An Interactive Servomechanism Demonstration

by

Jason M. Sachs

Submitted to the Department of Electrical Engineering and
Computer Science
in partial fulfillment of the requirements for the degree of

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Author ....
Department of Electrical Engineering and Computer Science
May 28, 1996

Certified by ....
John G. King
Professor of Physics
Thesis Supervisor

Accepted by ....
Frederic R. Morgenthaler
Chairman, Department Committee on Graduate Theses

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Abstract

Servomechanisms are a significant and increasingly common part of contemporary technology. Unlike other recent advances—lasers, robots, computers, and microwaves, for example—which are given much attention by science museums, they are relatively unknown to the public and even to much of the MIT community. A hands-on exhibit illustrating the principle and operation of a servomechanism in qualitative terms would help to remedy this. Design, construction, and field-testing of such an exhibit was the goal of this project.

Thesis supervisor: John G. King
Title: Professor of Physics

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Acknowledgements

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Professor John G. King for his willingness to sponsor this project, which would not have got off the ground without the encouragement, latitude and guidance he provided me. There should be more professors like him, more labs like his, more projects like this.

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To my father and grandfather

who taught me to appreciate math and science at an early age

and who used to take me to the St. Louis Science Center

in its previous location so many years ago

in a big house where there were colored lights

and sounds

and earthquakes

and dinosaurs

1. Overview

In the past hundred years, there have been quite a few technologically sophisticated inventions that came into widespread use (radios in the 1920's, televisions in the 1950's, microwave ovens in the early 1980's, cellular phones in the late 1980's, for example); this number has grown rapidly with the advent of the integrated circuit and the microprocessor. Unless there is some attempt to make them understandable to the majority of the people who use them, the conception that things work "by magic" may take hold. The hands-on museum has been one way in which technology has been brought down-to-earth; science museums draw millions of visitors per year to see thousands of exhibits on many aspects of science and technology. While seeing a partially-disassembled car engine (for example) may not make someone understand *exactly* how it works, such an exhibit may give people a little more of an idea what's going on and may make them a little more comfortable with their car.

One recent development that has not received much attention is the servomechanism. Servos have been around for over a century, first being used in the engines on steamboats [Burstall], and have been well-understood since World War Two, where they were used in automatic targeting mechanisms. Today they are found in automobiles, manufacturing equipment, and in almost half (44%) of American homes in the guise of compact disc players. [Trachtenberg] Yet they are not mentioned in schools; only the few who have taken certain engineering courses are exposed to servomechanism theory. Few science museums have exhibits on servomechanisms—television, lasers, holograms, and computers dominate in exhibits on contemporary technology.

This project attempted to fill this perceived gap by creating an interactive demonstration of a servomechanism, to show two things: first, how a servomechanism works, concentrating on the core idea that servomotors use negative feedback to control some parameter such as position or velocity, and second, what kind of things a servomechanism can do. The demonstration was aimed at a broad audience, namely the MIT community and its visitors, and concentrates on getting this idea across in a qualitative manner.

After constructing the exhibit, I had a number of people test the exhibit. The purpose of this was not only to see what the *exhibit* accomplished, but also to see *what people learned* (or did not learn) from the exhibit. (There is a subtle difference: the first is intended to evaluate the exhibit itself; the second is to find out something about how different people use it.) These trials led me to conclude that the exhibit was successful in exposing people to some of the phenomena of servomechanisms, but that in order to teach the core concepts of feedback, exploration of the exhibit on its own is not quite adequate. The exhibit does seem to be a useful tool, however, and its effectiveness could be greatly enhanced either through related exhibits on motors, sensors, operational servomechanisms, etc., or through guidance from a knowledgeable human being.

Although there are still some minor changes to be made at the time of this writing, it is planned that the exhibit will be placed on permanent view in Strobe Alley, the fourth floor of MIT's main hallway and a stop on campus tours. The eventual exhibit will be, I hope, an interesting means of exploring servomechanisms for people with a wide range of backgrounds.

2. Introduction

While I was in the middle of developing the exhibit described in the next chapter, I had the opportunity to work with some Cambridge sixth-graders in an investigation into how things work. The items involved included a lawnmower engine, an old rotary phone, a typewriter, and a computer motherboard. They had never looked inside any of these; for all they knew there might have been elves running around inside making them work, so to them the objects were *black boxes*—that is, a person who has access to a black box can perhaps figure out how to use something but does not know how it operates, and is often prevented from getting inside. The point of this activity was to try to get them to take off the cover of something and see inside the black box, which, in real life, is something you can't always do.

Several times I worked with Earl, a rambunctious youngster who had a lot of fun taking apart the phone and seeing how the dial worked to produce clicks. One week we had this computer motherboard to take apart. The time we had together quickly degenerated into a smashing session and Earl became frustrated (meanwhile I was having some fun unrolling a mylar capacitor with another student). When I asked him why, he said, "Electrical stuff is boring. You can't see how anything works." The computer motherboard is an example of something I call a *gray box*; it is something whose inner workings, though visible, are indecipherable and obscure, and often include too much detail to understand.

For the most part, I consider the existence of black boxes and gray boxes to be a bad thing, a sort of metaphorical Scylla and Charybdis blocking the way to learning. The project described in the following chapters came to exist because of this—first of all, black and gray boxes are bad in general, and second of all, the focus of the exhibit, a servomechanism, exists elsewhere almost exclusively in the form of black and gray boxes.

2.1. Why black and gray boxes are bad in general

The servomechanisms exhibit was motivated partly because of two observations:

- **Engineering students need more ways to gain physical insight into the material they are studying.** Over the past few years I have had the opportunity to help out many fellow students on problem sets in various subjects, and in many cases the difficulty is the same: they get the general idea of what is going on, they know roughly what equation to use to solve the problem, but they don't know how to apply it because they don't have a good sense of what the equation means. One student in particular was working on a transistor problem—he had the equation for collector current $I_C = I_S(e^{qV_{BE}/kT} - 1)$ in front of him, as well as a graph of various I_C vs. V_{CE} curves, but neither did any good to solve the circuit problem until he was finally able to understand what the transistor was actually doing in the circuit. To a beginning student, technical material often remains a gray box without the physical insight needed to understand the significance of numbers and equations.
- **The general public could stand to become more familiar with technology.** I often see non-technically-oriented people interact with devices like a TV or VCR as though they were magic boxes—the buttons do something but they don't know what, and when something goes wrong the object is to find the right button or sequence of buttons to push to fix it. A bicycle, on the other hand, may still be somewhat complex but all its functions are visible and it is not difficult to tell what is wrong when something doesn't work; rarely is using one confusing or frustrating. The important difference is not necessarily that one is more complicated than the other, but that the inner workings of a VCR are less accessible than those of a bicycle. The VCR is a gray box upon opening; the bicycle is not (and doesn't even need to be opened to see what's going on).

In both cases the problem is an unfamiliarity with science and technology in a society in which science and technology are increasingly prevalent. "Unfamiliarity" here refers to a lack of everyday experience of the kind people might have about the way plants grow or the way icicles form in the winter. John Bruer discusses the importance of such experience on education in his book *Schools for Thought*:

> In science, as in math, children often have a lot more knowledge than we think. Serious science instruction need not wait until junior high school. Children's knowledge about material objects and what causes them to move are rudimentary scientific theories. The challenge, as in early math instruction, is to understand children's theories and concepts and build effective instruction on them—instruction that helps students map their informal understanding of how the world works onto the formal scientific theories they encounter in school. [Bruer, p.139]

In other words, this informal understanding is a key with which to understand formal science and prevent it from being mysterious (i.e. a black box) or indecipherable (i.e. a gray box). This idea is not confined to elementary-level education:

> Some students do spontaneously connect the equations with more expert schemas. Others realize that their naïve schemas will not work in physics class, so they ignore their everyday knowledge, rely on means-end analysis to manipulate equations, pass the course, and go on to college physics where they do more of the same. Physics courses do not require that students learn physics. [Bruer, p.151]

But what about those areas in which there is no everyday experience? How can a student be expected to learn how to analyze transistor behavior in a circuit before he has ever seen the effects of a transistor in action? How can adults in our society be expected to learn how to program a VCR when it involves a seemingly arbitrary sequence of buttons that must be pushed? Without some sense of what is going on in the devices in these situations, both tasks can be performed only by rote, and in situations requiring troubleshooting or problem-solving (which happen often in the real world) where rote learning does not exactly apply (is the transistor carrying enough current that it might be overheating? are the batteries in the VCR's remote control drained?) a lack of at least some rudimentary understanding of how the device works can prove very frustrating.

Interactive exhibits such as those found in science museums may provide a partial solution, at least giving people the chance to explore and gain some informal understanding of the facets of science and technology that are familiar. That is what I hope this project has achieved.

2.2. Specific motivation for the servomechanism exhibit

Before I talk about the motivation for this particular project, let me present an example in case the reader is unfamiliar with servomechanisms.

The textbook for MIT's introductory signals and systems class for electrical engineers (6.003) discusses a demonstration known as the "inverted pendulum":

> Consider an inverted pendulum attached by a hinge to a car free to move along a horizontal track. Our objective is to design a driving system for the car that will use signals derived from the car and pendulum motions to stabilize the pendulum in its inverted position. The whole scheme may be considered a one-dimensional simulation of the common parlor trick of balancing a ruler or broom stick on end on your palm by moving your hand appropriately. The details of what we have in mind are shown in Figure 6.4-1 [Siebert, 178-9]

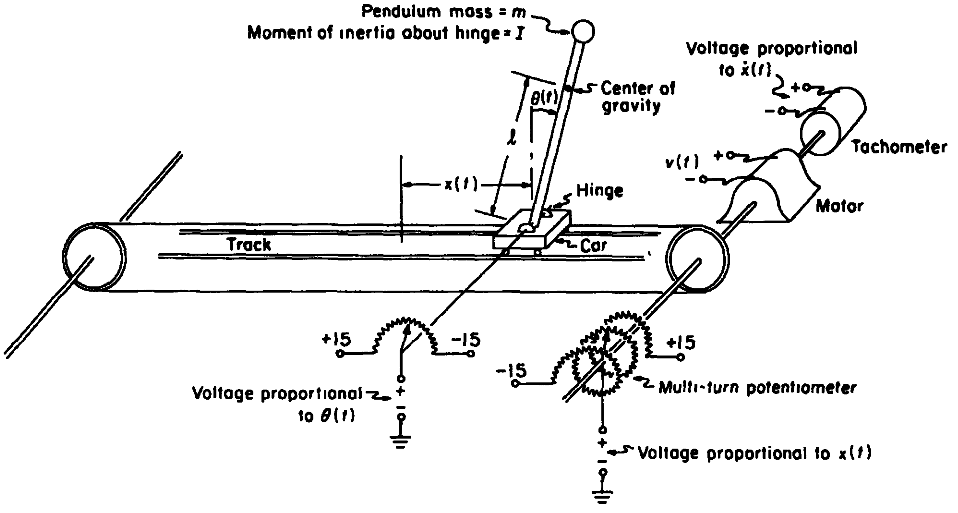

Fig. 1. An inverted pendulum. Reprinted from [Siebert] with permission of the publisher.

This system is a servomechanism—it uses an active power source (a motor) controlled by using feedback to set and maintain some velocity or position (here the angular position of the pendulum).

There are many concepts embedded in this idea, which is probably why servomechanisms are commonly discussed in engineering courses on control systems: negative feedback, most notably, as well as stability and disturbance rejection, and response time. In addition, there are practical limitations and nonlinearities that can be pointed out: static friction and backlash on the mechanical side, sensor noise and output power limitations on the electrical side. All of these can be considered qualitatively, which makes a servomechanism a good candidate for providing informal experience with technology.

In addition, they are relatively unknown to the general public, despite being fairly common. Science museums, which are one of the few ways the public can learn about science and technology outside formal education, do not, in general, include exhibits on servomechanisms. Among the dozen or so museums I have been to or contacted, only two had servomechanism exhibits: The Tech Museum of Innovation in San Jose, California, which specializes in exhibits on technology and has a few exhibits on servomotors and teleoperation, and the Exploratorium in San Francisco, which recently developed thirteen exhibits under the general heading of feedback and is generally recognized as one of the leading innovators in interactive exhibits. Other museums tended to be more science-oriented rather than technology-oriented (for instance, exhibits on polarization of light often use polarized film to demonstrate the phenomenon but I have seen few that mention how this can be utilized) and those exhibits that are technology-oriented cover “pop” inventions: lasers, television, computers.

In other words, servomechanisms could use some more publicity. (And they aren’t alone in the world of underpublicized inventions—how does a vending machine know what kind of money you give it, and why does it always refuse to take my dollar bill? It’s magic to me...)

At the other end of the spectrum, in the college engineering curriculum, all of the schools responding to my queries had some kind of demonstration or laboratory on feedback, the overwhelming majority of which involve three situations: an inverted pendulum similar to the one described above, a steel ball magnetically levitated using an electromagnet, or a “plain-vanilla” DC servomotor. Here the servomechanism is anything but neglected. However, there appears to be a gap in how these are utilized from a pedagogical standpoint: on one hand there are the demos—the 6.003 inverted pendulum, and the levitated steel ball shown in 6.302, the introductory feedback class at MIT—which are shown as examples of feedback, and left for motivated students to ponder. On the other hand, there are labs, like the 6.302 servomotor lab (students must evaluate the response of a DC motor, then determine the system function of an appropriate controller) or the “Pendubot” system at the University of Ilinois which involves a digital state-space controller for an inverted pendulum [Spong and Block], or a rotary inverted pendulum at Caltech [Murray], also utilizing a digitally-programmed controller. These all involve in-depth quantitative analysis and synthesis of a control system, which is good practice to learn how a controller might be designed, but there is a risk that a student can successfully complete the task by manipulating the necessary equations without a good understanding of what is physically going on.

My goal was to use these laboratories and demonstrations found in universities as a starting point, to pick out the important concepts and then create an exhibit that included these concepts but at a qualitative level rather than quantitative. My hope was that the resulting exhibit would be beneficial not only to beginning engineering students wrestling with unfamiliar concepts, but also to the general public to expose them to an interesting and growing area of technology.

