The Connected Construction Machine: The Integration of Wireless Technologies with Mobile Control Systems
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1 Executive Summary

The evolution of technology and its impact on construction machinery presents challenges for OEMs and vehicle designers. Designers must navigate the rapidly changing technology, select the right products for a cost-effective control system, and ensure they are adding functionality their customers will benefit from. Doing so usually requires that custom software is written specifically for their vehicle and application. Wireless connectivity to tablets and smartphones can be used to provide remote access to the vehicle, adding a number of new capabilities such as diagnostic data analytics in the cloud, wireless control through an app, and the integration of smartphone features like GPS and maps.

This white paper provides a high-level review of these technologies as well as the following:

- How tablet and smartphone integration is rapidly changing machine control systems
- The benefits and challenges with custom application software development
- Connectivity to the Internet of Things (IoT)
- Considerations of cloud-based data logging, diagnostics and prognostics
- An overview of electronic control technologies impacting construction machinery
- The use of technology to detect and prevent vehicle theft
- Integrating Tier 4 engines into a vehicle control system

2 Introduction

Vehicle control systems for construction machinery have evolved significantly over the years. Changing technology and a strict adoption of environmental and safety standards have driven OEMs to continuously redesign their products to keep up with the needs and expectations of the market and their customers. Vehicles must be more productive, offering more features, while using less fuel, generating less emissions, and without compromising safety. The evolution of technology on mobile equipment has an exciting history that brings with it new capabilities and possibilities. When used effectively, technology can help to solve challenges and introduce a higher level of functionality to the vehicle. One can see evidence of this when looking at the various vehicle subsystems:

- **Hydraulic** systems have evolved from manually controlled systems to hydraulic-over-electric direct wired systems, to systems that use electronic hydraulic controllers and proportional valve control. Each step introduced more hydraulic functionality and reduced the number of hydraulic hoses required.
- **Electrical** systems traditionally used relays for implementing simple control logic. While this was simple and cost effective, the limits of what could be implemented were quickly realized. Embedded controllers were introduced with microprocessors running software. The integration of electronic and hydraulic systems allowed for simple electronic control of on/off valves and closed loop control of proportional valves, pumps and motors.
- **Mechanical engines and transmissions** have been replaced with electronically controlled systems allowing for adherence to emissions standards and providing better fuel economy. The electronic controllers are capable of communicating over a wired network and use communication protocols such as J1939 over CAN. Manufactures can
add digital monitors to their vehicles to communicate with the engines and transmissions, and display data that was previously not available or only available over a wired connection.

- The **operator interface** has evolved from air core gauges to electronic instruments clusters, to graphical displays each offering more information to the user that was not possible before. The focus in recent years has been to enhance and improve the user experience, with touchscreen displays and ergonomic joysticks, however many operators still prefer rocker switches with good tactile feedback that can be operated reliably wearing gloves. CAN based versions of these products are also available, capable of communicating with other modules on the network.
- The evolution of **electronics** in general has brought new functionality and changed the way vehicles operate and the way they can be used. Mechanical analog devices have been replaced with electronic digital devices that communicate with each other over networks, allowing the exchange of high amounts of data. Data analytics give us a deeper understanding of how vehicles perform and how they can be improved. This allowed for the distribution of electronics across the vehicle reducing wire harness complexity, removing relays and adding wireless and remote connectivity.

In recent years, wireless integration with smartphones and tablets brings **connectivity** and is used for remote diagnostics, asset management and theft detection, remote operation or wireless control, as well as collecting and analyzing data in the cloud to measure and control productivity. Apps can be written to interface with machine controllers and used to implement automated functionality.

Perhaps the most important aspect that ties all of the vehicle technologies together is the **software** that runs on each electronic component. Every system needs sensors, actuators, displays and controllers, but the real value and complexity resides with the application software which is usually customized for each vehicle. The definition and development of the application software is key to differentiating one vehicle from another and, when designed well, can bring significant performance enhancements.

This white paper reviews these trends and emphasizes the use of technology and software as the best way for OEMs to remain competitive. The market is pushing for finer controls and enhanced functionality and the concept of precision construction is taking shape.

### 3 Technology Overview

A review of the technologies available to vehicle controls must consider not only the impact they have on the design of the system but also the overall value they bring to the operation of the equipment. The technology can be broken down into a number of categories including connectivity, operator interface, performance data, controls, application software, operator controls, sensors, actuators, vehicle power and drive and safety systems. This white paper reviews each of these, looking at both the history and the benefits of the related technology.

