AER201 – Engineering Design
Pipe Inspector Machine Proposal

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1. **Executive Summary**

This proposal presents the design concept for an autonomous robot that inspects circular pipes for abnormalities, which can be applied in the future towards detecting the buildup of radioactive materials. This is in response to a request made by the client, a nuclear power plant, which needs to frequently inspect its pipelines, and record the number and location of spots along a pipe.

The solution consists of two major sections: the moving platform, and the detection arm. The moving platform travels along one side of the pipe, and the detection arm positions sensors around the pipe to detect abnormalities. To avoid pipeline supports, two small servo motors will take the portions of the detection arm located under the pipe and rotate them by 90 degrees. At the end of the 120 inch pipe, the robot will travel back along the pipe to its original position. The entire process is designed to take place in under 3 minutes.

The cost of building the prototype will be $215.67. Small alterations to the final design may change the cost, though it will still be designed so that the final cost is under the budget constraints of $230. For funding this project, the three team members will pool monetary resources and share the costs of components equally.

The three members of the team will split the work of prototype development as follows: Alice Ye will write the processor code and provide the user interface of the machine, as well as assisting in soldering circuit boards. Amanda Aleong will be responsible for designing and building circuitry to control sensors and motors, and to connect the microcontroller to the electromechanical components. Lily Lau will build the electromechanical modules, including the chassis and the arm, and install other physical components such as motors onto the prototype.
2. Problem Formulation

2.1 Statement of Need

In many industries it is important to regularly check pipes for build-up of material [1]. Specifically, in nuclear power plants the accumulation of radioactive material can be detected from the surface of the pipe. Accumulation of radioactive material is a serious hazard and thus the pipes need to be checked frequently [2]. The challenge that comes up is to detect spots on the surface of a pipe and record the location of the spots with respect to a reference point. The development of an autonomous robot that can do this has great value in the industry. It will reduce the need to regularly check the pipes manually for build-up, as the robot will only record the build-up when it occurs. Thus the pipes need only be tended to by humans when the machine detects a spot.

2.2 Project Goals and Specifications

This project will focus on a scaled-down proof of concept prototype for a pipe inspector machine. The prototype will be designed to carry out the following tasks (all dimensions are given in inches):

- Move along the side of a pipe and return to the starting position.
- Detect black spots with diameter 2 – 2.5.
- Record the axial location of the spots along the pipe with the edge of the pipe as reference.
- Record the radial position of the spot.

The operation of the prototype is designed around specifications given by the client. Details of these specifications can be found in the AER201 Engineering Design Textbook.

The following is a summary of the constraints outlined by the client. These constraints must be met while allowing the prototype to fulfill its tasks:

- The robot must fit within a 23” x 23” x 23” box at all times.
- The total weight must be no more than 20 lb.
- Total cost of all components shall not exceed $230CDN.
- The machine must use its on-board power supply during operation.
- The machine shall provide a user-friendly interface for start/stop/information retrieval.
- Operation time must be less than 3 minutes.
- The machine must be safe to operate.

Other criteria that were considered when developing the concept of the design are:

- Time delay for detection – The amount of time that the detection mechanism would slow down the robot during operation in order to accurately locate spots.
- Sensitivity of Detection – The ratio of the circumference over which the detection mechanism can accurately locate spots.
• Ease of Construction – The degree to which the design will require custom parts or highly skilled labour.
• Cost of Parts – A more expensive part was considered less desirable.
• Robustness – The durability and strength of the design.
• Space – A more compact design was considered more desirable.

3. Literature Survey

3.1 Existing Designs

In order to further evaluate our design conceptualization, a review of similar concepts were surveyed, specifically **pipeline pigs used in trans-Alaska pipeline inspection**.

Pipeline pigs are used by engineers to perform periodic pipeline inspections in an attempt to keep pipelines operating safely. Pipelines are usually vulnerable to corrosion and cracking, thus, flaws and damage in the pipelines must be detected before they become leak bursts or serious environmental disasters. Some uses of pipeline pigs include:

- Crack detection
- Leak detection
- Temperature/pressure recording
- Corrosion detection
- Bend measurement
- Geometry measurement

Pipeline pigs are easy to use since they are put into the pipe on one end and taken out at the other. They are introduced to the pipeline and then are carried through the pipe by the flow of the liquid or gas, and can travel and perform inspections over large distances. Pipeline pigs also carry a small computer to collect, store, and transmit the data for analysis, and can perform for long ranges – up to 1000 km.

The pigs employ several techniques to perform inspections. Most pigs use a
magnetic flux leakage method as illustrated in Figure 2, but some also use ultrasound. Damaged areas of the pipe can’t support as much magnetic flux as undamaged areas so magnetic flux leaks out of the pipe wall at the damaged areas. An array of sensors around the circumference of the pig detects the magnetic flux leakage and notes the area of damage. Pigs that use ultrasound, have an array of transducers that emits a high frequency sound pulse perpendicular to the pipe wall and receives echo signals from the inner surface and the outer surface of the pipe.

On some pipelines it is easier to use remote visual inspection equipment to assess the condition of the pipe. Robotic crawlers of all shapes and sizes have been developed to navigate the pipe. The video signal is typically fed to a truck where an operator reviews the images and controls the robot, as shown in Figure 3.

3.2 Electromechanical Components

3.2.1 Moving Mechanical Arm

In order to better understand and select our design solution for the moving arm, research on some automated mechanical arms and their mechanisms used in current projects were conducted. One of these projects is the design of garbage trucks with a moving arm implemented by the City of Toronto. As shown in the Figure 4, a mechanical arm opens to a range twice the dimension of the bin’s width, grabs the bin by closing the clamp, and lifts it to the top of the vehicle to empty the material. Since the pipe to be inspected is circular, the opening-closing mechanism of an automatic circular clamp like the one depicted below was considered to solve the problem of the pipe supports.
3.2.2 Hinged Door

In order to position sensors underneath the pipe while also moving them out of the way of the pipeline supports when necessary, a hinge, similar to what is used in a hinged door, was considered to control the movement of an arm.

Hinged doors are hinged along one side to allow the door to pivot away from the doorway in one direction but not in the other. The axis of rotation is usually vertical. In some cases, such as hinged garage doors, the axis may be horizontal, above the door opening.

Doors can be hinged so that the axis of rotation is not in the plane of the door to reduce the space required on the side to which the door opens. This requires a mechanism so that the axis of rotation is on the side other than that in which the door opens inwards, such as the lid of a toilet.

The simplest form of hinged door that can be implemented in our design is the one whose axis of rotation is parallel to the plane of the door. This mechanism would allow the door to open in such a way that the optimal space is given to the arm to be able to move along the pipe and avoid abnormalities.

