Design Report for Robotic Wall Following Technique Using Ultrasonic Sensors

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1 Executive Summary

An SCOMP wall following program was designed for the Amigobot using sonar feedback to determine what velocity commands to send to each wheel. This program enables the robot to locate and travel parallel to a wall with inner and outer corners of 90°. The solution to this challenge is a state machine program that executes commands based on the current state and the measured distance to the nearest wall. The state machine consists of four states: "forward motion," "inside turn," "adjust outward," and "adjust inward." In "forward motion," the robot moves forward full speed until it senses a wall in front of it or no wall is sensed. If a wall is sensed in front of the Amigobot, the program switches to the "inside turn" state, turns 90°, and then proceeds to travel forward. If no wall is sensed, the Amigobot will adjust inward until it is parallel to the wall, and then continue on a straight path. A switch is used to toggle between following a wall on the left side or on the right side of the robot. The switch position determines turning direction and selects the ultrasonic sensors used to measure distance to the wall. Parallel motion to the wall is maintained by switching to "adjust outward" and "adjust inward" states, which correct the robot trajectory if the measured distance is not within an acceptable range of 20 ± 1 cm. Inputs to the state machine are ultrasonic sensory data. The outputs are velocities of the left and right wheels. During the final demonstration, the robot running this program was moderately successful in following the test course. It successfully navigated the wall on the right side and received an accuracy bonus. While the robot completed the course when following the wall on its left side, it did not receive an accuracy bonus and did not finish the course in the desired time frame.

2 Introduction

2.1 Design Problem

The goal of this project is to design an SCOMP wall following program that enables the Amigobot to follow walls. The design solution meets the following specications:

1. Use an eight bit velocity command where +127 (`0x007F`) is full speed forward, −127 (`0xFF81`) is full speed reverse, and zero is stop.

2. Control position by reading the cumulative rotation counter of the wheel.
3. Use velocity feedback and position feedback from the wheels via the existing optical encoder peripheral.
4. Provide a start button to begin execution after the robot is placed adjacent to a wall.
5. Use existing sonar and velocity control peripherals to issue commands to each wheel.
6. Travel parallel to a wall at a distance of 20 cm.
7. Select by switch or recompile to follow left or right walls.

The Amigobot was expected to navigate a course without collisions and in a specified time frame. A sample course layout is shown in Fig. 1.

In addition to the required specifications, the wall following program improved the user interface of the robot by enhancing the 7-segment, LCD, and LED displays.

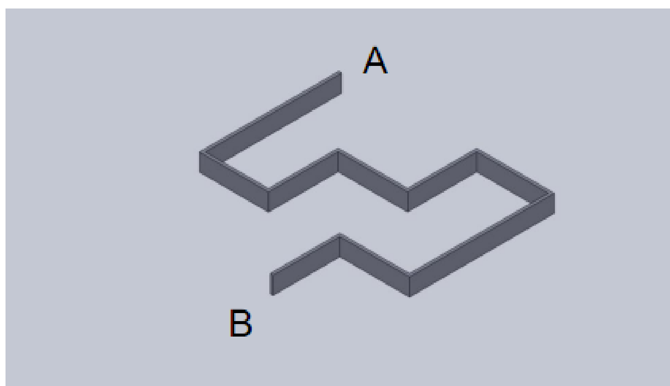


Figure 1. Sample course layout for robotic wall-following.

2.2 Design Solution

The SCOMP program written for the design problem is a state machine consisting of four states. In the "forward" state, the robot follows a straight trajectory until it senses a wall in front or no wall is sensed. If the Amigobot senses a wall in front of it, the program switches to the "inside turn" state, turns 90°, then proceeds on a straight trajectory. If no wall is sensed, the Amigobot adjusts inward until it is parallel to the wall. The two adjustment states, “adjust outward” and “adjust inward,” maintain parallel motion to the wall by correcting the robot trajectory when the measured distance to the wall is not within an acceptable range of 20 ± 1 cm.

A switch is used to toggle between following a wall on the left side or on the right side of the robot. The switch position activates the ultrasonic sensors on one side of the robot and determines clockwise or counterclockwise turning direction.

The initial approach discussed in the proposal implemented an additional “outside turn” state. During testing, it was discovered that the state causes the robot to turn prematurely and collide with the wall whenever the robot was not parallel to the wall. To overcome this challenge, the team used the “adjust inward” state to make incremental turns around an outside wall corner.

Additionally, the initial design called for one sensor reading from the lateral region of the robot and one from the forward region of the robot. During testing it was discovered that accuracy in maintaining the set distance improved when the minimum value of two sensors in the lateral and forward regions were used as inputs to the states.

The role of the LCD display had to be altered when the team ran into issues of consistency. The LCD display was initially expected to show the moving state the robot is in. Due to the display not working consistently, it was changed to show the basic startup states.