However, prior to addressing each of these, a general understanding of the overall vehicle architecture is provided. Consider the system block diagram provided below:
The introduction of new technology is fueled by the underlying need to improve some aspect of the vehicle's operation. We are driven to do things faster and more efficiently, using less fuel, producing less pollution, while enhancing the experience of the user and without compromising safety. Vehicles must operate reliably and when issues arise, they must be quickly diagnosed and resolved with minimum downtime. Technology can help to achieve these goals when used correctly.

Vehicle performance is not a general term but instead relates specifically to the type of vehicle and its application. For example, a wheeled loader's performance may be measured by cycle time to perform one loading/unloading cycle. Looking at the number of hand and foot movements required to perform these functions and minimizing the complexity will improve the performance. As another example, excavators are most productive when operated at
the peak of their power curve to maximize the power in their dig cycle. By designing a control system around this functionality, the most efficient use of power can be realized.

The block diagram shows a network of components, connected through software and working together as a system to achieve the desired outcomes. By utilizing the right technology and through the development of vehicle specific application software, it is possible to achieve a broad range of powerful functionality and support the continuously evolving cycle of vehicle performance enhancement.

4 Connectivity

People have become accustomed to a high degree of connectivity in their daily lives in part due to the widespread use of tablets and smartphones. Combining this technology with cloud computing allows for the storage and sharing of data, as well as widespread access to information and services. These technologies have advanced to a point where they can offer attractive options for construction machinery in the areas of remote monitoring, machine-to-machine (M2M) interfaces and data-logging. The following paragraphs provide a number of examples of how this technology can be used.

Mobile devices becoming ubiquitous has allowed for a new and cost-effective way to connect systems to the Internet. Solutions for remote monitoring of construction machinery have been available for several years, but these solutions involved having a telematics device with a cell modem installed on the machine that was connected to the Internet over a cell network, as shown in Figure 2. This approach requires each machine to have its own cell phone plan, making the cost of these solutions often higher than the benefit gained from remote monitoring.
However, since the vast majority of people now have cell phones that have data plans already associated with them, a cost-effective way for connecting machines to the Internet is to use mobile devices as a Wi-Fi hotspot (tethered device), which allows a Wi-Fi enabled machine to connect to the Internet via a tethered mobile device, as shown in Figure 3. This way, no separate cell plan is required for the machine itself, bringing down the cost for this functionality. This approach requires the operator to use a smartphone or tablet to enable the connection.
Figure 3: Wireless connectivity tethered through a smart device
The other recent technology change currently in effect is the exponential growth of what is known as the "Internet of Things". This growth of Internet connected devices in all aspects of daily life, such as cars, coffee makers, thermostats and almost everything that can be imagined. This growth has also resulted in a growth of an underlying infrastructure to facilitate cloud-connected devices. This includes everything from data storage, data management, metrics analysis and security management. As a result, it is relatively easy to develop a system for connecting and monitoring construction machinery remotely, because the infrastructure for such systems is already in place.

5 Operator Interface
With the exception of a fully automated application, all vehicles require an operator. The operator requires suitable controls to translate what they want the machine to do into actual motion. They also need feedback from the machine to give them information on the vehicle operation. The technology and products that facilitate these inputs and outputs make up the operator interface. There are many different technologies available and they will vary depending on the application, the vehicle and type of control required. Examples of feedback devices include instrument clusters, graphical displays, mobile devices and audible warnings. An overview of feedback devices is covered here and an overview of operator controls will be covered later in the document.

Display monitor technology is undergoing major changes, fueled by the proliferation of low-cost, highly capable smartphones and tablets. There are three different categories of displays that are typically used in construction applications. They are:

- **Instrument Clusters**: These are common to most construction machines and they can utilize a variety of different technologies. Typically an instrument cluster consists of any combination of indicator lights, bargraphs, gauges and an LCD. Historically these were hardwired components packaged together in an enclosure. Today most clusters contain electronics and a microprocessor running software to control the device. The information shown on the LCD can range from simple text to higher end graphics like gauges, images or camera monitors. Instrument clusters connected to the vehicle CAN bus provide most of the necessary information for real time operation of the vehicle.

- **Graphical Displays**: These are highly flexible color LCDs packaged in a rugged enclosure. They are often touchscreen or have soft-keys and navigation wheels and may have advanced features such as video integration (capable of connecting to cameras). Common screen sizes are 4.3", 7.0" and 12.1". The graphics and function of the displays are customized for the application and give a wide variety of monitoring and control capabilities. These displays have a high degree of flexibility and they are made specifically for rugged environments. The limitations with this type of product is cost, especially when compared to the cost of a tablet which offers similar or greater capability but is not designed for a rugged environment. The JCA OWL family of display units are an example of ruggedized high-end graphical displays that can be customized for control of a specific machine.