3.2.3 Moving the Robot

There are many different methods of moving the sensors along the length of the robot, and many viable chassis designs. In terms of locomotion, the robot can be made to travel using a four-wheel system, a tank-track system, or on rails. Further options that may be of importance include different motors that can be used. A wide variety of DC motors are commercially available, and DC motors are sufficiently powerful to carry the maximum 20 lb load, though they do not provide precise control of travel.
3.3 Sensor Components

A survey of available information was conducted to find useful methods of detecting pipeline spots and also external sensing of autonomous robot. These will be discussed in separate sections, 3.3.1 and 3.3.2, outlined below.

3.3.1 Spot Detection

The pipeline spots, made of black hockey tape, can be detected using a variety of methods. Possible sensors and mechanisms to detect these include photodetectors (eg. phototransistors, photodiodes, and photoresistors), as well as IR emitter-receiver pairs, radar sensors and fiber optic texture sensor systems.

**Photoresistors**: Photoresistors, or light dependent resistors, have decreased resistance when exposed to greater light intensity. They can be made of cadmium sulfide, and are often found in ambient light sensors, such as camera light metres. A quick survey of some sources show that typical photoresistors are only capable of detecting white/black at a close range of ~0.1 inches, which means that these sensors must be very carefully placed in order to efficiently detect pipeline spots.

**Photodiode**: Photodiodes convert light to a current or voltage. They are generally made of a semiconductor such as silicon or germanium, and have a more linear response to light than photoconductors [4]. Thus, it is possible that they can be used to detect a small difference in light levels caused by a black spot on the pipe. In addition, there are commercially available avalanche photodiodes that are more responsive to light, and may be used if sufficient light is not available. The cost of these is not prohibitive.

**Phototransistors**: Phototransistors, though similar to photodiodes, have a longer response time, and higher responsivity to light. They would therefore provide a greater current, which could reduce some costs associated with amplifying the photodiode’s current [4]. However, their longer response times may not be acceptable when developing a design that can quickly travel along the pipe.

**Infrared Emitter – Receivers**: Infrared sensors are fairly effective because they use infrared light, which is not usually found in ambient light. They have a range of usually around 10 cm, which is sufficient for our requirements. Furthermore, they are sensitive to material properties, which would be excellent for differentiating between different surfaces such as hockey tape and painted pipe.

**Radar Sensors**: Radar sensors have a longer range, of up to 2-3 meters. They send out sound signals and retrieve reflected signals, and measure the difference in these two wavelengths. They require a receiver as well, and are rather more expensive than the previous options, due to their long range.

**Fiber Optic Texture Sensors**: Fiber optics can be used to detect differences in texture between two materials, and have been used to assist in quality assurance as well as object recognition in
research settings [5]. Though promising in the research sector, these sensors are not widely available in a commercial setting yet, and the cost of developing a sensor may be extremely high.

### 3.3.2 Sensing Travel Along the Pipe

Infrared sensors are capable of detecting an object or line that is a distance away from them [6]. In fact, they are quite useful for detecting pipe from a fixed distance, since they are not able to distinguish colours as well as a visible-light sensor, and can be able to detect backgrounds of any colour. Thus, they would be useful for detecting the position of a robot. Some sources have successfully implemented these sensors in detecting a line on the ground for the robot to travel along [7]. In addition, an IR sensor could be used to detect the proximity of the pipeline supports.

Another method of detecting travel could be using a shaft encoder to detect the distance travelled. They have a rotating plate with a circumference that alternates in colour or some other property. By attaching this to a wheel, the angular rotations of the wheel can be measured to determine the final distance travelled – a mechanism commonly found in automobile odometers.

### 4. Conceptualization

#### 4.1 Design Process

The flowchart below details the design decisions made during the design process. These decisions were made based on available solutions for each task, and then evaluated based on how well they accomplished the constraints and criteria of the project. For each task, we performed a brainstorm of possible options, and then used a combination of Pugh Charts and AHP Analysis in order to select the best option. AHP Graphs are included in Appendix A.
4.1.1 Transportation Method

We considered many different options when designing the machine to travel along the pipe, especially whether to locate the chassis on the pipe or to build a robot that travels along the side of the pipe. Eventually we chose a robot that would travel along the side of the pipe, with a detection system would detect through an arm that extends over the pipe. Based on the dimensions of the pipe, as well as the criteria provided, it would be difficult to put the chassis under the pipe due to the pipeline supports. Furthermore, the robot would require more motors and control in order to steer around these supports. In addition, locating the chassis along the top of the pipe may apply too much force to the pipe, thus violating a constraint.
Based on the Pugh chart below, it was decided that the robot would travel along the side of the pipe.

Table 1: Pugh Chart to compare modes of transportation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Side</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity to Build</td>
<td>0.3</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Size</td>
<td>0.1</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Number of Sensors Required</td>
<td>0.2</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Material Cost</td>
<td>0.2</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Motors/Steering</td>
<td>0.2</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>1</td>
<td>+0.9</td>
<td>+0.1</td>
</tr>
</tbody>
</table>

4.1.2 Mobile Platform Wheel Configuration

Driving mechanisms are an important aspect of a mobile robot because they are responsible for moving the robot by providing the appropriate motive force.

The three most popular configurations we considered are: differential, drive, and steering wheels. Differential drives are two independently wheels that will move straight when driven at the same rate.

Drive wheels are coupled together with side coupling rods. A good example of driving wheels is the ones used on steam locomotives.

Steering systems are the most common and they are used in automobiles. They consist of one or two steerable wheels at the front and two powered wheels at the rear. The advantage of a steering system is that they are suited to move in open spaces and where course corrections are required. The added complexity, however, of the steering systems is not needed, since our robot only needs to drive in a straight line.

For our design concept, we chose four drive wheels, two at the front and two at the back of the mobile platform. This will ensure that the mobile platform does not turn around and moves straight parallel to the pipe. Considering space constraints, the mobile platform will move backwards along the pipe in order to return back to its original position. An AHP Graph for each option is included in Appendix A.

4.1.3 Spot Detection Mechanism

When the robot travels along one side of the pipe, it requires a mechanism to view around the entire pipeline in order to detect a spot. This detection system does not need to detect the radial position of the spot, but this would be a useful additional feature.

Three major categories of sensors were considered: photoelectric sensors, IR sensors, and ultrasonic sensors. The benefits and drawbacks of each are outlined below.

