

Control Design Guide for Smart Machines

The Control Design Guide for Smart Machines provides insight into the challenges machine builders face today and demonstrates proven methods and solutions that help innovative machine builders get ahead of the competition. Experience the impact graphical system design and customizable off-the-shelf hardware has on the design process and business success.

I Smart Machine Industry

There has been a lot of discussion recently about the proliferation of smart machines. These systems not only perform repetitive tasks at soaring speeds and high accuracy, but they adapt to changing conditions and operate more autonomously than ever before. Like previous generations of technologies, smart machines will impact almost every domain of life. They will alter how we produce goods, how doctors perform surgeries, how logistics companies organize storage, and even how we educate future generations.

Debates around the subject range from the fear of losing low- and middle-skilled jobs to the hope of sparking the resurgence of manufacturing in high-paying countries. While research institutes, economists, and the media debate the impact of machines infused with information technology, engineers and scientists are tasked with providing manufacturing systems that are dramatically more flexible and versatile. These systems must help the manufacturing industry satisfy the need for product variety and deal with the ever-decreasing life cycles of consumer goods.

Characteristics of Smart Machines

Two sides drive innovation in manufacturing equipment: one is individuality and complexity of produced goods and the other is the ever-increasing demand for productivity and quality. Machine and device builders no longer design single-purpose machines. They create flexible multipurpose machines that address today's manufacturing needs such as smaller lot sizes, customer-specific variations of products, and the trend toward highly integrated products that combine different functionality in one device.

Because modern machines can operate more autonomously than ever before, they can prevent as well as correct processing errors caused by disturbances like changing conditions in the raw material, the drift of the thermal working point, or the wear and tear of mechanical components. With an extensive network of sensors, smart machines hold information about the process, the machine condition, and their environment. This improves uptime and increases the level of quality. In addition, these systems can improve their performance over time and learn through mining data, leveraging simulation models, or applying application-specific learning algorithms.

Last but not least, machines exchange information with other automation systems and provide status updates to a higher level control system. This creates intelligent factories and automation lines that can adjust to changing conditions, balance the workload between machines, and inform service personnel before a machine fails.

Design Approach and Challenges

Modern machine control systems take advantage of data and information about the environment, processes, and machine parameters to adapt to changing conditions, perform tasks that are not purely repetitive, or increase efficiency and performance. Sensors and measurement technology play an increasingly important role because they give machine builders the ability to create systems that are aware of their environment, perform real-time process monitoring, ensure the health of critical mechanical components, and use this information for adaptive control. This requires control systems that can integrate sensor data, gather information in real time, and use information from multiple sensors in parallel with running high-speed control loops. High-performance embedded systems with

industrial-grade ruggedness provide direct sensor connectivity through modular I/O devices. Today leading machine builders adapt heterogeneous computing architectures that combine a real-time processor and programmable hardware to solve the most demanding applications.

To address today's manufacturing needs, machine builders must design highly modular systems that extend to satisfy customer specific requests or adapt on-site for different manufacturing processes and product variations—sometimes even without the need of operator interaction. Although a modular approach helps OEMs develop reusable components that they can use across their machine offering and simplifies the integration of off-the-shelf subcomponents, it significantly changes the way they do system design. The mechanical system's modularity needs to be reflected in the control system architecture. Rather than use a traditional monolithic system, modern machines are based on a network of control systems. A seamless communication infrastructure is required that can handle the time-critical data, lower priority data, as well as status information and communication with a supervisory system. To deal with the increased complexity of distributed embedded systems, machine builders can adapt a system design approach that is software-centric.

In the past, design teams were composed of mechanical, electrical, and control engineers who mainly focused on their individual design task. Today, however, modern machines require different design teams to collaborate much more closely.

