Complex Sensors

- **We already discussed:**
  - active versus passive sensors
  - reflective optosensors
  - reflectance
  - break-beam
  - various detectable object features
  - shaft encoding
  - speed and position
  - quadrature shaft encoding
  - modulated IR
  - IR communication

Today we are going to talk about ultrasonic and vision sensing.

Are those sensors active or passive?

Ultrasonic Distance Sensing

Ultrasonic Distance Sensing

- As we mentioned before, ultrasound sensing is based on the ***time-of-flight principle***.
- The emitter produces a *sonar **"chirp"** of sound*, which travels away from the source, and, if it encounters barriers, reflects from them and returns to the receiver (microphone).
- The amount of time it takes for the sound beam to come back is tracked:
  - starting the timer when the "chirp" is produced, and
  - stopping the timer when the reflected sound returns
- Is used to **compute the distance** the sound traveled.
- This is possible (and quite easy) because we know ***how fast sound travels***; this is a constant, which varies slightly based on ambient temperature.

Ultrasonic Distance Sensing

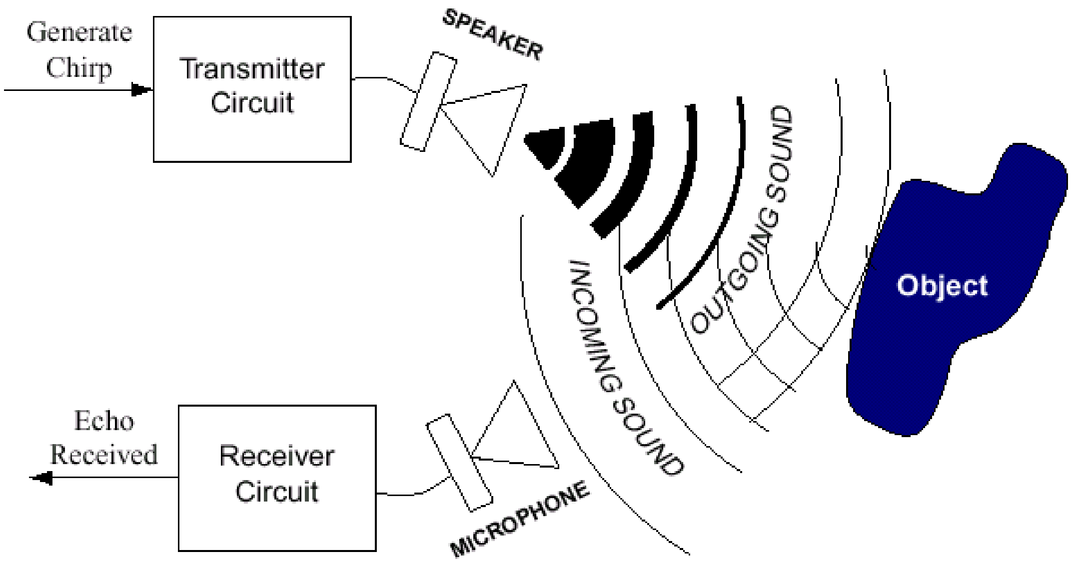
Ultrasonic Ranging

• Ultrasonic burst, or "chirp," travels out to an object, and is reflected back into a receiver circuit, which is tuned to detect the specific frequency of sound emitted by the transmitter.

• By measuring the elapsed time from when the chirp is emitted to when the echo is received, the distance may be calculated. In normal room temperature, sound travels about 0.89 milliseconds per foot

• Since the sound has to go out to the object and then back to the receiver, 1.78 msec of elapsed time corresponds to an object at one foot's distance from each of the emitter and receiver

• So the distance to the target object (in feet) is the time it takes for a chirp to make a round trip (in msec) divided by 1.78



Ultrasonic ranging

Measures the actual time-of-flight for a sonar "chirp" to bounce of a target and return to the sensor

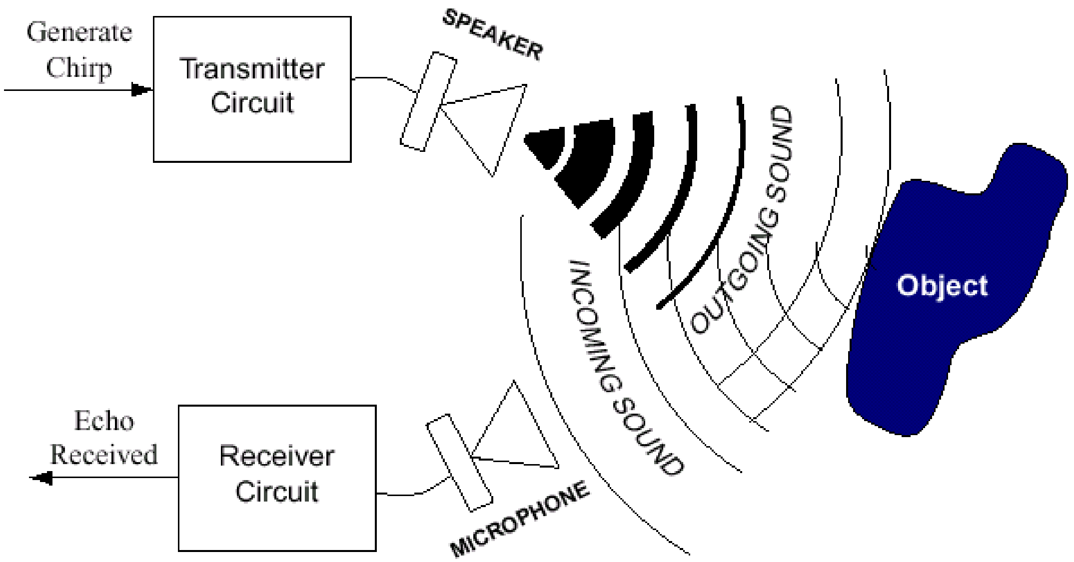
Greater accuracy than with IR sensing

Ultrasonic Distance Sensing

- Ultrasonic burst, or “chirp,”
    - travels out to an object,
    - reflected back into a receiver circuit, (tuned to detect the specific frequency of sound)
- Measures time-of-flight of “chirp”
- sound travels about 0.89 ms per foot / 1.78 ms for round trip
- distance to the target object (in feet) is the time it takes for a chirp to make a round trip (in msec) divided by 1.78

•Greater accuracy than with IR

•Bats use radar-like form of ultrasonic ranging to navigate as they fly



Ultrasonic Distance Sensing (cont)

- At room temperature, sound travels at 1.12 *feet per millisecond.*
  - Another way to put it that sound travels at ***0.89 milliseconds per foot.*** This is a useful constant to remember.
- The process of finding one's **location based on sonar** is called ***echolocation***.
- The inspiration for ultrasound sensing comes from nature;
  - bats use ultrasound instead of vision (this makes sense;
  - they live in very dark caves where vision would be largely useless).

Ultrasonic Distance Sensing

- Bat sonars are extremely sophisticated compared to artificial sonars;
- They involve *numerous different frequencies*, used for:
  - finding even the tiniest **fast-flying prey**, and
  - for **avoiding** hundreds of other bats, and
  - **communicating** for finding mates.

Specular Reflection

- A major disadvantage of ultrasound sensing is its susceptibility to ***specular reflection***
  - specular reflection means reflection from the outer surface of the object
- The sonar sensing principle is based on the sound wave reflecting from surfaces and returning to the receiver.
- The direction of reflection depends on:
  - the **incident angle** of the sound beam
  - the surface.
- **Thus**, important to remember that the sound wave will not necessarily bounce off the surface and "come right back."

Specular Reflection

- The smaller the angle, the higher the probability that the sound will merely **"graze"** the surface and bounce off,
  - thus **not returning** to the emitter,
  - in turn generating a false long/far-away reading.
- This is often called **specular reflection**, because smooth surfaces, with specular properties, tend to aggravate this reflection problem.
- **Coarse surfaces** produce more irregular reflections, some of which are more likely to return to the emitter.

Specular Reflection

- For example, in our experiments with PSUBOT, we used sonar sensors, and we have lined one part of the test area with wooden panel.
- It has much <u>**better sonar reflectance properties**</u> than the very smooth wall behind it. Big glass windows are also a trouble.
- In summary, long sonar readings can be very inaccurate, as they may result from **false** rather than accurate reflections.
- This must be taken into account when programming robots, or a robot may produce very undesirable and unsafe behavior.
- For example, a robot approaching a wall at a steep angle may not see the wall at all, and collide with it!
- Nonetheless, sonar sensors have been successfully used for very sophisticated robotics applications, including ***terrain and indoor mapping***
- They remain a very popular sensor choice in mobile robotics.
- We use them in PSUBOT and PEOPLEBOT.

- **Food for thought:**
  - what happens when multiple robots need to work together and all have sonar sensors?

Polaroid sensors

- The first commercial ultrasonic sensor was produced by **Polaroid.**
- **They** used them to automatically measure the distance to the nearest object (presumably which is being photographed).
- These simple Polaroid sensors still remain the most popular off-the-shelf sonars
- They come with a processor board that deals with the analog electronics.
- Their ***standard properties*** include:
  - 32-foot range
  - 30-degree beam width
  - sensitivity to specular reflection
  - shortest distance return

Polaroid sensors

- Polaroid sensors can be combined into phased arrays to create more sophisticated and more accurate sensors.
- One can find ultrasound used in a variety of other applications; the best known one is ranging in submarines.
  - The sonars there have much more focused and have longer-range beams.
- Simpler and more mundane applications involve:
  - automated "tape-measures",
  - height measures,
  - burglar alarms,
  - etc.
- *Sections covered above:* ***Martin: 6.3.***

Commercially Available Polaroid 6500

• Bats use radar-like form of ultrasonic ranging to navigate as they fly

• Polaroid Corp. used ultrasonic ranging in a camera to measure the distance from the camera to the subject for auto-focus system

  – Contemporary cameras use IR auto-focus: smaller, cheaper, less power

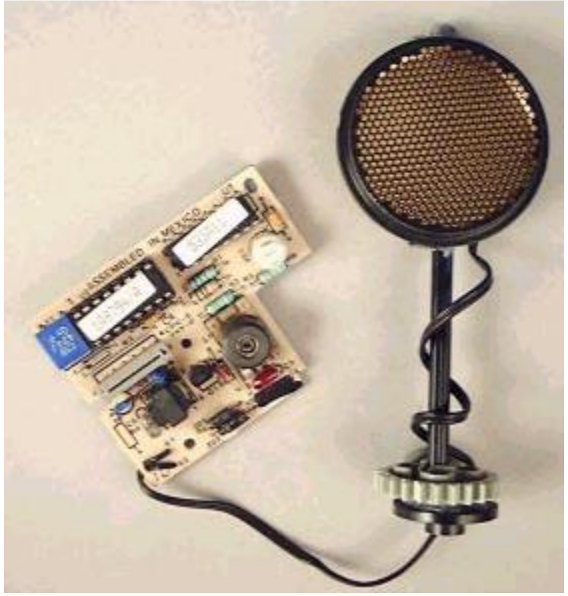
  – Ultrasonic ranging system is sold as OEM (original equipment manufacturer) kit (unpackaged board-level technology)

• Easily interfaced to Handy Board using 2-3 simple digital control signals

  • INIT: input to ranging board, generates chirp

  • ECHO: output indicates when chirp received

  • BINH: Blanking inhibit input: Signal to measure very close distances



Polaroid 6500 Series Ultrasonic Ranging System

Single board which holds all of the electronics

One ultrasonic transducer, which acts as both the speaker and microphone

Ultrasonic Distance Sensing

Details About Operation

Signal Gain. **Problem:** Echo from a far away object may be one-millionth strength of echo from a nearby object. **Solution:** 6500 board includes a variable gain amplifier that is automatically controlled through 12 gain steps, increasing the circuit's gain as time elapses while waiting for a echo to return.

Transducer Ringing. One transducer is used as transmitter/receiver (50 kHz). **Problem:** ringing problem: after transmitting outgoing chirp, transducer can have residual vibrations or ringing that may be interpreted as echo signal. **Solution:** By keeping initial circuit gain low, likelihood of false triggering is lessened. Additionally, however, the controller board applies a **blanking signal** to completely block any return signals for the first 2.38 ms after ultrasonic chirp is emitted. This limits the default range to objects 1.33 feet and greater. [close-up range: "blanking inhibit" input is used to disable this]

Operating Frequency and Voltage. Polaroid ultrasonic system operates at 49.4 kHz. Each sonar "chirp" consists of sixteen cycles of sound at this frequency. Polaroid board generates a chirp signal of 400 volts on the transducer. **Problem:** High voltage is necessary to produce an adequate volume of chirp, so that the weak reflected signals are of enough strength to be detected. Polaroid ultrasonic transducer can deliver an electrical shock. **Solution:** do not touch!

