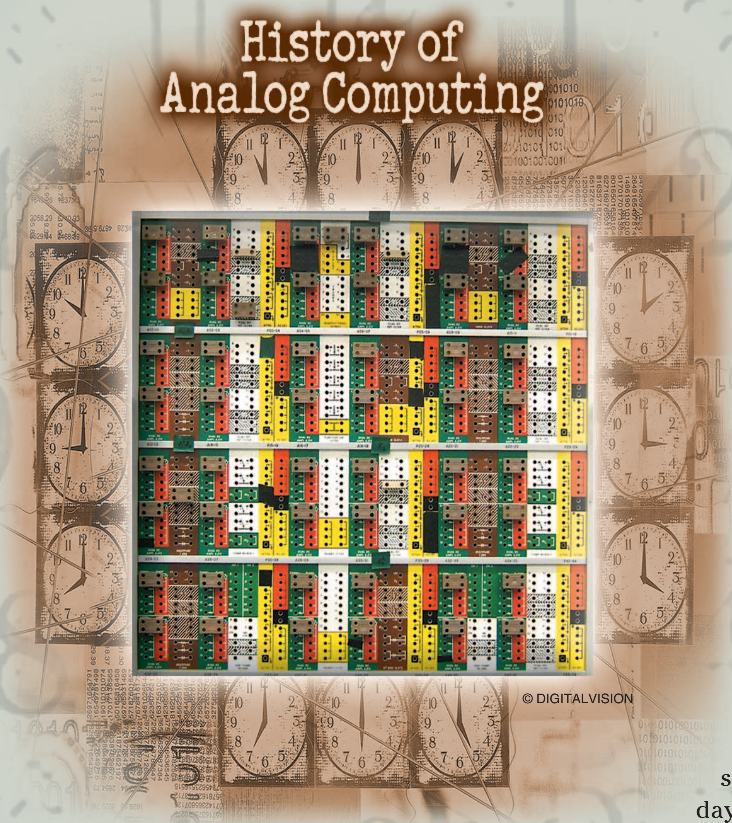
FEATURE

The Comdyna GP-6 Analog Computer

Alive but not exactly kicking

By Ray Spiess



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General-purpose consoles filled whole rooms and ran simulations that laid the foundation of our space program. These machines have disappeared except as science-fiction movie-set props. Keep a watchful eye when you're viewing *Star Trek* or similar show reruns, and you may recognize a Comcor, Reeves, or Beckman with added banks of flashing lights for communicating with aliens.

Fate has been kinder to the small analog computer. At least to our GP-6. The Comdyna GP-6 continues its timeless, engineering/educational role, primarily in the controls laboratory.

How Comdyna Started

It was spring of 1968. Chuck McVey had just fired me. Three years earlier, I helped him found Simulators, Inc. The venture was going nowhere, spending gobs of money, and we weren't getting along. Out of work, I had two choices: I could either start my own company like everyone else in those days, or I could seek employment. In the spirit of the times, I fabricated a sheet-metal model, named it the GP-6, snapped a couple of pictures, placed an ad in *Engineering Education,* and waited to see what would happen. If the ad produced some orders, I'd go into business. If not, I'd start interviewing.

Thirteen orders came in.

The GP-6 shipped that October wasn't exactly the GP-6 of today, but close, both conceptually and operationally. All the changes in all the years since, except for a subsequent digital microcomputer interface, have been internal. Originally crammed full of parts, the chassis evolved to become virtually empty.

What is remarkable, at least to my thinking, is that the GP-6, for its 36 years of production, essentially looks, operates, and performs the same as the GP-6 advertised by that sheet-metal

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mock-up. (See Figure 1.) It would seem that 36 years of production, of teaching the same concepts, should set some kind of record.

The GP-6 keeps going without change because the analog computer's application fundamentals, physical-system simulation, and linear circuitry have not and will not change. Students of today learn these fundamentals from patching simulations on the GP-6 exactly as the students of 36 (and more) years ago.

The analog computer retains its advocates because certain educators recognize that there's a limit to the use of shortcuts and clever devices in teaching the basics of a subject.

