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US ARMY COMMON POWERTRAIN CONTROLLER DEVELOPMENT FOR AVDS EFI ENGINE APPLICATION IN M88 VEHICLE

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ABSTRACT

This paper outlines the results from an ongoing collaborative development effort to apply a new powertrain controller in a real combat vehicle application. Specifically, TARDEC and L3T CPS have partnered to demonstrate a production viable electronically controlled fuel injected (EFI) version of the AVDS 1790 diesel engine, used in the M88 HERCULES vehicle. Highlights of the development project focus on coordinated engineering activity involving the following key enablers.

- *The neXtECU jointly developed by ETAS and TARDEC, custom engineered to become a common powertrain controller for use on the Army's future family of combat vehicles*
- *Engine control software jointly developed by TARDEC and L3T to perform EFI fuel system controls and auxiliary powertrain functions using the neXtECU*
- *AVDS 8CR 1050 hp engine with L3T design modifications to incorporate a derivative of a commercially available EFI fuel system.*

INTRODUCTION

The US Army continually seeks technology advancement to supply its fighting force with the most capable equipment. However, when technology evolves rapidly, managing material obsolescence presents major logistical challenges and expenses. This scenario is often applicable to electronic equipment involving microprocessor based software controls that characteristically have product life cycles as short as five years, or less. In automotive vehicles, electronic controls have done much to increase the performance of nearly all functional aspects. Commercial vehicle manufacturers depend on such technology improvements to differentiate products, achieve regulatory targets and maintain competitiveness with each new model year launch occurring every three to five years. Comparatively, a military vehicle with a fifty plus year useful life is exposed to multiple supersession cycles when commercially based electronic control components or systems are utilized. Compounding this supersession problem is the inherent proliferation of technology solutions that spreads throughout a vast fleet of military vehicles. Recognition of this technology obsolescence challenge prompted TARDEC to develop a new state of the art electronic controller capable of achieving all unique military requirements and controlling powertrain functions across the broad range of engines and transmissions applied in the US Army's fleet of ground vehicles. This paper highlights engineering efforts that have progressed to prove the concept of such a "common powertrain controller". The following sections present development examples outlined in three major areas each led by one of three collaborative team members, listed below.

1. Electronic Control Unit (ECU) design – led by ETAS Inc.
2. Electronic Fuel Injection (EFI) system integration on the AVDS engine – led by L3 Combat Propulsion Systems (CPS)
3. ECU software development to control the AVDS EFI engine – led by TARDEC

Highlighted activities from these three development areas focus on the systems engineering methods listed below, and described in the following sections.

- Requirements analysis and decomposition
- Failure mode analysis
- Bench tests
- Software modeling and simulation
- Analysis led design
- Dynamometer tests

neXtECU Controller & Embedded Controls Development Tool Chain

ETAS Inc. and TARDEC are jointly developing the common powertrain controller, denoted by the model name neXtECU. Key neXtECU features that are designed to support real-time controls development for vehicle electronic systems, as indicated in **Figure 1**. It will address numerous gaps identified in previous GVSETS APBI sessions. For instance, in the Ground Vehicle Power & Mobility area, the neXtECU provides a common and robust embedded control unit to support:

- Novel high-power density engine designs such as Opposed Piston designs (e.g. OPOC)
- Electrified auxiliary systems (fans, pumps, steering, Power-take-off)
- Smart controls for cooling system modernization
- Multi-speed transmissions for tracked/wheeled vehicles
- Engine control retrofit to allow operation on field grade fuels

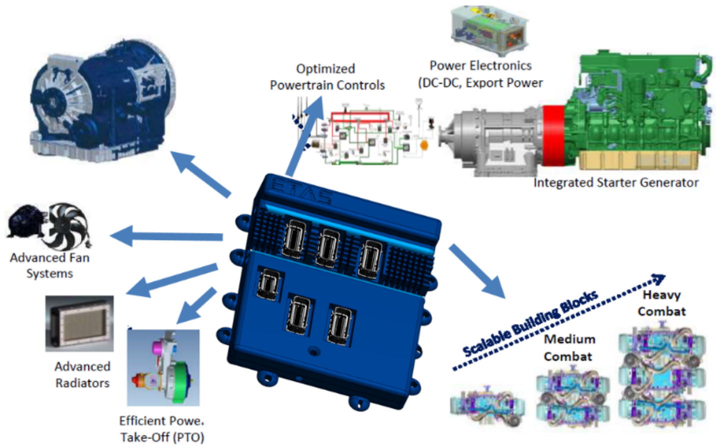

Figure 1: ETAS neXtECU Applications

The neXtECU input and output (I/O) capabilities that directly support the AVDS EFI integration include:

