Lab 6 CAN Network and Robot Interfaces

Goals
• Develop a layered communication system,
• Design and implement a hardware/software interconnect protocol.
• Interface two sensors and one motor needed for the robot.
• Use communication skills to work effectively as team.

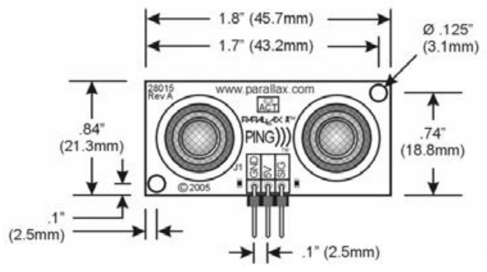
Review
• Textbook Chapter 8 and Sections 9.1 and 9.2
• Chapter 17 of the TM4C123 data sheet explaining basic extended CAN,
• IR distance sensor http://www.ece.utexas.edu/~valvano/Datasheets/gp2y0a21yk.pdf
• **Ping)))** sensor http://www.ece.utexas.edu/~valvano/Datasheets/PingAN.pdf
• **Ping)))** sensor http://www.ece.utexas.edu/~valvano/Datasheets/PingDocs.pdf
• Laser-raniging sensor https://www.st.com/resource/en/datasheet/vl53l0x.pdf
• CAN reference: http://www.kvaser.com/can/protocol/index.htm

Starter files
• **`CAN_4C123`** project (CAN driver)
• **`PeriodMeasure_4C123`** project (input capture)
• **`PWM_4C123`** project (PWM output)
• **`VL53L0X_TM4C123`** project (laser-ranging sensor driver)
• Sensor and motor board schematics/PCB layouts (**`Robot_Sensor.*`** and **`Robot_Motor.*`**)

This lab must be performed in teams of 3 to 5 students, which will also be the Lab 7 robot competition teams. Approval of the team by the TA is required before the preparation is started. Only one version of the software need be developed for each team.

Background

Lab 6 has two or three sensors distributed across two computers. Each computer collects data from one or more sensor and shares the data with other computer using the CAN. For Lab 6 you will use the USB supply for +5V, but in Lab 7 the +5V will come from linear regulators powered from the battery. The first sensor to interface is the **Ping))).** This is an ultrasound transducer used to measure distance. You will use this sensor with input capture to measure the distance to a wall or to another robot. In Lab 6, you will interface one Ping))), but your robot may have up to four Ping))) sensors.



The Sharp **GP2Y0A21YK** is an IR sensor, also used to measure distance. Similar to **Ping)))**, the goal is to measure the distance to a wall or to another robot. The sensor has an analog output inversely related to distance. The difficulty with **GP2Y0A21YK** sensors is that they are noisy. You must add both analog and digital filters in order to create a more stable and reliable measurement. Your system will also require some software calibration and calculations to implement a quantitative measure of distance. The Lab 7 robot will have up to four of these sensors, but only one will be used in Lab 6.

The most versatile sensor will be the **VL53L0X** time-of-flight based laser-ranging distance sensor by ST Microelectronics. The sensor comes pre-mounted on a breakout board by Alientek (ATK). It is interfaced to the microcontroller via a digital I^2C bus connection. Similar to the other sensors, it will require calibration. In Lab 6, you will interface one VL53L0X. The robot in Lab 7 has four unoccupied I^2C ports (two on the sensor and two on the motor board) that support up to four sensors in a default setup with one sensor per port. Additional sensors can be supported by daisy-chaining multiple ATK-VL53L0X boards on the same port (requiring special cabling and the extended version of the driver).

In Lab 6 you will have a third microcontroller separate from the two microcontrollers used in the CAN network of sensor boards and interfaces. This third microcontroller will spin one DC motor in both directions in an open-loop fashion. In Lab 6 the DC motor should be powered from an 11.1V bench supply. This third microcontroller will send PWM signals to the motor driver circuit. In Lab 6 this third microcontroller should be able to adjust the duty cycle of the PWM output so the software can make the motor spin fast or slow. The motor driver circuits will be provided on a separate motor PCB. In Lab 7, you will connect two motors to the robot's motor board and power it from the battery. However in Lab 6, you are just running one motor in open-loop fashion.