Mechatronics-oriented design tools improve machine development by simulating the interaction between mechanical and electrical subsystems throughout the design process. Historically, teams of engineers from different disciplines worked in silos and in sequential development. Design decisions were made independently, resulting in longer development times and higher costs. Now, to streamline development in a mechatronics approach, the teams work in parallel and collaborate on design, prototyping, and deployment. The ability to create virtual prototypes is a critical aspect of the mechatronics approach because it helps engineers and scientists explore machines before they are built.

Leading machine builders differentiate their smart machines through features that require the adoption of key technologies such as the following:

- A combination of multiple control systems and heterogeneous computing architectures
- A hardware and software platform that provides
 - Signal analysis tools, high-speed control loops, and algorithms
 - Simulation and modeling tools
 - Networking and communication capabilities
- A software-centric design approach that helps deal with the increased complexity of these systems

Learn more about NI tools and technologies for machine control applications at ni.com/machinedesign.

II Key Technologies

Decentralized Cooperative Control

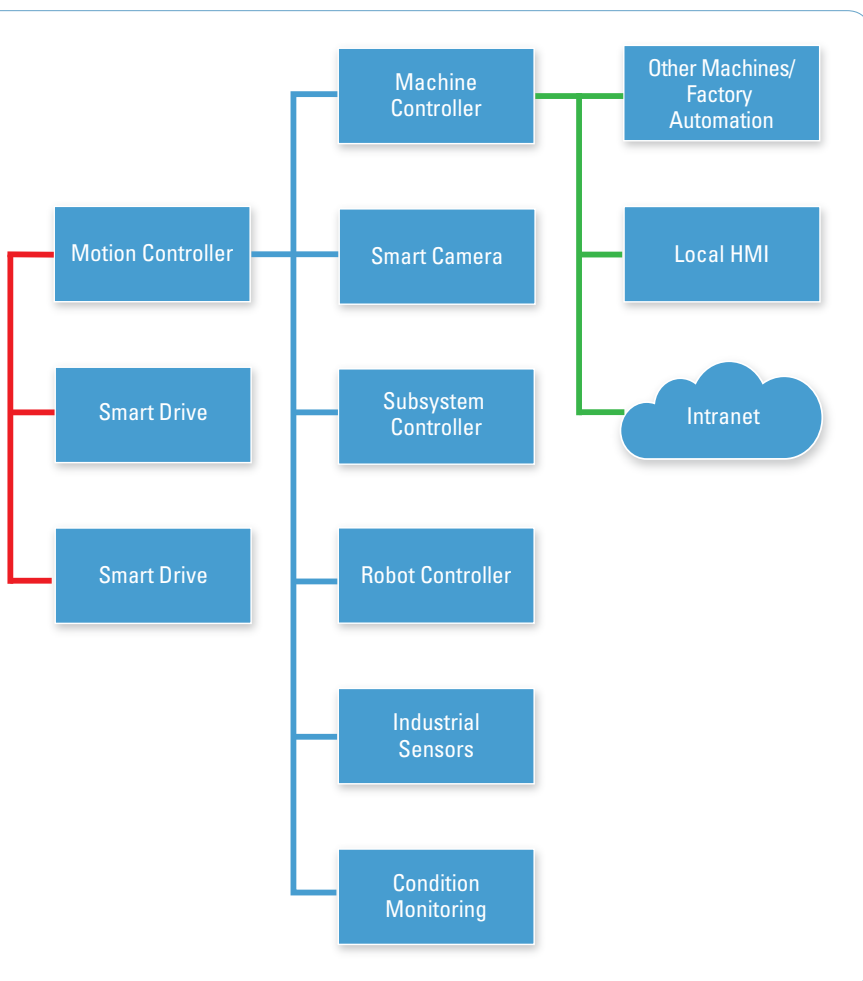
Modern machines follow a modular approach. They contain a network of intelligent subsystems that jointly perform all the automation tasks within the machine and communicate with higher level control systems on the plant level, making intelligent factories possible. To create systems that are adaptable and extendable, the control system architecture needs to reflect this modularity as well. Protocols for industrial communication are required to interconnect subsystems and maintain timing and synchronization. A shift toward a software-centric design approach and programming tools that provide the ability to use one design tool to implement different automation tasks allows customers to reflect the modularity of the mechanical system in their control software.