3. Design

In order to keep this exhibit from appearing either as a gray box or black box, I tried to keep the following guidelines in mind:

- **Emphasis on important issues.** A major goal of this project is to help get across the concept of feedback as applied to servomechanism operation. Details of operational servomechanisms, such as backlash, friction, and limitations in sensor accuracy and output power, may detract from the central idea, and should therefore be minimized, at least in an introductory exhibit. Hence the performance of an educational servomechanism may need to be quite different than a servomechanism used in commercial or industrial products: the educational servomechanism must not look or feel "wrong" to its user.
- **Flexibility.** On the other hand, the demonstration should not be limited to exploring these central ideas. As the director of the San Francisco Exploratorium stated: "When visitors can invent ways to use an exhibit they get a sense of discovery that is much more satisfactory than if they merely discovered what we thought they were supposed to discover. They stay with the exhibit for longer times and usually, but not always, end up by observing the behavior that we hoped they would when we conceived the exhibit... In fact in general, it is important to allow the variables in an exhibit to change enough so that the interesting effects disappear. One learns as much or more about an effect by its disappearance as by its appearance." [Oppenheimer] The exhibit should have enough parameters to vary so that people using it do not think to themselves, "Oh, if I could only do *that*..." when what they want to do could have been easily added to the exhibit or was even inherently present but restricted by the designer. Though not every way of using the exhibit can be anticipated by the designer, as much should be left open to the user as possible while still keeping some degree of focus.
- **Simplicity.** This is rather hard to achieve in an electronic system. (My guess is that Earl, the sixth grader mentioned in the previous chapter, probably wouldn't care for the exhibit I

developed, but who can tell?) The circuitry needed to pull off the desired behavior was rather complex. Fortunately, its *effects* are simple—but to most of the test subjects, the means by which the exhibit worked seemed somewhat magical. (More on this later.)

- **Clarity.** This is even harder to achieve in an electronic system. I tried to provide "cues" to give people as much information that they could see with their own eyes as possible.

The exhibit I designed is shown below in Figures 2 and 3, and is essentially a servomechanism controlled by variable-gain feedback.

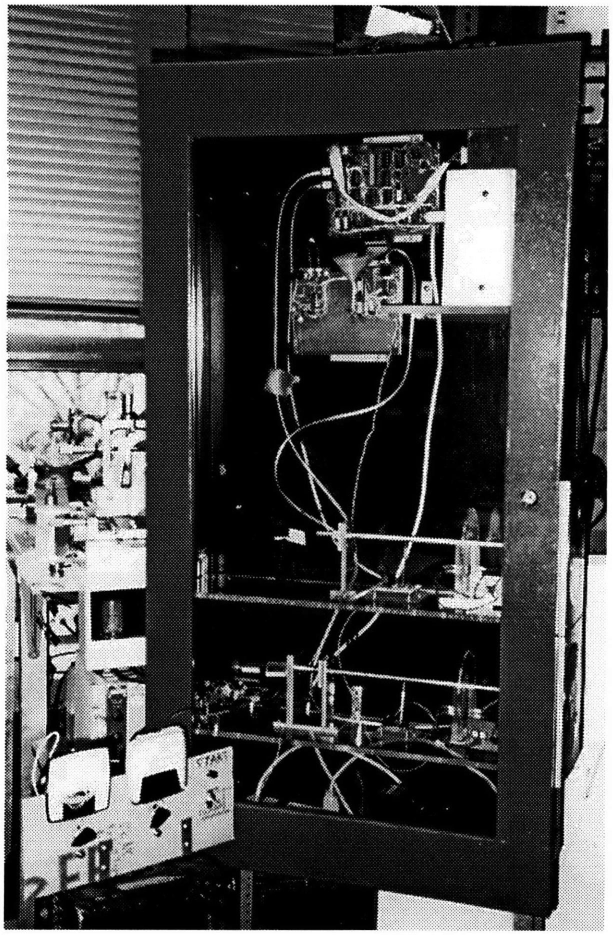

Fig. 2. The servomechanism exhibit. (currently undergoing final construction; items on the external panel shown in the lower left will be installed in the door of the exhibit, and text needs to be added to explain a bit of what's going on, but otherwise the exhibit is in its final form)

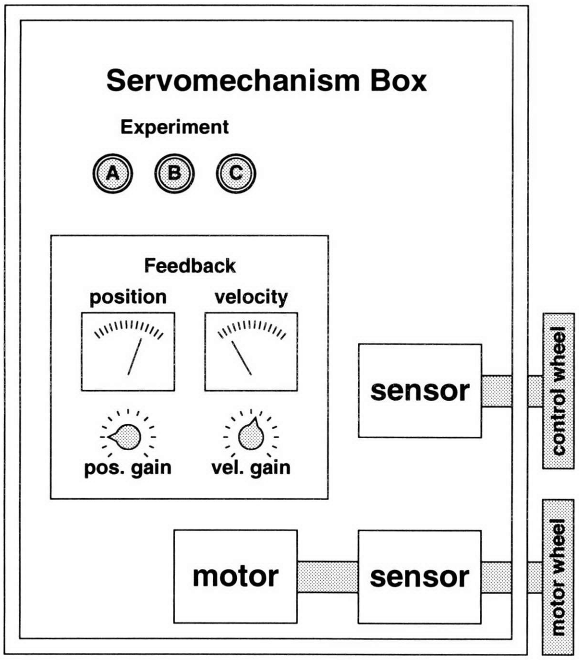

Fig. 3. A schematic of the servomechanism exhibit.

A geared-down DC motor is attached to a plastic wheel (the motorized wheel) by a steel shaft, and is driven by an electrically-controllable current source. Another plastic wheel (the control wheel) and steel shaft sit directly above the motorized wheel and shaft. The difference in position and velocity between the two wheels are displayed on analog panel meters. The function of the sensors and associated circuitry is to control the motor torque (which, in a DC motor, is essentially proportional to armature current) using position and/or velocity feedback, with variable gains controlled by knobs that the user can turn. In the primary operation of the exhibit, position reference comes from the control wheel, so that with proper feedback the motorized wheel should follow. In auxiliary operation of the exhibit, position reference comes from a digital source, so that a microcontroller can dictate the position of the motorized wheel. A block diagram of the system is shown below in Figure 4.

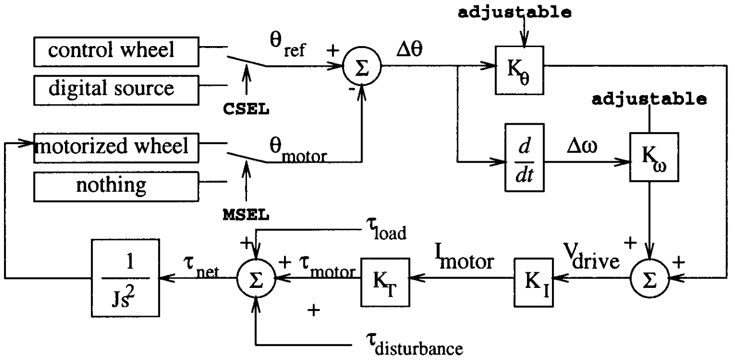

Fig. 4. Block diagram of the servomechanism exhibit.

From a system viewpoint, this is somewhat similar to the equipment used in the 6.302 servomotor labs, which also consist of a DC motor/feedback controller setup. In both cases, the user can alter the amplifier gains used in the controller to vary the performance of the system.

The issues emphasized, however, are different. In the 6.302 lab, the position reference comes from a waveform generator. This has meaning to students interested in frequency responses and step responses; for students unfamiliar or uncomfortable with these notions, selecting square waves or sine waves of a particular frequency is probably not the best source of a position reference. I chose a more intuitive source by having a second shaft and wheel—the particular reference "waveform" is controlled by the user. In plain English, the person looking at the exhibit can turn the control wheel and see how well the motorized wheel follows. The human body is not a particularly precise source for a reference signal, but this is supposed to be a qualitative exhibit. Alternatively, the user can pick a different "mode of operation" for the exhibit by selecting a switch, and the position reference may instead come from a microcontroller in order to show the response to "typical" position or velocity inputs.

The controller in 6.302 is a box with a lot of connectors, switches, and dials on it. This is good in that it frees users from having to design their own feedback and power amplifier circuits in order to let them concentrate on the control aspects of the system, but for a source of informal experience it is probably still too technical as it requires the user to connect BNC cables to appropriate points, use oscilloscopes to gather data, determine whether to use a voltage source or a current source, and choose an appropriate compensation capacitor at one point in the lab. I have given the user here only two knobs, one for position gain and one for velocity gain, and a switch to turn on or off something called "friction compensation", which is just a way of reducing the effects of motor and gear friction by adding a term to motor torque to oppose this friction. This is a simple controller (proportional-differential for position, or proportional-integral for velocity), but the point is for the effects of feedback to be made visible, and the controller is still flexible enough to make the effects of response time, steady-state error, overshoot, and stability appear at various settings. I did not want to have merely a "with feedback/without feedback" switch; this would be a way to show off feedback rather than explore feedback. I wanted users to be able to explore not only its effects but *why* it works. Specifically, if the time scale of feedback is faster than human perception, then a feedback system may appear to work instantly and perfectly—in other words, technology appears to be magic. By having the response be adjustable and on a visible time scale, feedback in this exhibit will hopefully become something tangible.

4. Implementation

4.1. Mechanical components

4.1.1. Motor

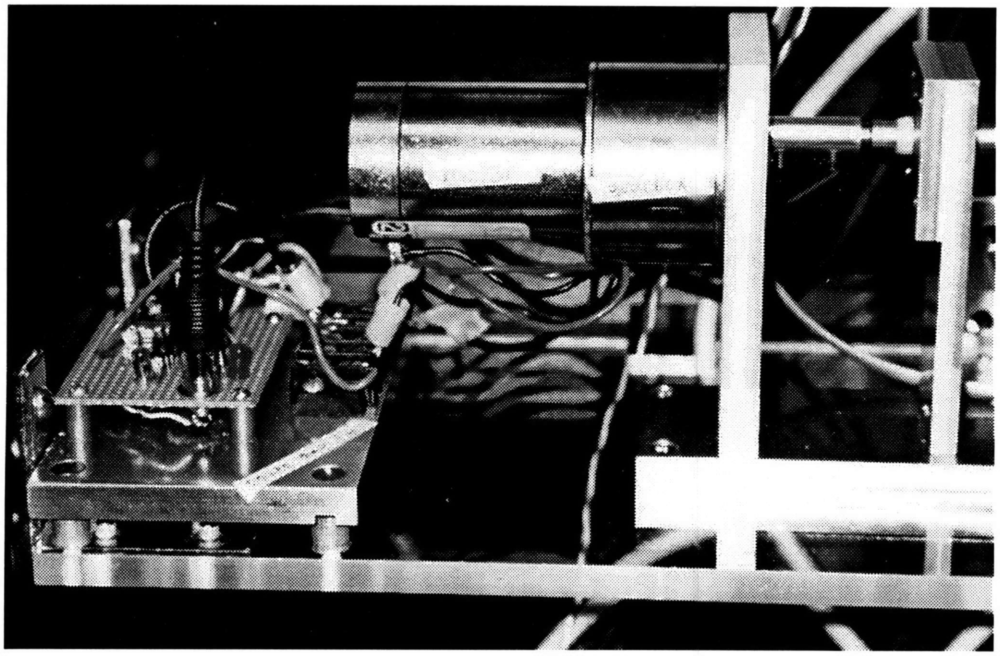

Fig. 5. Power amplifier and motor

The motor (shown in Figure 5) used is a Pittman GM9434 24V permanent magnet, DC brush-commutated motor with ball bearings, with a rated peak continuous torque of approximately 5 oz-in[1] at a current of about an ampere, and a no-load speed of approximately 260 rpm per volt. In addition, the motor had an 11.5:1 gearbox.

Since the exhibit is one that a person should be able to interact with, we have the following requirements:

- **Low speed.** It is hard for a person to rotate something at more than about three or four revolutions per second, or around 200 rpm.

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[1] Ounce-inches and rpm were given in the motor data sheets and are easier for non-metric folks to consider than newton-meters and radians per second. I leave it for the reader to convert to his/her favorite units.

- **Large dynamic range of torque.** The load requirements for the motor are unusual, since I wanted the person using the exhibit to be able to feel the motor trying to set and maintain its position. For this reason, a maximum force on the order of a few pounds was desired. With a six-inch diameter wheel, this means peak torques on the order of 100 oz-in. On the other hand, a low frictional torque (due to gear and bearing friction) is desirable because it represents a nonlinearity in the system, and also represents a load felt by users if they choose to turn the motor shaft themselves.

Having a gearbox helps to trade unneeded speed for extra torque, but it reduces the ratio of peak torque to friction torque by the efficiency ratio squared. Unfortunately, without a gearbox, the peak torque that a reasonable-size, reasonable-power motor can exert is rather feeble (a few oz-in at best).

The selected motor and gearbox combination was chosen as a compromise; although the motor is rated at 24V, the power supply used was only ±15V, but this still allows speeds of around 300 rpm (at the output shaft of the gearbox, motor back-EMF limits speed to about 23 rpm per volt). The gearbox efficiency is rated at 81%, so that on the actual output shaft, a net peak output torque of roughly 50 oz-in could be exerted at about an amp current.

Laboratory measurements yielded these values for the overall motor-gearbox system:

Torque constant	45 oz-in/amp
Frictional torque (static)	≈ 5 oz-in at 80 mA
Frictional torque (kinetic)	≈ 2.5 oz-in at 40 mA
Peak torque (after frictional losses)	61 oz-in at 1.46 amps
Top speed	340 rpm

With friction compensation (discussed later) the kinetic frictional torque can be stably reduced to about 1.5 oz-in.[2]

4.1.2. Sensors

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[2] This value is a very rough estimate based on comparisons in decay time of the bottom wheel's oscillation with and without friction compensation.

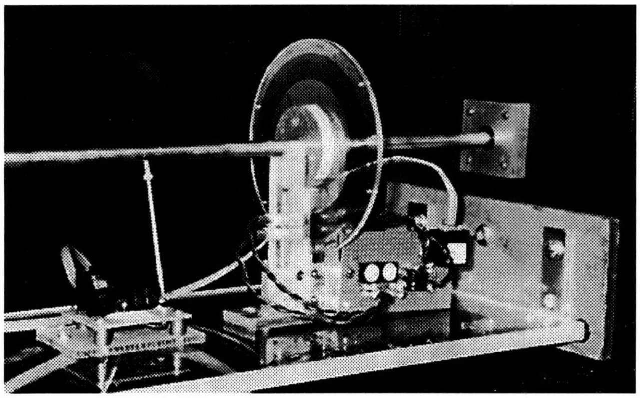

Fig. 6. Jason's Homemade Optical Encoder. The position sensor outputs an index signal, generated by the passage of a needle attached to the shaft through an optical interrupter (left) and two quadrature signals, generated by two photodiode pairs on either side of a plastic disk marked with two striped rings (right)

The sensors here (one shown in Figure 6) are two incremental optical encoders with quadrature quasi-sine-wave outputs of 1024 phases per revolution, that I was foolish enough to make myself. (They do work rather well, but the amount of time I spent to construct them was relatively large, and I would suggest buying commercial encoders rather than taking the do-it-yourself route.) These were chosen over other types of position or velocity sensors for several reasons:

- **Large angular range.** I wanted the angular range of the shaft to be unrestricted, so that a person could spin the control wheel continuously (i.e. a ramp input) and watch the motorized wheel follow, without seeing some weird wraparound effect[3] or being limited to a certain number of rotations, which would occur with a potentiometer as angular sensor. Sensors with frequency outputs, on the other hand, can be used in conjunction with a digital counter to provide a potentially unlimited range. This project uses 14 bits of angular resolution to keep track of ±8 revolutions, 1024 positions per revolution.
- **No drift.** By using a digital scheme for position, if the shaft is moved 12,503 positions clockwise and then 12,503 positions back, then the net change of position is zero, whereas if a tachometer were used to obtain a velocity signal and this were integrated to provide position information, then integrator drift would be a limiting factor.