Electrical Noise. **Problem:** High amplification causes sensitivity to electrical noise in the power circuit, especially the type that is caused by DC motors. **Solution:** all high current electronic and electro-mechanical activity be suspended while sonar readings are in progress, or provide the sonar module with its own power supply, isolated from the power supply of the robot's motors.

Ultrasonic Distance Sensing

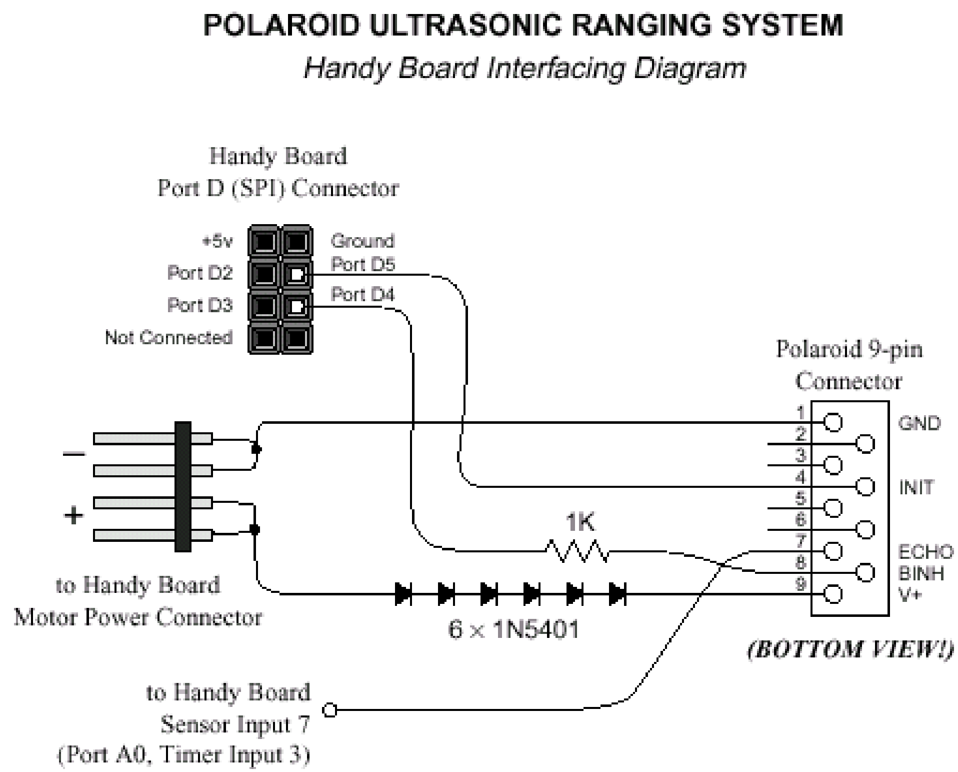
Exercises

1. ***Robot navigation.***
(a) Mount the Polaroid ranging unit onto the *HandyBug*. Determine the extent to which operating the *HandyBug*'s drive motors affects sonar readings.
(b) Write a control program to drive *HandyBug* around without crashing into objects.
(c) Mount the sonar transducer on a shaft driven from a servo motor, and write software to enable *HandyBug* to search for and then drive toward open spaces in its navigation routines.

2. ***Multi-sonar interference.*** Using two robots, each of which has its own sonar navigation system, characterize the nature of the interference (or lack of it) between the two sonar systems.

3. ***Mapping.*** Combine a sonar unit with a robot that has shaft encoders on its wheels, and create a demonstration application of a robot that can map its surroundings.

Connecting to the Handy Board



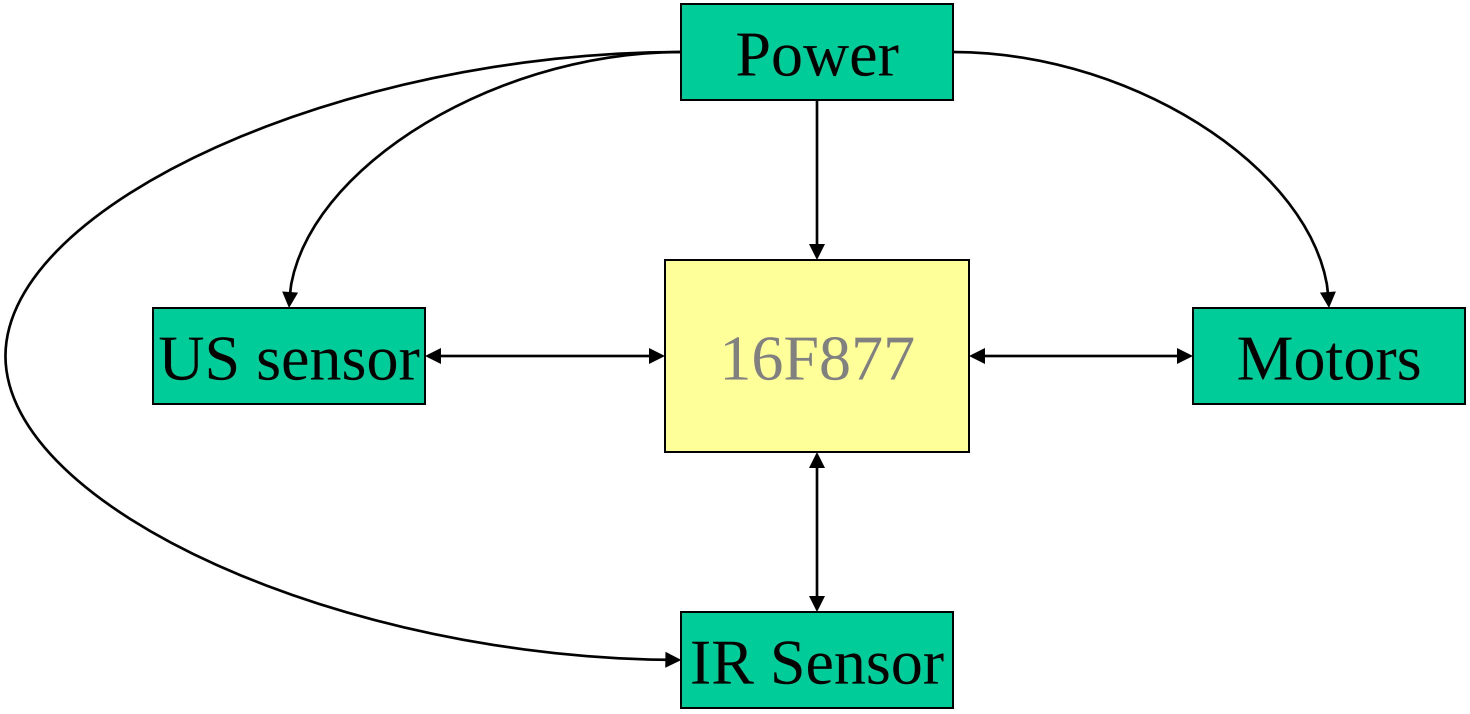
Driver Code is available

Roaming Security Watchdog

Design Objectives

- General Description:
  - An autonomous vehicle capable of avoiding objects in order to sense movement or infra-red sources for the security of a building.
- Core Functions:
  - Ultrasonic Sensing
  - Infrared Sensing
  - Independent drive motors for steering
- Possible Additional Items
  - Multiple Operating Modes
  - Better Alarm Generation

Block Diagram of the System

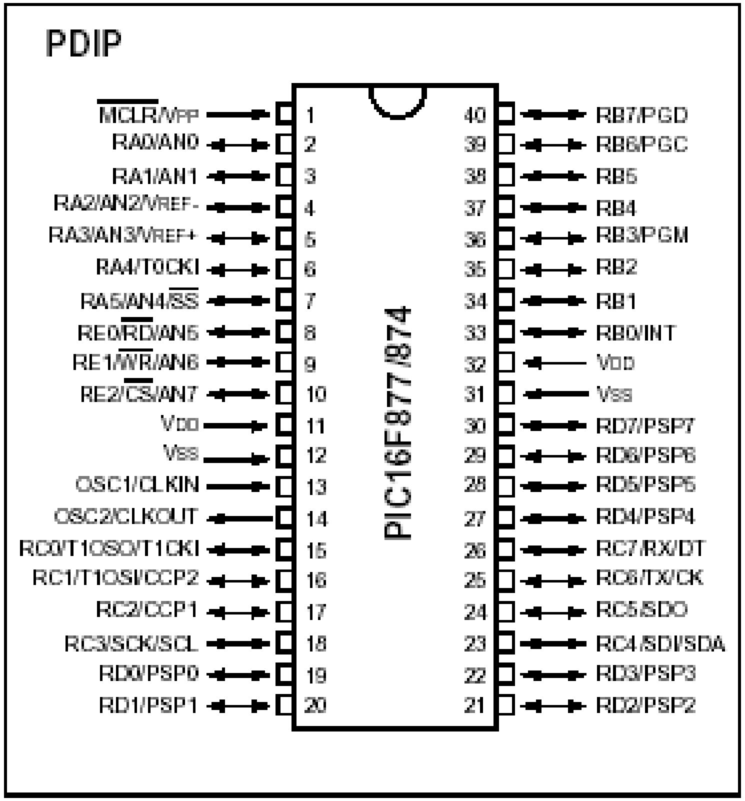


Why we chose the PIC16F877

- Fast clock (20MHz)
- 33 I/O lines
- Ease of programming (BASIC)
- Onboard RAM and Flash Memory Size
- Static Flash RAM
- Versatility in design possibilities
- Cost

PICMicro 16F877 Overview

- RISC Archetecture (35 commands)
- 20MHz clock input
- 200ns instruction cycle
- 8k of Flash Program Memory
- 14 Interrupts
- 3 Individual Timers
- 8 channel, 10 bit A/D converter
- Parallel Port optional input
- Brown Out Detection
- I^{2}C Communications
- Serial Communications
- 33 I/O Lines
- LOW COST (approx $7)



Software Design Method

- Individual Blocks (from initial diagram) functioning independently.
- Pre-determined variable names so that the software code can be pre-written to incorporate the blocks designed independently.
- Program logic into the drive mechanism.
- Steer the vehicle to avoid obstacles in real time using the Ultrasonic Sensors.
- Detect motion using the IR sensors and send an alarm.
- Monitor and remember current coordinates to map the room in memory for faster autonomous roaming. (Optional Learning)
- After detection of an intruder, decide a course of action.

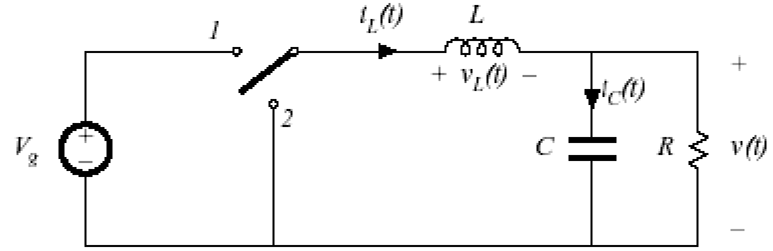
Possible Mechanical System

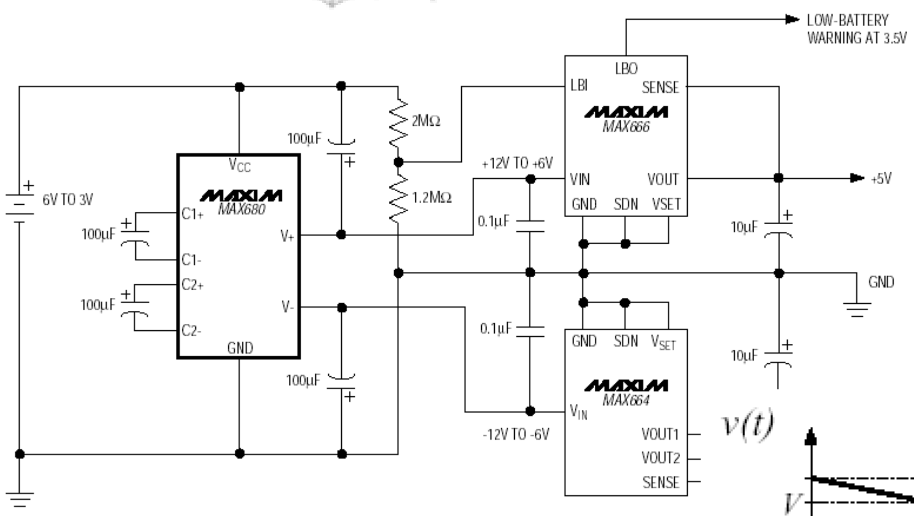
- Wooden Chassis
  - Plywood (approx. foot by foot)
- Tank treads
  - With two motors: one operating on each side.
  - Skid steering
- DC Motor
  - Bi-directional
  - Continuous
    - The application of power causes the shaft to rotate continually.
  - Servo Motor: Combines continuous motor with “feedback loop” to ensure accurate positioning of the motor.

