Electronic Analog Computing for Feedback Control

YongSik Jeon
yjeon@indiana.edu

Samuel Chun
sachun@indiana.edu

Computer Science Department
Indiana University
Bloomington, IN 47405

Prof. Jonathan W. Mills
CSCI B644 VLSI Fall 2003

Abstract

This paper describes one of the uses of analog computing in feedback control systems. Examples of feedback control systems are discussed, and it shows how the feedback control system improves with different methods for controlling the input from the output signal, and also shows the advantage of using analog computing for feedback control systems over digital computing and an example of an Extended Analog Computer (EAC) for an analog feedback control system with its benefits.

1. Introduction

In recent years, many areas have switched from analog to digital. As we can see, cell phones, music CDs, DVD movies, cable TVs, etc. Computing areas is not an exception thanks to the cheap digital processors, but there are some areas where analog computing is continually being used. One of those areas is feedback control.

Feedback control is the mechanism to maintain an equilibrium state. Without this there could be no manufacturing, no vehicle, no computers, and no regulated environment. With the help of digital computers, feedback control systems have been rapidly developing since the 1980s and became more applicable in diverse situations.

One example of analog feedback control system is found in our body. Actually, our bodies have numerous feedback controls. But one of the most obvious one would be the temperature regulator. When we get hot we sweat so the body cools down and when we get cold we shiver and burn stored energy so the body heats up. Even a small temperature change in our body can be fatal. So, it is very important that this feedback control system works properly.

Another example of a simple analog feedback control system is found in our bathroom. Whenever we use the toilet we flush. The flushing mechanism is a feedback control system. When we flush the feedback control opens the water valve to fill up the tank for the next flush and when the water fills up it will shut the valve off. This feedback control system was first invented in B.C. 270 by the Greeks. Their motivation was to measure time. They had water tanks with water flowing out of them. And they needed to keep a constant depth in the water tanks to make the water flow constantly.

In this paper, we are not interested in biological feedback control, nor are we interested in feedback controls that does not use electricity such as the one in the toilet. We are only interested in feedback controls that use electronic circuit based analog computing to decide the input from the output. These systems can be found in automotives, satellites, air planes, air conditioners, etc.

Why is analog computing more preferred for feedback control system than digital computing in some areas and what are the benefits of using an Extended Analog Computer (EAC) for the feedback control system? The following sections will explain how analog feedback control works and why analog computing would continue to be preferred in some areas of the feedback control systems, and the benefits of EAC feedback control system with an applicable example.

2. Actual Fields

Building Automation System

Most modern buildings use a centralized control system. It controls temperature and humidity, lights, elevators, fire sprinkler, etc.

Suspension controller for Automobiles

Automobile suspension is a shock absorber that links the car body to the axle. It dampens the jarring sustained in a moving automobile. Active suspension has a controller with a spring and a damper, which is included in a passive suspension, to control absorbance for a smoother ride.

Object tracing control for radar system

Aircraft during the 1950s and early 1960s carried analog computers as part of their radar equipment. These were used to provide targeting information for guns and missiles. The Heads Up Display (HUD) that projected information onto a piece of glass in front of the pilot relied upon computer input to help the pilot aim his guns or select his weapons.

Flight control for airplane

Flight control system for airplanes controls the attitude and the speed of the plane. The General Dynamics (now Lockheed-Martin) F-16, which entered service in the late 1970s and has been built in large numbers, was the first operational jet fighter to use an analog flight control system. The pilot steers the rudder pedals and joystick, but these are not directly connected to the control surfaces such as the rudder and ailerons. Instead, they are connected to a "fly-bywire" flight control system. Three computers on the aircraft constantly adjust the flight controls to maintain the aircraft in flight and reply to the commands from the pilot.

Flight control for satellite

The Apollo Lunar Module also used an analog computer flight control system and other U.S. spacecraft such as Mercury, Gemini, and Apollo all had computer flight control systems.

3. Feedback Control Systems

Control systems are designed so that certain designed signals, such as tracking errors and actuator inputs, do not exceed pre-specified levels. Feedback is widely used in automatic control systems. Basic diagram of a feedback control system is shown in figure 1.

