Sense & Respond
Lessons learned in support of condition-based maintenance programs through data acquisition, analysis and secure transmission

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ABSTRACT

This presentation will review the ongoing lessons learned from a joint Industry/DoD collaborative program to explore this area over the past 5 years. The discussion will review the effectiveness of integrating multiple new technologies (combined with select COTS elements) to provide a complete solution designed to reduce spares stockpiles, maximize available manpower, reduce maintenance downtime and reduce vehicle lifecycle costs. A number of new and emerging technology case studies involving diagnostic sensors (such as battery health monitors), knowledge management data accessibility, remote support-based Telematics, secure communication, condition-based software algorithms, browser-based user interfaces and web portal data delivery will be presented.

INTRODUCTION

In order to support necessary modernization of logistics, legacy weapons platforms must be upgraded and integrated to a plethora of emerging technologies and improved processes to enable a "Sense & Respond Logistics" paradigm.

Sense & Respond Logistics is "Knowing Sooner." [1]

MILITARY PLATFORM USED TO DEPLOY SENSE AND RESPOND

The Light Armored Vehicle (LAV) was chosen as the platform to support the Sense & Respond system. The LAV is a multi-wheeled, highly maneuverable mobile platform that was designed in the 1970's, fielded in the 1980's and was originally scheduled to be out of service in the early 21st Century. The LAV program is now expected to continue in its' mission well into the future as improvements to the platform and the changing shape of IW (Irregular Warfare) make the LAV an ideal Marine Corps combat platform. Its continued deployment has been made possible through a series of updates and modernization efforts such as the Service Life Extension Program (SLEP). The office of the Program Manager for the Light Armored Vehicle has deployed fleet vehicles in which a system of networked, embedded Telematics sensors and controllers have been integrated for test, measurement and control applications. Various configurations of Telematics and embedded sensor systems have been successfully deployed on dozens of vehicles over the past 5 years.

SENSE & RESPOND CONDITION BASED MAINTENANCE PROGRAM

Lessons Learned "It's about the data."

The most important lesson learned from the early phases of the LAV project was "…there must be a sophisticated data support infrastructure in place"[2]. All data collected and analyzed as a function of these efforts, as well as any of the conclusions, are dependent upon this supporting infrastructure.

A "best of breed"[3] hardware and software approach was used to effectively implement a fieldable architecture for the Sense & Respond program. Early efforts focused on determining what data to collect (everything!) how often to collect it (all the time!) and what critical vehicle systems to monitor (all of them!).

What developed over the course of the early phases inevitably led to a paring down of data collected, rates of data collection, and vehicle systems included in the study. In order to deliver an affordable, serviceable, and deployable system for the later phases of development, an efficient system evolved to manage the focus of the effort.

Vehicle maintenance personnel were involved throughout these efforts to tap into the vast reserves of 'tribal knowledge' accrued during the service life of the vehicle fleet. For example, battery failure and alternator failure were cited early on as common and expensive maintenance items, helping focus the development of a dedicated Battery Health Monitor that would operate independent of, and in tandem

to, other elements of the fielded solution.

Collaboration and Communication

Team members included military personnel, subcontractors, educational institutions and equipment suppliers. Clearly documenting team goals, expectations, timelines and deliverables proved instrumental to the advancement and obtainment of project objectives. This process led to a collaborative effort that provided adjustments to an ever changing project scope, resulting from early testing and system implementation progress.

Documenting the scope of work became a forcing function for team members that provided clarity and set expectations. For example, when it was decided that vehicle speed was to be captured as part of the data collection efforts, it was to be expressed in "Miles per Hour". Several team members translated this to mean "Miles" and "Hours", a misunderstanding that was only revealed during a team review of the first data set collected, when these two data items were not initially presented. This oversight was remedied on the next data collection and analysis iteration.

Leveraging existing standards and COTS technologies proved to be worthwhile where applicable. What proved most challenging was the compliance of MilStd specifications and testing requirements. Although some COTS equipment was eventually used for the project, much of the effort revolved around developing equipment, protocols, and use case scenarios that were compatible with the requirements

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for rugged, extreme duty and harsh environmental operation.