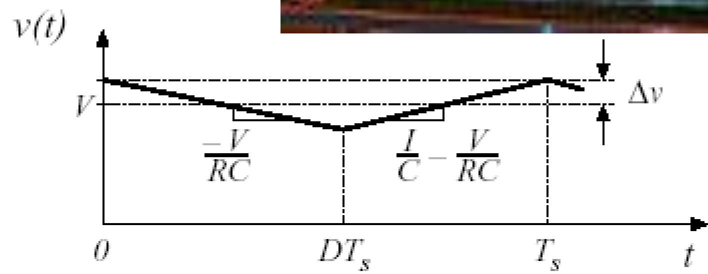
Motor Specifications

- DC Motor
  - Low-voltage variety: operating range at 1.5 to 12 V
  - 50% < operating range < 130%
- Speed
  - 0.5 ft per second
- Current Draw
  - The current draw of a motor increases in proportion to the load on the motor shaft
- Torque
- Gears

POWER SYSTEMS





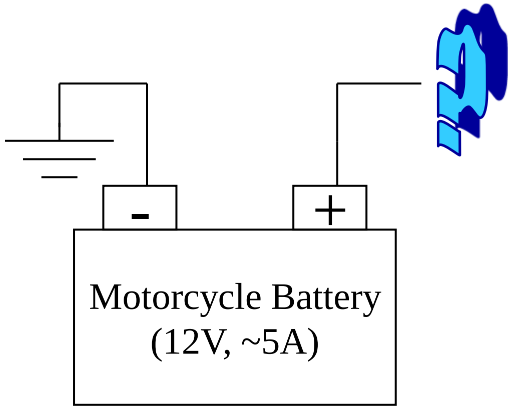


POWER SYSTEMS

THE ISSUE:

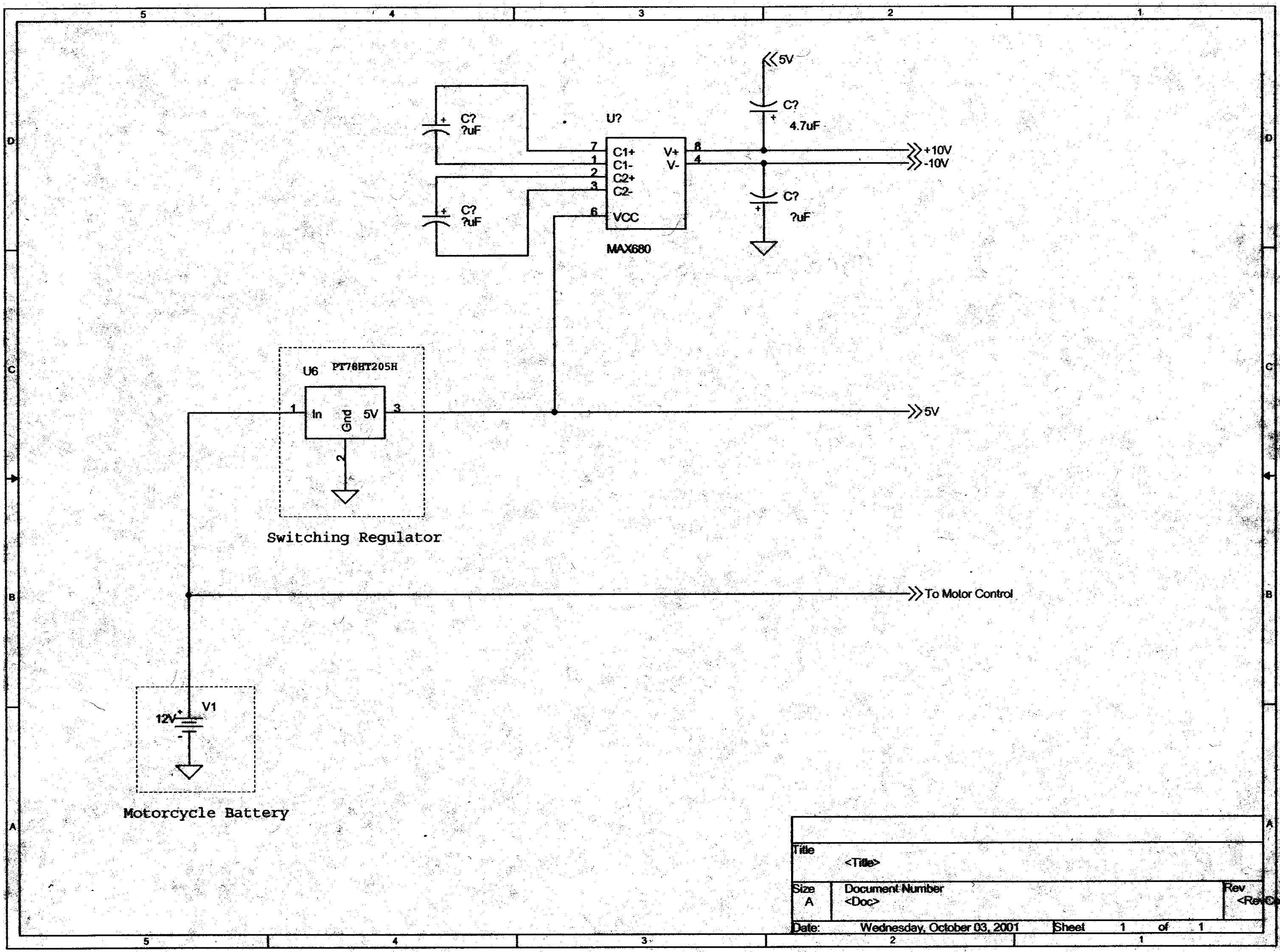
How will a single 12V motorcycle battery properly supply:

- Micro controllers and digital parts that require a very constant +5V supply
- Analog circuitry requiring anywhere from 5→12V, as well as ±10V supplies
- DC Motors that require fairly large current draws with bipolar operation



POWER OVERVIEW

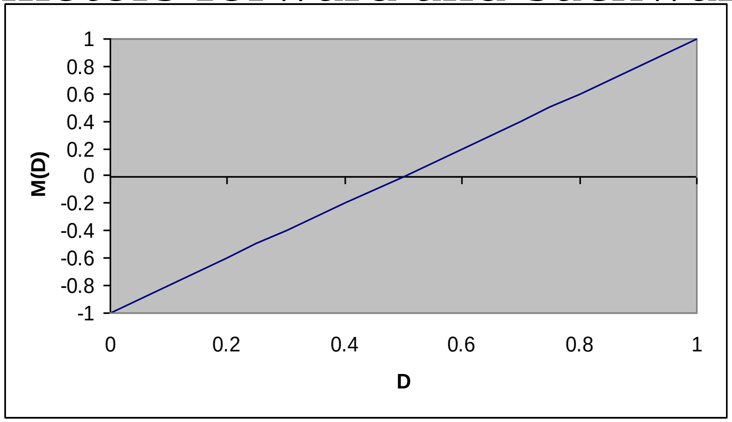
THE SOLUTION:



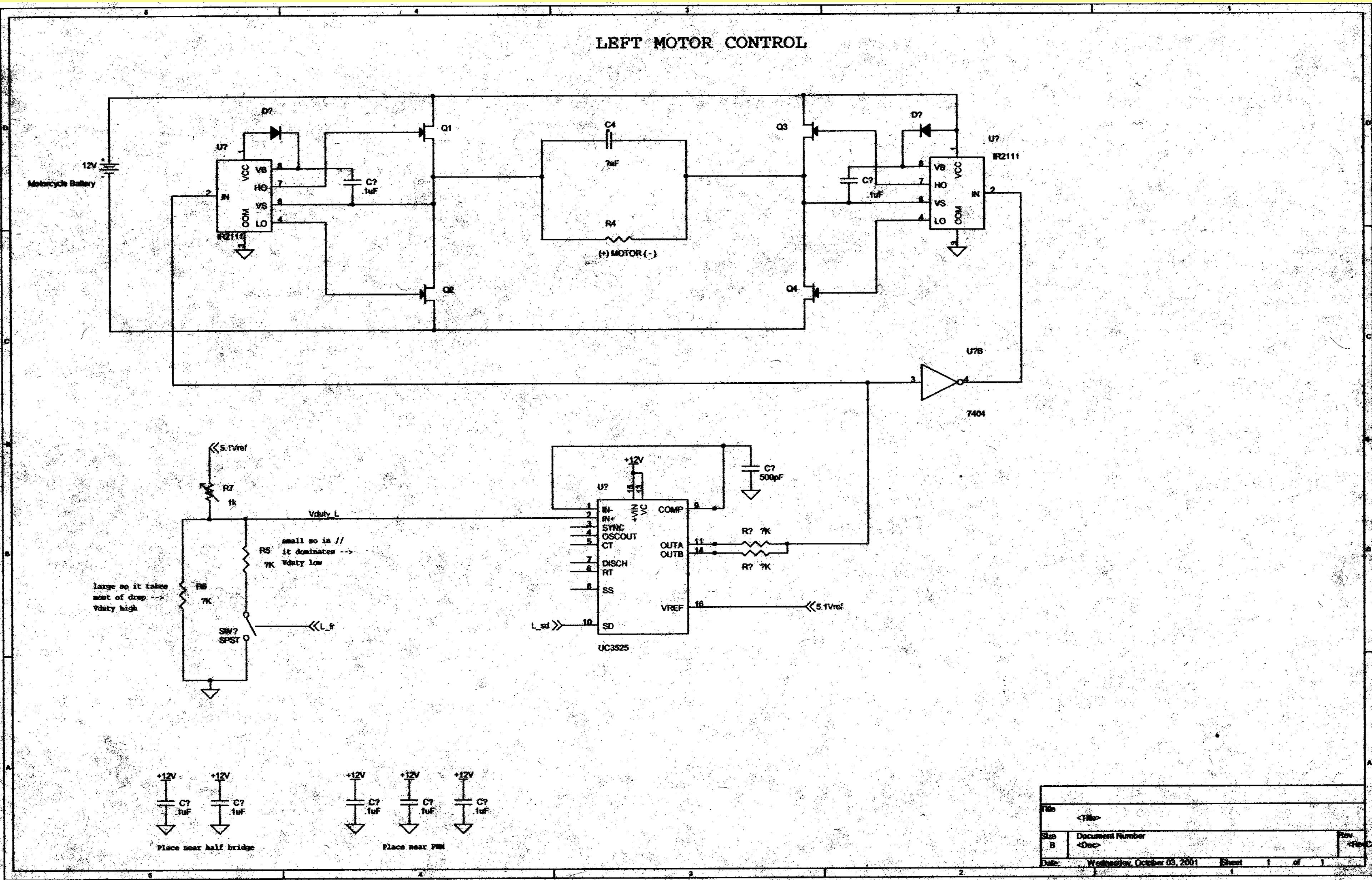
DC MOTOR CONTROL

The DC Motors will be operated both forward and backward, so both positive and negative voltages must be applied

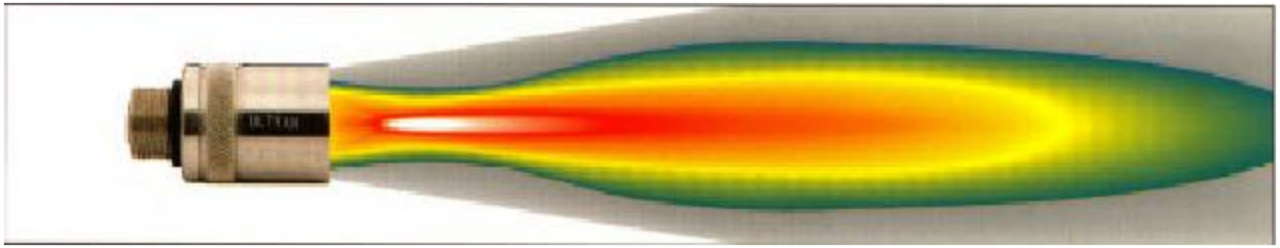
- At the moment, all we have to work with is a single 12V supply
  - An H-Bridge converter can be used to provide anywhere from –12V to 12V at the output by varying the duty cycle
    - By switching between two duty cycles, we can run the motors forward and backward