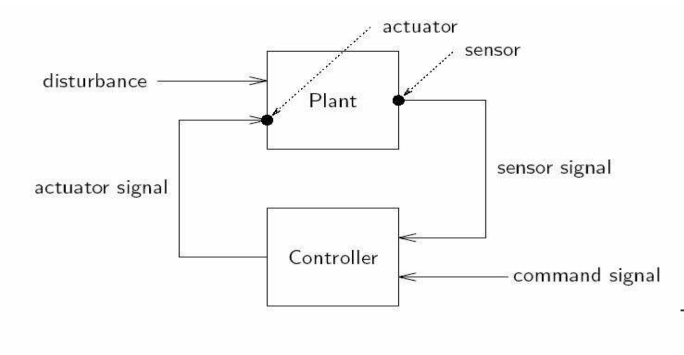


Figure 1. Diagram of feedback control system

The system to be controlled is the plant. (e.g. CD player, disk drive mechanics, aircraft, missile, car suspension, engine, industrial process, elevator)

A sensor measures the quantity to be controlled. (e.g. radar altimeter, GPS, strain gauge, accelerometer, tachometer, microphone, pressure and temperature transducers, chemical sensors)
An actuator affects the plant. (e.g. hydraulic, pneumatic, electric motors, pumps, heaters, aircraft control)

A controller or control processor processes the sensor signal to drive the actuator. There are analog and digital controllers. (e.g. human operator, mechanical controller, electro-mechanical controller, analog electrical controller, digital processor)

Disturbance is a signal from external of the plant that occurs unpredictably and disturbs the plant from reaching the pre-specified level. (e.g. wind gusts, earthquakes, external shaking and vibration, road surface variations)

The control law or control algorithm is the algorithm used by the control processor to derive the actuator signal.

4. Feedback Control

Common setup for feedback control system is shown in figure 2.

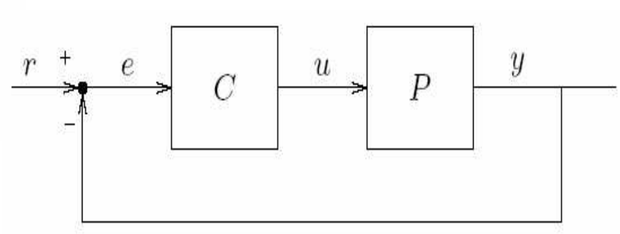


Figure 2. Feedback control

P is the plant.
C is the controller.
u is the plant input (actuator signal).
y is the plant output (sensor signal).

r is the reference or command input (what we'd like y to be).
e = r - y is the (tracking) error and can also be other signals e.g., disturbances and noises.

The goal of the feedback control is to make y ≈ r, i.e., e small (despite variations in P, disturbances).

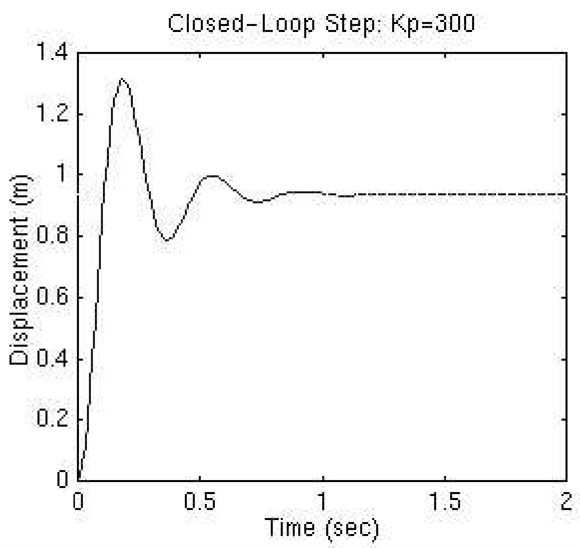
Proportional (P) controller

The equation of the P controller in time domain:

$$u(t) = K_p e(t)$$

K_p : proportional gain

Proportional control is the most basic control that is always used in the controllers. This is easy to develop, but cannot remove steady-state error.



