoring of stationary reciprocating engines and gas turbines with remote users in order to maximize the reliability and availability of such units. The monitoring system should log the engine parameters chosen by customer requirements, providing the real-time status of the engine and detailed data for inspection and maintenance outage The use of stationary engines is a dynamic application; for example, when considering changing emissions guidelines, the ability to monitor any of the more than ten thousand stationary reciprocating and turbine engines should prove invaluable when planning upgrades to meet regulatory requirements [15].

3.1 STATIONARY ENGINES

3.1.1 GAS TURBINES - INSTRUMENTATION

Gas turbine reliability is highly important to the customer. In order to keep reliability high, detection and identification of emerging failures and poor operation trends is critical. The most common factors that degrade gas turbines are vibration, shock, noise, heat, cold, dust, corrosion, humidity, rain, oil debris, flow, pressure, and speed [8].

Gas turbine monitoring systems make use of both real-time and recorded historical data from various subsystems to determine operation trends and predict potential faults.

The instrumentation used to collect data in the gas turbine application varies based on the parameter to be analyzed. For example, engine vibration is measured by transducers mounted throughout the engine assembly. Vibration data can then be processed offsite via the application of Fast Fourier Transforms; the system can then identify anomalous operating frequencies. When abnormalities in data cannot be clearly identified, as with the vibration data example, theoretical engine models from engine testing can be compared to models from actual engine data. The residual error between the two models may be used to identify deficiencies. For example, linear flow models constructed from fuel-flow data can be applied to condition monitoring of the combustion system [5].

3.1.2 DIESEL ENGINES INSTRUMENTATION

Condition monitoring is also of significant interest to the users of reciprocating engines. In much the same manner as turbines, the user of a reciprocating engine should be concerned with the collection of operating data – so that the operator may make informed decisions on engine condition, availability, and future operation. Pipeline companies rely on natural gas fired reciprocating engines to deliver natural gas through pipelines to users. Reciprocating engines are also used in the production of oil and natural gas on and off land. In order to assess equipment condition, determine machinery availability, and make decisions on operation, engine monitoring data is vital.

Engine instrumentation systems make use of a variety of transducers to collect data (e.g. fluid pressure measurements, cylinder temperatures). This data can then be used to assess the engine's condition – for example, vibration data can be processed and compared with theoretical models in order to differentiate the normal behavior of a healthy engine from behavior indicative of failure modes. The instrumentation applied is used to collect pressure measurements and vibration parameters. For example, the measured vibrations in a reciprocating engine are a mixture of periodic waves due to the rotating components and transient waves due to the reciprocating components of the engine. The instrumentation applied separates the normal vibrations of a healthy engine, due to pressure forces and inertial forces associated with the rotating components, from vibrations indicative of failure modes [6].

3.2 COMMUNICATIONS/CONTROL

3.2.1 COMMUNICATIONS

There are several different means for communicating with remote machinery. For example, the designer of a remote condition monitoring system might employ a wireless telecommunications network. On the machinery side of the network, there usually exists a control unit that marshals sensor data. This unit typically contains wireless transmission and reception capability, and can communicate with local telecom antennae or satellites. The sensor contains communication nodes which have built in computing power and wireless transmission and reception capability. Each wireless sensor communication node can communicate directly with the control unit, or through one or more other wireless sensor communication nodes in the network. The designer may also elect to utilize the internet, provided the machinery has internet access via one of a few protocols. Means of communications are varied, and should be selected based on site conditions.

3.2.2 PROTOCOLS

There are a number of protocols existing today for communication in any given medium. For example, readers may be familiar with LTE Advanced, used over cell networks. The IEEE publishes and maintains 802.11, a set of specifications used over wireless local area networks. Schneider Electric has published the Modbus protocol, which is frequently used in automation systems in industry.

Use of a common, well-documented protocol is a necessity in any monitoring system, lest the user of the system find themselves with unnecessary communications issues and converting hardware.

3.3 CONDITION MONITORING

In two last decades, the development of monitoring tools has been accelerated by advances in information technology, particularly, in instrumentation, communication techniques, and computer technology [7]. The use of modern intelligent sensors is employed for signal processing. Advances in these sensors reduce measurement errors and compress the data volume required for processing. The evolution of wireless technology streamlines data acquisition and accelerates data transmission to a central diagnostic location.

3.4 PREVENTATIVE MAINTENANCE DECISION MAKING

Condition monitoring must provide tools for preventative maintenance and recommendations to gain the maximum benefit of the monitoring data. Management of maintenance includes tools to plan and track maintenance, customizable maintenance intervals and maintenance alerts. The condition monitoring must also make decisions on how to operate. The condition monitoring recommendation will minimize owning and operating costs, including unplanned downtime and catastrophic failures that may lead to more costly repairs. The decision making process must be completed in a timely manner so as to alert the customer before significant damage occurs.

3.4.1 USER INTERFACES

Much work has been done in the creation of a proper user interface, and there exist a wide variety of tools for creating one, with standards (e.g. MIL-STD-1472G) describing how one should be made. Designers might choose a language to create such a system from Sun's *Java* or Nokia's *QT*. Human factors engineering is an entire field dedicated to the development of user-friendly systems.

4 REMOTE CONDITION MONITORING SYSTEM DESIGN FOR STATIONARY ENGINES

In order to design a remote condition monitoring system, we pursue the development of three systems simultaneously, all of these part of the whole. First, we explain the provisions that should be made for the *Communications System*. We then pursue the development of the *Condition Monitoring System* itself, and conclude with the design for the *User Interface and Decision Making System*.

4.1 COMMUNICATIONS SYSTEM

To design the *Communications System*, we should first ask ourselves what the consumer of our product would like to see. Applying axiomatic design, we propose the below Customer Needs (CNs), Functional Requirements (FRs), and associated Design Parameters (DPs); these selections are largely based upon our own experience and a review of the existing product literature [1-15] as seen in Table 4-1.

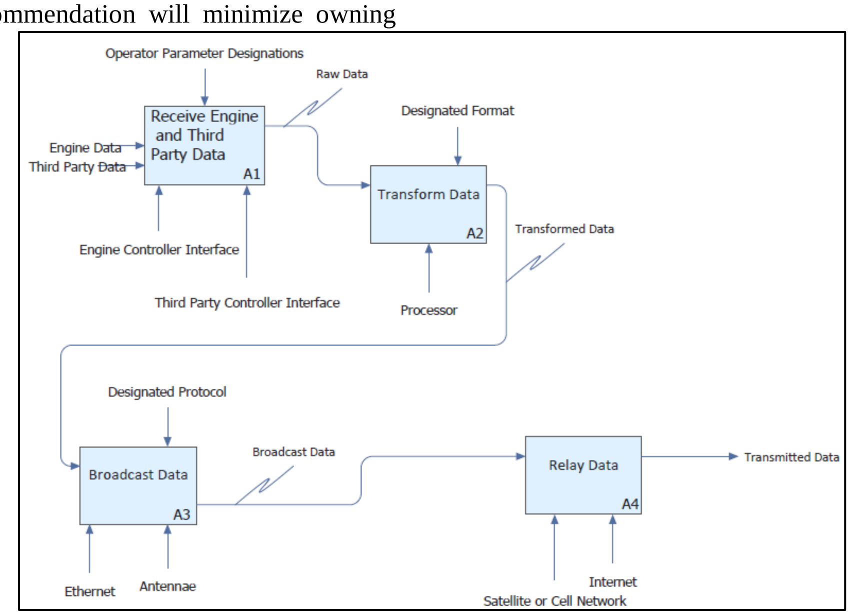

Figure 4-1: IDEF0 Diagram for Communications System

Table 4-1: Customer Needs, Functional Requirements, and Design Parameters for Communications System

CNs	FRs	DPs
Monitor assets in real time.	Real-time sampling.	Sampling capability of equipment.
Minimal downtime, and should not experience a major failure before an engine overhaul.	High reliability.	Redundancy (locally, within the communications network, and at destination).
		Reliability (system should be 85% reliable for at least an overhaul interval for the associated engine, with individual components being more reliable than the system as a whole).
Allow local and remote access.	Local and Remote ports.	Network characteristics (e.g. Ethernet, Fiber, antennae).
		Engine – communications system interface.
Easy integrated with equipment	Easy serviceability and setup.	"Black Box"/easily integrated and expandable components.
	Common, well documented networking protocols.	Network Protocol (e.g. Modbus).
	Common, well documented networking architecture.	Network characteristics (e.g. Ethernet, Fiber, antennae).
	Allow for interface with third party controllers and instrumentation.	Third party equipment – communications system interface.
	System should be turnkey.	"Black Box"/easily integrated and expandable components.
Little or no geographical limitations.	Option to utilize different communications media (e.g. satellite, cell networks)	Network characteristics (e.g. Ethernet, Fiber, antennae).
System should be secure.	System Security.	Firewalls.
	System backup (cloud).	Backup capacity.
Ability to monitor multiple assets.	Expandability (to include multiple assets).	"Black Box"/easily integrated and expandable components.
	Network should support at least 100 machines.	Engine – communications system interface.
		Third party equipment – communications system interface.
		Network Protocol (e.g. Modbus).
		Network characteristics (e.g. Ethernet, Fiber, antennae).
System should be affordable.	Low cost.	Equipment cost.

For example, in order to accomplish the requirement that we have a reliable system, we can provide either reliable equipment or redundant equipment – or both. In order to meet customer needs for integration, we should select a well-documented, common network protocol and physical characteristics (e.g. Modbus, Ethernet connections, FTP). We should also ensure that each component in our communications system is a "Black Box" – that is, the components receive a specified input and output in a known format without giving our customer any trouble or need to understand the operation at a low level. In doing so, we ensure easy serviceability and setup, and we lay the groundwork for an expandable system and keep costs down. This is shown by using IDEF0 in Figure 4-1 and a system schematic in Figure 4-2.

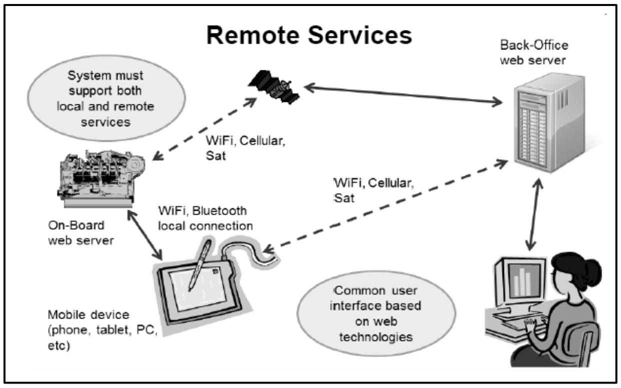

Figure 4-2: Illustration of Example System

4.2 ENVIRONMENT-BASED CONDITION MONITORING SYSTEM

To design the *Condition Monitoring System*, we again will need to look at possible consumers. However, in our experience, the consumers of engine data tend to need significant direction from the engine manufacturers in knowing what data to collect [10,14]. Really, there should only be a few customer needs here: the system should monitor the manufacturer-recommended parameters and the user-defined parameters related to third-party equipment, while marshalling all the data at a single access point.

For example, the engine manufacturer may recommend and provide the capability (via a suite of instrumentation) to monitor the air filter differential pressure, engine oil pressure, fuel filter pressure, ambient air temperature, bearing temperatures, fluid levels (coolant, oil, fuel), and a host of other parameters. Users, in our experience, may request to monitor equipment corrosion (or atmospheric salt); they might also be concerned about determining engine-room air quality for the safety of operating personnel, and seek to incorporate CO sensors, H2S sensors, and the like[10]. We formulate a list of CNs and FRs based on this knowledge and present the information in Table 4-2.