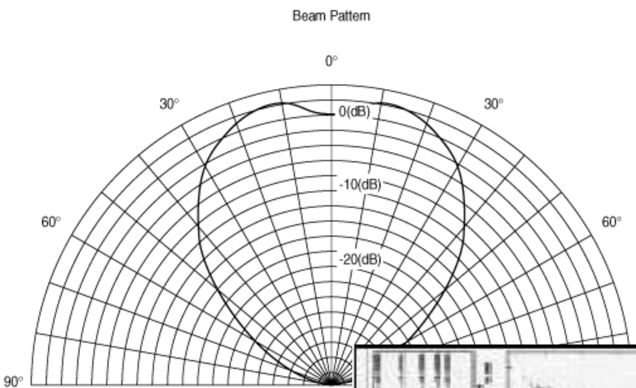


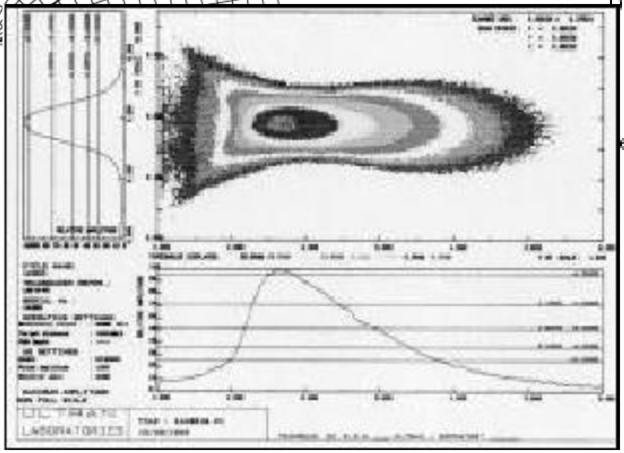
H-BRIDGE CONVERTER

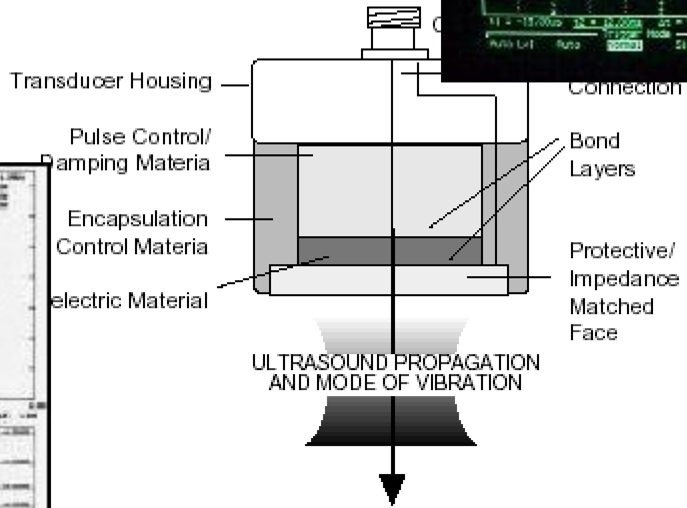


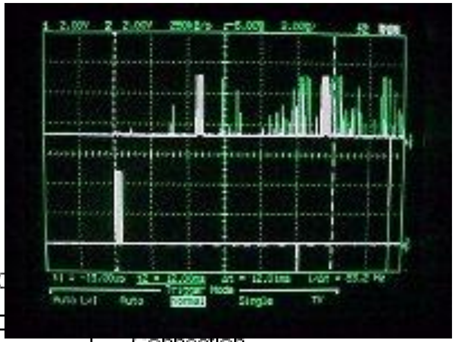
ULTRASONIC SENSORS



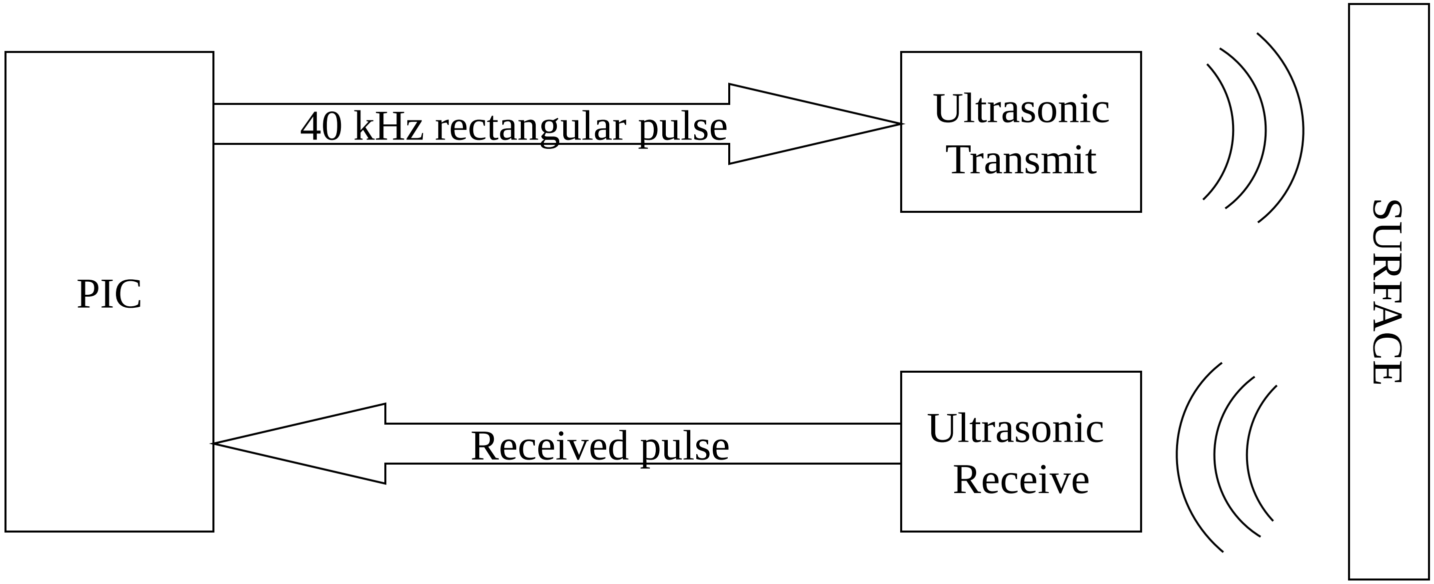








ULTRASONIC DISTANCE DETECTION REVIEW



To determine distance, the PIC will have a routine to determine the time duration between the sent pulse and the return pulse. From there, distance is determined by the simple relationship:

$$d = v_{sound} \cdot \Delta t$$

CREATING THE 40kHz PULSE

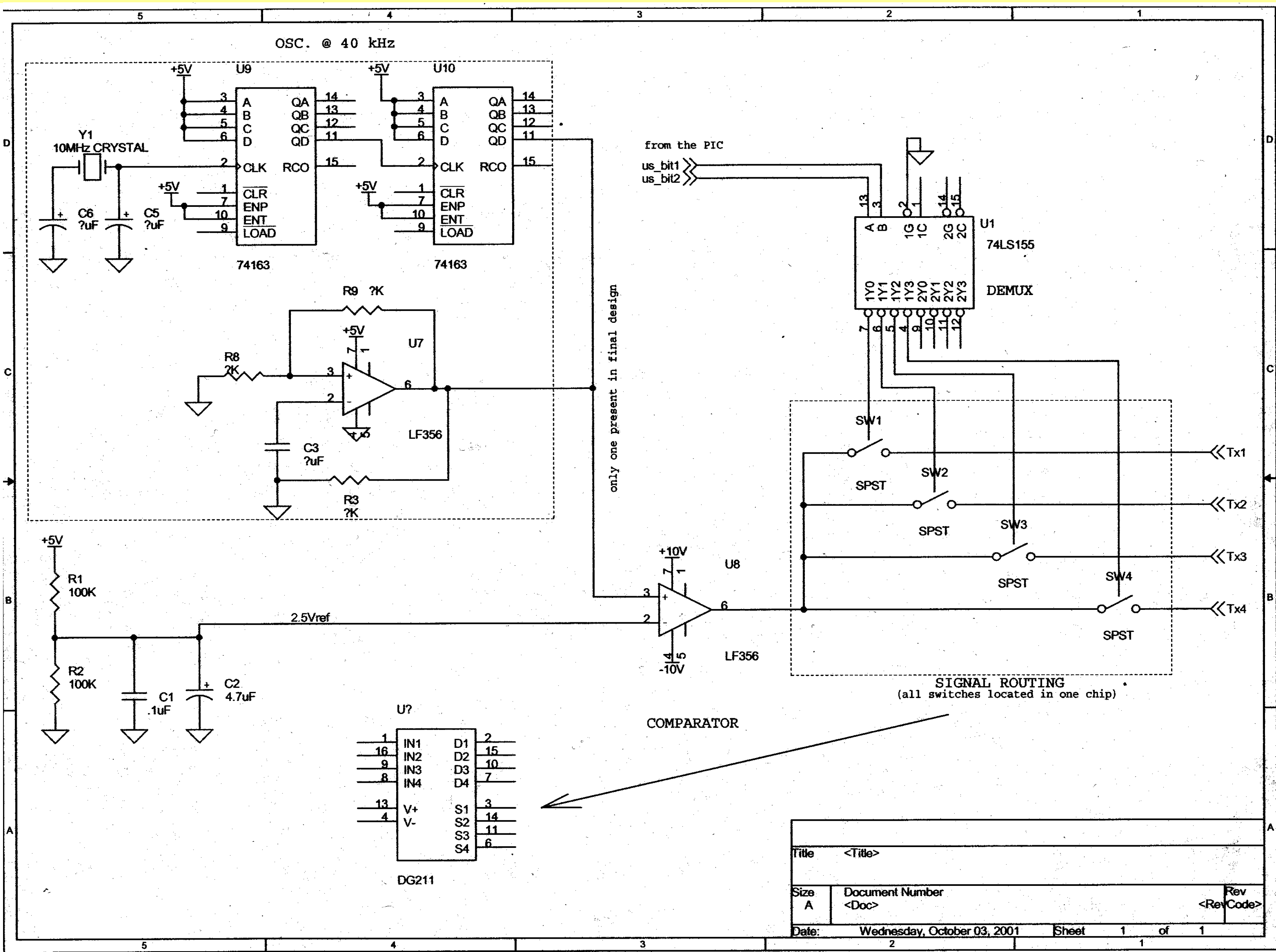
- In order for the detectors to work well, the transmitters must stay quite close to the 40kHz notch in the receiver's sensitivity.

- Three remaining possibilities for the 40kHz pulse generation:
    - Op Amp Oscillator Circuit—a simple op amp is used in combination with resistors and capacitors
    - 10MHz Crystal with 8 bit counting—the 10Mhz clock is used in combination with a divide by 256 counter to create a stable 39.06kHz oscillator
    - Interrupt Driven Counter on PIC—uses on-board counters on PIC to generate continuous 40kHz CMOS square wave

DISTRIBUTING THE 40kHZ PULSE

- Rather than create a 40kHz generator for each transmitter, a switching solution is used
  - Only one transmitter needs the 40kHz signal at any given time
  - Simple SPST switches can be used to distribute the signal to the appropriate transmitter
    - The PIC will control which transmitter to fire via two addressing lines into a de-multiplexor, which will then switch the appropriate SPST to allow the signal to pass

ULTRASONIC TRANSMIT CIRCUIT



ULTRASONIC RECEIVER REVIEW

•The ultrasonic receiver is designed to begin vibrating when there is a 40kHz wave incident upon it.

- •Although the reflected sound wave will not be identical to the transmitted wave in shape and especially magnitude, the frequency should be the same

  - →What about the Doppler effect?

