# MACHINE DESIGN

Machine Design (ISSN 0024-9114) is published by Penton Media, Inc., 1100 Superior Ave., Cleveland, OH 44114-2543.

Editorial content is indexed in the Applied Science Technology Index, the Engineering Index, SciSearch and Research Alert. Microfilm copies available from University Microfilms, Ann Arbor, MI 48106. Fax (313) 665-5022.

Permission to reprint: Barbara LoSchiavo; Purchased reprints: Phyllis Dixon (216-696-7000, ext. 9607); Advertising Materials: Advertising Dept., Machine Design, 1100 Superior Ave., Cleveland, OH 44114-2543, 216-696-7000. Inserts should be sent to Machine Design, Penton Press, 680 N. Rocky River Dr., Berea, OH 44017-1691.

Penton

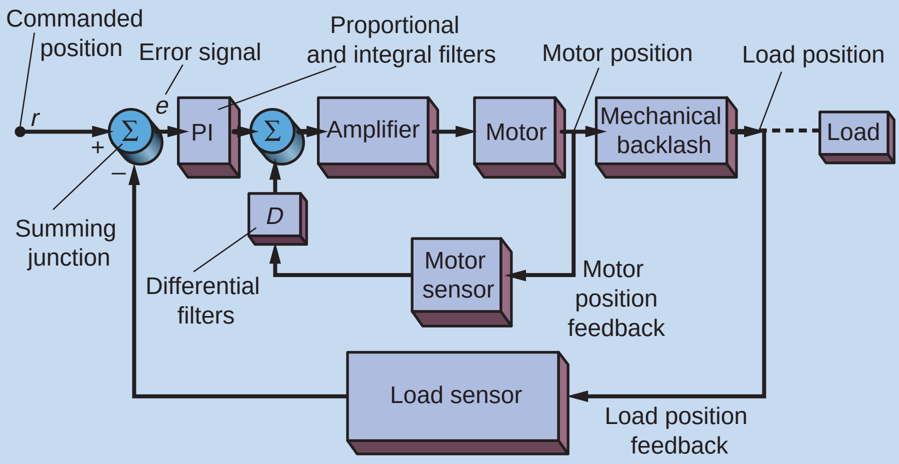
# Two feedback loops are better than one

*A new motion-control method using two feedback sensors and PID functions divided between their loops ensures superior accuracy.*

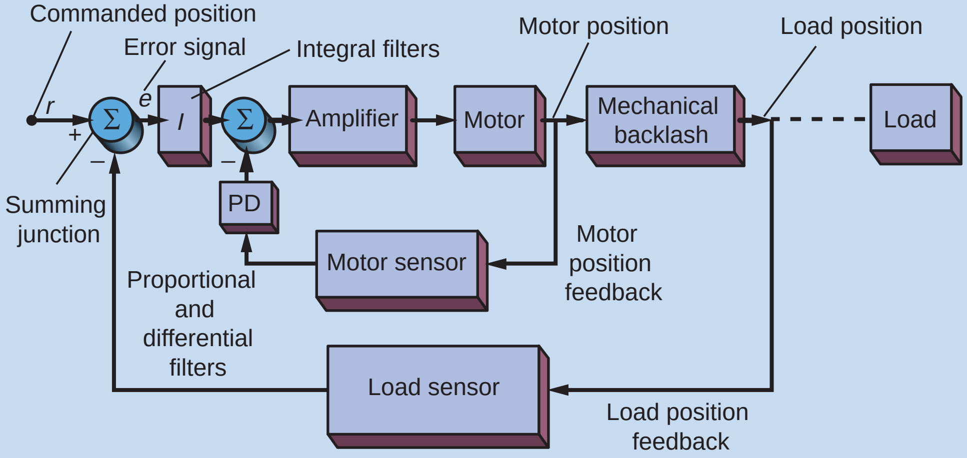
**JACOB TAL**
President
Galil Motion Control
Mountain View, Calif.

