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Advanced actuation technology for cyber-secure P2X engines

Controls, Automation, Measurement, Monitoring & Predictive Maintenance

John Karspeck, Woodward Inc.

Chris Ohlsen, Woodward Inc.
Tim Harper, Woodward Inc.
Brandon Gleeson, Woodward Inc.

ABSTRACT

The new generation of high-speed gas engines currently under development has higher power (BMEP) and boost pressure requirements. These system requirements drive higher differential pressure across throttle and bypass control valves, requiring increased actuator torque. As the large engine industry embraces hydrogen and natural gas (H2 and NG) fuel blends as a standard fuel of operation, many new engines are designed with blended H2 ratings ranging from 25% to 100% depending on the application and the engine architecture. Blending of H2 drives higher boost demand which in turn drives the need for higher torque actuation. These higher BMEP engines also operate at higher vibration levels; therefore, there is a need for actuators to have improved torque density to reduce their mass. The Woodward X-Series electric actuator was recently developed to meet these requirements and challenges. The Fractional Slot Concentrated Winding (FSCW) motor is a key enabler for the actuation technology to deliver higher torque at a compact size. This paper documents the design and optimization approach used on the X-Series to create an actuator that is more compact with improved ingress protection while maintaining reliable operation in the high vibration, elevated temperature on-engine environment. Additionally, any new components designed today need to meet the upcoming cyber security requirements.

In addition to the technical capabilities and features of the X-Series actuator, this paper will highlight challenges, such as secure network design and other countermeasures, that integrators must take into consideration when applying low-level components in a larger system to satisfy the system’s security objectives. It is important to design and maintain components of modern industrial control systems using a cybersecurity-guided development process. Woodward’s secure development lifecycle process, for which the X-Series is developed, is based on the international IEC-62443 standard and provides a framework that is inclusive of both secure system and component product development. Despite digital electronic limitations of components compared with the larger parent system (e.g., small memory footprint, datalink accessibility, etc.), the added cyber security features of the X-Series are tailored to reinforce the overall system’s security with a defense-in-depth methodology. The X-Series security capabilities will also be enhanced as the product evolves incorporating additional security capability over the product's lifetime.

1 INTRODUCTION

The new generation of high-speed gas engines currently in development have higher power (BMEP) and boost pressure requirements. These system requirements drive higher differential pressure across throttle and bypass control valves, requiring increased actuator torque. As the Large Engine Industry embraces hydrogen and natural gas (H2 and NG) fuel blends as a standard fuel of operation, many new engines are designed with blended H2 ratings ranging from 25% to 100% depending on the application and the engine architecture. Blending of H2 drives higher boost pressure which in turn drives the need for higher torque actuation. These higher BMEP engines also operate at higher vibration levels; therefore, there is a need for actuators to have improved torque density to reduce their mass.

The Woodward X-Series electric actuator was recently developed to meet these requirements and challenges. The Fractional Slot Concentrated Winding (FSCW) motor is a key enabler for the actuation technology to deliver higher torque at a compact size. This paper documents the design and optimization approach used on the X-Series to create an actuator that is more compact with improved ingress protection while maintaining reliable operation in the high vibration, elevated temperature on-engine environment.

In addition to the technical capabilities and features of the X-Series actuator, this paper will highlight challenges, such as secure network design and other countermeasures, that integrators must take into consideration when applying low-level components in a larger system to satisfy the system's security objectives. It is important to design and maintain components of modern industrial control systems using a cybersecurity-guided development process. Woodward's secure development lifecycle process, for which the X-Series is developed, is based on the international IEC-62443 standard and provides a framework that is inclusive of both secure system and component product development. Despite digital electronic limitations of components compared to the larger parent system (e.g., small memory footprint, datalink accessibility, etc.), the added cybersecurity features of the X-Series are tailored to reinforce the overall system's security with a defense-in-depth methodology. The X-Series security capabilities will also be enhanced as the product evolves incorporating additional security capability over the product's lifetime.

2 ACTUATOR DESIGN

The new generation of engines require an actuator architecture that provides more torque for the same volume (increased torque density) and reduced actuator mass. The X-Series is engineered with the requisite technology to meet these demands. Woodward is developing the X-Series actuators for the torque ranges outlined in Table 1, utilizing the methodology detailed in this section.

