Electronic Control for Hydraulic Applications—

A CASE STUDY

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Management Summary

This paper presents how electronics and software can be applied to a mobile hydraulic application—what the benefits are and how electro-hydraulics design has evolved over time. The specific system serving as the basis for this paper is a timber-logging trailer. The paper describes the components of the system, as well as the structure implemented for the electronics and software. The benefits provided by particular components and the system architecture are explained, and pictures of the trailer are included to show integral elements. Diagrams related to the software control algorithms show what is enabled using software and electronics that couldn't be implemented hydro-mechanically. Throughout the paper, it is explained how an open architecture and modular approach were utilized, and that this approach is key to a flexible, scalable and efficiently developed electro-hydraulic system.

Introduction

As the mobile industry evolves toward more sophisticated systems, it is integrating more electronics with traditional hydraulic systems to address end-user demands for higher performance and greater efficiencies. The trend of increasing electronic content in mobile applications has been apparent for years now, but the initial adoption has been somewhat slower than one would expect. Two issues that may have kept electronics from becoming more mainstream until now were uncertainty in regard to which standards (or lack of standards) to apply, and whether an open or proprietary architecture approach was best. At the onset of this case study, analysis was performed and a decision was made on the approach to

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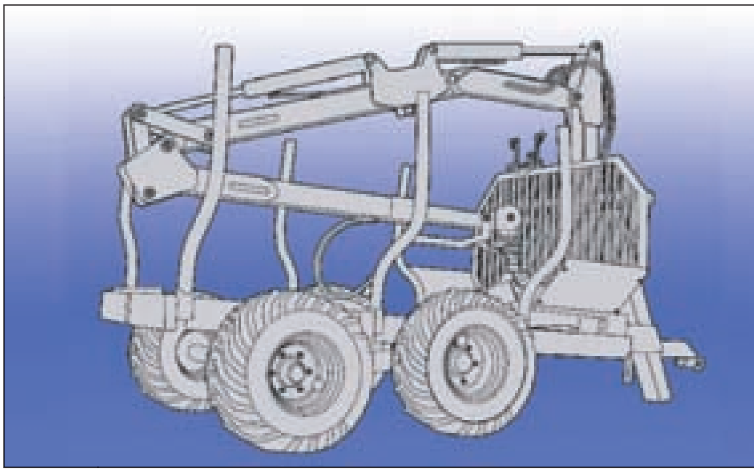

Illustration 1—The original timber-logging trailer, with manual hydraulic controls.

take regarding these issues. An open architecture that leverages existing industry standards was the position taken, as it offers the most flexibility and scalability to the final solution. An additional factor that gated the use of electronics in mobile hydraulic solutions was the harsh environment that mobile equipment faces during normal daily use. This has to be considered, and addressed as well, before any electronics can be used with confidence. A mobile piece of equipment—a timber-logging trailer (see illustration)—was chosen to develop, test and showcase a mobile electro-hydraulic solution using industry standards, an open architecture and extremely durable electronics. In this study, great attention was paid to the hardware and software architecture implementation, where distribution of control and reusability of software functions were key goals for effective and efficient development of the system. Using these specific architectural elements as a foundation, it is possible to demonstrate multiple types of specialized control functions on the machine. The use of an open architecture and predefined industry standards is credited with making this electro-hydraulic implementation a success, and is selected as the preferred approach for implementation of electronics and specialized software control for any application in the mobile industry.

Approach

Open Architecture/ Industry Standards

Utilizing industry standards for both software and hardware was an important element of the approach to the case study. Utilizing these standards provided a much wider selection of components to choose from to create the application and helped to ensure the interoperability of the different components as a system.