THE DOPPLER EFFECT

THE DOPPLER EFFECT

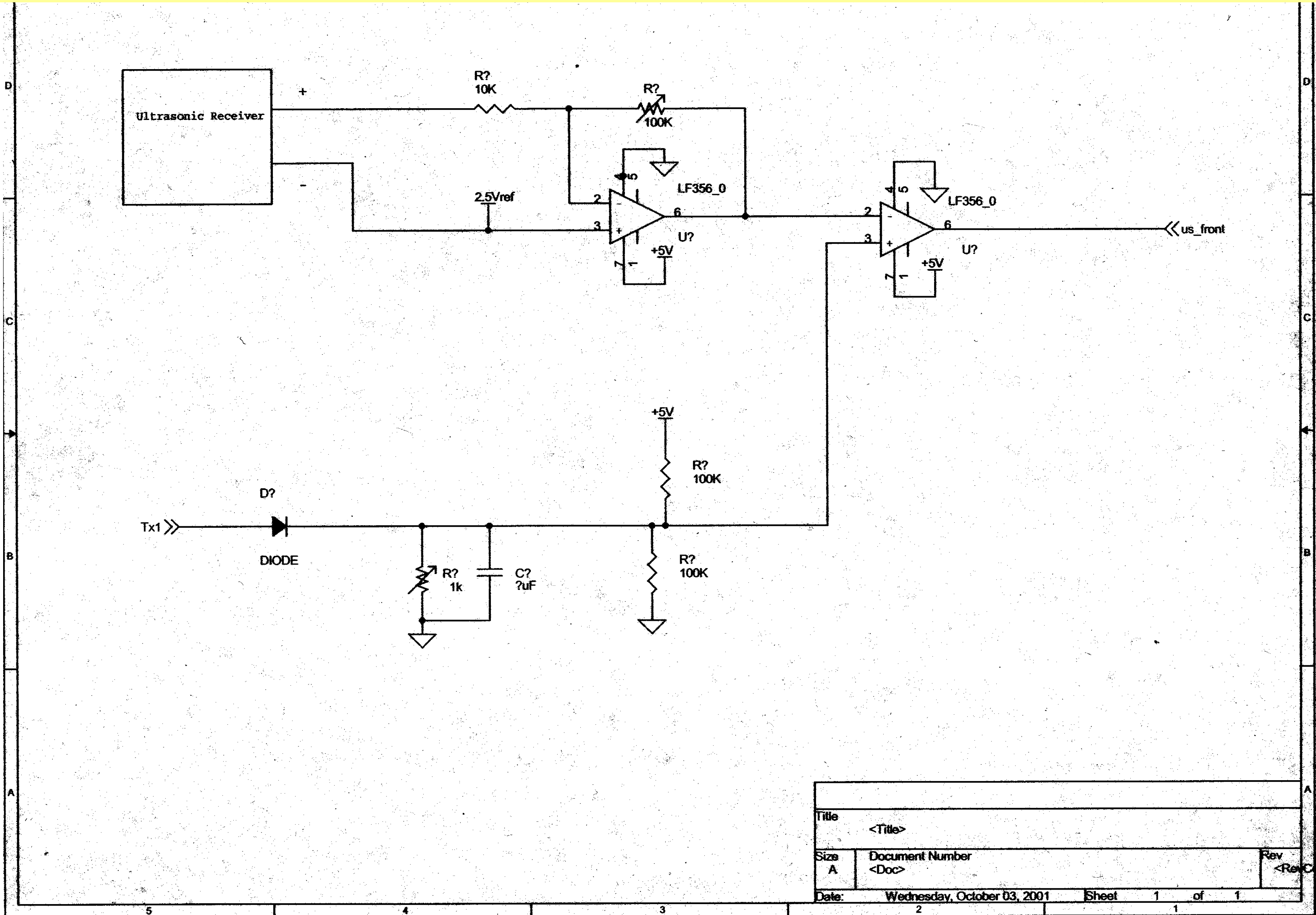
We probably won't have our Roaming Security Watchdog going that fast…

- But the fact remains that we are dealing with a source-receiver pair in motion, so the Doppler effect does occur according to the following equation:

$$f' = f_0\left(\frac{v \pm v_o}{v \pm v_s}\right)$$

As it turns out, the effect of Doppler shifting is negligible, even if our vehicle moved twice as fast as it currently does…

ULTRASONIC RECEIVE CIRCUIT



PYROELECTRIC SENSOR

- sensors detecting infrared heat
- Glolab RE200B ($4)
- crystalline material
- Frensel Lens ($4)
  - Human IR wavelength range 8-14μm
- Chassis placement

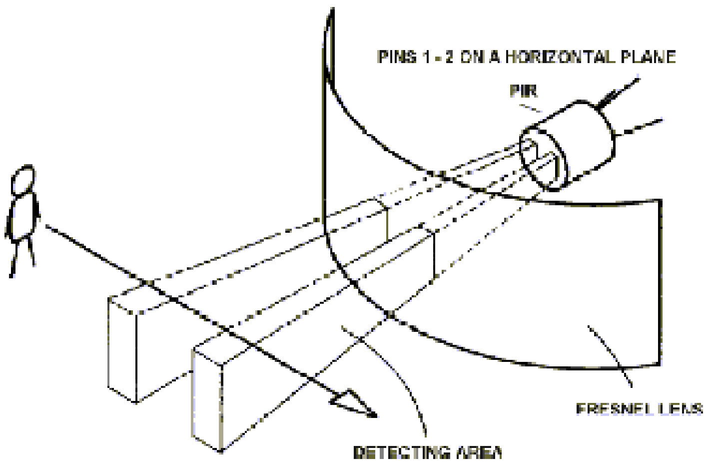
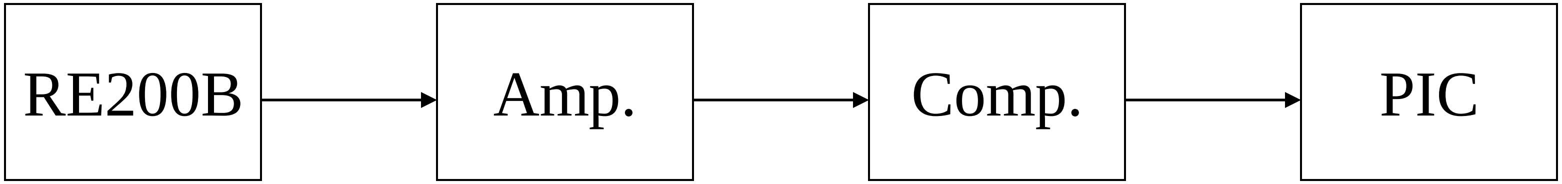


Figure 1

PYROELECTRIC SENSOR

- Output Characteristics
  - 20mV



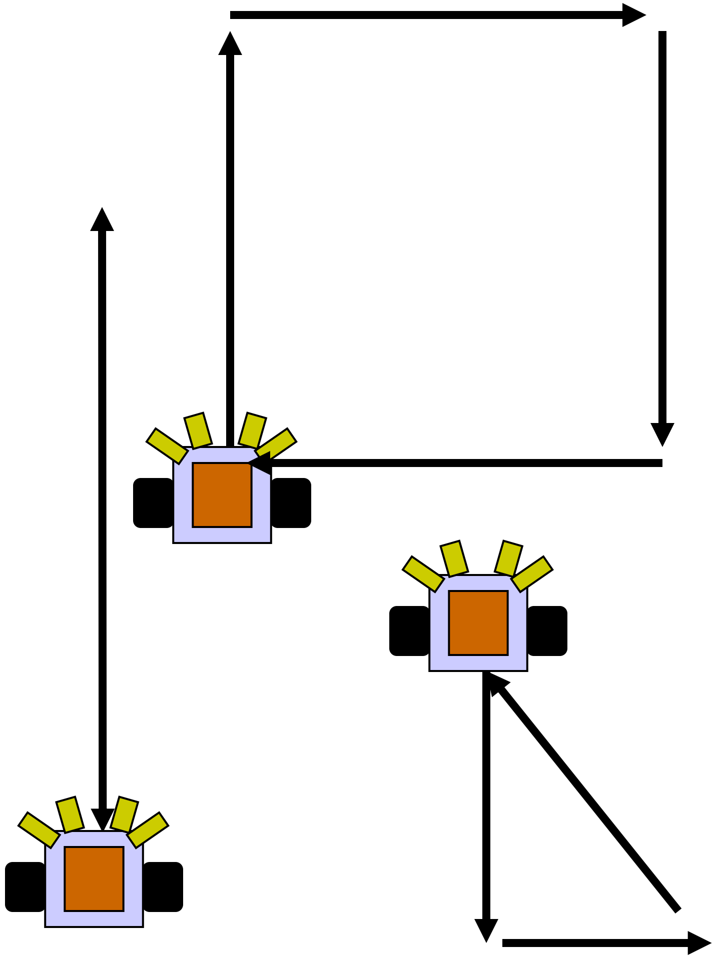
- Backup
  - Sound sensor

ADD-ONS

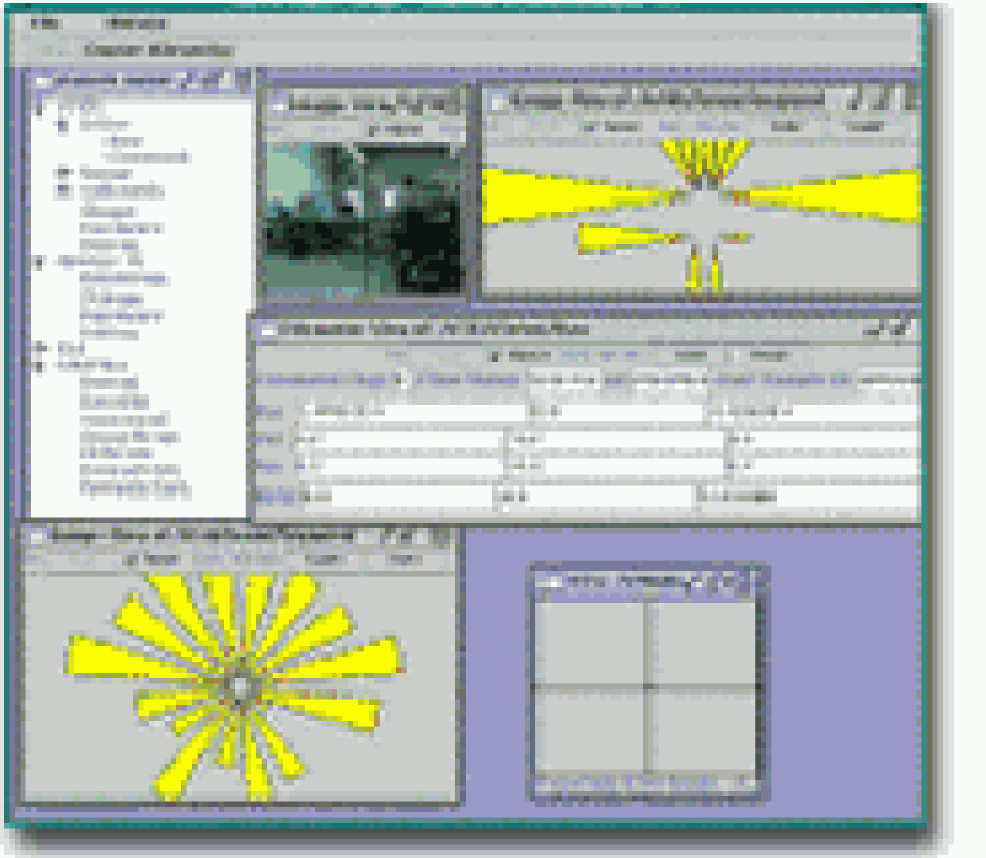
- Voice Alarm
  - talks with intruder
- Multiple Operating Modes
  - keep away
  - remote control
- Enhancement
  - other types of sensors
  - grouping of sensors for better detection/collision avoidance

DEMO

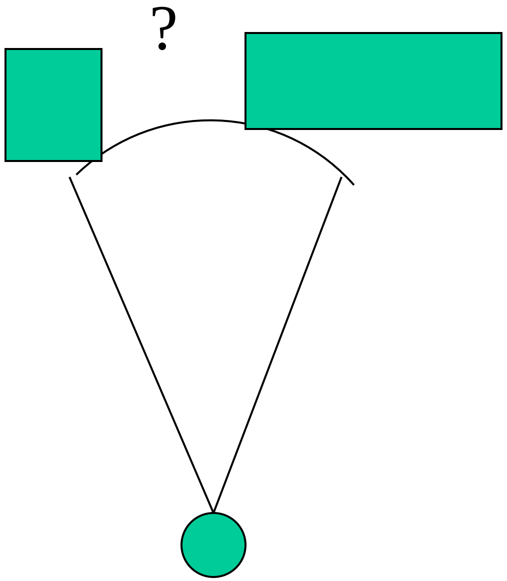
- Have your robot demonstrate the following movements using inverse kinematics, closed-loop encoder monitoring, and proportional control
  - Line: 36 inches forward, 180 degree turn, 36 inches forward
  - Square: 36 inches forward, 90 degree turn, 36 inches forward, 90 degree turn, 36 inches forward, 90 degree turn, 36 inches forward, 90 degree turn
  - Triangle: 16 inches backward, -90 degree turn, 12 inches backward, -307 degrees, 20 inches backward, 217 degrees
- Lab 7: Understanding Sonar