The process of regular team meetings, access to vehicles and personnel, and scheduled testing and review of test results was continued until project milestones were met.

Vehicle and Mission Specific Systems

Networked hardware modules for data collection and analysis had to be rugged, dust resistant and waterproof, able to withstand extreme temperatures, and utilize vehicle network standards such as SAE J1939 CAN and SAE J1708.

For updates, device firmware had the ability to be downloaded over the network to obviate the need to otherwise open a device enclosure or directly connect a programming cable.

Where legacy vehicle sensors were used for obtaining parameters like vehicle and engine speed, wiring and device installation was designed so as not to interfere with existing system functionality or space claim.

New sensor suites were designed and implemented to accommodate acquisition of parameters not otherwise supported, such as various engine and transmission system temperatures and pressures.

A J1939 network "sensor hub" was modified to bridge the gap between legacy and new vehicle sensing functionality. This provided a medium for on and off line data storage and transmission to back end enterprise systems. This sensor controller hub was built for the Sense & Respond mission requirements and was designed to easily implement enterprise level 'business rules' such as those to collect, analyze and disseminate vehicle data, alerts, and status values.

Of note was the decision to abandon an approach that used a COTS ruggedized computer or laptop to perform the functions of the hub. Cost, size, excessive power requirements, administration for Windows or Linux systems, rotating media failure, display damage and system boot up times led to the decision to remove the laptop from the vehicle. Of particular note was the desire for 'always on' operation of the sensor suite and monitoring systems which allowed for functionality even when the vehicle was turned off. This requirement was met using a dedicated, embedded sensor hub.

Secure communication

Getting the data off-platform, wirelessly, proved to be a significant challenge. The ultimate path was to utilize a DoD approved FIPS 140-2 wireless (802.11 B/G/N) router. The router was connected to the hub using an Ethernet connection encrypted with "Triple DES" SSL technology. Critically, the power for the wireless router was enabled through a relay controlled by the hub, permitting the router to remain transmitting until all vehicle data had been delivered after the vehicle was powered down at the depot.

Knowledge Management and Data Accessibility

For Sense & Respond, a number of techniques were used to determine if the data collected and once analyzed

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met the system architecture requirements for deployment in the field.

Collecting and processing data at rates appropriate to the task and intelligence within the data must take advantage of the system processing functionality in contrast to sending everything off platform for analysis. For example, in order to provide a vehicle operator with an alert during operation such as a battery failure or extreme temperature condition, the hub needed to process the appropriate data and provide the operator with a suitable alert in real-time. Waiting for data to be downloaded to a back end server for later analysis would clearly not be effective.

Another key piece of functionality desired by Marine personnel was the ability to collect data and automatically move it off platform without the Marine in the field facilitating the transmission. The embedded hub architecture fielded for Sense & Respond provided the functionality to enable this use case.

Condition based software functionality

For on-vehicle alerts and alarms, local dedicated displays, user input devices (buttons) and LED lamps were implemented for ease of operator use and installation.

Software algorithms designed to trigger alerts based on vehicle status and configuration were developed to run as firmware modules present in vehicle Telematics devices.

Browser based software interfaces and Web portal data delivery

For local maintenance purposes, a browser based Sensor Control Panel was implemented that would allow temporary wireless or direct connection to the vehicle Telematics system through the use of a Laptop or PDA based Portable Maintenance Aid. The software dashboard display will allow personnel to directly view live data coming off the vehicle in addition to augment tools and test equipment available in the field or at the depot.

For off-line data management and analysis, data sent to the depot IT server over the encrypted WiFi connection was housed in a standard SQL database to support retrieval and analysis using third party and custom software tools.

Integration of data coming from the vehicle platform, combined with other fleet data stored on the SQL server at the enterprise level allowed the development and deployment of Web based browser interfaces providing a common operating picture of individual vehicle and fleet readiness that is viewable by both maintenance personnel and fleet managers.