The design demonstration met most of the specifications outlined above. The robot successfully completed the course for both the left and right sided walls. It received an accuracy bonus for maintaining the desired 20 cm distance when following the right wall. However, it was unable to earn the accuracy bonus when following the left wall.

3 General Methodology

3.1 Process and Sensor Description

The wall following algorithm implemented follows the process found in Fig. 2.

A switch is used to toggle between following the left wall and following the right wall. The value of the switch determines which sensors are actively collecting data. The values of the following sensors will be used:

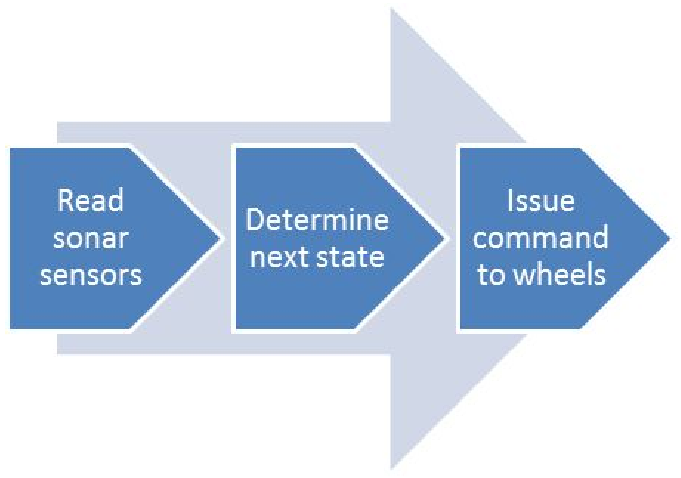


Figure 2. Flow chart of wall following algorithm.

- Minimum value of sensors s_4 and s_5 (s_0 and s_1 for left-wall following):
    - Measure the distance to the closest parallel wall (Fig. 3).
- Minimum value of sensors s_2 and s_3:
    - Measure the distance to an approaching wall (Fig. 4).

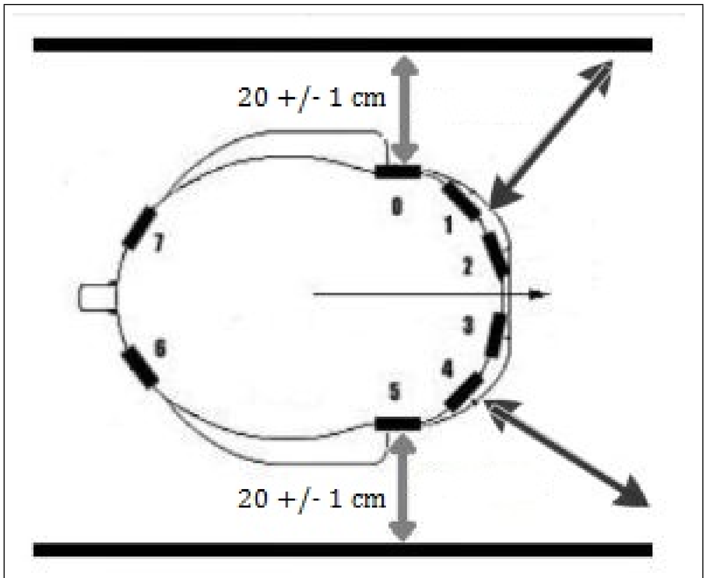


Figure 3. Sensors s_4 and s_5 (or s_0 and s_1) measuring distance to wall.

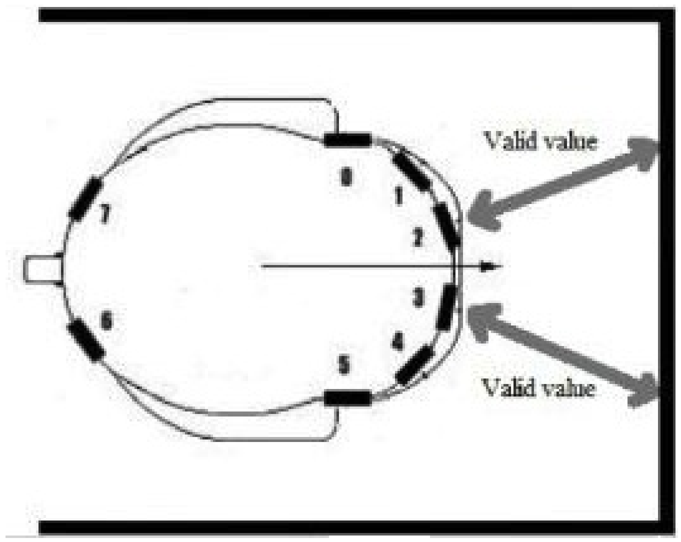


Figure 4. Sensors s_4 and s_5 measuring distance to front wall.