Photoelectric Sensors (including photoresistors, photodiodes, and phototransistors)
Advantages:

- Photoelectric sensors are widely available and relatively inexpensive ($0.50 - $2 each)
- Phototransistors are able to detect visible and infrared light, and have reasonable light sensitivity and response times

Disadvantages:

- Photoelectric sensors have a very short range of suitability (<1 cm). Many sensors will be required to adequately sense the entire surface of the pipe, which drives up cost and wiring complexity, as well as increasing programming difficulty.
- Because they also detect visible light, they are more affected by ambient light coming in from outside sources, and are consequently less accurate.

**IR Proximity Sensor**

Advantages:

- Reflective IR Sensors may be a good option because they are functional for up to a 10-30 cm range. This increased range means that fewer sensors will be required to detect around the entire pipe.
- Sensors are still relatively inexpensive, at $1-2 per transmitter-receiver pair.
- The black hockey tape is fairly efficient at absorbing infrared radiation, while the surrounding pipe is not

Disadvantages:

- IR Proximity sensors are possibly susceptible to ambient noises, such as a heat source, so they may not be as reliable.

**Ultrasonic Sensor**

Advantages:

- Sonar sensors have a very long range, so they can be used over a long distance.

Disadvantages:

- Ultrasound sensors are quite expensive, in the $15-$20 range
- The reflections off the pipe will not all be detected by one sonar sensor, so multiple sensors will still be required.

The following Pugh Chart was made to determine which sensor is most desirable. It was found that infrared sensors were the best fit. An AHP Graph is also included in Appendix A.

**Table 2: Pugh Chart for Sensor Comparison**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Photoelectric</th>
<th>Infrared</th>
<th>Sonar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.2</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>
4.1.4 Pipeline Support Detection and Avoidance

In order to use the IR sensors, we required some sort of “arm” to position the sensors around the pipe. A few different methods of accurately detecting spots under the pipe while still avoiding the pipeline supports were considered, below. More alternative designs for the detection arm can be found in an AHP Analysis in Appendix A.

**Mechanical Spring/Hinge Mechanism**

The mechanical spring/hinge system involves the two separate arms of the robot to swing backwards ninety degrees when encountering the obstruction.

**Advantages:**
- This method requires minimal circuitry and programming, which greatly reduces the complexity of the system.

**Disadvantages:**
- There is loss of accuracy and control, since the behaviour of the spring is not fully controllable, unlike a motor.
- Excess force may be applied on the base of the pipe, which may cause unwanted movement.

**Servo Motor Turning with Potentiometer**

The shaft of a servo motor will be attached to the lower arm to move it out of the way of the pipeline obstruction. After passing the obstruction, then the arms will retract back to their original position.

**Advantages:**
- Using a motor to turn the arm will allow for improved control over the action of the arm, and ensure that no excess forces will be placed on either the arm or the pipeline support.
- Separation of the arm into two separate components will allow for space constraints based on the maximum allowed width of 23” as well as the clearance available underneath the pipe.
Disadvantages:

- Adding two servo motors (one for each quarter section under the pipe) as well as increased sensors will increase the programming complexity, as well as the number of pins required to drive this mechanism.
- The cost of adding sensors and potentiometers is not cheap – we expect to spend $10-$15 on this turning mechanism.

Table 3: Pugh Chart to compare different sensor arms

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Mechanical Hinge</th>
<th>Motor with Potentiometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.2</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.3</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Space Restrictions</td>
<td>0.2</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Programming/Circuit Complexity</td>
<td>0.1</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.2</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>+0.3</td>
<td>+0.7</td>
</tr>
</tbody>
</table>

4.1.5 Control Chip Selection

The PIC16F877 was chosen to control the robot, though other processors were considered as well. Below is a chart that outlines the advantages of each, where criteria to be considered include the cost, instruction set, number of ports, and relevance/feasibility for this project.

Table 4: Chip Comparison Chart [8]

<table>
<thead>
<tr>
<th>Chip Type</th>
<th>Cost</th>
<th>Instruction Set</th>
<th>Number of Pins</th>
<th>Relevance Towards Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microprocessors (eg Pentium)</td>
<td>$50 - $500</td>
<td>High</td>
<td>Varies</td>
<td>No – excessive and unnecessary</td>
</tr>
<tr>
<td>PIC10F2xx – PIC16F81x</td>
<td>&lt;$5</td>
<td>Low</td>
<td>Varies</td>
<td>No – not enough commands</td>
</tr>
<tr>
<td>PIC16F877</td>
<td>$5</td>
<td>Mid-Range, 8k</td>
<td>33</td>
<td>Yes</td>
</tr>
<tr>
<td>PIC18F4620</td>
<td>$7</td>
<td>Mid-Range, 32k</td>
<td>36</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Based on the above chart, the advantages of the PIC16F877 are a slightly lower price. Another advantage is that increased support for this chip is available, since it is the main chip used in this course. The Devbugger board is programmed to use a PIC16F877, so it is easier to work with. In addition, the amount of pins available, as well as the commands, meets the needs of this project.
4.2 Alternative Designs

Different module designs were considered in the selection of our design concept for the moving arm. These alternatives are analyzed and presented here.

4.2.1 Cone-Bot

The Cone-Bot design is two-flap opening safe module, which will open outwards by turning an angle of 45°. (See Figure 6) If the connection between the flaps and the upper part is to be hinged, the flaps will easily lose control and will reduce the accuracy for the opening-closing mechanism. The flaps will be actuated from the exterior using a servo motor. The flaps will be initially locked, once the sensors detect the pipe support, the flaps will become unlocked, and after they have passed through the pipe, the flaps will be actuated by the servo motor to be turned 45°. The rotation angle of the flaps defined by the hinges which may be greater than 45° if not fixed also entails its great weakness.

In order to make the rotation more precise, hinges must be replaced by the axis of rotation of the servo motors, one in each side.

4.2.2 Square-Bot

The Square-Bot design consists of a square box frame made of wood with a side length of 13”. The array of sensors will be placed around the interior of the box frame. The bottom side of the box will be initially locked to the right side of the box. After the support is detected, the lock will be inactivated, leaving the door fall down. The flaw of this design is that the bottom flap will touch the floor, hence, it will not be able to open completely to a 90° turn.

4.2.3 Poly-Bot

The Poly-Bot consists of an n-gon shaped moving arm. This design illustrates the idea of having many sides connected to each other, as depicted by an n-gon thus, assembling a circled shape. The higher the number of sides the better. This design requires meticulous trigonometric calculations in order to ensure optimization for the sensing distance. Also, the appropriate material for building the n-gon shape is the aluminum, which bends properly thus, does not require any joints to attach to each other.

In order for the moving arm to pass through the obstruction, the sides of the lower half of the n-gon will move outwards at the required angle. However, the opening-closing mechanism is flawed due to the uneasiness for folding, sliding the sides without exceeding the space dimensions.
These alternative designs were eventually expanded on and desired aspects were incorporated into a final design, detailed in the following section.