- **Mobile Devices**: Mobile devices are readily available tablets and smartphones, like the Apple iPad/iPhone or Android devices. These devices have become so prolific that almost everybody has one of these devices with them.
at all times. This is a major game changer in considering operator interfaces for control and monitoring of construction equipment. The cost-benefit analysis for adding control and monitoring functionality changes significantly assuming that people already have a high-end display with wireless connectivity and GPS capabilities in their pocket. For this reason, tablets are a viable option for vehicle control operator interfaces and smartphones are becoming popular replacements for a remote control, or for new ways to augment a control system with additional monitoring and diagnostic capabilities. Since tablets and phones will be carried by the user rather than remain in the vehicle overnight, there is less need to design them for a rugged environment. A ruggedized box can be mounted within the cab to protect the tablet or phone while being used in the vehicle. Integrating mobile devices into a control application requires a controller that has Wi-Fi or Bluetooth capabilities to communicate to the mobile device, or a gateway device that can perform this function. Controllers such as JCA’s Falcon or Oriole have built-in Wi-Fi and Bluetooth capability that can be used for interfacing to mobile devices.

6 Telematics
Using mobile device technology, the user interface of the vehicle extends its reach far beyond the cab. Apps and web interfaces can be used to access any machine from anywhere. The possibilities this unlocks are vast and the benefits are evident:

- Remote Fault Monitoring: With wireless connectivity, it is possible to communicate vehicle faults and errors to a smartphone or tablet via an app. Or this information could be monitored by a dealer or fleet manager giving them immediate indication of an issue. If a replacement part is needed, the dealer could prepare to have the part transported to the vehicle, minimizing any down time.
- Data Logging and Intelligent Reporting: While data logging is not a new concept, the ability to use the data effectively is usually a challenge. Utilizing the processing power of the cloud, it is possible to analyze aggregate data from many users to produce application specific reports showing different information for the operator, the fleet manager, the dealer and the OEM. The objective is to extract the important data and produce metrics that people can use to improve machine performance.
- Prognostics: Prognostics is a method of predicting when components will fail by measuring how they are used and combining that information with knowledge about their life expectancy. By collecting data from multiple vehicles in a cloud environment and comparing that with component replacement data, it is possible to build prognostic intelligence. This information is used when servicing the vehicle to proactively replace parts that are getting close to their life span and result in less field failures and less downtime. Wireless connectivity and cloud based computing make it possible to build a large database of failure data and an intelligent proactive system.
- **Theft Detection and Asset Tracking:** Theft of vehicles from a construction site is an ongoing issue, costing many millions of dollars annually. Technology can be used to detect the location of vehicles and send alerts to owners to inform them of a possible theft. Many vehicles use an immobilizer that must be disabled using a key fob or code to make the vehicle operational. Insurance discounts may be offered in some regions for vehicles using this technology. Accelerometer technology could be used to detect unexpected vehicle movement, and GPS can be used to monitor vehicle location. A geo-fence can be created around a job site which is a virtual boundary defined using GPS data. If a vehicle crosses the boundary, an alert can be sent or the vehicle could be placed into a limp mode limiting its functionality. Data can be transmitted wirelessly to an app running on a smartphone or tablet.

- **Fleet monitoring:** Fleet monitoring requires the ability to monitor many systems, collecting all the data in a central location, and then processing the data to produce the analysis. This could be important for the fleet owner who wants to track the locations of all their equipment or see how each machine is being used, or for the OEM that wants to monitor machine usage trends for warranty or service purposes or to improve designs.
In addition to monitoring capabilities, Internet connectivity enables the integration of commonly available information such as mapping or weather data into the vehicle control system.

Platforms such as JCA’s Cumulus facilitate the connection from users to devices through the cloud and also utilize the processing power of the cloud to analyze large amounts of data from multiple vehicles. In the case of Cumulus, this is the backbone system that manages user account information and can be used for diagnostics, prognostics, trend analysis, warranty analysis, asset management, security and machine-to-machine (M2M) interfaces.

7 Vehicle Controls

The introduction of control technology is probably one of the most significant and powerful decisions to be made in the design of a vehicle. Technology has evolved from simple systems using relays, direct wired and direct hydraulic controls to smart systems that use a programmable controller. Today smart control systems must also provide connectivity, not only between controllers, but also wirelessly to mobile devices and the cloud. Wireless connectivity allows for the advanced features described in the previous sections of this document, which focused on measuring and improving the performance of the vehicle. This section reviews the machine control functions necessary for fulfilling the fundamental operation of the vehicle.