3.2 State Machine Description

The description of the states is listed below. The UML state machine diagram the team used to implement a solution is found in Fig. 5.

1. **Forward:** The robot moves forward alongside a wall. A tolerance of ± 1 cm is used to keep the robot in a range of 19-21 cm from the wall, measured by sensors s_4 and s_5 (or s_0 and s_1). If the distance to the wall is not within the specified range, the robot switches to one of the adjustment states, which are dependent upon which wall is followed. If a wall is detected in front of the robot by sensors s_2 or s_3, the robot switches to the "inside turn" state.

2. **Adjust Outward:** The robot veers slightly outwards to get back within the accepted distance range. After the robot is within the accepted distance range, the machine switches to the "forward" state.

3. **Adjust Inward:** The robot veers slightly inwards to get back within the accepted distance range. After the robot is within the accepted distance range, the machine switches to the "forward" state.

4. **Inside Turn:** The robot stops and turns 90° clockwise or counterclockwise, depending on if

the wall followed is on the right side or on the left side. Fig. 6 demonstrates this turn when the robot is following a right wall and is turning counterclockwise.

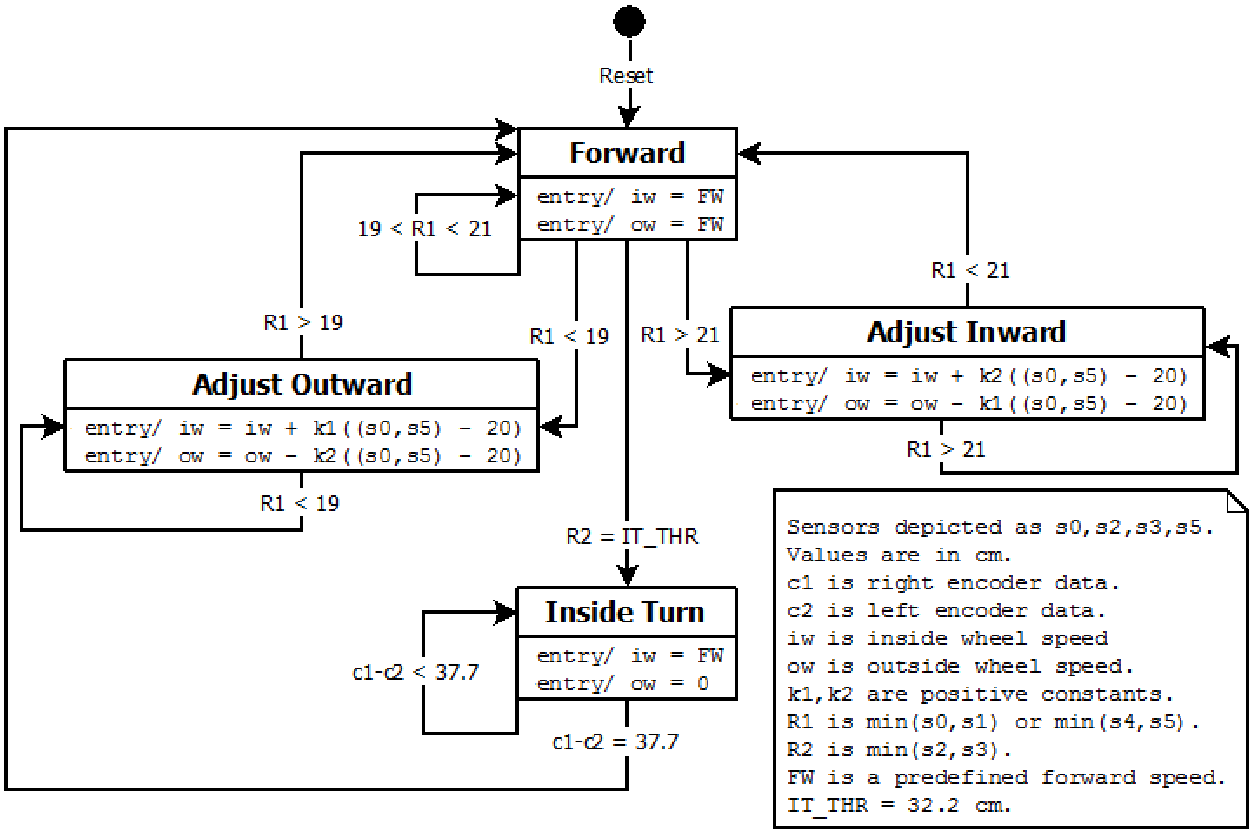


Figure 5. UML state machine diagram for wall following algorithm for Amigobot.