5. **Specifications**

5.1 **Overview**

The proposed machine consists of a mobile platform travelling along the side of the pipe, with an arm hanging over the top of the pipe. Attached to either side of the arm are two smaller arms that can rotate to avoid pipeline supports. An array of sensors on a moving arm extending on a side of the machine will detect black spots on the external circumference of the pipe. An opening-closing mechanism using servo motors will then open the smaller arms 90° to avoid the pipe supports and allow the machine to continue the pipe inspection.

The machine and all its mechanical and circuitry components will be powered by a single 12V 3AH lead acid battery. A DC motor will be used to drive the mobile platform, which carries the power supply, as well as circuits and controller boards. The logic of these motors and the array of sensors will be controlled by a PIC16F877 microcontroller.

5.2 **Electromechanical System**

5.2.1 **Mobile Platform**

The mobile platform will be made out of wood, wood screws, plastic wheels, and axels. The platform will be made of $\frac{1}{2}''$ thick fir wooden board. The wooden board will be used to allow the attachment of components securely. Also, the wooden board is selected to be $\frac{1}{2}''$ thick in order to optimize the weight of the board for balancing the weight of the supporting and sensing mechanisms along the pipe and to reduce the buckling of the platform. Fir wood is light, moderately stiff and has exceptional gluing, nailing, and screwing properties.

The mobile platform will be mounted on two pairs of wheels with the front pair of wheels powered by one motor. The two back wheels will help to lower the contact pressure applied on the powering wheels. All the wheels of the mobile platform will be drive wheels. The fact that
the wheels will stay fixed will ensure the mobile platform to move in a straight line parallel to the pipe, once it starts positioned at the start of the pipe. Thus, the mobile platform will allow the robot to move in one dimension parallel to the pipe.

The drive wheels will be actuated with a DC motor placed at the front wheels. The position of the DC motor will not affect its actuation because both pairs of wheels will be fixed. The base of the mobile platform will have four vertical support plates attached to each side of the platform (Figure 10). In addition, a ball caster will be placed in the middle of the bottom part of the mobile platform in order to reduce the drag friction and increase the balance. Also, most of the electric components including boards and the power supply will sit both on the top and bottom of the platform to keep the center of mass of the whole system stable.

Figure 10 Transportation Mechanism
5.2.2 Circular Moving Arm

The sensing mechanism will be placed in a circular moving arm. The circular moving arm will consist of a fixed shape of one half of a circle extending to the right. This arm will extend over the pipe to be inspected. Attached to this arm, two quarter circle arms will extend under the pipe. Once the sensors detect the pipe support, the circular arm will be capable of opening 90° similar to an opening door mechanism. After the sensors stop detecting the pipe support, the circular moving arms will return back to their original position and continue sensing for the black spots. The moving arms will be connected to the upper stationary arm through the axis of a HS311 servo motor, which drives the turning of the arms. The attachment of the axes of the servo motors to the moving parts of the circular arm will be reinforced through small pieces of wood.

The circular sensing arm will be made of polyvinyl chloride (PVC). PVC is the third most widely produced plastic and it is widely used in construction because it is durable, cheap, and easily worked. The geometry of a perfect circular shape is desired to ensure that the placement of each of the sensors is a uniform distance from the pipe, as the angle of light intensity reflected is considered for accuracy.

The dimensions of the circular moving arm are: 14” inches outer diameter and 13.073” inner diameter. These dimensions will ensure equidistance from each point of the pipe to the circular moving arm. Also, the pipe is easy to cut with a hack saw and burrs can be removed by using a file or sandpaper.

The circuitry, sensors and other electric components will be mounted on the PVC circular moving arm. Additional orientations of the arm can be viewed in Appendix B. A PVC pipe data sheet is included in Appendix C.

5.2.3 Connection of Moving Arm

The vertical supporting arm will be placed at the rightmost side of the pipe in order to keep the center of mass of the whole system stable. The horizontal supporting arm connecting the circular sensing arm with the vertical supporting arm will extend over the top of the sensing arm and will be fixed to it so that rotations and turning are avoided as much as possible. Both the vertical and horizontal supporting arms will be made out of wood, as the mobile platform, and will be joined by “butt joints”. Butt joints are the easiest and one of the strongest joints for wood joints. These butt joints will be enforced with wood glue before attaching the wood pieces with wood screws.
5.3 Circuit Systems

5.3.1 Sensors

Two circuits will be used for sensors, one for the upper array and the other for the lower moving arms. The circuits are separated for programming purposes as the lower sensors will be switched off when the arms are open. Eight IR LEDs will be connected in series to reduce the total current needed to power the circuit [9]. The IR receiver circuits are also shown. A comparator will be used to condition the output voltage of the receiver to be digital. The data sheets for the IR emitters and sensors can be found in Appendix C. Separate voltage dividers may be needed for the comparator depending on the calibration of the receivers. The delay of the receiver is in the range of 15μs which is small enough that it can be neglected for the purposes of this project. The output voltages are fed to the microcontroller separately to allow the radial position of the spot to be recorded.

Figure 13 shows the location of the sensors around the detecting arm of the mechanism. As stated above the upper sensors form a separate circuit to
the lower sensors. The sensors form a circular array around the pipe circumference. Since spots are at least 2 inches wide the sensors can be spaced out around the circumference and still detect spots at any location. Each sensor will be assigned a pin on the microcontroller and will be associated with a radial position.

5.3.2 Shaft Encoding

A shaft encoder will be incorporated into the design to determine the distance that the robot has travelled along the pipe. This encoder will also allow the location of the spot along the pipe to be recorded by the PIC microcontroller. It will consist of a break-beam IR detector that will give pulses to the microcontroller at fixed intervals as the wheel turns. The microcontroller can then count the number of pulses since the start of the operation and calculate the distance along the pipe.

5.3.3 Angular Direction Control of Servo Motors

The Servo Motor direction will be controlled using Pulse Width Modulation (PWM). The circuit which does this is shown in Figure. This circuit uses a 555 timer. The frequency of the output pulse is determined by the valued of R and C. The duty cycle of the PWM can be adjusted using the variable resistor. Values will be chosen to fit the specifications of the Servo Motor choses. Two Pulse Width Modulation circuits will be used, each with a fixed duty cycle. One circuit will output the duty cycle corresponding to 0 degrees. The other circuit will correspond to 90 degrees. The PIC will control the switch between the circuits to determine the orientation of the motor throughout its operation. Similar circuitry will be applied to the other servo-motor.

