The Quiet Hero of Feedback Control

Dr. Murat Dogruel

Control is everywhere! In addition to and much more than the man-made designs, it occurs naturally in most of the living beings. A simple look, for example, requires a control of focus and direction. A precise control is needed for stabilizing the temperature and chemical levels in the body. A baby needs to learn how to coordinate his head, crawl and walk by mastering the control skills. Animals and even plants need control to live in a challenging environment. Control system designs are crucial in industrial production, aerospace, transport, appliances, networks, and the list goes countless.

The basic principle of control, on the other hand, can be as simple as: "*If low, increase it; if high, decrease it.*" For example, for standing still, the brain continuously senses if you are dropping to one side, and automatically controls muscles to push you to the other side to correct the standing angle. This simple princeple is extremely useful, and called *negative feedback* since just the opposite action is applied to the system input.

A unitary feedback control structure, as shown in Figure 1, is used for control designs generally. Here, the system may be any process that needs to be controlled, for example, a cruise controlled car. Although, linear approximations may be available, generally the system has nonlinear dynamics. The disturbance, which is shown as an added unknown signal into the system input, actually represents all the external and internal unwanted effects throughout the system. For example the road and tire conditions, the quality of the fuel, the weight of the car, the wind effects, and the tilt of the road are always changing and normally could not be feasible to be measured or included into the system model. These unknown effects are considered to be disturbance.

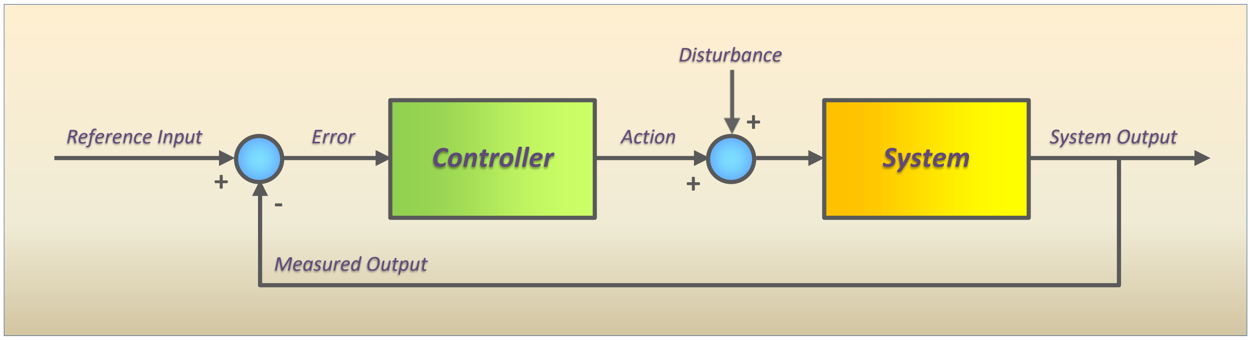

Figure 1: Unitary Feedback Control. The system input is modified by the controller such that the system output follows the reference input as close as possible. The reference is compared with the measured output and the error is supplied to the controller. The job of the controller is to decide on the correct action to be applied to the system input. Nonlinear effects and the disturbance may make this duty challenging. Simply using an integral controller can help dealing with these effects and may ensure zero steady state error.

The selected output of the system, the speed of the car in this case, is measured with a proper sensor. A desired reference input, generally a constant value, is supplied by the user. The error is the difference between the reference and the measured output. For an acceptable performance, the error needs to be kept as small as possible by the controller. To achieve and keep a small or zero error, the controller needs to continuously decide on the control action applied to the system input, the angle of the gas pedal for the car example.

Consider the situation that the controller does its job perfectly, and, the output reaches and follows the desired input without any error. In this case, the input of the controller will be zero! Actually a proper input value is needed by the system to reach and keep a desired output value for perfect tracking. The system may have nonlinear dynamics and together with the disturbance, calculating that proper input value may be complicated or impossible. The required gas pedal angle for that particular situation may nonlinearly depend on the current reference value, the tilt of the road, the wind conditions, and many other effects. At this point, how can the controller produce that mysterious proper value while its input is nothing but zero?

Normally, the response of a linear system to zero input is zero output (for zero initial conditions). Does that mean the controller may not be linear, because the controller needs to supply a proper output value although its input is zero? Furthermore, for a different reference or disturbance value, the input to the controller is still zero, although the controller output needs to be a different proper value to achieve perfect tracking. Therefore even a nonlinear system, like a fuzzy controller, will not do the job perfectly since a nonlinear function could only produce a single output value for zero input. However, the system needs different proper inputs for each of the reference and disturbance values while the input to the controller is zero for each case.

The integral control comes in to the picture at this moment. An integrator, although a linear system, can provide different constant outputs for zero inputs due to different previous conditions. Assume an integrator is employed on the controller. If the error is positive, that is the system output is below the desired reference level, the integrator integrates this positive value and automatically increases the system input by applying a negative feedback. If the error is negative, the integrator decreases the system input correspondingly. Therefore, the steady state error will be automatically reduced to the zero level in a stable system operation. The integrator will never let the error to be nonzero; it will continuously try to correct the output according to the desired reference level. By this simple way, a perfect steady state tracking could be possible. The mysterious value to be applied to the system input, for a particular constant reference and a constant disturbance, is correctly decided by the integral control. Therefore even for different road conditions, for going uphill or downhill, the integrator automatically controls the speed of the car by adjusting the gas pedal at the correct angle. It is actually as simple as "*If the system output is lower than the desired level, increase the system input; if higher, decrease it.*" This principle is simply and effectively accomplished by an integrator in a remarkable way.

