FROM ELECTRIC MOTORS TO FLEXIBLE MANUFACTURING: CONTROL TECHNOLOGY DRIVES INDUSTRIAL AUTOMATION

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Abstract: Industrial Automation has evolved from stand-alone, hard-wired relay panels to a contemporary, networked system that supports flexible manufacturing and enterprise integration. From precision control of machines and robots on the factory floor to flexible coordination of multiple cells of automation, advancements in control technologies have driven the evolution of industrial automation. The confluence of five technologies, control, computing, communications, software, and materials, is shaping the future direction of industrial automation systems. This paper summarizes the major technical trends, and highlights the continuing opportunities and challenges for the application of control technologies in industrial automation.

Keywords: factory automation, industry automation, control engineering

1. INTRODUCTION: EVOLUTION OF CONTROL IN INDUSTRIAL AUTOMATION

One of the earliest known control schemes could be found in water clocks of the Greeks and Arabs. Developments in control did not progress much until the dawn of the industrial revolution with control systems for temperature, level, pressure, and the centrifugal governor made popular by Watt's steam engine. With the developments in general purpose technology such as electricity, relays hardwired to *predetermined* logic became a popular means of control in factories. Following the rapid advances in electronics and the advent of integrated circuits, Programmable Logic Controllers (PLCs) provided an alternative to hardwired relays in industrial applications, and gave birth to what is widely accepted today as factory automation. The PLCs were programmed with relay ladder logic, which provided a flexible mechanism to make changes to the operation of machines in the factory without rewiring relays. The advent of digital communication networks on the factory floor allowed distributed control, i.e., control to be divided into cells that are geographically distributed, with significant reduction in the size of individual programs. In multi-cell systems, operation of multiple distributed controllers was coordinated with interlocks of data or I/O points in hierarchical structures of master controllers.

The advent of the Internet has greatly accelerated the availability of information from factory control at the right time, at the right place and in the hands of the right people to enable "e-manufacturing." The need for access to more and more data has driven the migration of networks like Ethernet down into the factory floor. In fact, the rapid adoption of Ethernet along with the growth in information and communication technology, has enabled the "shop floor" or the factory to be integrated with the "top floor", or business enterprise. Several enterprises serving a common business purpose are now tightly coupled to form a "supply chain." The focus has now expanded to achieve new efficiencies in the entire value chain through collaboration by integrating the supply chain through the use of standards such as web services, and by facilitating information flow throughout the enterprise through use of open architectures and associated protocols.

Collectively, these technologies are helping manufacturers meet today's most challenging manufacturing demands such as improving production uptime, meeting regulatory compliance, optimizing manufacturing, and maintaining an aggressive time-to-market goal. And, control technologies ranging from automatic control to autonomous control, are at the core of industrial automation. The breadth of applications of control technologies spans all three dimensions of today's collaborative enterprise (Fig. 1): (1) Value Chain (suppliers - customers), (2) Enterprise (shop floor - business) and (3) Product Life Cycle (design - support).

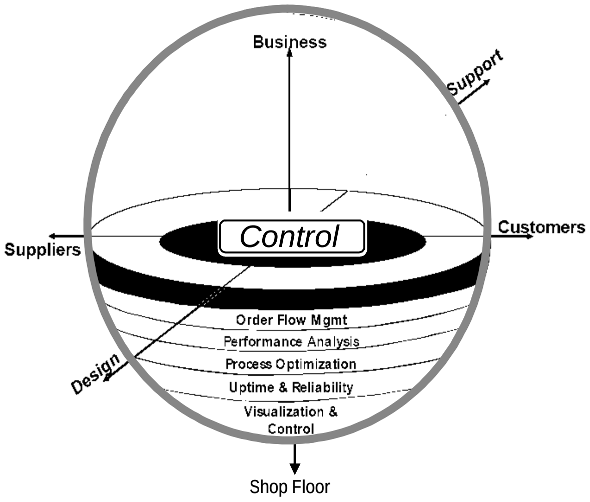

Figure 1. Collaborative Manufacturing

The next section provides a brief overview of the key trends driving industrial automation today, and the resulting challenges for the application of control technologies.

2. TECHNOLOGY TRENDS IN MANUFACTURING SYSTEMS

The evolution of modern manufacturing systems is driven by trends in five major technology clusters: Control, Communications, Computing/Electronics, Software/Information, and Materials. The rapid advancements in computing, communications and software technologies are driving a hitherto disconnected manufacturing enterprise to rapidly become connected with global business systems.

