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An Approach to CBM System Design

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ABSTRACT

As the industry looks towards Condition Based Maintenance (CBM) as the next maintenance paradigm, OEMs and suppliers are looking into their readiness in meeting the CBM challenges for the future. The US armed forces are currently investigating CBM for their Tactical and Combat vehicles as a means of improving combat readiness & equipment reliability, and reducing maintenance costs.

Many cutting-edge technologies will have to be integrated in designing the CBM systems that will support the next generation of vehicles. While most of the required technologies exist, a comprehensive design will be required to make CBM systems feasible and economical.

INTRODUCTION TO CBM

Every piece of equipment will need maintenance during its useful life. Equipment breakdown has a big impact on productivity and overall cost of operation. Prevention of equipment breakdown can significantly reduce the cost of maintenance, while improving efficiency and mission readiness. This is especially true for the high-value and mission critical equipment used by the US Army.

Note: While most of the discussion in this paper pertains to vehicles (tactical wheeled vehicles), the term "equipment" is used very loosely and covers manned and unmanned vehicles, robots, aircrafts, boats and many other resources that need periodic maintenance for optimal performance.

There are three major maintenance paradigms:

1) Corrective Maintenance: Maintenance is scheduled when equipment breaks down. The unscheduled downtime resulting from the equipment breakdown may result in significant loss of productivity, and higher maintenance costs.
2) Preventive Maintenance: Maintenance is scheduled periodically, regardless of the condition of the equipment. While this results in some predictability with regard to equipment downtimes, the cost benefits over the long term may not be better than corrective maintenance.
3) Condition Based Maintenance: Maintenance is scheduled only when equipment failure is imminent, as indicated by equipment data analysis

CBM provides the following advantages:

- Reduction in maintenance costs by avoiding unnecessary maintenance
- Lower probability of sudden equipment failure by predicting failure and taking preemptive corrective actions.

The key to a successful CBM system is the ability of the system to predict failure of the equipment and its components. The following section discusses the core components of a CBM system.

Also key to the CBM system, is a layer of abstraction, to allow technical experts to author CBM algorithms, without having to know the implementation details of the CBM system. Some of the CBM algorithms can be very complex depending on the sub-system that it is targeting. Hence, a practical CBM system will need a layer of abstraction that is well defined and well documented.

CBM SYSTEM OVERVIEW

A well-designed CBM system must seamlessly integrate many cutting-edge technologies. While most of the required technologies exist, the design has to take into consideration specific maintenance goals that may depend on the equipment, operating conditions and other parameters.

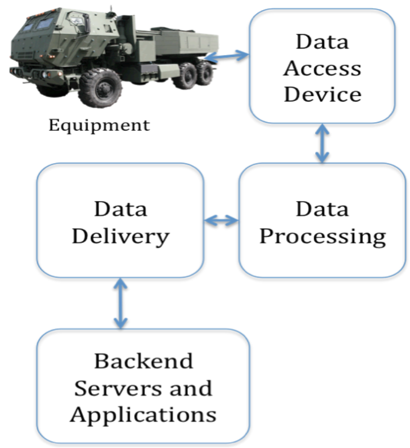

Figure 1: CBM System Overview

At a minimum, a comprehensive CBM system will consist of the following:

1) Data sources
2) Data access devices
3) Intermediate data processing
4) Data delivery strategies
5) Back end servers and applications

CBM SYSTEM COMPONENTS

Data Source

The key to any CBM system is the real-time data available to the decision engine. There are various data sources available on equipment today:

A) Vehicle network data: Initially introduced to efficiently support legislated emission requirements, vehicle networks have become a standard aspect of most vehicles and equipment in use today. Most contemporary equipment designs include a vehicle network. There is an assortment of data networks and/or protocols in use today. Some examples are CAN, SAE J1939, SAE J1708, GM UART, ISO 15765, MIL-STD 1553, etc. While most of the data on these networks is meant for normal operation and off-board diagnostics, the data is readily available for use in CBM related functions.
B) Analog Data: Many types of equipment have analog data ports that provide access to analog data. For example, many vehicles used in the US Army fleet today have an analog signal port that provides access to analog signals representative of parameters like engine oil temperature, manifold vacuum, fuel pressure etc.
C) Direct Data Access: Some equipment have data ports to directly access data, like pressure, temperature, current, etc. Some type of transducer is required to convert this raw data into an analog signal for processing by the CBM system.
D) External data: In addition to data available on the equipment, there may be cases where some external data is integrated with the equipment data. This may be available via custom equipment interfaced with or integrated into data access devices.