Other control methods can hardly achieve the same steady state performance since a different value needs to be supplied to the system input, while the controller input is always zero in a perfect tracking. To achieve zero steady state error, an integrator is required most of the times. Actually for completely linear systems, the system type must be at least 1, that is, an integrator must be present in the feedback loop, to achieve zero steady state error.

Adding a proportional component to the controller (PI control), on the other hand, may help the system output reach to the reference level faster, however, the proportional controller is useful at the transient state only, and, at the steady state it is completely useless since for zero input, it produces zero output, and all the work for obtaining and keeping the mysterious system input is carried out by the integrator only. Adding the derivative controller, a PID is formed and further improvements in the transient response, especially minimization of the overshoot, may be possible [1]. If the system itself includes the integral action internally, like in a position control with a DC motor, a proportional and derivative control (PD) may achieve the similar steady state performance without needing an extra integrator. A faster reaching the steady state may be important for control performance and several different control strategies could be employed for this purpose, however achieving the correct desired level is the number one performance criterion for many control designs in industrial applications. One way or the other, integral control is generally needed in this sense.

Instead of perfect tracing, if a certain amount of error could be allowed in the process, a high proportional gain can also provide successful results at the steady state. In this case, the error is multiplied by a high gain to obtain the necessary input to the system. In a stable operation, the error will be the system input value divided by the high gain, which can provide a satisfactory steady state performance for some applications. However the high gain control generally leads to an unstable behavior, especially for the systems with delay, and therefore is not preferred in many applications. Another alternative is sliding mode control [2], where the advantage of a very high gain is used for small errors, however for relatively higher errors, inputs at certain levels are injected to the system. Therefore the error is forced to be around zero at the sliding mode. Chattering is a common problem for this approach especially for the systems with delays.

Undoubtedly, integral control is not perfect and has some pitfalls too. The integrator gain, which adjusts the rate of the increase, must be carefully selected not to have unstable oscillations or undesirably large overshoots. Hunting or limit cycling can occur in some nonlinear systems, especially in mechanisms with Coulomb friction. Saturations on the actuators, large disturbances, or component malfunctions may lead to the windup of the integrator [1]. However, several anti-windup techniques are available, and relatively feasible to implement using the digital technology [3], [4]. Many PID gain adjustment techniques are available for engineers in practice [5]. Other than the proportional and derivative control, some existing methods, like fuzzy control, can be used in parallel with the integral control to obtain a better transient response [6]. In a recent paper [7], PI control is used for each complex harmonic component of the error signal, and it is shown that the PI control successfully works with complex valued gains and complex valued input signals.

The very first industrial control applications used the integral action to remove the offset error of the hydraulic and pneumatic pump regulators in 1830s [8]. A governor with an integral action was patented by William Siemens in 1846 [9]. Since then, the integral control is used in almost all industrial control applications: the steering of ships [10] in 1920s, pneumatic PID controllers in 1940s, electronic circuit versions in 1950s, digital, microprocessor, or PLC versions in 1980s [5], [11]. PID is still the most popular controller, and according to estimates billions of PID controllers are installed each year, mostly in PI form [12]. PID control effectively produces satisfactory results for the users of technology. Washing machines, air conditioners, vehicles, and cellular phones serve for the human needs, and work with this simple but effective control method. The integral control, as compensating the nonlinearities and disturbances, and achieving the zero steady state error by finding the mysterious input value need to be injected to the system, is the most critical and important component of the PID controllers. Hence, the title of the hero of feedback control is mostly deserved by the integral control.

References

[1] K. J. Åström and R. M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2008.

[2] K. D. Young, V. I. Utkin, and Ü. Özgüner, “A control engineer’s guide to sliding mode control,” *IEEE Transactions on Control System Technology*, vol. 7, no. 3, pp. 328–342, 1999.

[3] C. Bohn and D. P. Atherton, “An analysis package comparing PID anti-windup strategies,” *IEEE Control Systems Magazine,* vol. 15, pp. 34-40, April 1995.

[4] A.Visioli, "Modified anti-windup scheme for PID controllers", *IEE Proceedings - Control Theory and Applications*, vol. 150, no. 1, pp. 49-54, 2003.

[5] A. O’Dwyer, *Handbook of PI and PID Controller Tuning Rules*. London:Imperial College Press, third edition, 2009.

[6] M. Onat and M. Dogruel, “Fuzzy plus integral control of the effluent turbidity in direct filtration,” *IEEE Transactions on Control Systems Technology*, vol. 12, no. 1, pp. 65-74, 2004.

[7] M. Dogruel and H. H. Çelik, “Harmonic control arrays method with a real time application to periodic position control,” *IEEE Transactions on Control Systems Technology*, vol. 19, no. 3, pp. 521-530, 2011.

[8] S. Bennett, *A History of Control Engineering 1800-1930*. Stevenage: Peter Peregrinus, 1979, reprinted 1986.

[9] S. Bennet, “A Brief History of Automatic Control,” *IEEE Control Systems Magazine*, vol. 16, pp. 17-25, June 1996.

[10] N. Minorski, “Directional stability of automatically steered bodies,” *Journal of the American Society for Naval Engineers*, vol. 34, no. 2, pp. 280–309, 1922.

[11] C. Bissell, “A history of automatic control,” in *Springer Handbook of Automation,* S.Y. Nof, Ed. Heidelberg, Germany: Springer Verlag, 2009, pp. 53–69.

[12] K.J. Åström and T. Hägglund, “Auto-tuners for PID controllers,” in *The Impact of Control Technology* [Online], T. Samad and A.M. Annaswamy Eds. 2011. Available at http://www.ieeecss.org.