Today's mostly single-purpose manufacturing systems that are designed to produce the same part or component repetitively are migrating to adaptive and flexible manufacturing enterprises. This migration is driven by the global trend towards mass-customization. Consider the food industry for example, where manufacturers would like to create customized packages - one packaging for Wal-Mart, another for Tesco - to give their products a different identity on retailers' shelves. Another example is the pharmaceutical industry where the trend is towards manufacturing customized medications and dosage by requirements of each individual. This trend requires flexible control of the manufacturing enterprise.

The current focus on *energy efficiency and greater productivity* is driving the utilization of energy-efficient electric motors and controllers to replace eddy current, hydraulic, and pneumatic equipment. Since electric motors account for about 60 percent of the power demand in the U.S., a technology-driven cost reduction opportunity lies in the development of smaller, more efficient motors and controllers. For example, High Temperature Superconductivity (HTS) materials will drive new motors that are smaller, lighter, and much more efficient than today's conventional high-efficiency induction motors.

Also, improvements in chip-level integration of sensors, processing logic and associated architecture are enabling the evolution of smart, multi-function devices. One example is an integrated sensor for monitoring the fluid health of a bearing lubricant. We prototyped such an "intelligent" sensor utilizing MEMS technology, which is able to detect moisture ingress, particulate contamination, changes in viscosity, oxidation levels and changes in acidity. Integrated sensing, processing and communication will allow a plethora of such sensors to communicate with each other, and with controllers/processors for real-time control and diagnostics. With integrated sensors collecting immense amounts of raw data, users need a system that seamlessly converts this raw data into relevant information and presents that information to controllers and the enterprise level to prompt the most appropriate and timely response.

Figure 2 illustrates a layered view of an industrial automation system. The *real-time control layer* comprising the factory control system such as machine and robotic control, provides many challenging applications for automatic control including modeling, identification, adaptive control, discrete-event systems theory, and control system design utilizing both linear and nonlinear control methods. The higher level, *decision-making transactional layer* is responsible for interfacing with the business system for information such as a work order, and transforming the work order into a detailed schedule for the factory. Control technology applications at this layer include decision theory, cognition and control, and autonomous systems.

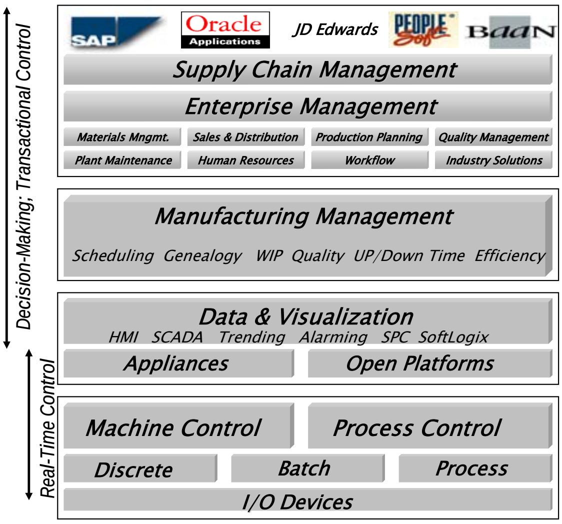

Figure 2. Layered Industrial Automation Architecture

In the following two sections, we will highlight the applications of automatic control and autonomous systems in industrial automation.

3. AUTOMATIC CONTROL: A KEY ENABLING TECHNOLOGY FOR INDUSTRIAL AUTOMATION

In this section, we will focus on the core technology that enables real-time control on the factory floor - Automatic Control. In theory, a workable control solution can be found for practically any application in industrial automation. Researchers have successfully modeled, simulated and demonstrated the efficacy of numerous control methods for mechatronics, robotics, machine control and process control applications. However, the actual implementations of automatic control in manufacturing plants reveal a preponderance of the classical PID control. Why hasn't industry embraced the numerous advances in modern control and implemented them in its processes? There are two key factors: (1) ROI (better, cheaper, and faster), and (2) ease of application. To be utilized broadly, a new technology must demonstrate tangible benefits, should be easier to implement and maintain, add more functionality, or substantially improve performance and efficiency. Many times, a promising approach is not pursued due to poor usability during operation and troubleshooting in an industrial environment. The PID due to its simplicity, scores well on this front.

As new, advanced manufacturing processes continue to evolve and the existing processes are pushed to their limits, the need to evolve the control architectures past the ubiquitous PID control into a new control arena is becoming a necessity. We believe that advances in information and communications technologies resulting in greater availability of connected computing resources, will provide the impetus to the greater adoption of automatic control methods beyond the classical PID.