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[3] The "weird wraparound effect" does occur but only if the two wheels differ by 8 rotations, which happened infrequently when people tried out the exhibit.

- **Useful velocity information at low speeds.** This project uses the analog information in the sensor output to provide velocity signals even when the shaft is moving slowly, by using a method described in Appendix A, loosely based on [Yokote, Watanabe, 1990]. Using digital quadrature signals with some sort of frequency-to-voltage converter may work well at high-speeds but at low speeds is limited in bandwidth by the frequencies involved.

4.1.3. Other significant mechanical components

The wheels that project outside the exhibit box are shrouded by an aluminum shield to prevent users from bending the shaft. (The exhibit needs to be rugged enough so that the gung-ho passer-by is not able to damage it easily. Fortunately these wheels are among only a few parts that can be reached from outside.) This also eliminates the use of the wheels' outside rims as a handhold; in order for there still to be some place to grip the wheel, round depressions were milled into the sides of the wheels (the painted dots in the photograph shown in Figure 7).

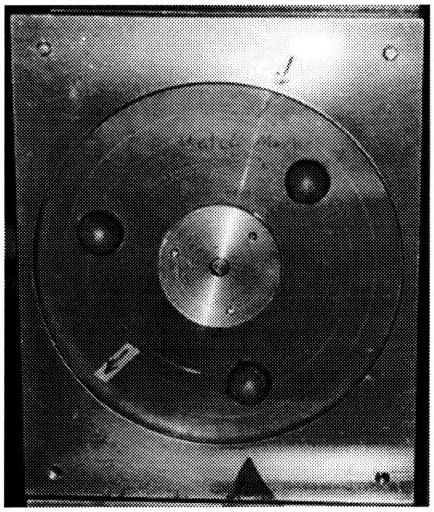

Fig. 7. A wheel to let people turn a shaft

The bearings used in this project are 8mm (inside diameter) ball bearings. These are easily obtainable and inexpensive when compared to other sizes of bearings; they should be available at athletic supply stores unless the market for inline skates ceases to exist in the near future. Unfortunately, metric shaft sizes were not easily available (in Europe I suppose this would not be the case), but 5/16" shafts were only slightly smaller, readily available at hardware stores, and seem to work just fine.

4.2. Electrical components

Detailed schematics for the circuits described in this section are listed in Appendix A in the order they appear here. I caution the reader, however; cost constraints and part availability led me to design certain circuits in ways that might not be considered sound engineering.

An overview (more detailed than the block diagram shown in the last chapter, less detailed than the schematics) of the electrical system is shown in Figure 8.

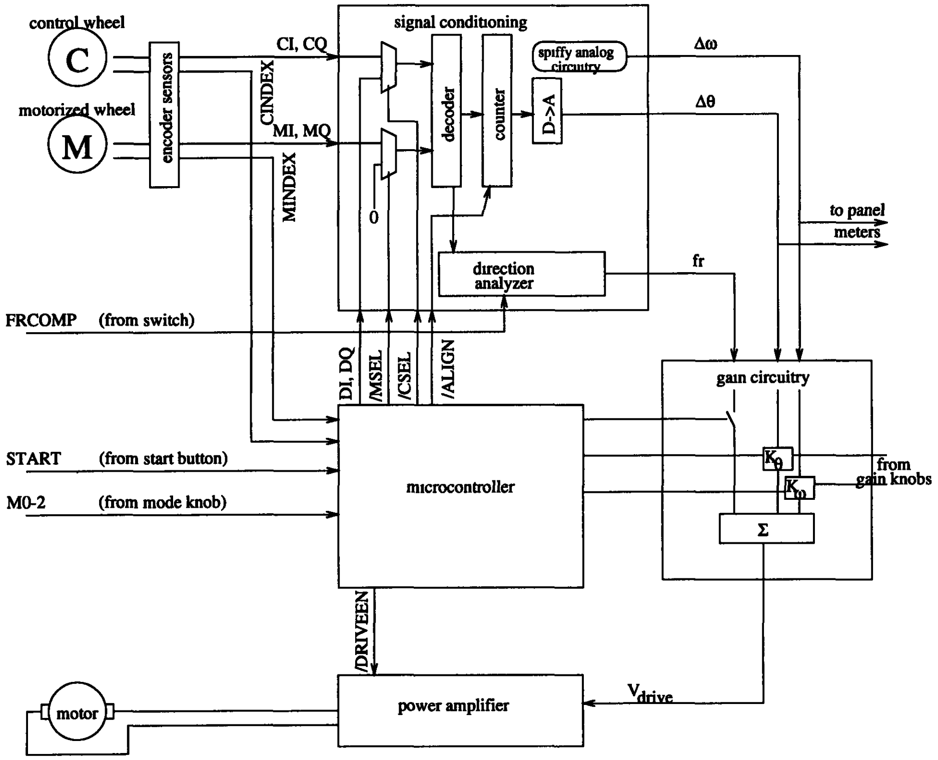

Fig. 8. Electrical system of the exhibit

4.2.1. Power amplifier

A linear amplifier run from a ±15V, 1.5A wall transformer power supply was used to power the motor. The amplifier is a current source with feedback taken from a small resistor in series with the motor to maintain accurate current levels of 0.19 amps per volt of input up to a maximum of about ±1.5A. The bandwidth of the amplifier is about 1kHz; this is more than adequate to drive the motor for human interaction (unless one wishes to use the vibrations of the motor to produce audio tones). Current rather than voltage output was chosen because of the linear relationship between DC motor torque and motor current. The motor's terminal voltage is related to motor speed but for conceptual purposes it is easier and more true-to-life for the advanced exhibit user to think of the motor exerting a torque than exerting a velocity, since torque is an immediate result of motor current, whereas velocity is achieved only through the interaction of motor torque with the inertia of the shaft and other load characteristics. In addition, stability of the amplifier feedback loop is easier to achieve in the case of controlling a current output for two reasons: current is directly measureable (the motor's back-EMF is not), and mechanical loads affect only the voltage necessary to achieve a given motor current, and not the motor current itself.

A switching amplifier would have been much more efficient—in fact, originally I had built a working pulse-width modulation power amplifier, but was unable to accurately control motor current using the circuit topology I had chosen. Fortunately, the power requirements of the motor are such that a linear amplifier can be used without having to take extraordinary measures to dissipate heat, beyond simply putting the amplifier's power transistors on a block of aluminum.

4.2.2. Signal acquisition and analog processing

A large amount of effort went into obtaining velocity and position difference outputs from the optical encoder signals; however, the circuitry here is rather flexible.

The sine-wave outputs of the encoder sensors are squared up to obtain digital quadrature signals; these are used to add or subtract the analog waveforms in such a way that, for rotations in the positive direction, the resulting waveform has positive slope for each phase of the encoder. This technique is described in [Yokote, Watanabe, 1990] as a hybrid method of stabilizing the position of servomotors by using the resulting waveform directly as a piecewise, approximately linear waveform as part of a feedback loop. In this exhibit the quasi-linear waveform is used to obtain a measure of velocity difference, and is discussed in more detail in Appendix A.

The position difference is obtained from a 14-bit counter using a digital-to-analog converter. The count up/count down signals are obtained from two digital quadrature channels using a programmable logic chip; rotation in one channel produces count pulses in the positive direction, and rotation in the other channel produces count pulses in the negative direction. These two channels can be multiplexed from among the motorized wheel's quadrature signals (MI and MQ), the control wheel's quadrature signals (CI and CQ), and a digitally generated set of quadrature signals, (DI and DQ), so that effectively the position reference can be selected from either the control wheel or a programmable source (the microcontroller discussed later).

These quadrature signals provide incremental position information; absolute position information is provided by index signals to synchronize the wheel positions upon startup. The index signals are obtained from a pair of optical interrupters that are blocked once per revolution by a small rod attached to each shaft.

4.2.3. Feedback circuitry

The input to the power amplifier is a weighted sum of the position difference, velocity difference, and friction compensation signals. The position and velocity differences $\Delta\theta$ and $\Delta\omega$ are attenuated by audio taper potentiometers[4] on the door of the exhibit, so that the user can change the gain of each signal. The resulting signals are then amplified and added together with a quad op-amp. The signal to the power amplifier can also be disabled by controlling the gate of a JFET connected to the summing node of the op-amp.

At maximum gain, the resulting signals are $0.3\ \frac{\text{volts}}{\text{degree}}\ (\times 0.19\frac{\text{amps}}{\text{volt}} \times 45\frac{\text{oz-in}}{\text{amp}} = 2.6\frac{\text{oz-in}}{\text{degree}})$ and $30\ \frac{\text{millivolts}}{\text{rpm}}\ (= 0.26\frac{\text{oz-in}}{\text{rpm}})$. The velocity signal is clipped to 1.4V (12 oz-in) maximum; when the velocity gain is too large, the system becomes unstable and the motor vibrates rather loudly, and is caused by the backlash in the gear train introducing a time delay between when a change

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[4] Initially I used linear potientiometers, but found that changing the knobs near the lower end of their range caused rapid changes in behavior. Audio taper potentiometers are quasi-logarithmic, as are most types of human perception, so the range of interesting behavior is better spread out across the range of the pot than in the case of linear taper potentiometers.

in direction is detected and when the motor can traverse the backlash angle and push back on the shaft. The clipping level was chosen as a compromise between making this oscillatory effect visible and keeping its amplitude low enough to reduce wear on the gear train. (Most of the test subjects who tried out the exhibit for this project had a tendency to turn the velocity gain to its maximum.) Both position and velocity signals are also low-pass filtered at a cutoff of roughly 1.5 kHz to cut the feedback path for high-frequency signals caused by electromagnetic interference and picked up by the long cables used.

4.2.4. Microcontroller

This exhibit used a programmable microcontroller, to manage overall exhibit behavior, rather than having a number of mechanical relays and timers. The microcontroller consists of a Microchip PIC 16C84 in conjunction with some additional circuitry designed by Pietro Russo to increase the effective number of inputs and outputs using a simple multiplexing technique, described in more detail in Appendix A.

5. Evaluation

5.1. Initial testing

The exhibit seems to work as designed; the motorized wheel follows the control wheel with dynamics appropriate to the particular selection of position and velocity gains K_θ and K_ω.

Specifically, there are many observations one can make:

(1) Increasing K_θ (by turning the left knob clockwise) makes the bottom (motorized) wheel follows the top (control) wheel more closely. (more gain = less steady-state error.)

(2) Increasing K_θ makes turning the bottom wheel more difficult. (more gain = greater disturbance rejection)

(3) Nonzero K_θ makes turning the bottom wheel feel like it's attached to a spring in that the further the wheel is turned, the harder the wheel tries to turn back. (in a spring, restoring force is proportional to displacement, which is equivalent to proportional position feedback)

(4) Nonzero K_θ makes the bottom wheel act like it's attached to a spring in that if the wheel is disturbed, it springs back and oscillates. Increasing K_θ makes the oscillation occur faster. (in an inertia-dominated system, proportional position feedback yields a second-order system with a resonant frequency that goes up with increased "springiness")

(5) With zero K_θ the left meter (showing position difference) often strays from zero. Changing K_θ to a nonzero value suddenly starts the motor turning until the meter shows zero again. With K_θ nonzero, the meter stays near zero unless the bottom wheel is forced to turn. (steady-state error is made small with proportional position feedback)

(6) Nonzero K_ω (set by turning up the right knob) does not affect how closely the bottom wheel follows the top wheel. (proportional velocity feedback doesn't affect steady-state position error)

(7) With nonzero K_ω and zero K_θ, the bottom wheel tries to follow the *speed* of the top wheel, if not the position. (proportional velocity feedback does affect steady-state velocity error)

(8) Nonzero K_ω also makes the turning the bottom wheel more difficult, but in a different way than in (2); there is a resistance when the wheel is moved quickly, but if the wheel is moved slowly there is no resistance. The larger K_ω is, the larger this resistance to motion is. (proportional velocity feedback works like a dashpot)

(9) Large values of K_ω make the system go unstable; there is a grinding noise, and the wheel vibrates back and forth. (gear backlash in conjunction with velocity feedback causes instability)

(10) With K_ω set to zero and K_θ set to a moderate value (what I call "poor-man's feedback"), step changes in the top wheel are followed fairly well by the bottom wheel, but if the top wheel is spun at low speed, the bottom wheel follows in a jerky manner and there is the sound of the motor slowing, then speeding up, then slowing, then speeding up. (ramp input; resonance without damping causes overshoot, undershoot)

(11) With the situation in (10), if K_θ is turned up, the frequency of the slowing down and speeding up increases. (resonant frequency goes up with increased "springiness")
(12) With the situation in (10), if K_ω is turned up, the motor's rotation becomes more smooth. (more K_ω = more damping)
(13) With any of the situations in (10-12), if the top wheel is given a fast spin, then at first the motor seems to follow it smoothly regardless of K_θ and K_ω as long as K_θ is nonzero. The left meter's pointer moves away from zero. When the pointer becomes near zero again, the slowing down and speeding up re-occurs. (saturation of a component in the feedback path alters the dynamics since the system is no longer acting in a linear fashion)
(14) With poor-man's feedback, if the top wheel is moved back and forth at the right frequency, the bottom wheel moves back and forth much more violently at the same frequency. (resonance yields a large output for a small input)
(15) With the situation in (14), if K_θ is turned up, this frequency increases (resonant frequency goes up with a stiffer "spring")
(16) With the situation in (14), if K_ω is turned up, this oscillation moves less violently. (damping decreases the resonant response)

Further discussion of the performance of the exhibit is best left for the next section; I found that watching other people test it was far more enlightening and interesting than when I did so myself.

5.2. Overview of the evaluation study

5.2.1. Background

Since this exhibit was destined to be placed in Strobe Alley, I thought it best to recruit a number of different people to come and try out the exhibit to see how it was used, and to find out what kind of information needed to be written down alongside the exhibit (the "copy", as the phrase is called in the field of graphic arts) for people to get the most out of the exhibit. The types of people recruited were those that would most likely see the exhibit: MIT students (non-engineers and engineers) passing through Strobe Alley, and adults and high school students visiting MIT.[5] Ten people participated in this study. They are referred to here by letters from A through M.[6] The subjects came from various backgrounds:

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[5] I did not actually solicit visitors but rather recruited non-technical MIT employees and Cambridge high school students for whom the interviews would be more convenient.