Smart control systems have been around for more than 25 years, but continue to evolve at a fairly rapid pace. Some of the aspects of a smart control system are technologies that have matured, and therefore are well-understood in the industry and most control system providers offer comparable solutions. These mature technologies include CAN communication (often communicating to the J1939 standard), driving of proportional valves with PWM control, PID control systems (both at the valve control level and at the higher function level) and sensors interfacing to analog, digital and frequency inputs. Modern systems consist of multiple networks of CAN modules all sharing data that is used to achieve vehicle functionality.

Smart controls are commonly used in construction equipment to perform a number of functions. Examples of these include boom control, steering control, drive control, suspension control, throttle functions, lighting, and general on/off switching of hydraulic valves to control different aspects of the vehicle. In each case joysticks, sensors and switches are connected to the inputs of an electronic controller. The controller uses software logic to determine how to energise its outputs to drive the actuators on the vehicle.

As an example, boom control typically connects the output of a joystick to a group of proportional valves through an electronic controller. Closed loop control routines using PID algorithms are employed and it is possible to achieve similar or better responsiveness as was possible in direct wired hydraulic system. These algorithms require fine tuning and testing on the target vehicle to work out any differences in pump characteristics, valve characteristics, and flow responsiveness. Typically the goal is to design a system that reaches its target output or position in the shortest timeframe, with zero overshoot or oscillation. The software is used to create the desired feel of the boom by dampening the movement for smooth operation.
Suspension control can be implemented in two very different types of systems, either as active suspension or as suspension modes. Active suspension replaces the traditional passive systems by monitoring and adapting the suspension system to changing conditions. This technology, developed for automotive, can be applicable to some vehicles. More common are electronically controlled suspension modes that change the ride height of one or both of the axles to assist vehicles, such as a Backhoe, with various dig operations.

Steering systems are also useful on vehicles that require a greater degree of maneuverability. Advanced steer-by-wire systems are possible giving full electronic control over the steering system. However more common is to have a mechanical front steer system combined with electronically controlled rear steering. These vehicle can operate in various modes such as 2 wheel steer, 4 wheel steer, or crab steer.

Another control example is the use of hydraulic power matching between a pump and an engine, commonly used in large excavators. As an excavator drives its bucket through a dig cycle, it is desirable to maintain engine loading within its peak power range. This can be achieved by de-stroking the pump as the engine approaches the target RPM. The performance of the excavator can be greatly improved through the design of this type of control.

Some vehicles use electronics to monitor or control the electrical power distribution from the fuse and relay panel. In a monitoring system, the state of fuses, circuit breakers and/or relays are monitored allowing any fault condition to be communicated to the operator for immediate attention. When a vehicle function becomes inoperable, these systems provide an indication if a fuse has blown, reducing the time it takes to troubleshoot the issue. In a power distribution control system, solid state electronics are used in place of fuses, circuit breakers and relays, to drive the loads directly. In these systems, current is monitored and circuit trip points can be set in software to shut off outputs when thresholds are exceeded. It is possible to allow different amounts of inrush currents or simulate other profiles similar to a fuse or circuit breaker. The advantage of a solid state system is that circuits can be reset through software, relay functions can be integrated into the software logic, and operational loads can be monitored, logged and reported providing insight into the vehicle operation. Controllers like the JCA Hawkeye were designed as a load center capable of providing these features.

There are certainly differences in capabilities between control platforms relating to these mature technologies, but any serious control platform provider should have sufficient solutions within these technology areas. Emerging or growing technologies for control systems are areas of more differentiation between control platforms. Some of these emerging technologies include wireless connectivity, M2M control/communication through cloud connectivity and data logging capability. Control platforms that have solutions for many of the emerging technologies allow for the greatest flexibility to add new functions as the features and needs for the vehicle control evolve.

The implementation of the application software in a smart control system can be an intimidating task for a company that has not worked with these types of systems. Some companies use a system integrator who can tie products together and write the application software. Others will develop their own in house capability for writing software. Companies can rely on the expertise of third parties companies like JCA Electronics for defining and creating the application specific software for each application by combining products into a system design to meet the customer
requirements. JCA emphasizes the importance of application software development in each project and the need for a clear, systematic approach to this development.