3.3 Navigating Corners

The robot's turning algorithm takes advantage of the course only containing turns of approximately 90°. Such sharp turns are not conducive towards "smooth" wall following techniques. Therefore, when necessary, the robot will execute a blind turn which relies on the optical rotary encoders on each wheel instead of the sonar data. The goal of the turning algorithm is not to pivot exactly 90° and then move in a straight line every time, but rather to quickly execute a precise turn which results in the robot being approximately parallel to and 20 cm away from the opposite wall, after which the robot can easily continue using sonar data to make accurate adjustments.

3.3.1 Detecting a Turn

The turning algorithm being implemented requires accurate detection of forward obstacles and discontinuities in the parallel wall in order to avoid turning prematurely.

The outside turn is not detected directly. Rather, the case of an absent parallel wall is handled by the "adjust inward" state. However, the sensor values for s_4 and s_5 (or s_0 and s_1) must be severely limited in order to avoid having the turn be executed too sharply. In the program the working value for these sensors is limited to `0x0140`, or about 32 cm.

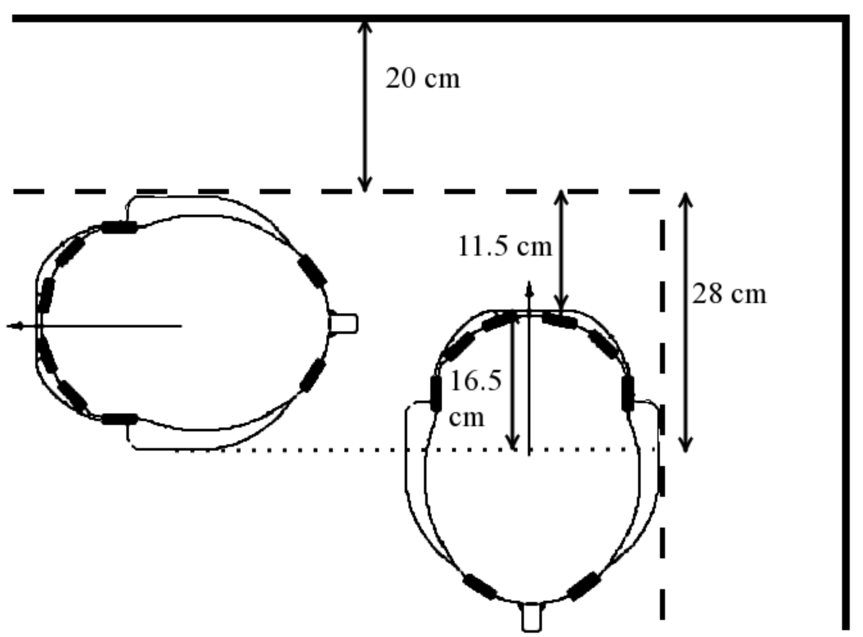


Figure 6. Geometry of an inside turn.

For an inside turn, the robot must begin turning once the front of the robot reaches the threshold `IT_THR`. The geometry for this turn is presented in Fig. 6, which indicates that `IT_THR` should be 31.5 cm. However, the forward sensors s_2 and s_3 are not pointed directly forward, but rather are at 12° angles, so the sensor reading for `IT_THR` should be $31.5/\cos(12°) = 32.2$ cm before the robot begins an inside turn. The inside turn is executed by stopping the inside wheel while driving the outside wheel forward until the robot has rotated 90 degrees (see 3.3.3).

3.3.2 Using Rotary Encoders

The optical rotary encoders on each wheel of the Amigobot provide an incredibly fine yet robust way to detect the rotational position of each wheel. Each wheel's position can be loaded through SCOMP's I/O through the I/O addresses `0x80`, `0x81`, `0x88`, and `0x89`, which respectively correspond to the given address names `LPOSLOW`, `LPOSHIGH`, `RPOSLOW`, and `RPOSHIGH`. The position datum from each encoder is a 32-bit number. For I/O purposes, this datum is split into two 16-bit numbers (the upper 16 bits and the lower 16 bits), each of which corresponds to the "low" or "high" I/O address for each wheel's position.

3.3.2.1 Physical Characteristics of the Rotary Encoders

The encoder datum increments by 39000 for each revolution of the wheel. The left encoder increments when the left wheel is in forward motion, while the right encoder decrements when the right wheel is in forward motion. Each wheel has a diameter of 10 cm, which results in a path of 31.42 cm being traversed for each wheel revolution so long as traction is maintained. Since there are 39000 "ticks" per revolution, one cm of linear wheel motion corresponds to 1241.41 ticks. This results in large-valued encoder data for relatively short distances. In order to simplify calculations and prevent bit carries between two 16-bit numbers (the high and low data), it is best to perform calculations on a single 16-bit number which can be produced by combining the upper eight bits of the "low" datum with the lower eight bits of the "high" datum, resulting in a reduction in encoder resolution by a factor of 256. After shifting and truncating the two 16-bit numbers into one 16-bit number, the physical characteristics of the encoder transform so that there are 152.34 ticks per wheel revolution and 4.85 ticks per cm of linear wheel motion.