Data Access Device

The CBM system will require hardware/software interface(s) to read data from the data sources. The interface device will depend on the type of data being retrieved from the equipment. Some of the interface types are listed below:

Vehicle network interface(s): These typically interface with the on-board vehicle network and provide access to the vehicle network data. The data available depends on the vehicle network and the particular equipment in which it resides. The interface device will have some knowledge of the vehicle network protocol and some intelligence on how to interpret the data. One example of a vehicle network interface device is DG Technologies' SWDS-D (Smart Wireless Diagnostic Sensor – Digital) device, which supports data access via J1939, GMUART, J1798, Haldex and ATEC protocols.

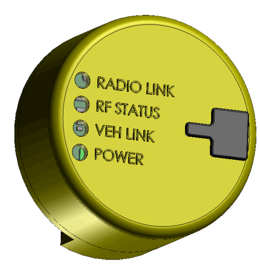

Figure 2: SWDS-D, Courtesy DG Technologies

Analog to Digital Converters or A/D Devices: This type of interface device provides access to the analog (or digital) signals available at specific ports on the equipment. A discussion of types and range of the analog signals are not within the scope of this document, but it must be noted that these are equipment dependent and must be designed or chosen based on the specific needs of a particular CBM solution. An example of an A/D device is DG Technologies' SWDS-A (Smart Wireless Diagnostics Sensor – Analog) device, which interfaces with the analog connector on many US Army Tactical Wheeled Vehicles, and provides access to dozens of analog signals.

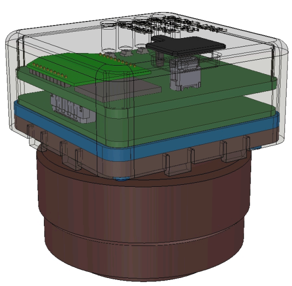

Figure 3: SWDS-A, Courtesy DG Technologies

Transducers: Transducers are typically used to read raw data, like temperature or pressure, and convert them to analog data. The analog data can be further digitized with an A/D converter. Below is a TK (Transducer Kit) Adapter designed by DG Technologies that interfaces with legacy transducers and provides the required A/D capabilities.

Figure 4: Wireless TK Adapter, Courtesy DG Technologies

External Data Interfaces: A CBM system may provide access to external data, like GPS, through a dedicated interface.

It is possible to have a single data interface device that can provide access to all the data. The different types of data would be interleaved and time stamped before being forwarded for further processing

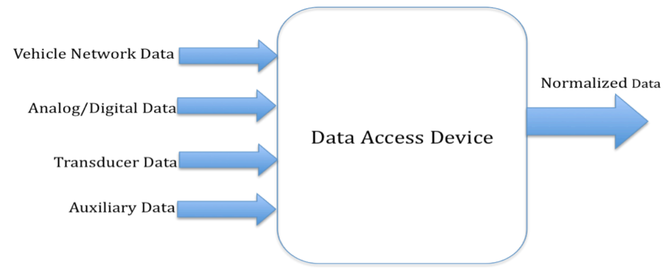

Figure 5: CBM Data Access Device

Intermediate Data Processing Unit (IPDU)

The intermediate data processing unit is the computational device, usually embedded in the equipment, and is responsible for:

- Interfacing with the data access device
- Retrieving data in real-time
- Storing and/or processing the real-time data
- Implementing CBM algorithms
- Monitoring and communicating CBM results

Central to the IDPU is the CBM Entity.

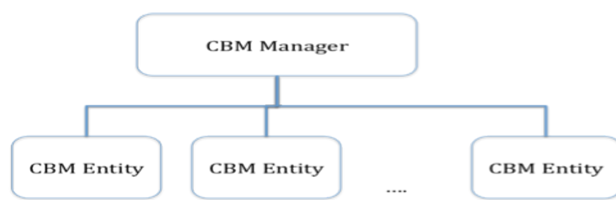

Figure 6: CBM Entity

A CBM entity is a process that:

- Computes the current (diagnostic) or future (prognostic) maintenance needs of a sub-system or component of the vehicle
- Receives equipment data, on a subscription basis, from the CBM Manager
- Processes the data based on predefined algorithm
- Delivers diagnostic and prognostic assessment reports to the CBM Manager

The CBM Manager:

- Manages one or more CBM entities
- Delivers subscribed data to the CBM entities

- Delivers equipment assessment reports to the subscribing applications

Since it is impractical to have in-depth knowledge of the inner working of every kind of equipment, the CBM entities are designed such that third-party technical experts can author the CBM entities without having an in-depth knowledge of the inner workings of the CBM system.