There was a time when the analog computer's future was supposed to lie in electronic patching. "Eliminate the patch panel," was the cry. So we did. Back in the 1980s, Comdyna designed Micropatch to be programmed by one of the new microcomputers. It worked pretty well. Didn't cost all that much. No one wanted it.

It turned out that the patch panel, much maligned over the years, has been the analog computer's strength, its source of durability.

So where's the progress? Progress has come from and can continue to come from students learning math modeling and simulation, inductive/deductive analysis, and the application of linear circuits . . . from the ground up.

In the Controls Laboratory

"What's that?" a student asks, showing up for the first controls lab and seeing the GP-6 and oscilloscope sitting on the bench. (See Figure 2.) "Didn't those things go out with the dinosaurs?" The assignment: the forever-first design of a servo-motor control of an inertial load. As it has been, from even before my day, a control design is proposed; its math model derived; parameters estimated, measured, or taken from manufacturer's data; and the mathematics *solved* to determine the best controller settings. Working with the analog computer, the math model is transformed into a program schematic. Parameters (that is, the system constants) are gathered from known data or estimates; dependent variables are amplitude scaled; the independent variable, time, is scaled; the program is patched; parameters are entered as potentiometer settings; and the program is run as the model's electronic analog, tested as if it were the real hardware. Where available, the real hardware, the servo-motor and load, replaces the patch-panel counterpart and is controlled by the patch-panel controller. When the experiment extends into digital control, analog/digital converters and a digital computer program replace the patch-panel controller, and the analog computer's job is done.

By conducting the design in such phases, the student compares step-by-step the theoretical model with its electrical analog and the electrical analog with the real system. He or she evaluates the simulation and hardware with identical test methods/instruments and in so doing compares the design, operation, and performance of digital and analog control.

Here, please allow me to brag about what students gain from the analog computer. First, classical control theory assumes continuous variables, so it makes sense for the first design to be a continuous controller. The analog computer enables the system to be controlled and the controller design to be electrically simulated.

How else would you build a real-system simulator? And, what better way to quickly understand system subtleties than to experiment with a real-system simulation of the system's mathematical model? Right away, it becomes apparent that physical laws and their math expressions are one

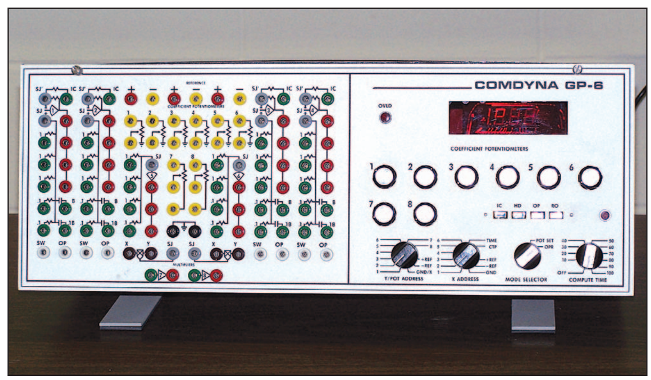


Figure 1. *The front panel of the Comdyna GP-6. Even after 36 years of production, the GP-6 essentially looks, operates, and performs the same as the GP-6 first advertised in 1968. (Photo courtesy of Daniel Block).*

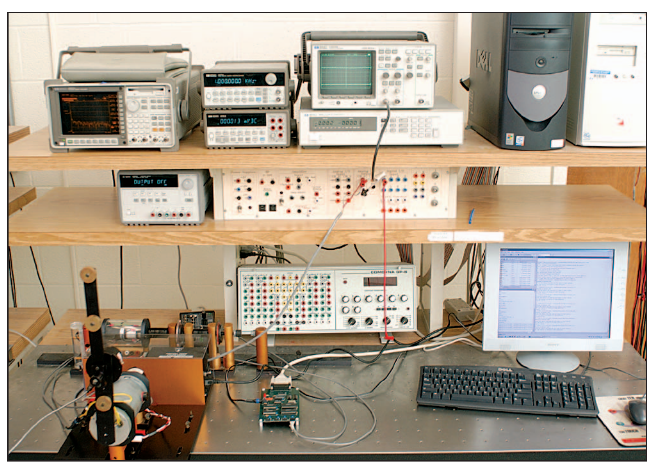


Figure 2. *The GP-6 (bottom, center) as used in the College of Engineering Control Systems Laboratory (COECSL) at the University of Illinois [1]. Each workbench contains a PC workstation, an analog computer, an oscilloscope, and a function generator. Control is implemented using the analog computer or through MATLAB using the workstation.*