Software platform. All system control software that exists in the main system controller was developed using a standardized software platform. The software platform, Eaton *CONTROL F* (x), leverages the IEC 61131-3 programming standard. This standard provides five graphical and textual languages for the programmer to choose from. The choice of multiple languages helps to better match the experience of engineers from different backgrounds. Someone with an industrial background can use *Ladder Diagram* for their programs, while a software engineer with a background in "C" programming may prefer to use *Structured Text*. Working hand-in-hand with this IEC standard is the concept of an open architecture. In using the IEC 61131-3 programming standard, along with an open architecture, the combination of different components to build the system is facilitated. There are no restrictions that the core components or the other devices have in order to be produced from the same, or any specific manufacturer. Any standard devices can be chosen as components for this system. Because an open architecture was used, a large variety of devices were available to meet the control needs of the timber-logging trailer. Standard devices have an additional benefit in that they are often less expensive because their production is not limited to serving a certain proprietary system, but rather they support any system leveraging an open architecture. Utilizing the IEC 61131-3 standard also helps the programmer create high-quality programs with fewer defects, as the programming system itself alerts the user to syntax and other errors. This standard facilitates program code reuse as well, which reduced the time and effort required to develop the software for this application.

System bus communications. Another dimension of the vehicle design where it is critical to adhere to standards and an open architecture is with the communication bus chosen for the timber-logging trailer. The bus structure implemented is the CAN 2.0B hardware layer, supporting the J1939 message protocol. The CAN hardware layer is widely used for bus communications in both the mobile and industrial markets, and the J1939 protocol is the messaging standard used by suppliers of components and systems in the mobile market, including many engine manufacturers. Similar in effect to the standards and open architecture implemented in the software, this approach to bus communications opens up the supply base for components that can be leveraged in an electro-hydraulic system. The use of standardized communication interfaces create a pool of component hardware to choose from that exhibits high quality levels at reduced per-unit cost. This provides a stable environment so that new development can be focused on higher levels of functionality. The degree of interoperability of components that leverage a standard is very important in the eyes of the end-users, as they desire to retain flexibility and scalability in their applications without being locked into a single supplier.

Environmental Resilience/Ingress Protection

Solutions for the protection of electronics in harsh environments are necessary before electronics can be considered to enhance mobile applications. Shock and vibration are obvious requirements, but just as important is how an enclosure protects the electronics from dust, dirt, humidity and fluids.

Housings that demonstrate an ability to provide protection from the ingress of foreign material are critical to electronics utilized in the mobile application space. An IP (ingress protection) 67 rating has become an expectation for the electronics that are used. This rating translates to a total resistance to dust and to temporary immersion in water. Some mobile electronic integrators are setting their sights on IP 68 and IP 69K ratings that indicate a component is protected to indefinite submersion down to 10 m deep and can withstand high pressure washes up to a pressure of 140 bar. The development of electronics and enclosures that can withstand environmental extremes has been critical to their adoption in the mobile market, and components that met these requirements were chosen for use on the timber-logging trailer application.

Case Study: Timber-Logging Trailer

In order to illustrate the benefits of electro-hydraulics outlined above, Eaton created a demonstration vehicle that showcases the potential benefits of supplementing traditional hydraulic components with electronics and software. The vehicle combines several innovative Eaton products that are particularly well suited to electro-hydraulic systems.

System Architecture

Physical description. The machine being discussed is a logging trailer equipped with a hydraulic arm and grapple. The primary function of the machine is to pick up logging timbers from the ground and place them on the trailer for transportation. The construction of the hydraulic arm resembles a typical three-link, articulated robot arm with three revolute joints and grapple end effector.

- The first revolute joint affects hydraulic arm rotation about an axis that is perpendicular to the ground (east-west shoulder rotation).
- The second revolute joint affects overall angle of the arm relative to the ground (north-south shoulder rotation).
- The third revolute joint affects the amount of arm extension (elbow movement).

Each arm link is fitted with a hydraulic actuator. All actuators are connected to an Eaton Ultronics valve system. An Eaton EFX1624 electronic control unit (ECU) controls the system. Two electronic joysticks, five rocker-style switches, five proportional proximity sensors and three traditional on/off mechanical limit switches provide control inputs. Each of these components is available from Eaton. A photo of the hydraulic arm with an inset diagram of the link and joint layout is shown in Figure 1.