- Twelve (12) Solenoid Injector Stages tuned to support Bosch CRIN 3 injectors providing the ability for multiple injections per cylinder to precisely tailor the fueling.
- Precise angular engine position detection utilizing the Bosch Generic Timer Module (GTM) configured to detect the specific CAM and CRANK pattern of the M88's particular variant of the AVDS engine.
- Over sixty (60) total analog inputs, a subset of which interface to position, pressure and temperature sensors on the AVDS such as throttle position, air pressures, and fuel/oil/air temperatures.
- A subset of the thirty (30) sensor supply channels are utilized to supply stabilized 5 volts to the various active analog sensors such as the throttle position sensors and the various air/fuel/oil pressure sensors.
- Five (5) high-current inductive load control outputs allow for power control of related subsystems such as fuel metering pump, flame start pump and electric manifold heater (EMH) system relay.
- A minimum of fifteen (15) digital and thirty (30) pulse width modulated (PWM) outputs allow direct signal/control of AVDS features such as the fuel metering valve as well as the flame start pump and starter relay.

The neXtECU software development environment consists of the development tool chain and basic software. The development tool chain includes the GNU based compiler/linker, an AUTOSAR [1][2] basic software package with associated tooling to allow integration of applicable application software (ASW) such as the diesel engine control software described in this paper. The development tool chain also includes an A2L generation interface allowing the addition of ASW specific measurements and calibrations for use with ETAS' INCA [3] tool. The basic software provided with the neXtECU controller includes a pre-configured setup including real time operation system (RTA-OS RTOS) and device drivers for the various controller hardware interfaces.

EFI Integration on AVDS Engine

L3T CPS is focused on integrating an electronically controlled high pressure fuel system on the AVDS engine. When originally developed over fifty years ago, the mechanically controlled pump-line fuel system was state of the art; and, reliably delivered performance for a 750 hp rating. The AVDS engine has evolved much since then. But, vehicle demands for power have grown to as much as 1500 hp, twice the original output. Achieving such an increase in power requires precise control of injection metering and timing to manage combustion within the durability and reliability limits of the engine. Building on over a decade of proof of concept type work, L3T CPS now has shifted development to incorporate a commercially available fuel system. Specifically, the engine is being redesigned to apply the Bosch Modular Common Rail System (MCRS) [4], currently in production for use on various high horsepower commercial engines. **Figure 2** shows the major elements of a Bosch MCRS system.

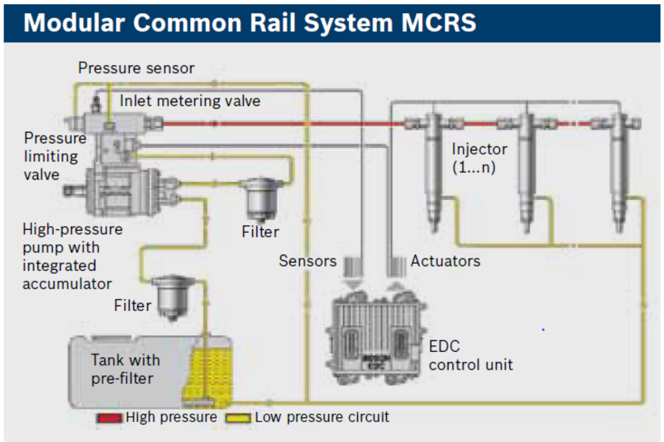

Figure 2: Bosch MCRS [1]

Following design integration of the MCRS fuel system, L3T CPS will develop a production viable EFI engine controlled by the neXtECU. Current development progress is summarized below, outlined by systems engineering activities.

Requirements Analysis

The M88 HERCULES vehicle is targeted for initial use of the EFI engine. Hence, engineering requirements were primarily derived considering this target application. Customer feedback helped to establish several critical goals for an EFI engine:

1. Maintain or reduce unit cost
2. Improve life cycle cost by at least 10%
3. Improve reliability by at least 10%
4. Increase rated power to 1350 hp
5. Maintain compliance to all other existing performance requirements

These high level requirements have been decomposed at the engine system level, and at each of the three major subsystems effected by the MCRS integration: 1) Auxiliary Drivetrain, 2) Fuel and 3) Electronic Control System. The requirements analysis involved the following methods.