While simple systems might get away with the classical concept of one central controller connected to decentralized I/O, modern machines implement a control architecture with a hierarchical structure where

higher level control systems are connected to slave controllers that perform clearly defined and contained automation operations.

Traditional programmable logic controllers (PLCs) still play an important role in this setup, especially for the implementation of Logic or Safety functions, but modern machine control systems incorporate embedded control and monitoring systems to implement advanced control, machine vision, and motion control capabilities or machine condition monitoring. Besides connectivity to a main controller, the intelligent subsystems usually can also interact with systems on the same level to trigger and synchronize tasks to enable applications like high-performance vision-guided motion or position-based triggering and data acquisition.

One of the biggest challenges for machine builders today is the adoption of embedded technology. In the face of tight time-to-market requirements and fierce competition, they don't have the time and resources to justify the development of custom embedded hardware. Oftentimes, they don't have the embedded engineers on staff, leaving them with the option of outsourcing these efforts.



Decentralized Cooperative Machine Control System

Hardware selection for machine control systems can be a daunting task. System engineering departments often need to trade the ease of use and low risk of black box solutions with the performance and price benefits of a custom embedded system, allowing them to build in differentiated features that can make all the difference between their machine's success or failure in the marketplace. Because custom solutions usually drive these design teams out of their comfort zone, they often tend toward traditional solutions knowing full well that this might limit their capability to add the differentiating smarts to their machines.

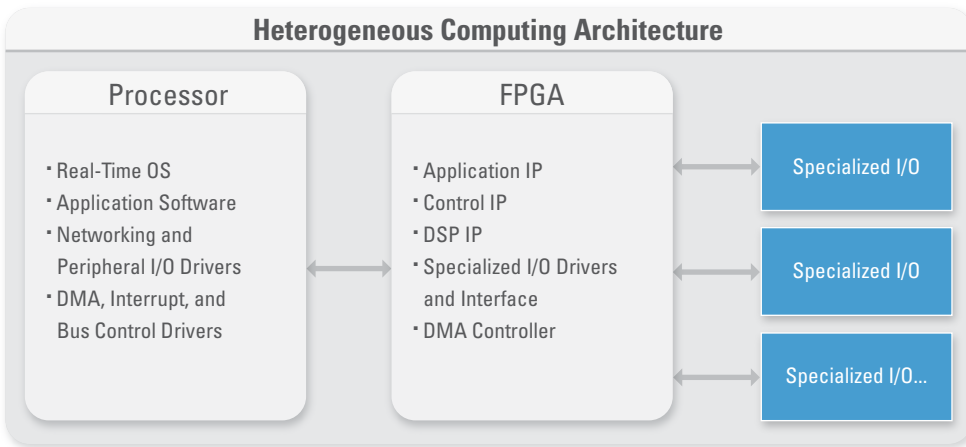
To address these challenges, National Instruments offers a platform-based approach that gives domain experts the ability to configure a modular embedded system and program different automation tasks with one graphical design tool. This approach, known as graphical system design, is adopted by leading machine builders and uses NI LabVIEW graphical programming and the LabVIEW reconfigurable I/O (RIO) architecture. LabVIEW graphical programming helps leading machine builders master increasing system complexity. Machine builders can use LabVIEW to consolidate their development toolchain and further streamline the design process with add-on modules for motion control, machine vision, and control design and simulation; features for machine prognostics and condition monitoring; and extensive support for I/O hardware and communication protocols.

The LabVIEW RIO architecture offers a hybrid approach: a fully customizable off-the-shelf platform, with programmable FPGAs, that provides access to a wide range of existing I/O modules from NI and third-party vendors. Using the features and IP provided through the LabVIEW FPGA Module, machine builders can focus on the design and optimization of their custom algorithms rather than spend weeks or months on hardware design or use a third-party company to design yet another application-specific black box embedded solution. Custom I/O front ends and board-only versions based on the same architecture provide an additional level of flexibility.