3.3.3 Executing a Turn

The linear path lengths of each wheel are related by a constant such that when the difference in path lengths of each wheel is equal to that constant, the robot is oriented precisely at an angle θ to its starting orientation. If the robot has a wheel track of R and the linear path lengths of the right and left wheels are represented respectively by C_1 and C_2 (Fig. 7), then the robot has turned

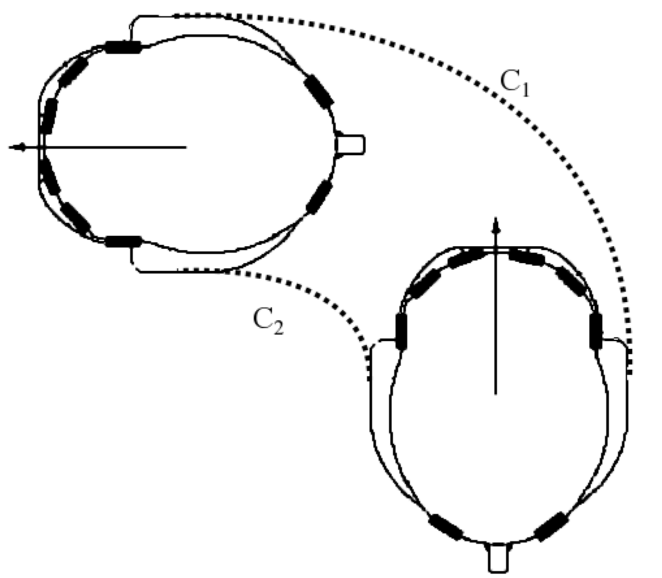


Figure 7. Path lengths C_1 and C_2 as the robot turns.

positive (counterclockwise) θ radians when the following equation is satisfied:

$$C_1 - C_2 = \theta R \tag{1}$$

For instance, if the Amigobot ($R = 24$ cm) is to turn 90° then continue forward, the robot should cease turning when $C_1 - C_2 \geq 0.5\pi(24) = 37.7$ cm, or about 181 (`0x00B5`) ticks. Experimentally, it was found that at higher speeds the wheels of the robot slipped slightly when the robot decelerated from a turn, so the working value of this constant was lowered to 154 ticks (`0x009A`).

3.3.4 Adjustment States

Once the lateral sensors detect that the robot is outside of the 20 ± 1 cm range, the robot enters one of two adjustment states. The robot feeds back the detected range difference to the left and right wheel velocities.

The program uses a cumulative adjustment where each loop iteration is paused for 100 ms. During each loop iteration, the angular velocity for each wheel is set to a new value based on its previous value and the measured distance to the wall, R_1:

$$\omega_i[n] = \omega_i[n-1] + k_1(R_1 - 20) \tag{2}$$

$$\omega_o[n] = \omega_o[n-1] - k_2(R_1 - 20) \tag{3}$$

ω_i is the inside wheel velocity (right wheel for right-wall following), ω_o is the outside wheel velocity, k_1 and k_2 are positive constants, and R_1 is the minimum value of sensors s_4 and s_5 (or s_0 and s_1).

3.4 SCOMP Alterations

Several alterations to the SCOMP program were made in the form of new instructions:

1. **MULT** - The built-in Altera® megafunction `LPM_MULT` was implemented into SCOMP, with the module multiplying the accumulator, `AC`, and memory data register, `MDR`. The 32-bit result vector for `LPM_MULT` is latched and spread across 16-bit registers `LO` and `HI` when SCOMP enters the `EX_MULT` state.

2. **MLO** - The contents of the `LO` register (the lower 16 bits of the result of `LPM_MULT`) are latched onto the `AC`.

3. **MHI** - The contents of the `HI` register (the upper 16 bits of the result of `LPM_MULT`) are latched onto the `AC`.

4. **DIV** - The megafunction `LPM_DIVIDE` was implemented to divide `AC` by `MDR`. The remainder of the megafunction result is latched onto register `REMAI`.

5. **REM** - The contents of `REMAI` are latched onto the `AC`.

6. **SHIFT2** - The megafunction `LPM_CLSHIFT` was implemented to shift by a variable amount. Instead of the shift magnitude being four bits of `IR` as in the original `SHIFT` instruction, the shift amount for `SHIFT2` is specified by the first four bits of `MDR`. Additionally, in order to simplify the assembly program, the shift direction was inverted so that when `MDR(4)` is low, a right shift is indicated.

7. **SHIFT3** - A third instance of megafunction `LPM_CLSHIFT` was implemented in order to provide a variable rotating shifter. The megafunction parameters are identical to those of `SHIFT2` except for the shift type.

The `MULT`, `MHI`, and `MLO` intructions are used in the two adjustment states for the multiplication required in equations 2 and 3. The divide instruction as well as the two shift instructions are used in manipulating the LED displays as described in section 3.5.