- Failure Mode Assessment – historical review of engine and subsystem issues
- Boundary Diagrams – illustration of subsystem scope and interactions
- Performance Analysis – 2D model calculations to derive performance requirements including auxiliary drivetrain load and fuel system flow

Bench Test

An inline three cylinder model high pressure fuel pump was selected as the optimal match for the AVDS engine. Retention of the existing fuel pump drive location was a constraint established by a critical requirement to deliver retrofit kits for conversion of fielded mechanically controlled engines. CAD modeling, shown in **Figure 3**, revealed the EFI pump must be mounted at an angle to fit in the constrained space of the engine valley and retain the existing driveline. Verification of the angled mounting configuration was necessary to proceed with auxiliary drive design. A bench test stand (shown in **Figures 4** and **5**) was devised to verify fuel pump operation, particularly lube oil flow and drainage, at extreme angle orientation. Positive bench test results confirmed feasibility of the angled mounting arrangement.

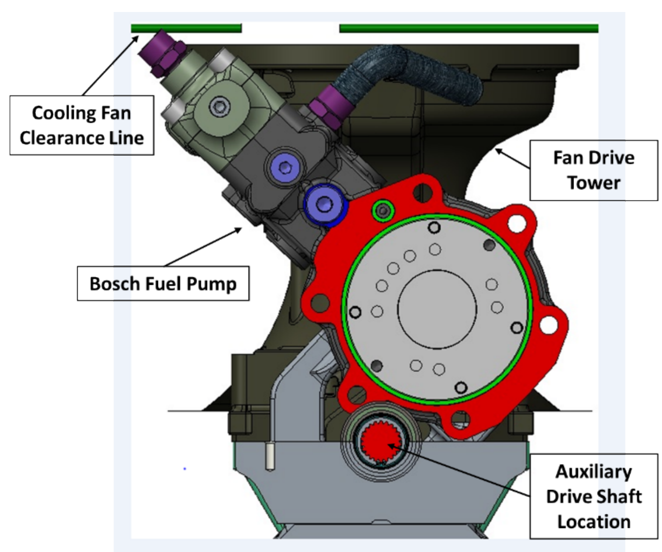

Figure 3 – EFI Pump Mount Orientation

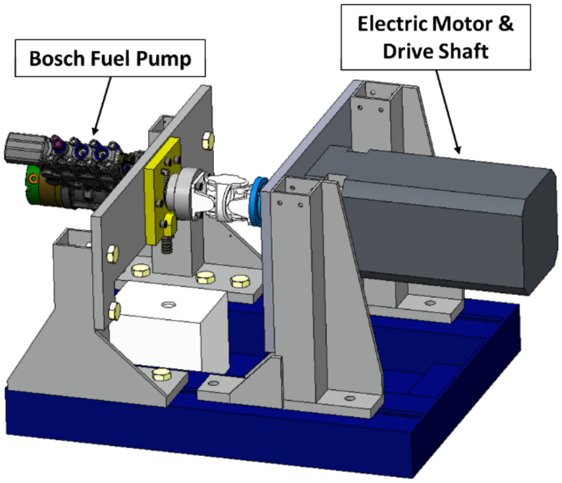

Figure 4 – EFI Pump Test Rig Concept

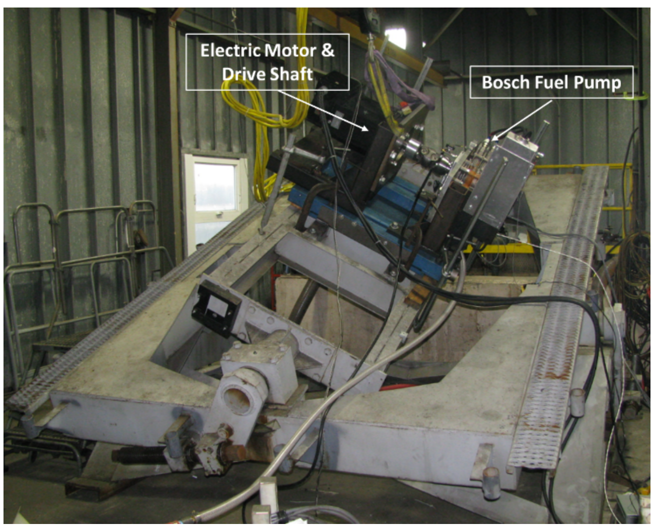

Figure 5 – EFI Pump Tilt Test

Analysis Led Design

Combinations of 2D calculations, 3D CAD, FEA modeling, and advanced simulation modeling (GTPower and PowerGear analysis software) was performed to derive technical requirements, select design concepts and optimize design solutions. Some examples follow.