and the same. (Obvious in definition but not necessarily in perception, especially for the young student.) It's been, over the years, one of those experiences where light bulbs turn on. *I get it!* The common denominator: mathematics, that is, physical laws expressed as mathematical functions.

Indulge me also to put in a plug for one of the analog computer's often forgotten virtues. The rigors of programming (system simplification, amplitude scaling, and time scaling), so maligned during the analog computer's golden era, were frequently instrumental in solving problems, even before the simulation was run. Shortcuts offered with digital languages haven't always been to the problem solver's advantage. Bypassing simplification, amplitude scaling, and time scaling encouraged confused, unwieldy simulations where the problem-solving suffered essentially by not seeing the forest for the trees. Those who have struggled with analog computer programs know inherently the importance of dynamic range, the benefits of working with properly scaled variables, and the weighing of internal loop frequencies to judge when variables can be disregarded because of response time differences. Engineers who haven't struggled have had to learn such concepts another way.

Not to be overlooked, while students wrestle with analog computer programming and patching, they are learning the fundamentals of linear circuits. There's no avoiding it. Programming the analog computer requires an understanding of operational amplifiers; the not-so-obvious qualities of high gain, negative feedback, high input, and low output impedance in applying Kirchhoff's Laws; the converting of operational amplifiers into summers and integrators, multipliers/dividers; and many other elements of program schematics. What better way to learn about linear circuits than to be forced to create one?

Way back, in ancient history, when I was an Electronic Associates Inc. (EAI) sales engineer, prospective customers would take a doubtful look at the TR-48 or one of the other EAI models and ask how long it would take to learn how to program one of those things. The answer: "Hours when a problem is to be solved. Days or even weeks without one."

Linear circuits owe their development to the analog computer. A most difficult, unstable device, the operational amplifier was perfected in the due course of analog computer research, development, and design. Designers also had to come up with schemes for analog voltage multiplication, division, polar/Cartesian resolution, logarithm and arbitrary function generation, and other inventive simulation tools. And, the schemes had to work. Our space programs, Mercury and Apollo, depended on it. The analog computer at the time was the only means for solving the complex, nonlinear simulations critical to the space program's success.

Motivation? Consider the operational amplifier that today can be bought for pennies costing a US$1,000, US$1,200, or US$1,500 apiece, a system of them going for a US$1 million and more. It was the major players, EAI, Applied Dynamics, Boeing, Reeves, and others chasing big bucks that laid the foundation, first in vacuum tubes, then transistors, that evolved into the linear, integrated circuits of today.

The analog computer dead? No way. Every linear circuit is an analog computer.

Why Are They Still Around?

There's no denying the attrition of analog computers in the engineering labs. I can offer no argument to counter the contention that analog computers have limited use, are clumsy apparatus that take up valuable bench space, and are often taught by laboratory assistants who have never seen one before. It's a wonder that any are around, that certain faculty stick with the old analog computer no matter how persuasive the reasons not to. Why? I asked.

The following are brief, first-hand answers from faculty who were kind enough to respond. The first is from Umit Ozguner, Electrical Engineering, Ohio State University. Prof. Ozguner's controls laboratory has been and continues to be distinguished by highly imaginative and creative projects. Umit Ozguner writes:

> Hi Ray,
>
> It was nice to hear from you. I was going to respond immediately but wanted to see if my students could use the GP-6 for a new application that I had. That worked out fine, and now I can indeed report we have a recent application.
>
> For a number of years, I have been involved in developing autonomous vehicles (mostly self-driving cars), and we now have in our hands a large truck to automate. We intend to use a fairly sophisticated real-time software operating system with digital feedback control, and I wanted to try out the software in the lab before deploying it on a huge, heavy vehicle.
>
> So we have now simulated the longitudinal dynamics of the truck (not very complex) on the GP-6 with the A/D and D/A to be used on the truck and the real-time computer control to be implemented. The students who were scared about analog computing first seemed happy enough and want to try lateral control (more complex) now.
>
> Best wishes,
> Umit

Thanks, Umit.

