LAB 1
AN EXAMPLE MECHATRONIC SYSTEM: THE FURBY

Objectives	To see the inner workings of a commercial mechatronic system and to construct a simple manual motor speed controller and current amplifier.
Preparation	Read Lab 1 and the multimeter, breadboard, function generator, and oscilloscope tutorial web pages.
Tools	Prototyping breadboard, power supply, multimeter, wire cutter/stripper, function generator, and oscilloscope.

1 Introduction

This first lab will introduce you to the equipment at your workstation, show you the inner workings of a commercial mechatronic system, and demonstrate the basic elements of mechatronic design.

2 The Furby

The Furby, made by Tiger Electronics, is a commercially successful robot pet. The old version, circa 2000, includes a single actuator with an interesting gearing system driving the eyelids, ears, mouth, and waist; a speaker for talking; custom-made microprocessors; and a variety of sensors such as a microphone, a light sensor, a tilt sensor, an infrared emitter and receiver, a motor encoder, and touch sensors. Despite having only a single actuator, its innovative design allows it to exhibit a range of interesting behaviors.

The goal of this part of the lab is to understand the design of the Furby by identifying its parts. We have already dissected it for you by removing its fur and plastic case.

Tasks

a. On the answer sheet, indicate each of the following parts of the Furby by **labeling** the lines with the appropriate numbers.

1. The +6V terminal. (The Furby takes four 1.5 V AA batteries.)
2. The ground terminal.
3. The Furby's DC motor.
4. The encoder.
5. The light sensor.
6. The "home" position sensor.
7. The stomach touch sensor.

b. After this lab, you will have built a breadboard that looks something like the figure handed out with the lab. Use this as a guide in building up your breadboard. Keep

things neat by cutting wires to length so that they run vertically or horizontally and lie flat on the breadboard.

We begin by hooking up the Furby cable and the power distribution strips, as shown in the accompanying figure.

o Connect the Furby I/O cable to the breadboard as shown in the figure, and connect the ground and +5V lines to the distribution strips. To do this, use solid (not stranded) 22 AWG wire (22 wire gauge; wires get bigger as the gauge decreases). Use black wire for ground and red wire for +5V. Cut the wire from the spool and use your wire stripper to strip off approximately 1/4 inch of the insulation at each end of the wire. Do NOT connect the Furby power cable yet (we will not need this until the last part of the second lab).
o Hook up the power distribution strips to the binding posts.

Verify that your breadboard matches the figure.

3   The Manual Speed Control Circuit

We will build a manual speed control circuit and current amplifier. We could try to build the whole thing at once and test it. **But this is never a good idea.** Always build the pieces first, and once you are sure the individual pieces are working, put them together. If the whole system does not work now, then the problem is isolated to the interaction of the two subsystems.

In summary, always decompose the system into subsystems (and perhaps the subsystems into subsubsystems). Then build from the bottom up, making sure each subsystem works as expected before connecting them together. This has the following benefits:
o Makes it easier to isolate problems and prevent them from occurring.
o Minimizes the potential for catastrophic failure, such as the output of one system destroying a component of another system.

Our first problem is to build the motor control circuit. We divide this problem into two parts. (1) We will design a manual speed control circuit which consists of a knob that the user can turn to set a control signal between –5V and +5V. (2) We will build a current amplifier circuit, which boosts the current from the speed control circuit to run the motor. Here we concentrate on the first part.

Tasks

a. Using your multimeter, **measure** the total resistance of the potentiometer (pot) given to you by the TA. Also, look at the resistance between one end of the pot and the wiper terminal as you rotate the knob.

wiper

Top view
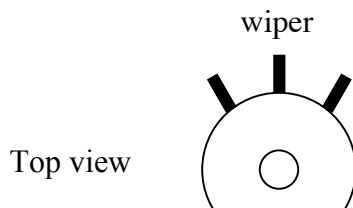
b. In the circuit below, **find** the resistance value R that limits the voltage at the wiper to be between –5V and +5V as we turn the pot. **Be sure to show your work for all calculations in the labs!** Since our resistor set comes in a finite number of resistances, **choose** a resistance in the set that maximizes the output voltage range while keeping it within –/+5V.