Heterogeneous Computing Architecture

As machine control applications grow in complexity, hardware architectures and embedded system design tools must evolve to address increasingly demanding requirements as well as minimize design time. Historically, many embedded systems have featured a single CPU, so system designers have relied on CPU clock speed improvements, the shift to multicore computing, and other innovations to achieve the processing throughput required by complex applications. However, more and more system designers are migrating to computing architectures that feature multiple distinct processing elements to provide a more optimal balance between throughput, latency, flexibility, cost, and other factors. Heterogeneous computing architectures provide all of these advantages and enable the implementation of high-performance embedded systems for advanced machine applications.

To illustrate some of the benefits that heterogeneous computing architectures can provide, consider an architecture composed of a CPU, an FPGA, and I/O. FPGAs are ideally suited to handle parallel computations such as parallel control loops, signal processing operations on a large number of data channels, and the execution of independent automation tasks within one system. Additionally, because FPGAs implement computations directly in hardware, they provide a low-latency path for tasks like custom triggering and high-speed, closed-loop control. Incorporating FPGAs into computing architectures also improves the flexibility of embedded systems, making them easier to upgrade than systems with fixed logic and adaptable to changing I/O requirements. Coupling a CPU and an FPGA in



Embedded system designers can combine a microprocessor and an FPGA in a heterogeneous computing architecture to use the strengths of each processing element and more optimally meet complex application requirements.

the same heterogeneous architecture means that system designers do not need to choose between these FPGA advantages and the corresponding strengths of a CPU. Additionally, a heterogeneous architecture can be more optimal than attempting to adapt a single-element solution to a problem that the element is not well suited for. For example, a single FPGA might handle a parallel task requiring low latency equally as well as a large number of CPUs.

Although embedded system designs that feature multiple processing elements have many advantages, they raise some challenges when it comes to software development. The specialized architectures of individual processing elements and the fragmented set of tools and expertise required to program them means they often require large design teams. For example, FPGA programming commonly requires knowledge of VHDL programming—a skill that can require a significant training investment, larger staff, or costly outsourcing. Additionally, developing the software stack to support a heterogeneous architecture



NI CompactRIO combines a heterogeneous computing architecture with a wide range of I/O modules in a compact and rugged form factor.

is a considerable undertaking that involves driver integration, board support, middleware for interelement communication, I/O interface logic, and more. System designers can address these challenges with an integrated hardware and software platform composed of a standard heterogeneous architecture, interchangeable I/O, and high-level system design software. Building on knowledge of the underlying hardware, high-level design tools abstract both the system architecture and I/O during the development process, improving productivity and reducing the need for system designers to manage low-level implementation details. When developing embedded systems based on heterogeneous architectures, system designers can use high-level system design tools that can abstract the architectures of individual computing elements, such as FPGAs, and provide a unified programming model that can help designers take advantage of the capabilities of different elements. Furthermore, abstraction in high-level design software aids in the concise description of functional behavior and facilitates code reuse despite changes in hardware or communication interfaces.

Off-the-shelf embedded system platforms based on heterogeneous architectures are available today and can eliminate the need to design custom hardware. With the LabVIEW RIO architecture, National Instruments provides an off-the-shelf platform in a variety of form factors and performance levels spanning from board-level NI Single-Board RIO to industrially packaged NI CompactRIO and PXI. A broad ecosystem of I/O modules, including analog and digital measurements and industrial bus connectivity, helps engineers use these platforms in smart machine applications.

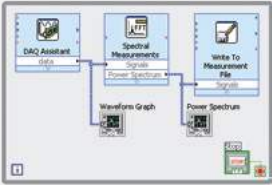
LabVIEW makes it possible to program CPUs and FPGAs on heterogeneous hardware using a consistent graphical programming approach. In addition, LabVIEW abstracts system timing, I/O access, and interelement communication based on knowledge of the underlying architecture and it provides a wide range of IP libraries for automation tasks like motion control, machine vision, condition monitoring, prognostics and diagnostics, and many more.