Functional description. The end user operates the machine from a control chair and manipulates two electronic joysticks and several rocker switches in order to achieve the desired functionality. The operator may select from two distinct modes of operation—open-loop control or closed-loop control. Open-loop control refers to user input routed directly to the valve system for vehicle control. The user input is directly related to the flow demand that is routed to the valve system, and therefore the user has direct control over movement of the system. If the desired movement is not immediately obtained, the operator simply makes an adjustment to the input to achieve the desired result. The term closed-loop control refers to the system managing the flow demand routed to the valve system to achieve the desired movement or desired position. Instantaneous errors may exist between the desired position and the actual machine position for a very brief period, but over time the system controller will automatically adjust the demand routed to the valve system to reach the desired location.

When the machine is operated in open-loop mode, the relationship between the user input and the amount of flow requested can be adjusted (flow gain). The system allows for three preset gain adjustment settings—off, economy and power.

- The "off" setting will force all flow commands to zero, regardless of any joystick input.
- The "economy" setting will result in a flow demand that is 20% of the max system flow for a corresponding maximum input command from the joystick.
- The "power" setting will result in a flow demand that is 80% of the max system flow for a corresponding maximum input command from the joystick.

At any given time, the user may also modify the preset gain adjustment setting in increments of 1% via one of the rocker switch controls. The operator may also command movement of the three major machine axes from one of the provided inching control rocker switches. For any given flow gain setting described above, the corresponding inching control will result in a flow demand for a given work circuit, which is one tenth of the corresponding joystick input for the same circuit.

When operated in closed-loop control mode, the operator is simply required to press and hold the closed-loop control activation button on the joystick and the machine is automatically controlled to the pre-programmed home position. This function is enabled by the position feedback provided by the proportional proximity sensors. The position information from these sensors is processed by the system controller. The controller then makes adjustments to the machine position by directing flow demands to the Ultronics valve system. The three major axes of motion are also fitted with mechanical limit switches. The system controller monitors these inputs and prevents movement by any work circuit whose limit switch has been activated. A photo of the control chair with two Eaton Ultronics joysticks is shown in Figure 2; and a display/control panel with a programmable Eaton VFX display

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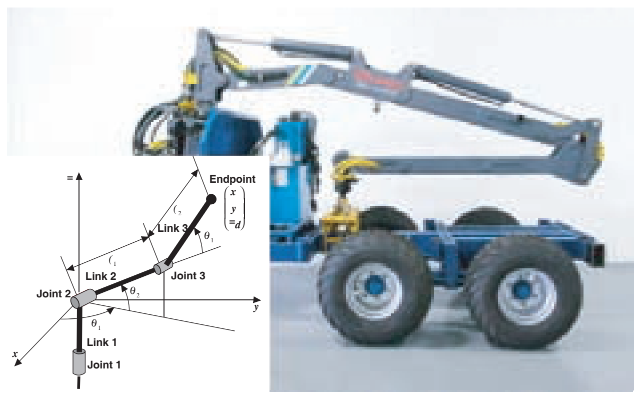

Figure 1—Hydraulic arm and diagram of joint layout.

Figure 2—Control chair.

and Eaton CAN-based eSM and eVU rocker switches/display is shown in Figure 3.

Hydraulic description. The system uses a vented hydraulic reservoir at atmospheric pressure. Hydraulic flow is generated by a fixed displacement hydraulic pump driven by electric motor. A pressure relief valve is fitted to the output side of the hydraulic pump in order to control maximum system pressure by providing a regulated flow path back to the reservoir. The primary hydraulic flow path is from the pump to the Ultronics control valve. The electrically actuated control valve is equipped with a pressure-conditioning input section, followed by six highly configurable work sections. Each valve section is equipped with a mechanical pressure relief that regulates maximum pressure in each work circuit. All valve sections are spring-centered to block flow in the center position; this prevents flow to/from the double-acting cylinders in the absence of a valid command signal. A hydraulic schematic of the system is shown in Figure 4.

Figure 3—User interface.

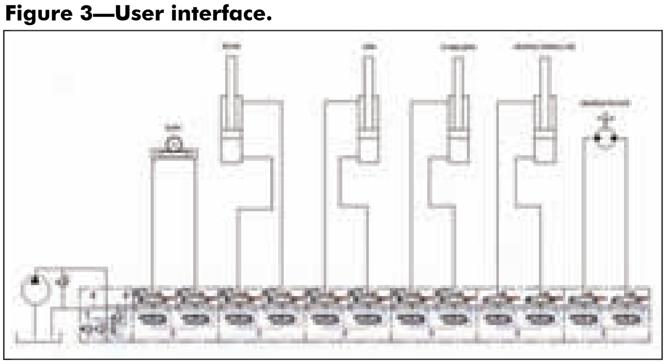

Figure 4—Hydraulic schematic of the work circuit.