3.1 Why PID is Still the Mainstay In Industrial Applications

An industrial manufacturing plant can be divided into four types of applications: extraction, processing, finishing, and assembly, with manufacturing processes broadly in three categories: continuous, batch, and discrete. Raw materials enter the plant and finished goods exit. Control of the systems in-between range from the well known Single-Input Single-Output (SISO) PID controllers to the more challenging Multi-Input Multi-Output (MIMO) modern control techniques.

PID controllers continue to be the work-horse of the industry today. Although no real system is truly linear, many systems can be approximated by a linear system. Also, a system may be segmented into piecewise linear subsystems. PID controllers adequately handle 3 main problems: proportional gain drives the controller based on the system error, derivative control dampens out disturbances, and integral control eliminates steady state error. These gains may have to be de-tuned in order to obtain a stable response; however, a given system in most cases, can be tuned to operate well under numerical control. For example, the plot on the left hand side of Fig. 3 illustrates the response of a physical system where the bandwidth was too high for unknown (un-modeled) system resonances. The plot on the right hand side shows how the system can be stabilized by reducing the bandwidth, yielding a compromised but stable response. This is a well understood technology and readily accepted by the industry. Operators trained in PID control can develop the intuition and understanding to manually tune the gains for control loops. As manufacturing systems become more complex with a growing number of multivariable systems, we believe there is significant potential for the application of alternative control technologies over the classical PID technique.

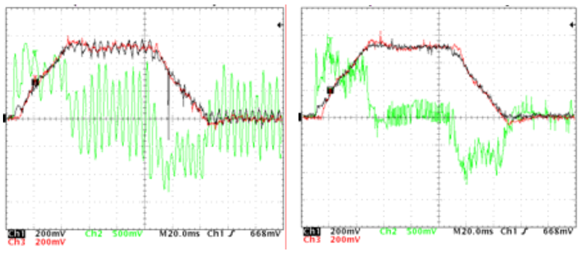

Figure 3. Acceptable PID performance after de-tuning of gains

3.2 Intelligent Control: Applications in Industrial Automation

Let us briefly consider the application of "intelligent" control schemes to factory automation. Neural Networks, Fuzzy Logic, Genetic Algorithms, and Expert Systems, each have their benefits and challenges for implementation. For example, certain types of Neural Networks require training data to calculate the weights. In many cases, it is impractical to operate an industrial process over its entire operating range to collect this data. Fuzzy Logic systems require an expert who knows the process to be able to transfer this knowledge into the rules and input/output data sets, which is not a straightforward task. We note that fuzzy logic has become a popular control scheme for cement manufacturing because of its superior performance over other techniques. This is a direct result of the commitment of significant effort between the cement plant experts and fuzzy logic control designers. However, a *general purpose* fuzzy logic engine to control complex multivariable systems does not exist today.

Although systems based on intelligent control can be made to work (as in the cement application), the question still remains on whether the new system is significantly better than an existing solution, is easier to install, test/verify, and maintain, and is it worth the change.

3.3 Modern Control Technologies For Industrial Automation

Recent advances in estimation and modeling, coupled with ubiquitous computing and networked systems, are paving the way for future applications of modern, automatic control techniques in industrial automation. Demanding applications with increasing requirements for precise and stable control can benefit from the application of model-based control methods such as:

- LQR theory, which calculates the optimal gain matrix K such that the state-feedback law u = -Kx minimizes some cost function J = Integral{x'Qx + u'Ru + 2*x'Nu}dt subject to the state dynamics xdot = Ax + Bu.

- LQG theory, which is similar to LQR with the main difference being that noise is introduced into the calculations.

- H-infinity controllers, which calculate the controller F(s) and the parameterization K(s) using the loop-shifting formulae. Given any stable infinite norm U(s) less than or equal to one, F(s) is formed by wrapping feedback U(s) around K(s).

- H-2 control, which has the same operation as H-infinity but with a 2-norm instead of the infinity-norm.

- The mu-synthesis technique, where the objective is to find a stabilizing controller F and diagonal scaling matrix D such that the infinite norm constraint is less than one. i.e. mu-synthesis uses H-infinity to automate the finding of D-F through multiple iterations.

- Linear Matrix Inequalities (LMI), a design tool to help perform control design and system identification. A LMI is any constraint of the form A(x) = A0 + x1A1 + x2A2 + … +xnAn < 0. LMIs can be applied to all of the previous techniques.

- General model-based control methodology called Model-Predictive control (MPC), wherein dynamic optimization problem is solved on-line at every instance of control execution, is another potential technology that has applications in industrial automation.

There are numerous examples of challenging control applications in Industrial Automation for the application of the above methods. We will briefly outline two applications: position registration in printing presses, and electronic line shaft (ELS).