Table 1. Actuator Sizes Studied

Actuator Model	Transient Torque (N-m)
X-2.5	2.5
X-5	5
X-10	10

2.1 Actuator Magnetic Architecture

The traditional Large Engine actuator technology has been the Limited Angle Torquer (LAT). LAT technology has performed well, as evidenced by its decades of reliable use in the Large Engine market but its torque density can't be improved further due to intrinsic limitations of a single-phase actuator technology. In an LAT, there is significant unutilized volume between the teeth and coils as shown in Figure 1. This is due to the fixed number of teeth and poles that is needed for torque production using a single coil phase.

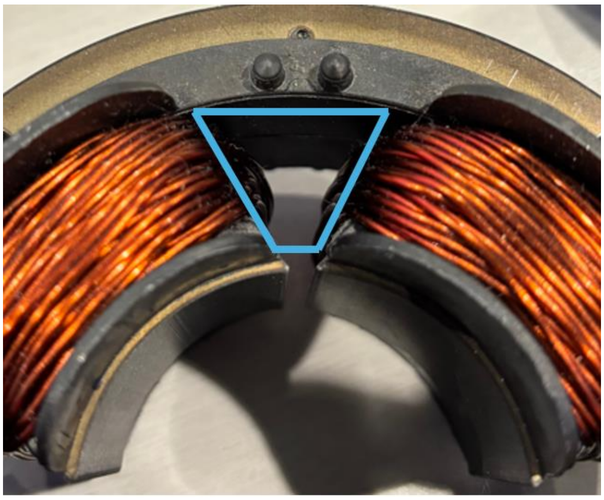

Figure 1. The blue region shows the volume of unused space in an LAT coil.

The FSCW 3-phase magnetic architecture used in the X-Series improves the torque density by allowing the flux to be vectored to synchronize with the rotor position using field oriented control (FOC) techniques. With optimal slot and pole combinations a FSCW 3-phase actuator can generate nearly constant torque at any operational angle. This allows for space-efficient construction by better utilizing the volume in the stator to package additional teeth and coils as shown in Figure 2.

Figure 2. 3-phase FSCW stator reduces the unused space inside the stator.

An additional benefit of FSCW X-series actuator is extended angular travel. LATs, as their name implies, are limited in their range of angular travel due to their single-phase construction; LATs do not have the ability to commutate. The range of travel in an LAT is typically limited to 75 deg. or less due to torque roll off at the extremes of travel. X-Series applications can travel to 90 deg. or beyond due to the ability of the FSCW technology to commutate. This increased travel can benefit valves using X-series by increasing the valve turn-down, the ratio of max flow area to min controllable flow area.

2.1.1 Actuator Torque Density Optimization

To ensure the actuator is optimized for the best torque density, the X-Series underwent several rounds of design optimization and test. During the optimization phase the salient features of the actuator were parameterized for efficient Finite Element (FE) optimization of the magnetic design. An in-house optimization tool minimizes the actuator volume subject to several constraints including magnetic torque, heat generation, and cogging torque. The optimization algorithm uses a parallel particle swarm optimization algorithm [1] to find the minimum volume; Figure 3 shows the design tool minimizing the objective function subject to the actuator's operating constraints.

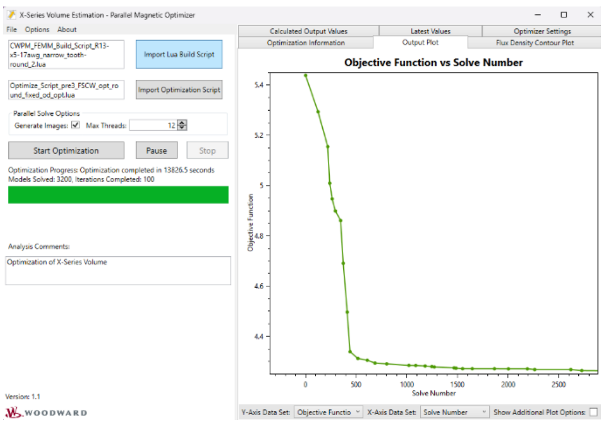

Figure 3. Optimization tools are used to minimize the actuator volume subject to coil resistance and torque constraints.

Once the finite element (FE) optimization is complete, the design parameters are integrated into the actuator's CAD solid model. Then, additional thermal FE analysis is conducted to determine the anticipated temperature profile of the complete actuator, including the driver electronics, prior to manufacturing the actuator design iteration.

