Improving an analog computer by adding digital electronics and a digital computer interface

by Robert Joseph Horning

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering
Montana State University

Abstract:
The following thesis discusses some possibilities of improving an analog computer by adding digital circuitry and an interface to a digital computer. The thesis work involved modifying an Electronic Associates Inc. TR-48 analog computer and interfacing it to a Digital Equipment Corporation PDP11/03 digital computer. Hardware built as part of the thesis includes circuitry to detect when one of the amplifiers in the analog computer is about to go out of range, circuitry which gives the digital computer the ability to input the output voltage of any amplifier, and circuitry that allows the digital computer' to stop and start the analog computer. A real time clock was also built and added to the digital computer as part of the thesis work. All of the hardware implemented is described in detail in the thesis. The thesis also describes an example problem that demonstrates the capabilities of the implemented system. The example problem shows that an analog computer can be greatly improved by adding digital circuitry and a digital computer interface.

The thesis discusses some additional hardware that could be added to the system. It is concluded that giving the digital computer complete control of the analog computer would be unfeasible except for special purpose systems because of the tremendous amount of software that would have to be written on the digital computer.

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Date 5/21/79

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AND A DIGITAL COMPUTER INTERFACE

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ROBERT JOSEPH HORNING

A thesis submitted in partial fulfillment
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MASTER OF SCIENCE

in

Electrical Engineering

Approved:

Roy M. Johnson
Chairman, Graduate Committee

Paul E. Uhlrich
Head, Major Department

Henry L. Parsons
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

June, 1979

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ABSTRACT

The following thesis discusses some possibilities of improving an analog computer by adding digital circuitry and an interface to a digital computer. The thesis work involved modifying an Electronic Associates Inc. TR-48 analog computer and interfacing it to a Digital Equipment Corporation PDP11/03 digital computer. Hardware built as part of the thesis includes circuitry to detect when one of the amplifiers in the analog computer is about to go out of range, circuitry which gives the digital computer the ability to input the output voltage of any amplifier, and circuitry that allows the digital computer to stop and start the analog computer. A real time clock was also built and added to the digital computer as part of the thesis work. All of the hardware implemented is described in detail in the thesis. The thesis also describes an example problem that demonstrates the capabilities of the implemented system. The example problem shows that an analog computer can be greatly improved by adding digital circuitry and a digital computer interface.

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Chapter I

INTRODUCTION

1.1 Introduction

The purpose of this thesis is to demonstrate that a small analog computer, when augmented with a small digital microcomputer, can be turned into a much more versatile computer tool. The thesis does not attempt to produce an end product comparable with a modern commercial hybrid computer but shows that our existing analog computer can be considerably enhanced in its capabilities by the addition of a digital computer and interface.

The following section gives a brief description of how an analog computer and a digital computer solve differential equations. It also discusses some of the advantages and disadvantages of each procedure. Section 1.3 discusses some of the advantages that might be gained by interfacing an analog computer to a digital computer while still operating primarily in the analog mode.

Chapter Two gives a more detailed description of the circuits designed and built and the software actually written.

Chapter Three discusses some suggested projects. It includes some designs that were not actually implemented.

Chapter Four gives some conclusions that were arrived at as a result of the research.

1.2 A Comparison of the Two Types of Machines

Analog computers are primarily used to simulate systems that can be described by a set of differential equations. In particular relationships the outputs of electrical systems to the inputs can be represented by differential equations. It is possible to adjust the components of a mechanical system so that it may be represented by the same differential equations as a given electrical system, with all the variables of the mechanical system represented by voltages. The primary component of an analog computer system is the operational amplifier (op amp). With resistive feedback the op amp acts as a voltage summing amplifier. With capacitive feedback, the output is the integral of the sum of the inputs. The op amp can also be made to differentiate, but differentiators are highly susceptible to noise and thus are seldom used. There are other components that are present in most analog computers, but these will not be discussed here. For more information on the components of an analog computer, see references (1), (2), and (3).