+12V

R

potentiometer V_1

R

-12V
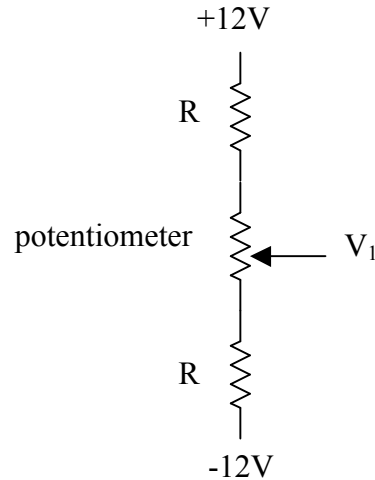
c. Now build the circuit from part (b) on the breadboard, as shown in the breadboard figure. **Record** the range of voltages at the output (wiper) terminal as you turn the pot. To test a point on the breadboard, you can stick a wire out of the breadboard, attach an alligator clip, and attach the alligator clip at the other end of the cable to the multimeter probe.

d. **Calculate** (don't use your multimeter) the amount of current running through the three resistors.

e. The Furby motor can be controlled by a voltage in the range of –/+5V. Our speed control circuit gives a voltage in this range. Why can't we just run the motor with this circuit, and forget the amplifier stage? The major problem is that the motor requires more current than the speed control circuit provides. The motor "pulls down" the output of the circuit. This is called "loading," and it occurs when the "output impedance" of the first circuit is not sufficiently lower than the "input impedance" of the second. For a similar reason, you can't use the 5V "high" output from a typical digital logic chip to run the motor; the chip can't provide enough current.

Let's simulate the Furby motor with a 10 ohm power resistor you will get from the TA. *(Note: An actual DC motor has more complicated behavior than a resistor.)* This resistor is rated at 3 watts, unlike the 1/4 watt resistors in our resistor kits. Attach one end of the 10 ohm resistor to the output of the speed control circuit (the potentiometer wiper) and the other end to ground. (You will need to insert another wire to attach to ground. What color should you use?) **Calculate** the voltage range you expect to see at the wiper. (As always, show your work.) Now experimentally **verify** the voltage range.

f. The resistors in our resistor kit are 1/4 watt resistors, meaning that they should not be used to dissipate more than 1/4 watt of power. Remember, the power dissipated by a resistor is $P = IV = V^2/R = I^2R$. Based on the voltage range you observed experimentally above, **calculate** the maximum power dissipated by the 10 ohm resistor.

g. Now disconnect the 10 ohm resistor. Based on the current in part (d), **calculate** how much power is dissipated by the speed control circuit. This power is dissipated regardless if the motor is running or not. Notice a tradeoff: we can decrease the effect of loading if we decrease the resistances of the resistors and pot in the speed control circuit. However, this comes at the expense of more power being dissipated by the speed control circuit, even when the motor is not running. In general, we want to decouple "signal" circuits (the speed control circuit) and "power" circuits (the current amplifier). We can design, test, and build them individually if the input impedances of the power circuits are much higher than the output impedances of the signal circuits.

You have finished building the manual speed control circuit. We will build the current amplifier next.