After initial design and analysis, each actuator prototype iteration undergoes torque and thermal verification at Woodward's laboratory. Thermal testing is done to measure the electronics and actuator coil temperature and compared to the magnet, stator, and circuit board component thermal limits. This information is correlated to the thermal model for future design iteration if necessary. Torque production is also measured at peak temperature to ensure compliance with the actuator's maximum ambient temperature specification.

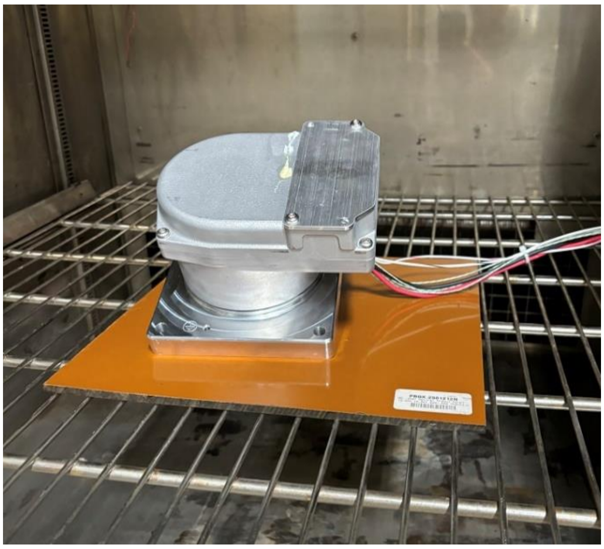

Figure 4. X-Series undergoing thermal testing at Woodward's technology campus.

2.2 Improving Vibration Capability for On-Engine Application

Valves and controls mounted on engine must be designed to reliably handle the adversarial vibration that is input into the device from the engine. The actuator itself must be designed to reliably operate in this environment but it's overall mass also has an influence on the size of the piping and bracketing structure it's attached to. Reducing the mass of the actuator can help reduce the forces imparted on the valve and piping structure attached to the actuator.

Throughout the actuator design process minimizing actuator mass was paramount. With the mechanical and magnetic optimizations, the X-Series can achieve approximately a 50% reduction in actuator mass relative to successful LAT designs. The X-5 actuator shown in figure 5 is half the mass of the ProAct model II while delivering the same level of torque. This size reduction is a direct consequence of a well optimized FSCW architecture and is not realizable with LAT single phase actuator designs.

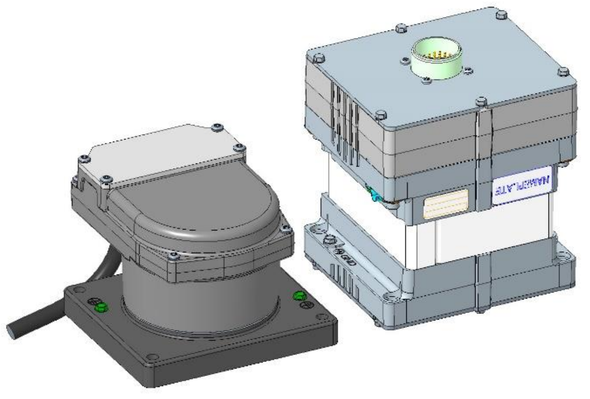

Figure 5. X-Series and ProAct Model II size comparison. X-Series generates the same amount of torque and is half the mass of the ProAct Model II.

To ensure reliable operation in the presence of vibration, engine mounted actuators must be subjected to extensive vibration testing. Testing is performed both at room temperature on a shaker table and at maximum ambient temperature for the device. Woodward has found the RV3 random vibration level covers most large engine applications.

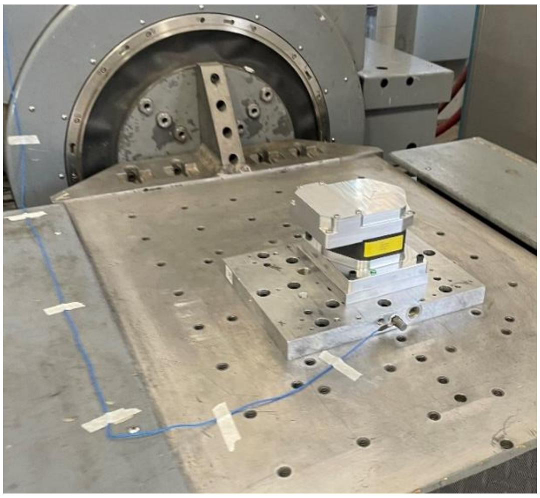

Figure 6. Early X-Series prototype undergoing vibration testing at Woodward's Technology Center.