Magellan Sonar Display

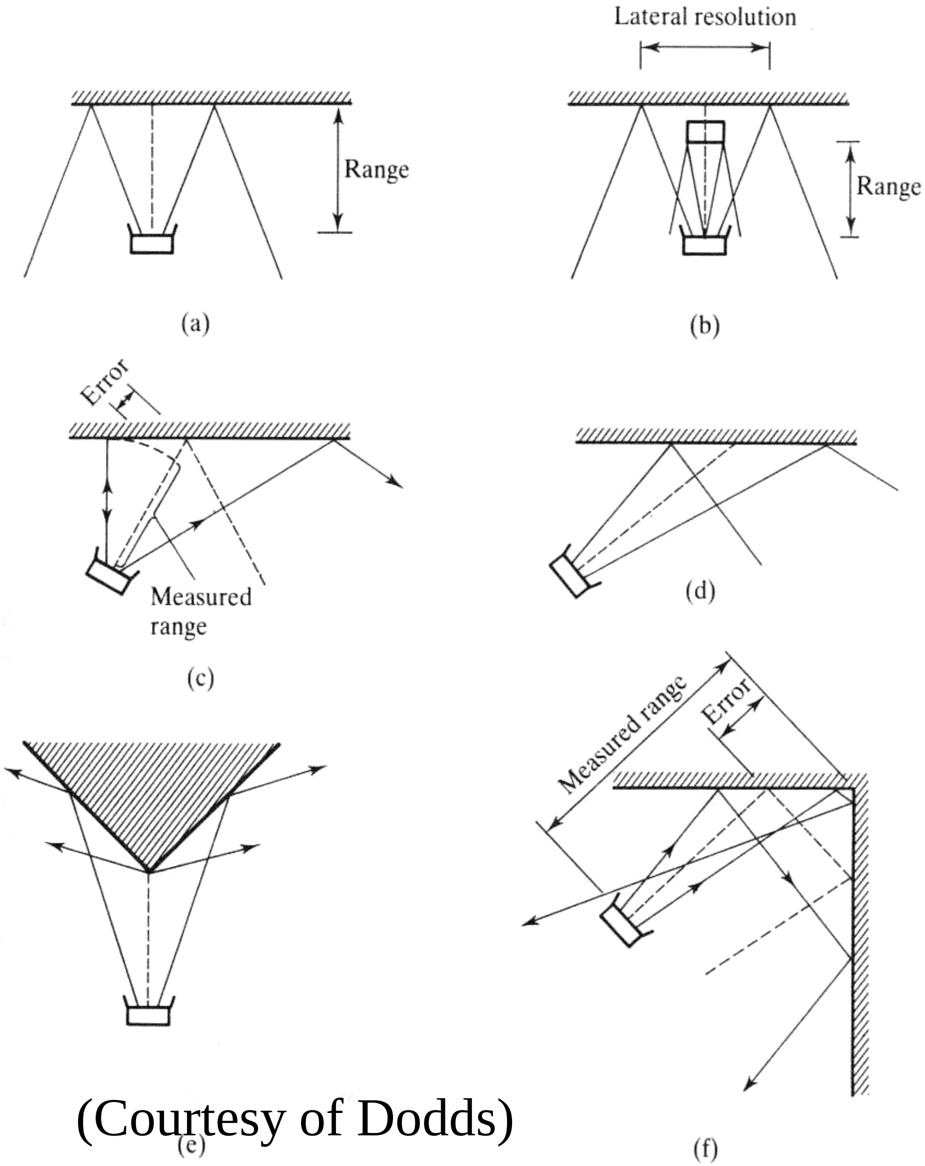


Sonar Beam



- Distance is not a point distance
- Sonar beam has angular “spread” (about 30 degree dispersion in Polaroid module)
- Closest point of object is somewhere within that arc
- Need multiple readings to disambiguate – but readings take time; tradeoffs

Sonar effects



(a) Sonar providing an accurate range measurement

(b-c) Lateral resolution is not very precise; the closest object in the beam's cone provides the response

(d) Specular reflections cause walls to disappear

(e) Open corners produce a weak spherical wavefront

(f) Closed corners measure to the corner itself because of multiple reflections --> sonar ray tracing

(Courtesy of Dodds)

resolution: time / space

Other Sources of Error

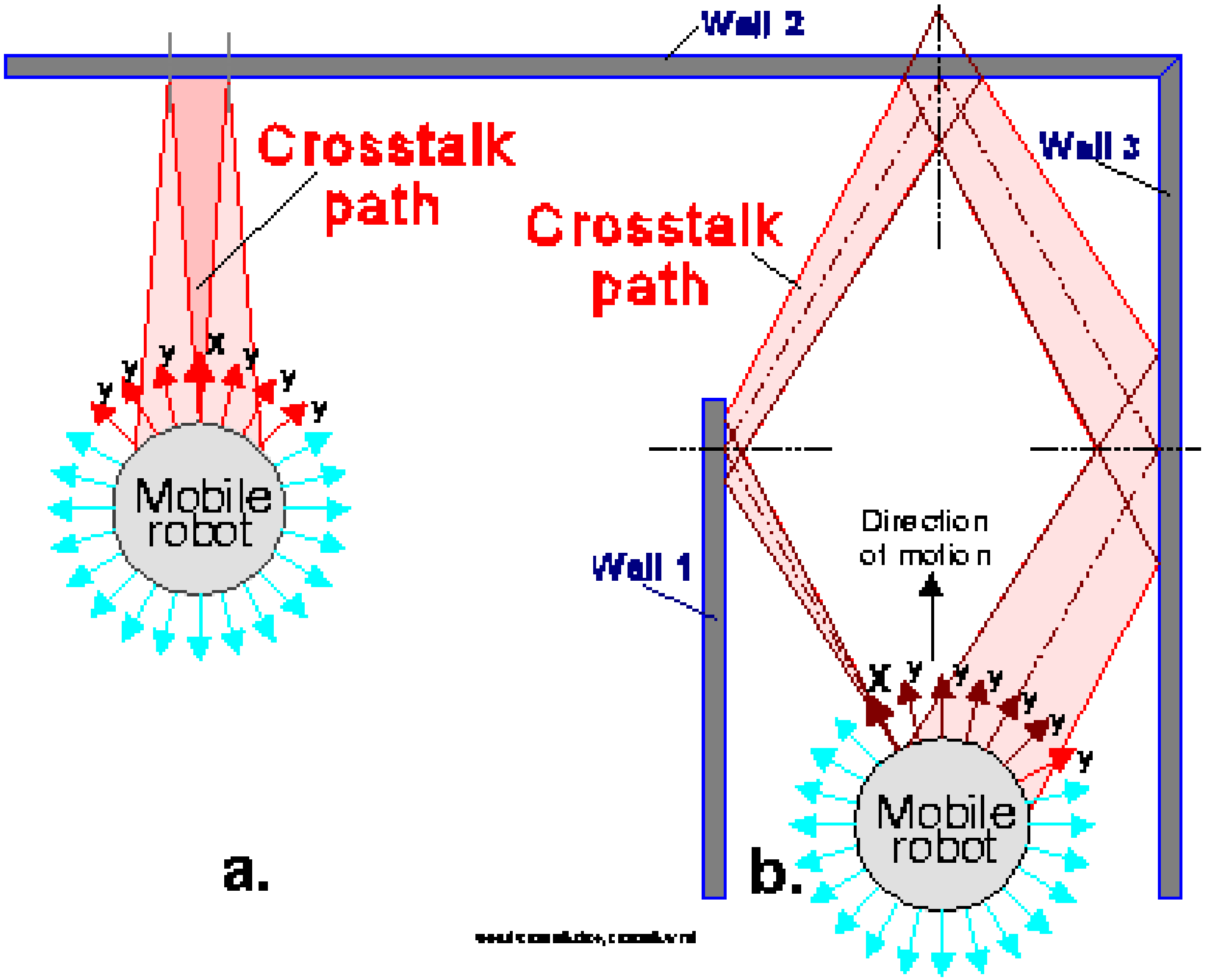
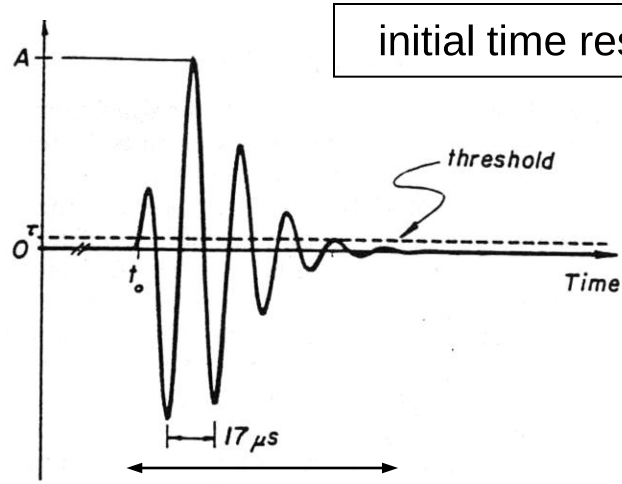


Figure 4.1: Crosstalk is a phenomenon in which one sonar picks up the echo from another. One can distinguish between a. direct crosstalk and b. indirect crosstalk.

- reflectance of surface to sound – signal strength, non-specular reflections, signal absorption, approach angle
- corners
- Crosstalk/ghost images – reflected sound received from wrong transmitter
- change in speed of sound due to temperature and humidity

Sonar modeling

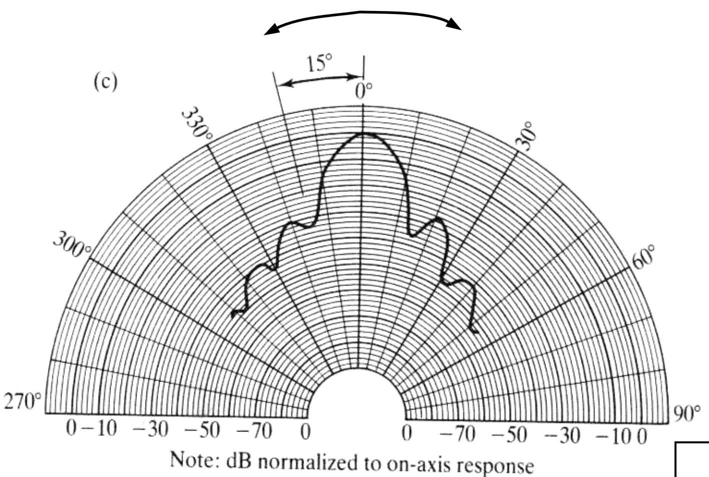
initial time response



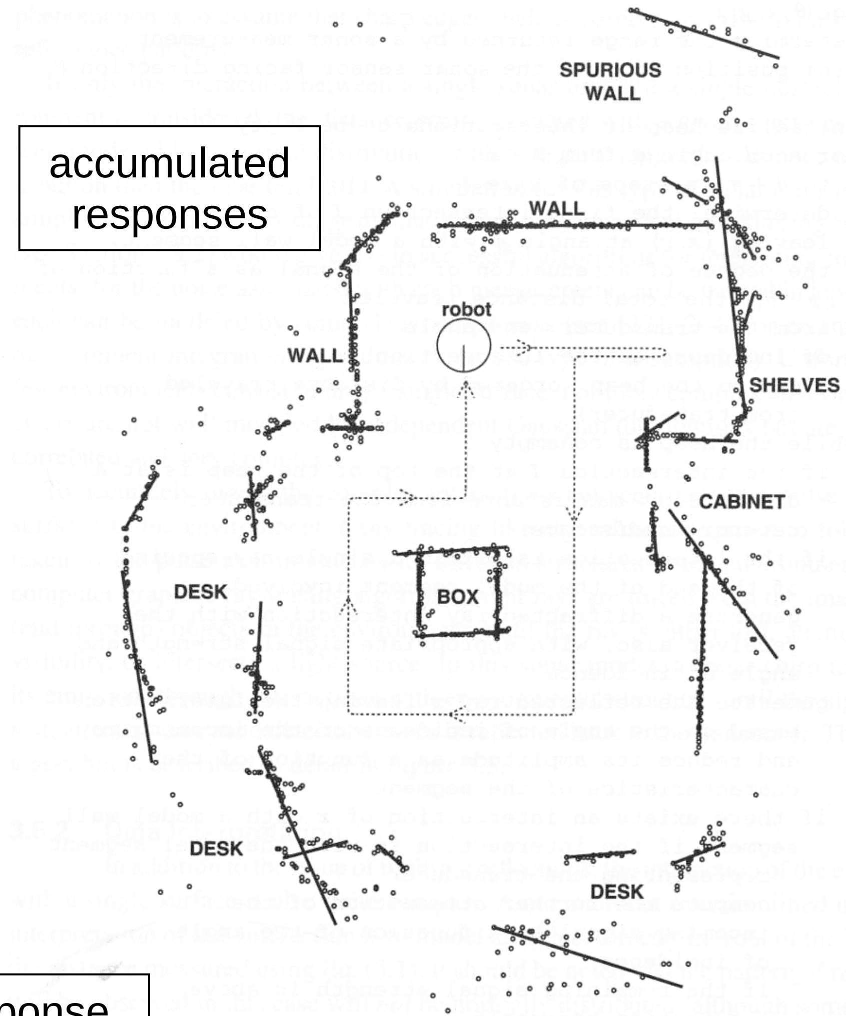
blanking time

accumulated responses

cone width



(Courtesy of Dodds)