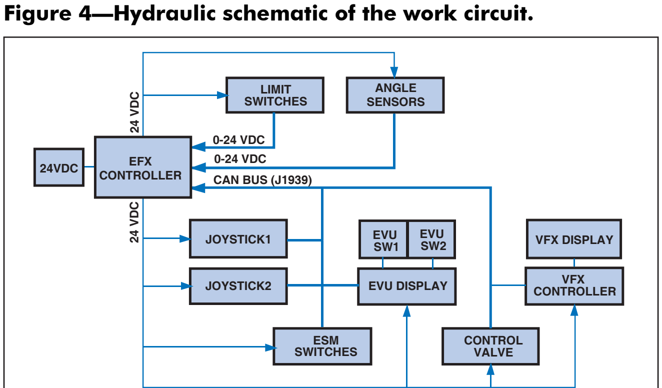

Figure 5—Electrical interface drawing.

Electrical description. The machine is powered by 240 volt AC power. Incoming AC power is routed in parallel to the hydraulic pump electric motor and to Eaton's Cutler-Hammer 160-watt DC power supply. The power supply ensures that system voltage is regulated to 24 volts DC. The system voltage is routed through an emergency power shut-off switch to the sectional control valve, joysticks, machine control rocker switches, LCD display controller, LCD display module, proximity sensors, limit switches and system electronic control unit. All operator control inputs are sent from the respective input devices to the system control ECU through a digital Controller Area Network (CAN) communications bus. All system control signals are likewise sent from the system control ECU to the sectional control valve via CAN bus. The sectional control valve in turn provides several feedback signals to the ECU by sending messages back to the system controller over the same CAN communication bus. The CAN bus is also utilized to send system status and feedback data from the ECU to each of the electronic visualization devices. Electrical control signals from the proportional proximity sensors and mechanical limit switches are routed directly to the ECU as traditional analog and digital control inputs. A simplified electrical interface drawing is shown in Figure 5.

Distribution of control. The Ultronics control valve is configured to provide inner-loop control of the flow through each work circuit. The Ultronics control valve is a standalone system capable of a wide variety of application-specific control tasks. Each valve section contains an electronic digital signal processor that executes proprietary software control algorithms. In the system being discussed, the valve inlet section is configured to sense the load on each work section and control system pressure in order to meet the instantaneous pressure requirements of the system. This function enables the hydraulic system to use all power available when required and yet maintains optimum efficiency by minimizing power consumed to only that which is required by the system at any given moment. Each work section of the control valve is configured to control the flow that passes through that section. The electronics and software algorithms that are executed on the control valve provide an inner-loop flow control function that provides consistent performance despite continuously changing system conditions. The system control ECU provides outer-loop control of system movement. The primary function of the system control ECU is to interpret the inputs from the user and select the appropriate commands to send to the valve system. The system control ECU is also responsible for monitoring system feedback information and taking appropriate action when necessary. Another critical function the system control ECU performs is providing system information to each of the available visualization devices for display to the operator.

Software Architecture

Application description. Eaton *CONTROL F(x)* was used to create the software application that coordinates all system functions. Eaton's EFX1624 electronic control unit (Fig. 6) executes the software program. The software is written, compiled and downloaded to the controller using built-in features of the *CONTROL F(x)* programming system. The programming system connects to the controller through RS232 serial or CAN bus interfaces.

The EFX controller executes the software application as a single program task. The controller reads system inputs, executes the software control logic, and then writes the results to system outputs. At the end of each cycle, execution of the program is started once again; the application will repeat this process indefinitely and as quickly as possible. An exception to this process could be utilized in other applications where specific programming logic is implemented so that counters, interrupts or user intervention control the timing of the program execution. The application created for this system runs as a freewheeling task and typically completes in about 5 milliseconds.