RV3 is a 22.1 Grms, 10-2000 Hz random profile based on the MIL-STD-202F, M214A. The RV3 test is run for 3 hours per orthogonal axis. The RV3 capability of the X-Series is an improvement over the ProAct which has a vibration specification Woodward RV2,12.8 Grms random profile.

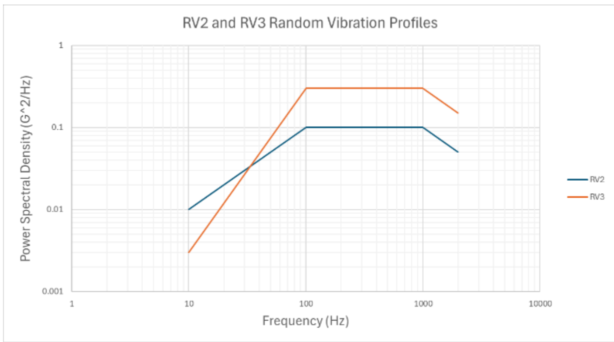

Figure 7. Comparison of RV2 and RV3 random vibration power spectral density profiles.

In cases where an engine's vibration Power Spectral Density (PSD) signature significantly differs in shape relative to the RV3 profile alternative calculation and verification strategies can be employed for X-Series using the Dirlik damage method as discussed in [2].

2.2.1 Compact Actuator Packaging

The physical volume of the optimized X-Series actuator is more compact than traditional single-phase LATs making the same torque. It has been found through technology analysis that the volume of an optimized FSCW winding topology can produce twice the torque in the same volume of an LAT (at the same ambient temperature). This increase in torque for the same physical size allows the actuator to be packaged in the same or similar locations as previous LAT actuators while benefiting from twice the torque. An example is the X-Series 48 mm CBV shown in Figure 8. This CBV valve can operate under increased boost pressure, up to 6.5 bar,a, because the X-Series actuator generates twice the torque as the F-Series in the nearly the same volume.

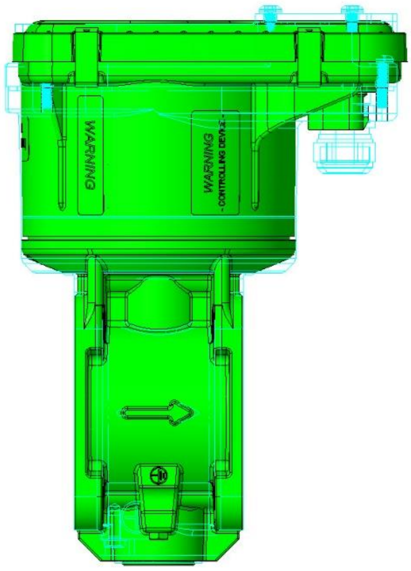

Figure 8. Overlay of X-Series (blue outline) over F-Series (green). X-Series generates 2X the torque as the F-Series.

2.2.2 Actuator Ingress Protection

New generation engine programs frequently require the increased ingress protection level of IP69K. To handle the higher ingress rating the X-Series employs a sealing strategy comprising of a metallic stator and electronics housing sealed by static o-rings. This is a proven and fielded design strategy used Woodward's On-Highway (OH) products, which must be capable of repeated pressure washing during engine cleaning cycles. Additionally, this strategy was utilized in the R-Series geared actuator.

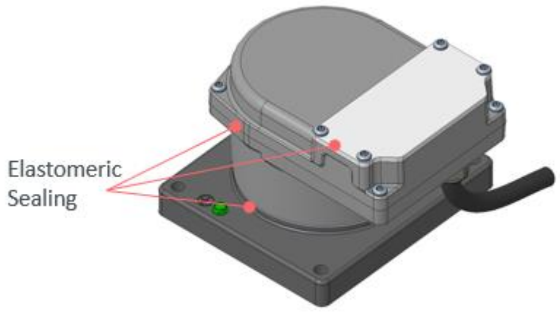

Figure 9. Sealing interfaces.

Connections from the engine wiring harness are made through a gland nut into terminated to spring terminals. The terminal connections can readily be accessed through an access cover that is retained by threaded fasteners and sealed by o-ring as shown in Figure 10.