Graph 1. Response characteristic of a P controller

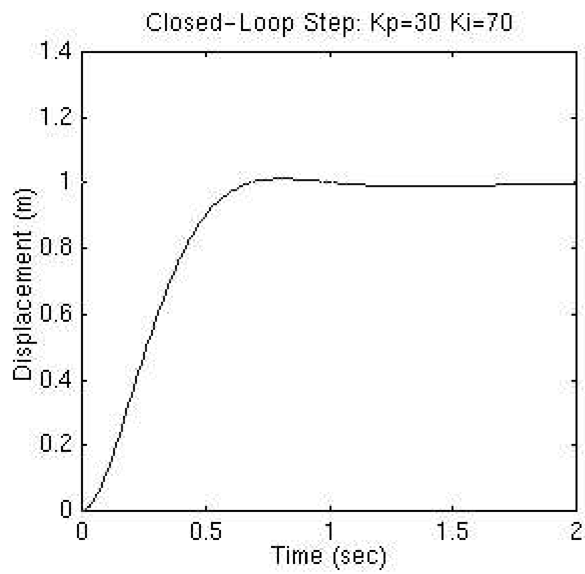
Proportional-Integral (PI) controller

The equation of the PI controller in time domain:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau$$

K_i : integral gain

Proportional-Integral controller is used to eliminate steady-state error, but if integral gain is mistuned, the system can become unstable and the response time can be slower.



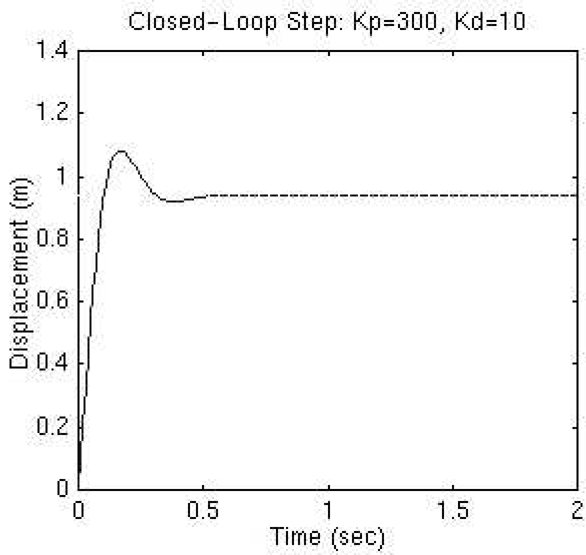
Graph 2. Response characteristic of a PI controller

Proportional-Derivative (PD) controller

The equation of the PD controller in time domain:

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t)$$

K_d : derivative gain
PD control increases the stability of the system and makes the response time faster, but with the presence of noise in the system, it can increase the differential portion of the equation resulting in negative effect for the input.



Graph 3. Response characteristic of a PD controller

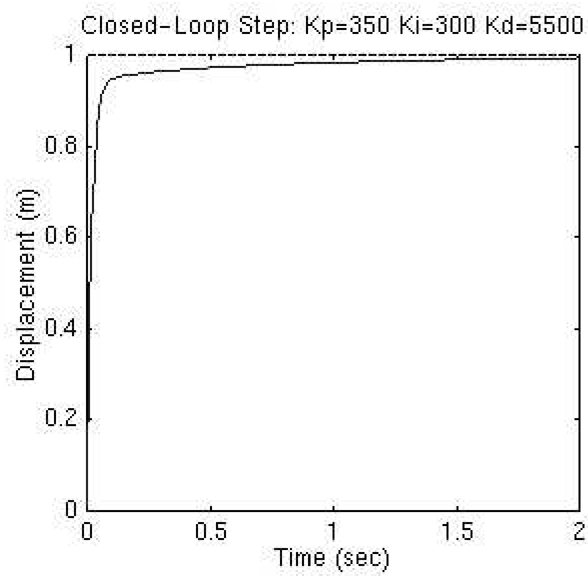
PID (Proportional-Integral-Derivative)

The equation of the PID controller in time domain:

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int_0^t e(\tau) d\tau$$

More than 80% of the feedback controllers are PID controllers in the actual fields, because its performance is good and it is easy to tune.