The motor board and corresponding microcontroller will also control a servo for the steering of your robot. Servos are a popular mechanism to implement steering in robotics. Ranging from micro servos with 15oz-in torque to powerful heavy-duty sailboat servos, they all share several common characteristics. A servo is essentially a motor for which you set the desired position or angle. The servo "knows" two things: where it is (the actual position) and where it wants to be (your desired position). When the servo receives a desired position, it attempts to move the servo horn to the desired position. The task of the servo, then, is to make the actual position equal to the desired position. For more information on servos, search the web site: http://www.brookshiresoftware.com/

If there are 5 students on the team, you can have different students design the IR and laser-ranging sensor interfaces, or add a 4th type of sensor. You could add a touch/contact sensor (a mechanical bumper switch). The data from all sensors is displayed on the LCD. The CAN interface must be used. Interrupts, FIFO queues, semaphores, and the OS must be used in an appropriate manner. The hardware/software system is modular, because in Lab 7 you will create up to four copies of the IR distance sensor, up to four copies of the Ping))), up to four copies of the laser-ranging and two copies of the motor output driver. You will integrate these components on the two microcontrollers in Lab 7.

There are background tasks on each node: data acquisition and CAN I/O. The data acquisition threads will measure parameters (Ping, IR, laser-ranging or touch sensor) and send its measurement to a companion foreground thread (like Labs 2 and 3). A periodic task will start the **Ping)))** measurement every 100 ms. The time delay will be measured with an input capture interrupt. A periodic task will sample the ADC measuring distance with the **GP2Y0A21YK** sensor. Another periodic task will perform regular **VL53L0X** distance measurements. Make sure the execution times of the background threads are short and bounded. A foreground thread will manage the CAN I/O and the LCD display. The CAN identifier will specify the data type. The data field can be formatted however you wish. The CAN receiver thread runs in the background, accepting messages from the other nodes. Since the CAN is dedicated, you can use CAN filters however you wish. As always, you are allowed to implement the system in an alternate manner, as long as the basic educational objectives of the lab are achieved. The appropriate use of semaphores and FIFO queues are expected.

Choose a CAN channel bandwidth between 500,000 and 1,000,000 bps, and leave it as a constant. Also leave the time-quanta settings as shown in the CAN starter files. To change data bandwidth, you will adjust the ADC sampling rate for the **GP2Y0A21YK** IR sensor. Start with a data acquisition/transmission rate so slow (e.g., 500/sec) that collisions will be rare, and all the FIFOs are usually empty. Then, keeping the CAN channel bandwidth fixed, increase the sampling rate (number of ADC samples/sec and number of CAN transmissions/sec) until the maximum bandwidth is reached, without loss of data. It is possible to implement this network using just the **Data Frame**, ignoring the **Remote Frame**, the **Error Frame**, and the **Overload Frame**. Similarly, you can implement just the **Standard CAN 2.0A**, instead of the **Extended CAN 2.0B**. CAN does force a priority structure on the network, but you can implement priority however you wish.

Preparation

1) Download, unzip, and compiler the CAN starter project. Integrate the low-level CAN functions into your Lab 3, Lab 4 or Lab 5 OS. Add semaphore calls to the CAN routines in appropriate places. Include any Lab 4 or Lab 5 software you might which to include in your robot. This application sends 4-byte messages. You may wish to increase the message length to 8 bytes.

2) Assign sensor interfaces and study the I/O pin assignments for your Lab 7 robot. Overall, you can use up to four input captures for the four **Ping)))**, four ADC channels (for the four **GP2Y0A21YK** IR sensors), four I^{2}C interfaces

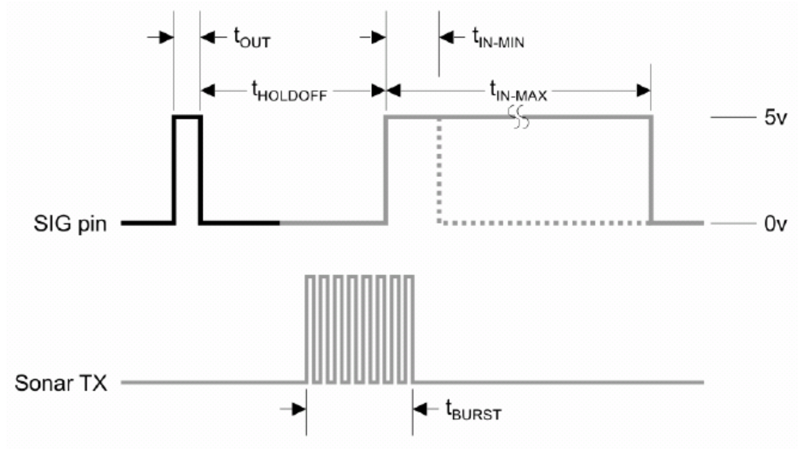


Figure 6.1. Ping))) sensor signals. See PingDocs.pdf for an explanation of this figure.