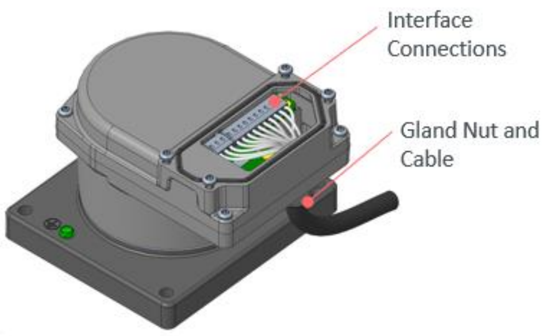

Figure 10. Electrical connection access.

3 ELECTRONIC CONTROLS

The electronic control for on the X-Series was developed to complement the compact design of the FSCW actuator. A complete actuator control solution is packaged inside the actuator; an external driver is not needed. The control solution features proven position control algorithms, accurate position sensing, and the capability to expand to CAN-FD communication. Additionally, the electronics also feature standard PWM and analog demand circuits, such as 0-20 mA, so it can be applied to the current generation of engines as well as next generation engines with CAN communication.

3.1 Embedded Actuator Controller

Multi-phase FSCW actuator control is more computationally intensive than LAT single phase control. To enable accurate and responsive position control of the X-series actuator, the embedded control algorithm must simultaneously control flux to the three coil phases while synchronizing to the rotor's sensed angular position. This puts additional sensing and processing demands on the embedded electronics and control software.

The embedded control and electrical design are capable of simultaneously sampling the current and analog position and running the physics-based control loop at frequencies that do not degrade the bandwidth or dynamic response of the actuator while also retaining sufficient computational headroom for additional application expansion for fuel control valves like TecJet or Electronic Pressure Regulation System (EPRS). The control model is physics based which, unlike a PID control, eliminates manual actuator performance tuning.

3.2 MotoHawk Control Software

The embedded electrical hardware and software are joined together through a Woodward MotoHawk application. MotoHawk is a Simulink based development environment that allows low level access to the electrical peripherals using MotoHawk driver blocks. Since MotoHawk uses Simulink, control algorithms can be easily ported into the application, with little to no change. Additionally, MotoHawk applications are controller independent once a MotoHawk Module Descriptor block is created for the target processor. This reduces the work required to update the software application if enhanced processors are used in future updates of the actuator. [3] can be consulted for further benefits of MotoHawk, especially in the context of ECU development.

3.3 Customer Interface and Communication

To enable a compact form-factor an I/O strategy was developed around the majority of actuator use cases for stand alone actuation, compressor bypass valves, and fuel control valves such as TecJet. The customer electrical connection is made through a spring terminal connection that has been shown to be a field proven and vibration capable connector on R-Series and ProAct applications. The I/O enables 0-20 mA inputs, PWM inputs, two CAN channels, discrete output, and three discrete inputs that can be used for harness coded CAN or run enable inputs.

Next generation engine platforms are expected to eventually require CAN-FD. The X-Series control incorporates this capability as well as existing legacy CAN protocols utilized on ProAct actuators and industry standard protocols, like SAE J1939.

4 X-SERIES VALVE APPLICATIONS

The X-Series torque density and modern embedded electronic control solution can enhance valve designs and be applied to a wide range of applications including compressor bypass valves (CBV) and Integrated Throttle Bodies (ITB), TecJet fuel metering valves, and gaseous fuel electronic pressure regulator systems (EPRS).

4.1 Compressor Bypass Valve

The increased boost pressures for the next generation engines impart more aerodynamic torsional load on the compressor bypass valve shafts. The improved torque density of the X-Series makes it possible to package a CBV solution that generates twice the torque of an LAT in the same physical space of the incumbent product.

To handle the increased pressure and torque requirements several modifications to the traditional CBV butterfly metering design were made including: increased shaft and plate stiffness to reduce closed flow leakage, increased rolling element bearing size for load capability, and valve to actuator shaft coupling with the necessary torque capability improvements.

Figure 11. X-Series 68 mm CBV prototype next to an LAT based F-Series CBV.

Next generation engines can require hydrogen as a fuel source with blends ranging from 25-100% hydrogen. Woodward has identified materials compatible with hydrogen for the Large Engine market through literature research and controlled exposure testing with hydrogen at internal and external labs. Woodward has incorporated the results from this hydrogen research into the X-Series CBV to ensure the materials exposed to the hydrogen blend are compatible with the upcoming fuels.

