

Inverted Pendulum Control: Hardware

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Introduction: Implement a “hands-on” project for the UCLA Controls Course (EE141)

EE141: Principles of Feedback Control

- **Introductory controls class**
 - Only controls class required for electrical engineers.
 - Includes instruction in mathematical modeling of systems, root locus, and frequency response.
- **Current lab projects are not ideal**
 - Require expensive machinery which is not accessible to individual students.
 - Inverted pendulum control project is an inexpensive alternative; each student would build and interact with an inverted pendulum device.

The inverted pendulum project and kit

- **A classic controls problem**
 - Inherently unstable system needs to be actively balanced.
 - Feedback from system used to control the motion of the cart to keep the pendulum from falling.

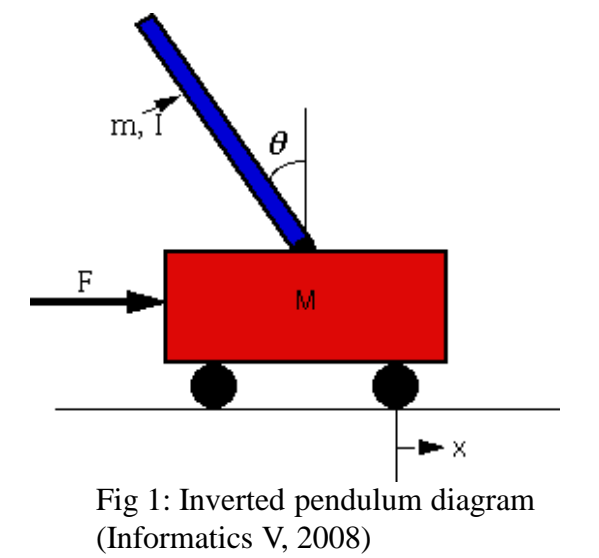


Fig 1: Inverted pendulum diagram (Informatics V, 2008)

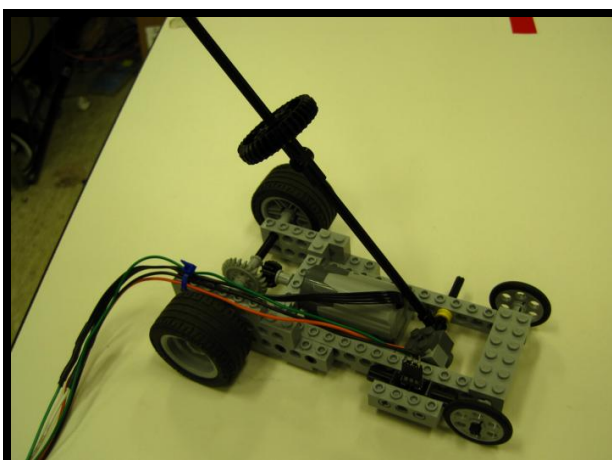


Fig 2: Assembled inverted pendulum cart

Students may build their own inverted pendulum cart

- Cart consists primarily of readily available Lego pieces.
- Students will be given a kit with parts to create the cart, as well as the hardware and software needed to control it.
- Provides hands-on experience in active control techniques.

Problem Description: Kit assembly needs to be simple and accessible

Multiple systems are required

- **Hardware, software and circuitry**
 - Students construct a physical Lego-based cart.
 - They interact with LabView applications to experiment with inverted pendulum control.
 - Some circuitry is required to link the inputs and outputs of the computer software with the physical cart.
- **Building and integrating these systems may be time-consuming**