Fuel Supply Pump – To achieve the 1350 hp design target, an Excel analysis was used to model fuel system flow requirements considering consumption, high pressure pump performance characteristics, and system loss over an engine life cycle. The analysis revealed the existing AVDS low pressure supply pump was inadequate to achieve the new performance requirements. The data was then used to evaluate alternative pumps and select an optimal one.

Auxiliary Drive – An Excel analysis was used to determine the cumulative instantaneous and average torque applied to the auxiliary drive shaft under various engine operating conditions. The worst case drive torque values and vibratory torque predictions from GTPower simulation served as inputs to perform FEA modeling of the auxiliary drive arrangement. FEA stress predictions combined with gear analysis software results and CAD package constraints were used to design the optimal drive arrangement shown in **Figure 6** below.

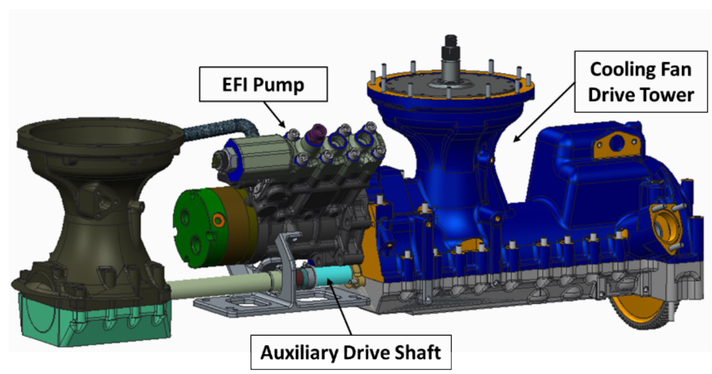

Figure 6 – Auxiliary Drive Arrangement

Cooling Fan Tower and Auxiliary Drive Housing – The new EFI fuel pump and auxiliary drive arrangement required revision to the structural design of the cooling fan tower cast housing. CAD modeling identified opportunities to achieve a less complex structure. Compared to the old mechanical fuel system that requires a two-piece fan drive tower, the simplified EFI driveshaft can fit within a single casting. A combination of CAE tools helped to optimize the casting geometry. FEA modeling, exemplified in **Figure 7**, served to minimize stress. Mold flow modeling, performed by the casting supplier, insured a producible design.

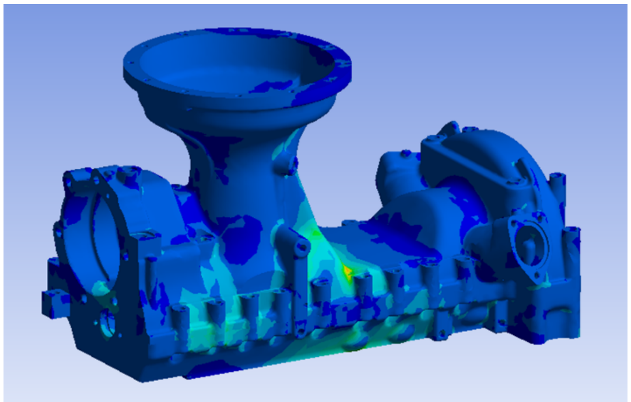

Figure 7 – FEA of 1-Piece Fan Tower

The EFI design work progressed through completion of critical design and procurement of prototype components is ongoing. Pending material availability, engineering activity focused on evaluating the performance of the neXtECU with TARDEC supplied software, as outlined in the following section.

Engine Controls Software

TARDEC Ground Vehicle Power and Mobility, Realtime Control Systems (RTCS) team has been working with ETAS, Inc., for three years, on the development of the neXtECU. TARDEC's role, in that time, has been to jointly fund, with ETAS, the material, labor, and management costs of the development, as well as to define and refine requirements from a military vehicle perspective. In addition, TARDEC and ETAS have jointly developed a set of tools and procedures for programming the neXtECU that simultaneously take advantage of all of the advanced capabilities that the new platform has to offer, while preserving the ability to continue utilization of existing TARDEC application software and libraries going forward.