4.2 Fuel Control and X-TecJet

Power to X (P2X) fuels have become a major trend in the Large Engine industry. High speed, single-point gas engines continue to make strides on increased power density, performance, emissions, and efficiency, but must also operate on a wider range of fuels including methane, landfill gas, coal gas, hydrogen, and ammonia. Hydrogen-blended methane, 100% hydrogen, and ammonia are key P2X fuels that need to be supported for high-speed gas engines in the P2X age. However, these advancements bring new challenges. For the fuel-delivery system, the broader array of fuel gases drives new requirements for elastomer compatibility, resistance to metallurgical embrittlement, and stress corrosion cracking. Higher power density and BMEP tends to increase the vibration signature of the engine and adjustments in flow requirements drive new valve sizing. The fuel metering device plays a key role in enabling such trends to be successful.

Woodward’s X-TecJet™ product line is a series of single-point fuel metering valves poised to meet these challenges with key technology advancements, building upon the foundation of the

X-Series actuator. The higher torque density of the X-Series provides a more compact actuator for the larger range of metering valves, improving fatigue life in high-vibration environments. The modern embedded electronics allow for fuel-flexible, fast and accurate flow control algorithms, along with the ability to interface with the latest pressure sensing technology. Coupled with a new mechanical valve design that provides material compatibility for P2X fuels and improves serviceability for component overhaul, engine operators can enjoy a more capable TecJet™ for the next generation of natural gas and P2X engines.

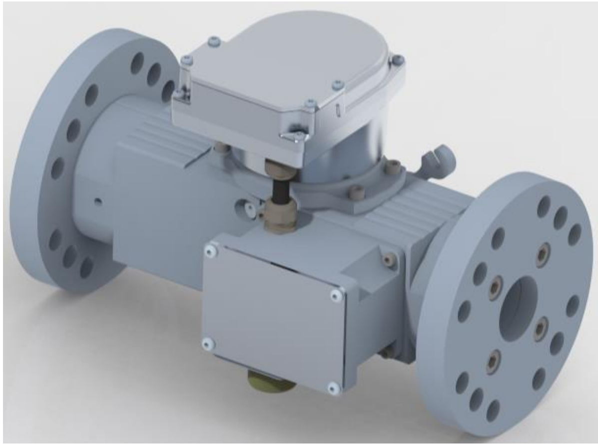

Figure 12. X-Series-Based TecJet™ X50 prototype.

4.3 Electronic Pressure Regulation System

The combination of onboard controls and torque dense actuation lend itself to a compact electronic pressure regulation system for multipoint fuel metering valves such as SOGAV. The EPRS has been successfully tested on natural gas and on P2X fuels such as ammonia and hydrogen, in addition to natural gas. For SOGAV applications the EPRS can precisely control the pressure of the fuel manifold using a model-based pressure control to reduce the system tuning and optimize the pressure response. Further information about multipoint P2X fuel operation of SOGAVs can be found in [4].

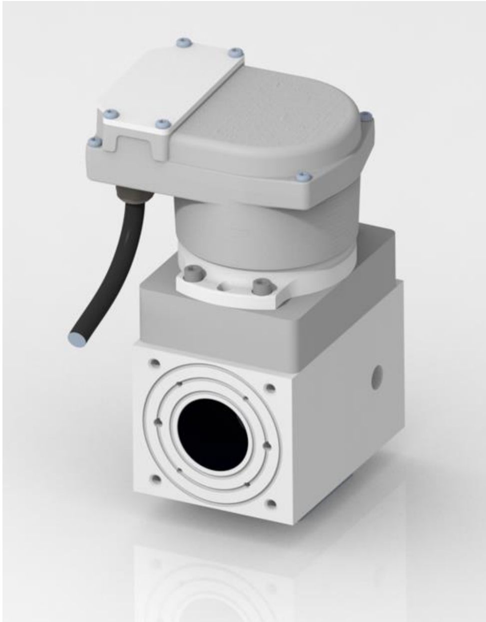

Figure 13. Electronic Pressure Regulator.