3.5 Amigobot Display Additions

Several additions were made to the robot display to improve the user interface. Memory locations used to write to and read from are designated in capital letters.

Figure 8. Implementation of both seven-segment displays.

- Two displays are used to show the velocity of the left and right wheels.
  - These are written to `SEVENSEG` whenever `LVELCMD` or `RVELCMD`, the wheel velocities, are changed (Fig. 8).
- The third display shows the velocity of the robot (Fig. 8).
  - This was done by altering the `IO_decoder` and the block diagram files so that the second 7-segment display could be written. It is named `SEVENSEG2` and mapped to 0x05 on the IO address space map.
  - `IO_decoder` was altered by adding and enabling a signal for the second set of the 7-segment LEDs and copying the setup of the `HEX_DISP` module used for the current 7-segment display.

Figure 9. The LCD display on the DE2 board.

- The LCD display (Fig. 9) shows the current state the program is in.
  - This was done by altering the LCD display to accept ASCII values representing numbers. The SLCD was altered to take in an ASCII enable, `ASCII_EN`, which tells it to interpret the incoming argument as a state to be output in ASCII format.
  - There are four states. The LCD displays `RDY!` when the program is ready to start. It then displays `KEY2` to tell the user to press `KEY2` and start the program. Once the program starts, the screen displays `LEFT` or `RGHT`, telling the user which side of the wall the robot is following.
  - The states were encoded into a binary code of 16 bits. For example, the `RDY!` output string was encoded as `0x0` and the `KEY2` command as 0x1. The strings shown on the LCD display were hard coded using the binary state representations.

Figure 10. The red and green LED arrays on the DE2 board.

- The red LEDs (Fig. 10) light up to show the turning rate of the robot.

- Two lit LEDs in the middle (LEDs 7 and 8) form the base pattern, which is displayed when the robot is moving in a straight line. Otherwise, the displayed pattern is shifted with the rotating shifter by an amount proportional to the difference between the left and right wheel velocities. This causes the pattern to shift left if the robot is turning left, and vice-versa.

- The green LEDs (Fig. 10) are used to display a completion bar for the "inside turn" state.
    - This was done by altering `IO_decoder` and the block diagram files so that the green LEDs could be used. It is called `GLED` and mapped to `0x07` in the IO address space map.

3.6 Assignments

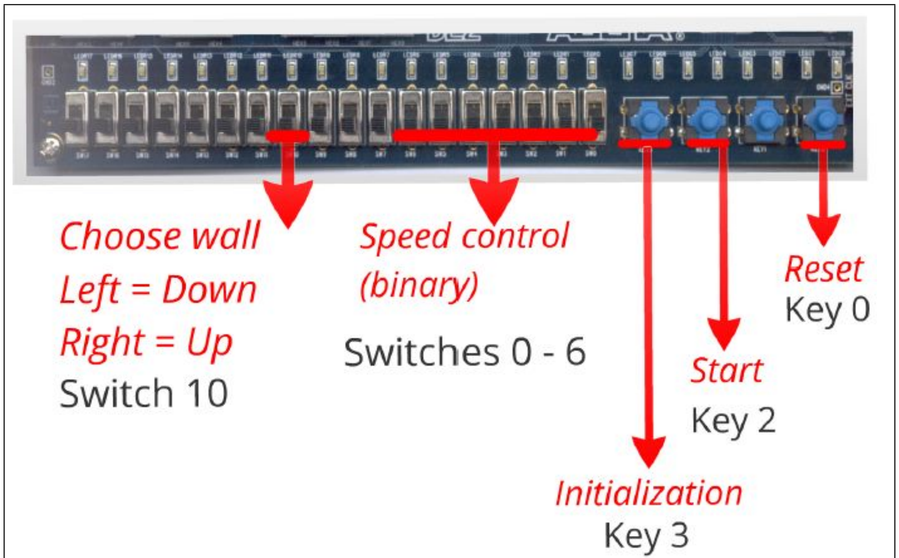


Figure 11. Function assignments for DE2 peripherals.

The switch and button assignments on the DE2 board are shown in Fig. 11. Switches `SW0` through `SW6` are used to encode in binary the speed at which the robot will travel. Switch `SW10` selects which wall is to be followed, with a low value indicating the right-wall following program.

To start the program, a series of steps must be followed. First, the switches are toggled into the desired positions. `KEY3` is then pressed to initialize the robot. Lastly, `KEY2` is pressed to start the program. `KEY0` may be pressed at any time to reset the program.

3.7 Significant Modifications

Several significant modifications were made to the original design:

- The original program consisted of five states. During testing it was discovered that the inaccuracy of sensor data when the robot was angled to the wall caused premature transitions to an "outside turn" state. To solve this problem, the state was removed. To navigate outside turns, the "adjust inward" state is used. A subroutine in this state limits the value of the lateral sensors to prevent the robot from turning too sharply.

