

## Faster is better: High-speed Model-Free Adaptive control

By Dr. George S. Cheng

*Adaptive control is helping create faster, more accurate control for many applications. In this article, control industry leader Dr. George Cheng describes the concepts behind Model-Free Adaptive (MFA) control and shows its benefits compared to Proportional-Integral-Derivative (PID) and model-based control. He also highlights the elements of a real-world application in piezomotor control.*

Since the beginning of time there has been a desire to move life along at a faster pace. In our world today, speed is indeed often the most decisive factor between winning and losing.

This *faster is better* rule impacts our industry in a huge way. For example, saving a second or two in a semiconductor wafer process step can substantially reduce the cost of ownership of a multimillion dollar tool. For some control components such as a gas flow or liquid flow controller, a quarter or half second faster to force the flow to track its setpoint can be decisive. In high-end motion control, customers demand subnanometer accuracy and submicrosecond control update rates.

### Why PID and model-based control fail

The speed bottleneck of a piece of equipment is often related to its automatic control system, which has three key elements: sensors, actuators, and controllers. When equipment becomes more complex and the flexible production capability is critical, high-speed adaptive control systems become critical and must deal effectively with problems including:

- Nonlinearity
- Dead-zone and hysteresis
- Open-loop oscillating
- Large  $\tau$ -T ratio (where  $\tau$  is delay time and T is time constant)

- Rapid and irregular setpoint trajectory changes
- Noise, disturbances, and changing operating conditions

PID controllers can be embedded in high-speed control equipment, but cannot deal effectively with all these problems. Since PID is a fixed controller with no adaptive capability, its parameters have to be retuned when process dynamics, product types, or operating conditions change.

A model-based adaptive control approach can be difficult and costly to implement because developing a process model and keeping it accurate always pose a challenge. For dynamic modeling based adaptive control, there may not be enough time and data to learn a new model. Control experts typically design a high-speed complex control system with precise process models requiring significant financial and time investments. These systems usually require special hardware and software that are difficult to build and change.

Fundamentally, the control speed and the control algorithm complexity will always be in conflict. Therefore, a simpler control algorithm is always desirable, no matter how much computing power is available.

### Benefits of MFA control

MFA control, as its name suggests, is an adaptive control method that does not require process models. This patented technology has been developed by CyboSoft. An MFA control system is defined to have the following properties:

1. Precise quantitative knowledge of the process is not necessary
2. Process identification mechanism or identifier is not included in the system
3. Controller design for a specific process is not needed

4. Manual tuning of controller parameters is not required
5. Closed-loop system stability analysis and criteria are available to guarantee the system stability[1]

Based on the core MFA technology, CyboSoft has developed a set of general-purpose MFA controllers, each of which solves a tough control problem:

- Single Input Single Output (SISO) MFA to replace PID and eliminate controller manual tuning
- Nonlinear MFA to control nonlinear processes
- Time-optimal MFA to reach control condition in minimum time
- Feedforward MFA controller to deal with measurable disturbances
- Antidelay MFA to control processes with large  $\tau$ -T ratio
- Robust MFA to protect the process variables from running outside their bounds
- Time-varying MFA controller to control time-varying processes
- Multiple Input Multiple Output (MIMO) MFA to control multivariable processes

MFA control products provide cost-effective and user-friendly solutions for the high-speed complex control market. MFA controllers do not require process models that are difficult to develop and maintain. Once installed, no controller tuning is required. In most cases, MFA controllers can directly replace the legacy controllers such as PIDs and achieve immediate improvements in control performance resulting in significant economic benefits. Due to their general-purpose nature, MFA controllers have been deployed in almost every sector of industrial control applications[2].

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## Single-loop MFA control system structure

The system structure of a SISO MFA control system, shown in Figure 1, is as simple as a traditional single-loop control system that includes a SISO process, a SISO MFA controller, and a feedback loop.

The control objective for the controller is to produce an output  $u(t)$  to force the process variable  $y(t)$  to track the given trajectory of its setpoint  $r(t)$  under variations of setpoint, disturbances, and process dynamics. In other words, the task of the MFA controller is to minimize the error  $e(t)$  in an online fashion. The minimization of  $e(t)$  is achieved by:

- The regulatory control capability of the MFA controller
- The adjustment of the MFA's weighting factors allowing the controller to deal with process dynamic changes, disturbances, and other uncertainties