[6] Subject B never showed up, and I thought it prudent not to use the letter I (for reasons of grammatical ambiguity: "I was a complete moron. I had no idea what he was doing. He dozed off

A	MIT student, biology major
C	Cambridge high school student
D	MIT employee finishing up master's degree in archaeology
F,G	MIT employees with background in business
H	MIT student, biology major
J	MIT student, architecture major
K	MIT student, biology major
L	MIT student, aero-astro major
M	Cambridge high school student

F and G participated together; the other interviews took place individually.[7]

These interviews were loosely based on Crispin Miller's study of learning through designing in mechanical engineering [Miller], and were not meant to be a formal study but rather to provide some feedback about how people approach the exhibit. From this point of view, the interviews were very useful and revealed many things that would have been impossible to foresee.

The format of the interviews went as follows—I spent about five minutes inquiring into the subject's science background (did they take physics? did they like physics? did they visit the Museum of Science often?). This was followed by a brief description of the setup, since the exhibit copy had not been written yet: that there were two wheels connected to different shafts, one connected to a motor; that the motor was an electric motor; that circuitry was hooked up to try to make the motor turn in such a way that the bottom (motorized) wheel would follow the top wheel; that the two knobs affected this; and that the subject was free to touch anything on the outside of the exhibit box (i.e. the two wheels and knobs). They were then told to begin exploring the exhibit and asked to see what they could figure out, specifically what effects the knobs had on how the bottom wheel followed the top wheel. After fifteen or twenty minutes of this, I gave them some more information about what was going on and asked them to try things that they

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in the middle of the interview; it would be safe to say that I should have stayed home and caught up on the sleep he needed."). I also neglected to use the letter E, for some reason.

[7] The joint interview was an experiment and was the idea of the two subjects themselves. In retrospect this made it more difficult to tell their opinions and ideas apart, but it forced them to communicate with each other and this interaction made it much easier to tell what they were thinking, if not individually than at least collectively, and this far outweighed the drawback of not getting separate results for each of them.

hadn't tried in the first part. This format was adhered to in most cases; occasionally I departed from this plan if the need arose.

5.2.2. General findings

In general, most of the interviews proceeded similarly: people made a lot of good observations but everyone seemed to approach the exhibit as a kind of puzzle, which was a bit of a blunder on my part, considering I did ask them to try to figure out what was going on. I had meant the exhibit as a sort of guided exploration into the nature of servomechanisms, but without the exhibit copy (or a person) to explain what kind of things were happening, this guidance was missing. By the later interviews, I began to realize this and tried to provide hints that might help. All subjects saw the kinds of things I had intended them to see (each of the situations listed in the beginning of the chapter were observed by many of the subjects, either without my assistance or with a small hint), but rarely did any of them come up with ramifications or causes for what they had seen.

I found this surprising and somewhat disappointing; the exhibit did seem to provide quite a bit of informal experience with the way servomechanisms work (for example, several of the subjects noticed that when there was position feedback but not velocity feedback, the bottom wheel followed the top wheel but in a jerky manner that disappeared with the introduction of velocity feedback), but did not seem to provide a clear path to understanding the "big picture." Servos are more remote and complex (conceptually) than I had thought; some of the comments I received from the subjects themselves were that there were a lot of things in the exhibit to consider at once, and that there were things that became much clearer after I gave them an explanation at the end.

After the interviews I sat down and wrote out a list of various concepts associated with servomechanisms, most that came up during the interviews and a few others that did not but which I consider relevant to my own understanding. This evolved into the following diagram, shown in Figure 10:

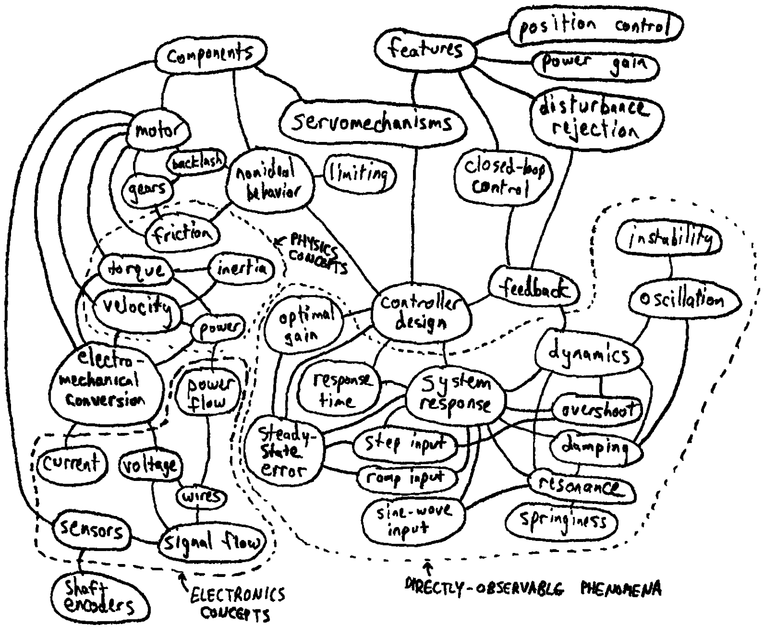

Fig. 10. Part of the author's servomechanism schema. A vast and interconnected set of concepts are needed to understand servomechanisms well. The subset in the lower right marked "DIRECTLY OBSERVABLE PHENOMENA" was what I hoped people would begin to develop from the exhibit. The subsets on the left I had taken for granted in designing the exhibit; these caused confusion for inexperienced users. The upper area of the diagram includes ramifications and subtleties that probably need to be pointed out as they are not apparent unless the user knows what to think about or look for.

Such an associative network is referred to as a "semantic network" in [Hofstadter] and as a "schema" in [Bruer], and I found it useful when analyzing the interviews.

What seemed most apparent was that without critical aspects of the schema, there was enough confusion to prevent the subjects from knowing what was going on. These "pieces of the puzzle" tended to be either electronics concepts and causal information that could not be visually discerned (i.e. that a wire carried position information from a sensor to a circuit board), or physics concepts implicit in a good understanding of motors and rotational motion.

The exhibit did seem especially useful, however, as a cognitive tool, both in getting across concepts and in understanding the way people thought about them.

Several of the concepts in question are discussed in the following sections.

One final note: K is quoted here more often than other subjects, because he was far more articulate about what he was seeing and thinking than others, and therefore his interview provides some very good illustrations of the kind of "roadblocks" that most of the subjects (with perhaps the exception of L and M) encountered.

5.3. Subjects' conceptual difficulties

5.3.1. Connectedness

The largest difficulty seemed to be that people didn't know what was causing what in terms of the individual parts of the system. (Trouble with what was causing what in terms of the whole system was expected.) For instance, several subjects were perplexed that movement of the top wheel caused movement in the bottom wheel (with the knobs turned up) but that moving the bottom wheel did not cause movement in the top wheel. F, and G, in particular, were looking for some kind of mechanical connection; to them, the knobs appeared to be affecting the gearbox of the motor in some way:

> **F:** Well, I was wondering whether there was an adjustment in the gearbox... which...
> **JMS:** An adjustment in the gearbox? What sort of—
> **F:** Well, okay... the more you turn that knob on... or to the right...
> **JMS:** Which knob?
> **F:** ...the more noise, this knob. [points to right knob]
> **JMS:** That one.
> **F:** ...the more noise is being created, which might suggest that there's something that's more tightly... there's a tightening of that, of something against that rod. And that's creating the noise... which in return, might... create more stored energy as something, I don't, I don't know the language, but what do you think?
> **G:** I don't know. I think, I think there is an effect here because this had slowed down so maybe there is, maybe it pulls this enough so that it does affect the gearbox.

K, as well, attributed a change in gearbox behavior to the right knob as well, comparing the increased resistance to motion (when K_ω was increased) to changing gears on a bike; the knobs seemed to control "some variable in the motor, or something."

F and G also spent a great deal of time thinking about power and energy flow that seemed to distract from the remainder of the exhibit. I asked them what they thought was going on, and they immediately turned to this idea of power and energy:

> **G:** Well we know, let's take it from the basic, we're gonna have to go from the basic.
> **JMS:** Okay.
> **G:** We know that the power... the knobs here are bringing the power to the motor, so if you watch where the connection is... Oh. Okay. Let's trace. The wires are coming through... and the wire is connected up here, which, if you look at the red and white wire... say, the power is coming up...

Their attempt to see where the motor power was coming from was thwarted, though, when they traced a wire back to the START button, which had nothing to do with motor power. (In reality, the cables bringing power to the motor and the wires carrying the signals that control the motor's torque are physically separate, which would have introduced more confusion even if they had managed to trace a specific wire back from the motor.) Other subjects were bothered by not knowing how the exhibit knew the wheels' positions. There are a number of paths along which information and power are flowing between different parts of the exhibit; this was an unintended cause of obscurity and attention will be paid to this in developing the exhibit copy.

5.3.2. Rotation and motor torque

I had grossly misjudged the way people think about motors, specifically the separation of power, velocity, and torque. From a system design standpoint, a motor outputs torque based on input current; velocity is something that results from the interaction of torques with a rotating object's inertia; and power is something not directly related to design of a control system but rather an indirect concern, namely how to provide the flow of energy necessary to achieve a desired torque at a certain speed. This was *not* the viewpoint I saw people take during the interviews; several subjects seemed not to consider torque, speed, and power as separate entities. F and G considered the motor almost exclusively in terms of energy:

> **F:** Well, it seems to me that we're having more stored energy when this [the motorized wheel] becomes harder to move, so that somehow the movement of that is creating energy which is being stored in continuing movement

right here so... but this [the control wheel] is no more difficult to move in any scenario... this is constant... C [the control wheel] is constant in terms of moving that, is that correct?
G: That's correct, where M [the motorized wheel] isn't.
F: Where M isn't, so somehow when M is hard to turn, it's going in sync, it's storing energy.

A did think of motors in terms of speed and torque, although she said she considered motors as producing a speed, and that torque was something that the motor exerted when something got in the way of the motor; the motor had to work harder. K did not seem to separate speed and torque at first, until I asked him about it:

JMS: When you think of a motor, what do you think about?
K: I think of... on and off.
JMS: On and off.
K: Yeah.
JMS: Do you mean like, like... whether it's turning or not turning?
K: Right. But I guess it... it can turn in both directions, so that makes sense, so if... if the motor's trying to turn in the opposite direction as I'm turning this, then... then of course it's gonna... become harder for me.

M's conception of motors seemed similar to A's (motors produce speed) and this eventually led to a discussion of why proportional feedback is not "good enough" for the motor-wheel system in the exhibit; initially he was of the opinion that knowing where the wheel was gave enough information for the motor to get to the right place and then shut off, although upon discussing the matter he realized that the motor velocity would not decrease to zero immediately and that it was torque that was being controlled directly, not speed.

These views on speed and torque lead me to believe that a more fundamental exhibit on motors and rotation should probably be developed. For the servomechanism exhibit, I could write out a short paragraph explaining that the motor produced torque (rotational push?) but words alone are not enough to provide good understanding, and even though it is possible to explore motor operation to some extent with this exhibit, there are enough complicating factors in it to warrant a separate and simpler exhibit on motors alone.

5.3.3. Disturbance rejection

Another source of confusion I encountered in the interviews was a kind of surprise that the bottom wheel, when disturbed, felt like a spring or a dashpot (people used the term "resistance" instead; as K put it, like "biking up a hill"). This mode of operation of a motor seemed unfamiliar—motors are things that turn, so what's going on here? A, D, H, J, K, and L all noticed this (C, F, G, and M noticed how difficult it was to turn the bottom wheel but did not seem to recognize that the wheel felt like a spring), K in particular:

> **K:** This winding up is *really* weird, 'cause I... I... I can't imagine, um... I can't imagine what it would be that's, that's building up like that, I'm thinking it would be some sort of, if it's, if we're talking about... what this could be... 'cause it really does feel like a spring, but I really don't think that, that there's a spring here, um... what else could we build up like that... magnetism? 'Cause when it finally does break through that barrier, it does sort of feel like, that you're breaking, like, that, pulling two magnets apart, and they finally come apart, 'cause they give like that.[8]

The springiness (resistance to movement of the bottom wheel away from equilibrium position) of turning up K_θ, and the "resistance" (resistance to movement of the bottom wheel at velocities different than that of the upper wheel) of turning up K_ω are examples of disturbance rejection but were not seen as related to the ability of the bottom wheel to follow the top wheel's position. Here is K again, spelling out what is going through his mind:

> **K:** Um, okay, are these two related? Let me think. Um, let's see, this building up... well, it's obvious to me that, that these two [wheels] are very different, as in, this one is following this one.
>
> **JMS:** The, the motorized one?
>
> **K:** The bottom one is following, right. And the, and the motor is simulating what's going on up here.
>
> **JMS:** Okay.
>
> **K:** And, um... the similarity... I mean, the... the difference... the diff—and as far as this winding [the fact that the motor felt like a spring and could be "wound up], lemme think about this winding, what's causing this winding? It could just be that, playing with the motor, and that... it's... going against what the... I guess the motor can spin either way, and so when I start manually cranking it, it's sort of, uh... well, it's doing work back, so that it always wants to go, I mean, it's just the motor is... stiff, in that it's always gonna resist, 'cause... because, uh....
>
> **JMS:** Here's another suggestion—why don't you try playing with the knobs a little bit, yeah.

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[8] The "barrier" K refers to is a phenomenon caused by the position counter wrapping around; upon continued turning, the position difference suddenly jumps from a positive to a negative number and with nonzero K_θ, motor torque suddenly switches direction.

K: Okay, let's see if I can change this... so we have a right and a left, this one's already on, right?

JMS: Yeah.

K: [turns left knob all the way down] So that's off. So... see if we can crank this [left knob] all the way up, let's see... [The bottom wheel oscillates a bit.] Those lights are going wild. [Gives top wheel a good spin, watches bottom one follow.] Is that going for longer? [Turns off left knob, spins top wheel, bottom one doesn't follow.] Aha ... [turns on left knob, bottom wheel suddenly tries to catch up to top wheel] Whoa. [turns knob off and on] This just seems like it's the power source for... this bottom one.

JMS: The, the [left] knob?

K: Yep. [spins top one again] Yeah. So yeah, [spins top one again, bottom wheel follows, turns left knob off, bottom wheel slow to halt but top one keeps on going] you can totally stop that one. [turns knob on again, turns it up slowly] So it's saying how closely it's gonna follow that top one. [Moves top wheel]

JMS: Hmm.

K: Yeah, 'cause when it's low, it doesn't quite mimic the top one, but then when you increase it, it starts following it better.

JMS: What about the, uh, the effect it has on when you turn the... bottom one.

K: Ah.

JMS: Try that.

K: Is there more tension? It feels like there's going to be a lot more tension... hmmm, maybe not. [bottom one gives way, doesn't spring back]

JMS: Oh—oh, yeah, ha ha, you... no, um, the exhibit is set to turn off after about eight minutes, so you have to hit this... um, hold on for a second. [presses START] Yeah, just give the top wheel a spin.