Table 4-2: Customer Needs, Functional Requirements, and Design Parameters (Condition Monitoring System)

CNs	FRs	DPs
Monitor manufacturer recommended parameters.	Measure engine manufacturer suggested variables.	Engine instrumentation suite (e.g. MPUs, pressure/temperature sensors).
Monitor user-defined parameters (e.g. atmospheric quality, device location, fuel content).	Allow for integration of user sensors into the condition monitoring system.	Customer instrumentation suite (e.g. air quality monitor, location/GPS)
The data should be collectible at a single source.	Marshal collectable data in a single location.	Engine master controller.
	System uses industry standards for all sensors, or proprietary ones if they exceed specifications and are well documented.	Customer master controller.
		Marshalling box(es).
		Industry standards.

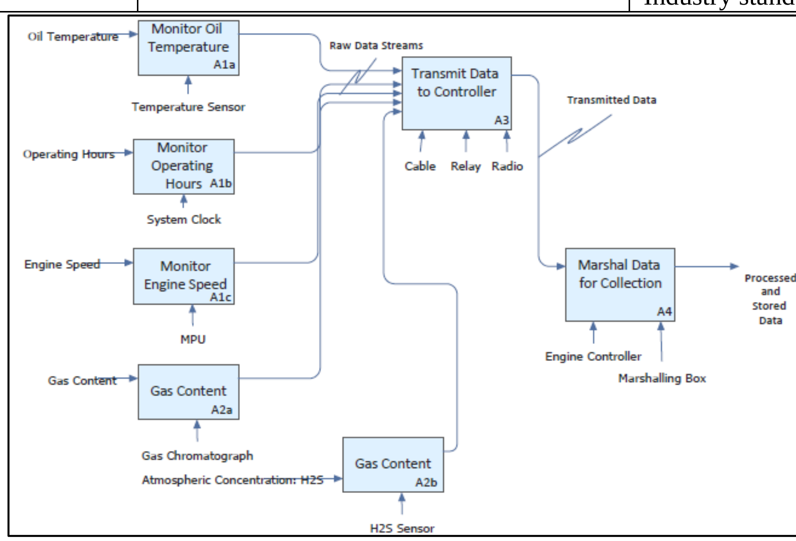

Figure 4-3: IDEF0 Diagram for Condition Monitoring System

Our condition monitoring system should be designed in such a way that both the engine data and customer data can be marshalled at a single point for collection by our *Communications System*. The instrumentation suites are highly variable depending on where the assets are operated, and should be decided on a case-by-case basis. When working with a customer, this should best be handled at the beginning of a project, to avoid integration issues. This is shown in Figure 4-3.

4.3 USER INTERFACE AND DECISION MAKING SYSTEM (PREVENTATIVE MAINTENANCE)

Finally, we must consider the *User Interface and Decision Making System*. A good system should advise maintenance decisions based on manufacturer recommendations and user-defined indicators and alert the users when maintenance is needed. It should keep records of operation and maintenance activity for all desired assets, should illustrate benefits and risks of performing or not performing maintenance, and should be designed intuitively and simply. The customer needs and functional requirements are included in Table 4-3.

Much of this is dependent on the engine manufacturer. For example, engines will have unique oil change intervals to use as a scheduling template, but there should also be a decision made based on oil degradation, perhaps determined by a change in viscosity suggested by the oil manufacturer, which both should play into the development of a decision making algorithm. This scenario should hold for all engine parameters and for third party monitoring (e.g. hazardous gas concentrations). [12,13]

Users should be able to monitor cost savings, costs to perform maintenance, maintenance histories, and the like. They should also determine the format of their interaction with the system – be it a mobile interface or website – and the manner in which they receive alerts. It is very common to receive requests for smartphone alerts when working with SCADA systems. The top level use case is shown in Figure 4-4.

Table 4-3: Customer Needs and Functional Requirements for User Interface and Decision Making System

CNs	FRs	DPs
Illustrate purpose and cause for maintenance, while providing maintenance recommendations.	Advise maintenance decisions.	Decision making algorithm.
	Interpret engine data.	Manufacturer recommendations (e.g. maintenance schedules).
	Illustrate risks and benefits of preventative maintenance.	Accounting algorithms.
Allow access to history of all included assets.	Maintain a history of all assets.	Database.
Send alerts to users via customer defined medium when maintenance is needed, and prioritize alerts.	Be able to broadcast alerts email.	Email alert system.
	Be able to broadcast alerts over SMS	SMS alert system.
	Be able to broadcast alerts over Phone	Phone alert system.
	Prioritize alerts – from minimal concerns to emergency alerts.	User interface programming.
Intuitive to use, and have a GUI.	User interface should be simple.	User interface design.
	Open source database access language	Language (e.g. QT, SQL).
	System designed in accordance with recognized and nomenclature.	Relevant standards (e.g. MIL-STD-1472G)
System should display real-time information for all assets.	User interface should show location of assets and display desired information.	User interface design.
	Machine Template Design	Machine templates.
System should be customizable to allow for user defined events and scheduling.	User should have the capability to set custom alerts and events.	User interface programming.
Tiered Access for different users (e.g. government organizations).	Different user access levels.	User interface programming.
Emergency personnel are able to access the system, and be alerted in a disaster.	System uses standards for notifying emergency personnel specific to region.	Relevant standards.

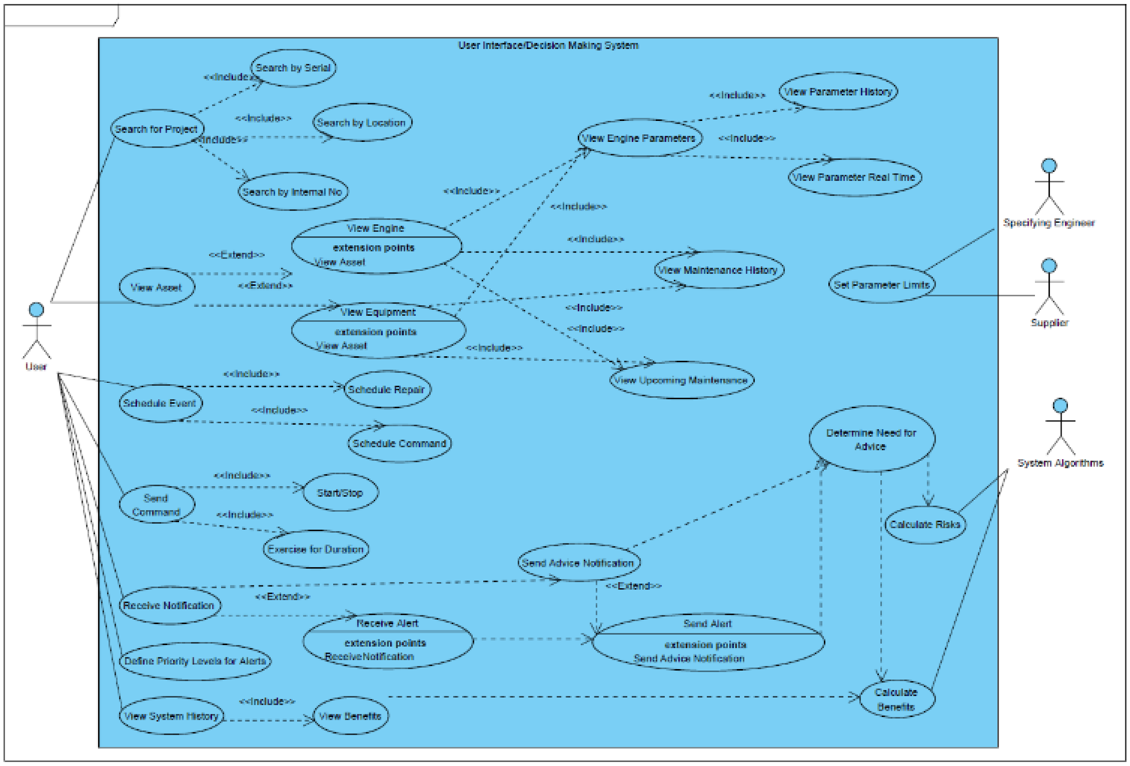

Figure 4-4: Use Case Diagram for User Interface and Decision Making System

5 EVALUATION

In order to understand how the remote monitoring system compares to other systems on the market, an evaluation of three currently available remote monitoring systems was performed. In these evaluations, the features of the Use Case systems were compared to the determined functional requirements of our remote monitoring system. This allowed for an understanding of the locations in which the new system outperforms its competitors.

5.1 APT REMOTE MONITORING SYSTEM

The Advanced Power Technologies monitoring system was designed to monitor parameters on systems at remote locations. The system works on any third party engine and allows the users to read current and historical data on their system from the comfort of their own home or office. The system is lacking in the diagnostics department. Although parameters can be monitored and recorded on a number of different systems, the data is not analyzed in any way. Therefore this system fails to meet many of the requirements laid out by the function requirement breakdown performed by the team. The functional requirements not met by the system are displayed in Table 5-1.

Table 5-1: Functional Requirements Not Met by APT

Advise maintenance decisions.
Interpret engine data.
Illustrate risks of not performing preventative maintenance. Real time risk assessment.

5.2 GE DIESEL RECIPROCATING ENGINE MONITORING SYSTEM

The GE Diesel Reciprocating Engine Monitoring System was designed and developed as a remote monitoring and diagnostics software specifically for GE Diesel Engines. The system allows users to view and record data in remote locations as well as analyzes the data and makes recommendations for repair when needed. The system meets many of the functional requirements of the team but is design primarily as a proprietary system. The system cannot be applied to other engine manufacturers and as such, it is limited in its capability of customization. Table 5-2 shows the functional requirements not met by the GE Diesel Engine RM&D software.

Table 5-2: Functional Requirements Not Met by GERM&D

Local server emergency fall back.
Allow for interface with third party controllers and instrumentation.
Allow for integration of user sensors into the condition monitoring system.
Marshal collectable data to Customer Team.
SMS alert system.
Phone alert system.
Map common variables across competitor engines.
Send special protocol information to alert emergency, OEM and government parties in case of engine disaster.

5.3 GE GAS TURBINE MONITORING SYSTEM 1

The System 1 GE gas turbine monitoring system is a remote diagnostics system design by GE to detect operational issues with GE gas turbines. The system records, monitors, and analyzes data continuously and alerts customers of issues if anything is found. Since the system was primarily designed to detect failures in the turbine system, it is lacking in many of the remote monitoring features that are included in other systems. The System 1 technology does not have a remote portal to view current running conditions of the turbines. In addition, the system was designed for use with GE turbines only, so it does not collect data from other system. Table 5-3 highlights the functional requirements not met by System 1.

Table 5-3: Fundamental Requirements Not Met by System1

Allow for interface with third party controllers and instrumentation.
Give third parties (government and OEM agencies) access to all relevant metrics based on security rolls.
Allow for integration of user sensors into the condition monitoring system.
Marshal collectable data to Engine Team
Marshal collectable data to Customer Team
Map common variables across competitor engines.

6 CONCLUSION

With an ever-growing concentration of responsibilities in different geographic locations (e.g. plant management vs. plant location) and regarding the benefits of preventative maintenance (and to aid it, diagnostic tools), the deployment of remote condition monitoring systems is only going to become more ubiquitous and more important. Here, we have proposed, based on the evaluation of existing systems and our experience, how to design an effective remote condition monitoring system that meets the needs of the user. We have made use of *Axiomatic Design* to propose an ideal system.

We have suggested these systems be considered as at least three subsystems – *Condition Monitoring, Communications,* and the *User Interface*, to aid in an effective design. By doing so, it becomes easier to employ specialized technologies and expertise in solving relevant problems.