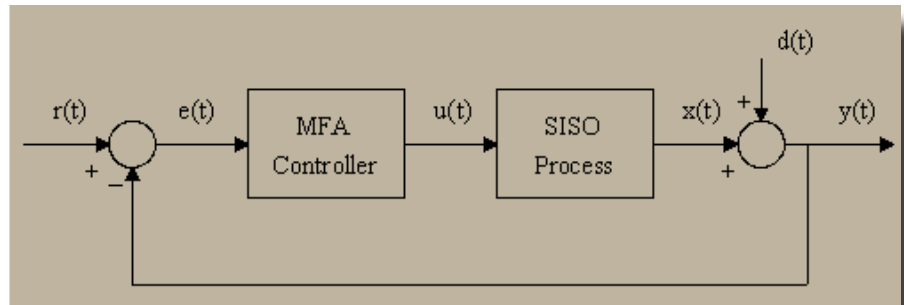


Figure 1

## MFA controller architecture

Figure 2 illustrates the core architecture of a SISO MFA controller. Used as a key component, a multilayer perceptron neural network consists of one input layer, one hidden layer with  $N$  neurons, and one output layer with one neuron. Within the neural network there is a group of weighting factors ( $w_{ij}$  and  $h_i$ ) that can be updated as needed to vary the behavior of the controller. The algorithm for updating the weighting factors is based on the goal of minimizing the error  $e(t)$ . Since this effort is the same as the control objective,

the adaptation of the weighting factors can assist the controller in minimizing the error while process dynamics are changing.

Also, the neural network-based MFA controller *remembers* a portion of the process data providing valuable information for the process dynamics. In comparison, a digital version of the PID remembers only the current and previous two samples. In this regard, PID has almost no memory, and MFA possesses the memory essential to an *intelligent* controller.