K: Oh, I see. Oh, I have to give the top wheel a spin. [spins top wheel, bottom wheel follows]

JMS: There you go.

K: It turns off every eight minutes?

JMS: [sheepishly] Yeah.

K: Okay, let me see [tries to stop bottom wheel with hand, there is the sound of plastic rubbing past skin] if this has a lot of resistance, I bet you it does. [smiling] Oh, god. This is a very scary machine. Uhhh! [works hard to wind lower wheel around] Oh, that's not too bad. Is this going to explode when I wind this up—

JMS: Yeah, yeah, watch out [position difference meter shows about six or seven revolutions of the wheel have elapsed] right, right about now—

[Motor torque suddenly switches direction, wheel lurches free of K's grip. K laughs, motor wheel gets to next equilibrium and oscillates around that point a little.]

K: Hey, why'd it stop? [winds up motor wheel, lets go, wheel again undergoes underdamped oscillation which is more rapid than when K_θ was smaller; K seems to see the fact that the wheel doesn't oscillate for as long a time as "stopping", even though the motion is still as underdamped as before.] I don't like the way that stops [repeats winding up the motor].

JMS: What don't you like about it?

K: [laughing] 'Cause I want it to like, slowly wind down. [mumbles] See that? It just like—oops, I keep pulling on this thing—it just goes, and then it just stops, and then, um, so what is this [left knob] increasing, then? This is

> increasing... it has something to do with this going, something to do with the motor... in that it's changing the amount... of work... I guess, that's, uh, necessary to do things. Hmmm.

K observes what is going on, but he's not sure what's causing it, or what it means, exactly. At the end of the interview, I explained to K that the position difference and velocity difference were being used to drive the motor to follow the upper wheel as well as to bring the lower wheel back after being disturbed, and he seemed to understand (I was searching for a word to describe the situation, and he said "compensate" before I could finish my sentence) yet was still unsure how the motor could make the wheel feel like a spring.

This kind of confusion does not seem like it can be remedied simply by a clear explanation, although that would help, and certainly the phenomenon should be pointed out.

5.4. The exhibit as a discussion tool

The next three sections talk about ancillary behavior of the exhibit. While this is not directly related to the core servomechanism/feedback concept, such behavior does fit into the big picture and is part of a good understanding of servomechanisms; I used the phenomena as a jumping-off point to get a discussion going. These sections are included to illustrate how the exhibit might be useful as a tool to exploration.

5.4.1. The educated user

L provided a very interesting interview: he was an aero-astro major at MIT but had spent his junior year abroad in France and had taken a controls course there, one that was heavy on theory and had little hands-on or practical components, so he had never seen a servomechanism yet was familiar with the language and mathematics needed to understand one. Although he had some of the same difficulties as other subjects in terms of not knowing what was going on, when he was given pieces of information he did not take long to connect them with what he already knew about control systems.

Towards the end of the interview, after I had revealed the function of the meters and knobs, there were a few situations I posed for L to try to explain. Here is one of them (situation 13 as listed in the beginning of this chapter):

> **JMS:** [after setting K_θ to a moderate value and K_ω to zero] You spin the top one, the bottom one spins, and then all of a sudden it sort of, like, stops spinning, and... does something... and... can you look at the, if you look at the meter [that shows position difference] and do that again [spin the top one]...
>
> **L:** Mmm-hmmm.
>
> **JMS:** Could you possibly explain... why it's doing that... that probably wasn't too clear of a question...
>
> **L:** So for a while, the velocity's the same, and then all of a sudden it... there's a difference, and then it reacts to that, slows up and down, slows up and down...
>
> **JMS:** What's happening when... ummm... hmm, this is kind of a trick question... the... do you think the motor can provide infinite torque on the shaft?
>
> **L:** Uh... [laughs] no...
>
> **JMS:** So what happens once it hits its limiting value—
>
> **L:** Okay, so, so when I... yeah... so when I spin the top one really fast, there's a disp— there's a position difference, so the velocity... it puts as much torque on it as it can, and the velocity reaches some limiting factor, and... as the top one slows down, then the bottom one gradually catches up to it in position, and once it gets to the same position, then it turns off the velocity. Then when the velocity differential is... is around the same... or, no, it's not the same... well, once it, once it catches up, the bottom... the velocity jumps [the bottom wheel goes in spurts] when the displacement is zero... 'cause—
>
> **JMS:** The velocity jumps...? You mean—
>
> **L:** The... the displacement gradually goes down... and then when it gets to zero, then... that's when it starts doing funky stuff.
>
> **JMS:** Oh, you mean the oscillation.
>
> **L:** Yeah.

This situation is something called "synchronization" or "startup"; errors in the system that would normally be driven to zero are very large and an element in the system saturates (here the power amplifier is putting the full supply voltage across the motor and the motor is going as fast as it can) until the error term decreases enough for that element to be brought out of saturation and into its linear regime, at which point the system re-enters its normal behavior. L has his own way of thinking about the situation, some of which is not quite correct (he seems to think normal behavior does not re-occur until the position difference is zero, rather than when it is at the maximum value for which the power amplifier can operate in a linear fashion), but the important point is that he has *some* way to understand it, at which point a formal explanation could be brought in to help him further his theoretical understanding and connect it with this first-hand experience.

5.4.2. The "clueful" user

M's interview surprised me quite a bit; he was essentially the only subject to see some ramifications of the parts and the whole of the exhibit. He did not have the formal training to understand control theory, yet was quick enough to catch on to what he was seeing, that I was able to have a conversation with him (unfortunately after the recorded interview had ended, so I do not have a direct quote) about why proportional-differential feedback was "better" than proportional feedback alone. In fact, this idea of "better" came up earlier in the interview, when he was deciding what the "best" position of the knobs in order to make the bottom wheel follow the top wheel. At first he just stated what he thought the best positions for K_θ and K_ω were, but then he hesitated:

> **M:** Well, I mean, best is sort of subjective.
> **JMS:** Okay, yeah, what are you using as sort of a "best"?
> **M:** By best I'm sort of thinking of most quickly and regardless of what else is happening.

In technical terms, M is looking for the fastest response time (and was in fact the only one to think of the motor's response explicitly in terms of time; many subjects seemed content to have the steady-state error be zero) and the smallest compliance to disturbances.

M also connected the exhibit back to his experience in other areas: the optical encoder reminded him of something he had seen on the inside of a hard disk drive (apparently a moirè pattern used to detect the radial position of the arm connected to the drive head). When I mentioned how feedback could be used to correct for the deficiencies in a driving system because generally sensors were more accurate than actuators, he was reminded of some new kind of speaker he had heard of, where an accelerometer was placed on the woofer to sense the speaker's vibration (I'm not sure what the function of this would be; perhaps to correct for bass distortion).

In short, M seemed to incorporate what he had seen in the exhibit into his first-hand experience. M has not yet heard of transfer functions and is not familiar with second-order dynamics in a system, but if he gets to that point in his education he will probably have a base to build on, from experiences like these.

5.4.3. The naïve user

F and G had very little training in science at all; there were concepts that I had trouble talking to them about because I didn't know what wording to use or how to explain something to them without going off on tangents to more basic concepts (like the torque/speed/power confusion discussed earlier). However, their interview was useful as a way to see where confusion was occurring, and an experienced teacher might be able to use such a discussion to develop alternative explanations or demonstrations.

I had brought up the topic of resonance (without using the word) by setting K_θ to a moderate value, turning K_ω to zero, and shaking the top wheel back and forth:

> **G:** Oh my goodness, M is going on its own... M is going off on its own—look at that stored energy, look at the red light.
> **JMS:** Now if I turn that knob [the left knob] up try that... is that any different?
> **G:** It's more following the C.
> **JMS:** What do you think the left knob is doing? How does that affect it... if I turn it down?
> **G:** I wonder if the left knob is controlling, is bringing M more into line with C. Right now they're out of sync.
> **F:** Let's go all the way over. [turns up K_θ] Are they in sync now?
> **G:** They're closer in sync. So that has something to do—
> **F:** That's all the way up.
> **G:** All the way up, bringing M into line with C.
> **F:** Okay, could you go back and forth, like shh-shh-shhh-shhh and see what happens?
> **G:** No, it's still in line, still in sync.
> **F:** Yeah.
> **JMS:** If I turn that knob, if I turn that back where I had it before, so it was—
> **G:** See, it's going on off on its own, M is going off on its own.
> **JMS:** Okay, now I'm going, now I'm gonna turn the right one up a little bit, try that again.
> **F:** Yeah.
> **JMS:** If I turn it up some more...
> **G:** See, M is going off on its own.
> **F:** Yeah. [mumbles something]
> **G:** There is, there seems like a little more stored energy in M.

JMS: Okay, so there's energy, energy stored in the motor?
F: Energy stored [points to right knob], and here's alignment control [points to left knob].
JMS: Okay, so the left one controls alignment... and the right is... huh.

Unfortunately, the discussion slipped back into the "What are the knobs doing?" question rather than "Why is the wheel going off on its own?"; I think if F and G had known more about how the exhibit operated, then the exhibit might have been a useful tool to explore resonance, although perhaps this is too much like using a calculator to add 2 and 2 (which I have seen high school freshmen do); a simpler demonstration with springs and dashpots would suffice and would probably be a bit clearer.

In all three of these cases, however, it seemed clear that the exhibit was a good tool for discussion, allowing both experienced and inexperienced students to express their ideas and conceptions through *doing* something rather than just talking about it or writing it down on paper.

6. Conclusions

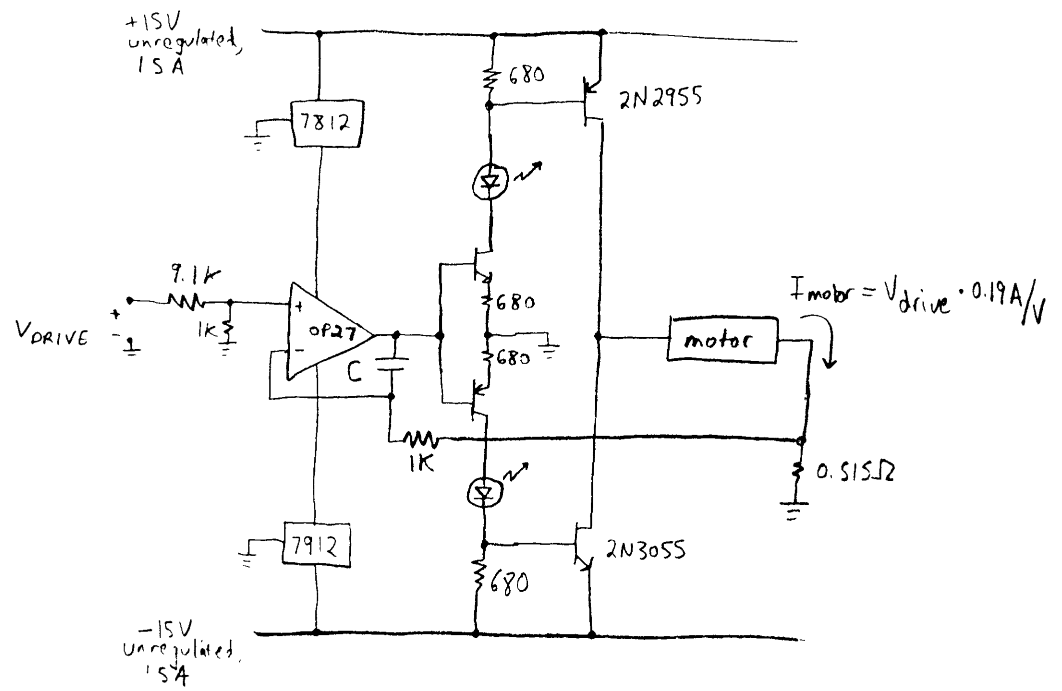
The servomechanism exhibit described in the preceding chapters was designed as a clear and insightful way to understand servomechanisms through qualitative exploration of a variable-gain PD feedback position control system. When it was tested by typical users, however, the "clear and insightful" quality of the exhibit did not seem to appear at first.

The exhibit did seem to be an excellent tool for observation of servomechanism concepts for people with a variety of backgrounds. The kind of reasoning necessary to understand the resulting observations, to see why something is happening and to comprehend its significance, cannot be provided by the exhibit alone; good copy is in the process of being written to provoke the kinds of thinking that inexperienced users might not be able to produce on their own.

Another way of using the exhibit is as a tool to discuss resultant phenomena (resonance, backlash, limiting) or deeper issues (proportional vs. PD feedback) in conjunction with an "expert" who is well aware of these.

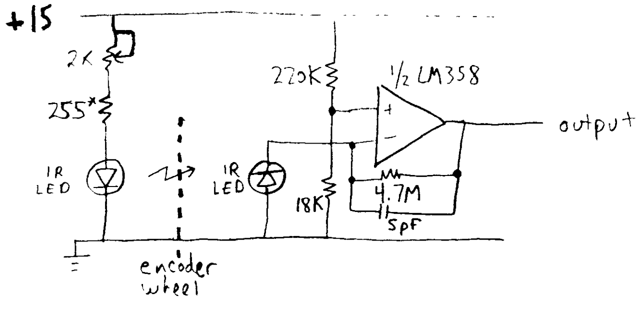
Future research might include developing a series of more basic exhibits: one on motors and rotation to help point out the separate natures of torque and speed, perhaps another on quadrature encoders, perhaps a few more on electrical circuits, signals, and power. Perhaps the reader has some ideas of his own.

Appendix A. Circuit diagrams



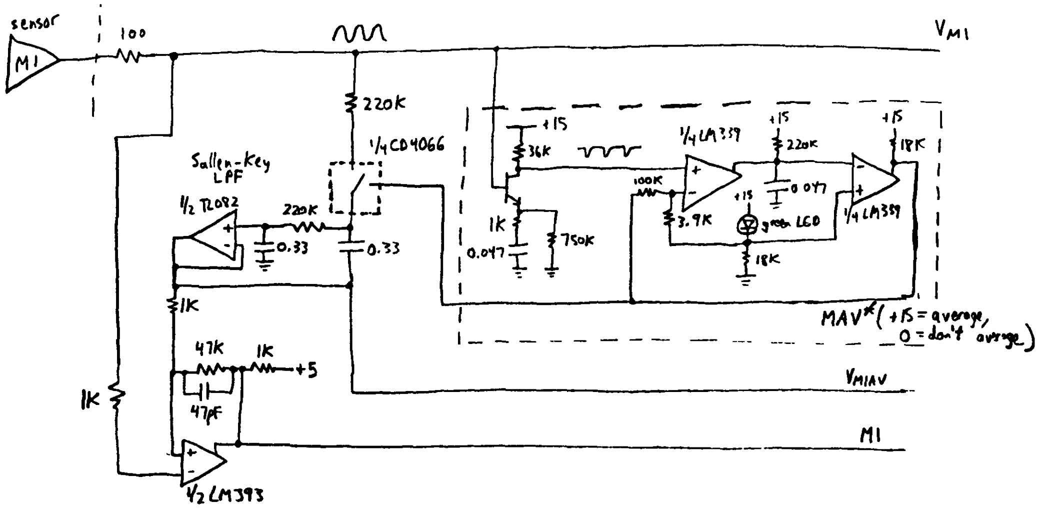
C = 4700pf to roll off gain at high frequencies

Fig. 11. Power amplifier.