Learn more about the LabVIEW RIO architecture and NI's offering of heterogeneous computing platforms at ni.com/embeddedsystems.



With NI Single-Board RIO, customers can combine a custom I/O board with an off-the-shelf embedded board hosting the real-time processor and FPGA.

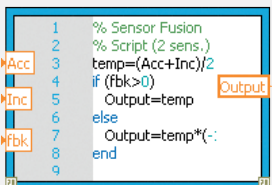
Data Flow



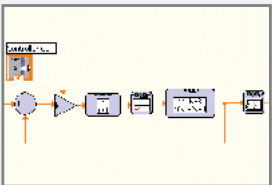
C | HDL



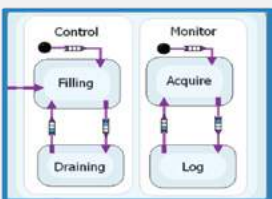
Textual Math



Simulation



Statechart



Mechatronics Design Approach

In the design of a modern machine, every decision has a ripple effect. If the mechanical team decides to change the material and therefore the weight of a mechanical component, it has an influence on the motor sizing or sometimes even on the type of motor needed to efficiently operate the machine. Switching from a stepper motor to a servo motor significantly increases the complexity of the control algorithm and the requirements concerning the system performance of the embedded system processing the algorithm. Improving team communication and collaboration between mechanical, electrical, and control engineers is crucial. In addition, tools that offer seamless integration and help engineers share data and information throughout all phases of the development cycle can lead to vivid collaboration.

Mechatronics represents an industry-wide effort to improve the design process of modern machines. It integrates the best development practices and technologies to streamline design, prototyping, and deployment.

Software tools play a key role in adopting a mechatronics design approach. By exposing different models of computation to engineers and letting them choose the approach that is best suited for their task, LabVIEW helps engineering teams lower the cost and risk of machine design. LabVIEW blends multiple models of computation with expressive timing and concurrency constructs prove useful in developing and implementing cooperative control systems. It is important that this environment give system designers the ability to smoothly move from desktop simulation to real-time prototyping to hardware-in-the-loop simulation to deployment. The capability to use heterogeneous targets such as microprocessors, FPGAs, and GPUs, ensures that the most appropriate computational elements are employed in various applications.

Useful models of computation for machine control include data flow, statecharts, ANSI C and VHDL code, textual math, multirate, simulation, and feedback control. Dataflow programming can facilitate the creation of parallel tasks such as communication, monitoring, and control. Additional models of computation for programming include ANSI C for microprocessors and VHDL for FPGAs. Math-oriented, textual programming can accommodate custom .m files developed by researchers and engineers for various components of the physical system. A multirate computation can facilitate digital signal processing. Dynamic system simulation and feedback control can also be represented by a separate model of computation that includes signal flow representation. Statecharts are another model of computation that are often used to represent discrete logic. Although these models of computation may be needed to run on desktop computers early in the design process, a system development environment should facilitate their deployment to embedded control and monitoring platforms.

*Multiple Models of Computation
Needed for Cyber-Physical Systems*

Another key element is the interoperability with other design tools. Spanning from CAD software tools for mechanical design and simulation to electronics simulation and layout all the way to multiphysics simulation packages, LabVIEW offers interfaces to the most common engineering tools through common file formats or co-simulation.

Interoperability with software and hardware components from multiple sources helps the resulting systems to be extensible and reconfigurable. Machine designers should steer away from black box approaches with closed architectures.

Learn how NI tools support a mechatronics design approach at ni.com/mechatronics.

Reconfigurable Motion Control

Whether it is individual motors or a set of motors that perform coordinated movements in a multidimensional space, motion is typically a vital part of the machine functionality.