Difficulties with circuit assembly

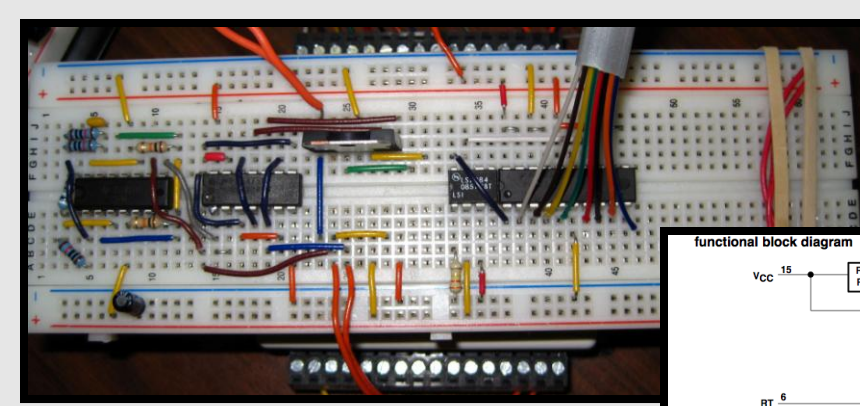


Fig 3: An example of the completed circuitry for the inverted pendulum cart

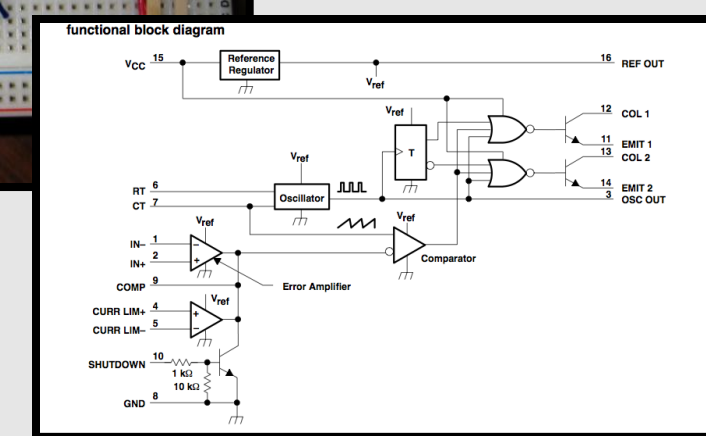


Fig 4: This preexisting diagram is confusing, and would not be sufficient to assemble a working circuit

- **Progress for some may be slowed by lack of circuitry experience**
 - A circuitry class is not a reinforced prerequisite for EE141.
 - Existing information on proper assembly of the circuits was confusing.
- **Assembling and troubleshooting these circuits is difficult and frustrating**

Students should be working with the controls aspect of the system, not struggling with the circuits!

Proposed Solution: Simple, step-by-step documentation of the circuitry

Hardware Documentation

Section 1.1
Operational Amplifier Based PWM Circuit

Theory:
This circuit is a combination of a Schmitt Trigger, an Integrating Amplifier, and a Comparator. The Schmitt Trigger takes the output of the Integrating Amplifier as the non-inverting input and takes a 2.5V DC signal in the inverting input. The output is governed by the equation
(1) $V_o = A(V_{in+} - V_{in-})$
The feedback is positive in the op amp, which means that the value of A is very high. If $(V_{in+} - V_{in-})$ is just as high as it possibly can, which is the 5V supply rail of the op amp, it will be sent as low as possible, and in this case, the signal will then be 0 due to the high gain of the op amp. If the input to the op amp is 0, however, in our case, we cannot use 0 as the inverting input signal at 2.5V so that the DAC is capable of reading the signal for rails. When we assume the input signal into the integrating amplifier as it goes from 0 to 5V, we can find the two line equations that describe the output of the op amp.

Building and Testing the Circuit

Figure 8: Schematic of the Regulating Pulse Width Modulator Circuit (Note that the pin numbers in the schematic are not the SG 3524)

Required Parts
1. Regulating Pulse Width Modulator IC (SG 3524)
1. 10k ohm resistor

1. At pin 4 (V+), connect a 5V supply and connect pin 11 (V-) to GND. These are the supply rails.
2. Follow the schematic in Figure 1 to connect the rest of the components. Figure 2 includes the pins for a typical quad op amp.
3. Build the triangle and square wave generating circuit first.
4. At the outputs of the two op amps, you should see the square wave from 0 to 5V and the triangle wave at a similar voltage range (similar to Figure 5). The DAC has limitations at this frequency; however, so if the square wave looks more like a trapezoid, this is due to the sampling rate of the DAC.
5. Once both signals work, connect the triangle wave output to the input of the third op amp.
6. Check all connections and make sure signal to the first op amp does not exceed the 5V supply rail. The output of the PWM also changes (as seen in Figures 4 and 5). The signal for the DAC output of the DAC.

Figure 20: 555 Timer output (red) and DAC output (green) as seen on Circuit Dashboard. (Note that the two signals are on different time scales)

Figure 21: Completed Digital PWM Circuit

Fig 5: Documentation sample

- **Documentation for each circuit is broken up into three sections**
 - *Theory*: background information on the principles of operation behind the circuit.
 - *Building and Testing the Circuit*: Step-by step instructions on how to build the circuit and relevant diagrams.
 - *Expected Results*: Includes information on how the finished circuit should function and what it might look like.
- **Designed to be easy and informative**
 - Written for people with limited circuit building experience.
 - Conveniently collects all important information in one place, including excerpts on basic functionality and pin attributes from datasheets.
 - Students can use provided hardware and software to compare the output from their circuits against sample output waveforms included in the documentation.
 - It is possible to exactly duplicate the sample circuit from the picture, so a frustrated student can move on from a difficult circuit.