We have also shown a functional breakdown of each subsystem, making it clear how such systems might be developed. Finally, we have shown how our proposed system compares to what exists in the field today, and how currently deployed systems might be improved.

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ANNEX A

ADVANCED POWER TECHNOLOGIES REMOTE MONITORING SYSTEM FOR GAS RECIPROCATING ENGINE

Introduction: APT Background and History

Advanced Power Technologies (APT), based in Lafayette, IN, is a manufacturer of power management and distribution systems; they specialize in creating these systems for generator sets operating in standby and prime power applications, and have extensive experience with Caterpillar stationary engines.

One product offered by APT is *APT View*; a custom Supervisory Control and Data Acquisition (SCADA) system. APT View allows the customer to control and monitor their equipment both on personal computers and via a web application.

Key Challenges to APT in Deployment of APT View for an Anaerobic Digester Facility

APT was given the task of developing a monitoring and control system for an Anaerobic Digester Facility, in which cow manure at a dairy farm would be converted to fuel in order to run a Caterpillar reciprocating gas fired engine. Disregarding the technical challenges in creating the digester system or modifying an engine to run on the digester gas, APT had to ensure that specific engine parameters could be monitored by the customer, had to monitor power plant output/performance, had to monitor digester pressures, flare temperatures and flow, and had to clearly display gas consumption for collection by the EPA (which would grant credits to the customer based on the 'clean' power they produced and distributed to the surrounding community). All of this information had to be available in real time and historically, and had to be available to different parties, in different geographic locations, with different levels of access. Further, the system had to be easily usable and understood, and had to issue alarms via email to the customer when faults were detected.

Referring to the previous table, it is readily apparent that APT had a great deal of information to make available in a concise manner.

Summary/Solution

APT created a user interface and system of alarms in order to meet the customer needs. In order to access the system, the user needs only the IP address of the controlling unit onsite and a password; upon accessing the system, all users are greeted with the below screen:

Table A-1: Measured Parameters and Sources (Customer Needs for Condition Monitoring System)

Parameter to be Measured	Source
Total Gas Consumption	Boiler
Total Gas Consumption	Engine-Generator
Total Gas Consumption	Flare
Flare Temperature	Flare
Flare Flow	Metering Valve (Flare)
Digester Gas Pressure	Digester
Boiler Flow	Metering Valve (Boiler)
Discharge Pressure	Vent
Gas Flow	Engine-Generator
Phase and Average Voltages	Engine-Generator
Frequency	Engine-Generator
ekW Output	Engine-Generator
kVAR Output	Engine-Generator
Breaker Status	Engine-Generator
Engine-Generator Faults	Engine-Generator
Power Factor	Engine-Generator
Engine Speed	Engine-Generator
Engine Hours	Engine-Generator
Battery Voltage	Engine-Generator
Engine Oil Pressure	Engine-Generator
Coolant Temperature	Engine-Generator
Inlet Air Temperature	Engine-Generator
Oil Filter Differential Pressure	Engine-Generator
Turbocharger Outlet Pressure	Engine-Generator
Phase and Average Current	Engine-Generator
Load Levels	Engine-Generator
Cylinder Temperature	Engine-Generator
Bus Phase Voltages	Bus
Bus Frequency	Bus
System Alarms	Any/All

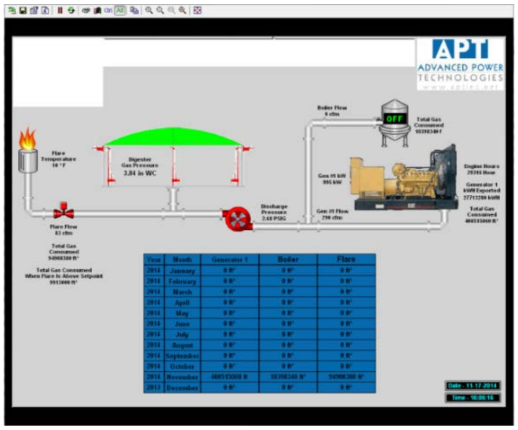


Figure A-1: Initial Screen

This screen has representative icons for system components – the flare, valves, vent, digester, boiler, and engine-generator. These icons are instantly recognizable by a novice user, and can be selected for further details. Also of note here is the large, blue spreadsheet at the base of the screen – this shows total gas consumption in any given month. Users from the EPA are only allowed to access this screen, and can quickly access information related to the awarding of credits – the kWh exported and the gas produced/consumed.

Should the user select the engine-generator icon, they are greeted with the below screen:

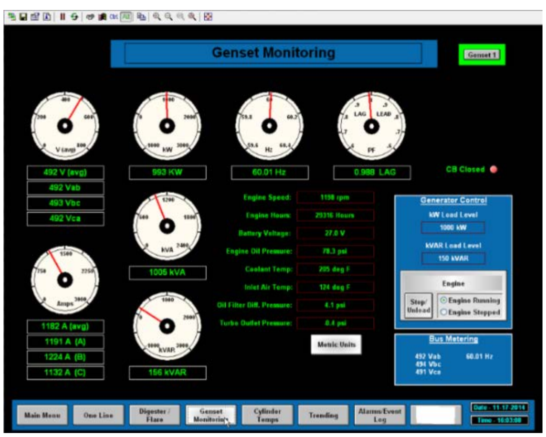


Figure A-2: Genset Monitoring Screen

From this screen, the user can quickly view and record various engine-generator parameters; they can view the units in metric or customary units, and they can also access various other screens showing additional data. For example, they might want to see the system one line to see if the system bus is energized:

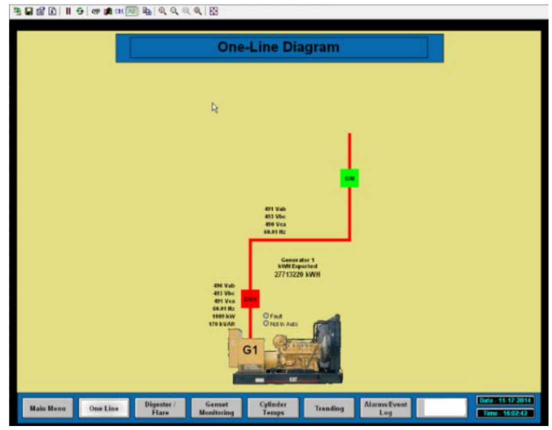


Figure A-3: System One-line

This screen also illustrates if there is a faulted condition with the generator. The fault details can be accessed in the Alarm Event Log. If the generator main breaker is closed, typically the open condition will break the continuous red line, and if the bus is energized, along with various electric power metrics.

The user can also view engine cylinder temperatures which are of major concern with gas reciprocating engines, as the gas-fired units can run at very high temperatures, damaging gaskets, seals, and the like:

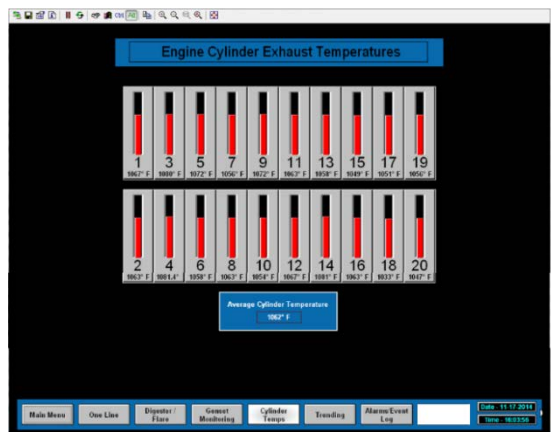


Figure A-4: Cylinder Exhaust Temperatures

Or the user can view a trend of any data points the system collects:

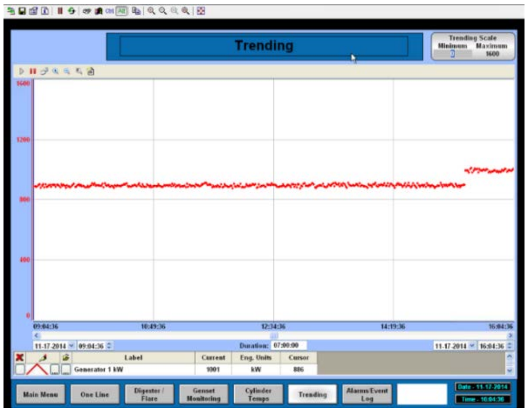


Figure A-5: Generator kW Trending

Here, the user can choose to display any number of parameters for any duration. The "Trending Screen" pulls data from a system parameter log which is built over time as the system polls the remote site (this system was setup to poll the site every minute). The system parameter log is stored by APT on their servers, and is a simple database that can be repurposed by the user or by APT to make maintenance decisions or show other system trends:

B	C	D	E	F	G	H	I	J
	Gen1_Batt_Volt	Gen1_Coolant_Temp	Gen1_Current_A	Gen1_Current_B	Gen1_Current_C	Gen1_Eng_Oil_Pres	Gen1_Eng	Gen1_Freq
0:00:00	26	98	471	480	471	414	1800	60.04
0:01:00	26	93	464	474	465	417	1799	60.03
0:02:00	26	95	464	475	465	415	1800	60
0:03:00	26	99	454	464	457	410	1799	59.99
0:04:00	26	91	455	465	456	419	1799	59.99
0:05:00	26	95	468	477	469	419	1800	60
0:06:00	26	97	478	489	481	415	1800	60.02
0:07:00	26	97	453	463	455	414	1798	59.99
0:08:00	26	94	456	466	458	412	1799	59.99
0:09:00	26	99	463	470	463	411	1799	59.99
0:10:00	27	89	458	466	457	419	1798	59.97
0:11:00	26	94	460	467	459	416	1798	59.96
0:12:00	26	97	461	469	459	414	1798	59.97
0:13:00	26	97	461	466	457	414	1799	59.96
0:14:00	26	99	467	471	462	410	1798	59.96

Figure A-6: System Parameter Log

In this case, APT is not ultimately responsible for maintenance decision making, and this would lie squarely with the customer or plant management staff. The goal of this system was simply to provide remote access and monitoring capability to the user. Either party, however, retains the ability to setup various alerts – for example, the user can setup an alarm if the oil pressure dips below a certain threshold, although in practice this is usually indicated by the engine controller and is set there. Via the website, the user can pull down a record of all system alarms, which can prove useful in locating problem components:

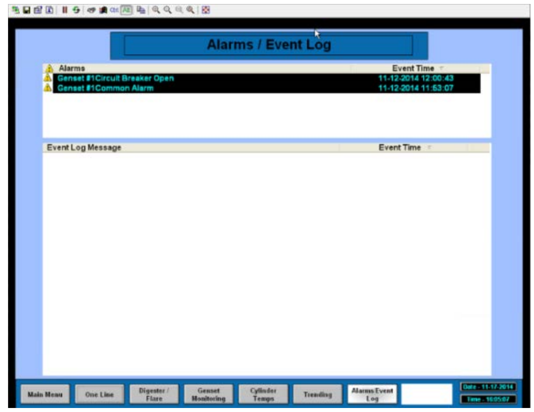


Figure A-6: Alarm Event Log

Alarms and alerts are also issued to the remote user via email; emails contain a breakdown of the system alarms to be addressed:

```
Alarm Summary

003|05/03/2011|07:56:29.751|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|07:56:52.126|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|07:57:14.001|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|07:57:21.516|Gen1_CAR|Genset #1Common Alarm|1|1|1.000000|1|0| |2|1|
003|05/03/2011|07:58:47.188|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|07:59:09.688|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|07:59:17.219|Gen1_CAR|Genset #1Common Alarm|1|1|1.000000|1|0| |2|1|
003|05/03/2011|08:01:22.282|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:01:44.157|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:01:45.360|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:02:06.657|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:02:30.438|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:02:50.735|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:03:13.157|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
003|05/03/2011|08:03:14.407|Gen1_Batt_Charger_Alm|Genset #1 Battery Charger Alarm|1|1|1.000000|1|0| |2|1
```