The IPDU can also, optionally, have the capability to store data and/or CBM assessments for off-board post-processing. The frequency, size and nature of the data storage will depend on the specific implementation.

Data Delivery

Most of CBM related data retrieval and processing will take place on-board the equipment, in real-time. Large amounts of processed data and CBM assessment information, however, will be transported to remote servers for archiving and post processing. In some cases, all of the processing may occur on remote servers in real-time. To allow for these modes of operations, many data transport technologies are available.

Below are some of the available options:

Wired data transport: Many dependable and proven wired data transport technologies are available. Among them are:

- RS232 (serial)
- USB
- Ethernet.

While USB link is reliable for most applications the data throughput over the serial (RS232) interface may be too low for any practical application. In case where a very high throughput is required, Ethernet may be the only choice.

Wireless data transport: Owing to the cumbersome nature of the wired interfaces, wireless interfaces have begun to be very popular. Also in some situations, a wireless link may be the only practical option.

In the selection of a wireless data transport technology a few factors need to be considered:

- **Data Throughput:** This will depend on the end applications. A low throughput may be sufficient for generic diagnostics, but may be insufficient for applications like remote ECU reprogramming

- **Data Security:** OEMs are very sensitive to third-party applications introducing unapproved data on the vehicle networks. This is due to security and safety implications. Therefore, there will invariably be some security regimen to regulate data written and read from the vehicle networks.

  In addition, consumers' privacy has to be taken into consideration when data is being transmitted wirelessly over the air. Therefore, any network strategy must have data encryption and other security features as a standard.

- **Cost of operation:** The chosen technology must be cost effective. This again will depend on the end application. The cost models can range from a high initial cost/low operating costs option to a low initial cost/high operating costs option.

Some of the available wireless technologies are:

- **IEEE 802.15** (Zigbee): Short range, reliable, lower throughput
- **Bluetooth:** Short range, popular with consumer electronics
- **IEEE 802.11x**: The ubiquitous wireless Ethernet or WiFi. These are in wide use in office and home networks, and currently extend to consumer devices like TVs and Bluray players. This is ideal for reliable data transport over mid-range with a reliable range sometimes extending up to half a mile.
- **IEEE WiMAX**: WiMAX is a telecommunications protocol that originally was a high bandwidth fixed wireless access technology. It met with success for mobile networking when its mobile variant, backed by Intel, was released as a standard. WiMAX provides both fixed and fully mobile Internet access. It provides speeds up to 40Mbps with the IEEE 802.16m update expected to offer up to 1 Gbps.
- **3G**: Generation of standards for mobile phone communication that is very popular with mobile phones and mobile phone based data transport. This is an ideal choice for long haul data transport, especially with equipment on the move.
- **LTE** (Long Term Evolution): A robust cellular data network that goes beyond 3G technology. LTE provides downlink peak rates of at least 100 Mbps, an uplink of at least 50 Mbps. LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz. LTE implements an all-IP (Internet Protocol) architecture and is no longer using circuit switching as its base technology.

- **4G**: 4G is the fourth generation of cellular wireless standards. It is a successor to the 3G and 2G families of standards. 4G service operates at 100 Mbit/s for high mobility communication and 1 Gbit/s for low mobility communication

As can be inferred from this discussion, there are many ready-to-use options for wired and wireless data-delivery. The choice depends on the specific application needs, cost and throughput requirements. Also, most of the discussed data transport technologies have built-in encryption support. Encryption will be a critical requirement, especially for deployed, mission critical US Army equipment.

Back-end Servers and Applications

Most of the CBM components are usually hidden from the end user, who interacts with the CBM system via a set of end-user applications. The application suite will interact with the remote server(s) that acts as the repository for the CBM data as well as manages the end-to-end connection between the user domain and the equipment. While most of the CBM decision engines are expected to be hosted on the device embedded in the equipment, the architecture should allow for some decision engines to run on the remote servers.

