The Case for Deep Integration

Introduction

The term “integration” can take on a variety of meanings in industrial settings. To some, it means applying principles of systems engineering to manage multiple properties of a system as a whole. To others, it’s about achieving proper form factor – the size, shape, and other physical specifications of products.

In the world of fluid power, the term “deep integration” promotes thinking of a machine as a system and using a holistic approach to design. If integration generally means combining one thing with another, deep integration can be taken to mean combining multiple things together intelligently to work as a system. Deep integration, however, does not just mean bundling multiple components and linking them individually; it means enabling subsystems to communicate with other subsystems and help the machine to function more efficiently and precisely.

Historically, industrial design has taken components and assembled them into a system. Deep integration starts at the opposite end – looking at a system and what the customer wants to accomplish, then building subsystems and the components within them.

The key driving force in the evolution of deep integration is embedded electronics – the sensors, software, and controls built into devices. The increased use of embedded electronics is often called the “smart machine movement,” as it has enabled conventional devices such as pumps and motors to apply intelligence in accomplishing tasks. The reasons customers might need deep integration vary, but we can categorize them in three areas:

• To achieve greater flexibility and efficiency in the machine design process
• To deliver improved safety, performance, and productivity in the field
• To compete in an industry that’s evolving faster than ever before and get products to market
Drilling down further, original equipment manufacturers (OEMs) and end users face numerous challenges in today’s marketplace. Some of these include:

- Space limitations
- Efficiency
- Time to market
- Increased global competition
- Regulations
- Ce-capitalization of fleet owners
- Workforce demographics
- Model proliferation

To examine how deep integration can help address those challenges, we present two case studies: one focused on the automotive engine and one more broadly encompassing fluid power systems.

**Evolution of a “Smart” automotive engine**

The automotive engine evolved dramatically in the 1970s and 1980s, as tighter emissions standards, pursuit of better fuel economy, and various other factors led automotive designers to seek more efficient engine operation. This quest for greater efficiency required applying new ideas to basic engine principles. As a review, internal combustion engines generally need three elements to function:

- Air – Typically oxygen-based
- Fuel – Hydrogen from a hydrocarbon
- Trigger – An ignition system

A fourth element – timing – is important to make sure the first three elements are available in the correct amount, at the right place, and at the right time.

Conventional engines used carburetors to control fuel mixtures and magnetos to provide ignition. Electronics enable engines to become increasingly electronically controlled, as shown in Figure 1.

**Figure 1. Engines have evolved from using primarily mechanical controls to electronic controls.**

<table>
<thead>
<tr>
<th>Automotive engine controls</th>
<th>Electronically controlled engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>From carburetors &amp; magnetos to...</td>
<td>ECU</td>
</tr>
<tr>
<td>Air</td>
<td>Fuel</td>
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</tbody>
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Carburetors generally relied on mechanical linkages that connected the driver’s foot pedal to the carburetor. Subsystems within the carburetor controlled the air-fuel mixture, typically based on a fixed ratio. Mechanical choke systems adjusted the mixture for starting cold engines. The introduction of electronic choke systems had limited success, followed by electronic solenoids that adjusted idle speeds. These were small steps toward integration, but stopped short of integrating multiple products.

Larger steps occurred as more advanced electronics became available during the adoption of regulatory factors such as emissions standards. On the input side of engine design, the introduction of sensors measured airflow to engines and monitored crankshaft and camshaft operation. Output devices such as injectors and ignition coils controlled certain operations. The electronically controlled engine employed a closed-loop control, with sensors to measure parameters such as exhaust oxygen content and generally improve precision and reliability. With the introduction of more electronic capabilities, components and systems experienced deeper integration. Manufacturers and consumers resisted due to initial cost increases and fear of the unknown, but the addition of electronics to engines gained momentum. The benefits in emissions reduction and fuel economy were dramatic in the late 1970s and early 1980s, as shown in Figures 2 and 3. This coincided with enactment of tighter emissions standards in the U.S. and other nations.

**Figure 2. Vehicle emissions dramatically reduced between 1975 and 1990**

<table>
<thead>
<tr>
<th>U.S light duty vehicle emissions standards (Approximation)</th>
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<tbody>
<tr>
<td>CO</td>
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<tr>
<td>0%</td>
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</table>

**Figure 3. Fuel economy for cars and trucks increased greatly between 1975 and 1985**

<table>
<thead>
<tr>
<th>Average estimated fuel economy by model year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
</tr>
<tr>
<td>70+% increase in 10 years</td>
</tr>
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The growth of integrated electronics produced many other benefits, as the concept of deep integration took hold. Benefits included the following:

- Improved performance through greater engine power density and physical downsizing
- Extended maintenance intervals
- Drivability – less skill required to perform certain operations
- System coordination – linking engine, transmission, suspension, braking, and other systems
- Living room comfort – cruise, adjustability, low-NVH, ride control, and infotainment
- Safety improvements – anti-lock braking, airbags, traction control, stability control
- On-board diagnostics (OBD)
- Hybrid integration
- Telematics – transmission of computerized information

Clearly, the integration of electronics has forever changed the automobile engine and will likely continue to do so as technology advances.
Electronics in hydraulic systems

Much like the automobile engine has evolved, so have hydraulic systems. Categories of hydraulic products today are quite similar to those of the past, with pumps, motors, valves, hoses, and fittings still serving as the building blocks of hydraulic systems. The components themselves, however, have evolved dramatically, with electronics providing new capabilities at the product level and at the system level in linking products together. Advanced controllers and displays allow more intelligent operation of systems, with software such as Eaton’s Pro-FX providing a common link to various products, as shown in Figure 4.