5.3.4 Speed & Direction of DC Motor

The Zheng DC Gearhead Motor will be used and the above circuit will be used to adjust its speed and direction. The PWM section of the circuit is the same as the circuit that will be used for the Servo Motors, except that the frequency and duty cycle will be adjusted to suit the Zheng Motor. The duty cycle will be fixed so that the motor drives the robot forward at approximately 15cm/s. The PWM section is connected to a Bipolar H-Bridge which controls the direction of the motor. This Bridge is also connected to a switch to allow the PIC microcontroller to determine the direction of the motor. The duty cycle of the signal sent into the H-Bridge will determine the speed of the motor.
5.4 Microcontroller System

5.4.1 Program Structure and State Diagram

Below is a flow chart outlining the state diagram to program the autonomous robot. The program consists of the following major stages: Operation, Polling or Checking, Interrupt Service Routines, and End. Complete pseudocode for the programming component is outlined in Appendix D.
Overall Programming Flow Chart

A summary of details of each stage are as follows:

- Robot travels forward: The DC Motor is turned on during this stage. While moving, the motor is constantly polling the checking mechanisms.
- Polling/Checking Mechanism:
  - **Spots**: First we check to see if 15 spots have been detected. If so, return to the start position. Otherwise, we continue polling.
  - **Distance**: Then we check to see how far we have travelled. If we have reached 120 inches, then the robot will stop and go backwards.
  - **Moving Arms**: Next we check to see if the arm is open. If it is open, and we have reached past the pipeline support, then we close the moving arms.
  - **Sensors**: We poll through each array of sensors (top and bottom) in order to check and see if a spot is detected on the pipe. If detected, then a led light signal is turned on, and the location of the pipe is written to EEPROM. Otherwise, continue driving the motor.
- Pipe Support ISR: If a pipeline support is detected, then the location and “moving arm” bit are written to EEPROM. Then the moving arms are opened.
- Emergency Off: The robot will halt all mechanical movement if this button is pressed. Motors and sensors will be turned off, and the current state will be stored in EEPROM.
- End: After coming back to the finish line, user interface will resume in order to display operation information.

Sensor Polling Subroutine

While travelling forward, the robot continuously calls this subroutine in order to check the IR sensors to see whether a spot has been detected. In addition, sensor arms must be considered –
if the arms are open in order to pass over a pipeline support, then the sensors underneath the pipe cannot be considered.

**Pipeline Support Interrupt Service Routine**

During the operation of the pipe, it is possible that the robot will encounter a pipeline support. In this case, the robot must move its sensor arms located underneath the pipe, so as to ensure that these arms do not strike the support. After detecting this support, the following interrupt service routine is executed:
5.4.2 User Interface

The user interaction screens will consist of the following four modes:

1. Start: After turning on the power, there should be a standby mode to wait for the user. The user will see the screen:

   Welcome! Press <A> to start

2. Operation Mode: The user will be able to press <0> to perform an emergency exit. This will terminate all current mechanical activities. With sufficient time, additional features such as resuming previous activities will be implemented.

3. Completion: The display will show four options:
   a. Finish – end program
   b. Time – view amount of time required to complete the task
   c. Number of Spots – display the number of black spots found
   d. Spot Info – show the distance of each spot from the start line

5.4.3 Pin Assignments

The inputs and outputs required, as well as the number of pins needed are outlined in the following chart. Then, these pins are evaluated and organized in order to fit in the limited 33 pins available on the PIC16F877, or the 36 pins on the PIC18F4620.

<table>
<thead>
<tr>
<th>Component</th>
<th>Purpose/Use</th>
<th>I/O</th>
<th>Number of Pins Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Motor</td>
<td>Drive machine forward</td>
<td>Out</td>
<td>2</td>
</tr>
<tr>
<td>RTC Clock</td>
<td>Keep Real Time</td>
<td>In, Out</td>
<td>2</td>
</tr>
<tr>
<td>LCD</td>
<td>User Interface</td>
<td>Out</td>
<td>8 - 11</td>
</tr>
</tbody>
</table>
Based on the above chart, it can be seen that up to 31 pins are required to complete tasks. However, interrupts will be used for the keypad during operation of the robot, so the keypad will only use 1 pin during operation. This brings the total number of pins used at any one time to 22-24. Further pin-saving techniques used in the above chart include interrupts will be used for the shaft encoder, so that will only require 1 pin as well. Also, the 16 IR Sensors located around the circumference of the pipe will be selected using a mux system, so only 5 pins are required, as opposed to 16 pins if there were 1 pin for each sensor. Therefore, the 33 pins available on the PIC16F877 are more than sufficient for the task.

The organization of pin ports is outlined below:

- **Port A** contains I/O pins that will be used for the IR Sensor Array, which contains 16 IR sensor-emitter pins that are arranged around the circumference of the pipe.
- **Port B** contains interrupt-pins, which will be used for the proximity sensor, as well as the keypad encoder and shaft encoder.
- **Port C** contains the pins that are used for clocked input or output, so it may be suitable for pulse-width modulation of the motors. Thus 6 pins will be used to control the DC motor and two servo motors.
- **Port D** works well as a parallel port for a bus, and will be used for operating the LCD.
- **Port E** will be used as select bits for a multiplexer to choose between ports on the sensor array in Port A.
## 6. Project Management

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Start</th>
<th>End</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Initiation</td>
<td></td>
<td></td>
<td>Activating the project team and setting goals.</td>
</tr>
<tr>
<td>Project Planning</td>
<td></td>
<td></td>
<td>Creating a detailed project plan.</td>
</tr>
<tr>
<td>Project Execution</td>
<td></td>
<td></td>
<td>Implementing the project plan and monitoring progress.</td>
</tr>
<tr>
<td>Project Monitoring</td>
<td></td>
<td></td>
<td>Regularly reviewing project status and adjusting as necessary.</td>
</tr>
<tr>
<td>Project Control</td>
<td></td>
<td></td>
<td>Ensuring the project stays on track with contingency plans in place.</td>
</tr>
<tr>
<td>Project Closure</td>
<td></td>
<td></td>
<td>Finalizing the project, including summaries, reports, and learning from experience.</td>
</tr>
</tbody>
</table>

---

*Note: The table above is a simplified representation of project management tasks. Actual project planning and execution would involve much more detailed planning and tracking.*
7. Budgeting