8 Application Software

Embedded systems consist of many components that must work together as a system to provide the desired machine functionality. It is the software that provides the connectivity between each component and can help optimize each of their unique features. Software can be thought of as the glue that ties the system together. For every system, there is almost always a need to develop software that is unique and custom to that application. This comes with benefits and challenges.

The benefits are that OEMs have the opportunity to customize the behavior of their product through software which, in a sense, is limitless in what can be done. Using the available technologies (sensors, actuators, etc.) software can be written to not only implement the desired features, but can be used to modify the ‘feel’ of the machine. For example, while every Telehandler has a joystick that controls the boom, how fast that boom moves and whether it moves smoothly or abruptly can be modified in software. Features like vertical or horizontal path control can be written into the software to aid in specific applications. While these are just examples, these types of features can be used by OEMs to differentiate their vehicle from their competition. Software is powerful in what it can bring to the behavior of a vehicle system.

The challenges are usually tied to the software development process and ensuring the end product is reliable. Common to all forms of product design, it is important to follow a process that involves a definition of product requirements, followed by design and development, followed by verification testing. Software is no different and possibly further complicated by the fact that obscure bugs in code are difficult to find. It is therefore critical to spend time defining thorough requirements prior to initiating any software development project. The requirements then serve as the criteria for verification testing. In a typical project, once the requirements are complete, about 1/3 of the time will be spent implementing functions, 1/3 of the time will be spent implementing the diagnostic and fault functionality, and another 1/3 will be spent on testing. Most project estimations focus heavily on the implementation of functions but are light on the diagnostics and testing. However, a well-developed diagnostic system combined with thorough verification testing make the difference in having a trusted and reliable system. When developing software with a third party, OEMs should rely on a clearly defined, phased process for software development, involving them as a customer from start to finish. While software development in a vehicle application can be challenging, the benefits far out weight the efforts of implementation.

9 The Connected Control System

Today’s vehicle systems are implemented as a system of connected components. Utilizing CAN based communication, products can share data and work together to achieve the machine functionality. As an example, a CAN based switch could be used to activate functions on different controllers driving independent
actuators. This connectivity is the reality of modern control systems. The following sections review these system components looking at the operator controls, sensors, actuators, and vehicle power & drive.

9.1 Operator Controls
The user interface requires products that allow the operator to control the vehicle. Each of these products provide unique features suitable for the application and they must be connected with the vehicle control system. Examples of controls for the operator are joysticks, switch panels, multifunction steering wheels and remote controls. A few of these technologies are discussed here.

Rocker switches and other simple operator controls are well established technologies. Trends in these areas are moving these controls to CAN bus based switches and controls. CAN switches result in less wiring, require fewer input channels on controllers, and allow for more flexibility in functionality. The switch function and LED indication can easily be adjusted with programming in the system controller. This additional functionality comes at a higher cost of switches, so this needs to be evaluated to determine if it is the right solution for the application. Regardless of the electrical interface, rocker switches are often preferred over membrane or touchscreen interfaces due to the tactile feedback they provide to the user.

Joystick technology also is a fairly well-established technology with most trends moving towards CAN-based joysticks, with the same trade-offs as for switch controls. There are a wide range of joysticks which range in size, capability, ruggedness, reliability and cost. Some offer advanced features such as force-feedback in which the effort to move the joystick varies in response to the vehicle environment. Capacitive sensors to detect operator presence can be used to avoid inadvertent actuation of the joystick. The sensors detect that an operator is in contact with the handle grip and used to tell the system if the joystick movement is valid. All of these attributes need to be considered when choosing the right joystick for the application.

Ruggedized remote controls are used in many applications requiring wireless control. These are typically wireless joysticks and switches with relatively simple functionality (i.e. press button = activate function). Again, because of the wide adoption of mobile devices, a high-end control device is most likely already in most people’s pocket. This opens up new possibilities in wireless control, where applications that in the past did not justify the cost of a dedicated remote can now be wireless control applications. This is not to say that dedicated remotes are obsolete; there is certainly still a place for a ruggedized remote with large buttons that can be activated with work gloves. Instead, it means that there is a new consideration in the design of systems. Some controllers can be used as both a wireless transceiver and a controller interfacing with either a mobile device or a dedicated remote.

9.2 Sensors
Sensors are an integral part of any vehicle control system. They are used to measure all sorts of system attributes that may be important to the application such as position (angular or linear), speed, acceleration, proximity,
temperature, weight, level, pressure and humidity, just to name a few. Because of the magnitude of the different
types of sensors, only a few of the most common sensing considerations are highlighted here.