The University of Wisconsin has been using analog computers at their Madison, Milwaukee, and Platteville campuses. Prof. Dan Cobb, who has taught at both Milwaukee and Madison, writes:

> I have been using the GP-6 analog computer in my instructional lab on automatic control at the University

of Wisconsin since I created the course in 1996. Although I do not use all of the analog simulation features, I have found the amplifier patch bay to be indispensable for quickly assembling circuits. With half of my course devoted to analog control, students are frequently required to build analog compensators to drive electromechanical hardware. As long as analog methods continue to be used in control and signal processing, systems like the GP-6 will be advantageous for instruction and prototyping.

Students find the GP-6 far more convenient to work with than breadboarding techniques. The patch bay offers banana plug connections, potentiometers with a digital readout, a built-in voltmeter, power-supply voltages, an overload indicator, and short-circuit protection. Its size also adds to its functionality. Furthermore, the units are virtually impervious to abuse. With the GP-6, students only have to worry about broken wires. Two of our units were purchased more than 20 years ago and are still fully operational, so I expect that the GP-6 will outlive most of the other equipment in the lab.

You can visit Prof. Cobb's lab at his Web site [2].

Prof. Peter Meckl, Mechanical Engineering, Purdue University:

Ray,

Yes, we still use them, primarily to illustrate continuous domain controller design. We want students to make a connection between controllers (PID and lead/lag) and op-amp circuits, which analog computers illustrate very nicely. We have the students develop simple controllers for a servo table (motor and amplifier with position feedback) using the GP-6. At the end of the course, we use Quanser equipment, which has the WinCon interface with MATLAB Simulink so we can do a purely digital controller. But we haven't yet given up on the analog computer, since it's the best way to implement a continuous controller.

Dr. Robert Paz, Klipsch School of ECE, New Mexico State University:

Ray,

The analog computer continues to be a valuable teaching tool for students studying linear systems. It provides a simple way to realize analog transfer functions. Even in our modern "almost-all-digital" world, there are settings in which true analog devices are necessary.

One of the applications I like to teach students about in my course "Computer Control Systems" is the tracking of various signals. It turns out that for tracking almost anything but a constant input, it is impossible to get a true "ripple-free" response using a digital controller alone. For example, if a motor is to track a sinusoid, the input to the motor must be a pure sinusoid in order for the output to be a pure sinusoid. A digital controller alone will generally give intersample "ripple" because the output of a zero-order hold (D/A converter) cannot faithfully represent a true sinusoid. However, using a continuous-time (analog) model of the reference signal in conjunction with the digital controller can achieve a smooth, ripple-free result. The analog computer is thus the perfect companion to the digital computer for such a setting.

Prof. Ian Petersen, School of Electrical Engineering, University of New South Wales at the Australian Defence Force Academy:

Dear Ray,

As you know, I have for quite a few years used the GP-6 analog computer in the control systems laboratory in the School of Electrical Engineering at the Australian Defence Force Academy. The primary users of the laboratory are undergraduate students who are training to be officers in the Australian Defence Forces (Army, Navy, and Airforce).

When I first arrived at the school in 1985, the control systems laboratory had a small amount of equipment including two old EAI analog computers and some "feedback" servo systems. The available equipment was inadequate for the increasing numbers of students in the control course. The GP-6 combined with the Comdyna servo system was chosen as a suitable platform for building a practical control laboratory. Over the years, the laboratory built up to five workstations. Initially, data capture, printing, and digital control were done using the board and software available with the GP-6, but later we switched to dSPACE hardware and software.

The GP-6 provided a valuable tool for modeling physical systems and implementing analog controllers. In my opinion, the GP-6 provided students with a valuable educational experience in connecting the theory in lectures with physical hardware.