Figure A-7: Alarm Summary for Genset 1 (Email Attachment)

Users can access the system via any means that allows them to browse the internet, provided they have access to the IP address and password of the onsite hardware:

Figure A-8: Mobile View

The SCADA system is also easily expandable and can be modified as the onsite conditions change and the design evolves. For example, should the user need to add a secondary engine:

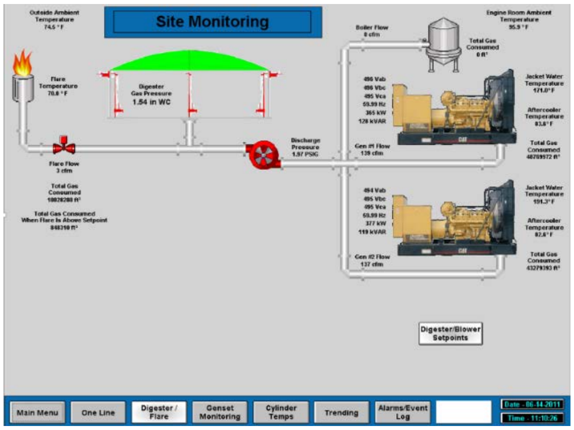


Figure A-9: Paralleled Engines

Conclusion

APT created an intuitive user interface that displayed all the requested system parameters (i.e. they met the needs of the customer). This system has been invaluable to the customer when working with the EPA and has made it much easier to justify the installation of a digester and engine-generator for power output – they can quickly quantify how much power they have exported, which is a source of revenue for the dairy farm. Further, the user is provided with a log of all the relevant engine operating data, which allows them to view trends and draw conclusions about maintenance before a catastrophic failure. The cylinder exhaust temperatures are of particular interest. Finally, the user receives alerts when issues arise, allowing them to make decisions quickly, and minimize potential downtime at the site without purchasing additional hardware (e.g. redundant generator sets).

References

[1] (2014) APT View SCADA. Retrieved from http://www.apt-power.com/products/process-controls/scada-systems/.

[2] A. Stesselboim, Personal Communication, November 2014.

ANNEX B

GE TRANSPORTATION REMOTE MONITORING AND DIAGNOSTICS SOFTWARE IN AFRICAN APPLICATIONS

Introduction: GE Remote Monitoring and Diagnostics

GE Transportation remote monitoring and diagnostics software was developed by GE for the application of GE's locomotive business. When a locomotive is sold, the customer is given an option to purchase a maintenance and service agreement with their new locomotive. This agreement begins a 20 year partnership with the customer and GE. The customer agrees to pay for a yearly subscription to GE and in return GE performs routine maintenance and repairs on the locomotive. In addition to the performing all maintenance and repairs, GE also guarantees a reliability for the customers product.

In an effort to reduce failures and better understand fleet operation, GE Transportation developed the GE Remote Monitoring and Diagnostics Software. Remote monitoring and diagnostics continuously monitors engine and locomotive parameters. Algorithms perform analysis on the parameters received and issue recommendations for repairs when anomalies occur. The issued recommendations and data are analyzed by GE experts and sent to the field when work is needed.

As of recent, the GE transportation team has come to the decision to expand the Remote Monitoring and Diagnostics Software into the stationary power industry. Data is analyzed and monitored using the same tools as the locomotive industry and recommendations are issued to the customer when if services are needed.

The African Market and Need for and Remote Monitoring and Diagnostics Software

The African Continent is one of the largest growth markets in the world for the diesel stationary power industries. Nigeria's unmet power demands are expected to exceed 200 GW by 2030. [1] The combination of a lack of established grid system, large oil deposits, and remoteness of power applications makes small scale power generation much more appealing than the large power plant alternative. In addition to the increasing need for power in Africa, the nation is one the harshest environments that a diesel engine will experience. Weather conditions reach extreme temperatures, air can be saturated with sand, and the labor is limited and typically less educated than a similar power application in a more developed location. The combination of these factors makes an African Diesel Power Plant an ideal location for the implementation of a remote monitoring system. The system aides in the lack of educated labor and can more closely monitor the condition of systems in an extremely harsh environment.

GE RM&D Capabilities

The GE RM&D software has capability of remotely monitoring and analyzing data continuously from Diesel engines all over the world. The system constantly uploads engine parameters to a remote location where they are monitored and analyzed. Data is uploaded with a number of different technologies including WIFI, cellphone, satellite, and land lines. The remote monitoring system has the capability of monitoring all the parameters listed in Table B-1.

Table B-1: Measured Parameters on GE Diesel Engines

Parameters to be Measured	
Barometric Pressure	Engine Fault Status
Turbo Speed	Load Limit Status
Oil Temps (Inlet/Outlet)	Engine RPM
Water Temps (Inlet/Outlet)	Engine HP output
Oil Pressures (Inlet/Outlet)	Fuel Demand
Water Pressures(Inlet/Outlet)	Fuel Value
Fuel Temperature	Engine Advanced Angle
Fuel Pressure	Engine Duration Angle
Air Temperatures	Air to Fuel Ratio
Air Pressures	ECU power supply status
Crankcase Pressures	Main Bearing Temperatures
Exhaust Temperatures	Starting Air Pressure
Engine Operating Mode	Pre-lube Pump Status
Increase Power Demand	Decrease Power Demand

Data obtained by the RM&D software is utilized in a three different methods. These methods are understanding fleet operation, automated analysis of engine health, and expert monitoring of engine health. Understanding the operation of your fleet is extremely important to power supplier all over the world. Reliable data on power usage and engine operation allows companies to plan operational maintenance and understand the potential need for additional power. Figure B-1 depicts a typical power usage plot of a GE diesel engine produced by the GE RM&D system. Using the plot show in Figure B-1, a power generation company can ascertain that their Generators are rarely operating in optimal efficiency range (80%). This should lead them to better management of their generator fleet.

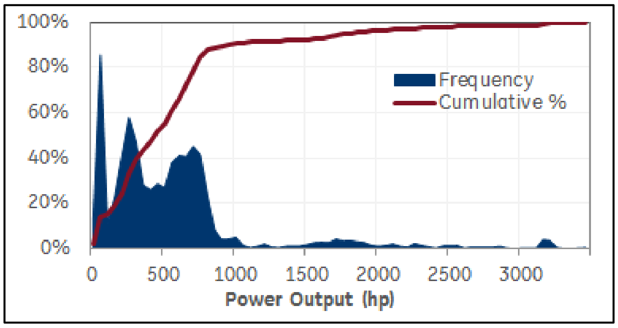


Figure B-1: Horsepower Output of Diesel Engine

In addition to operational awareness, the GE RM&D system does continuous automated analysis on data that is remotely received from a GE engine. The data is run through two analysis tools. The first tool is a rule based algorithm tool that allows the user to pinpoint issues by comparing multiple engine parameters to one another. If all conditions are met, the system will initiate a recommendation for repair to GE experts. The second automated system analyzes data trends over time and looks for changes in the data. Changes in data trends typically indicate that some issue is present with the engine. Many times a data parameter trending upward can indicate an issue prior to a stationary alarm. One such parameter that is trended is crankcase pressure. If the crankcase pressure begins to trend up, on site representatives are recommended to perform cylinder liner and turbo inspections to ensure extra air is not entering the crankcase. Figure B-2 depicts data from a GE Diesel Engine. Note the recommended operating limit has not been exceeded but the rise in crankcase pressure during steady state operation indicates an issue with the engine.

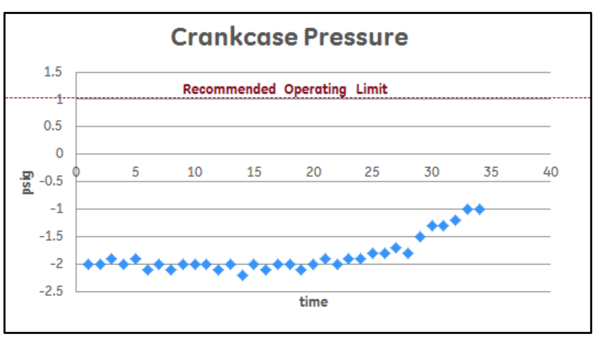


Figure B-2: Crankcase Data from GE Diesel Engine

The third method that RM&D data is used is manual monitoring of engine parameters. At any given time, the GE RM&D system allows users to view existing running conditions of the engines. This data is accessible by web portal. The data available is not only the current running condition of the engine but also historical data. This allows users to plot and manipulate data in any method that is best served for their purpose. It also allows data to be quickly inputted into other fleet management systems such as MAXIMO or Oracle. In addition to viewing data, users can monitor open engine issues on their entire fleet from a centralized location. Figure B-3 depicts a set of open engine issues that are on a customer fleet. Note: customer information omitted for privacy reasons.

Urgency	Case	Asset	Road Initial	Customer	Status	Title	Creation Time
W	P911065	625120019	[redacted]		Open	Engine Exh Temp Deviation from Average Cyl temp (L4)(250)(Thre1)	11/24/2014 18:22:29
W	P910146	625120012			Open	Oil Filter Pressure Differential (250)(Thre1)	11/24/2014 04:23:22
W	P907239	625120011			Open	Oil Filter Pressure Differential (250)(Thre1)	11/22/2014 04:40:07
W	P907183	625130006			Open	Low Fuel Pressure Detected (250)(Thre1)	11/22/2014 02:14:53
W	P907173	625120004			Open	Hot Manifold Air Temp (250)(Thre1)	11/22/2014 02:00:06
W	P906797	625120015			Open	Oil Filter Pressure Differential (250)(Thre1)	11/21/2014 18:00:31
Y	P906783	625120015			Open	Engine Fuel Temp Sensor (EFT) (250)	11/21/2014 17:50:06
Y	P906782	625120016			Open	Fuel Oil Pressure Sensor (FOP) (250)	11/21/2014 17:49:45
W	P906744	625120013			Open	Low Fuel Pressure Detected (250)(Thre1)	11/21/2014 16:44:09

Figure B-3: Open Engine Issues in GE RM&D portal

Conclusion

The diesel engine stationary power market is in dire need for remote monitoring systems on their power plants. The environment faced in remote continents such as Africa is one of the harshest in the world and requires constant monitoring by educated remote individuals. GE Transportation has created a monitoring tool that is capable of fulfilling the needs of its customers. Not only does it provide tools to view data remotely, it also provides tools to analyze and monitor the data. The system allows customers to be more at ease when setting up power plants in remote locations because their engines are being monitored continuously.