5 CYBER SECURITY

In addition to the technical innovations of the X-Series that were added to meet the system requirements of modern high-speed gas engines, the X-Series is also designed with Woodward's secure development lifecycle process (SDLC). Woodward's SDLC is based on the international IEC-62443 standard and provides the framework for a cybersecure-oriented product development process. Operational Technology (OT) systems have become particularly vulnerable targets for cyberattacks due to their size, complexity, age, and long-lived maintenance/upgrade cycles. Cyberattacks of OT systems in recent times have caused everything from system malfunctions, instability, system shutdowns to destruction of property and loss of revenue.

5.1 X-Series Product Environment

As part of the evaluation of the X-Series cybersecurity considerations, it's important to understand the typical use-case of an X-Series within an industrial control system. A useful guide for this evaluation is the Purdue model for industrial control as illustrated in Figure 14. The Purdue model was designed as a reference model for data flows in computer-integrated manufacturing with automated plant processes and defines the standard for building an ICS network architecture that supports OT security via network layer separation and dataflow management between each layer [5,6].

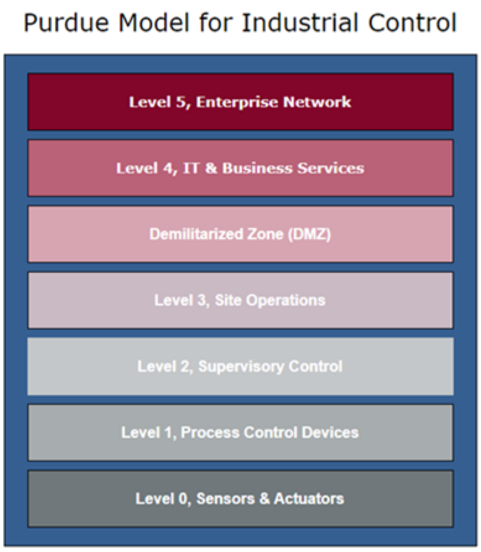

Figure 14

Application of the X-Series is done at a component level of Level 1 – Process Control devices within an OT system. The X-series operational environment is typically actuation of engine subsystem components such as throttles, bypass valves, and pressure regulators, is physically on-engine mounted, and receives process commands via hardwired commands or a dedicated on-engine based CAN network from an engine control system (ECS) as illustrated in Figure 15. A second CAN network is used for service, configuration, and firmware updates and generally requires physical access.

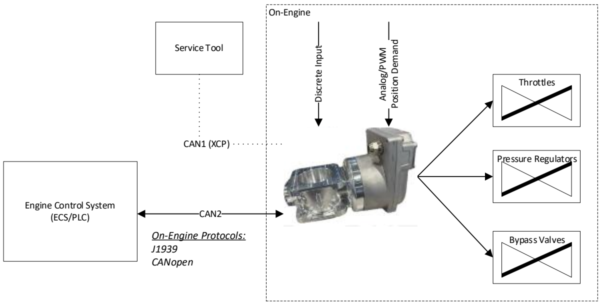

Figure 15

5.2 X-Series Actuation Cybersecurity

Despite the low-level operational environment of the X-Series and the fact that many cybersecurity defenses are applied at higher levels of the Purdue model, a defense in depth strategy is key to overall system security and the X-Series is being developed with Woodward's SDLC process in order for system integrators to enable multiple layers of security to protect the system's assets. X-Series security considerations include physical security, security policies, network architecture, firmware patching and malware prevention, and access control and are planned with a phased approach as illustrated in Figure 16.

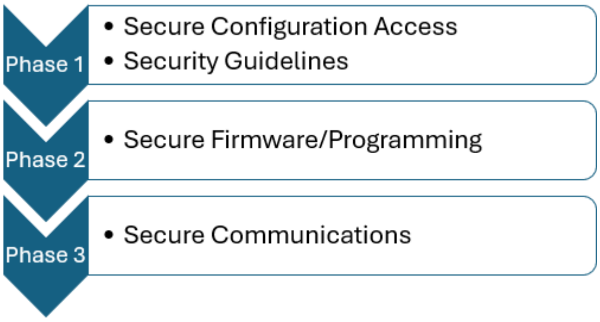

Figure 16

5.2.1 Phase 1

Security considerations focus on addressing physical security, security policies guidelines, and access control of X-Series configurations and firmware programming. X-Series monitoring and configuration is secure through a dedicated Woodward service tool and service interface using a user-level, password authorized, seed-key mechanism of the XCP protocol. Access levels include monitor only, service, development, and programming; where monitoring enables a read only access mode, service provides a limited read write access mode required for service operations only, development enables end-user device configuration, and programming enables firmware upgrades. This enables system integrators to secure against different levels of unauthorized access and support a mechanism for authentication. In addition to secure configuration management, a security manual is included with the product for system integrators which provides a description of the security context and strategies for the X-Series. The security manual covers security configurations, physical security considerations, security policies and procedure guidelines, user access information, decommissioning, and product security alert reporting and notifications.