(for **VL53L0X** laser-ranging sensors), four digital outputs for the two DC motors two of which should be PWM, one PWM output for the servo, and some inputs for bumper switches or mode configurations. In addition, you should keep the UART interface for the interpreter, and the LCD to monitor robot status. The sensors, motors and servo must be interfaced using two microcontrollers and boards (one sensor and one motor board). You must be friendly and document your interfaces well. It is easier to design for the Lab 7 integrated sensor system now, than it will be to move a sensor from one interface to another later.

3A) One student in the group designs the interface for the **Ping)))**. There is one **SIG** pin used for both output and input (see Figure 6.1). The fundamental approach will be to: 1) make the **SIG** pin an output; 2) issue a 5 μs output pulse (which causes a sound pulse to occur); 3) switch the **SIG** pin to back to an input; and 4) measure the time until the echo is received. The HCSR04 sensor is a little easier to interface because it has a separate input and output pin. $\mathbf{t_{IN}}$ will be a pulse width measurement using input capture. The pulse width time is equal to twice the distance to the object divided by the speed of sound. The distance **d** is therefore $\mathbf{d}$=$\mathbf{c}$* $\mathbf{t_{IN}}$/2, where **c** is the speed of sound, and $\mathbf{t_{IN}}$ is the time for the sound to travel to the object, reflect and travel back to the sensor. You will perform this measurement about 10 times per second. Using the appropriate OS commands, write foreground and background software that samples distance approximately 10 times a second and sends the data to other node on the system using CAN. You might want to disable interrupts during the 5μs pulse ($\mathbf{t_{OUT}}$) if you are using blind cycle counting for the time delay, so the OS does not suspend the thread during the pulse output.

3B) A second student in the group designs the interface for one **GP2Y0A21YK** IR and one **VL53L0X** laser-ranging distance sensor. The analog output signal of the **GP2Y0A21YK** has two types of noise. Notice the huge noise spikes in Figure 6.2 occurring about every one ms. On the spectrum analyzer you will also see both white noise and periodic EM field noise. During the procedure part of this lab you measure the noise of your system using a spectrum analyzer. The sensor board provides an analog low pass filter (LPF) with gain=1 for IR sensor inputs. The wheel diameter is about 8 cm, and the motors will spin up to 120 RPM, giving a maximum speed of about 50 cm/sec. Let x(t) be the distance to the wall as the robot travels at 50 cm/sec. Using the transfer function of the transducer, estimate the maximum slew rate, **s**, in volts/sec needed from the sensor interface. If the input were to be V=**A**sin(2πft), then the maximum slew rate dV/dt is 2πfA. Assuming **A** to be about 1 V, if the maximum slew rate is **s**, the maximum frequency response needed is s/2π. The cutoff frequency of the analog LPFs should be about 10*(s/2π)[1]. Using the appropriate OS commands, write foreground and background software that samples distance approximately 2 times the LPF cutoff frequency and sends the data to the other computer on the system using CAN. Figure 6.3 plots data collected with the **GP2Y0A21YK** IR sensor employing a 2-pole 20 Hz Bessel LPF. Implement an additional 3-wide median digital filter to remove the noise spikes. Another nonlinear filter could be used in place of the median if you want.

[1] The cutoff of the analog 2-pole Butterworth LPFs on the sensor board is 50 Hz.