The solution to a problem on an analog computer is a voltage, observable on an oscilloscope or a voltmeter, or recorded on an XY plotter. The solution may be real time or it may be scaled in time. For problems with small time constants, time is slowed down by increasing the time constants in the analogous electrical system. For problems with large time constants, time is speeded up by decreasing the time constants in the analogous electrical system. Usually the amplitude must also be scaled in order to stay in the linear range of the op amps. For more information on time and amplitude scaling, see reference (1).

The analog computer is controlled manually. The problem is first wired on a patch board (this is where the bulk of the work is in programing an analog computer). Next the computer is put in RESET mode and a static check is made, i.e., the initial conditions are checked for validity. Finally the computer is put in OPERATE mode and the solution is generated. At any time during the run of the program the computer may be put in HOLD mode. In this mode the solution is stopped and conditions can be changed or observed and the problem restarted.

When an op amp goes out of its linear range on the analog computer, an indicator light goes on telling which amplifier is out of range. The problem with this is that the light does not come on until the amplifier has been out of range for a few seconds and thus the problem must be restarted from the beginning.

When a digital computer is used to solve differential equations, numerical methods are used to approximate the solution. Methods such as Runge-Kutta and Adams-Molton, when used with a small enough step size, can get very nearly exact solutions to differential equations (4). On the other hand, an analog computer cannot be expected to have more than about one per cent accuracy.

A digital computer also has the advantage of having a greater dynamic range. One of the big advantages that a digital computer has over an analog computer is greater ease in programming and debugging the problem. Modern hybrid computers have alleviated this problem through the use of FORTRAN type programs that set up the problem through the digital portion and through the implementation of auto-patching.

There are three main advantages to using an analog computer. The first is that once the problem is set up it will run faster. The second advantage is that the problem can be set up so that there is a one-to-one correspondence between the different blocks of the system being simulated and the components of the analog computer. Finally, it is not necessary to learn numerical analysis as is necessary to understand a digital algorithm.

1.3 Advantages of Combining an Analog and a Digital Computer

In recent years prices of digital circuitry and digital computers have dropped to the point where it has become feasible to incorporate digital circuitry and a computer interface into most electrical equipment of any complexity.

A digital computer can be used to control and monitor an analog computer. The outputs can be monitored and results stored so that curve fits can be done on the data later, off-line. The digital computer can also be used to monitor the op amps to check when they are about to go out of range, and to put the analog computer in HOLD before the solution becomes incorrect because of non-linearity in the op amps. When this occurs the digital computer can indicate the action to be taken by the programmer in order to stop the analog computer from going out of range or perform the necessary operation if digital control circuits are part of the system. The digital computer can also be used to do an automatic static check and to set up initial conditions on the integrators. If this were done, iterative problems such as solution of boundary value differential equations using the shooting method could be solved automatically (2, 4).

There are many more ways in which a digital computer might enhance an analog computer, but only the above will be discussed in this thesis. The next chapter will describe the circuits that were actually built and the software that was written. Chapter Three will describe the hardware and software that would have to be implemented in order to obtain all the capabilities mentioned above.

Chapter II

THE IMPLEMENTED SYSTEM

2.1 Introduction

This chapter gives the description of all the designs that were actually implemented as part of the thesis project. It first gives a brief description of the two computers that were used in the project. These are the Electronic Associates Inc. TR-48 Analog Computer and the Digital Equipment Corporation's PDP11/03. Next, the hardware that was added to the two computers is discussed. This includes two boards that were purchased for the PDP11/03 and one that was designed and built by the author. The two boards purchased were an analog-to-digital converter and a 16 bit parallel I/O board. The custom board was a programable real-time clock. Equipment added to the TR-48 analog computer includes an interface to the digital computer and circuitry to place the analog computer in the HOLD mode and then signal the digital computer to take action when an amplifier is about to go out of range. In the final section of this chapter software that was written to demonstrate the use of the system is described.

A block diagram showing how the different parts of the system are interconnected is shown in Figure 2-1.