National Instruments offers motion control as an integral part of LabVIEW and the LabVIEW RIO architecture. Machine builders can design and validate advanced motion profiles using the benefits of graphical programming and quickly deploy them to embedded control and monitoring hardware.

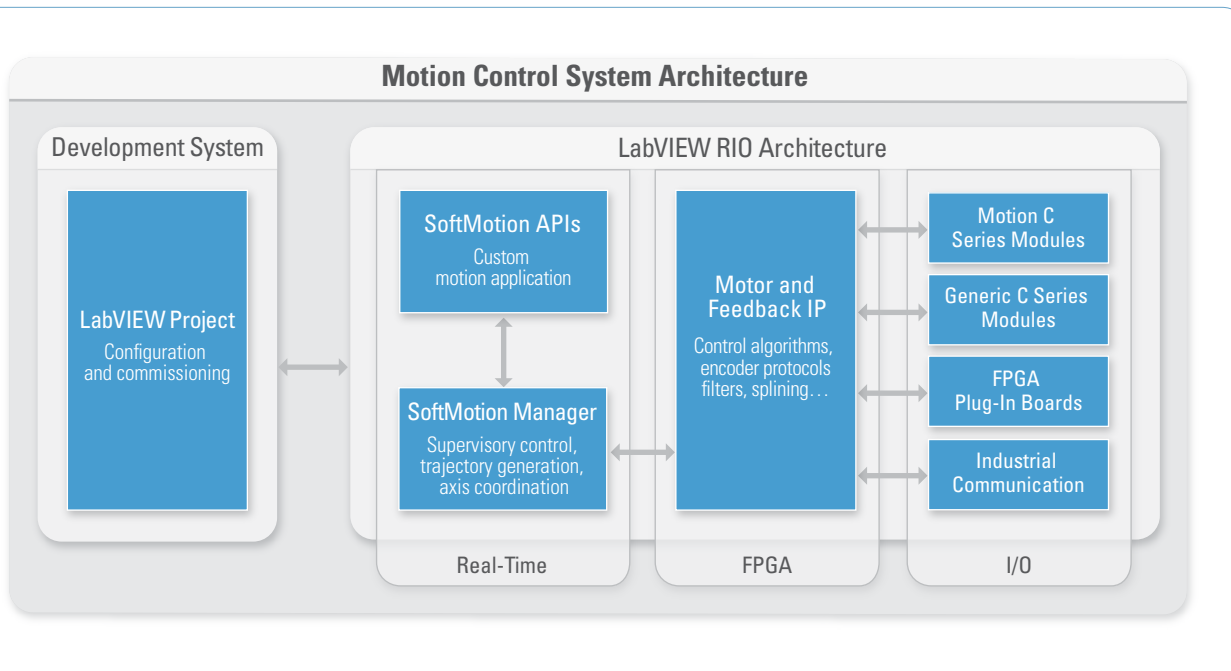
By using standard interfaces to drives and motors like step and direction, p-command, analog, or industrial protocols, engineers can build powerful multiaxes motion control systems. In addition, the line of embedded NI C Series drives and the motion IP provided through the LabVIEW NI SoftMotion Module allows highly integrated embedded motion control systems and unmatched flexibility and customization.



LabVIEW NI SoftMotion and AKD EtherCAT drives offer an ideal solution for multiaxis motion control based on CompactRIO or PXI.

Motion Control System Architectures: Reconfigurable Versus Traditional

Fixed-function controllers and drives are shipped with firmware that implements behavior that cannot be modified by the user. These controllers and drives could be optimized for a very specific purpose such as driving a CNC endmill spindle or designed with the intent to be as generic as possible to cover a wide variety of applications within or even across industries. As long as operated within the designed use case, these fixed-function controllers and drives are usually effective choices for implementing an application. Customers can take advantage of all the design work and feature definition, such as advanced filtering, autotuning, test panels, diagnostic tools, and a host of other features baked into the firmware, that went into that product.



The LabVIEW NI SoftMotion Module provides the feature sets and performance of fixed-function motion controllers with the ability to customize as needed.