A major control challenge in modern printing presses is the synchronization of one motor/drive system to the next on a web line. The individual motor/drive performance for a given roll is also a challenge. Synchronizing the system to obtain *perfect registration* of four colors on a sheet of paper is a difficult control problem. These motors are connected through a gearbox to long shafts with flexible couplers. The shafts are connected to large inertial rolls that have the paper wrapped around them. The gearbox, shafts, and couplers introduce lost motion and resonance in the system to make control a difficult objective. It is not uncommon to have inertia ratios between the load and motor of up to 50:1. Current approaches include inertia adaptation or acceleration feedback to increase the electronic inertia of the system, thus effectively making the system stiffer to disturbances at high frequencies. This is similar to adding velocity feedback to dampen oscillations at the mid frequencies. There is significant potential for a model-based control technique to improve the control performance of this application.

Although Electronic line shaft (ELS) systems have been around for awhile, there exist significant opportunities for improvements. An ELS system is commonly used in many continuous web applications such as paper converting and printing. Through the application of modern control methods, the opportunity exists to dramatically improve the performance of web line systems in the following areas: dynamic synchronization of motors, electronic “camming,” and tension control. Closing the acceleration feedback loop greatly aids the performance of an ELS system. However, additional analysis of the acceleration loop and its interaction with the current loop is required. This may be extended to the analysis of the jerk and other control loops as well.

The above is just a narrow sample of the large number of challenging opportunities for modern, automatic control methods in industrial automation. We expect to see greater application of such methods in the future, which will supplant the current dominance of the PID.

4. AUTONOMOUS CONTROL

Most factory automation systems feature tightly-coupled automation components, with fixed pre-configured automation. While this works well in many instances, it is vulnerable to single-point of failure, is difficult to expand as the plant’s needs change, and makes behavior prediction or dynamic response to unanticipated events in the system difficult to achieve.

Today’s complex, multi-cell systems challenge control engineers for coordinating the operations of many small controllers. The proper operation of these linked controllers depends on a fixed sequence of preplanned operations. The current trend toward consumer-directed, customized manufacturing will drive a higher frequency of changes and eventually, a highly flexible architecture for manufacturing systems. In a flexible manufacturing system, the underlying control system needs to tackle the numerous changeovers in the mainline configuration, tool allocation, material distribution, process steps, and product quality. In this section, we will focus on the *higher-level* control and decision making in an industrial control system.

Autonomous Control systems that can distribute intelligence to eliminate any single point of failure and make future expansion much easier are currently being investigated and prototyped by a large number of researchers. In such a system, software agents are typically used to negotiate and dynamically allocate tasks to the system's resources. These autonomous software agents hold the promise to reduce system downtime by reconfiguring the system in real-time in the event of a failure. Such actions improve the productivity of the manufacturing plant and enable the life of the capital equipment to be extended by dynamically planning repairs, enhancements and upgrades in accordance with the production demand.

4.1 Autonomous Agents

Autonomous agents are software modules, usually associated with a physical entity such as a pump, valve, motor, pipe, or sensor that has local goal-directed behavior and control (autonomy). In addition, an agent possesses cooperative, collaborative capabilities to work in conjunction with other agents to satisfy a more critical, overarching goal. Clusters of agents dynamically form and negotiate amongst themselves on how each will control a part of the overall system to achieve new and important capabilities. This mode of operation is highly distributed - there is no centralized control - and no central point of failure. The analogy for such control methods comes from biological systems where beings cooperate to capture food more efficiently, carry heavy objects, or form structures. An international standards organization, Foundation for Intelligent Physical Agents (FIPA), is focused on establishing a common framework and language for disparate agents to communicate and collaborate in problem solving and control. There are several development and simulation tools available today to support efficient system development of such systems.

To illustrate the application of autonomous agents, we now provide a summary of an application to shipboard automation.

4.2 Control of Chilled Water Distribution

On a certain class of Navy ships, a chilled water system is utilized to cool missile launchers following the launch of a missile. Chilled water is routed through a network of pipes and valves that have significant redundancy. The Navy identified this system as requiring a distributed, fault-tolerant control system to allow, (1) continued operation in the event of failure due to battle damage or other means, (2) automatic system reconfiguration for achievement of the cooling objective, and (3) elimination of a single point of failure in the system. A highly distributed intelligent shipboard automation system with a large number of autonomous agents was designed for the control of the chilled water system (Fig. 4). Each agent is programmed with operation-specific intelligence. The intelligent agents carry out flexible negotiation utilizing a capability-based language.