For the current project, TARDEC has leveraged and extended the EFI software that it developed, and successfully implemented, for a Caterpillar (CAT) engine that is currently running in a dynamometer test cell at Wayne State University (WSU), and is supporting joint TARDEC / WSU research efforts. That same TARDEC EFI software has been extended to drive the 12-cylinder AVDS 1790 for this project.

Using generally available controller technology, running a 12-cylinder engine would require two ECUs, operating in tandem. The neXtECU has sufficient capability to perform all required control tasks within one unit.

TARDEC and L-3 Technologies (L-3 Tech) have formed a Cooperative Research and Development Agreement (CRADA) that provides the basis for cooperation in this effort, with L-3 Tech adapting the AVDS engine to incorporate the Bosch MCRS fuel system, and providing subject matter expertise and requirements regarding the behavior and calibration of the software. TARDEC has taken advantage of L-3 Tech support to develop an EFI control system that, as of the writing of this article, is currently being tested in TARDEC's RTCS laboratory.

A significant activity in the RTCS approach to embedded system software development has always been the re-use of functions from existing software. The implementation of this approach typically takes the form of Test-Driven Development (TDD), where software is matured and developed as it is being tested on the bench. This approach; however, is not possible without having the necessary equipment that simulates a sufficient engine system response.

Under the CRADA, L-3 was able to provide a simulator, produced by VI Engineering. The major components of the simulator are shown in **Figure 8**. TARDEC controls engineers used the simulator to produce the Alpha phase of 1790 engine software development. The Alpha phase is where baseline feature/functions, as were specified by L-3's requirements, were implemented and tested. Because TARDEC had access to this critical piece of equipment, the RTCS team was able to successfully adapt the existing software to manage the 1790 engine. TARDEC has been able to demonstrate the operation of the software system on the target hardware: injectors; sensors; simulated fuel rail pressure, torque and speed in real-time, throughout the development cycle. Use of the simulator enabled initial software development to occur in only three months. Future use of the simulator will include creating a baseline calibration dataset for the Beta release software that will be deployed on the engine.

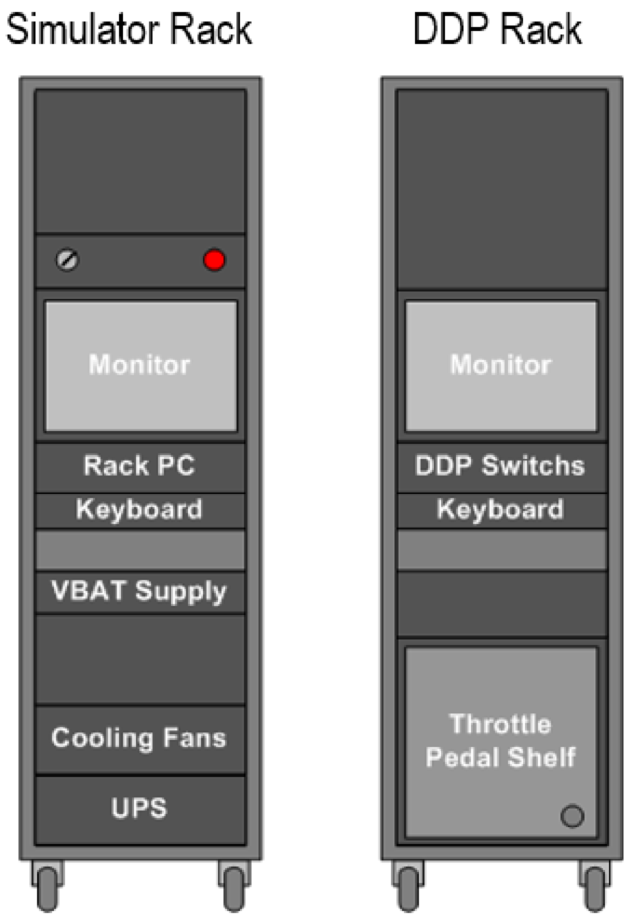

Figure 8 - L3T AVDS 1790 Engine Simulator

The project plan calls for the TARDEC-developed EFI control system to be delivered to L-3 Technologies' facility in Muskegon, Michigan, for installation in a dynamometer test cell and integration with a 1790 engine. Subsequently, engine testing and data acquisition will be performed to enable calibration of the EFI system to support operation of the engine under standard atmospheric temperature and pressure conditions, with the goal of increasing engine output to 1350 hp, while maintaining compliance to all other performance requirements.