- It was originally proposed to use the LCD display to show the state that the wall following program is currently in. However, since the LCD is not timed on the same clock as SCOMP, the team encountered problems timing the latching of IO data into the LCD when other IO peripherals, such as motor and sensor control, were also being used. To solve this problem, the role of the LCD display was changed to display the basic startup states and not the current wall following state.

- The original design called for one lateral sensor s_5 (or s_0) and one forward sensor s_2 (or s_3) whose data would serve as inputs to the state machine. Since the sensor readings were inaccurate when the robot was oriented at an angle to the wall, it was decided that using pairs of sensors would be optimal. A pair of sensors, s_4 and s_5 (or s_0 and s_1) was used for the lateral region, and the pair s_2 and s_3 for the forward region. The minimum value of each pair was used as the working value for the distance of the robot to a wall in either the lateral or forward region.

3.8 Project Management

The finalized Gantt chart that was used during this project can be found in Appendix A.

4 Technical Results

4.1 Final Demonstration Results

The course used for the final demonstration consisted of five straight wall segments, with four outside turns and four inside turns. Each straight segment of the course was approximately four feet.

The results of the final demonstration showing the **expected**, **actual**, and **difference** in values of scores can be found in Table 1. The expected values for the completion, accuracy, and time are based on test runs performed during lab periods.

Table 1. Results of wall following demo

	Completeness (%)			**Accuracy** (%)			**Time** (min:sec)		
	Exp.	**Act.**	**Diff.**	**Exp.**	**Act.**	**Diff.**	**Exp.**	**Act.**	**Diff.**
Right Wall	100%	100%	-	100%	100%	-	1:15	1:23	0:08
Left Wall	100%	100%	-	100%	0%	100%	1:15	5:52	4:37
Total Time							2:30	6:15	3:45

The robot did not collide with the wall on either run. It received an accuracy bonus for five out of the ten sections it completed.

The robot completed the course following the right wall in one minute and 23 seconds, which was eight seconds slower than the expected time. The robot was 100% accurate during this run.

The team experienced problems during the left wall following demonstration. The problems encountered were due to the prevalence of sequential inside turns in the particular left-wall following course presented. One issue identified was that the robot was inconsistent in detecting its distance to a forward wall, which is crucial to execute an inside turn. The result was that the robot would frequently turn too early or too late and would be unable to readjust to recover in time for the next turn. The problem was in the range-calculating algorithm implemented and not in the hard-coded 90° turns using rotary encoder measurements, since the turns executed were exceptionally consistent. The time to complete the course was a result of several trial runs due to near collisions. The robot was switched for another robot at the behest of the professor due to strange sensor behavior on the left side. This event caused additional setup and upload delays. The robot was able to succesfully complete the course, but did so without maintaining a constant distance to the wall.

4.2 Outcomes

The results from the final demonstration and test runs suggest that the robot can consistently and accurately complete a wall following course predominantly composed of outside turns. When performing sequential inside turns, the robot is often unable to successfully navigate the course. In either case, the robot must travel very slowly to avoid collisions with the wall.

5 Conclusions

5.1 Overview

Overall, the design allowed the robot to successfully complete the course. The design met all specifications. However, maintaining a constant distance to the wall proved to be a challenge. While the robot did not have problems maintaining accuracy when following the right wall, it was unable to produce the same results when following the left wall. Accuracy on the right wall following depended strongly on suppressing the speed of the robot. The robot completed both courses without collisions and penalties.

5.2 Strengths and Weaknesses of Design

There are several strengths of this design. The robot is able to successfully complete the course and avoid collisions. The design allows the robot to run at variable speeds chosen by the user by selecting switches on the DE2 board. The informative display greatly helps in debugging processes and provides insight into how the program is running.

A weakness of this design is that the Amigobot cannot utilize its speediness and complete the course successfully without collisions. Extra time, in the form of slow movement, must be used in order to accurately follow the wall. Additionally, the algorithm itself is inefficient and produces inconsistent results. The inefficiency stems from the multiple 100 ms wait loops in the adjustment states that slow down sensory input tremendously. Wall following inconsistency may be attributed to an inflexible algorithm unable to handle sensor inaccuracies.

5.3 Recommendations

For future work, a useful development would be to show the moving states on the LCD display as initially proposed. This would allow for quicker and more effective debugging and would be a useful addition to the display.

Another development would be to encode the green LEDs to show more functions as they are executed. The current design uses the green LEDs only as a completion bar for the "inside turn" state. Animating the LEDs for other states could aid in debugging purposes and improve the display.

While this design takes the minimum of two adjacent sensory values, it could be edited to use weighted values of the sensors. Allowing some sensors to take precedence over others would allow the robot to accurately determine its orientation relative to the wall.