The materials and equipment costs of the proposed design are listed below. The total estimated cost is $215.67, which is within the budget limit of $230. The total estimated mass of the whole robot is 2.3 kg, which satisfies the maximum weight of 20 lb = 4.4 kg. The material costs provide some flexibility in case changes are made to the design.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Dimensions</th>
<th>Number</th>
<th>Total Mass (g)</th>
<th>Unit Cost</th>
<th>Total Cost</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels</td>
<td>Plastic</td>
<td>4.5” diameter x 2 cm width</td>
<td>4</td>
<td>125.0</td>
<td>2.00</td>
<td>8.00</td>
<td>Active Surplus</td>
</tr>
<tr>
<td>Wheel axle</td>
<td>Aluminum rod</td>
<td>0.25 diameter x 8”</td>
<td>2</td>
<td>9.0</td>
<td>8.79/m</td>
<td>3.57</td>
<td>Active Surplus</td>
</tr>
<tr>
<td>Drive motor</td>
<td>Zheng DC</td>
<td>25mm diameter x 54 mm</td>
<td>1</td>
<td>180.0</td>
<td>9.00</td>
<td>9.00</td>
<td>U of T Design Store</td>
</tr>
<tr>
<td>Chassis base</td>
<td>Plywood</td>
<td>450 m³</td>
<td>1</td>
<td>238</td>
<td>0.99/8’</td>
<td>7.99</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Fasteners</td>
<td>Wood screws</td>
<td>1” length</td>
<td>20</td>
<td>16.2</td>
<td>0.07 (estimated)</td>
<td>5.00 (estimated)</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Wheel frame</td>
<td>Aluminum</td>
<td>Brackets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular Arm</td>
<td>Plastic PVC</td>
<td>14” outer diameter (2 in long)</td>
<td>1</td>
<td>624.0</td>
<td>18.50</td>
<td>18.50</td>
<td>Harrison Plastic [10]</td>
</tr>
<tr>
<td>Servo Motor</td>
<td>HS311 90°</td>
<td>70.1mm x 22.3mm x 37.7mm</td>
<td>2</td>
<td>70</td>
<td>7.00</td>
<td>14.00</td>
<td>U of T Design Store</td>
</tr>
<tr>
<td>Gears</td>
<td>Worm Gears</td>
<td>--</td>
<td>1</td>
<td>5</td>
<td>2.00</td>
<td>2.00</td>
<td>U of T Design Store</td>
</tr>
<tr>
<td>Battery</td>
<td>12V 3AH Lead Acid</td>
<td>134mm x 67mm x 60mm</td>
<td>1</td>
<td>800</td>
<td>25.51</td>
<td>25.51</td>
<td>Design Store</td>
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<tr>
<td>Circuitry</td>
<td>Resistors</td>
<td>--</td>
<td>40</td>
<td>10</td>
<td>0.05</td>
<td>2</td>
<td>Active Surplus</td>
</tr>
<tr>
<td>Circuitry</td>
<td>Transistors</td>
<td>--</td>
<td>10</td>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>Active Surplus</td>
</tr>
<tr>
<td>Circuitry</td>
<td>Inductors</td>
<td>--</td>
<td>10</td>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>Active Surplus</td>
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<tr>
<td>Circuitry</td>
<td>555 timer</td>
<td>--</td>
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<td>0.30</td>
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<td>3.00</td>
<td>12.00</td>
<td>Active Surplus</td>
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<tr>
<td>MicroController</td>
<td>Pic DevBugger Board</td>
<td>--</td>
<td>1</td>
<td>200</td>
<td>50</td>
<td>50.00</td>
<td>Design Kit</td>
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<tr>
<td>Real-Time Clock</td>
<td>DS1307</td>
<td>--</td>
<td>1</td>
<td>10</td>
<td>5.00</td>
<td>5.00</td>
<td>Design Store</td>
</tr>
<tr>
<td>LCD</td>
<td>16x2 Backlight LDC</td>
<td>--</td>
<td>1</td>
<td>20</td>
<td>6.00</td>
<td>6.00</td>
<td>Design Store</td>
</tr>
<tr>
<td>Sensors</td>
<td>IR detector/Emitter</td>
<td>--</td>
<td>16</td>
<td>30</td>
<td>1.30</td>
<td>20.8</td>
<td>Creatron</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>2319.2</strong></td>
<td></td>
<td><strong>215.67</strong></td>
<td></td>
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</table>
8. Conclusion

We expect that this proposal will successfully meet the request to develop a prototype that travels along the side of the pipe and is capable of detecting up to 15 spots on a pipeline in less than three minutes. After developing the concept and evaluating many alternative designs, it is believed that this design will be fully functional and reliable, and will accurately and effectively detect imperfections along the pipe. This prototype demonstrates a proof-of-concept that can be expanded in the future to inspect pipelines for deterioration in various hazardous working conditions, all for a cost of less than $230.

Challenges in the success of the project include time management. Though much of the circuits and microcontroller systems can be completed outside of lab hours, fabrication of electromechanical components is limited to a 5-8 hour window in which there is laboratory access. This could present a potential bottleneck in system integration of the project. Careful planning of the time available is required in order to complete the physical machine fabrication. In addition, the microcontroller member and circuit member are expected to complete and perform preliminary testing on their systems by the end of Week 6 in order to assist with assembly and of physical components an assist with overall integration. These issues can be overcome with careful communication between members, as well as precise deadline management that allows for additional time to test and integrate. Overall, we expect that the design will be successful and provide an excellent proof-of-concept of the function of pipeline detection.
Appendices

Appendix A: AHP Analysis for Decision-Making Process

i. Mobile Platform Wheel Configuration

![Wheel Configuration Diagram]

<table>
<thead>
<tr>
<th>Wheel Configuration</th>
<th>Space Usage</th>
<th>Speed</th>
<th>Cost</th>
<th>Path Correction Reparability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- Drive Wheels
- Differential Wheels
- Steering Wheels

ii. AHP Analysis for Spot-Detection Mechanism

![Sensor to Detect Spots Diagram]

<table>
<thead>
<tr>
<th>Sensor to Detect Spots</th>
<th>Range (10&gt;x&gt;1 cm)</th>
<th>Reliability</th>
<th>Cost</th>
<th>Time Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.15</td>
<td>0.4</td>
<td>0.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Photodiode
- Phototransistor
- Photoresistor
- Radar/Ultrasound
- IR Emitter
iii. Pipeline Support Detection and Avoidance – Sensor Arm Design
Appendix B: Final Sensor Arm Design

1. Angular view

2. Front View
3. Servo Motor at one side of the Circular Moving arm

4. Back View
5. Back View of Opened Arms at a 90° Angle Turn

6. Front View of Opened Arms at a 90° Angle Turn
7. Right Side View of the Opened Arms at a 90° Angle Turn

8. Left Side of the Opened Arms at a 90° Angle Turn
9. Close-Up to the Servo Motor when Doors are Open
Appendix C: Component Data Sheets