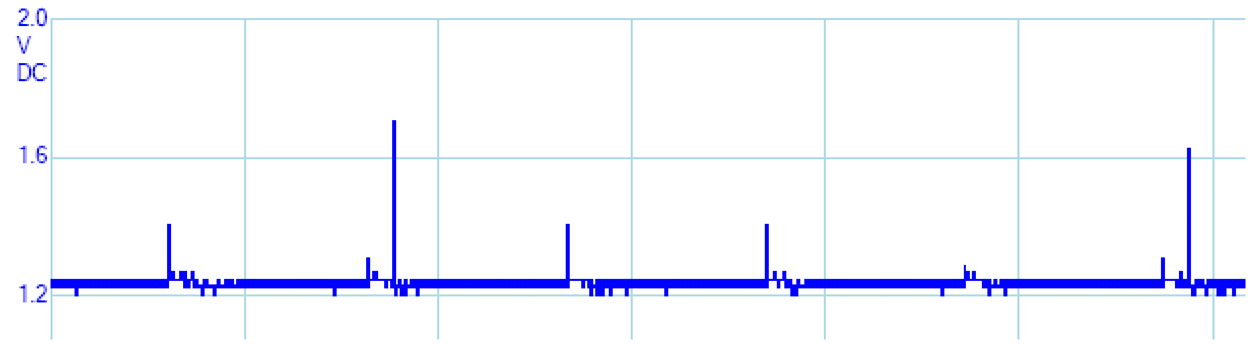


Figure 6.2. GPY0A21YK sensor output, distance=20 cm, DC mode, voltage scale is 0.4 V and time scale is 1 ms.

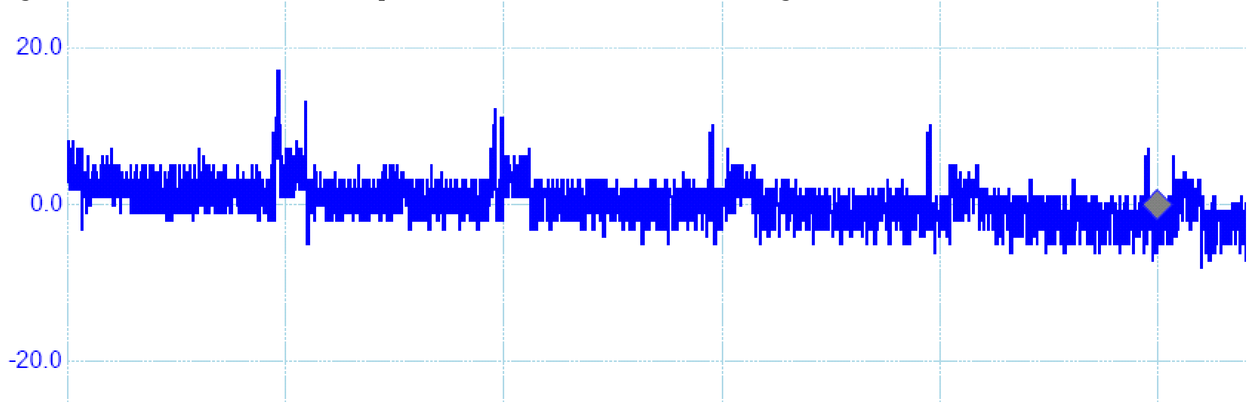


Figure 6.3 GPY0A21YK filtered output, distance=20 cm, AC mode, voltage scale is mV and time scale is 1 ms.

For the **VL53L0X**, interface the sensor to any of the available and not otherwise occupied I^{2}C ports using the provided driver. The I^{2}C port used by the driver can be configured through conditional compilation options in the VL53L0X_I2C.h header file. You need to profile the existing VL53L0X measurement routine so you can use the appropriate OS feature (background periodic versus foreground with sleeping). Write software that samples distance approximately 10 times a second and sends the data to the other CAN node.

3C) A third student in the group designs the interface for one **DC motor**. The interface must allow for the software to control direction and power. Controlling direction will be handled via the H-bridges on the motor board, and controlling power will require PWM output from the microcontroller. This motor interface need not be integrated into the other components in Lab 6 (integration will occur in Lab 7).

http://youtu.be/p4QevDMCuKo

Figure 6.4. Measurements of motor voltage. The DC motor is controlled via PWM.

3D) A fourth (or the third) student in the group designs the servo interface. The first step to understanding how servos work is to understand how to control them. All timing and electrical characteristics described here have been experimentally determined from a "HS-303 HiTec" servo. The servo is controlled by three wires: ground (black), power (red), and command (yellow). Power is usually between 4V and 6V and should be separate from system power (as servos are electrically noisy). Even small servos can draw over an amp under heavy load so the power supply should be appropriately rated. Though not recommended, servos may be driven to higher voltages to improve torque and speed characteristics. Servos are commanded through PWM signals sent through the command wire. Essentially, the width of a pulse defines the position. For example, sending a 1.5ms pulse to the servo, tells the servo that the desired position is 90 degrees. In order for the servo to hold this position, the command must be sent at about 50 Hz, or every 20 ms.