Angular position sensors are probably the most versatile sensor for position monitoring. These can be used not only
for sensing the angular position of parts of a machine, but can easily be adapted for linear position monitoring and
height sensing.

One of the most common sensing challenges is linear position sensing for hydraulic cylinders. This poses a challenge
because there are three main ways to have linear position sensing integrated into a cylinder, and all of these are
prohibitively expensive for most applications. As a result, the most common method used is to use an angle sensor
(which is relatively low-cost and sufficiently robust) with an application specific mechanical assembly that translates
the linear motion into angular motion. Figure 5 shows an example of one possible configuration.

![Figure 5: Linear Position Sensing with Angle Sensors](image)

The three common integrated solutions all require modification of the hydraulic cylinder or a specialized hydraulic
cylinder. These integrated solutions use magnetostrictive sensing, linear transducers with external magnet or an
etched cylinder with a code reading module. Two out of the three solutions can be implemented in any third party
cylinder, but one of them is exclusive to one particular brand. All of these solutions involve extremely high cost of
cylinders and, as a result, are often explored in the design stage but then rejected because of cost reasons.

Rotary speed sensing is also a very common need in most applications and usually achieved with gear-tooth type
sensors. These are typically based on hall-effect technology (often three-wire sensors) or magnetic pick-up sensors
(often two-wire sensors). While this is a well-established technology, there are many considerations in choosing the
right sensor technology (such as speed, distance to sensor, electrical signaling, mounting type and location, etc.).

Another sensing requirement for certain applications is weight measurement. This is typically done with the use of
load cells. One example of an application using load cells is tip over detection on a vehicle with an extendable boom.
In this application, the load cell is positioned to measure load on the rear axle and used to determine how close the
vehicle is to a forward tip over. While maintaining vehicle stability is usually left to the expertise of the operator, this
technology can be used to provide useful feedback. Load cells have unique signaling requirements and typically require interface modules specifically designed for this purpose. Sensors provide input data to the control system and selecting the right sensor is crucial in the design process. Contactless sensors such as Hall Effect sensors are usually more reliable and are a good option if available. Software can be used to read, filter, and interpret sensor data, but a sensor with too much noise or the wrong resolution can impact the system's overall ability to perform correctly. To avoid this, careful consideration to select the correct sensor should be reviewed early in the design process.

9.3 Actuators

Actuators are components on the vehicle that make things move. They are used to control the boom, the stabilizer legs, bucket movement, vehicle drive, and a wide variety of other functions. Typically, the operator demands movement through a joystick which is connected to an electronic controller which in turn is connected to an actuator. These system components are linked through application software to provide smooth control of the vehicle. There are primarily three types of actuators in construction machinery. These are hydraulic, electric and pneumatic.

Hydraulic systems are probably the most common method for control because of the versatility and power offered by hydraulics. Both rotary and linear motion are easily achieved using hydraulic motors and hydraulic cylinders. Also, since the hydraulic pump is provided by the vehicle, it is usually fairly cost effective to use hydraulics control functions. Hydraulic technology is fairly well established and has not changed significantly in many years, although small improvements have been made in the last decade. The general trend in hydraulics is moving towards proportional control for fine and smooth movement where needed.

Electric actuator technology has probably made the most advancements in the last decade, most specifically related to linear actuators. Electric motors for rotary motion are a well-established technology that has not significantly changed in years. Linear actuators, on the other hand, have gained in popularity, mostly in applications where accurate linear motion and feedback is required. Unlike hydraulic cylinders, integrating linear position sensing capability into linear actuators does not add significant cost to the linear actuator. The major disadvantage for electric drive systems in mobile applications is the large currents (and therefore large wires) required to carry the current for the motor/actuators. Since most mobile system are low voltage systems (12V or 24V) systems, high current is required to provide the power requirements for the application. Linear actuators become very interesting in small power requirements, because the accuracy of the linear actuators are an advantage, without the cost of high current actuation.

Pneumatic systems are not decidedly common for construction equipment, generally because they are not as powerful as hydraulic systems and require a separate air compressor as a power source. Pneumatic systems are controlled in very similar ways to hydraulic (with valves that can be driven with solenoids), but do not allow for as fine a control as hydraulic systems.
9.4 Vehicle Power & Drive

The engine represents the principle source of power on any vehicle. The transmission transfers this power into vehicle movement. Advancement of technology has allowed engine manufacturers to deliver higher performance, with low fuel consumption, while meeting the legislated limits for emissions. Technology has allowed transmission manufacturers to design more efficient products making better use of the available power. When the engine and transmission controllers work together, they can optimize performance, improve fuel economy and produce a more eco-friendly vehicle.