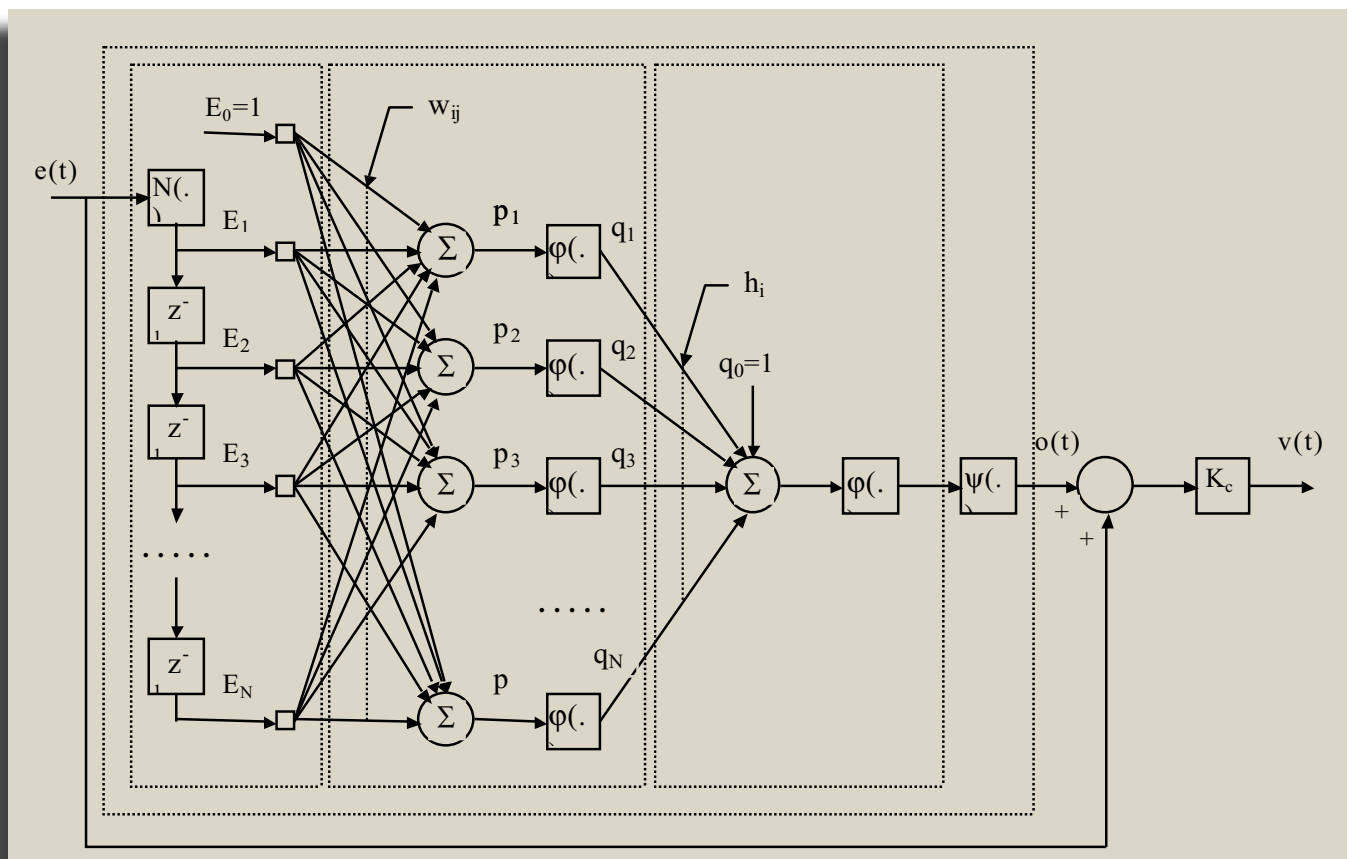


Figure 2

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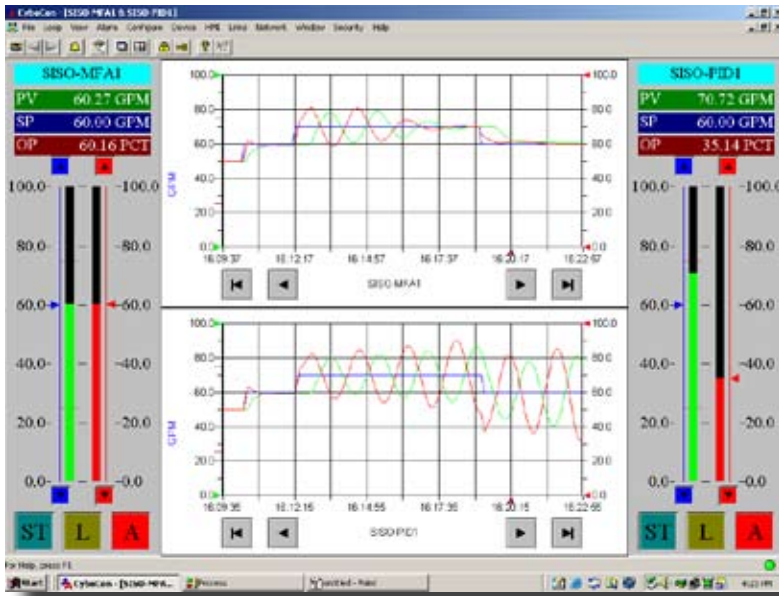


Figure 3

## Adaptive capability of MFA controller

The adaptive capability of MFA is illustrated when compared with PID in Figure 3. The performance of MFA (top) measured against that of PID (bottom) shows how MFA adapts when process dynamics change. From the beginning,

MFA and PID control two identical processes. Then both processes have a major dynamic change causing the systems to oscillate. The PID system continues to oscillate while MFA quickly adapts to an excellent control condition. When the setpoints are changed again, the MFA system no longer shows oscillation.

If both controllers start from a sluggish situation, MFA will control the process faster and better while PID will remain sluggish.

MFA's adaptive capability can be used in equipment or control device *autocalibration*. In many situations, when the equipment is properly calibrated and the controller is tuned, control performance has to be consistent during its normal operation. That means any oscillation or sluggishness of the control system is not desirable. In this case, MFA controllers that have the autocalibration feature can be used.

First, the system is put into an autocalibration mode to allow the MFA controllers to adapt until the system runs in an optimal condition based on certain criteria or specifications. For a high-speed system, autocalibration will take only a few seconds. Then, the system can be switched to the *normal operation* mode, where the controllers are fixed to provide consistent performance. As long as the system runs inside the defined operating condition, the controllers don't need to adapt. Third, the adaptive information