Remote Support

Remote support of installed Telematics systems was accomplished through a suite of technologies including Event Sensitive Triggering scripts and in system, field downloadable firmware for repurposing equipment as well as instituting and modifying business rules for equipment operation.

An ability to 'drill down' into vehicle systems data to examine potential failure modes is crucial to the goal of analyzing relevant data for Sense & Respond mission objectives. The Telematics system employed must be

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able to be reconfigured to 'take a closer look' at specific systems of interest. For example, data acquisition rates and specific data filter coefficients needed to be customizable on the fly, providing the capability to collect raw unfiltered data on an as-needed basis, taking advantage of the flexibility and power of the fielded Sense & Respond system.

SENSOR SYSTEMS SUPPORTING SENSE AND RESPOND

Battery Health Monitor
Vehicle battery replacement and associated system maintenance costs were minimized using a Sense & Respond approach to the early diagnosis and detection of potential battery failures. Many military vehicles utilize 24 Volt electrical systems which may be implemented using multiple 12 Volt Lead Acid batteries wired in series and parallel.

Batteries wear and degrade over time due to variation in manufacturing process or in their implementation. As batteries age, there is a decline in efficiency and other characteristics such as rest Voltage which may be measured to predict compromised battery performance or failure.

In a multiple cell battery pack employed on the LAV, one poorly performing battery can degrade the rest of the battery and charging system compromising vehicle performance. The ability to detect a single point of failure in the vehicle electrical system prior to additional system degradation is essential to predicting system failure and responding appropriately to the problem at hand.

Although the vehicle operator has a battery pack voltage meter available on the system console, it is not useful for measuring individual cell Voltage. Additionally, a mechanism to calculate and report battery health, Voltage and charge state was a requirement of the Sense & Respond program.

Shots Fired Sensor
The Light Armored Vehicle's 25mm Bushmaster chain gun is the vehicles' main battle weapon. The total number of rounds put through this battle cannon factors into the maintenance schedule for the barrel, which must be removed and inspected regularly. In addition, it is desirable to know the total number of rounds that have been fired and the number of unused rounds remaining during operation of the vehicle in battle conditions.

The current method for keeping track of rounds fired relies on manually entering information into a log book, which is cumbersome and prone to error. The desire to automate the data collection effort to count rounds fired for this weapon suggested that a "Shots Fired Sensor" (SFS) be developed for this platform. Additional challenges were presented when it was determined that any modification to the gun or attachment of electronic devices to the mechanism would be impractical from an installation and operation standpoint. The placement of the gun in the vehicle turret presented additional challenges, as it was impractical to route vehicle electrical or network cables between the turret and vehicle chassis.

The solution to the problem was to design a device that would be mounted in the vehicle cabin, well away from the turret or gun itself. A mounting location

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was chosen in the rear of the vehicle as being most convenient and out of the way of the vehicle crew. To detect the firing of the main gun, a microcontroller based system was designed to use a complement of multiple axis accelerometers that would respond to the acoustic vibration signature of the gun being fired. This acoustic signature is transmitted directly through the vehicle hull itself during operation of the 25mm chain gun. Each round fired produces recoil energy that is directly measured, recorded and analyzed by the SFS, keeping a running total of shots fired.

Potential interference from neighboring vehicles shooting, road vibration and variations in the acoustic signatures of different rounds and barrel and turret orientation are filtered out using Digital Signal Processing (DSP) performed by the SFS. Field testing of the SFS has confirmed better than 99% accuracy in counting rounds fired during routine vehicle operation. The SFS has a local display for standalone operation, as well as a built in J1939 vehicle network for reporting to networked equipment.

Analog to J1939 CAN Converter

The Light Armored Vehicle was designed before the advent of the vehicle networking technologies that are in widespread use today. All current over the road trucks and vehicles in the commercial sector as well as new military land vehicles are designed to have their electronic modules and subsystems communicate over a variety of specialized vehicle networks as opposed to using a point to point wiring harness as is the case with legacy vehicle platforms. The use of high speed digital network technology in the automotive design space has reduced cost, increased reliability, and led to innovations and safety features not otherwise possible.