Future Development

Collaboration on this development project will continue through 2017 and beyond. Below is a description of some of the planned development and visions of future collaborative opportunities.

neXtECU Controller Variants

The neXtECU controller hardware will have multiple variants available to lower the overall cost of development while still retaining a common software development environment. Currently the neXtECU consists of a lab/dyno targeted development controller with XETK [5] and automotive grade MOLEX harness connectors [6]. A lower cost control unit will be offered without XETK and will utilize the ASAM MCD-1 Universal Measurement and Calibration Protocol (XCP) over a Controller Area Network (CAN) bus as implemented via the free ETAS' XCP integration package (XCP-IP) software [7][8]. This lower cost unit is targeted for those applications where the high speed – high bandwidth capabilities of the XETK are not needed; such as, fleet evaluations or for sub-system developments; and, such as fan controls or other integrated vehicle controls.

For combat vehicle production use of the neXtECU family of controllers will be extended to replace the Molex MX123 connectors with MIL-DTL-38999 connectors [9] as well as adding further radiation hardening features to include Nuclear Event Detection (NED) and protection circuitry [10].

Dynamometer Tests

A functional test of a prototype neXtECU with the initial software developed by TARDEC is scheduled for initial engine testing in August 2017. The prototype control system will be installed on an AVDS engine configured with a concept level version of Bosch MCRS fuel system. Dyno tests will be performed under controlled steady state conditions to evaluate functional capability of the control system and software. Desired outcomes include proof of concept for the control system and identification of required software and calibration revisions. A more mature controller and software will then be developed for use in follow-on dyno tests planned when the new production intent fuel system hardware is available in December. Design verification of the integrated system is planned to continue throughout 2018.

The team's longer-term vision involves vehicle integration work, potentially including the following activities.

- Integrate the AVDS EFI engine with neXtECU controls into an M88 vehicle
- Evaluate vehicle mobility with a 1350 hp rated engine
- Characterize EFI engine performance improvement in terms of vehicle fuel economy, smoke signature and crew comfort.
- Expand controller use to perform more integrated vehicle functions, including enhanced driver interface (control & communication), hydraulic system (winch) control, cooling fan clutch control, lube oil system monitoring/replenishment, vehicle speed control, system diagnostics, prognostics & maintenance management.
- Prove the common controller concept is feasible and move from concept to production development.

Summary

ETAS Inc., L3T CPS and TARDEC RTCS have collaborated to develop a state of the art common powertrain controller and have proven its application on an AVDS EFI engine. The project serves in a practical way to prove the controller is feasible and valuable to the US Army by applying the neXtECU on a real combat vehicle engine. The collaborative engineering effort largely involved:

- Analysis led design integration of a Bosch MCRS fuel system on the AVDS engine
- ECU software development using ETAS's embedded tool chain and an EFI system simulator

Future development plans aim to complete design verification of the neXtECU controlled AVDS EFI engine and perform higher level system integration in an M88 vehicle.

REFERENCES

[1] https://www.etas.com/en/products/applications_autosar.php
[2] https://www.autosar.org/
[3] https://www.etas.com/en/products/inca_software_products.php
[4] Bosch website - http://products.bosch-mobility-solutions.com/specials/de/crs/pdf/MCRS_en.pdf
[5] https://www.etas.com/en/products/xetk.php
[6]http://www.molex.com/molex/products/family?key=mx123_sealed_connection_systems&channel=products&chanName=family&pageTitle=Introduction&utm_source=ds&utm_medium=lit&utm_campaign=general
[7] https://wiki.asam.net/display/STANDARDS/ASAM+MCD-1+XCP
[8] https://www.etas.com/en/products/xcp_integration_package-details.php
[9] http://quicksearch.dla.mil/Transient/46A846689AFF43AA90442ECED6F40D02.pdf (MIL-DTL-38999M)
[10] https://fas.org/nuke/control/mtcr/text/mtcr_handbook_item18.pdf (Nuclear Event Detector)