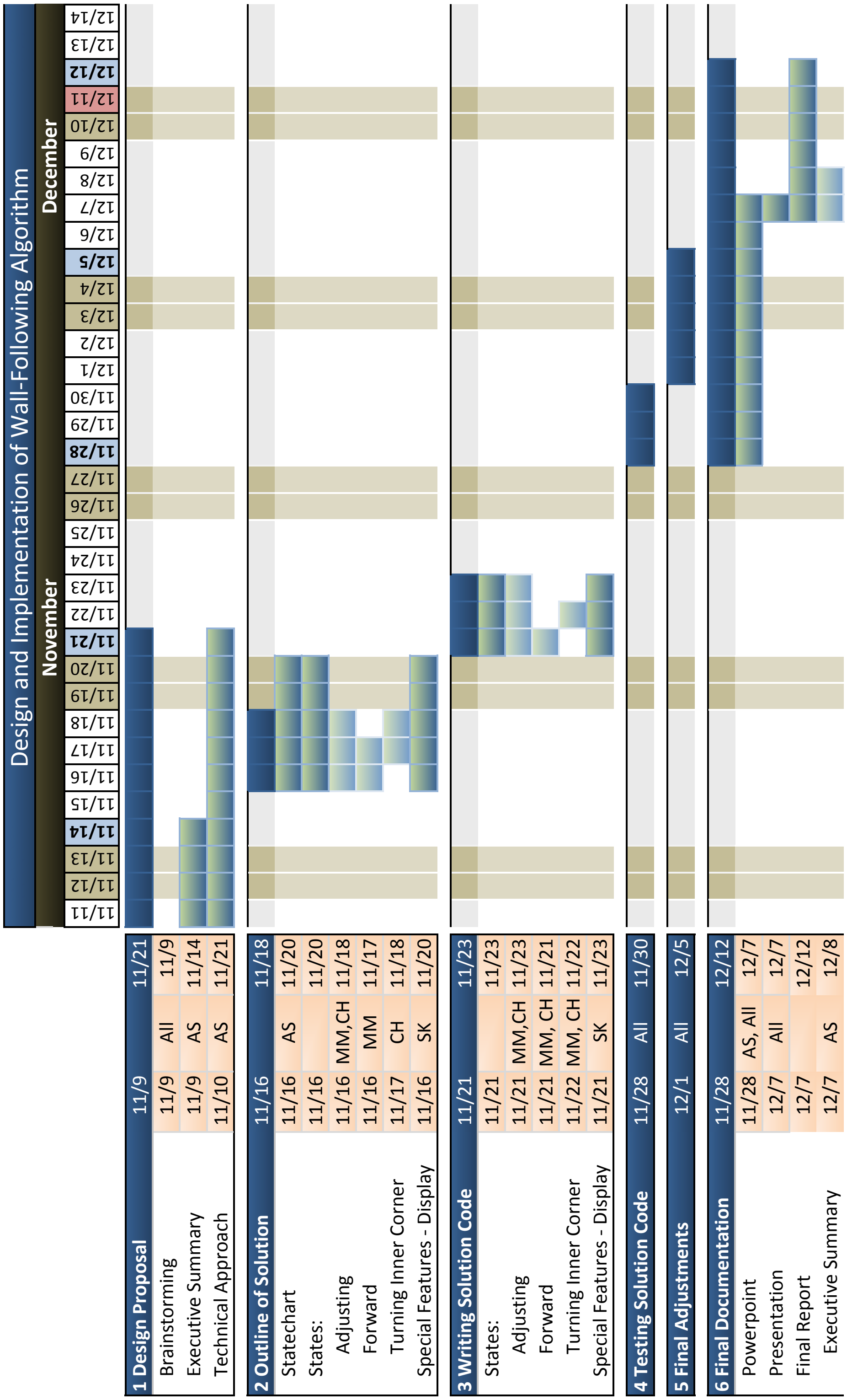
Due to limited computational resources in assembly language, the measurement algorithm used to detect turns is not as accurate as desired. A major improvement to the program would be to compute a more accurate measurement algorithm, such as averaging the forward sensor data over multiple instances of time.

5.4 Optimizations

In order to optimize the design, the 100 ms wait loops should be removed from the adjustment states. The loops decrease the frequency of adjustment greatly, which prevents the robot from moving too quickly. In order to remove the wait loops, the adjustment states would have to be rewritten in order to remove cumulative additions.

Additionally, the invalid value of the sonar sensors should be changed from `0xFFFF` (-1) to a large positive number, `0x7FFF` (32767). Since the code implemented includes many `JNEG` instructions, this would prevent having to include special consideration for invalid sensor readings. Ideally, this would be changed at the hardware level of the sonar sensors.

Appendix A: Gantt Chart



Appendix B: Logbook

Appendix C: Design Proposal