4   The Current Amplifier

The current amplifier we will build is a simple "push-pull" circuit. It consists of two power transistors: one to "push" current through the motor, and one to "pull" current through the motor, allowing us to run the motor in both directions. If we only wished to run the motor in one direction, a single transistor would suffice.
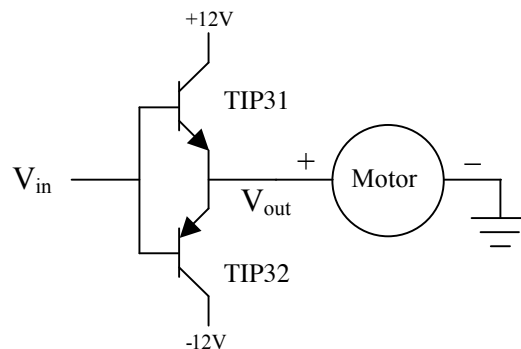
The operation of this circuit is quite simple. For sufficiently positive values of the input voltage, the TIP31 npn transistor will turn on, and the output voltage will be one diode drop lower than the input voltage. Current flows from the +12V supply through the motor to ground. For sufficiently negative values of the input voltage, the TIP32 pnp transistor will turn on, and the output voltage will be one diode drop higher than the input voltage. Current flows from ground through the motor to the −12V supply.

This is a very simple amplifier. It has some undesirable properties, and we could do better by incorporating an operational amplifier and feedback, or by using pulse-width modulation. It may also be a good idea to protect the motor and amplifier using additional "flyback" diodes. These are topics for later in the course. For now, this simple circuit will serve the purpose.
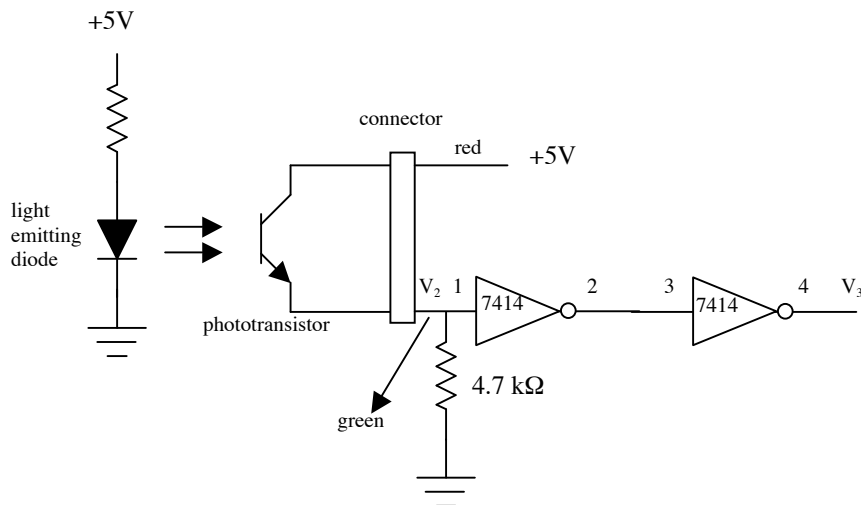
Tasks

a. Without dismantling the speed control circuit you have already built, build the push-pull amplifier circuit. The transistor on top is npn (TIP31) and the transistor on the bottom is pnp (TIP32). Do not connect the motor yet. Instead, use the 10 ohm resistor in its place; connect it at one end to the emitters and at the other end to ground. Now connect the output of the speed control circuit V_1 to the input of the amplifier circuit V_{in}. **Record** the max range of the voltage $V_1 = V_{in}$ as you turn the pot. **Explain** why it is or is not the same range you observed in part 3(c).

b. Turn the potentiometer so that V_1 is -2V. Increase V_1 slowly up to 2V, and **record** the range of V_1 values for which V_{out} is approximately 0V. This is called the "deadband." This deadband is an undesirable property of the amplifier, and can easily be eliminated by the use of feedback as we will learn later.

c. Remove the 10 ohm resistor, and connect V_{out} to the + terminal of the motor. Turn the pot and see how the Furby moves. **Record** the max ranges of the voltages V_{in} and V_{out} as you turn the pot. Pay particular attention to the motion of the gears in the back. **Draw** a rough sketch of V_{out} vs. V_{in} on your answer sheet.

d. Turn off the power supply. We will measure the current flowing through the motor. Change the red lead of the multimeter to the 10A connection, and put the multimeter in series with the circuit: V_{out} goes to the red lead of the multimeter, and the black lead of the multimeter goes to the + terminal of the motor (via wires attached to the breadboard; again, you can use alligator clips). Now turn on the power supply, turn the pot to its maximum setting (V_{in} is maximum), and **record** the maximum current flowing through the motor. Turn off the power supply, take the multimeter out of the circuit, and reattach the amplifier output directly to the + terminal of the motor.