If you were to send a pulse longer than 2.5 ms or shorter than 0.5 ms, the servo would attempt to overdrive and damage itself. Once the servo has received the desired position (via the PWM signal) the servo must attempt to match the desired and actual positions. It does this by turning a small, geared motor left or right. If, for example, the desired position is less than the actual position, the servo will turn to the left. On the other hand, if the desired

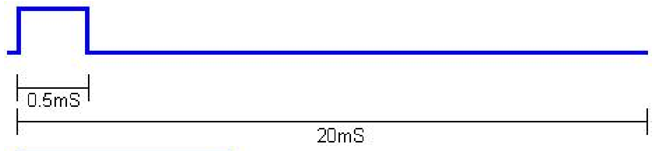
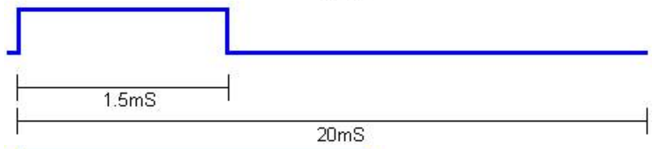
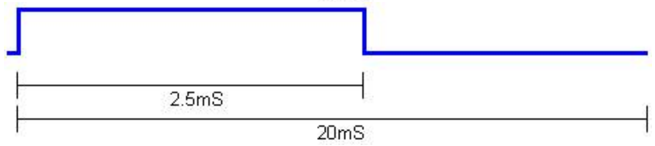
Position	Pulse Width	Example Pulse
Minimum	0.5ms	
Center	1.5ms	
Maximum	2.5ms	

Figure 7.6. The timing constraints of the ***HS-303*** servo (http://www.brookshiresoftware.com/) *not drawn to scale.*

position is greater than the actual position, the servo will turn to the right. In this manner, the servo "zeros-in" on the correct position. Should a load force the servo horn to the right or left, the servo will attempt to compensate. Note that there is no control mechanism for the speed of movement and, for most servos, the speed is specified in degrees/second. Indeed, one of the primary tasks of electronics is to synthesize servo speed control by stepping through a series of positions. The servo outputs on the motor board are powered by an additional 7805 voltage regulator, creating a separate +5V source just for the servo. If you connect the servo to the +5V used by the microcontroller, then the servo will cause transient power losses to the microcontroller, causing software resets.

4) Finally, write background/foreground threads that accept CAN messages from the network. The foreground thread displays the most recent data from all nodes, including itself. Count the number of times a packet is lost (i.e., the CAN receiving ISR calls **`CanFifo_Put`** and the FIFO is full.

Procedure
1) Modify your Lab 3, Lab 4 or Lab 5 OS to run on the two microcontrollers.

2) Test the CAN physical layer of the network. There are terminating resistors at each end of the cable. These resistors eliminate reflections and limit the rise/fall times of the voltages on the network. To test the network hardware, you can run one of the StellarisWare/Valvano starter examples. Next you will debug your integration of the CAN programs into the two computers.

3) One by one, debug the sensor interfaces. Please verify proper operation of the circuit before testing using software on the microcontroller. Also remember to turn off both 3.3 and 5 V power when moving parts and wires on your circuit. Double check the power connections every time before applying power.

4A) Using known distances, calibrate the **Ping)))** so it measures distance accurately. The **maximum deviation** (or **span**) is the difference between maximum and minimum data points given a fixed distance. The **range** is the minimum and maximum distances at which the measurements can be accurately obtained. Write software that measures the average, standard deviation and maximum deviation of 10 consecutive measurements (one second). The walls of the race track will be pieces of 3.5 by 3.5 inch cedar wood. The location will be the outdoor ECJ plaza (with the ETC T-Room/Student Lounge as indoor backup location in case of rain). The 19 cm wide robot will travel down a race track about 80 cm wide. Envision trying to speed your robot down the race track keeping a constant distance to the right wall. At what heights from the floor would it work? At what angles to the wall would it work? In order to determine the range, accuracy and noise level, take measurements (average, standard deviation and maximum deviation) at 5 known distances while detecting the race wall at outdoor and indoor locations. Calculate accuracy as the average absolute value of the differences between truth and measured. Standard deviation and maximum deviation are measures of noise.