The *CONTROL F(x)* programming system gives the user the choice of several programming languages—ladder diagram, instruction list, structured text, sequential function chart, function block diagram and continuous function chart—with each having certain advantages and disadvantages. For this system—i.e., visualizing the control strategy as a continuous flow of signals that stream into the application as inputs, which are processed by the control algorithm, and finally flow out of the application as outputs—seemed particularly fitting. To accomplish this, the continuous function chart language was chosen as the primary programming language for nearly all program modules.

The software application is split into several subprograms, each with specific responsibility to interface with the main system functions. A high-level block diagram of the application organization is shown in Figure 6.

Abstraction for reusability. One of the significant strengths of the *CONTROL F(x)* programming system is the built-in support for code reuse. Any program or program component that is created can easily be captured in a program library. These library files can then be easily folded into other applications by simply creating a library reference. One example of the use of a function library is the hardware function libraries that are provided by Eaton to accompany each EFX controller. These libraries contain function blocks that enable users to quickly and easily interact with the controller. For example, function blocks are provided that enable initialization of key hardware components such as the CAN interface. By providing function blocks that are well tested and documented, the user is able to concentrate on programming at the application level rather than implementing the specific details of a hardware interface. Eaton has taken this concept one step further with the introduction of function libraries that handle all necessary interface details between the EFX controllers and a growing list of complementary products. Examples of products that are already supported include Ultronics ZTS16 control valves, Ultronics joysticks, eSM switch modules and eVU display modules. The software application developed for control of the demonstration vehicle makes use of several of these function blocks.

Another technique used in this application that promotes code reuse is the creation of function blocks that are generalized to the highest extent possible. For example, general-purpose function blocks have been created to perform all of the control logic for control of a work circuit. Specific functionality of each particular work circuit is achieved through the ability of each instance of a work circuit function block to operate on a distinct set of data items. Every work circuit provides some translation of user input to valve flow demand through the use of a gain factor. The specific value used by each function block is unique, even though the general algorithm used inside each block is identical. This philosophy minimizes the effort required to test and validate the control application and improves the maintainability of the code.

Specialized Control

One of the primary advantages of using software to implement system functions is the fact that algorithms can be easily changed and adjusted. Even though it is possible to implement a proportional control circuit using only hydraulic and electronic components, the ability of a software implementation to be much more easily adapted makes it the logical choice. A software implementation can be changed from a proportional controller to a proportional-integral controller, for example. Software implementations are also commonly cheaper to develop from the start, since a control algorithm can be easily copied and multiplied as many times as required for the task at hand. Finally, as any algorithm begins to grow in complexity, it becomes more and more useful to describe the algorithm using a combination of symbols and text that can be quickly tested and corrected if problems are found. Several functions of the timber trailer demonstration vehicle that are particularly suited to this type of expression in software are described in more detail below.

Single degree of freedom closed loop control. One type of advanced functionality that has been incorporated into the system being discussed is the ability to control the absolute

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Figure 6—Eaton EFX 1624 electronic control unit.

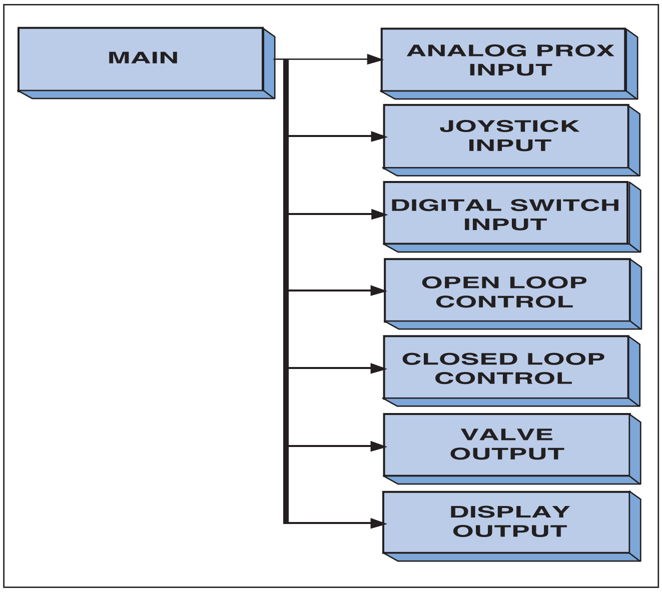

Figure 7—Software application organization.