The problem with fixed-function controllers arises when machine builders need to step outside the capabilities defined by motion controller and drive firmware. These scenarios become common as machines become more specialized and increasingly sophisticated. A common requirement seen in manufacturing applications is the synchronization of I/O with motion data (most often position and sometimes velocity or acceleration). The I/O types involved can vary widely from application to application, as can the precision and measurement rate. Simple measurement types like digital triggering are in many fixed-function devices, given the application requirement doesn't exceed the number of built-in I/O channels. More complex measurement devices necessitate the addition of a dedicated data acquisition system to handle the rates and I/O types. The higher the data rate, the more difficult it is to adequately synchronize this acquisition to motion data. Above 2 to 3 kHz, deterministic buses like EtherCAT necessitate a powerful master controller or special acquisition and data decimation that causes problems. Above 10 kHz, digital buses generally start to become impractical. Dedicated trigger

lines can still be used between systems, but can be difficult to configure. Inline processing, custom triggering of data for storage, and a host of other desirable features in these machines become the bottlenecks to implementation because of high effort or complexity of implementation.

The alternative solution machine builders often turn to is custom design. With a custom-built motion controller or drive, machine builders can define exactly the behavior they want to see out of the system. However, custom design is costly, time-consuming, and has its own set of limitations. Alternatively, the design and manufacturing can be outsourced to a third-party company, but this approach is expensive and might expose core IP that differentiates a machine from the competition.



C Series drives allow the implementation of fully customizable embedded motion control systems based on CompactRIO or NI Single-Board RIO.

To combine the full feature sets and performance of fixed-function devices with the ability to customize them as necessary, machine builders need a persistent framework that can be developed along the lines of a fixed-function device with lots of testing and iterative feature improvements. It should be modular such that the user can completely define the components of the system to meet specific and demanding application needs.

The LabVIEW RIO architecture and LabVIEW NI SoftMotion Module give machine builders the best of both worlds by allowing them to program motion profiles with a high-level motion API and connect to fixed-function smart drives. By moving the critical motor control IP to the FPGA and using special drive, drive interface, or generic I/O modules, machine builders can keep their high-level motion code and customize the lowerlevel IP.

The ability to reconfigure a standard framework—customizing where necessary but still using the rest—is a powerful concept. In this software architecture, motion tasks are disaggregated so that engineers can choose where to run a particular task to meet the needs of the application. Furthermore, each task or block is open; engineers can modify the functionality down to a very low level. Finally, machine control software packages should be constructed to be modular such that specific tasks could be modified and customized without impacting other blocks in the system. This modular approach is, to a large extent, hardware agnostic. This means engineers can mix and match components to create the hardware system that meets their needs in terms of axis count, processing power, integration with other I/O subsystems, and level of customization.

The flexibility this approach provides is powerful. Engineers can use it to easily achieve coordinated motion with an FPGA-controlled drive and an external smart drive from two different manufacturers. Engineers could also coordinate many different types of motors and use a different type of feedback for each, all without changing the existing trajectory generation or move profile software. In essence, any functionality provided by using modular I/O and an FPGA can be integrated into an axis of motion, and that axis of motion can be integrated with other axes of wildly different configurations.

[Learn more about NI's offering for motion control at **ni.com/motion**.](https://ni.com/motion)

Machine Vision

For decades the machine industry has seen a growing trend in the adoption of machine vision technology. By adopting image acquisition and processing, applications like quality inspection, robot guidance, pick-and-place operation, or part sorting took a quantum leap in performance. The connectivity to main machine controllers and motion control systems through industrial protocols gives engineers the ability to integrate machine vision into existing processes and make decisions based on image analysis results. Powerful embedded systems that use the latest processor and FPGA technologies allow even tighter integration and the execution of different automation tasks on one hardware platform, enabling applications like visual servoing and dynamic manipulation.