5.2.2 Phase 2

Phase 2 security considerations focus on addressing firmware updates that may occasionally be released to address new or updated functions and security patches. These include features such as secure boot and signed/encrypted firmware and programmer tools. Secure boot validates application firmware on bootup using a modern version of cryptographic algorithms and keys in order to prevent un-authenticated firmware to execute on the X-Series unit. Signed and encrypted firmware and programmer tools binaries prevent in-transmit binary modification and use of malicious software programming tools.

5.2.3 Phase 3

Phase 3 security considerations focus on addressing future secure communications extensions of existing on-engine protocols (e.g., J1939-91C) that can enable authenticated and/or confidential on-engine network X-Series commands from the engine control system. This can help mitigate the possibility of command injection (i.e., command message spoofing) and denial of service (dos) attacks.

6 CONCLUSIONS

The new generation of large engines need electric actuation solutions with improved torque density, and onboard electronic control developed with Cybersecurity considerations. The X-Series uses an optimized 3-phase FSCW construction that improves the torque density by approximately a factor of two relative to traditional LAT technology. This reduces the actuator volume and mass, which improves vibration loads on the system and allows for improved packaging solutions to provide higher levels of ingress protection relative to previous LAT solutions.

The X-Series onboard electronic control, with its physics-based control algorithms, was developed with cybersecurity considerations. The software application uses Woodward's SDLC and X-Series will develop cybersecurity capability in a phased approach starting with secure access considerations phase 1, then secure firmware updates in phase 2, and finishing with secure communication protocols in phase 3.

Finally, valve applications developed with X-Series benefit from compact size and additional travel. These two enhancements allow for valves to handle increasing loads, as engine power density increases, and minimize the overall valve size. During the design process it is ensured that the valve materials are compatible with P2X fuel sources such as hydrogen blends and ammonia in addition to natural gas.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

FE – Finite Element

CAD – Computer Aided Drafting

FSCW – Fractional Slot Concentrated Winding

LAT – Limited Angle Torquer

DOS – Denial of Service

SAE – Society of Automotive Engineers

EPRS – Electronic Pressure Regulation System

CBV – Compressor Bypass Valve

ITB – Integrated Throttle Body

SDLC – Software Development Life Cycle

XCP – Universal Measurement and Calibration Protocol

ECS – Engine Control System

P2X – Power to X

BMEP – Brake Mean Effective Pressure

OT – Operational Technology

PSD – Power Spectral Density

OH – On Highway

ICS – Industrial Control Systems

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9 CONTACT

John Karspeck is a systems engineer for industrial control systems at Woodward, Inc. Mr. Karspeck graduated with a MSME from Colorado State University (2005) and has been employed by Woodward since 2006. Mr. Karspeck has been involved in the development of large engine electromagnetic actuators and injectors, fuel valves, and exhaust wastegate valve applications at Woodward, Inc.

Email: john.karspeck@woodward.com

Chris Ohlsen is software engineer for large engine controls at Woodward, Inc. Mr. Ohlsen graduated with a BSME from The University of Texas at Austin (2008) and a MSECE from Colorado State University (2012). Mr. Ohlsen has been employed by Woodward since 2010 and is involved in the development of embedded controls and applications.

Email: chris.ohlsen@woodward.com

Tim Harper is an electrical engineer for industrial engine systems at Woodward, Inc. Mr. Harper began at Woodward in 1988 and graduated from the Irl C. Martin Academy of Industrial Science concentrating in electronics (former in-house technical school at Woodward) in 1990 and while working, continued to Colorado State University for a BSEE (1999). Tim is involved in the development of electronic engine controls and actuators at Woodward, Inc.

Email: tim.harper@woodward.com

Brandon Gleeson is a mechanical development engineer for large engine controls at Woodward, Inc. Mr. Gleeson graduated with a BSME from the Colorado School of Mines (2002). His design experience includes fuel injectors and fuel system component for mobile and off-highway gaseous-fueled industrial engines, as well as high temperature exhaust valves for turbine-side exhaust flow management.

Email: brandon.gleeson@woodward.com