References

[1] (2014) *The Energy Collective*. Retrieved from http://theenergycollective.com/roger-pielke-jr/288381/graph-day-africa-power-needs

ANNEX C

GAS TURBINE CASE STUDY

Introduction

The General Electric *System 1* Condition Monitoring Software is a platform for real-time optimization of equipment. System 1 provides information on actual engine condition with remote access capabilities. One application of this software is on gas turbines at a North Sea offshore platform complex. The gas turbines are used to generate the platform's electricity and thus reliable operation is critical. This case study reviews the deployment of *System* 1 for the monitoring of gas turbines on an offshore platform in the North Sea, and in particular considers an interruption in power provided to the facility. [1]

Background – Facility

The Buzzard field is located in the central North Sea, 100 kilometers northeast of Aberdeen, UK, and 55 kilometers from the coast at Peterhead. The field consists of a gross oil column of 750ft that is expected to yield more than 550 million barrels of oil equivalent. The site complex consists of three interconnected offshore platforms operated by Nexen Petroleum U.K. Limited. The complex began producing oil in January 2007. At peak production, approximately 200,000 barrels of oil equivalent per day are produced. [4]

A total of three gas turbines are used to produce the platform's electricity. The turbines utilize lube oil to lubricate the thrust and journal bearings, provide cooling and prevent rust and corrosion. Lube oil is therefore vital to successful operation of the turbines. The primary source of lube oil for the turbines is an AC-powered pump which switches over to a DC-powered backup pump to maintain a minimal lube oil flow in the event of a power failure. During start-up of one of the gas turbine units, several unexpected trips occurred. The switch-over logic appeared to local operators to be functioning normally; however, analysis using the System 1 Condition Monitoring system found this was not the case. [1], [4]

Case Background – Software

Data for use with *System 1* is collected onsite and can be analyzed remotely. This case study involved a diagnostic services engineer working onsite and a diagnostics manager working from a corporate office who connected to the Buzzard complex site's System 1 Condition Monitoring system. The data analysis was performed remotely and the root cause was identified allowing the customer to take corrective actions. The gas turbine unit's machine train diagram from the System 1 software is shown in Figure C-1. The figure also shows the vibration transducer arrangement. [3], [2]

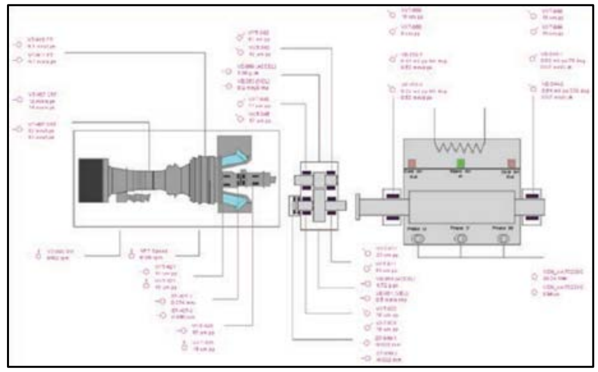


Figure C-1: System 1 Software Machine Train [2]

Case History

Not long after the Buzzard complex was commissioned, one of the gas turbine units tripped due to power interruptions with the control systems. The event occurred at 8:57AM on January 6th, 2007. Prior to this event, the unit was started, ramped up to normal operating speed, synchronized, and loaded to 2 MW. The load was increased to 5.5 MW and left running at stead-state conditions overnight. [1], [2]

It was determined that this trip was due to a failure in the control system. The failure interrupted power to the turbine control system, including the fuel gas detection subsystem. The system is programmed to trip the turbine when a loss of signal occurs. When the turbine tripped, operators also ensured that the DC minimum lube pump had switched on and was operational by checking the motor current indication in the main switch room. [1], [2]

On January 7th 2014 at 7:41AM, the unit tripped again this time from the plant shutdown system. When the turbine tripped, operators again ensured that the DC minimum lube pump had switched on and was operational. The unit was restarted and ran for approximately two hours before tripping a third time. The third trip was from the plant shutdown system. After the third trip, operators reviewed turbine data and observed excessive bearing temperatures during the January 6th trip. This information was relayed to the remote diagnostics team to determine the severity and consequences of the excessive bearing temperatures. The System 1 software was used to determine bearing temperature, gap voltage, and rotor speed measurements as shown in Figure C-2. These measurements were compared to baseline data. [1], [2]

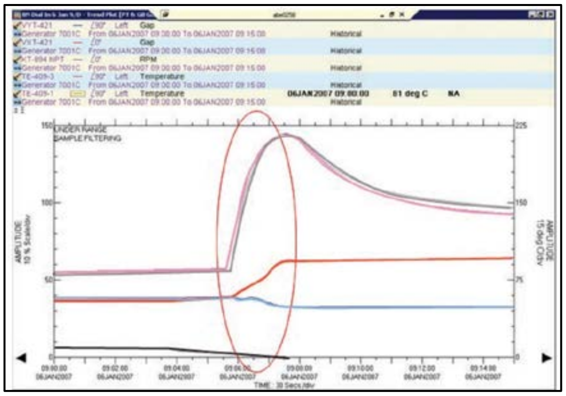


Figure C-2: System 1 Critical Parameters [2]

Bearing temperatures began to rise when the speed of the unit slowed to around 2400 rpm. This rapid increase in bearing temperature was thought to be due to a bearing rub. A corresponding increase in gap volts was also seen from the data. This could cause removal of bearing material due to contact between the rotating shaft and stationary bearing pads. Comparing gap voltages before the trip with those taken after the trip proved the rotor was sitting lower in the bearing. This conclusion was validated further by the fact that the increase in bearing temperature occurred at the same times as the gap voltage change. [1], [2]

To further confirm the conclusions, archived data for a "normal" coast down profile, Figure C-3 was compared with the coast down data from the trip, Figure C-4. [1], [2]

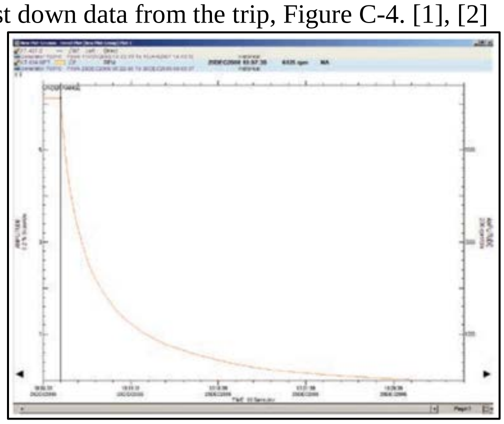


Figure C-3: "Normal" Coast Down Profile [2]

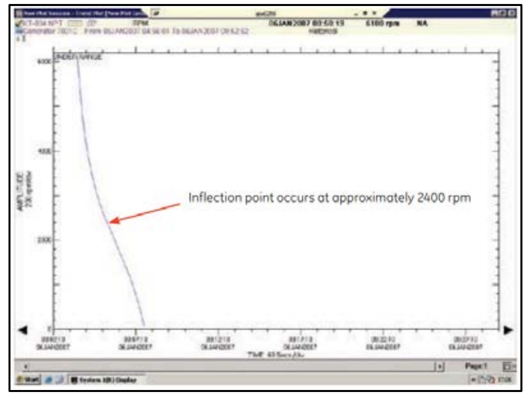


Figure C-4: Trip Event Coast Down Profile [2]

The coast down started normally but at approximately 2400 rpm, the rate of deceleration began to increase rather than decrease. This is an expected behavior if a rub is occurring and high frictional forces are being generated as the rotor slows. These actions would cause complete removal of rotor babbitt material and therefore a physical inspection is necessary. Upon physical inspection, a wiped bearing was found with signs that the damage was due to lack of lubrication.

The lube oil pumps were further inspected after the findings and the oil system's accumulator circuit was found to not be operating as intended. Oil pressure was not being maintained during the trip of the AC pump and following start of the DC pump. The DC pump was operational but the lube oil pressure was not adequate during the switchover. The control system logic was updated to maintain adequate oil pressure and the unit was returned to service without further incident. [1], [2]

Conclusion

The monitoring system used at the Buzzard complex allowed for a successful diagnosis of trip events of one of the complex's gas turbines. The System 1 monitoring system provided critical data to identify the root cause and a means for comparison to baseline operational data. The system's inherent remote capabilities allowed for quick diagnoses and direct support from off-site personnel. This eliminated delays and expenses.

References

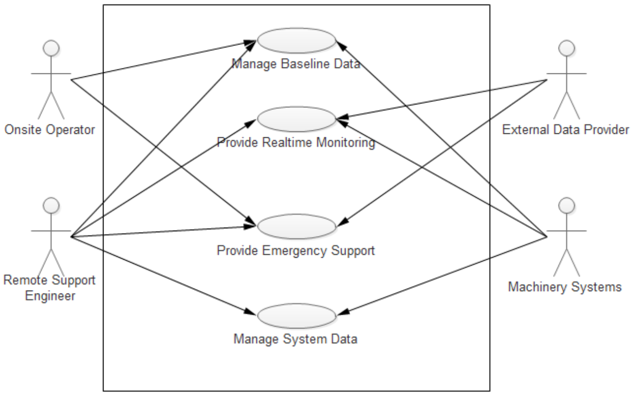
[1] GE Energy Services: Nexen Case Study:
Diagnosing a gas turbine problem from 800 km away