Other Work: Encoder-Less Design

- **The cart currently uses an optical encoder to get data on pendulum position**
 - *Advantages:*
 - Quite accurate, with 256 digital positions.
 - Does not introduce much friction.
 - *Disadvantages:*
 - Somewhat expensive.
 - Requires substantial circuitry, wiring and programming to operate.
- **It may be possible to use a variable resistor instead**
 - *Advantages:*
 - Accurate in a small range, giving analog position data.
 - Significantly lower cost than an encoder.
 - Simpler to operate, eliminates an entire circuit.
 - *Disadvantages:*
 - Produces more friction, which may be problematic
 - Loses accuracy in larger angles.

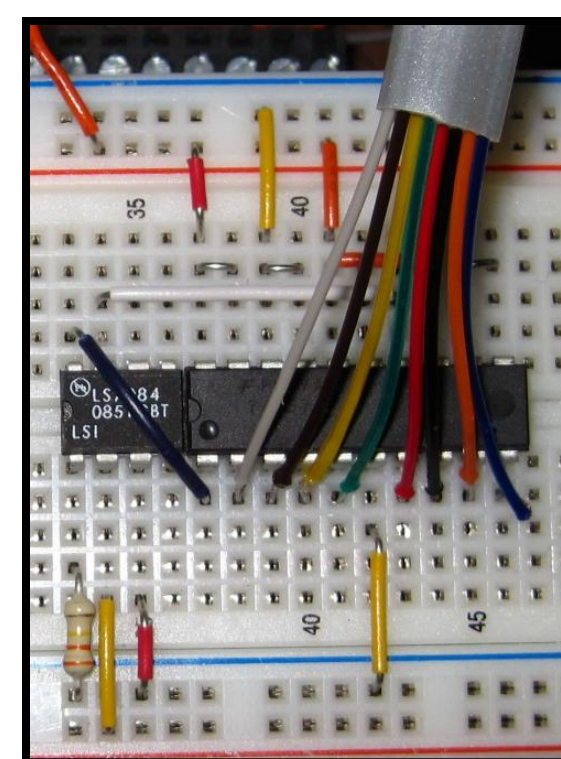


Fig 6: Part of the circuitry and wiring for the optical encoder

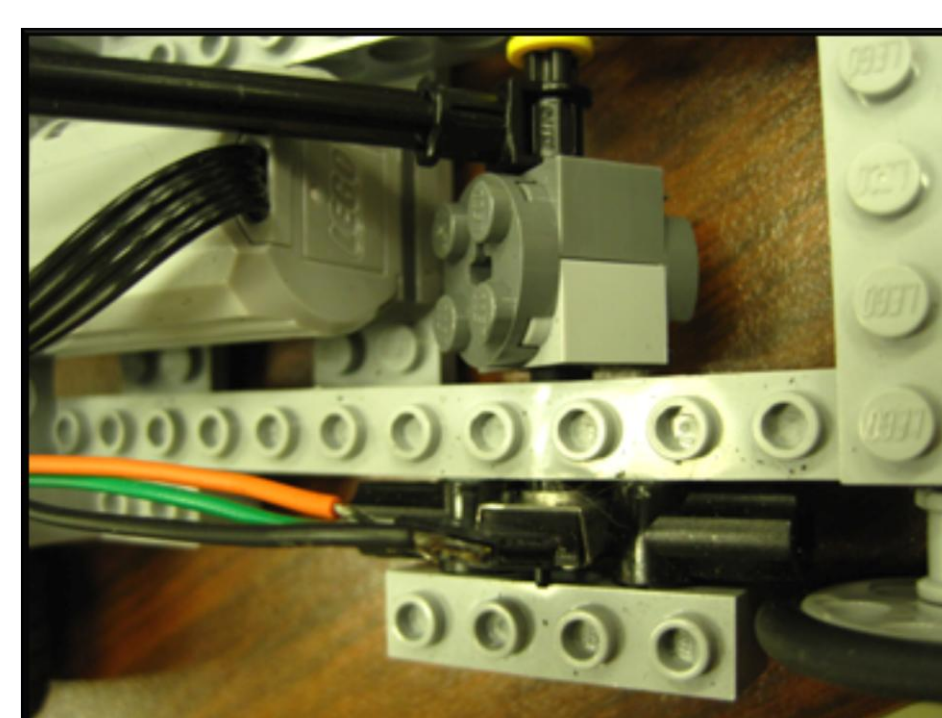


Fig 7: Variable resistor installed in a cart