In the chilled water system there are 3 subsystems: plants, mains and services. There is one plant per zone (2 zones), and there are 14 vital and 2 non-vital services. The water-cooling plants are modeled as single agents. The main circulation piping is partitioned among 'T' pipe sections, which are also agents. There are standalone valves in the main circulation loop for the supply and return lines represented by valve agents. The total system has 68 agents. Each agent is associated with capabilities and each capability is associated with a specific set of operations. The negotiation among agents uses local planning and negotiated planning (i.e., cooperation), and the agents use their local 'world observations' to determine their actions which are translated into execution steps. The agents are loosely coupled, and when dynamic interactions occur during the decision-making process, logical relationships are temporarily established. The agents make internal calls to the operations offered by their local capabilities, and in negotiated planning, agents discover each other's capabilities.

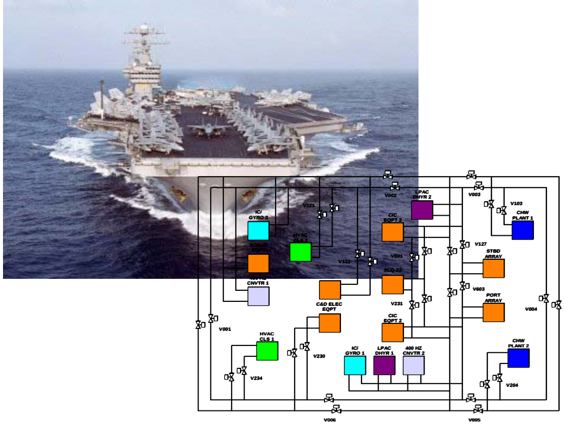

Figure 4. Agents for Chilled Water System

The architecture is organized according to the following characteristics:

1. Autonomy: Each agent makes its own decisions and is responsible for carrying out its decisions toward successful completion.
2. Cooperation: Agents combine their capabilities into collaboration groups (clusters) to adapt and respond to diverse events and goals.
3. Communication: Agents share a common language to enable inter-operation.

4. Fault tolerance: Agents possess the capability to detect equipment failures and to isolate failures.

The shipboard autonomous system prototype was successfully tested in the laboratory, and also validated on an actual chilled water distribution system. The prototype demonstrated the accomplishment of the three primary objectives relating to fault-tolerance, continuous performance, and elimination of a single point of failure. A brief summary of the lessons learned from this work are, (1) simulation in-the-loop was required throughout the agent implementation cycle to properly design and architect the system, (2) although the system is highly distributed, some degree of centralization is required to ensure system stability, sub-optimal performance, and reduce the number of agents and complexity, (3) implementation can be on COTS controllers and no special hardware is needed, and (4) interoperability standards and communication interfaces can be based on standard protocols such as FIPA, Ethernet/IP, and CIP™.

As stated earlier, the primary benefit of this architecture is flexibility. Intelligent agents are easy to scale, and hold great promise for reducing system downtime. Such systems will be useful in an automation system for flexibility, and continuous operation in the event of failures.

5. CONCLUSION

Since the industrial revolution, control technology has driven the evolution of the modern manufacturing enterprise. Systems theory and control design are ubiquitous in industrial automation systems, from the control of individual electric motors to the control of complex processes. Continued evolution of industrial automation offers a wide range of opportunities for the application of most modern control methods, as well as decision theory and autonomous systems.

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REFERENCES

Discenzo, F., F. Maturana, R. Staron, P. Tichy, P. Slechta, V. Marik (2004): Prognostics and Control Integration with Dynamic Reconfigurable Agents, *IASME Transactions, Issue 2, Volume 1, April 2004.*

Marik, V, M. Fletcher, and M. Pechoucek, (2001) Holons and Agents: Recent Developments and Mutual Impacts. *International Workshop on Industrial Applications of Holonic and Multi-Agent Systems, HoloMAS.*

Marik, V., P. Vrba, M. Fletcher (2004): Agent-Based Simulation: MAST Case Study, *BASYS 04, Vienna, Austria.*

Maturana, F., R. Staron, and K. Hall (2004):Real Time Collaborative Intelligent Agent Solutions, *IEEE International Conference On Systems, Man and Cybernetics, The Hague, The Netherlands.*

Staron, R, F.P. Maturana, P. Tichy, and P. Slechta (2004): Use of an Agent Type Library for the Design and Implementation of Highly Flexible Control Systems. *8th World Multiconference on Systemics, Cybernetics, and Informatics, SCI2004, Orlando, FL.*

Vasko, D., F. P. Maturana, A. Bowles, and S. Vandenberg (2000): Autonomous Cooperative Systems for Factory Control. *PRIMA 2000, Australia.*