PVC Pipe Data Sheet

<table>
<thead>
<tr>
<th>Schedule 40 Dimensions</th>
<th>O.D.</th>
<th>Average I.D.</th>
<th>Min. Wall</th>
<th>Nom. Wt./Ft.</th>
<th>Max. W.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>0.405</td>
<td>0.349</td>
<td>0.068</td>
<td>0.051</td>
<td>810</td>
</tr>
<tr>
<td>1/4</td>
<td>0.540</td>
<td>0.434</td>
<td>0.088</td>
<td>0.086</td>
<td>780</td>
</tr>
<tr>
<td>3/8</td>
<td>0.675</td>
<td>0.473</td>
<td>0.091</td>
<td>0.115</td>
<td>620</td>
</tr>
<tr>
<td>1/2</td>
<td>0.840</td>
<td>0.602</td>
<td>0.109</td>
<td>0.170</td>
<td>600</td>
</tr>
<tr>
<td>3/4</td>
<td>1.050</td>
<td>0.804</td>
<td>0.113</td>
<td>0.236</td>
<td>480</td>
</tr>
<tr>
<td>1</td>
<td>1.315</td>
<td>1.029</td>
<td>0.133</td>
<td>0.333</td>
<td>450</td>
</tr>
<tr>
<td>1 1/4</td>
<td>1.660</td>
<td>1.360</td>
<td>0.140</td>
<td>0.450</td>
<td>370</td>
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<tr>
<td>1 1/2</td>
<td>1.900</td>
<td>1.590</td>
<td>0.145</td>
<td>0.537</td>
<td>330</td>
</tr>
<tr>
<td>2</td>
<td>2.375</td>
<td>2.047</td>
<td>0.154</td>
<td>0.720</td>
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</tr>
<tr>
<td>2 1/2</td>
<td>2.675</td>
<td>2.445</td>
<td>0.203</td>
<td>1.136</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>3.500</td>
<td>3.042</td>
<td>0.216</td>
<td>1.488</td>
<td>260</td>
</tr>
<tr>
<td>3 1/2</td>
<td>4.000</td>
<td>3.521</td>
<td>0.226</td>
<td>1.789</td>
<td>240</td>
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<tr>
<td>4</td>
<td>4.800</td>
<td>3.998</td>
<td>0.237</td>
<td>2.118</td>
<td>220</td>
</tr>
<tr>
<td>5</td>
<td>5.563</td>
<td>5.016</td>
<td>0.258</td>
<td>2.374</td>
<td>190</td>
</tr>
<tr>
<td>6</td>
<td>6.625</td>
<td>6.031</td>
<td>0.280</td>
<td>3.733</td>
<td>180</td>
</tr>
<tr>
<td>8</td>
<td>8.625</td>
<td>7.942</td>
<td>0.322</td>
<td>5.619</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
<td>10.750</td>
<td>9.976</td>
<td>0.365</td>
<td>7.466</td>
<td>140</td>
</tr>
<tr>
<td>12</td>
<td>12.750</td>
<td>11.889</td>
<td>0.406</td>
<td>10.534</td>
<td>130</td>
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<td>14</td>
<td>14.000</td>
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<tr>
<td>18</td>
<td>18.000</td>
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<td>0.562</td>
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<td>20.000</td>
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<td>24</td>
<td>24.000</td>
<td>22.544</td>
<td>0.687</td>
<td>33.632</td>
<td>120</td>
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</table>

* Denotes these sizes are dual marked as being in compliance with both ASTM D1785 (pressure pipe) and ASTM D2516 (drain, waste & vent pipe DWV).

IR LED Data Sheet for model #LTE-5208a [11]

<table>
<thead>
<tr>
<th>ABSOLUTE MAXIMUM RATINGS AT TA=25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARAMETER</td>
</tr>
<tr>
<td>Power Dissipation</td>
</tr>
<tr>
<td>Peak Forward Current (300pps, 10 μs pulse)</td>
</tr>
<tr>
<td>Continuous Forward Current</td>
</tr>
<tr>
<td>Reverse Voltage</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
</tr>
<tr>
<td>Lead Soldering Temperature [1.6mm(.063&quot;) From Body]</td>
</tr>
</tbody>
</table>
### Electrical Optical Characteristics at TA-25°C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>MIN.</th>
<th>TYP.</th>
<th>MAX.</th>
<th>UNIT</th>
<th>Test Condition</th>
<th>Bin No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Radiant Incidence</td>
<td>(I_e)</td>
<td>0.44</td>
<td>0.96</td>
<td>1.68</td>
<td>mW/mti</td>
<td>(I_e = 20) mA</td>
<td>BIN A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.64</td>
<td>1.20</td>
<td></td>
<td></td>
<td>BIN B</td>
<td>BIN C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.80</td>
<td></td>
<td></td>
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<td></td>
<td>BIN D</td>
</tr>
<tr>
<td>Radiant Intensity</td>
<td>(I_e)</td>
<td>3.31</td>
<td>7.22</td>
<td>9.02</td>
<td>mW/sr</td>
<td>(I_e = 20) mA</td>
<td>BIN A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.81</td>
<td>9.02</td>
<td></td>
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<td>BIN B</td>
<td>BIN C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.02</td>
<td>12.63</td>
<td></td>
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<td>BIN D</td>
</tr>
<tr>
<td>Peak Emission Wavelength</td>
<td>(\lambda_{max})</td>
<td>940</td>
<td></td>
<td></td>
<td>nm</td>
<td>(I_e = 20) mA</td>
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<tr>
<td>Spectral Line Half-Width</td>
<td>(\Delta \lambda)</td>
<td>50</td>
<td></td>
<td></td>
<td>nm</td>
<td>(I_e = 20) mA</td>
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</tr>
<tr>
<td>Forward Voltage</td>
<td>(V_f)</td>
<td>1.2</td>
<td>1.6</td>
<td></td>
<td>V</td>
<td>(I_e = 20) mA</td>
<td></td>
</tr>
<tr>
<td>Reverse Current</td>
<td>(I_r)</td>
<td>100</td>
<td></td>
<td></td>
<td>(\mu) A</td>
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<tr>
<td>Viewing Angle (See Fig.6)</td>
<td>(2\theta_{12})</td>
<td>40</td>
<td></td>
<td></td>
<td>deg.</td>
<td></td>
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</tr>
</tbody>
</table>

### Typical Electrical / Optical Characteristics Curves

(25°C Ambient Temperature Unless Otherwise Noted)