2.2 The Analog Computer

The TR-48 is a general purpose analog computer that was built in the early 1960's. The TR-48 has forty-eight op amps of which fourteen

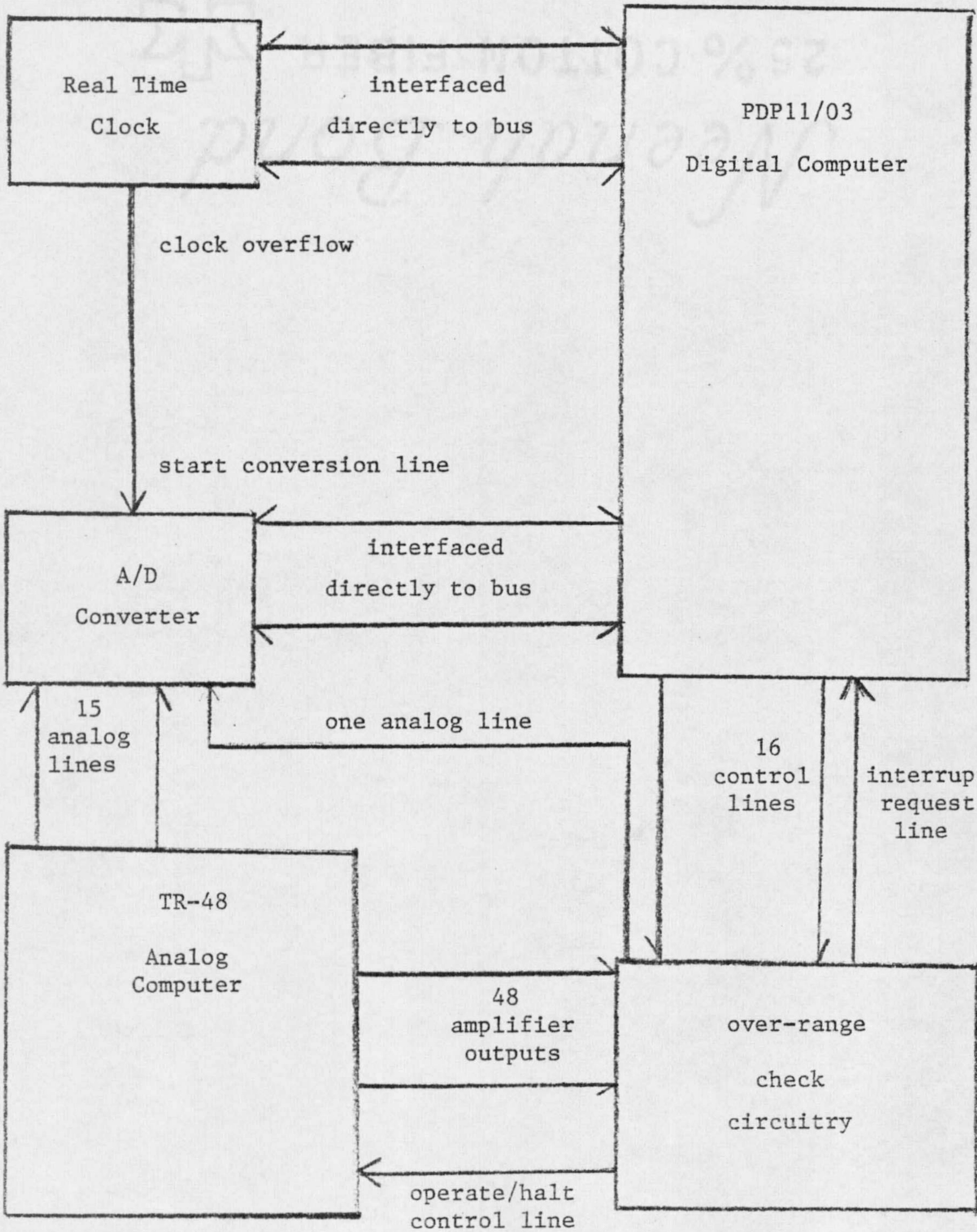

Figure 2-1 : System Block Diagram

may be used as integrators. It also has a number of other functional blocks such as comparators, multipliers and diode function generators, but these have no significant effect on the designs presented in this thesis. The linear range of the op amps is from minus ten volts to plus ten volts.