[2] GE Energy Services: Remote Machinery Diagnostic Services at Nexen Petroleum

[3] GE Measurement and Control

[4] Offshore Technology: Buzzarad Field Project

ANNEX D
USE CASES

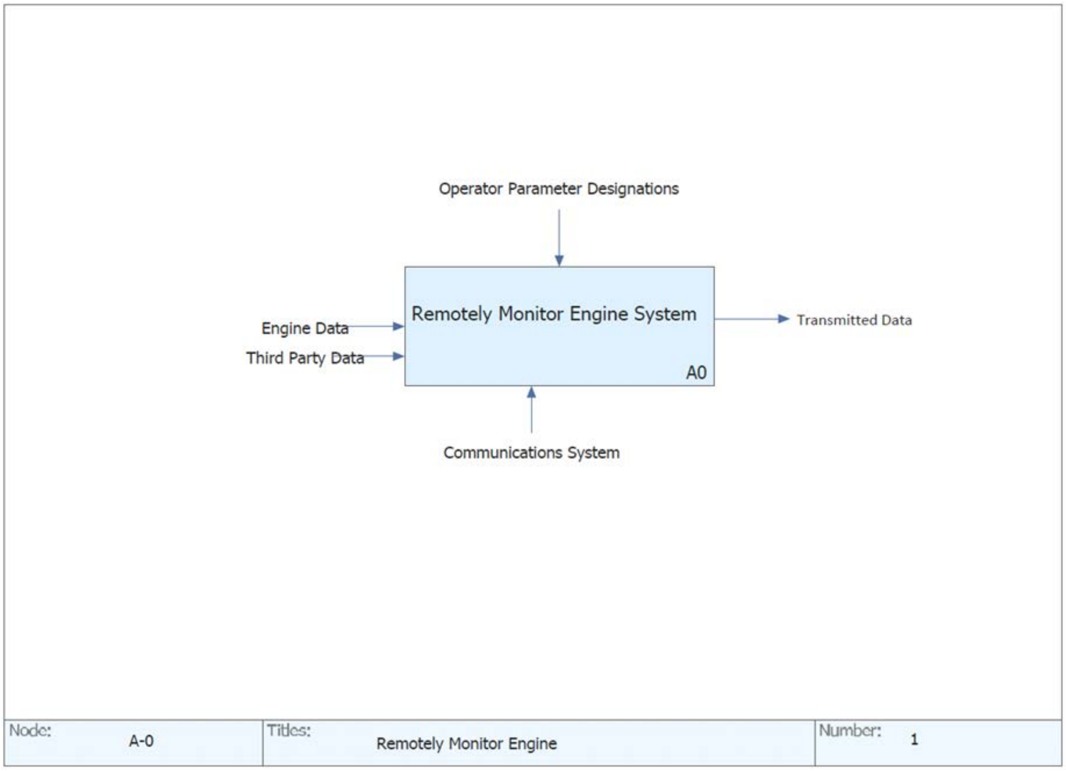


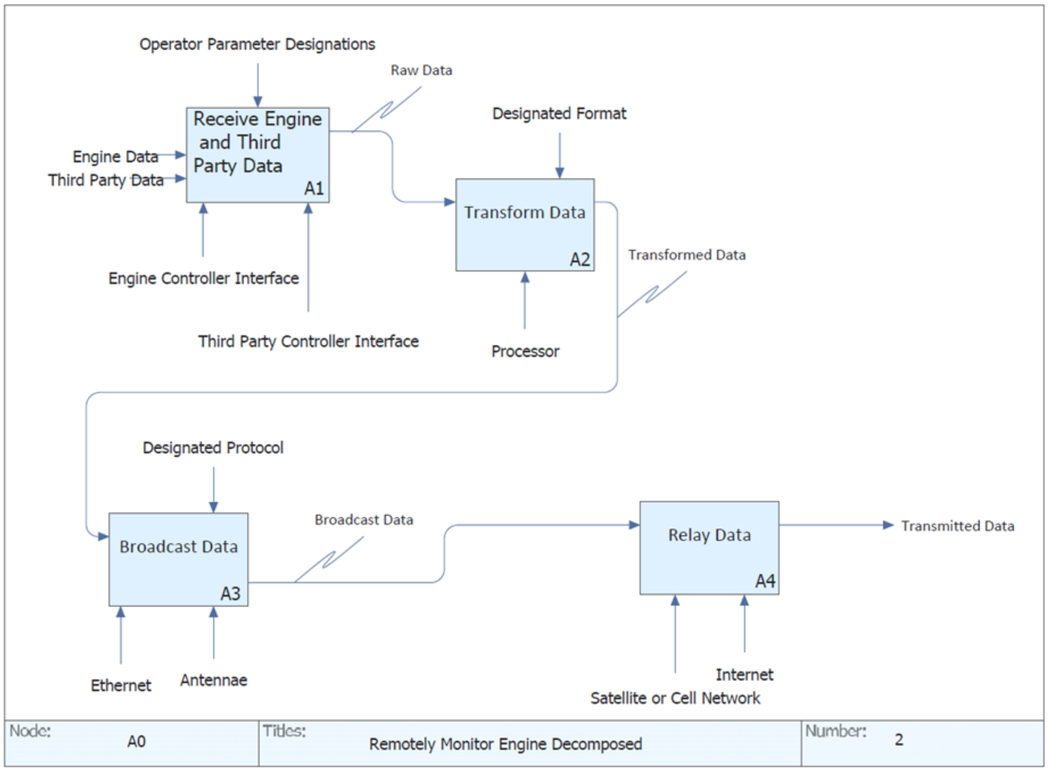
Use-Case: Provide Real-Time Condition Monitoring
Actors: External Data Provider, Machinery Systems, Remote Support Engineer
Trigger: Machinery is brought on-line
Preconditions: Machinery is off-line
Post Conditions: Machinery is off-line
Success Scenario: 1. System monitors operation such as temperatures, subsystems, oil condition, engine conditions, control systems 2. System provides notification 3. Assess routine issue 4. Identify automatic response 5. Send automatic notification 6. Record automatic notification 7. System communicates with Remote Support Engineer 8. Provide requested real-time data 9. Provide requested baseline data 10. System operates until scheduled maintenance
Alternatives Flows: System trips

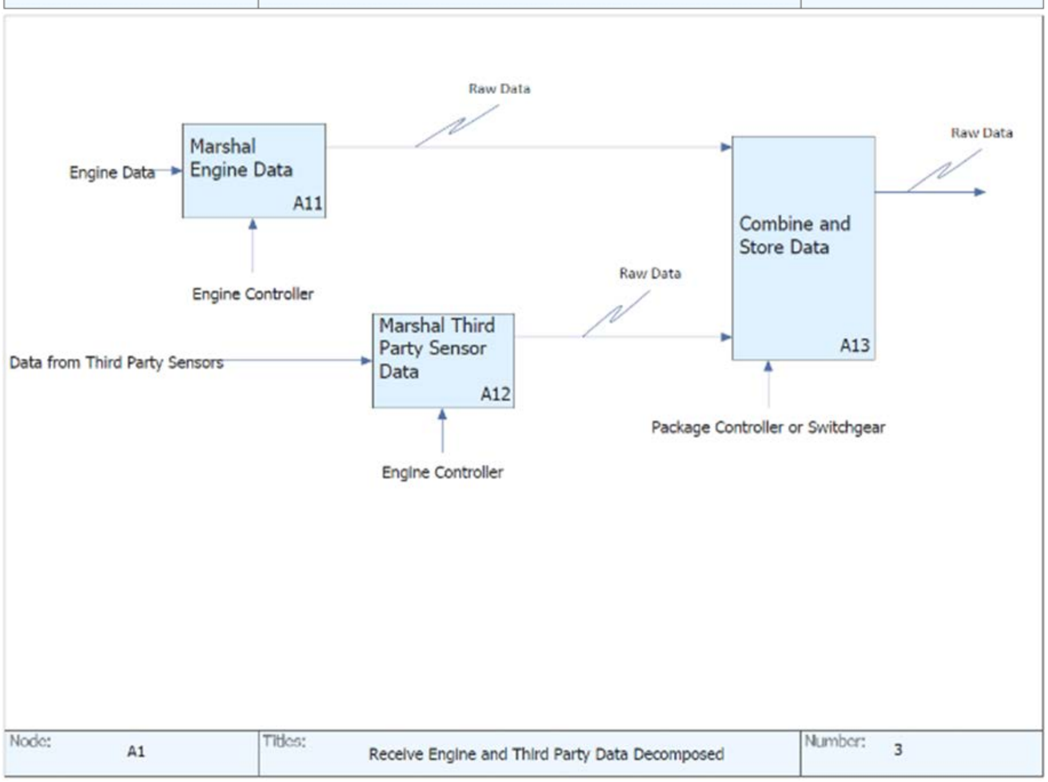
Use-Case: Manage System Data
Actors: Actors: Machinery Systems, Remote Support Systems
Trigger: System is brought on-line
Preconditions: System is off-line
Post Conditions: System records are up-to-date
Success Scenario: 1. System evaluate maintenance records 2. System update database with results of system monitoring 3. System analyze collected data, provide maintenance notifications 4. System update maintenance records
Alternatives Flows: System is taken off-line

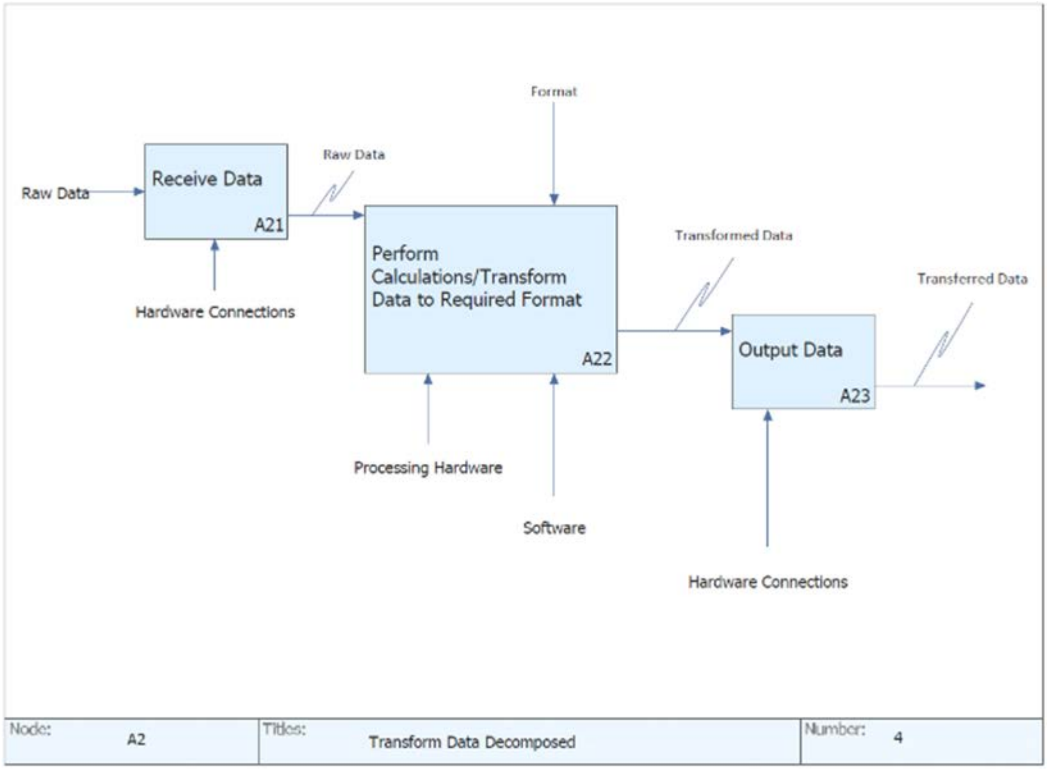
Use-Case: Provide Emergency Support
Actors: External Data Provider, Remote Support Engineer, Onsite Operator
Trigger: Identification of abnormal operation
Preconditions: Normal operation
Post Conditions: System operation recommendation provided
Success Scenario: 1.System assesses abnormal operation 2. Receive alert 3. Record alert 4. Identify alert 5. Contact onsite operator 6. System communicates with remote support engineer 7. Provide requested real-time data 8. Provide requested baseline data 9. Provide recommended response 10. Assess the situation 11. Identify recommended response 12. Send recommended response 13. Record recommended response
Alternatives Flows: System accesses normal operation or trips