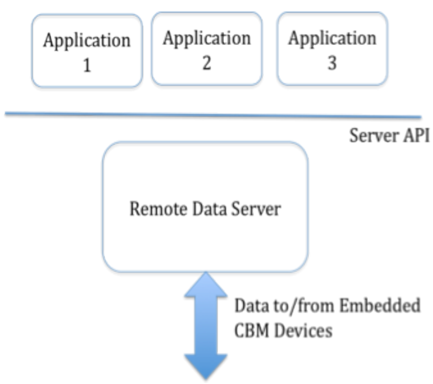

Figure 7: Multiple Applications Accessing CBM Data Server

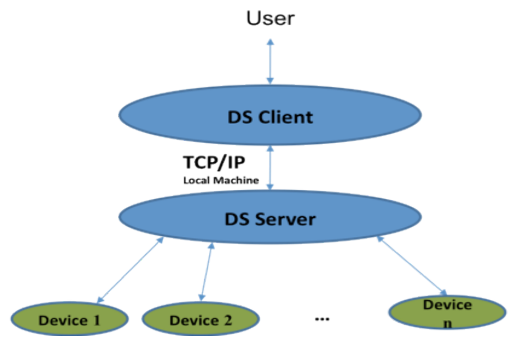

Figure 8: User Access to CBM Server Functionality (Courtesy DG Technologies' SWICE Architecture)

A typical application suite will consist of the following components or applications:

1) CBM Data Interface
2) CBM Authoring Tool
3) CBM Configuration Tool

CBM Data Interface

CBM Data interface allows access to data stored on the CBM device and/or the server. The CBM data interface application allows the user to:

a. Browse the data stored on the CBM device(s)
b. Present the stored data in a user defined format
c. Present live run-time data in a user defined format
d. Download and archive stored data

Note: A new data format, the Army Bulk CBM Data Format (ABCD Format) is the currently prescribed standard for formatting and storage of all CBM related data.

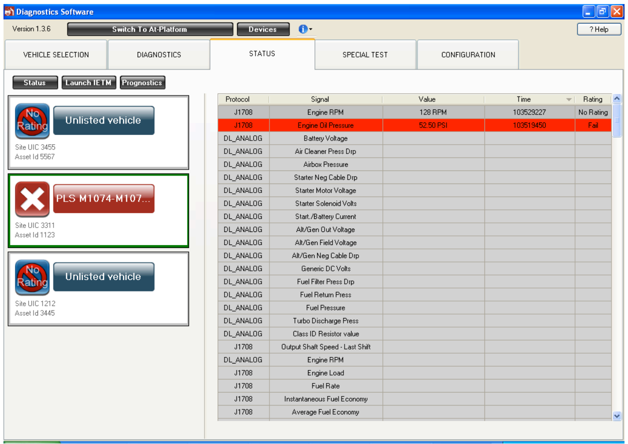

Figure 9: CBM Data Interface Example: Live Data Monitoring Capability in Diagnostics Software (DS) Application (courtesy DG Technologies)

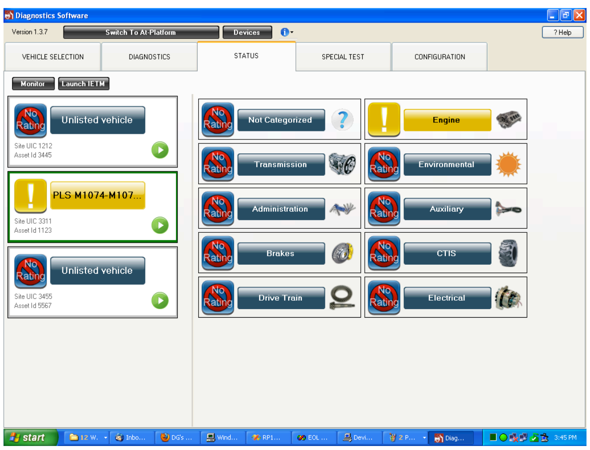

Figure 10: DS Displaying Vehicle Health Status, Courtesy DG Technologies

CBM Authoring Tool

As discussed in previous sections, designing CBM algorithms will require in-depth knowledge of the equipment in question. As this level of familiarity can exist only among a small group of experts, any practical CBM system must have the means for the experts to design and implement CBM algorithms without having to have a detailed understanding of the underlying CBM devices, interfaces, data formats etc. A CBM Authoring Tool provides this level of abstraction.

In the CBM system the CBM entity will have well-defined interface rules that the authoring tool will follow. The CBM Authoring Tool will make available all the data available on the equipment and allow the author to subscribe to a set of data required by the algorithm. As discussed before, the CBM Manager will be the clearinghouse for all the data subscriptions and provide the requested data at the requested periodicity to the CBM Entity.