Prof. Petersen has placed a complete, first control design manual on his Web site and it can be downloaded in Acrobat format [3].

Prof. Dan Block, University of Illinois, writes:

Ray

We have four laboratory assignments that use the Comdyna analog computers. All these labs are part

of control systems theory courses we teach here at the University of Illinois.

1) One lab introduces the students to analog computers demonstrating the summer, differentiator, and integrator. These students know very little about op amps so this is their first introduction to them.
2) Then we have three sets of labs that use the analog computer to control the position of a dc motor with dc tachometer feedback for speed and a pot for angular position. The students implement a PD controller with tachometer feedback for D, a PD controller with differentiation of the pot as D, and finally a lab that implements a lead controller design.
3) We also use the analog computer to perform a PI speed controller for the same dc motor with tach feedback.

I have no plans of removing the analog computers from my 18 benches here in the Control Systems Lab. The only lab that I see being removed in the near future is the lead controller design. The wiring for that controller can be very confusing for a first time analog computer user. We did use them more in the past and have moved many of the controller implementations to Simulink auto code generation implementations. But we plan on keeping at least one lab for a class using the analog computers. I feel it is very important to show students that these controllers can also be implemented with analog circuitry.

We also use the analog computers for simple summing circuits to combine signals for digital filtering labs.

Dan

Prof. Julio C. Mandojana, Electrical Engineering, Mankato State University:

I have used analog computers (Comdyna) as part of a junior-level laboratory for at least ten years. Our department runs two programs in parallel, one for electrical engineering and one for electronic engineering technology. Students in both programs are required to take a class on control systems. Engineering students take the control class in their junior year, while the technology students take an equivalent class in their senior year.

In both classes, the experiments are:

1) simulation of a positioning system; we have the actual plant. The results of the analog simulation are then compared to a digital simulation using Scilab or MATLAB
2) repeat the previous experiment adding velocity feedback.
3) simulation of the open-loop plant to be controlled digitally from a PC.

We purchased the computers sometime in 1990–1991, and their operation has been flawless since then, except for the occasional cleaning of a potentiometer. The analog computer has been a great tool for us for two reasons: it provides a quick way of implementing a control algorithm and it gives the student a "picture" of the solution to a differential equation. It is difficult to overemphasize the insight into a control problem given by an analog simulation. The students do get a better understanding of dynamic problems when they see how solutions change under the variation of coefficients.

Prof. YangQuan Chen, Electrical and Computer Engineering, Utah State University:

Dear Ray

The GP-6 is an asset for control and mechatronics education. We have three GP-6s actively being used in ECE5320 Mechatronics. The GP-6 has been used as a plant emulator for rapid real-time control system prototyping labs. The role of "analog computing" of the GP-6 should now be shifted to applications such as acting as a flexible bread board, a plant emulator, an analog signal conditioning unit, and analog controller implementation among many other possibilities.

From my observation, GP-6 can stay alive forever in control education.

Prof. Rachid Manseur, Electrical and Computer Engineering, University of West Florida:

Ray,

An important practical step in the design and development of a control system, after digital computer simulations, is laboratory test-bench verification and testing. Analog computers are used in our linear controls lab to teach undergraduate students about analog simulation of systems described by differential equations. Our first two laboratory experiments are about the analog simulation of first- and second order differential equations.

And Why They're Not

Locating schools that discontinued the use of their analog computers was more difficult in that the individuals responsible for the analog computers were invariably no longer with the institutions. One exception, the U.S. Naval Academy, was once a leading proponent of analog computers. Prof. Robert DeMoyer writes:

Ray,

We discontinued the use of general-purpose analog computers about ten years ago. The digital

> simulation package Vissim initially became the simulator of choice, and then Simulink. The reasons for the change were what you might expect. The change was made because digital simulators are faster to program and easier to use, more accurate, more capable, and require virtually no maintenance. Furthermore, we felt that we should provide the students with experience using a simulator that they are likely to encounter in engineering practice. What has been lost is a tool to teach troubleshooting. This loss is by far overshadowed by the gains previously mentioned.