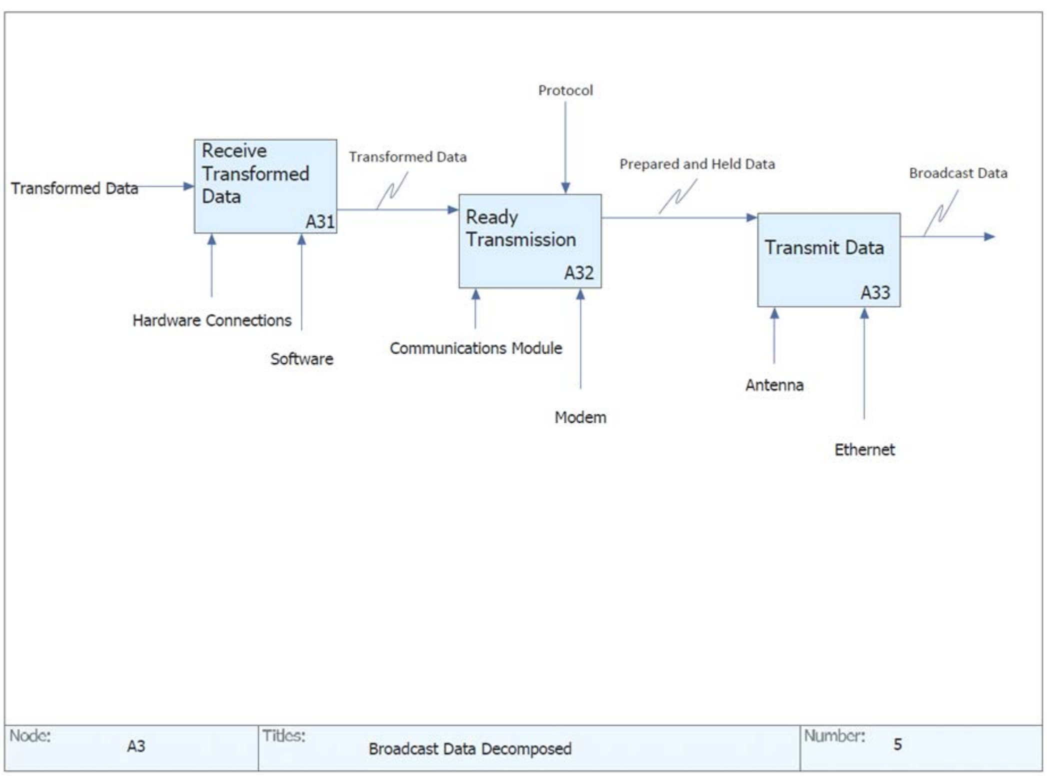
ANNEX E
IDEF0 DIAGRAMS

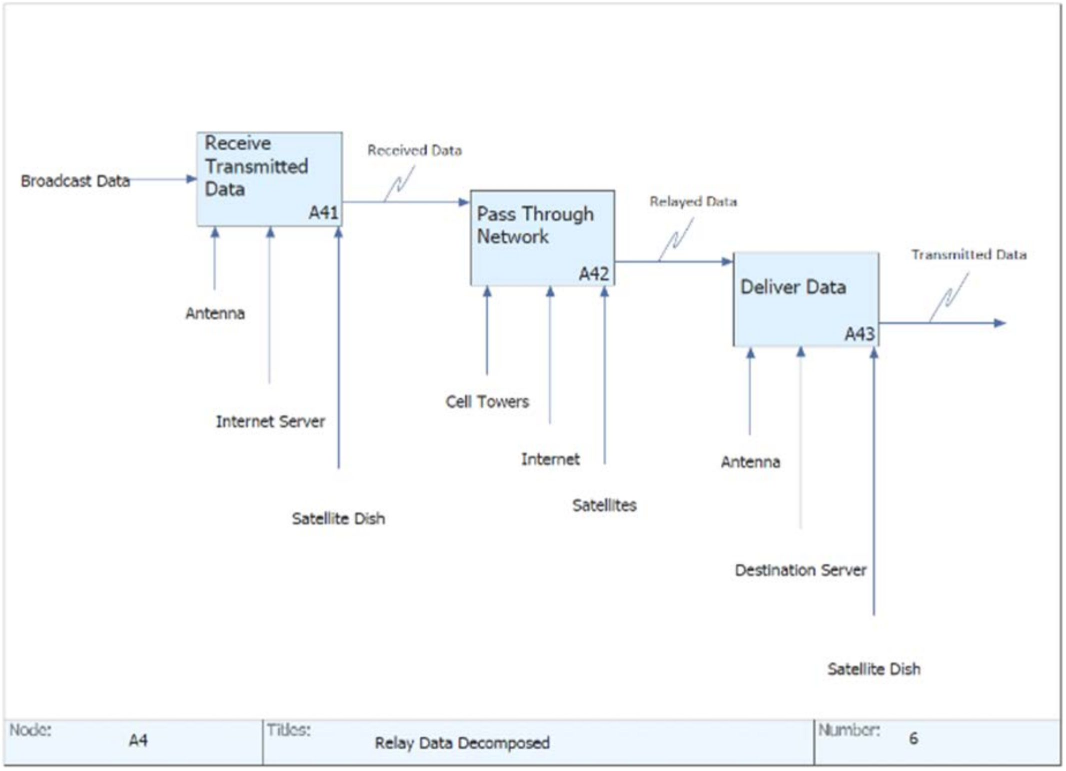



Operator Parameter Designations
Raw Data
Receive Engine and Third Party Data
A1
Engine Data
Third Party Data
Designated Format
Transform Data
A2
Engine Controller Interface
Third Party Controller Interface
Transformed Data
Processor
Designated Protocol
Broadcast Data
Broadcast Data
A3
Relay Data
A4
Transmitted Data
Ethernet
Antennae
Internet
Satellite or Cell Network
Node: A0
Titles: Remotely Monitor Engine Decomposed
Number: 2

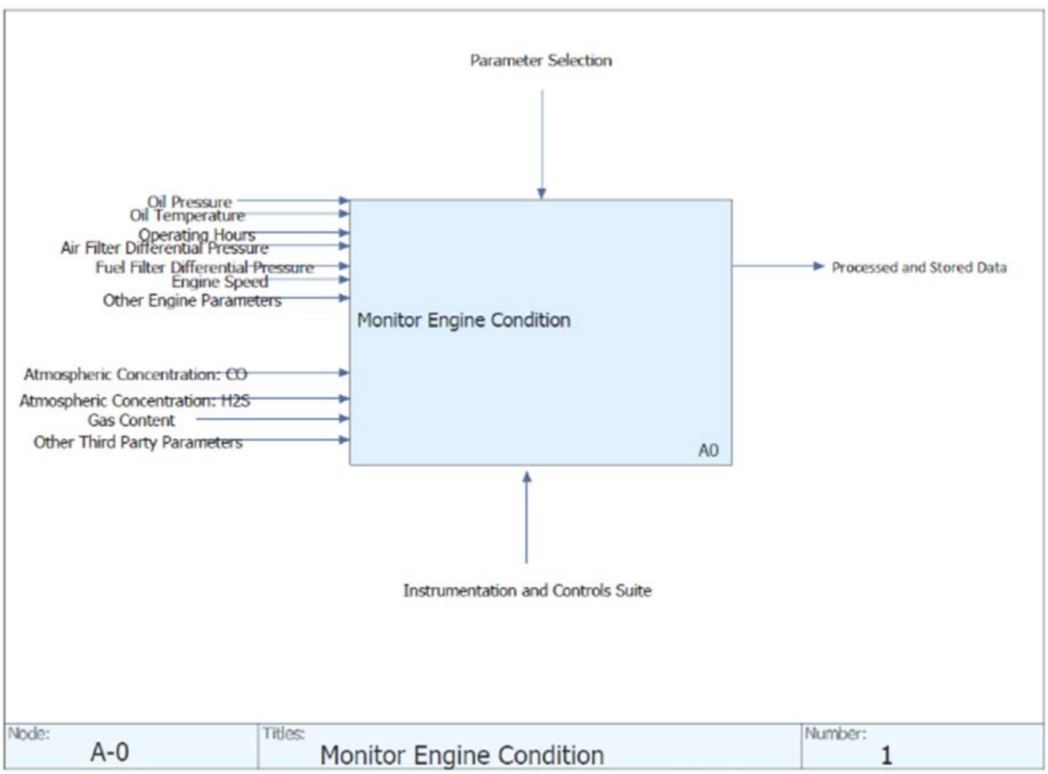

Raw Data
Marshal Engine Data
A11
Engine Data
Raw Data
Combine and Store Data
A13
Engine Controller
Raw Data
Marshal Third Party Sensor Data
A12
Data from Third Party Sensors
Package Controller or Switchgear
Engine Controller
Node: A1
Titles: Receive Engine and Third Party Data Decomposed
Number: 3


Format
Receive Data
A21
Raw Data
Raw Data
Hardware Connections
Perform Calculations/Transform Data to Required Format
A22
Transformed Data
Output Data
A23
Transferred Data
Processing Hardware
Software
Hardware Connections
Node: A2
Titles: Transform Data Decomposed
Number: 4

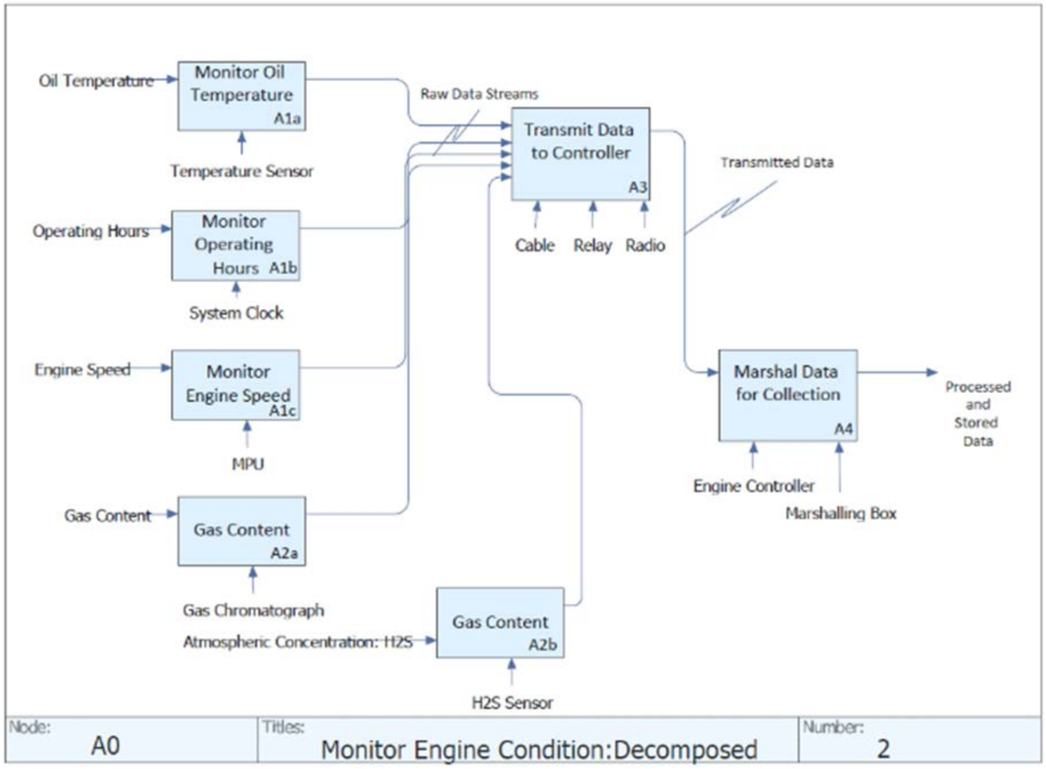

Protocol
Transformed Data
Receive Transformed Data
A31
Transformed Data
Ready Transmission
A32
Prepared and Held Data
Transmit Data
A33
Broadcast Data
Hardware Connections
Software
Communications Module
Modem
Antenna
Ethernet
Node: A3
Titles: Broadcast Data Decomposed
Number: 5