The SAE J1939 vehicle network is based on an implementation of the Controller Area Network (CAN) specification that has been widely adopted for use in heavy truck and bus applications, and more recently in military vehicles. It was determined early in the Sense & Respond development effort that J1939 would be utilized by any new vehicle module and Telematics equipment fielded as part of the program.

The Light Armored Vehicle, lacking native J1939 networking support, presented a challenge in terms of interfacing newly developed Sense & Respond hardware devices with existing legacy sensors and electrical wiring already installed on platform. The converter module was developed to interface with these legacy systems and provide a methodology for incorporating such systems into the newly networked platform. Additionally, vehicles such as the MTVR, which do have J1939 network infrastructure delivered by the manufacturer, may benefit from using the converter module to add items such as Fuel Level to their native network infrastructure.

Each module contains 30 analog and digital inputs available for direct connection to a vehicle electrical system and associated sensors. The device contains all of the signal conditioning required to operate on devices present on 12 or 24 Volt vehicle electrical systems, such as knobs, switches, gages, dials and displays. Additional

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signal conditioning was also provided to connect the converter module to Hall Effect and Variable Reluctance sensors, typically used to measure and send analog signals used to display vehicle speed (VSS) and engine speed (RPM). Circuitry was employed to measure electrical current (Amperes) for direct connection to vehicle batteries, alternators, or other devices where current use monitoring is helpful for fault detection, prevention, and system status.

The converter module is capable of measuring, digitizing, and pre-processing vehicle voltage, current, pulse modulated signals and analog waveforms. It applies a customizable scale and offset to convert data into engineering units such as "Miles per Hour", and transmits an appropriate CAN data packet with user definable SPN and PGN values per the J1939 specification.

Telematics Hub

The Light Armored Vehicle requires a process for collecting and transmitting data off platform. This data is then used for analysis and alerts to operators and maintainers of current or potential issues that may exist with the vehicle or its subsystems.

Early in the program it was determined that the use of a ruggedized laptop computer, commonly referred to as an "On Board Computer (OBC)" to perform this function was a critical weak link in the early fielded test vehicles. Mechanical problems related to use in harsh environments, excessive power consumption, fragile rotating magnetic media, cumbersome size and mounting restrictions all were factors weighing

negatively against its continued use in the program.

Most importantly, however, was the time and operational limitation imposed by having to 'boot up' the OBC before network data collection and reporting could begin. As the OBC required the engine to be running prior to operation, critical system information that could only be obtained during vehicle cold cranking and startup would be missed.

The need to overcome these limitations drove development of the Telematics Hub. The Telematics Hub is capable of instant on and always on operation, providing the ability to collect, analyze, process, store and transmit data off platform.

The Telematics Hub was developed to be a microcontroller based device capable of storing large volumes of data on a Secure Digital (SD) Flash Memory card. This data storage media is solid state, and operates in harsh vibration and extreme temperature environments that would otherwise destroy rotating magnetic media such as computer hard drives.

The Telematics Hub requires no operator intervention and is capable of running unattended providing a way to completely automate the process of data collection and dissemination.

The Telematics Hub has the unique capability to connect directly to a Secure, FIPS 140-2 Router (such as the devices already certified for DoD operation. This capability allows for the achievement of a Sense & Respond program goal providing minimum cost

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with the highest levels of reliability and security.

CONCLUSION

Commercial technology and implementation approaches exist to significantly increase the modernization levels of legacy ground vehicles in the field of data collection, analysis and transmission. The Sense & Respond program team has pioneered the design and validation of a complete solution designed to reduce spares stockpiles, maximize available manpower, reduce maintenance downtime and vehicle lifecycle costs. This work included the successful validation of several practical solution approaches involving diagnostic sensors (such as battery health monitors), knowledge management data accessibility, remote support-based Telematics, secure communication, condition-based software algorithms,

browser-based user interfaces and web portal data delivery.

REFERENCES

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