Over the past few decades, federal standards for off-road diesel engines have phased in regulations that limit the amount of emissions that can be produced. The most recent phase, known as Tier 4, went into effect in 2015. Engine manufacturers have introduced various control technologies to meet these regulations while minimizing the impact to cost and fuel economy. Control systems include a variety of sensors to measure temperature, pressure, air flow, position, speed and sensors to measure the composition of exhaust gases. This data is fed into an electronic engine controller used to control fuel injection to each independent cylinder at every engine cycle. The engine controllers support communication over the J1939 CAN bus and can be tied into the vehicle network, communicating with other modules.

The introduction of the electronic engine controller presents a number of challenges for vehicle designers. In many cases the engine controller is the first electronic component to be added to the vehicle and to use it effectively, other CAN based products are needed to complete the system. Vehicles that already have electronic control systems are still challenged to showcase the benefits of the new engine technology and justify the additional costs.

The most common implementation is to add a J1939 CAN based instrument cluster or small graphical display to show engine data such as engine speed, temperature and oil pressure which were traditionally read via direct point to point wiring. The cluster reads engine fault data and displays warnings to the operator via red and amber warning indicators and LCD messages. Throttle position is measured using an angle sensor on the foot pedal or a hand operated rotary potentiometer and sent to the engine over the CAN bus. Higher end systems use color graphical displays to show data and give the vehicle cab a more sophisticated look and feel.

These multifunction terminals serve as the primary display connecting all the vehicle systems including drive control, work modes, HVAC, radio and other vehicle sub-systems. A unique skill set is often required to incorporate all these features into a user-friendly graphical user interface (GUI).

Transmissions have also seen an evolution of technology and currently there are numerous approaches that vehicle manufacturers can utilize depending on their application. Traditionally vehicles used mechanical transmissions that consisted of a series of mechanical gears providing different speed ratios between the input and output shafts. Electronically controlled transmissions (automatic transmissions) are similar in that they use mechanical gears, but the shifting is electronically controlled, a manual clutch is not used, and can be replaced by a torque converter.

More recently the market has seen the introduction of CVTs or continuously variable transmissions which remove the traditional gearing approach and effectively provide an infinite number of gear ratios. This technology has a number of advantages, with the most significant advantage that the engine and transmission can maintain a
constant match between their operating power curves rather than hunting for the correct gear. CVTs don’t suffer from shift shock experienced in mechanical gear based transmissions and can still operate over a wide range of speeds. CVTs remove the need for an inefficient torque converter, run cooler, and can operate more efficiently at lower engine RPMs all bringing an overall improvement in fuel efficiency.

CVTs can be implemented using a few different technologies; perhaps the most relevant of these for the off-road market is the hydrostatic transmission. This arrangement uses a combination of a variable displacement hydraulic pump and motor to transfer engine power to the tracks or wheels. While hydrostatic transmissions are not great for higher speed vehicles, they offer high torque at lower speeds making them a good option for many off road vehicle applications. The arrangement of the pump and motor can also be used for vehicle braking by using the pump to slow the flow of hydraulic oil to the motor and thereby slow down the vehicle.

Both automatic and hydrostatic transmissions use electronic modules to control their functionality. These modules communicate over the J1939 CAN bus and, similar to engine controllers, transmit information about how they are functioning over the network. Gear information along with transmission oil temperature, oil pressure, and transmission fault messages are examples of common data transmitted. With an automatic transmission, a gear shift lever is used to select a gear or request an upshift or downshift. The shifter is either hardwired directly to the transmission controller or connected over the CAN bus. The electronic controller drives the shifting of the transmission by energizing the various clutch solenoids with specific timing to ensure a smooth shift.

With a hydrostatic transmission, the desired speed is controlled by the operator via a foot pedal or joystick and once again this information is sent to the transmission controller using either direct wired inputs or over the CAN bus. By changing the angle of the swash plate in the pump, the transmission controller can vary the flow of hydraulic oil to the motor which in turn affects the speed of the vehicle. Some controllers are capable of driving either automatic or hydrostatic transmissions.

The software that resides in a transmission controller is integral to the operation and feel of the transmission. Typically the development of this type of product requires many hours on the vehicle fine tuning the behavior. Not only do each of the shift patterns need to be thoroughly tested, but shifting while under load can have different responses that need to be evaluated. It is important to have combined expertise of both the transmission and software when developing this type of product.

10 Functional Safety

Safety is defined as freedom from unacceptable risk of physical injury or of damage to the health of people, either directly, or indirectly as a result of damage to property or to the environment.