Similar to the motion capabilities that are added to the LabVIEW environment in the form of an add-on module, the NI Vision Development Module is a comprehensive library with hundreds of scientific imaging and machine vision functions that machine builders can program using LabVIEW software and deploy to appropriate embedded control and monitoring hardware.

[Learn more about NI's offering for machine vision at **ni.com/vision**.](https://ni.com/vision)



NI vision hardware and software tools allow machine builders to implement vision inspection and scientific imaging tasks.

The Changing Landscape for Machine Designers

Demands to reduce the design cycle and design more complex machines with increased functionality have profoundly changed the design approach. Design tools can now offer an unprecedented level of flexibility and speed. Algorithms and tools that were available only for high-end research a few years ago are now breaking into the industrial market along with the increased capabilities to cycle in the design between hardware and software.

National Instruments provides software tools that seamlessly interact with other design tools and can be used to deploy to heterogeneous hardware platforms to quickly generate prototypes and evaluate and modify different controller configurations. NI also delivers the necessary path to migrate all the code written in the prototyping phase to a more custom, flexible platform without the hassle and cost associated with rewriting code.

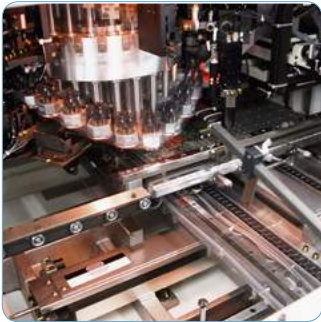
If you are pushing the edge with a high-performance machine that needs to be better, faster, and smarter than previous designs, you are probably running into cases where you need advanced I/O, custom motion control, machine vision, accurate timing and synchronization, and specialized control algorithms. You are stepping outside the boundaries defined by traditional devices. When you do so, a reconfigurable architecture becomes the most effective way to implement these systems.

III Application Examples



Wafer Processing

In semiconductor manufacturing, there is a never-ending push for greater efficiency and semiconductor material yield. As circuit features shrink in size and global price competition intensifies, wafer processes push the physical and operational limits of equipment manufacturers. One result is the increasingly narrow tolerances for the physical and electrical parameters of incoming wafers used in delicate process steps, such as mask and etch. Automation Works uses integrated National Instruments motion and vision tools to help develop cutting-edge semiconductor manufacturing equipment.



Electronics Manufacturing

While many fiber-optic parts are still hand assembled, the Albuquerque division of LightPath Technologies designed an integrated, automated approach to produce collimators, which are gradium lenses fused to fiber-optic cables that help direct light. The performance and reliability of these intricate parts are integral to the overall performance of the telecom systems.



Automated Welding

Tasked to develop a rugged, cutting-edge, automated pipeline welding system, Serimax decided to use CompactRIO. With the help of an NI Alliance Partner, they created a powerful system that adapts to address various customer requirements, provides maximum uptime, meets the highest reliability and quality standards, offers worldwide support, and has flexible hardware and software that can address control and monitoring needs throughout existing machine types in the future.



Metal Forming Machine

Bevel and cylindrical gears can be found everywhere—from automobiles and airplanes to trucks and tractors to wind turbines powering a thousand homes to the lawn mowers and power tools found at these homes. Gear tooth surfaces and spacing are critical parameters to improve operational characteristics. Using the LabVIEW RIO architecture, Viewpoint Systems and Gleason Corporation added exciting new capabilities to their gear finishing machines, allowing them to produce higher quality gears in 30 percent less time.



Medical Devices

The field of protein crystallization is an important component of the drug-discovery process. Proteins under investigation are mixed with various combinations of reagents in an attempt to discover a recipe that will create conditions suitable for the formation of protein crystals, which can then be examined via X-ray diffraction. The number of possible permutations of mixtures can reach the millions, making the search for the optimum recipe tedious. Coleman Technologies uses NI embedded control and monitoring tools to build a medical device that fully automates the process of identifying protein crystals.

Learn more about these applications and find examples for a specific industry at ni.com/solutions.