* Two ½W, 510Ω resistors in parallel.
The 2K pot here is used to adjust the output amplitude

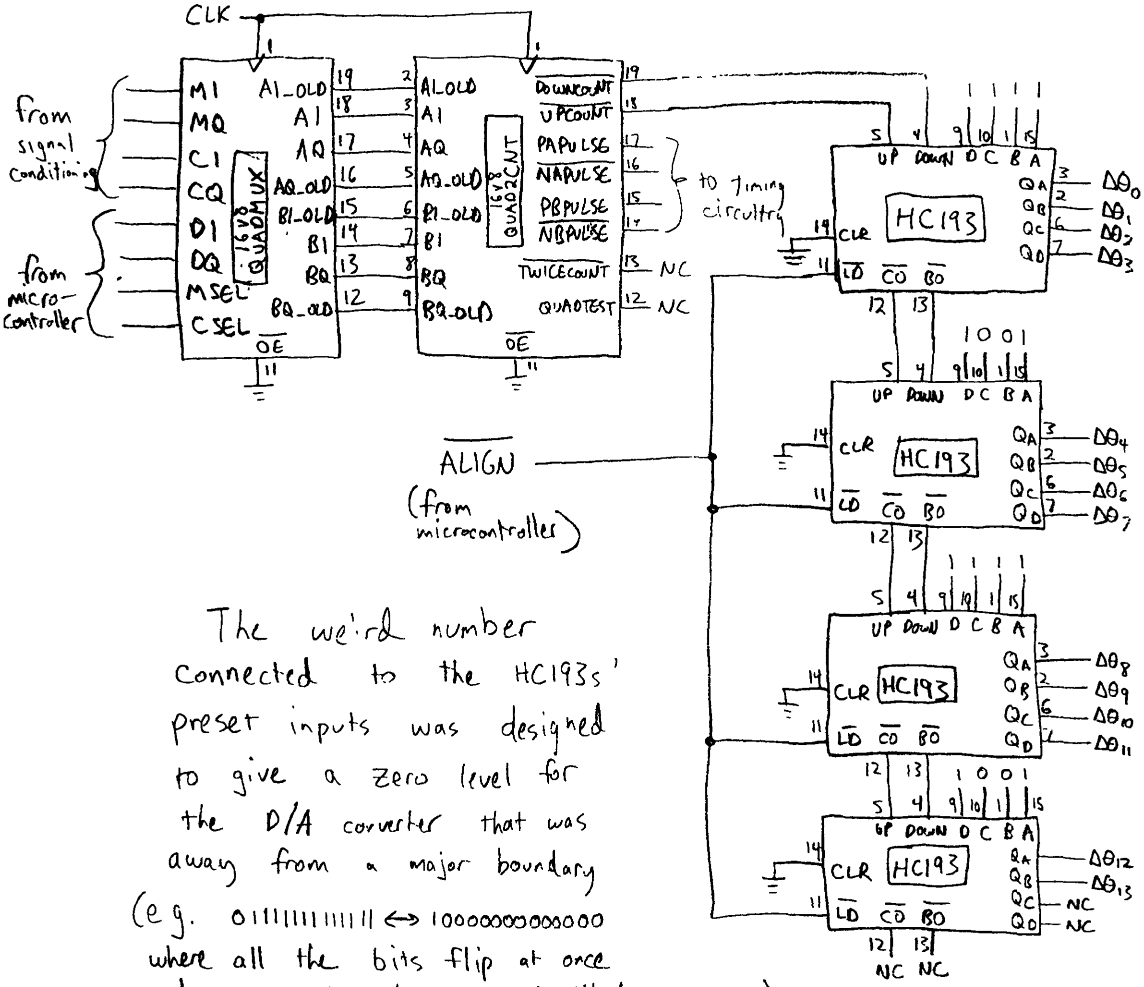
Fig. 12. Shaft encoder sensor.



*MAV is obtained from V_{M1} but serves as a control voltage for the CD4066 in the averaging circuit for both V_{M1AV} and V_{MQAV}, and similarly for CAV (obtained from V_{C1} but used for V_{C1AV} and V_{CQAV}), so there are only 2 of the circuit inside the dashed line.

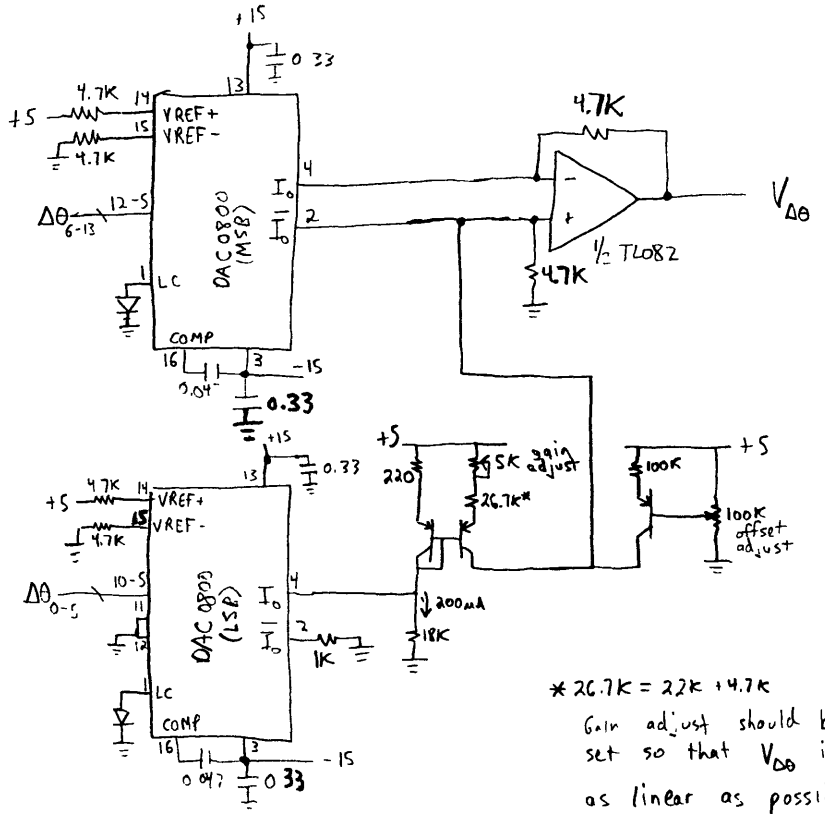
Fig. 13. Averaging and squaring-up circuitry. One of four circuits, shown here for the MI sensor; MI and MQ form a quadrature pair for the motorized wheel, and CI and CQ form a quadrature pair for the control wheel.

The encoder sensors shown in Figure 12 have unpredictable and possibly slowly-drifting (due to changing temperature, long periods of time, plate tectonic movement, etc.) DC offsets, so to get a good average value, their signals are averaged when the wheels are moving at moderate velocities to ensure accuracy in subsequent circuitry. Most notably they are used to make sure the resulting digital encoder signals are 50% duty-cycle square waves. The circuit shown in Figure 13 does work adequately, although proper design would probably use some kind of sample/hold circuit instead of my analog-switch-plus-low-pass-filter implementation. Also, the circuit in the dashed box, which determines whether the encoder signals are of a high enough frequency to warrant averaging, should be replaced by some sort of frequency-to-voltage setup in a proper design. Or there's always the possibility of using commercial sine-wave optical encoders with known DC offsets.



The weird number connected to the HC193s' preset inputs was designed to give a zero level for the D/A converter that was away from a major boundary (e.g. 01111111111111 <-> 10000000000000 where all the bits flip at once and non-monotoriety is most likely to occur)

Fig. 14. Position difference register.



* 26.7K = 22K + 4.7K

Gain adjust should be set so that $V_{\Delta\theta}$ is as linear as possible for a digital ramp input

Fig. 15. Digital-to-analog converter.

The digital-to-analog converter uses two 8-bit D/A chips to make up a 14-bit D/A converter with offset and gain trimming to ensure linearity of the resulting output. Proper design practice would be to purchase a high-resolution D/A converter, but part availability and cost constraints led me to design it this way.

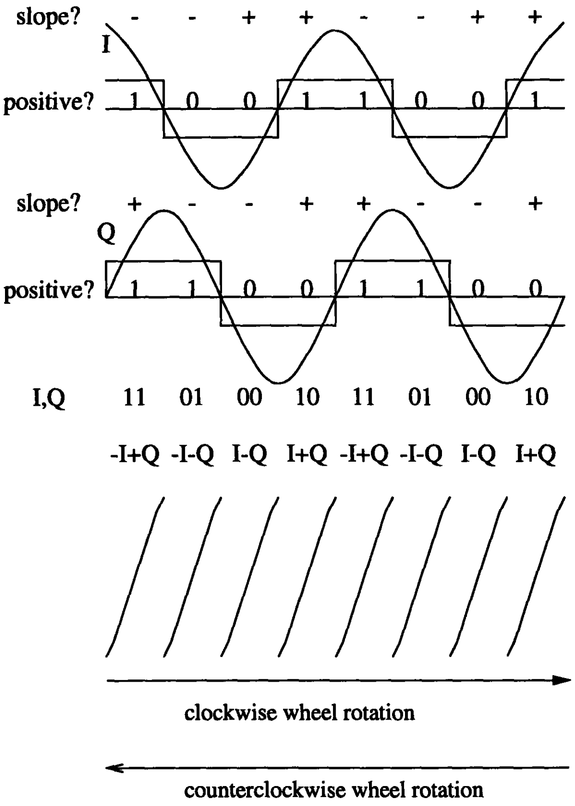
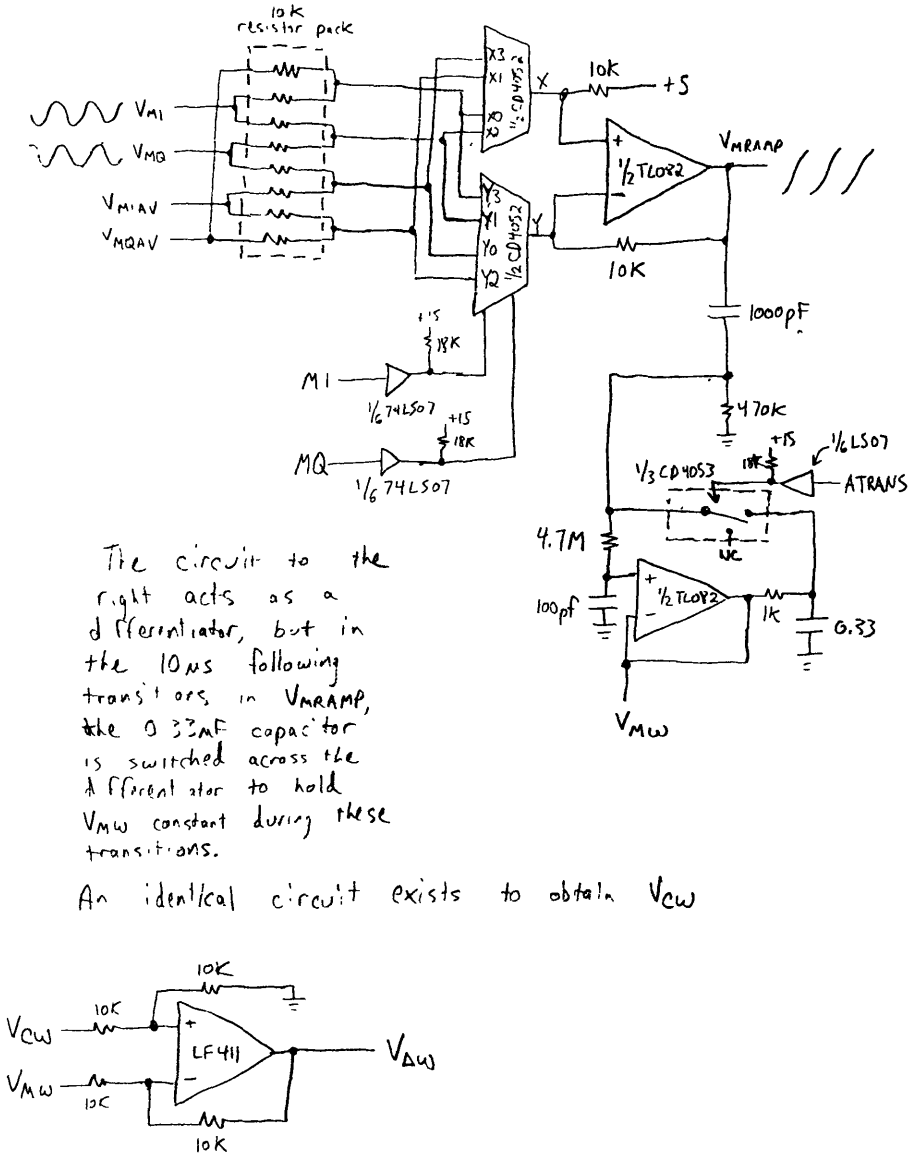


Fig. 16. Quadrature to sawtooth transformation

By adding or subtracting the quadrature signals properly (as shown in Figure 16), the resultant sum is approximately a sawtooth signal, which provides analog information about the position of the wheel within each phase. (Digital information is constant within each phase). [Yokote, Watanabe, 1990] In phase 01, for instance, the I signal is negative and decreasing (for clockwise rotation), and the Q signal is positive and decreasing. Since both signals are decreasing for clockwise rotation, adding the negation of each results in a signal that is increasing for clockwise rotation. For perfect input waveforms, the resultant waveform is a sine curve from -45° to 45°. Yokote and Watanabe use this as a nonlinear sensor for position within each phase; this is used for feedback stabilization and the exact slope is less critical than the waveform's smoothness and monotonicity. Here I have used the waveform to obtain a measure of velocity; with the exception of transition periods in the waveform (when the digital quadrature signals change state), the slope of the waveform has a ripple of about 14% for sine-wave inputs, and can be used to determine the to determine the velocity of the wheels, by using the modified differentiator shown in Figure 17. This is essentially just a plain RC differentiator with a clamping capacitor to remove the effect of transitions in the sawtooth.



The circuit to the right acts as a differentiator, but in the 10 μs following transitions in V_{MRAMP}, the 0.33μF capacitor is switched across the differentiator to hold V_{MW} constant during these transitions.

An identical circuit exists to obtain V_{CW}

Fig. 17. Velocity-determining circuitry.