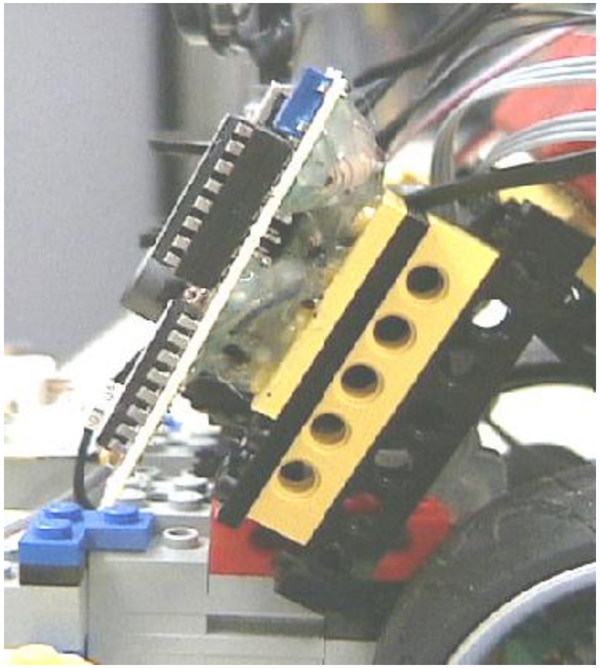
spatial response

Sonar vs. IR

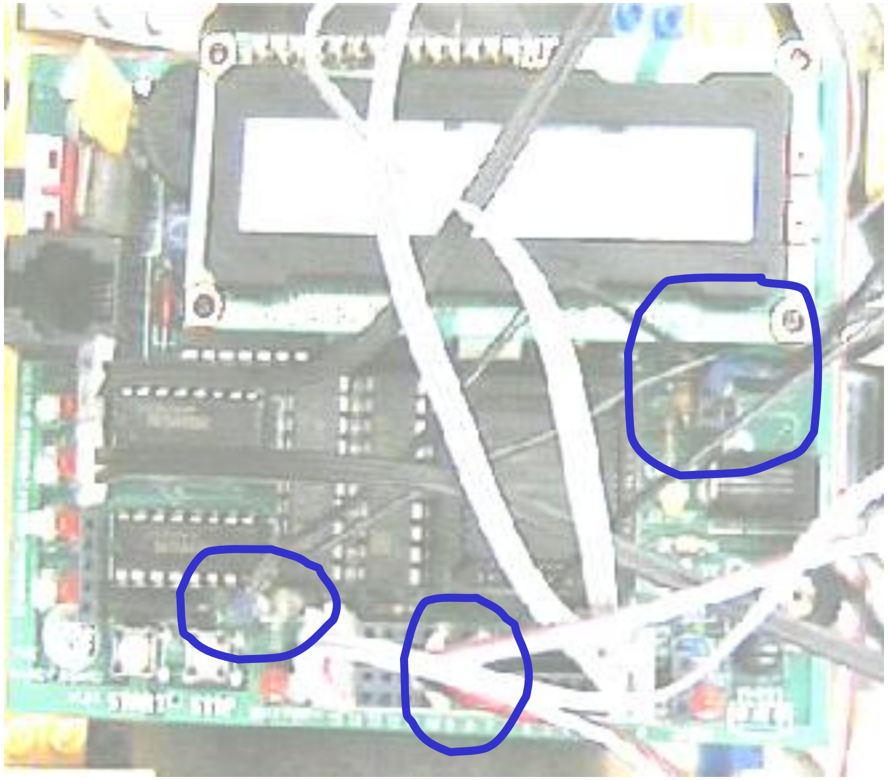
- Both can be used as distance sensors
- Sonar is more commonly used
- Sonar cannot easily be used between 1 and 6 inches from obstacle

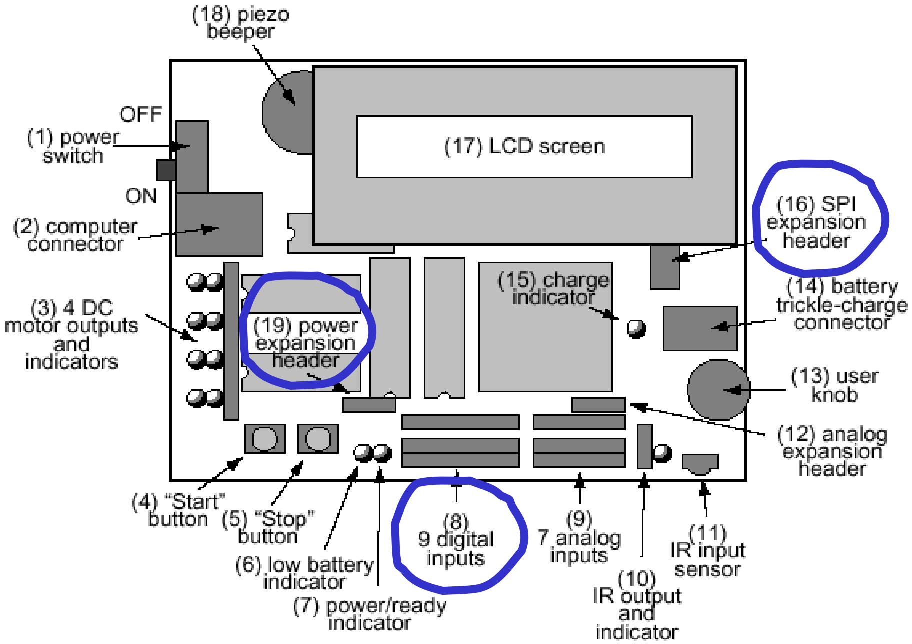
Attaching and programming sonar

Attaching Sonar and Circuit Board



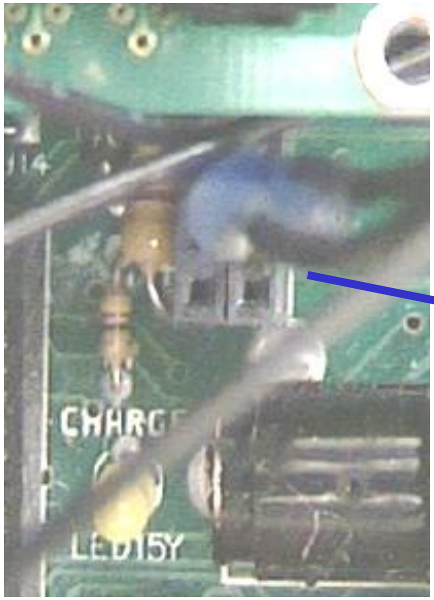
Wiring Sonar and Circuit Board

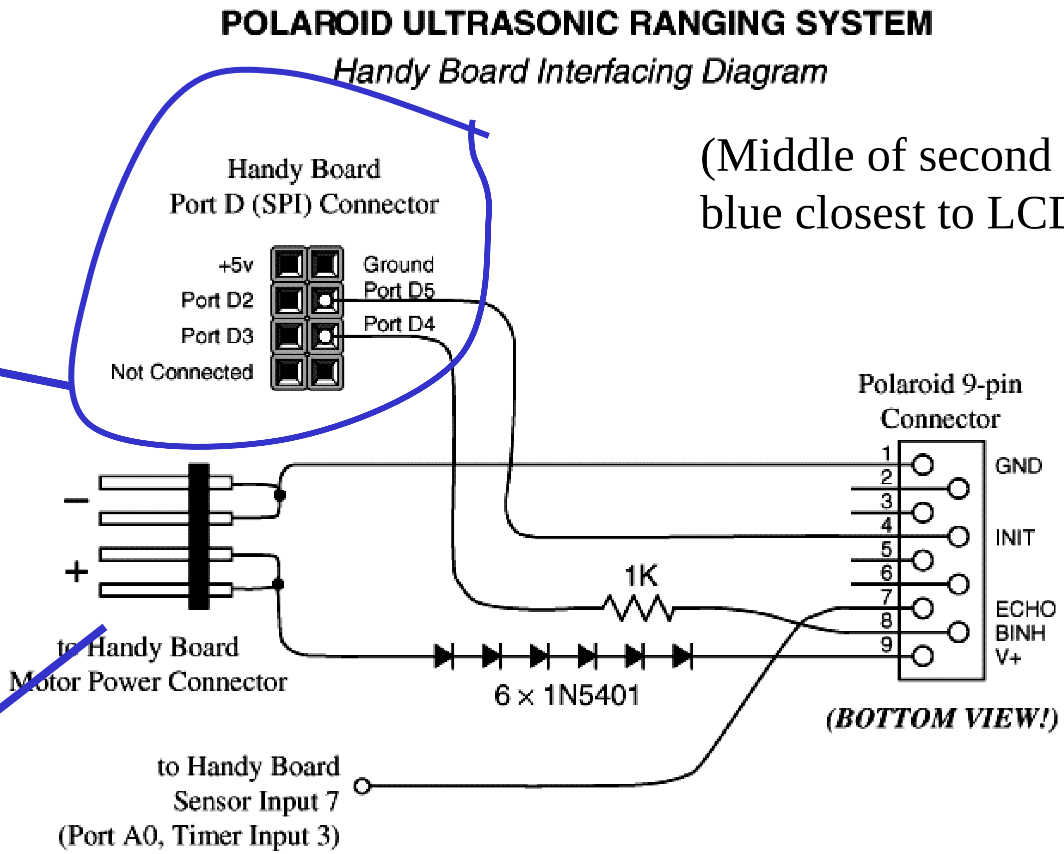




- 3 connections
  - SPI expansion header (2 pin cable)
  - Digital port 7 (3 pin cable)
  - Power expansion header (4 pin cable)

Wiring Sonar and Circuit Board





(Middle of second column, blue closest to LCD)

(Blue on left)

http://lcs.www.media.mit.edu/groups/el/projects/handy-board/software/sonar.html

Sample Sonar Code*

- initialization code:

```
void sonar_init() {
    bit_set(0x1009, 0x30);      /* sets output pins for
                    sonar pulses and blanking */
    bit_set(0x1021, 1);         /* trigger on rising edge
                            of sonar echo */
    bit_clear(0x1021, 2);
}
```

* The code in this slide and the next two are already in sonar.c – just load sonar.c to use the functions

Grabbing a Sonar Sample

```
int sonar_sample() {
    int start_time;
    poke(0x1023, 1);              /* clear tic3 flag */
    start_time= peekword(0x100e);  /* capture start time */
   bit_set(0x1008, 0x20);         /* trigger pulse */
    while (!(peek(0x1000) & 0x1)) { /* wait until receive echo */
       if ((peekword(0x100e) - start_time) < 0) {
          /* if too much time has elapsed, abort */
          bit_clear(0x1008, 0x20);
          return -1;
       }
       defer();                    /* let others run while waiting */
   }
    bit_clear(0x1008, 0x20);       /* clear pulse trigger */
    return peekword(0x1014) - start_time;  /* tic3 has time of
                                              echo */
}
```

Getting Closer Readings

- Allow reading of echo sooner (shorter blank period .5 msec vs 2.38 msec, inches vs. 1.33 feet)

```
int sonar_closeup() {
    int start_time;
    poke(0x1023, 1);              /* clear tic3 flag */
    start_time= peekword(0x100e);
    poke(0x1008, 0x20);
    while ((peekword(0x100e) - start_time) < 1000);
    bit_set(0x1008, 0x30);        /* turn on BINH */
    while (!(peek(0x1000) & 0x01)) {
        if ((peekword(0x100e) - start_time) < 0) {
            /* if too much time has elapsed, abort */
            bit_clear(0x1008, 0x30);
            return -1;   }
        defer();}
     bit_clear(0x1008, 0x30);
     return peekword(0x1014) - start_time;   /* 0x1014 is tic3 */
}
```

Using the Sonar Functions

```
void sonar_display()
{
    sonar_init();
    while (1) {
        int result;
        result= sonar_sample();
        if (result != -1) printf("%d\n", result);
        else printf("*******\n");
        msleep(50L);  /* need to pause between
                    readings */
    }
}
```

Converting from Sonar Reading to Distance

- Distance (ft) = ((counts/2000) * 1.1)/2
  - (or 2.75 * (counts/10000))
- Sound travels 1.1 feet per millisec
- (In average air conditions)
- .5 microsecs per timer count (10000 counts = 5 millisecs)
- Example
  - 10000 counts
  - 5 millisecs * 1.1 ft/millisec = 5.5 feet
  - 5.5 ft/2 for round trip time = 2.75 feet for 10000 timer counts

  -→ ((10000/2000) * 1.1)/2 = 2.75

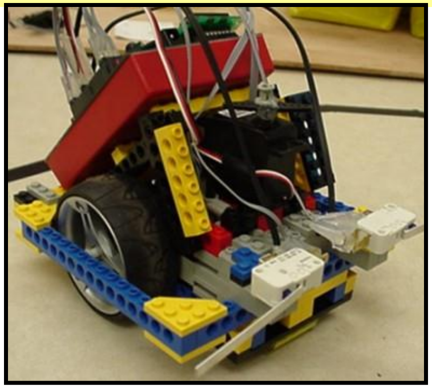
Using Sonar Library, With count-to-feet translations

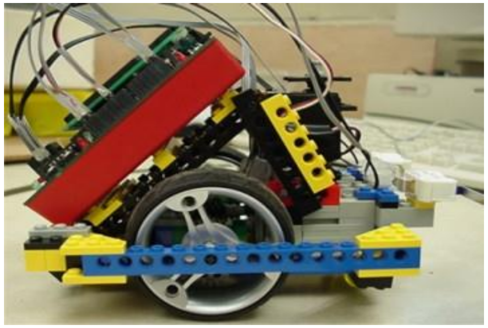
```
void main(void) {
float dist, cdist;

sonar_init();

  /* Normal sampling routine */
 dist = 2.75 * (sonar_sample() / 10000.0);

  /* Close range sampling */
  cdist = 2.75 * (sonar_closeup() / 10000.0);

}
```