**Figure 4.** Software such as Pro-FX can link hydraulic components together

Mobile valves, for example, have evolved from simple mechanical valves to load-sensing valves such as the Eaton CLS series to advanced electrohydraulic valves such as the Eaton CMA valve, which provides independent metering and other features to differentiate machine capabilities. The controller area network (CAN)-enabled CMA valve includes on-board electronics and sophisticated software algorithms, providing a plethora of intelligence and control.

As product capabilities have grown, new software provides the mortar to help system components work together. Products are designed to be compatible with the software and other products. In Eaton’s product line, products are deemed “Pro-FX ready,” meaning they are capable of communicating with other products via Pro-FX software. They match with other products to streamline the process of software application development at the subsystem and system levels.

As an example, consider the work, auxiliary, and steering circuits of a machine, as shown in Figure 5. The products shown match not just from a hydraulic sizing and performance perspective, but also from a controls integration perspective. Each product has been mapped, and the specific functionality for each product has been developed and packaged into a function block, which is pre-built software tool that accomplishes common tasks for that product.

These function blocks exist at the machine level, not just at the subsystem level. This allows operations such as coordinated movement of several work surfaces with one operator input, perhaps an X, Y, and Z control. Advanced features for power management could also be incorporated, helping match power availability with hydraulic loads and demands and available power from the engine, based on communication over the machine’s J1939 bus.

**Figure 5.** Various products match with others and linked via software

Efficiency gains can be achieved from accurate system sizing, alternative architectures, and advanced hydraulic products. To match the growing efficiency and productivity expectations, hydraulic subsystems must be closely coupled with the engine control.

To see how these concepts apply in the field, consider a telescopic boom, as shown in Figure 6. An advanced CMA valve captures actuator pressure-port sensor data. The valve networks with a load-moment indicator, an HFX control, and a VFX display to provide the operator with visualization of safe/accurate load placement. Other value is achieved by extending functionality through peripheral sensors such as load weighing.

**Figure 6.** Embedded electronics can help provide safe and accurate load placement on telescopic booms

As an additional example, consider a high horsepower wheel loader, perhaps an extraction machine in a mining application. Accurate power management is required to allow the engine power to be shared among various hydraulic products, as well as the power transmission system. Cross-system data sharing enables power optimization at the machine level. A CMA valve is networked with a load-weigh system, Pro-FX controller, display, electronic display control, and fan drive pumps to provide smooth power flow under various conditions.

Eaton recently applied deep integration concepts in analyzing a hydraulic hybrid system for a lift truck, as shown in Figure 7. With fuel consumption typically a key factor in operating lift trucks, one objective was to reduce fuel consumption, with a secondary objective of increasing productivity. Eaton collected extensive duty-cycle data and performed computer simulations to identify inefficiencies and opportunities for increased fuel efficiency. Customer feedback indicated 20-percent fuel savings were desired with payback periods of one-half year to one year. Simulations indicated fuel consumption could be reduced by upwards of 35 percent.
A holistic system approach was used to design an energy management system (EMS) to improve overall machine efficiency. The machine was retrofitted with various hardware that included a medium-pressure over-center pump, connected to the engine; a medium-pressure over-center motor, connected to the axle differential through a reduction gear; a central manifold connecting the pump and motor; hydraulic accumulators to capture and store energy; and various other products, as shown in Figure 8.

Figure 8. An EMS was designed for the hybrid lift truck to improve efficiency

The EMS’s single pump drives the machine and powers the work circuits and the steering system. The pump operates as an open-circuit pump, rather than as a closed-circuit pump typical in propel applications, which have separate charge pumps and work circuit pumps. The pump is essentially converted to a motor for short periods. The accumulators capture energy primarily through regenerative braking. The captured energy allows power buffering, meaning the engine can operate at its most efficient operating conditions.

Based on testing in a controlled environment, fuel savings for the lift truck were quantified under various loading, lifting, and VDI duty-cycle conditions. (VDI stands for ‘Verband Deutscher Ingenieure’, a common standard for comparing fuel consumption of different forklift trucks.) Up to 35 percent savings were achieved in some cases, and well over 20 percent was achieved in most cases, as shown in Figure 9.

The actual savings differed somewhat from the predicted savings because actual lifting generally does not occur at full speed, as was assumed in the simulations. This resulted in the predicted savings being slightly higher (37 percent average) than actual, but the actual savings were still above customer expectations.

Where to start?

If deep integration is a new concept, you can take steps to implement the concept, such as:

- Become familiar with Stage 5 emission regulations, which the European Commission proposed for previously unregulated engines.
- Become familiar with the European machinery directive, which includes measures to establish safety levels in machinery.
- Review safety integrity level requirements for your products and customers
- Make deep integration part of your overall business strategy
- Reach out to suppliers, distributors, and integrators for assistance.

By taking these steps, deep integration can become part of an overall business strategy and offer many benefits. As a power management company, Eaton is investing heavily in application engineering, modeling tools, smart components, and various other product and software development efforts, and is eager to help develop deep-integration solutions.

About Eaton

Eaton is a power management company with 2015 sales of $20.9 billion. Eaton provides energy-efficient solutions that help our customers effectively manage electrical, hydraulic and mechanical power more efficiently, safely and sustainably. Eaton has approximately 97,000 employees and sells products to customers in more than 175 countries. For more information, visit www.eaton.com.

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