Dual-loop control systems

STANDARD DUAL-LOOP CONTROL



IMPROVED DUAL-LOOP CONTROL



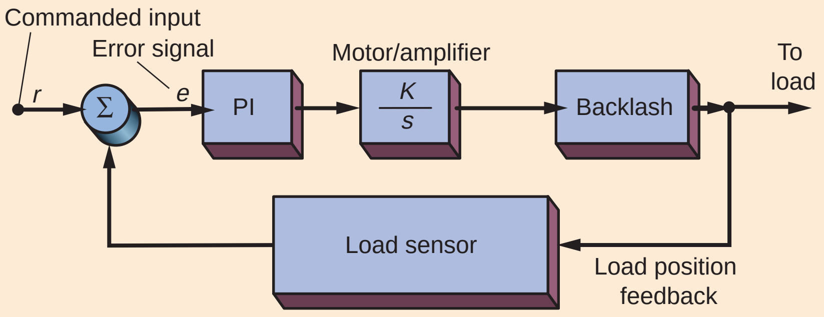
The standard dual-loop control system (top) processes the motor feedback loop through a differentiator filter (*D*) — a damping signal proportional to motor velocity — and processes the load sensor through proportional and integral filters. The improved dual loop, however, moves *P* to the inner loop and uses only *I* in the main forward loop. Moving the *P* makes the inner loop predominate and the system becomes more stable.

Couplings between motors and loads in most motion-control systems are not sufficiently rigid. When a controller commands the motor to move a load, compliance in the coupling lets the motor and load oscillate or seek slightly different positions. This action produces a small error commonly called backlash.

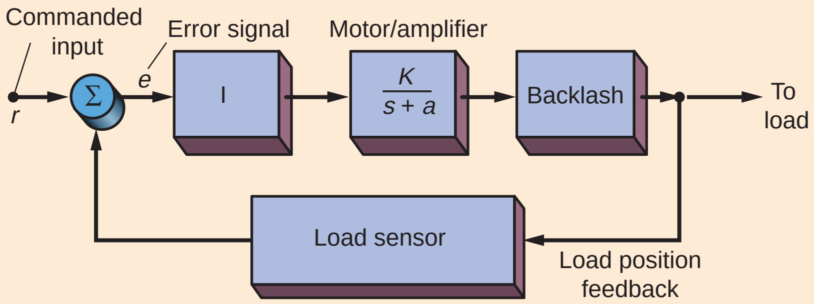
Designers faced with the problem usually install a feedback sensor on the motor or the load to let the controller compensate for such errors. Placing the feedback sensor on the motor provides stable and accurate control of motor position. Backlash, however, prevents the load from reaching the exact same position. Alternatively, placing the sensor on the load closes the loop

## Math models of dual loops

### STANDARD DUAL LOOP

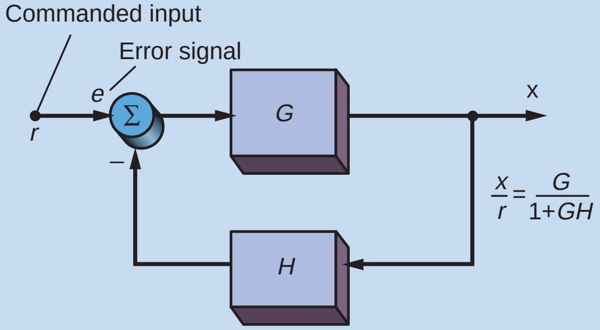


### IMPROVED DUAL-LOOP



In the standard dual-loop control, the feedback in the inner loop is *D*, a derivative function, meaning the whole inner loop behaves as an integrator, which is the reciprocal of the differentiator. In contrast, the improved dual loop includes the *PD* terms in the inner loop which implies that the inner loop acts as a low-pass filter.

## Basic feedback-control system



The transfer function, $x/r = G/(1+GH)$, for any general feedback-control system may be approximated by $x/r = G/GH = 1/H$ in the range of low frequencies where open-loop gain is high; $GH > 1$. This simplified result suggests that a closed loop acts like the reciprocal of its feedback.

around the backlash, but the dynamic behavior of backlash adds delay to the loop's response time still making the system unstable.

### THE BEST OF BOTH

The search for a feedback-control method that corrects for complete motion trajectories and does it quickly led to developing a continuous dual-loop configuration. This system employs two sensors, one on the motor and the other on the load, and a control loop for each. The outer loop closes on the load sensor while the inner loop feeds from the motor sensor. A compensation filter consisting of PID functions is divided between the two loops. The functions P and I apply to the outer loop, and D works in the inner loop.