There are six modes of operation on the TR-48 analog computer.

(1) The POTSET mode is used to set up the problem by applying ten volts across the potentiometers so that they can be set to the desired values.

(2) The SLAVE mode is used when it is desired to run two TR-48 computers in parallel.

(3) The REP-OP mode, or repetitive operation mode, is used when it is desired to display the solution to a system with a small time constant on an oscilloscope. The problem will be restarted at a predetermined rate. With the introduction of a good storage oscilloscope this mode is not as essential as it once was.

(4) The RESET mode causes the intial conditions to be loaded into the integrators. It is used to make static checks and to start a problem.

(5) In the OPERATE mode the problem is being run. Normally the programmer will put the computer in RESET mode and then OPERATE mode.

(6) HOLD mode suspends the solution. All the op amps will hold their values when the HOLD mode is entered.

The designs in this thesis will give the digital computer and digital circuitry control of the OPERATE, RESET, and HOLD modes.

2.3 The Digital Computer

The PDP11/03 is a 16 bit microcomputer system with 28K words of memory and a dual floppy disk. It has extensive software including a monitor, an editor for building files, file handling programs, a FORTRAN compiler and a macro-assembler. The PDP11/03 treats all input-output devices as memory locations. This makes it quite easy to add new boards to the system. Input-output modules occupy the addresses from 28K to 32K. Daisy-chained grant signals provide a priority-structured interrupt I/O system (5). Priority is determined by the physical location of devices on the backplane. When an I/O device's interrupt request is granted, the device sends to the processor a vector address that points to the location in memory of the interrupt servicing routine, thus eliminating the need for device polling on the occurrence of an interrupt. The PDP11/03 uses a software stack to store return addresses for interrupt routines and subroutine calls. This makes it quite simple to write transparent interrupt routines and subroutines which will automatically sequence correctly.

2.4 The ADV11-A Analog to Digital Converter

In order to monitor the solution to a problem on the analog computer, the digital computer must be provided with an analog to digital (A to D) converter. It was decided that the ADV11-A A to D converter built by Digital Equipment Corporation was adequate for the job. The ADV11-A is a 12 bit converter and uses a successive approximation technique to make the conversion. It multiplexes sixteen single ended or eight quasi-differential analog channels. The A to D converter can operate in single ended mode or quasi-differential mode. (It is not true differential in that it does the A to D conversion on one line and then does the A to D conversion on the other line and takes the difference.) The single ended mode was selected because the computers are in close proximity to one another so that the noise picked up in the cable would be negligible compared to the noise picked up in the patch board. (The currents in the cable are very small compared to the currents in the patch wires.) The analog input range is between -5.12 volts and +5.12 volts.

The ADV11-A takes up two address locations on the PDP11/03 bus. One location is a buffer that holds the results of the conversion. The other location is a 16 bit status register which is used to control the converter and to monitor its status. For a complete description of the status register see reference (6). Only the features of the status register used in the designs for this thesis are discussed below.

A to D Start - This is a bit that is set by program control and causes the ADV11-A to start a conversion.

External Start Enable - This bit is set by program control and allows an external signal to cause a conversion to start. The external signal must be provided to a tab on the ADV11-A board and conversion starts on a high to low transition of this signal.

A to D Done - This bit is set by the ADV11-A when a conversion is done and the result is ready in the buffer. When the buffer is read the A to D Done bit is automatically cleared.

Done Interrupt Enable - This bit is set by program control and causes the ADV11-A to generate an interrupt request when a conversion is done, i.e., when A to D Done is set.

Multiplexer Address - This is a set of four bits set by program control that give the channel address on which the conversion is to be made.