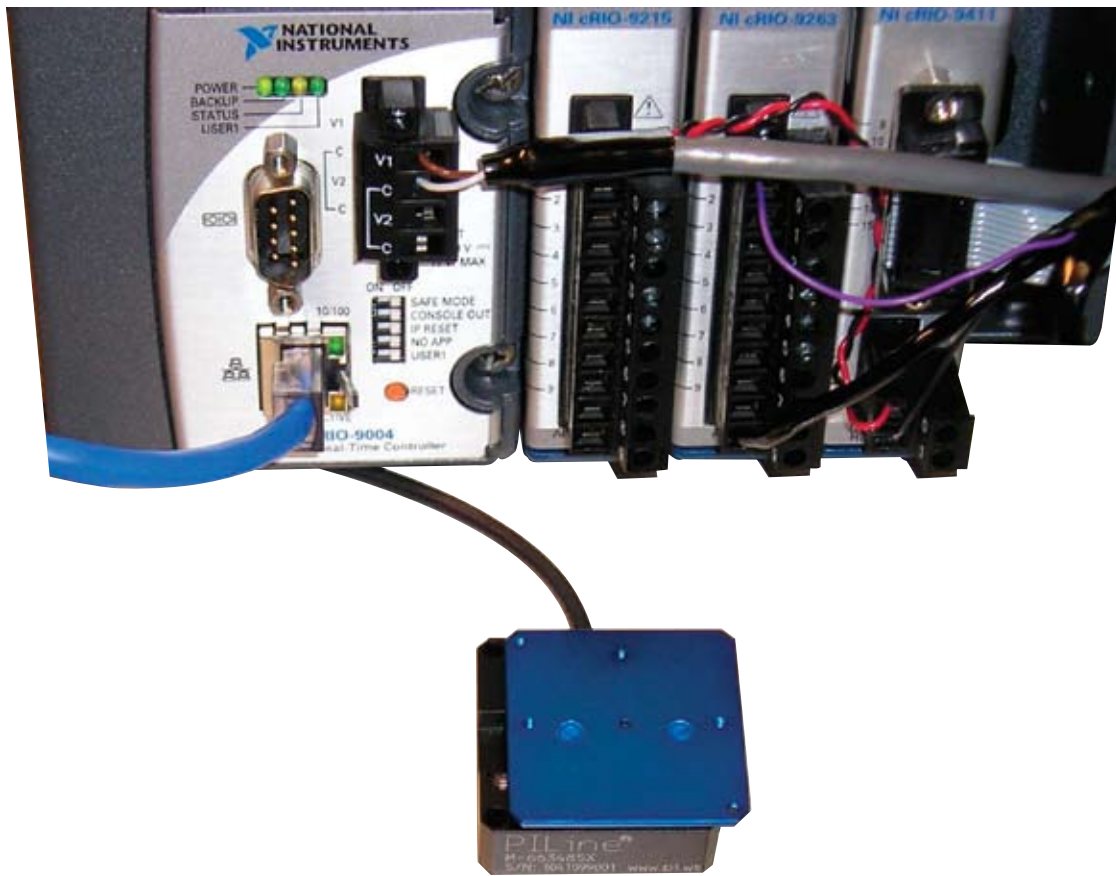


Figure 4

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of the MFA controllers can be saved in a database so that such information or value(s) can be preloaded the next time the equipment is to run in the same condition. The autocalibration feature can save a lot of manpower in applications where tedious one-on-one manual calibration is required for each control loop or device.

## Application: MFA piezomotor control

A general-purpose high-speed MFA control system is based on National Instruments' (NI's) CompactRIO embedded control and data acquisition platform. The combination of NI's LabVIEW software, related hardware including a PC, CompactRIO, Compact Fieldpoint, PXI, and third-party specialty hardware and software makes it a user- and developer-friendly Programmable Automation Controller (PAC) platform, well suited for high-speed control applications.

CyboSoft has embedded a variety of MFA controllers into the LabVIEW platform and can deliver a general-purpose high-speed and high-precision adaptive control solution running on NI's CompactRIO PAC system with performance (10 microsecond updates and I/O using an FPGA, 1 millisecond run time in the operating system) and precision (with 16-bit analog inputs and outputs) previously unattainable with off-the-shelf hardware.

Figure 4 shows a CyboSoft time-optimal MFA controller in NI's CompactRIO controlling a piezomotor manufactured by Physik Instrumente, which demonstrates consistent control performance whether the piezo stage has weight or no weight on it.

## Benefits of high-speed MFA control

High-speed MFA control solutions offer many benefits:

1. Consistent control performance in all operating conditions
2. Elimination of controller manual tuning
3. Lower support costs
4. Safer high-speed operations
5. Higher production throughput

Most importantly, MFA has become an enabling technology for a new generation of equipment where high-speed, long-

range, high-accuracy motion control with adaptive capability is essential.

For example, oil or gas well drilling is typically done manually by drilling machine operators. The drilling speed and efficiency can be inconsistent depending on the operator's skill and work attitude. If the drill bit hits a rock, the operator would want to penetrate slowly to avoid breaking the drilling bit. If the drilling is going through mud, the operator would want to penetrate as quickly as possible under certain safety boundaries.

Based on this idea, automatic drilling equipment is developed to improve the drilling safety and efficiency by automatically controlling the *rate of penetration and weight on bit*. However, each drilling rig can be different due to its design and type, wear and tear of the mechanical components, and so on. In addition, the operating conditions will be different from rig to rig, and from location to location, the controllers used in drilling equipment often require parameter tuning. Retuning PID controllers requires experienced engineers or technicians to travel to a remote location after each rig up-and-down. This effort can cost both time and money. MFA-based autodrilling equipment eliminates the need for controller tuning providing major economical and competitive benefits to the equipment vendors and users.

## Faster MFA is better

To serve the high-speed control market, MFA controllers are typically embedded in custom hardware. Since MFA is *model-free*, the MFA control software functions have a very small *footprint* and can run at high speed in a regular embedded environment. This capability makes the MFA control solution even more compelling for customers or equipment vendors using high-speed control. This revolutionary technology allows users to achieve significant advantages by being faster and more competitive. **ES**



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