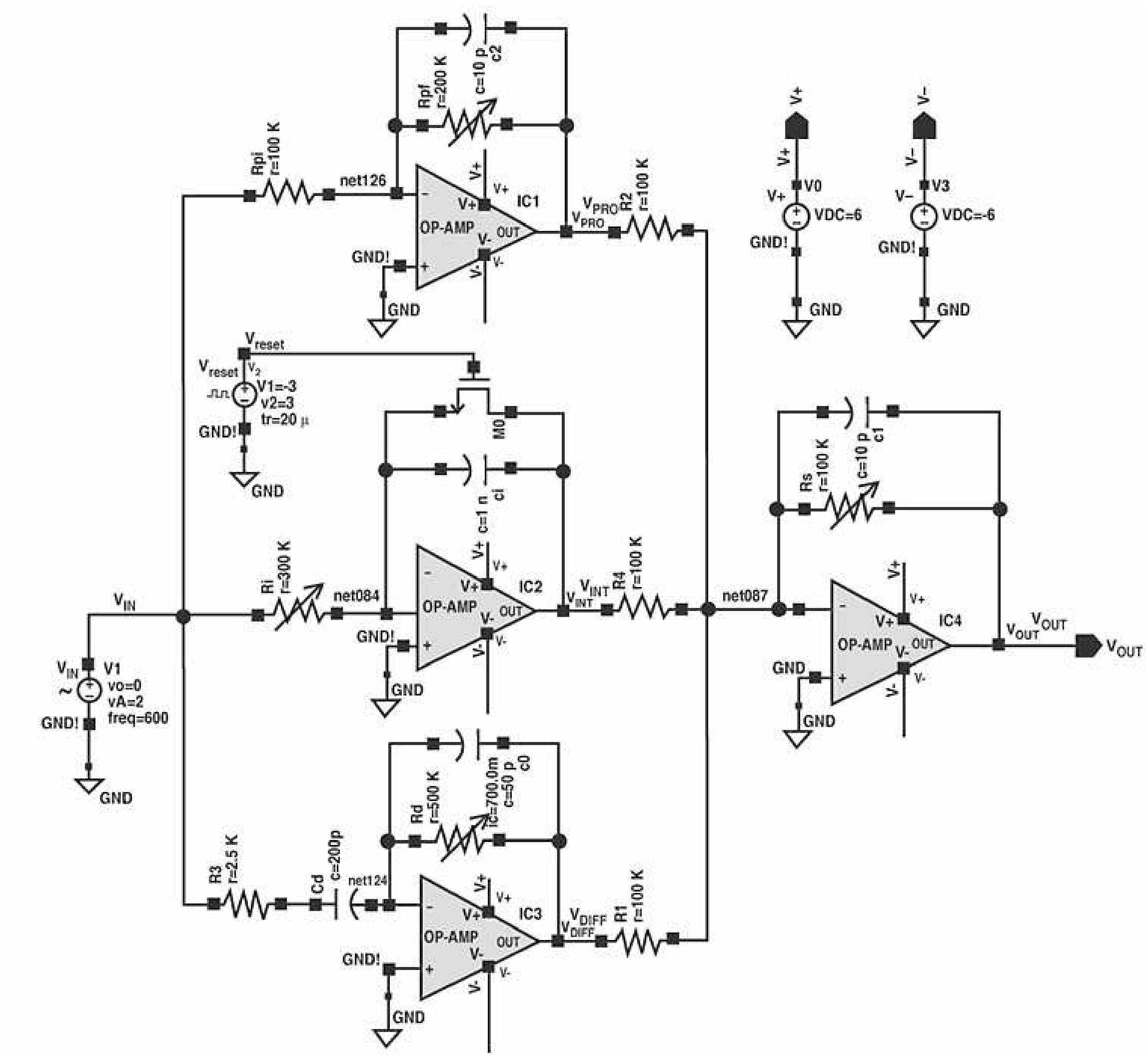
Actual control of the PID controller is the combination of P, I and D controls.