A testament to the analog computer's invincibility: Rather than junking unused units, laboratories put them up for sale. Check eBay. Every so often, you'll find (how do they say it?) a previously owned Comdyna GP-6 for sale.

A few years ago, I received a telephone call. The man introduced himself as Dan Slater. He had a personal laboratory with a few GP-6s purchased from surplus listings. An engineer by occupation, one of his side interests was music synthesis. He had just published a paper in *Computer Music*, an MIT publication, on two analog circuits for enhancing the performance of a Moog synthesizer. As brought out in the paper, the circuits were patched and run on one of his GP-6s. The reason he called, other than to introduce himself and make known his application, was that musicians were contacting him and he wished to refer them to Comdyna.

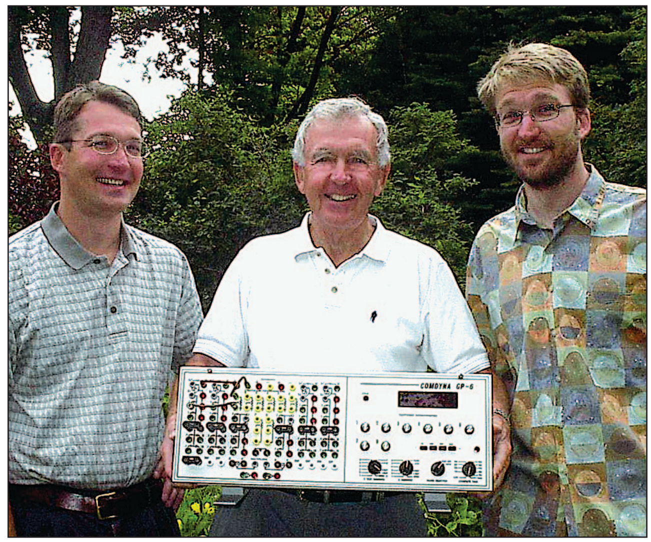
I thought, what a nice application. Maybe Comdyna should be in the music business. I offered on our Web site (it's still there [4]) one of our GP-10s stripped down to handle his circuits at my lowest possible price. I didn't sell any. Even at its reduced price, the special music analog computer couldn't compete with the old GP-6s offered on eBay.

Useful as they are, virtually no analog computers today are purchased for (nor are many old analogs retained in) the laboratory as programmable circuit signal processors. Too bad. Like Dan Slater's circuits, a low-cost analog computer like the Comdyna panel-mounted GP-10 offers an easy and reliable means to quickly have a prototype circuit up and running.

If Just for a Different Name

The roots of linear circuitry are analog computer programs. It was the analog computer where the operational amplifier was perfected. It was in programming the analog computer that engineers concocted the innovations that led to today's linear circuit designs. It was the hybrid computer where logic and analog functions were first combined, where early digital computers operated in parallel with analog systems. And so on. It has long been my opinion that the analog computer's misfortune has been to share with digital the name computer. Given some other name, there may have been no analog versus digital battle waged successfully by digital computer advocates, and the two may have coexisted on the basis of shared strengths and weaknesses. Maybe if, from the beginning, the analog computer were called, let's say, an analog simulator . . .

. . . ah, mellowing into old age, now one of the old analogers (*old* the acknowledged redundant modifier), I'm waxing sentimental.



On the left: Randy, the older son. On the right, Ray. Both helped out after high school hours and in the summer. Randy is an electrical engineer who works for Motorola. Ray runs the Web site for D.U.I.T. of the University of Wisconsin.

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Ray Spiess (rspiess@comdyna.com) was born and raised in Cincinnati, Ohio. He graduated from Purdue University with a B.S.M.E. in 1958. He joined Electronic Associates, Inc. in 1962 as a sales engineer in their central region office. In 1965, he helped Charles McVey found Simulators, Inc., where he designed much of the 240/480 Simulator. In 1968, he left Simulators, Inc. to start his own company, Comdyna, Inc. His company, Comdyna, has been building a line of analog computers ever since. He can be contacted at Comdyna, Inc., 305 Devonshire Road, Barrington, IL 60010 USA.