A to D Error - This bit is set by the ADV11-A for one of three reasons. It is set if an external start is attempted before the channel multiplexer has had time to settle. It is set if an attempt is made to start a conversion when a conversion is in progress. Finally, it is set by failing to read the results of a previous conversion before the end of the current conversion.

Error Interrupt Enable - This bit is set by program control and causes the ADV11-A to generate an interrupt request when the A to D Error bit has been set.

When using the ADV11-A, the programmer must be careful not to start a conversion for nine microseconds after the channel multiplexer address has been set. The multiplexer must be given this amount of time to settle.

The conversion time of the ADV11-A is thirty-two microseconds.

When interrupt I/O is used, a through-put rate of about 32 KHz is obtained if all the conversions are made on one channel. If the input channel is changed between every conversion, nine microseconds must be added to the conversion time thus dropping the through-put rate to about 25 KHz.

It was necessary to build a distribution panel for the A to D converter. Because the ADV11-A has an input range from -5.12 to +5.12 and the TR-48 analog computer has a range from -10 to +10 volts, it is desirable that some of the channels on the A to D converter have divide by two voltage dividers. This was done to the top five channels (10-15) by inserting 10 K-Ohm voltage dividers. On these channels this lowers the input impedence to the A to D converter to 10 K-Ohm. This is acceptable because of the low output impedence of the op amps on the analog computer. However, caution should be taken if the distribution panel is used elsewhere. The problem could be corrected by adding op amp buffers to the inputs of these channels.

Appendix A contains the listing of a program that will assist the user in calibrating the voltage dividers on the distribution panel, along with directions on how to use the program.

For more information on the ADV11-A board and information on how to program it, see reference (6).

2.5 The DRV11 16 Bit Parallel Board

In order to communicate with the digital circuitry that was added to the analog computer, a DRV11 16 bit parallel input-output board was purchased from Digital Equipment Corporation. The DRV11 was used only for output. Therefore, the input channel could be used for some other purpose.

The DRV11 has an output buffer, an input buffer, and a status register. The status register has two request flags that can be set by the circuitry with which the computer is communicating. It also has an interrupt enable bit for each of these flags. When the interrupt enable bit is set and the corresponding request flag is set, the DRV11 will generate an interrupt request. Lastly, the DRV11 status register has two flags which are set and cleared under program control.

How the output buffer register was used to control the digital circuitry will be described in Section 2.7.

For a more detailed description of the DRV11 board, see reference (6).

2.6 The Real Time Clock

In order to do data acquisition or real time control using a digital computer, it is necessary to have samples accurately spaced. Thus there was a need for a programable real time clock. A clock could have been purchased from Digital Equipment Corporation, but the only one available had more features than were necessary and also took two slots on the PDP11/03 backplane where a custom board would take only one slot. It was also decided that the real time clock would be more economical to build than to buy. Since this board was built as part of this thesis, a detailed description of its use is given here. Appendix B has a detailed description of how the board is put together along with schematics for the board.

The real time clock has a buffer register and a status register. The buffer register is loaded with a negative number (in two's complement form). When the clock is enabled the buffer is loaded into a set of counters. The counting frequency is determined by three bits of the status register. When the counter overflows, the overflow flag of the status register is set, a pulse is given on an external connector tab (this can be used to start the A to D converter), and the buffer is loaded into the counters again. If the interrupt enable bit is set in the status register, the real time clock will generate an interrupt request. If the overflow flag of the status register is not cleared by the time that a second overflow occurs, an error flag is set. Table 2-1 summarizes how the bits of the status register are used. (The bits are numbered Ø to 15, from right to left.)

The time base for the real time clock is a 2 MHz crystal oscillator which, when divided by two, produces the needed 1 MHz signal. The 1 MHz signal is divided by ten four times to give the other needed frequencies.

When an external frequency is to be used with the counter, the signal should be connected to connector tab A. (See Figure 2-2 for the location of connector tab A.) The external input is TTL-compatible and consists of one TTL unit load.

When an overflow occurs a pulse will be generated on connector tab B.