Graph 4. Response characteristic of a PID controller

Analog controllers

Generally a control task is performed by specifically combined ICs. Simple controls can be carried out using analog ICs, such as operational amplifier circuitry. An integrated circuit (IC) is the basic component of "Control Electronics". IC is a small electronic device made out of a semiconductor material.



$$V_{OUT}(t) = \frac{R_{PF}}{R_{PI}} V_{IN}(t) + \frac{1}{R_I C_I} \int V_{IN}(t)dt + R_D C_D \frac{d}{dt} V_{IN}(t) \quad (1)$$

Figure 3. An example of an analog circuit for PID control. This analog circuit calculates PID control response according to Equation 1. Sensor signal V_{IN} is amplified by IC1 (P mode), integrated by IC2 (I mode), and differentiated by IC3 (D mode), and all three modes are summed by IC4 to derive control response $V_{OUT.}$

5. Extended Analog Computer (EAC) Feedback System

EAC is a very powerful machine, and at the same time it is very simple. It is easily programmable, unlike General Purpose Analog Computers (GPAC), by manipulating the Lukasiewicz logic arrays (LLA). Not like GPACs, an EAC is a Turing-complete model, and this simple and powerful machine can be used to directly solve problems like Partial Differential Equations in systems and many more.

EAC implementation

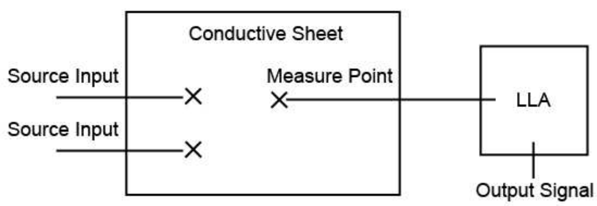


Figure 4. Basic diagram of an EAC

Extended analog computers can be implemented on a conductive sheet with number of Lukasiewicz logic arrays (LLA). One or more sources or sinks are place on the conductive sheet, then current flows through the conductive sheet making a gradient pattern. The current is measured from a chosen measure point or points. Then the measured current is fed into the LLAs, which outputs an analog signal according to the LLA function.

LLAs are somewhat similar to the digital logic gates, but there is only one input. It also uses analog signal for its input and output. There are mainly 27 LLA functions. With these LLA functions and the conductive sheet, logic gates can be created.

This is the mathematical model of the extended analog computer (this model has no boundary conditions):

$$V_p = \sum_{\text{sources}} \frac{I_i}{d_i^2} - \sum_{\text{sinks}} \frac{I_j}{d_j^2}$$

Voltage at any point p is the sum of all source (I_i) voltages divided by the distances to the point minus the sum of all sink (I_j) voltages divided by the distances to the point. Until recently, people believed EACs were not possible to implement.

EAC feedback control system

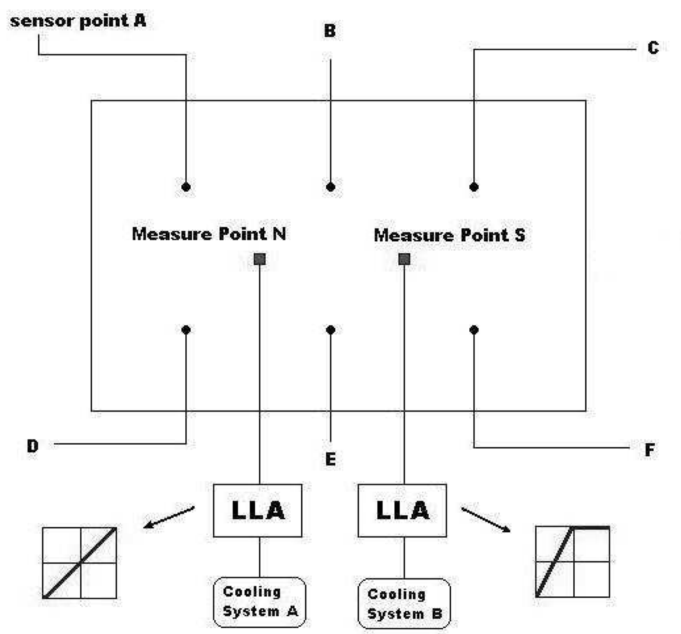


Figure 5. Example of an EAC feedback control system for a temperature control

Figure 5 is diagram of an EAC feedback control system for a cooling system, which can be for a building temperature controller.