e. Using your results from parts (c) and (d), **calculate** the power dissipated by a transistor when the pot is at its maximum setting. The power is the current multiplied by the voltage drop from the collector to the emitter. Notice that if you run the motor in one direction for a while, one transistor heats up while the other is cool. The one that heats up is the one that is on. Feel the backs of the transistors to notice this (but be careful not to get burned!). The power is dissipated as heat, and this is the reason we use metal *heat sinks* to conduct away the heat from power transistors, microprocessors, and other electrical elements that dissipate a lot of heat.

5 The Encoder Signal

As a motor rotates, an encoder generates a number of pulses proportional to the amount of rotation of the motor. By counting these pulses, we can keep track of the total amount of rotation. Our Furby has a simple type of encoder. A wheel with a hole in it rotates with the motor, and a light beam sensor detects the hole as it passes the sensor. We will learn about more sophisticated encoders later in the course.
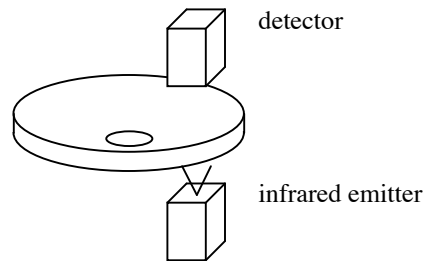
We will build the circuit below. Everything to the left of the connector is already present; we will only build the portion to the right of the connector.


Tasks

a. Connect the Furby's power cable to +5V and ground on the breadboard. This will power the light emitting diode. Connect the green lead of the Furby cable to a 4.7 kΩ resistor running to ground on the breadboard. (Do not build the rest of the circuit yet.) Disconnect the + terminal of the motor, so the motor is not powered. Attach oscilloscope probes to test the voltage V_2. Using the small wooden dowel given to you by the TA, turn the motor slowly and observe the voltage V_2. You should observe that once per revolution of the motor, the voltage increases. This is where the detector "sees" the emitter. Roughly, the phototransistor (detector) produces an amount of current proportional to the infrared light acting on it, up to saturation of the transistor. More light causes more current which gives a higher voltage at V_2. We

would like a minimum voltage of 0.4V or less and a maximum voltage of 2V or more. Hopefully the 4.7 kΩ resistor will give us this kind of range. If not, try a different resistor.

After you've chosen the resistor, **record** the resistance value and the voltage range at V_2.

b. Now we will build the rest of the circuit. We can think of V_2 as the *signal*, and the rest of the circuit as the *signal conditioning circuit*. So far we have an analog voltage, but we want to turn it into a digital signal. We use two TTL Schmitt trigger inverters for this purpose. (This circuit is also used in the Furby's internal circuitry.) Each input exhibits hysteresis: when the output changes state, the input must undergo a large change for the output to change again. This allows us to convert the noisy, slow-changing, non-TTL pulse generated by the phototransistor into a clean TTL pulse, as shown below.
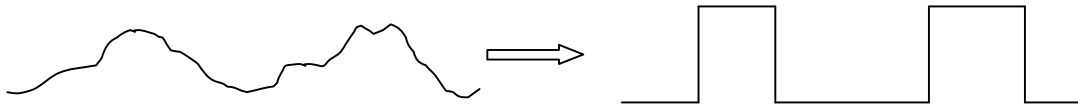
We will look at the effect of hysteresis. Insert the 74LS14 hex Schmitt trigger inverter into the breadboard. Always put the notch of the IC toward the top of the board for consistency. Hook up the power (+5V) and ground pins. Connect pins 2 and 3, as in the circuit above. Use the function generator to apply a 100 Hz triangular waveform at pin 1, with a minimum value of 0V and a maximum value of 4V. Use the oscilloscope to monitor the voltages at pins 1 (the input) and 4 (the output). **Sketch** two cycles of the input and output voltages as a function of time, and notice the effect of hysteresis. Now **sketch** the plot of V_3 versus V_2 to see the hysteresis more obviously. **Explain** this sketch.
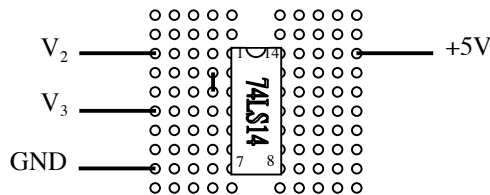
Now connect the output from the phototransistor in (a) to pin 1 of the 74LS14. Use the oscilloscope to observe the waveform at V_3 as you rotate the motor using the manual speed control circuit. This waveform could be fed into a counter chip to keep track of the amount rotated. A real encoder has two signals so we know which direction the motor is rotating, allowing the counter to count up or count down, depending on the direction.