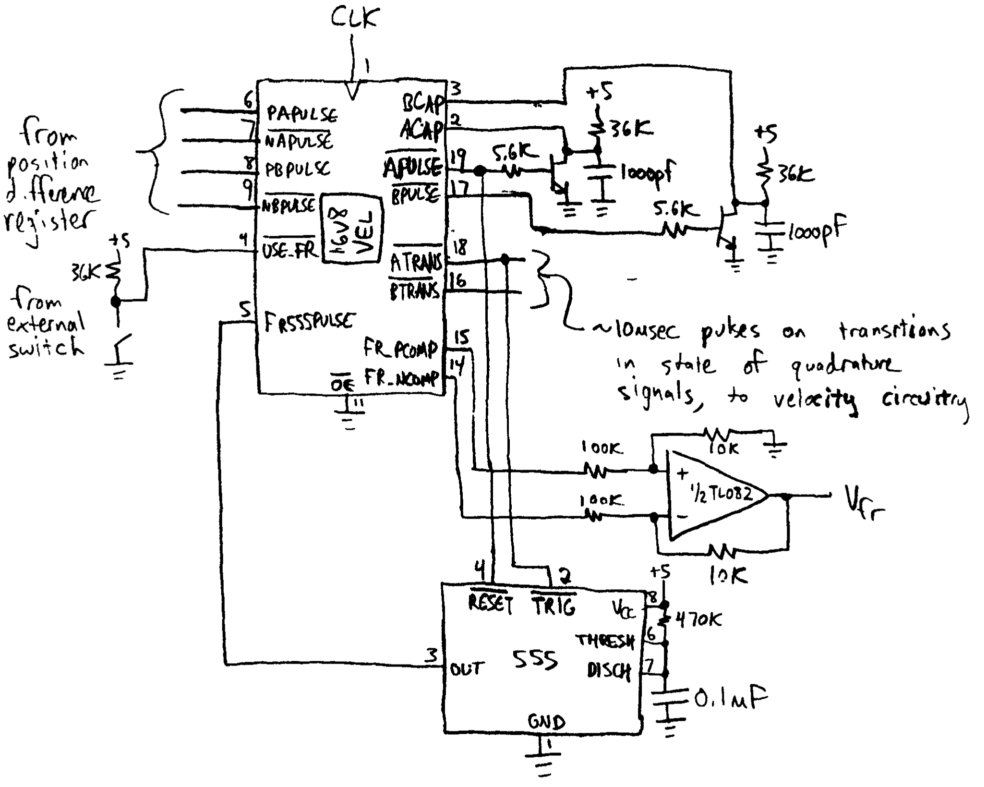


Fig. 18. Timing circuitry.

The timing circuitry in Figure 18 produces 10 microsecond pulses for the velocity-determining circuitry, and 20 millisecond retriggerable pulses for the friction-compensation circuitry. This is *not* good design but there was little board space remaining and I did not have enough room to use three monostables. Proper design would be to use an LS221 or other such one-shot, or even better, to produce a digital delay and not muck around with capacitors.

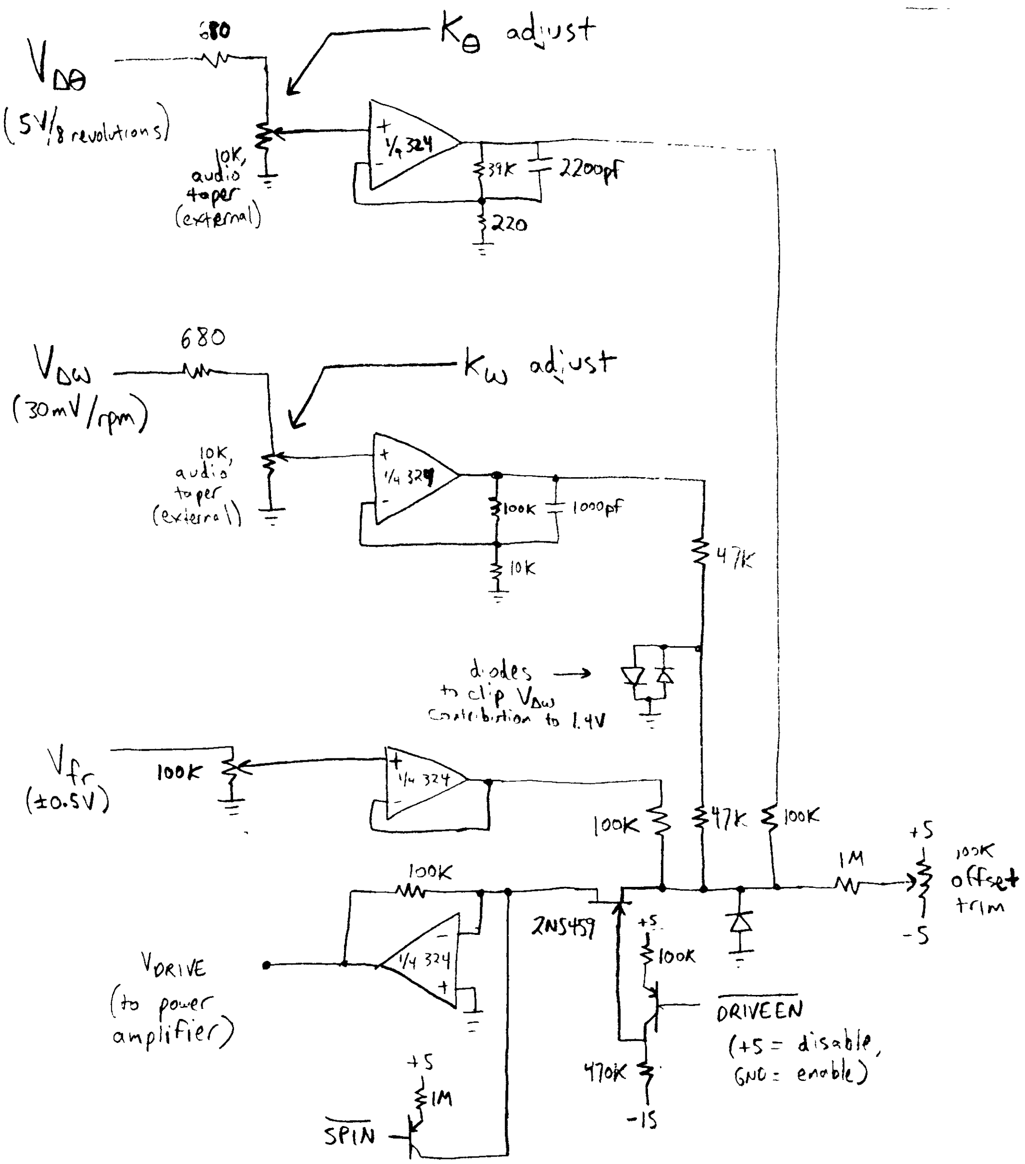


Fig. 19. Feedback circuitry.

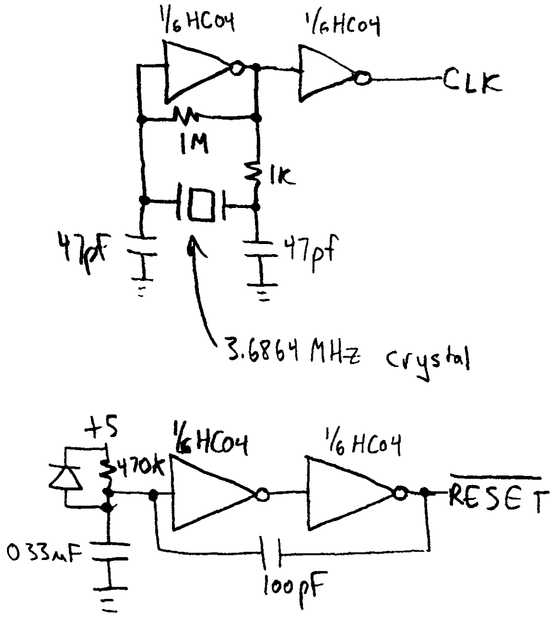


Fig. 20. Miscellaneous circuitry. Reset and clock signal generators—things that are very hard to design improperly. The 100pf capacitor in the reset circuitry is used to provide positive feedback.

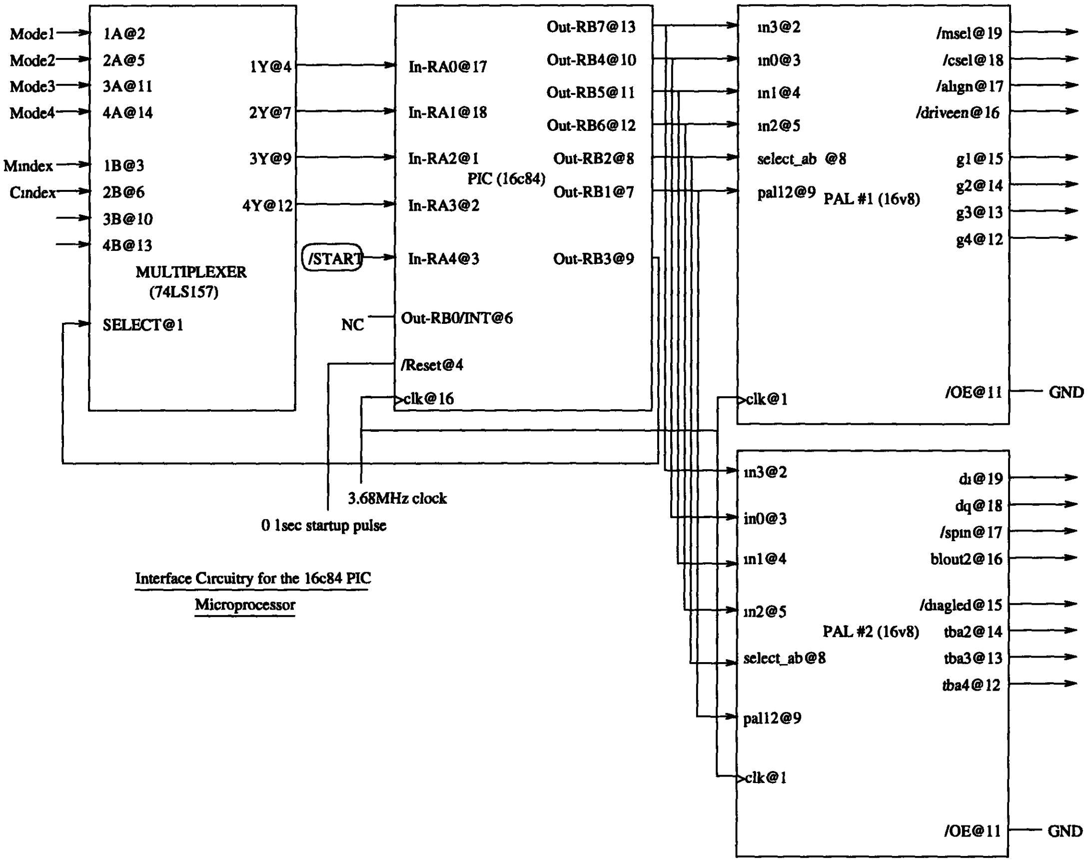


Fig. 21. Microcontroller. The microcontroller consists of a Microchip electrically-erasable 16C84 chip with multiplexing circuitry. (Courtesy of Pietro Russo)

The microcontroller shown in Figure 21 is an inexpensive way to control the overall behavior of the exhibit. There are a number of control signals that enable the motor, reset the position difference register, and so on. In order to make this flexible, I used a Microchip PIC 16C84 controller, available for about ten dollars. It is a bit simpler than chips like Motorola's 68HC11 or Intel's 80C196 microcontrollers; these are PLCC chips with around 40 pins with lots of features and are meant to be used with supporting circuitry (EPROMs, RAM, a serial interface, etc.). The 16C84 has 13 input/output pins, which are not quite enough to handle all the signals for this project, so Pietro Russo, a sophomore in electrical engineering, designed a multiplexing system to increase the effective number of inputs and outputs.

A dual 4-input multiplexer (74LS157) receives input signals and outputs (specifically, the mode bits which connect back to a multi-position switch on the outside of the exhibit, as well as the index signals that tell if the shafts are in their starting position) to four of the inputs on the 16C84's A port. The remaining pin on the A port is connected to the START signal, which connects to a button on the exhibit that a user presses when he or she wishes to start the exhibit.

The outputs come from two PAL (programmable logic array) chips, and are essentially four 4-bit registers; four of the pins from the 16C84's B port represent those data bits, and two more of the B pins are used to select which register is currently active. One other B pin is used to select the bank of inputs used on the 74LS157, and the remaining B pin is unused.

The B byte has the following format, then:

bit								effect
7	6	5	4	3	2	1	0	
d3	d2	d1	d0	isel	osel1	osel0	unused	selects the input bank isel and the output register [osel1,0]
1	0	1	1	0	1	1	x	selects input bank A and sets output register 11 to 1011
0	1	0	0	1	0	1	x	selects input bank B and sets output register 01 to 0100

The registers are assigned as follows:

register	bit			
	3	2	1	0
`00`	driveen	align	csel	msel
`01`	blout2	spin	dq	di
`10`	g4	g3	g2	g1
`11`	tba4	tba3	tba2	diagled

So, for instance, when the lines `movlw 0x4a` and `movwf PORTB` appear in the microcontroller code, the pattern 0x4a = `0100 1010` is sent to the B port. This selects input bank 1 (bank B) and sets output bank 01's register to be 0100. This sets `di`, `dq`, and `blout2` to be disabled and enables `/spin`.