There are total of 6 sensor inputs, which are from different parts of the floor, to the conductive sheet. The voltage of the current from each sensor will reflect the temperature of that region. This will create a gradient manifold of temperature of the room.

There are two cooling system connected to this EAC by two LLA functions. The current from the measure points are fed into each LLAs. LLAs will decide according to its function to turn the cooler on or not.

LLA functions are depicted in Figure 5 in a square box. The x-axis represents the input voltage and the y-axis represents the output voltage. The LLA function for measure point (S) is designed to be more sensitive to temperature change. This can be useful if that region is near the window or it is facing south. This region will get heated faster than other regions of the room due to insulation or the sun.

As shown in this example, EAC can be easily used to build a fuzzy cooling system, which not only saves power but is efficient and in-expensive.

6. Conclusion

Many feedback control systems have switched from analog to digital, because of the power of digital computers. There are some advantages and disadvantages of using an analog feedback control system. The first advantage is that analog systems are simple. It also means they are cheap and easy to build. Digital system needs A/D converters, D/A converters, and digital signal processors which cost additionally. Even though, the price of digital chips have gone down it is still more expensive. Second, it consumes less energy. Many feedback control systems are found in small items, such as a MP3 player or a micro robot. For these kinds of items, power consumption is a very important issue. Analog feedback control system uses less power than digital feedback control system. Third, analog system performs better in speed than digital system. Up to a certain precision, they can outperform the digital system.

There are couple disadvantages of using an analog feedback control system as well. First, it lacks precision. Analog feedback control system will outperform the digital system, but if the system requires higher precision, a digital system will be a better solution. Second, there is a limitation to apply complicated non-linear equations into the systems. Third, it cannot control a sophisticated system. It is more efficient to use a digital system for a sophisticated system such as an electronically controlled engine that has many sensors and controllers.

We will see many more products with feedback control which is a kind of artificial intelligence. For example, a chair that adjusts according to the physical properties of the individual by itself. As described in the paper, many areas have been digitalized including the feedback control systems, but because of the advantages of the analog feedback control system, it will continue to be used, and with EAC feedback control system, simpler and better A.I. system, like a fuzzy logic, would be possible.

References

[1] Carnegie Mellon – PID Tutorial: http://www.engin.umich.edu/group/ctm/PID/PID.html

[2] Brion Christine, DongInn Kim. *Simulating the Recticular Formation via Extended Analog Computer*. Computer Science Department, Indiana University.

[3] C. A. Desoer, M. Vidyasagar. *Feedback Systems: Input-Output Properties*. Academic Press, New York, 1975.

[4] R. C. Dorf. *Modern Control Systems*. Addison-Wesley, 1998.

[5] G. F. Franklin, J. D. Powel. *Feedback Control of Dynamic Systems*. Addison-Wesley Publishing Co. 1986.

[6] B. Friedland. *Control System Design: An Introduction to State-Space Methods*. McGraw-Hill, 1986.

[7] W. H. Gwon, O. G. Gwon, G. S. Hong, J. H. Lee. *Control System Engineering*. Chungmoongak, 1999.

[8] I. M. Horowitz. *Synthesis of Feedback Systems*. Academic Press, New York, 1963.

[9] Hugh Jack. *Dynamic System Modeling and Control*. 2003.

[10] F. L. Lewis. *Applied Optimal Control and Estimation*. Prentice-Hall, 1992.

[11] A. I. Mees. *Dynamics of Feedback Systems*. Wiley, New York, 1981.

[12] Patricia Mellodge. *Feedback Control for a Path Following Robotic Car*. Electrical Engineering, Virginia Polytechnic and State University, 2002.

[13] Jonathan W. Mills. *Polymer Processors.* Computer Science Department, Indiana University.

[14] Jonathan W. Mills. *Programmable VLSI Extended Analog Computer for Cyclotron Beam Control.* Computer Science Department, Indiana University.

[15] Heather Roinestad, Camilo H. Viecco, Ian Bobbitt, Adam Miller, Stefan Obereichholz-Bangert, Ryan R. Varic. *Study of a Model of an Extended Analog Computer*. Computer Science Department, Indiana University.