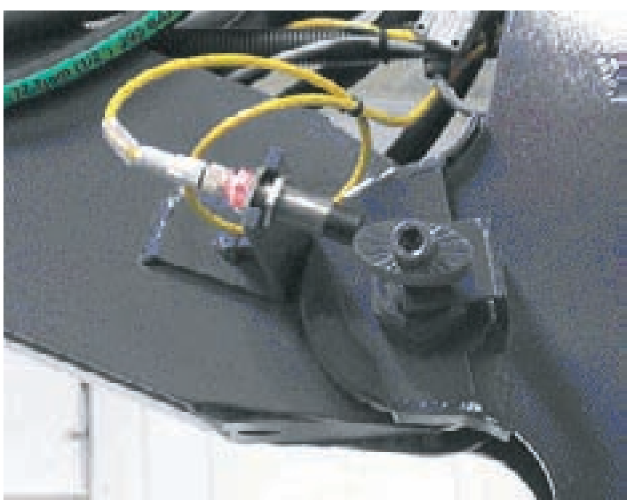

Figure 8—Sensor and elliptical target for measuring boom joint angle.

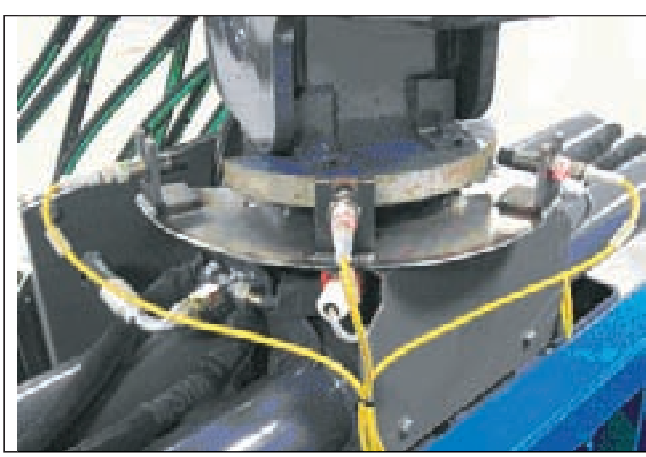

Figure 9—Sensor configuration for determining boom rotation.

position of a particular machine axis. Each of the three major axes of machine motion is equipped with highly accurate proportional proximity sensors. These sensors are products of Eaton's electrical product division and are able to sense the distance between metallic objects and the sensor face. An elliptical target is mounted to each machine joint, which rotates with the joint. By mapping the distance between the sensor face and the rotating target to physical joint angles using a calibration instrument, a low-cost, angular-position feedback mechanism is created. Figure 7 illustrates the sensor configuration for the joint of the machine that allows raising and lowering of the boom.

The sensor layout described above is limited to a physical range of motion of about 90°. In applications where a larger range of motion is required, it is possible to use an array of sensors whose information is consolidated through software. An example of this type of sensor configuration also exists on the machine being discussed (Fig. 8).

The physical range of motion for this axis of machine motion is about 180°. Although two sensors would theoretically satisfy the requirements for this function, three sensors have been utilized to allow for the mechanical variations that inevitably occur during fabrication of the mounting components, and the need for flexibility in mounting orientation that is required for this axis of motion.

With all angular position sensors in place and calibrated, the system software is able to determine the orientation of the three primary machine joints at all times. This feedback information enables closed-loop control of the joint angles. With this type of control in place, the user can enter joint angles directly from a user interface to position the machine at any given location by simply entering the desired joint angles. However, to prevent the addition of a more complicated user interface to this demonstration machine, a simple home function was implemented. When activated by pressing a single button on one of the joystick controls, this function automatically moves the machine to a preset home position. For the sake of simplicity, an arbitrary target point was chosen within the range of motion of the machine. The joint angles were noted and programmed into the software algorithm as command inputs to three separate position controllers, one for each axis of motion.