Appendix B. Code

quadmux.eqn

Quadrature-signal multiplexer PAL

```
device 16v8;
'Jason M. Sachs
'Thesis work: quadrature -> clock pulse converter
positive mi@2, mq@3, ci@4, cq@5;
         ' raw input signals from motor and control wheels
positive di@6, dq@7;
         ' digital controller's substitute for ci + cq
negative msel@8, csel@9;
positive register
         ai@18, ai_old@19,
             ' in-phase A
         aq@17, aq_old@16,
             ' quadrat. A
         bi@14, bi_old@15,
             ' in-phase B
         bq@13, bq_old@12;
             ' quadrat. B
ai_old = ai;
aq_old = aq;
bi_old = bi;
bq_old = bq;
ai = mi * msel + ai * /msel;
aq = mq * msel + aq * /msel;
bi = ci * csel + di * /csel;
bq = cq * csel + dq * /csel;
```

quad2cnt.eqn

Quadrature-signal to count pulse PAL

```
device 16v8;
'Jason M. Sachs
'Thesis work: quadrature -> counter pulse converter
'             for two differential channels
'       (equal movements in opposite senses should
'             provide no net change in the counter)
positive
         ai@3,
         ai_old@2,
             ' in-phase input A
         aq@4,
         aq_old@5,
             ' quadrat. input A
         bi@7,
         bi_old@6,
             ' in-phase input B
         bq@8,
         bq_old@9;
             ' quadrat. input B
' these pins were chosen to match the LS374 outputs.
positive papulse@17;
             ' + pulse on the "a" signal
negative napulse@16;
             ' - pulse on the "a" signal
positive pbpulse@15;
             ' + pulse on the "b" signal
negative nbpulse@14;
             ' - pulse on the "b" signal
negative register downcount@19;
negative register upcount@18;
```

```
negative register twicecount@13;
positive quadtest@12;
napulse = aq_old * /ai_old * ai
       + /ai_old * /aq_old * aq
       + /aq_old * ai_old * /ai
       + ai_old * aq_old * /aq;
papulse = /aq_old * /ai_old * ai
       + ai_old * /aq_old * aq
       + aq_old * ai_old * /ai
       + /ai_old * aq_old * /aq;
pbpulse = /bq_old * /bi_old * bi
       + bi_old * /bq_old * bq
       + bq_old * bi_old * /bi
       + /bi_old * bq_old * /bq;
nbpulse = bq_old * /bi_old * bi
       + /bi_old * /bq_old * bq
       + /bq_old * bi_old * /bi
       + bi_old * bq_old * /bq;
upcount = papulse * /pbpulse + nbpulse * /napulse
           + twicecount * upcount;
downcount = pbpulse * /papulse + napulse * /nbpulse
           + twicecount * downcount;
twicecount = napulse * pbpulse + papulse * nbpulse;
 ' double pulse in the same direction
quadtest = (ai * aq + /ai * /aq);
 ' test the phase difference by low-pass-filtering this signal
```

vel.eqn

Velocity-discriminator and timing-pulse PAL

```
device 16v8;
'Jason M. Sachs
'Thesis work: velocity-circuit controller + misc stuff
positive papulse@6,
 pbpulse@8;
negative napulse@7,
 nbpulse@9;
' decoded pulses for the two channels
positive acap@2,
 bcap@3;
negative register apulse@19,
  bpulse@17;
' pulses in either direction  (registered)
negative register atrans@18,
        btrans@16;
' low on transitions (1 clock period preceding edges in the xx_old
'                     phase signals as well as 1 clock period after)
negative use_fr@4;
positive fr555pulse@5;
positive fr_pcomp@15;
positive fr_ncomp@14;
define intapulse (papulse + napulse)
define intbpulse (pbpulse + nbpulse)
atrans = atrans * !acap + intapulse;
' begin transition when either pulse happens.
' end transition when the capacitor charges up.
btrans = btrans * !bcap + intbpulse;
apulse = intapulse;
bpulse = intbpulse;
define timeup (!fr555pulse & !atrans)
' the 555 used is triggered by atrans and produces a pulse of about
        ' 20 milliseconds.
fr_pcomp = use_fr * (fr_pcomp * !napulse * !timeup + papulse * !fr_ncomp);
' begin with a positive pulse & we're not in negative compensation.
' end if we get a negative pulse (reverse direction)
' or if the capacitor charges up & it's time to stop.
fr_ncomp = use_fr * (fr_ncomp * !papulse * !timeup + napulse * !fr_pcomp);
```

uctl1.eqn

Microcontroller interface PAL #1

```
device 16v8;
'Pietro Russo
'urop work: outputs of powerful pic processor processed in this place
'servo-motor project
'pal#1
positive in3@2, in0@3, in1@4, in2@5;
'input signals will be either:
'tierA /msel /csel /align driveen respectively
'tierB /4 outputs to gain circuitry
positive blah6@6, blah7@7;
'not used as of now but might be inputs in future
positive select_ab@8, pal12@9;
'select_ab will choose between tierA (if set to low) and teirB (if set to high)
'pal12 will choose between this pal (pal#1) if set to low or the other one if high
negative register
  msel@19,
  csel@18,
  align@17,
  driveen@16;
'these are negative logic signals
negative register
  g1@15,
  g2@14,
  g3@13,
  g4@12;
'these 5 along with the other 3 above are the outputs and are registered so that
'they will hold their value until called upon to change
'note: you will need to send 4 signals even if you only want to change one
'this will be apparent by the following code:
msel = /pal12 * /select_ab * in0  +  /pal12 * select_ab * msel  +
        pal12 * msel;
'if pal12is low this means this pal is selected and so the first two terms become active
'then if select_ab is low this means tier 1 is selected and so the output becomes whatever
'is at in1.  If pal12 is high term 3 is active and it holds the previous value
csel = /pal12 * /select_ab * in1  +  /pal12 * select_ab * csel  +
        pal12 * csel;
align = /pal12 * /select_ab * in2  +  /pal12 * select_ab * align  +
         pal12 * align;
driveen = /pal12 * /select_ab * in3  +  /pal12 * select_ab * driveen  +
           pal12 * driveen;
g1 = /pal12 * select_ab * in0  +  /pal12 * /select_ab * g1  +
      pal12 * g1;
g2 = /pal12 * select_ab * in1  +  /pal12 * /select_ab * g2  +
      pal12 * g2;
g3 = /pal12 * select_ab * in2  +  /pal12 * /select_ab * g3  +
      pal12 * g3;
g4 = /pal12 * select_ab * in3  +  /pal12 * /select_ab * g4  +
      pal12 * g4;
```

uctl2.eqn

Microcontroller interface PAL #2

```
device 16v8;
'Pietro Russo
'urop work: outputs of powerful pic processor processed in this place
'servo-motor project
'pal#2
positive in3@2, in0@3, in1@4, in2@5;
'input signals will be either:
'tierC DI DQ blout1 blout2 respectively
'tierD TBA1 TBA2 TBA3 TBA4
positive blah6@6, blah7@7;
'not used as of now but might be inputs in future
positive select_ab@8, pal12@9;
```

```
'select_ab will choose between tierA (if set to low) and teirB (if set to high)
'pal12 will choose the other pal if set to low or this pal (pal#2) if set to high
positive register
  di@19,
  dq@18;
negative register
  spin@17,
  blout2@16;
negative register
  diagled@15,
  tba2@14,
  tba3@13,
  tba4@12;
'these are the outputs and are registered so that
'they will hold their value until called upon to change
'note: you will need to send 4 signals even if you only want to change one
'this will be apparent by the following code:
di =  pal12 * /select_ab * in0  +  pal12 * select_ab * di  +
     /pal12 * di;
'if pal12is high this means this pal is selected and so the first two terms become active
'then if select_ab is low this means tier 1 is selected and so the output becomes whatever
'is at in1.  If pal12 is high term 3 is active and it holds the previous value
dq =  pal12 * /select_ab * in1  +  pal12 * select_ab * dq  +
      /pal12 * dq;
spin = pal12 * /select_ab * in2  +  pal12 * select_ab * spin  +
        /pal12 * spin;
blout2 = pal12 * /select_ab * in3  +  pal12 * select_ab * blout2  +
          /pal12 * blout2;
diagled = pal12 * select_ab * in0  +  pal12 * /select_ab * diagled  +
     /pal12 * diagled;
tba2 = pal12 * select_ab * in1  +  pal12 * /select_ab * tba2  +
     /pal12 * tba2;
tba3 = pal12 * select_ab * in2  +  pal12 * /select_ab * tba3  +
     /pal12 * tba3;
tba4 = pal12 * select_ab * in3  +  pal12 * /select_ab * tba4  +
     /pal12 * tba4;
```

uctl.asm

Microcontroller code

```
#define __16C84
#include <pic.inc>
; Base program
; Jason Sachs 4/28/96
; This program does the following:
; Wait for start signal.
; Spin motor, wait for motor index signal to cycle on and off,
; switch in motorized shaft's quadrature signals
; Flash LED to indicate user should spin control wheel, wait for control
; index signal to cycle on and off, switch in control shaft's quadrature
; signals
; Begin normal operation, sit here for about 4 minutes, then wait for
; start signal again and repeat.
; defs for setting which bank of registers are being used
#define PAGE0 bcf STATUS, 5
#define PAGE1 bsf STATUS, 5
; shorthand stuff
;define registers that will be used
#define jwr 0x0e
#define tick0 0x10
#define tick1 0x11
#define tick2 0x12
#define cdt 0x13
#define i 0x14
#define j 0x15
#define k 0x16
#define l 0x17
```

```
#define oldporta 0x18
#define oldtick1 0x19
#define movj(r) movf r, 0 @ movwf jwr
; move register r -> jwr
#define startbit 4
#define cindexbit 1
#define mindexbit 0
resetv:
; reset vector
        goto main
        nop
        nop
        nop
intv:
; interrupt vector (happens once every 1024 clock cycles, ~ 1ms)
        ; reset timer flag
        bcf INTCON, 2
        ; countdown
        decf cdt, 1
        ; count up the "tick" register
        incfsz tick0, 1
        retfie
        incfsz tick1, 1
        retfie
        incf tick2, 1
        retfie
clrtick:
; this routine resets the "tick" counter
        bcf INTCON, 7
        clrf tick0
        clrf tick1
        clrf tick2
        bsf INTCON, 7
        return
flashdiag:
; this routine flashes the "diag" bit about four times a second
        movlw 0x0e
        btfsc tick0, 7
        iorlw 0x10
        movwf PORTB
        return
wait:
; this routine waits a # of interrupts specified by what's in the W register
        movwf cdt
        waitloop:
        incfsz cdt, 0
        goto waitloop
        return
setup:
; setup routine
        ; set PORTB to output
        bcf STATUS, 6
        PAGE1
        movlw 0x00
        movwf 06
         ; enable all bits of TRISB
        movlw 0xc1
        movwf 01
         ; set OPTION to internal timer, prescaler = /4
        PAGE0
        ; enable timer interrupts only, clear tick
        movlw 0xa0
        clrf tick0
        clrf tick1
        clrf tick2
        movwf INTCON
        return
quiet:
```

```
        ; disable motor & stuff.
        movlw 0x00
        movwf PORTB
        ; driveen, align, csel, and msel false
        movlw 0x04
        movwf PORTB
        ; ___, spin, ___, and ___ false
        movlw 0x02
        movwf PORTB
        movlw 0x06
        movwf PORTB
        return
main:
; main program
        call setup
        call quiet
startwait:
        btfsc PORTA, startbit
        goto startwait
        ; wait for start (negative true)
        call clrtick
        movlw 2
        call flashn
        movlw 0x40
        movwf PORTB
        ; assert "align"
        movlw 0x80
        movwf PORTB
        ; deassert "align", assert driveen
        movlw 0x4a
        movwf PORTB
        ; assert "spin", set SELECT to the B bank of inputs
        movlw 200
        call wait
        ; wait for 0.2sec
m1onwait:
        btfss PORTA, mindexbit
        goto m1onwait
m1offwait:
        btfsc PORTA, mindexbit
        goto m1offwait
m2onwait:
        btfss PORTA, mindexbit
        goto m2onwait
        ; wait for mindex (positive true) to become set, clear, set
        ; (so that the motor gets a chance to really spin)
        movlw 0x90
        movwf PORTB
        ; assert "driveen" and "msel"
        movlw 0x02
        movwf PORTB
        ; deassert "spin", set SELECT to the B bank
        movlw 3
        call flashn
c1onwait:
        call flashdiag
        btfss PORTA, cindexbit
        goto c1onwait
c1offwait:
        call flashdiag
        btfsc PORTA, cindexbit
        goto c1offwait
c2onwait:
        call flashdiag
        btfss PORTA, cindexbit
        goto c2onwait
        ; flash the "diag" bit until cindex is set, clear, set
        movlw 0xb0
```

```
        movwf PORTB
        ; assert "csel", "msel" and "driveen"
        movlw 4
        call flashn
        goto mainloop
; ~~~~~~~~~~~~~~~~~~~~~~
; example: flash LED's, wait ~ 10 msec, unflash LED's,
;          wait ~ 70 msec, repeat, until tick2 becomes nonzero.
;          (128 * 256 * ~1msec = ~32 seconds later)
flash:
        movlw 0x16
        movwf PORTB
        return
unflash:
        movlw 0x06
        movwf PORTB
        return
flashn:  movwf i
flashnloop:
         call flash
         movlw 20
         call wait
         call unflash
         movlw 40
         call wait
         decfsz i, 1
         goto flashnloop
         return
mainloop:
        btfss tick2, 2
; 2nd bit of tick2 becomes true 4 * 256 * 256 interrupts after
        ; resetting tick, or about 4 minutes later.
        goto mainloop
        movlw 10
        call flashn
        call quiet
        goto startwait
; go back and wait for start
```

Appendix C. Consent form

The interviews performed for this project were conducted with approval from the MIT Committee on the Use of Humans as Experimental Subjects (COUHES) as project #2315. Subjects were given the consent form shown on the following two pages.

Evaluation Interviews for the Interactive Servomechanism Demonstration

Informed Consent Document

Jason M. Sachs
April 29, 1996

Your participation as a subject in these interviews is voluntary. You are free to withdraw your consent to be interviewed. You may also withdraw your consent to have the information gained during the interview used in any way. You may stop the interview at any time.

Purpose

These interviews are part of a research project I am conducting for my master's thesis, to develop an educational exhibit on servomechanisms, one that could conceivably be found in a museum in the future. The exhibit consists of a box on the wall with some wheels sticking out on one side and some meters, buttons, and knobs on the front, all of which are intended to provide a way to explore servomechanisms. The interviews are being conducted in order to see how different people learn from the exhibit.

Procedures

You will be asked some questions about your science background. Then you will be given time to try out different ways of using the exhibit. I may ask you questions as you go along and may ask you to try certain activities using the exhibit (example: "What if you turn the red wheel but not the gray wheel?") that you may not have thought of doing.

The interviews will be recorded on audiotape and should take between 30 minutes and one hour. If you wish, you may make sketches during the interview.

There is no foreseeable physical risk. If you find the interview uncomfortable you may leave at any time. You are also free to ask questions about the project at any time; I will attempt to answer them to the best of my ability.

All subjects will be given a $5 gift certificate good for Toscanini's Ice Cream for participation in the study. You may also benefit from this interview by learning something about motors and servomechanisms.

Confidentiality and Anonymity

Transcripts from the audiotape of your interview may be quoted in my thesis. However, it is up to you what you want done with the audiotape itself and any sketches you make during the interview. You may what you want done with this evidence by checking one of the boxes at the end of this document.

In any case, your name will not appear in print or on tape.

Questions

If you have any questions regarding the project, feel free to contact Professor John G. King at 253-4180, MIT room 26-457.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787, if I feel I have been treated unfairly as a subject.

☐ I agree to allow audiotapes and/or sketches made during this interview to be archived.

☐ I do not wish to allow audiotapes and/or sketches made during this interview to be archived; they will be destroyed at the completion of this project.

I consent to be a subject in this experiment under the terms described above.

____
Name (printed)

____________________________ ____________________________
Signature Date

If you are under the age of 18, your parent or guardian must also sign this document. Your parent or guardian may also observe the interview.

I give permission for the individual named above to participate in this experiment.

____
Name (printed)

____________________________ ____________________________
Signature Date

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