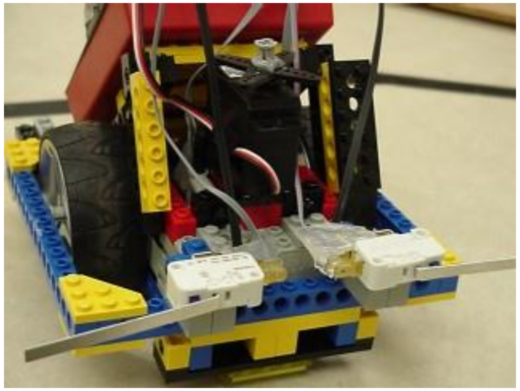
Today

- Understanding sonar
- Attaching and programming sonar
- Servo motors and programming
- Sonar for obstacle avoidance
- Serial communication review

Servo Motors and Programming

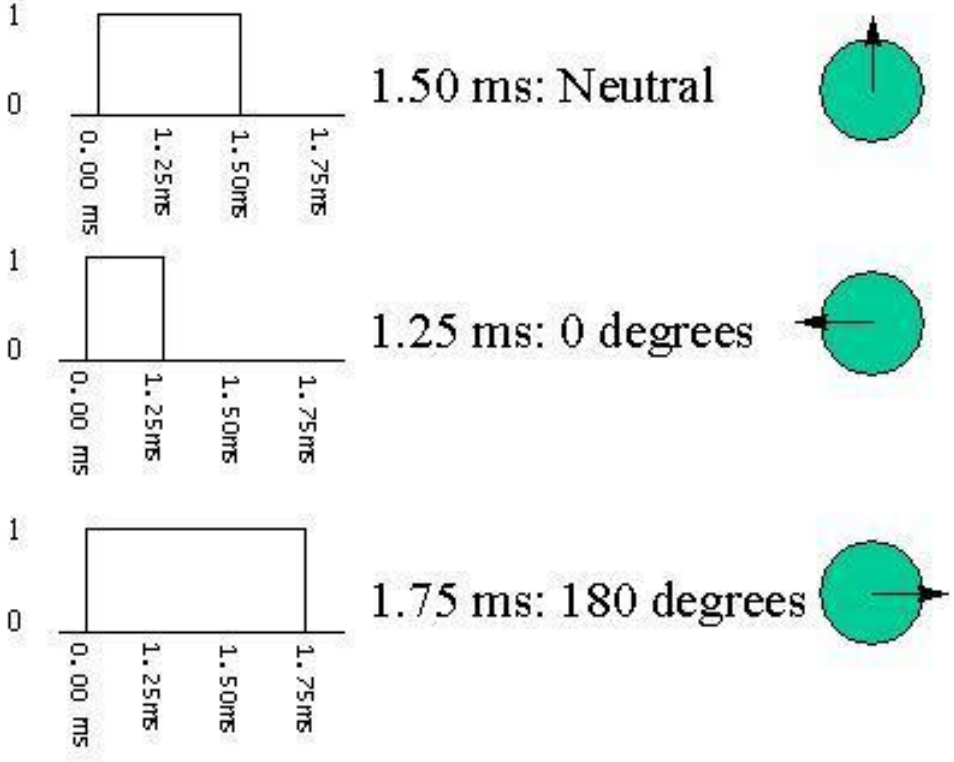






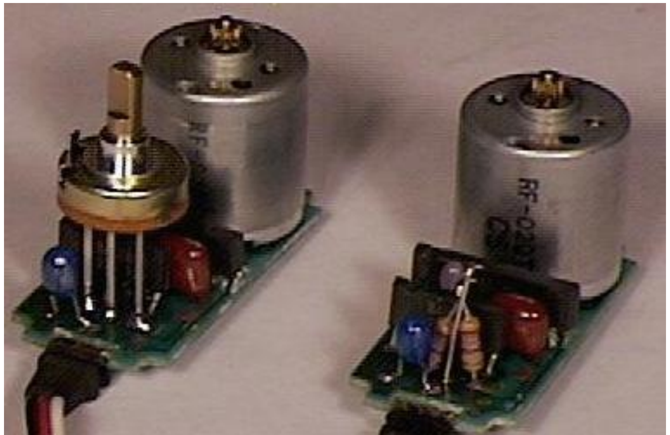
- Package includes:
  - Dc motor
  - Gear reduction
  - Shaft positioning sensor and control circuit
- Command output shaft to move to a certain angular position
- Three wires: power, ground and control
- Use digital port number 9

Servomotors



“direct” position control -- in response to the width of a regularly sent pulse

modified to run continuously →



Servo Motor Output Commands

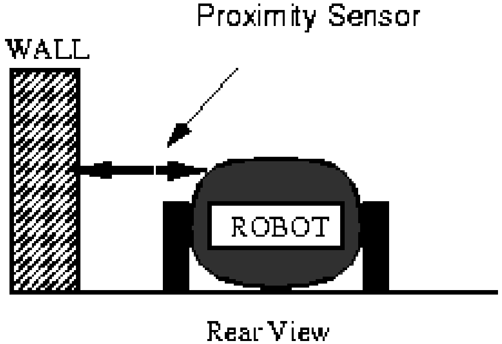
- `Need to load servo motor library -- servo.icb` and `servo.c (done by default)`
- `void servo_on()      void servo_off()`
  - Enables/Disables servo output waveform.
- `int servo(int period)`
  - Sets length of servo control pulse. Minimum allowable value is 1400 (i.e., 700 sec); maximum is 4860. Function return value is actual period set by driver software.
- `int servo_rad(float angle)`
  - Sets servo angle in radians.
- `int servo_deg(float angle)`
  - Sets servo angle in degrees.
- For our specific servos, you must set the MIN_SERVO_WAVETIME variable to 600, and the MAX_SERVO_WAVETIME variable to 4400 for a proper mapping between degrees/radians and pulses.

Servo Turret

- Attach forward-facing servo motor to robot
- Can use to mount various sensors that can actively scan a scene

Sonar for obstacle avoidance

Review: Closed-loop Control



Using a Proximity Sensor to Measure Distance to a Wall

- Drive parallel to wall
- Feedback from proximity sensors (e.g. bump, IR, sonar)
- Feedback loop, continuous monitoring and correction of motors -- adjusting distance to wall to maintain goal distance

(Courtesy of Bennet)

Review: Separate Sensor State Processing from Control

Functions might each make use of other sensors and

```
void follow_wall()
{
    while (1) {
        int state= wall_distance();

        if (state == TOO_CLOSE) veer_away_from_wall();
        else if (state == TOO_FAR) veer_toward_wall();
        else drive_straight();
    }

}
```

Figure 11.5: Wall-Following Function

(Courtesy of Bennet)

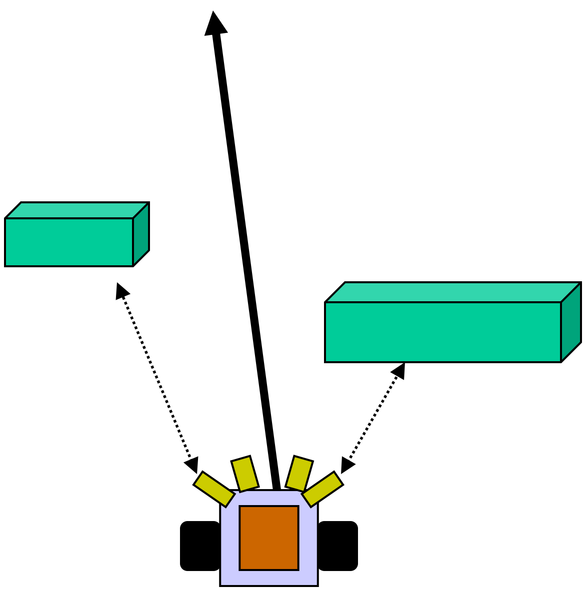
Use Proximity Sensor to Select One of Three States

```
int TOO_CLOSE= -1;
int JUST_RIGHT= 0;
int TOO_FAR= 1;
int TOO_CLOSE_THRESHOLD= 50;  /* Embedding threshold constants in this */
int TOO_FAR_THRESHOLD= 150;   /* manner in a real program is not good */
                              /* programming practice.  Instead, they */
                              /* should be placed in a separate file. */

int wall_dist_prox()
{

    /* get reading on proximity sensor */
    int prox_value= analog(PROXIMITY_SENSOR);

    /* assume smaller values mean closer to wall */
    if (prox_value < TOO_CLOSE_THRESHOLD) return TOO_CLOSE;
    if (prox_value > TOO_FAR_THRESHOLD) return TOO_FAR;
    return JUST_RIGHT;

}
```

Sensor used to select one of three states

(Courtesy of Bennet)

Obstacle Avoidance and Tracking Using Sonar



- Have continuously running task update obstacle state:
  - Left, right, both, neither
- If one obstacle detected use closed-loop control to keep it away from robot
- If two obstacles detected
  - Estimate distance and try to pass in-between with closed-loop control, if possible

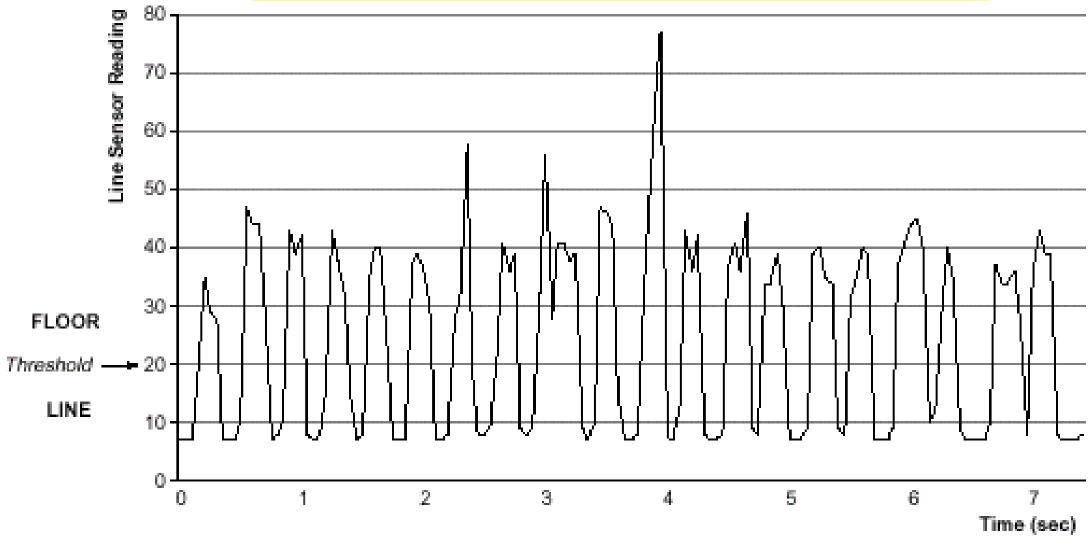
Review: Simple Processing Using Single Threshold

- Robot ground sensor can be in one of two states:
  - State A: Over line
  - State B: Over floor
- Compare sensor reading with setpoint value
  - If less than this threshold set variable to indicate robot is in State A
  - Otherwise, set variable to indicate State B
- What to use as setpoint threshold?
  - midpoint between floor value and line value
  - **E.g.** 10 when aimed at the floor, and 50 when aimed at the line → choose 30 as setpoint threshold

Review: Two Thresholds for Hysteresis

- Problem with single threshold – variances in sensor readings
  - Bump on floor may spike the readings
  - Shiny spots on line may reflect as well as the floor, dropping the sensor readings up into the range of the floor
- Solution: **two setpoints** can be used
  - – Imposes **hysteresis** on the interpretation of sensor values, i.e., prior state of system (on/off line) affects system's movement into a new state

Line Following performance run :
Setpoint =20




```
int LINE_SETPOINT= 35;
int FLOOR_SETPOINT= 10;
void waituntil_on_the_line() {
     while (line_sensor() < LINE_SETPOINT);
}
void waituntil_off_the_line() {
     while (line_sensor() > FLOOR_SETPOINT);
}
```

Review: Separate Sensor State Processing from Control

Functions might each make use of other sensors and

```
void follow_wall()
{
    while (1) {
        int state= wall_distance();

        if (state == TOO_CLOSE) veer_away_from_wall();
        else if (state == TOO_FAR) veer_toward_wall();
        else drive_straight();
    }

}
```

Figure 11.5: Wall-Following Function

(Courtesy of Bennet)

- Michael Walker
- Jason Jones
- Charlie Hwang
- Mitch Tu
- Maja Mataric
- Fred Martin

Understanding sonar and servos

http://plan.mcs.drexel.edu/courses/robotlab/labs/lab07.pdf