**FIG. 1 SPECTRAL DISTRIBUTION**

**FIG. 2 FORWARD CURRENT VS. AMBIENT TEMPERATURE**

**FIG. 3 FORWARD CURRENT VS. FORWARD VOLTAGE**

**FIG. 4 RELATIVE RADIANT INTENSITY VS. AMBIENT TEMPERATURE**
IR Receiver Data Sheet for model #LTR-3208E [12]

**ABSOLUTE MAXIMUM RATINGS AT TA=25°C**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MAXIMUM RATING</th>
<th>UNIT</th>
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<tbody>
<tr>
<td>Power Dissipation</td>
<td>100</td>
<td>mW</td>
</tr>
<tr>
<td>Collector-Emitter Voltage</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>Emitter-Collector Voltage</td>
<td>5</td>
<td>V</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-40°C to +85°C</td>
<td></td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>-55°C to +100°C</td>
<td></td>
</tr>
<tr>
<td>Lead Soldering Temperature [1.6mm(.063&quot;) From Body]</td>
<td>260°C for 5 Seconds</td>
<td></td>
</tr>
</tbody>
</table>
**ELECTRICAL / OPTICAL CHARACTERISTICS AT TA=25°C**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYMBOL</th>
<th>MIN.</th>
<th>TYP.</th>
<th>MAX.</th>
<th>UNIT</th>
<th>TEST CONDITION</th>
<th>BIN NO.</th>
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<tr>
<td>Collector-Emitter Breakdown Voltage</td>
<td>$V_{(BE)C0}$</td>
<td>30</td>
<td></td>
<td></td>
<td>V</td>
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<td>BIN A</td>
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<tr>
<td></td>
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<td>$E_E=0mW/cm^2$</td>
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<tr>
<td>Emitter-Collector Breakdown Voltage</td>
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<td></td>
<td>V</td>
<td>$I_E=100\mu A$</td>
<td>BIN B</td>
</tr>
<tr>
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<td>$E_E=0mW/cm^2$</td>
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<tr>
<td>Collector Emitter Saturation Voltage</td>
<td>$V_{CE(SC)}$</td>
<td>0.1</td>
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<td>V</td>
<td>$I_C=100\mu A$</td>
<td>BIN C</td>
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<tr>
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<td>$E_E=1mW/cm^2$</td>
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<tr>
<td>Rise Time</td>
<td>$Tr$</td>
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<td></td>
<td>$\mu s$</td>
<td>$V_{CE}=5V$</td>
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<tr>
<td>Fall Time</td>
<td>$Tf$</td>
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<td>$\mu s$</td>
<td>$I_C=1mA$</td>
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<td>$R_L=1K\Omega$</td>
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<tr>
<td>Collector Dark Current</td>
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<td>nA</td>
<td>$V_{CE}=10V$</td>
<td>BIN F</td>
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<td>$E_E=0mW/cm^2$</td>
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<tr>
<td>On State Collector Current</td>
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<td>1.68</td>
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<td>mA</td>
<td>$V_{CE}=5V$</td>
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<td>1.12</td>
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<td>$E_E=0mW/cm^2$</td>
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<td></td>
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<td>1.44</td>
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<td>$\lambda=940nm$</td>
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<td>2.08</td>
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<td>2.40</td>
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</tbody>
</table>
TYPICAL ELECTRICAL / OPTICAL CHARACTERISTICS CURVES

(25°C Ambient Temperature Unless Otherwise Noted)

FIG. 1 COLLECTOR DARK CURRENT VS AMBIENT TEMPERATURE

FIG. 2 COLLECTOR POWER DISSIPATION VS AMBIENT TEMPERATURE

FIG. 3 RISE AND FALL TIME VS LOAD RESISTANCE

FIG. 4 RELATIVE COLLECTOR CURRENT VS IRRADIANCE

FIG. 5 SENSITIVITY DIAGRAM
Appendix D: Pseudocode for the PIC16F877

Constants
Maximum Travel Distance = 120 inches
Maximum Spots = 15
Number of Radial Sensors = 16

Tables
User Interface
Display
Keypad

Counters
Operation Time
Distance Travelled
Number of Spots
Sensor Disable
Array for each spot
Position Along Pipe = distance from start line
Radial Position = sensor number × circumference ÷ number of radial sensors

Keypad_interrupt:
    if (start button = pressed)
        goto main

Main:
    Enable Emergency_Stop_Interrupt
    Disable Keypad_Interrupt
    Initialize counters
    Initialize arrays
    Start Operation_Time_Counter
    Turn DC motors on
    Enable Distance Interrupt

Poll:
    If (Number_of_Spots = Max_Spots | Displacement = Max_Distance)
        Goto Travel_Back
    If (Support_Arm open)
        If (Distance – Distance_of_last spot <0)
            Support_arm = closed
            Turn on servo motors to close support arm
        Else
            goto Poll_Lower_Sensors

    Poll_Upper_Sensors
        Set sensor_number counter ==0
        If(Sensor == 1)
            {
                Goto Spot_Detected
            }
        Else if (sensor_number == Number of Radial Sensors/2)
            {
                Goto Poll_Lower_Sensors
            }
Sensor_number++  
Goto Poll_Upper_Sensors

Poll_Lower_Sensors  
Set sensor_number counter == Number of Radial Sensors/2  
If (Sensor == 1)  
    Goto Spot_Detected  
Else if (Sensor_number == Number of Radial Sensors)  
    Goto Poll  
Sensor_number++  
Goto Poll_Lower_Sensors

Spot_Detected:  
Number_of_Spots ++  
Turn on LED Signal  
Store (displacement constant) of pole into array  
Store (sensor number) into array for radial position  
Enable Sensor_Disable timer for 3 inches  
//to prevent sensor from detecting the same  
//spot  
Turn off LED Signal  
Goto Poll

Travel_Back:  
Turn wheel motors off  
Store Distance_Travelled  
Turn motor on backwards  
Return_Displacement ==Distance Travelled

Poll_Back:  
If (Return Displacement <=0)  
{  
    Turn off motors  
    Store Time Taken  
    Goto LCD_StandbyMode  
}  
Goto Poll_Back

LCD_StandbyMode:  
Disable Start Interrupt  
Display User_Interface  
//A. Done B. Time  
//C. #Spots D. Info  
Enable Keypad Interrupt

Keypad_Interrupt:  
If (A pressed)  
    Goto end  
If (B pressed)  
    Display Time  
If (C Pressed)
Display Number of Spots
If (D Pressed)
   Display first Pole Distance and Radial Distance

Display_Loop:
   If (1 pressed)
      Pole Number ++
      Display next Pole Distance and Radial Distance
   If (2 pressed)
      Skip next line
      Goto Display_Loop

Return

Distance_Interrupt:  //signals that shaft encoder has caused an interrupt
   Distance++
   Temporarily disable distance interrupt
Return

Emergency Stop Interrupt:
   Store register values in EEPROM
   Turn off DC Motors
   Turn off Servo Motors
Return
Bibliography