A version of this continuous-loop method has been around for several years and has proved successful for improving system stability. To stabilize the control system, it needs a damping signal proportional to the motor velocity. But in applications where the motor velocity is derived and not measured, any load velocity out of phase with the motor comes from the load sensor. Therefore it may not effectively damp the system. On the other hand, a sensor on the motor ensures that the derived signal is the motor velocity, and therefore improves the system stability.

Though the continuous-loop method stabilizes systems with backlash, the improvement is not always sufficient. For example, systems with relatively large backlash have comparatively low gain with slow response and long settling time. A one-second response time for moving the motor to the correct position is unacceptable.

An improved method recently developed at Galil is called the general dual loop. The structure of the dual loop is preserved, but PID functions are divided differently. The I function executes in the outer loop and PD handles the inner loop and stabilizes systems with backlash more effectively.

These dual-loop systems handle two position errors, the motor position error measured by the motor

## How the loops stack up

| Parameters | Single loop | Standard dual loop | Improved dual loop |
|---|---|---|---|
| $K_D$ | 6 | 200 | 800 |
| $K_P$ | 4 | 9 | 50 |
| $K_I$ | 0 | 1 | 10 |
| Motion time (msec) | ∞ | 520 | 142 |
| Bandwidth (Hz) | 2 | 70 | 280 |

Comparisons of the three types of feedback clearly show the significant improvement in bandwidth and response time of the improved dual loop configuration.

encoder, and the load position error measured by the load encoder. Filtering can be applied to either one. Since the motor position error represents the motor state, using that error in the control algorithm improves the loop stability. When all three operations are based on the motor sensor, the motor moves to the position where the motor error is zero, but the load sees a position error from the backlash. Thus, the filters must be divided between the two errors to gain stability and accuracy.

The standard dual loop executes the D operation on the motor error and the PI operations on the load error. But the improved dual loop goes a step further. It performs both P and D operations on the motor error to improve loop stability, and applies the I to the load encoder. The integration forces the motor to move when the load accumulates a position error, thereby assuring load accuracy.

The transfer function of any closed loop such as the one shown in the figure, *Basic feedback-control system*, is

$$\frac{X}{r} = \frac{G}{1+GH}$$

In a range of low frequencies where the open-loop gain is high, the transfer function is approximately

$$\frac{X}{r} = \frac{G}{GH} = \frac{1}{H}; \; GH >> 1$$

This simplified result suggests that a closed loop acts like the reciprocal of its feedback. This principle may be applied to the two dual loops. In the standard continuous dual loop the feedback in the inner loop is a derivative function D, therefore the whole inner loop acts as an integrator, the reciprocal of the derivative. The resulting system is shown in the figure, *Standard dual-loop control*.

In the *Improved dual-loop control*, however, the feedback loop includes the PD terms which implies that the inner loop acts as a low-pass filter. The P and D terms may be programmed to select the filter frequency $a$ sufficiently high to make the inner loop act as a constant in the effective frequency range.

A test system was assembled to examine the effects of the two designs. One system was built with a backlash of 10° between the motor and the load. Three control methods were analyzed, a single loop based on a load sensor, a standard dual loop, and an improved dual loop. The test results summarized in *How the loops stack up* show the best PID parameters for each case. To compare the control methods objectively, the measured time $t$ was based on the resulting bandwidth and the time needed for the system to precisely move one motor turn.

The single loop operating a 2-Hz bandwidth would not stabilize with an integrator, therefore it never reached final position. The standard dual loop increased the PID parameter to allow a settling time of 520 msec and a bandwidth of 70 Hz. The improved dual loop permitted even higher PID parameters and a settling time of only 142 msec with a bandwidth of 280 Hz. ■

### WE WANT YOUR FEEDBACK.

| | |
|---|---|
| *Did you find this article interesting?* | ***Circle 745*** |
| *Do you want more information on this topic?* | ***Circle 746*** |

*Comment via e-mail to*
**mdeditor@penton.com**

*What related topics would you like to see covered? What additional information on this topic would you find useful?*