Functional Safety is part of the overall vehicle system functionality that depends on the system operating correctly in response to its inputs including correct operation in response to operator error, component failures and environmental impacts.
As more and more electronically controlled systems are introduced, vehicle designers must remain particularly aware of the potential safety hazards and implement measures to address them. Designing functional safety into a vehicle requires designers to follow a systematic process which starts with the identification of potential hazards and their associated risk levels. This is used to classify the system’s Safety Integrity Level (SIL) which defines the allowable failure rates of the system. It must be possible to show that the final safety functions meet these criteria.

Achieving functional safety is not only the responsibility of the electronic controller but instead must be addressed on a system level to ensure that the overall vehicle responds in a safe and predictable manner in line with the SIL criteria. On a connected machine, safety functions may be distributed across multiple products making it more challenging to address the safety risks with a single SIL rated product. Where possible, addressing functional safety by making the overall system inherently safe is ideal and less costly. For example, the use of interlocks within the windings of a motor to shut down the motor when it gets too hot, may be an acceptable form of implementation. Other applications may use autonomous vehicles or methods to remove the operator from a dangerous environment to avoid the safety concern all together.

Each application requires careful analysis and consideration to determine the appropriate approach. Some cases require the use of a SIL level electronic controller which has been designed to be compliant with the governing functional safety standard. These controllers are designed so that they will fail in safe and predictable modes and utilize redundant circuitry and software that monitors the functionality of the primary controller. Integration of a SIL controller adds significant cost, and is most often only required when the cost and complexity of implementing safety on a system level becomes too great. In many cases a safety relay or a redundant circuit could prevent the need for an expensive and complex SIL controller.
11 Summary

This paper has provided an overview of the current technologies used in construction machinery and demonstrated that vehicle connectivity brings many benefits to customers. Components such as controllers, displays, operator controls, sensors and actuators are connected to the on-vehicle network allowing for the distribution of functionality across the machine. Using WiFi or Bluetooth to connect to mobile devices and the Internet allows for M2M communication, asset management, remote access and other progressive capabilities. There is no one-size-fits-all solution for any mobile control system, but there are certainly new trends and technologies that should be considered.

Technology that supports vehicle connectivity represents the future trends in mobile functionality. The connectivity people have become accustomed to in their daily lives fuels the technology that can now be used cost effectively in a mobile environment. Dedication towards continuous improvement requires that we learn and understand the performance of each machine and take strides towards better efficiency, less fuel consumption, increased productivity, and safer job sites. Platforms exist to allow a broad range of functionality that can be implemented through custom application software, an essential element in any mobile application. Continuing the trend of history, wireless connectivity and custom software are the next steps in technological evolution of mobile equipment.

Next Step
JCA has a development process that helps companies walk through the complexity of heavy machinery design. Follow this link to access the infographic.
12 About JCA Electronics

JCA is an electronic integration centre that is able to apply the right technology, products, and services in a cost effective and timely manner.

JCA specializes in the design and manufacture of electronic control systems for original equipment manufacturers. JCA strives to not only understand the design and function of our customers’ products, but also the company that produces it. Starting with requirements and concept, next prototyping and testing the system, and then through production and service, the company’s design systems effectively blend physical and digital products. JCA’s innovative devices incorporate wireless technology and machine-to-machine (M2M) communications, to enhance customer’s time to market and the experience and productivity of their end users.

JCA Electronics: full integration of electrical, electronics and software systems

At JCA, our engineering team works with our customers to define a system, design and develop everything from mobile device apps and application specific control software, to system schematics and wire harness drawings. We then have manufacturing capabilities to provide the core components of the system: wire harnessing, control/switch panels, controllers and displays. We are agnostic to any particular sensors and actuators (hydraulics), such that we can help choose the right sensors and actuators for the design regardless of the manufacturer. We help our customers define the right control system for the application, whether this is a simple control system with only switches and wire harnessing, or a smart control system using our family of controllers, anchored by the JCA Falcon controller. The JCA controllers can interface with any type of display, mobile devices, or other 3rd party products. This allows designers of heavy equipment to start simple and build towards systems with more functionality, adding building blocks to the existing system, rather than starting over when new functionality is needed as the system progresses. This also is beneficial for manufacturers who have a variety of different machines, some with high end control requirements, and others with simple control requirements; JCA has a solution that can fit all of these applications.
Let us outline your system

Let’s discuss your electronic system needs. Our experts can help you arrive at a detailed solution that fits your particular application.

Contact us today for your immediate system assessment.

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