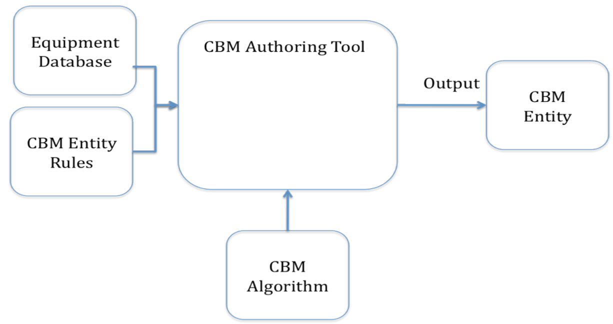

Figure 11: CBM Authoring Tool Flow

After the data requirements are determined, the CBM Authoring tool will allow design of computation rules for processing the data and assessing the health of the vehicle based on the computation results. The complexity of the allowed computation will vary among different implementations and may be as complex as allowing a full range of mathematical operations, including differentiation and integration.

The output of the CBM Authoring tool is a CBM Entity, generated as per the rules of the CBM Device that would be hosting this CBM Entity. It is very likely that a common standard for the CBM Entity will emerge, based on the ongoing R&D effort.

CBM Configuration Tool

The CBM Configuration tool will be responsible for:

- Managing the CBM Entities on the CBM Device
- Uploading and downloading CBM Entities to and from the CBM Devices
- Activating and deactivating the CBM Entities

Once the CBM Entity is generated it can be uploaded, activated and managed via the CBM Configuration Tool

Below is a representation of a complete CBM System:

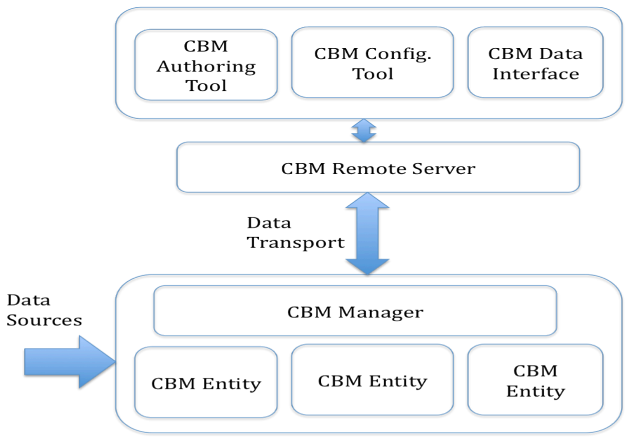

Figure 12: CBM System Architecture

Conclusions

As all the technology pieces required for a practical CBM System are currently available, a good CBM system design will seamlessly integrate some or all of these technologies into a reliable and cost-effective solution for future CBM needs. This paper offers some insights into a implementable design of CBM system based on this principle.

The US Army's PD TMDE (US Army) has successfully implemented these CBM design concepts in the SWICE program.

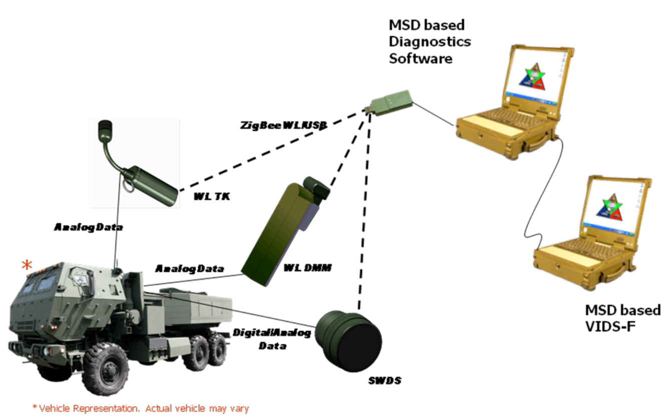

Figure 13: SWICE System Overview, as implemented for US Army's PD TMDE

The SWDS component of the SWICE platform provides the vehicle network and analog data access, in addition to providing a powerful Linux based computing platform, and on-board storage capabilities.

The SWDS platform also provides the aforementioned CBM framework for hosting CBM entities that take advantage of wide range of available data, storage capability and the powerful computing platform.

The SWICE framework also includes support for legacy transducer data and data from other COTS devices (for example a COTS Digital Multi-Meter).

As Data transport options the SWICE design has support for high speed USB and wireless Zigbee, with expansion capability to include support for IEEE 802.11x

SWICE has detailed specifications covering CBM entity generation rules, and use cases, to help third-party experts to generate and host a myriad of emerging CBM entities specialized for individual needs.

REFERENCES

[1] S. Prasad and M. Zachos, "Vehicle Networks with Wide Area Network Services", SAEISS Technical Paper Series, December 2010.

[2] M. Zachos and S. Prasad, "Vehicle Embedded Health Monitoring and Diagnostic System", IEEE AutoTestCon 2009.