6 Workstation Checkoff

Tasks

a. Return all tools to their original location and make sure all equipment is turned off, except for the computer. Do this after each time you use your workstation.

Summary

o   Decoupling signal and power circuits, signal loading
o   Power dissipation
o   Current amplification
o   Signal conditioning

LAB 1 ANSWERS

1 Introduction

2 The Furby

a. Label the parts of the Furby with the correct number.
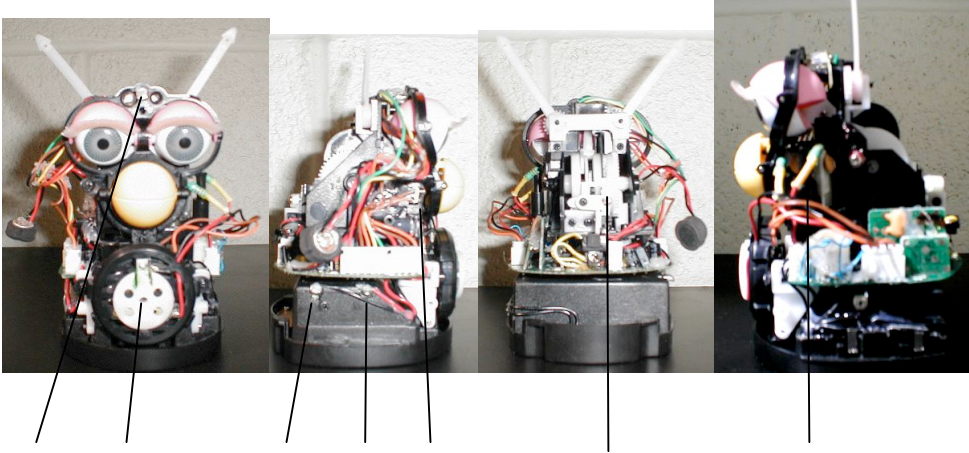
3 The Manual Speed Control Circuit

a. Total pot resistance (give units): _____

b. R = _____   Chosen resistor: _____

c. Measured voltage range: _____

d. Calculated current: _____

e. Calculated voltage range: _____   Measured voltage range: _____

f. Maximum dissipated power: _____

g. Power dissipated by the speed control circuit: _____

4 The Current Amplifier

a. V_{in} range: _____
   Explanation:

b. Deadband: _____

c. V_{in} range: _____ V_{out} range: _____

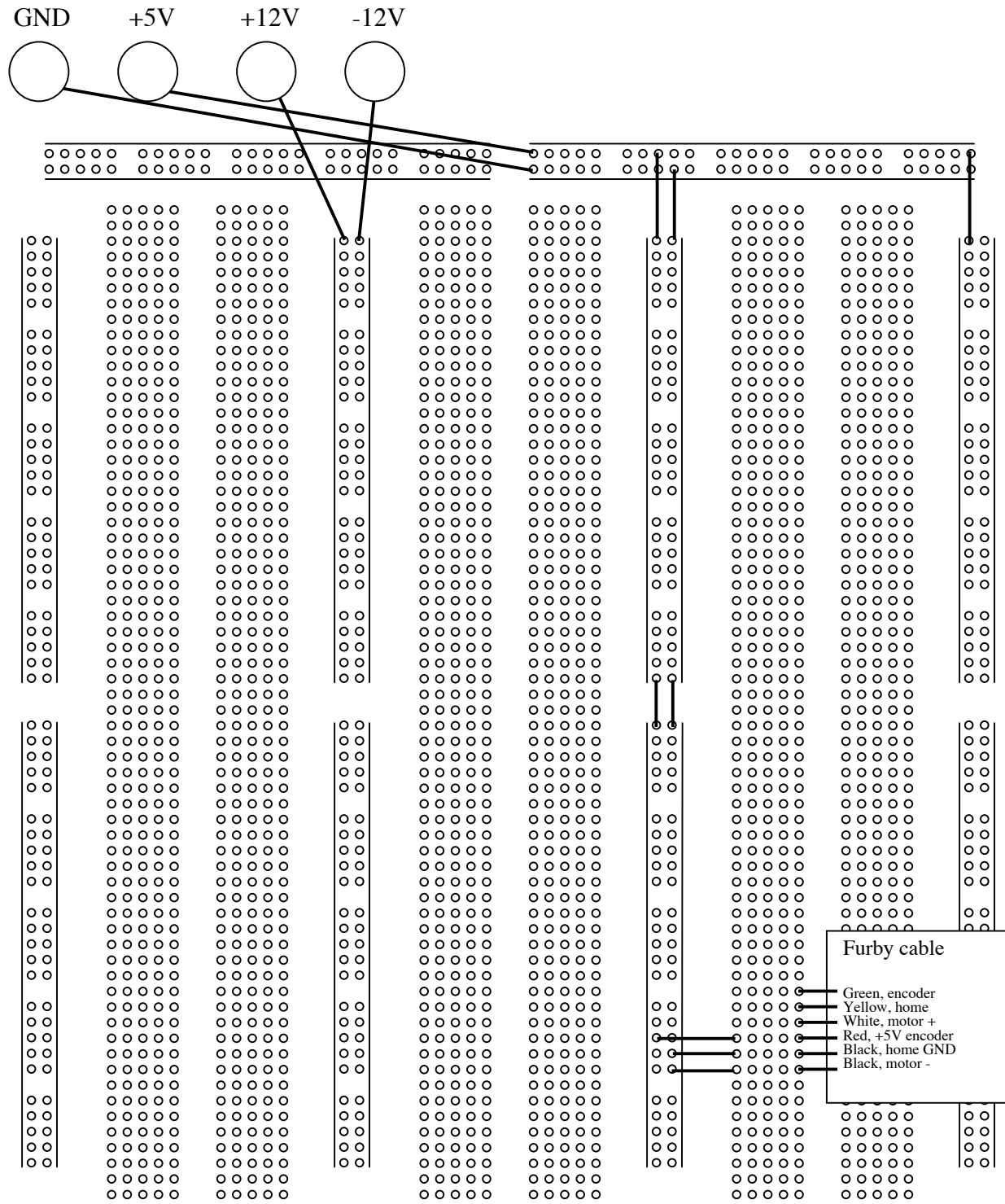d. Max motor current: _____

e. Power dissipated by transistor: _____
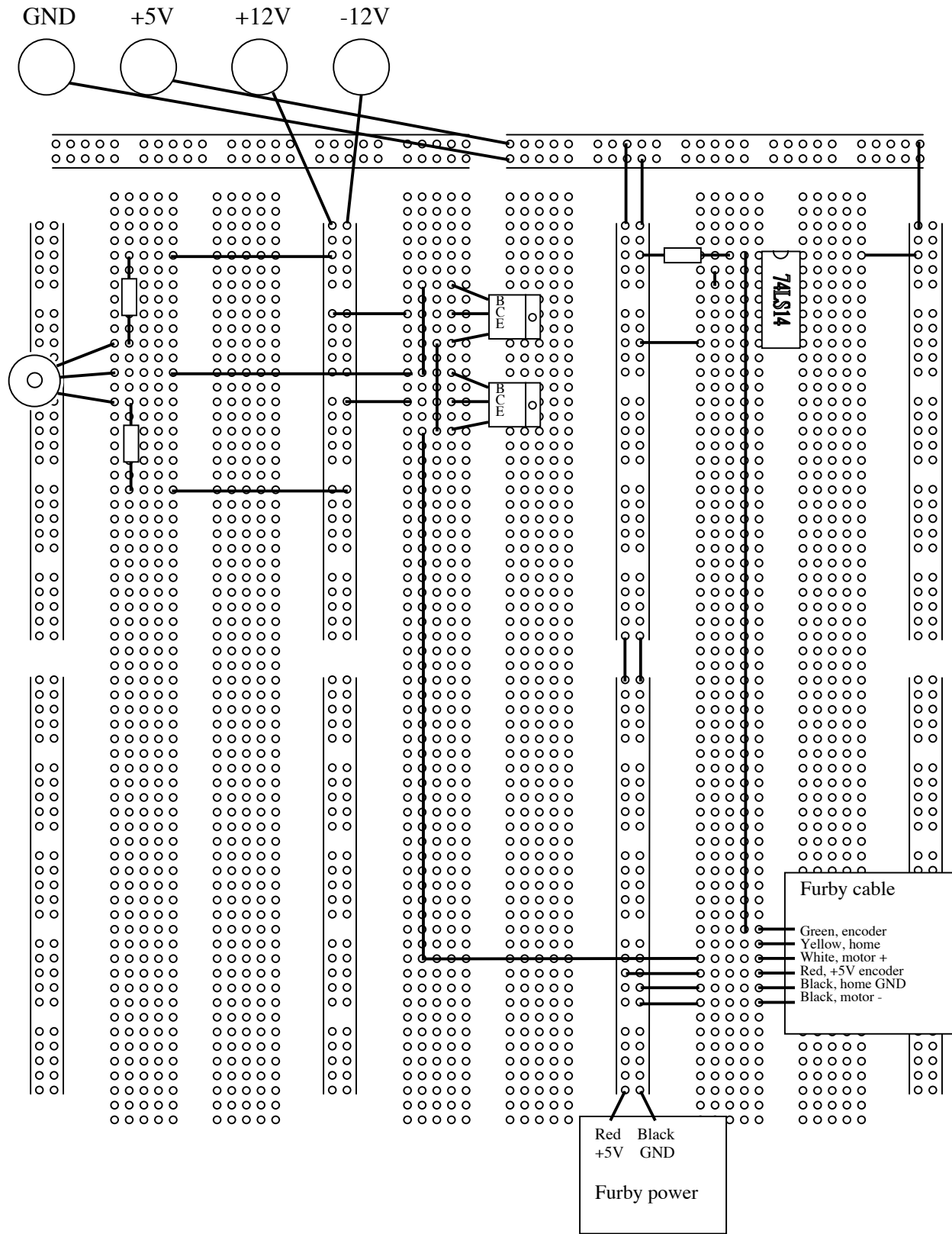
f. Transistor gain: _____

5 The Encoder Signal

a. Resistor used: _____   Voltage range at V_2: _____

b. Attach sketches of (1) V_2 and V_3 as a function of time over two cycles, and (2) V_3 as a function of V_2. Explain this second sketch.

GND   +5V   +12V   -12V

Furby cable

Green, encoder
Yellow, home
White, motor +
Red, +5V encoder
Black, home GND
Black, motor -

The breadboard at the end of part 2 of Lab 1.

GND   +5V   +12V   -12V

74LS14

B
C
E

B
C
E

Furby cable

Green, encoder
Yellow, home
White, motor +
Red, +5V encoder
Black, home GND
Black, motor -

Red   Black
+5V   GND

Furby power

The final circuit.