Truth d_T	Measured d_M	Standard Deviation	Span

Average accuracy (in cm) = $\frac{1}{5}\sum_{i=0}^{4}\left|d_{Ti}-d_{Mi}\right|$

4B) Using known distances, calibrate the **GP2Y0A21YK** and **VL53L0X** sensors so they measure distance accurately. Write software that measures the average, standard deviation and maximum deviation of consecutive measurements over a one second time period. Look at the data sheet to choose the optimal orientation of the sensor to detect the wall while the robot is moving. Using the same scenario described in procedure 4A, at what heights from the floor would it work? At what angles to the wall would it work? In order to determine the range, accuracy and noise level, take measurements (average, standard deviation and maximum deviation) at 5 known distances while detecting the race wall at its possible outdoor and indoor locations. Similar to Ping))), determine accuracy, range and noise for this sensor. Given a constant distance, measure the **GP2Y0A21YK** noise at the output of the LPF with a spectrum analyzer.

4C) Measure the current and voltage delivered to the motor under a no-load condition. Once the wheel is placed on the motor shaft and the robot placed on the ground, the current will increase 4 to 10 times this amount. You will not be able to increase the voltage above the 11.1V from the battery, so the design of the H-bridge will significantly affect the speed of your robot.

4D) Test the servo operation for setting and holding different horn positions via software.

5) Put all the pieces together so data measured in each node is available in both computers. The file system is not needed for Lab 6. Measure a typical CAN frame with a dual trace scope showing both the output of the microcontroller and CANH on the actual bus.

6) Measure the maximum sustained bandwidth of the system, under the conditions that virtually no data is lost. Keep the CAN channel speed fixed at 500,000 (or 1,000,000) bps and increase the sampling rate of the **GP2Y0A21YK** sensor, while measuring the number of lost packets. “Sustained” means the measurement should occur over many seconds, so that the steady state behavior is measured, and not a start-up behavior measured when all the FIFOs are initially empty. Which factor limits the bandwidth? Consider factors such as the speed of the CAN channel, the speed of the ADC converter, execution speeds of various background threads, execution speed of foreground program, or the LCD display speed.

Checkout (show this to the TA)

Show the sensors, motors and servo in operation creating scope tracings similar to Figures 6.1 to 6.4. Be prepared to discuss factors such as accuracy, noise, and reproducibility. Connect a logic analyzer to CAN signals PE4 and PE5. Explain these two signals as data are communicated across the network.

Deliverables (exact components of the lab report and lab submission)

A) Objectives (1/2 page maximum)

B) Hardware Design

1) List of interface and pin assignments of the sensors and motors used in your system (Preparation 3)

C) Software Design (documentation and code)

1) CAN module including its FIFO
2) Software to implement the sensor measurements
3) Software to implement the distributed data acquisition

D) Measurement Data

1) Table of **Ping)))** data at 5 known distances and average accuracy (Procedure 4A)
2) Table of **GP2Y0A21YK** and **VL53L0X** data at 5 known distances and average accuracy (Procedure 4B)
3) Spectrum of **GP2Y0A21YK** noise (Procedure 4B)

4) Motor current and voltage under no-load conditions (Procedure 4C)
5) Scope traces of CAN signals measured on both sides of the MCP2551 (Procedure 5)
6) Network bandwidth (Procedure 6)

E) Analysis and Discussion (2 page maximum). In particular, answer these questions

1) What is one advantage of the **Ping)))** sensor over the **GP2Y0A21YK** sensor?
2) What is one advantage of the **GP2Y0A21YK** sensor over the **Ping)))** sensor?
3) What is one advantage of the **VL53L0X** sensor over the others, and vice versa?
4) Describe the noise of the **GP2Y0A21YK** when measured with a spectrum analyzer.
5) Why did you choose the digital filters for your sensors? What is the time constant for this filter? I.e., if there is a step change in input, how long until your output changes to at least 1/e of the final value?
6) Present an alternative design for an H-bridge and describe how your H-bridge is better or worse?
7) Give the single-most important factor in determining the maximum bandwidth on this distributed system. Give the second-most important factor. Justify your answers.

F) Post-mortem concerning team member interactions (attached to the report)

1) Each team member evaluates each other team member including oneself
    - Simply list one or two weaknesses.
    - Simply list two or three strength characteristics.
2) Major failures in the way the team interacted (if any)
3) Major successes in the way the team interacted

G) Peer Review (each student submits independently and confidentially directly to the TA)

1) Classify each team member including oneself as:
    - worked harder than average (explain), worked an average amount, worked less than average (explain)