When these position controllers are activated by the user by pressing and holding the activation button on the joystick, the angle position controllers begin to automatically generate flow demands to each affected section of the Ultronics control valve. This has the effect of moving the machine autonomously from any arbitrary starting position to the home position without any further input from the user, other than the continuously active enable signal. This type of function could be used to automatically return a machine to a ready position with minimal user input and maximum efficiency. It should be obvious how this type of function can significantly reduce operator fatigue and increase the level of reliability and safety related to this phase of the process. What may not be as obvious to the casual observer is the ability of the machine to be easily adapted to slightly different variations in the application. For example, the speed of movement could be easily adapted to suit the particular material involved in the process by simply adjusting a few parameters in the software. This allows an identical set of mechanical and electronic components to be used to achieve significantly different results.

Multiple degree of freedom coordination control. This type of coordinated control of multiple, related axes of motion has not yet been implemented on the machine discussed throughout this paper. However, it is an obvious extension of the existing control capabilities of the machine and will likely be developed in the near future. This type of control algorithm is similar to the features mentioned above in that they would be extremely difficult to implement with only hydraulic components and/or electrical circuitry. The ability to have software executing within the system opens up a broad area of advanced functionality that brings enhanced value to nearly any product. One significant example of this type of feature is the ability of a machine to coordinate several axes of motion to achieve precise control over the movement path. This concept is well demonstrated in the discussion of the capabilities of a common telescopic lifting system. On these types of vehicles, it is common to find one hydraulic circuit which controls the angle of the boom with respect to the ground, another circuit which controls the amount of extension of the boom, and yet another circuit which controls the angle of the tool at the end of the boom relative to the boom itself. These types of vehicles are commonly used to move materials on and off vertically stacked shelving. Previously, in order to move materials from the ground to a particular storage location the operator was required to manipulate several user input devices simultaneously. Precisely coordinated movement of two or three input devices was very common in order to achieve a movement path that not only kept the material parallel to the ground but also moved along a path that was the most efficient in terms of speed and power consumed. However, with the addition of software controls the user input can be reduced to a single simplistic input. The user would only be required to move a joystick in a single direction, for example, while the software monitors the position of the machine and moves all related circuits in unison to achieve a desired movement that is perfectly vertical while maintaining an orientation of the end tool that is exactly parallel to the ground.

When this type of coordinated control is combined with the natural ability of software to be scripted, the result is even more powerful. Indeed, a machine could be programmed to automatically lift materials from the ground to the first shelf when the geometry of the shelving and material is known. Or, if the machine is commonly moved through a repeatable path of movement like in the case of a hydraulic arm for loading and unloading railcars or cargo ships, these movements could also be automated through the use of software. It is quite possible that the range of applications that could benefit from these types of software controls is practically limitless.

Conclusion

Specialized control of mobile applications has become more and more important to suppliers and customers alike. Traditionally, hydraulic mobile application components were chosen to attack space constraints, with the components with the most force-per-area winning out. As specialized system control and efficiency gain greater focus, it has become possible to supplement the power of hydraulics with electronics and software to attain new performance goals. This case study of the timber-logging trailer is a great example of taking an existing application and advancing its functionality by implementing an electro-hydraulic control system. New capabilities are now available on the trailer at the flip of a switch, and the vehicle can accommodate efficient operation by users of different skill levels. Specific, differentiating capabilities of certain components are packaged and distributed in on-board electronics.

These electrical and hydraulics components retain a standard interface to the rest of the application, however, to ensure they can be leveraged in a modular and scalable open architecture. Rugged, programmable standalone electronics are implemented for supervisory control. These, too, leverage standards so that they have the flexibility to be cooperatively developed, modified and serviced by the supplier, customer or end-user. All of these concepts proved to be key elements to the rapid and successful development of the timber-logging trailer, and should be used on any mobile machine development project in order to meet both internal as well as external market requirements for electro-hydraulics in mobile applications.

Additional Sources

1. CAN in Automation, *www.can-cia.org*, the international group that supports CANopen and other CAN protocol layers.
2. PLCopen, *www.plcopen.org*, the global organization focused on support of the IEC 61131-3 programming standard.