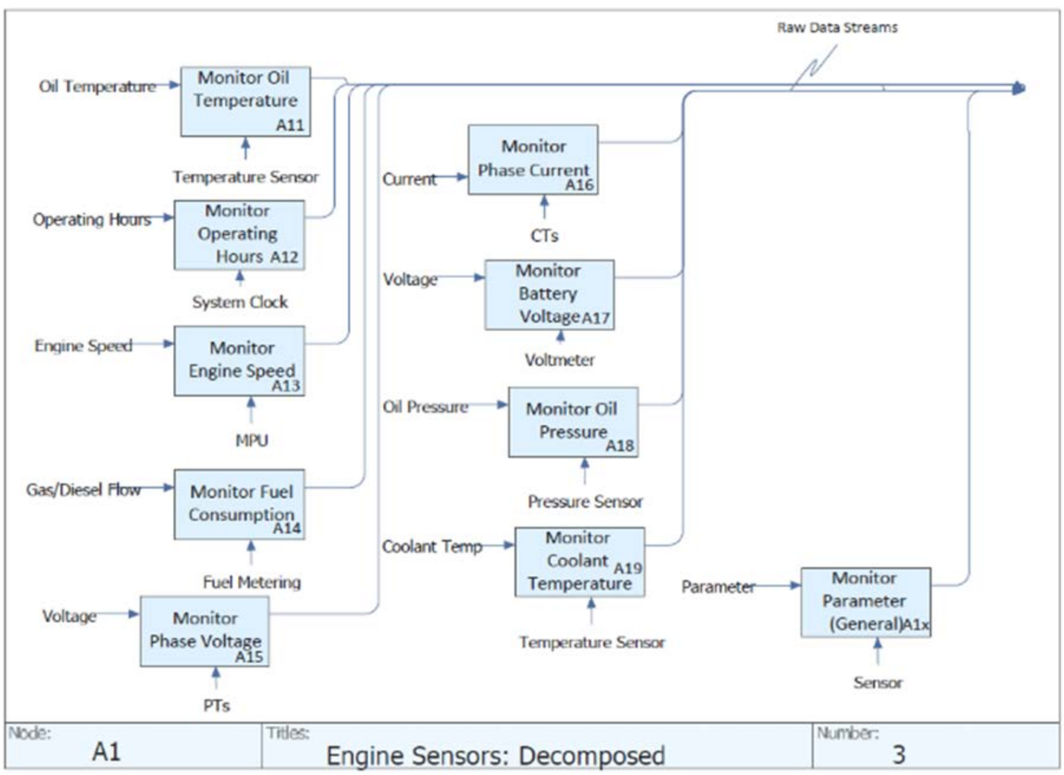


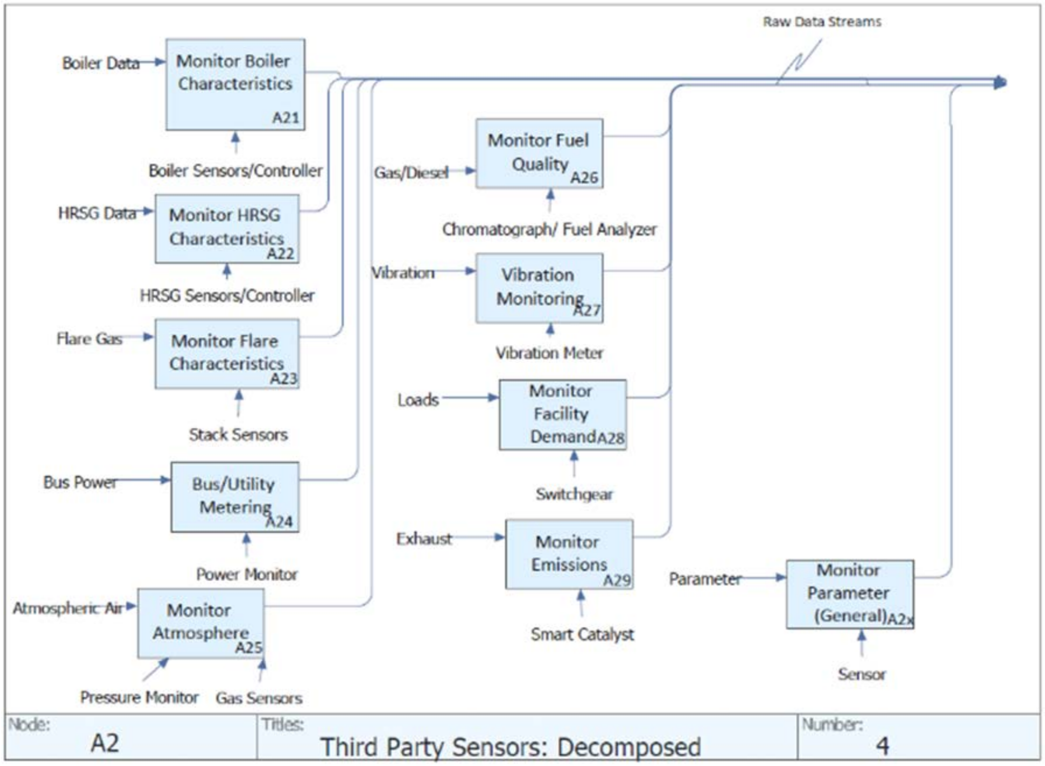
Receive Transmitted Data
A41
Broadcast Data
Received Data
Antenna
Internet Server
Satellite Dish
Pass Through Network
A42
Relayed Data
Cell Towers
Internet
Satellites
Deliver Data
A43
Transmitted Data
Antenna
Destination Server
Satellite Dish
Node: A4
Titles: Relay Data Decomposed
Number: 6

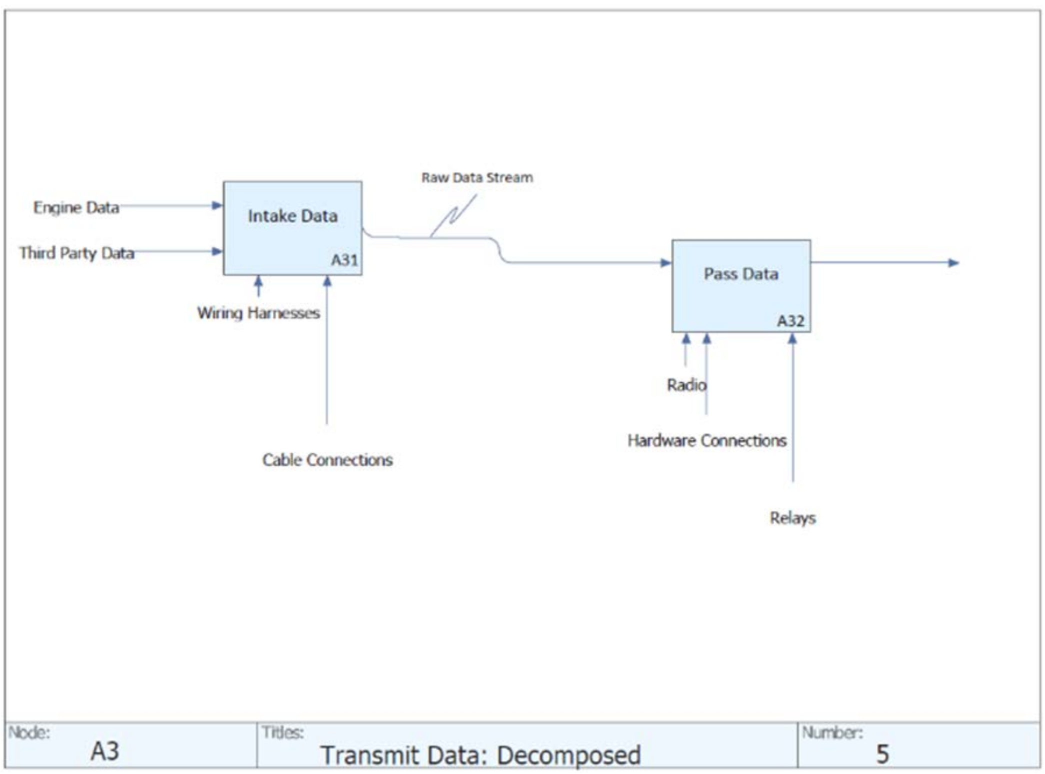


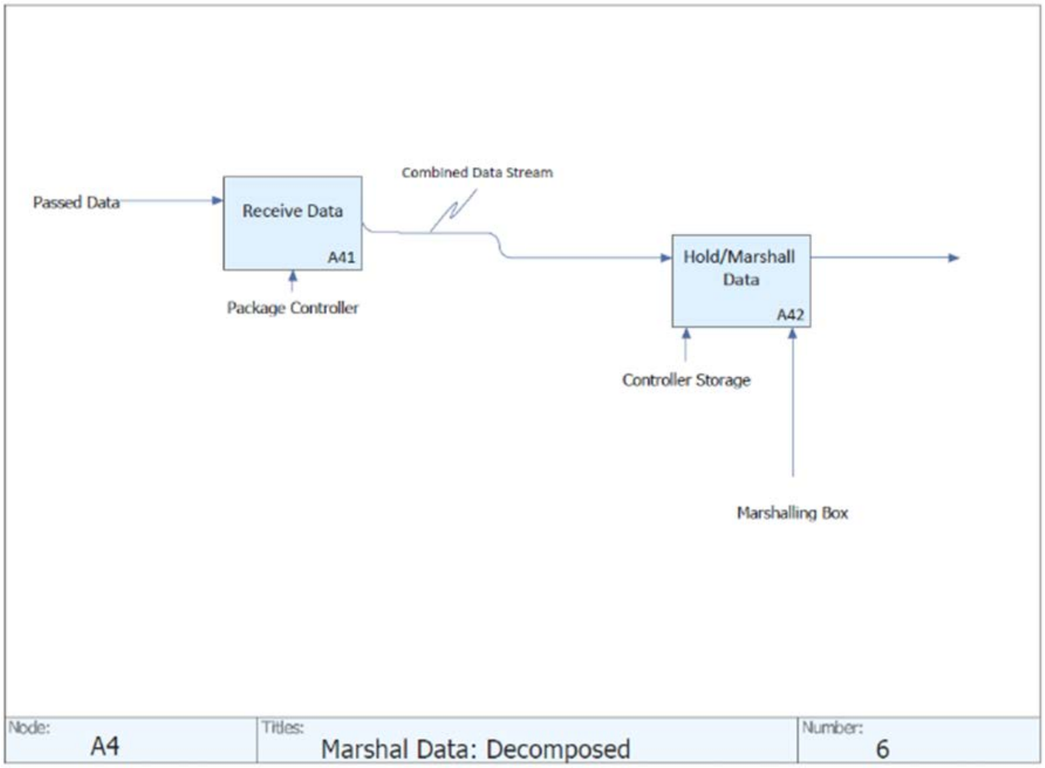
Parameter Selection
Oil Pressure
Oil Temperature
Operating Hours
Air Filter Differential Pressure
Fuel Filter Differential Pressure
Engine Speed
Other Engine Parameters
Atmospheric Concentration: CO
Atmospheric Concentration: H2S
Gas Content
Other Third Party Parameters
Monitor Engine Condition
A0
Processed and Stored Data
Instrumentation and Controls Suite
Node: A-0
Titles: Monitor Engine Condition
Number: 1


Oil Temperature
Monitor Oil Temperature A1a
Temperature Sensor
Raw Data Streams
Transmit Data to Controller A3
Cable
Relay
Radio
Transmitted Data
Operating Hours
Monitor Operating Hours A1b
System Clock
Engine Speed
Monitor Engine Speed A1c
MPU
Marshal Data for Collection A4
Processed and Stored Data
Engine Controller
Marshalling Box
Gas Content
Gas Content A2a
Gas Chromatograph
Atmospheric Concentration: H2S
Gas Content A2b
H2S Sensor
Node: A0
Titles: Monitor Engine Condition:Decomposed
Number: 2


Raw Data Streams
Oil Temperature
Monitor Oil Temperature A11
Temperature Sensor
Operating Hours
Monitor Operating Hours A12
System Clock
Engine Speed
Monitor Engine Speed A13
MPU
Gas/Diesel Flow
Monitor Fuel Consumption A14
Fuel Metering
Voltage
Monitor Phase Voltage A15
PTs
Current
Monitor Phase Current A16
CTs
Voltage
Monitor Battery Voltage A17
Voltmeter
Oil Pressure
Monitor Oil Pressure A18
Pressure Sensor
Coolant Temp
Monitor Coolant Temperature A19
Temperature Sensor
Parameter
Monitor Parameter (General)A1x
Sensor
Node: A1
Titles: Engine Sensors: Decomposed
Number: 3


Raw Data Streams
Boiler Data
Monitor Boiler Characteristics
A21
Boiler Sensors/Controller
HRSG Data
Monitor HRSG Characteristics
A22
HRSG Sensors/Controller
Flare Gas
Monitor Flare Characteristics
A23
Stack Sensors
Bus Power
Bus/Utility Metering
A24
Power Monitor
Atmospheric Air
Monitor Atmosphere
A25
Pressure Monitor
Gas Sensors
Gas/Diesel
Monitor Fuel Quality
A26
Chromatograph/ Fuel Analyzer
Vibration
Vibration Monitoring
A27
Vibration Meter
Loads
Monitor Facility Demand
A28
Switchgear
Exhaust
Monitor Emissions
A29
Smart Catalyst
Parameter
Monitor Parameter (General)
A2x
Sensor
Node:
A2
Titles:
Third Party Sensors: Decomposed
Number:
4


Engine Data
Third Party Data
Intake Data
A31
Wiring Harnesses
Cable Connections
Raw Data Stream
Pass Data
A32
Radio
Hardware Connections
Relays
Node:
A3
Titles:
Transmit Data: Decomposed
Number:
5


Passed Data
Receive Data
A41
Package Controller
Combined Data Stream
Hold/Marshall Data
A42
Controller Storage
Marshalling Box
Node:
A4
Titles:
Marshal Data: Decomposed
Number:
6