University of Cincinnati

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I, Adam Meece, hereby submit this original work as part of the requirements for the degree of Master of Science in Electrical Engineering.

It is entitled:

Laser Guided Navigation System for the Automated Floor Profiler – String Walker Edition

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Laser Guided Navigation System for the Automated Floor Profiler – String Walker Edition

A thesis submitted to the Graduate School

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in partial fulfillments of the requirements for the degree of

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in School of Electrical Engineering and Computing Sciences

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by

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Abstract

Floor profiling is the process of measuring the flatness and levelness of the floor. These quantities are found by measuring the displacement of the floor in one foot increments, along straight lines. The floor profile is represented by F-numbers, which is the industry standard as per ASTM E1155. FF is the floor flatness and FL is the floor levelness. The objective of this thesis is to develop and introduce a system of devices for efficient navigation for the autonomous floor profiler. This will be accomplished through a new laser guided system for navigation.

The system consists of two laser devices for the floor profiler to track on straight line paths and alignment lasers, called String Walkers, and two peripheral lasers, acting as tripwire stopping points for each line, heading sources for movement between lines, and alignment lasers for setup. The String Walkers utilize servos for movement and laser oscillation, as well as IR and ultrasonic proximity sensors for navigation. The final configuration of the String Walker has an estimated battery life over 11 hours under normal operation.

The laser guidance navigation system was tested for accuracy in straight-line travelling, as well as autonomous navigation functionality. It was found that the oscillating laser provided consistent signals to the Floor Walker device at all distances by varying the oscillation angle from 1-3 degrees. At the furthest distances, 1° is used, while at the closest distances 3° is used. The String Walker is able to consistently travel between measurement lines with excellent accuracy and precision.

Using the String Walker and peripheral lasers for laser guidance reduced the standard deviation from a straight-line path from 0.765" with gyroscope-feedback navigation to 0.224" with the laser guidance navigation system.

Acknowledgements

I am thankful to Dr. Fred Beyette for introducing this project to me during senior design, as well as agreeing to advise me on it for my thesis work. His insights have been incredibly helpful over the course of the project.

I am immensely grateful to have had Chad Whaley as my colleague on the Floor Walker aspect of this system and for acting as a sounding board for many design ideas and decisions. Without him, the system would be incomplete.

I would like to thank Professor Jim Everly for guiding me in the statistical analysis of the test data for this system.

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1. Introduction

1.1 Floor Profiling

Concrete floor profiles vary depending on the application of the floor. In the basement of a house, the floor does not need to be perfectly flat or level. Alternatively, in a distribution center, the floors may need to be ultra-flat or level for operations to be conducted safely and effectively. Floor profiling is the process of measuring the flatness and levelness of the floor. These quantities are found by measuring the displacement of the floor in one foot increments, along straight lines. There are two sets of measurement lines, measured perpendicularly to each other, as show in figure 1.1 [4].

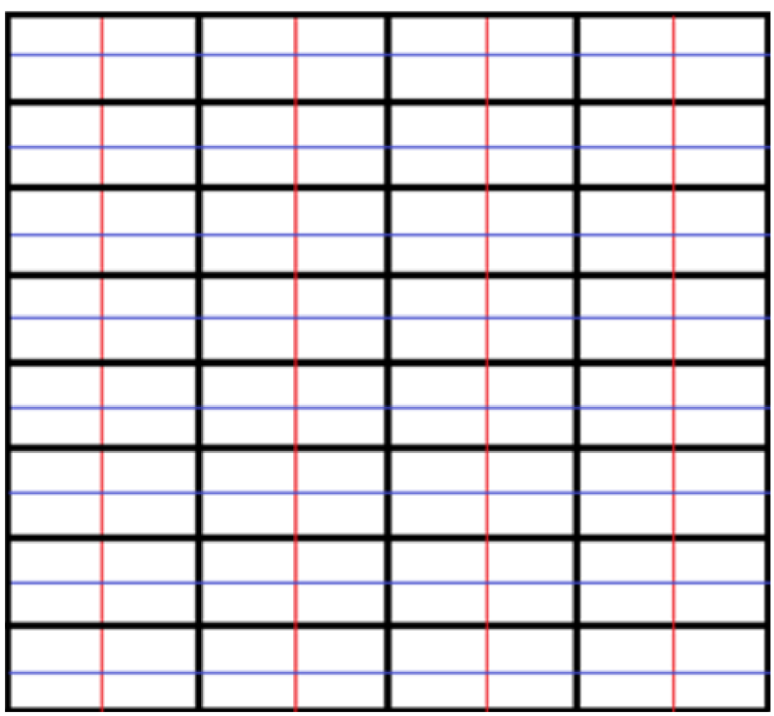


Figure 1.1: Perpendicular floor profile measurement lines [4]

1.1.1 F-Numbers

The displacements along the measurement lines are used to produce F-numbers that represent the floor. F-numbers are the industry standard for floor profiles as per ASTM E1155. There are two F-numbers, F_F is the floor flatness and F_L is the floor levelness. Floor flatness is the statistical quantification of a 24-inch curvature, representing how bumpy the floor is over short distances [1]. Floor levelness is the statistical quantification of 10-foot slopes, representing variation over extended distances [1]. Examples of these quantities are shown in figures 1.2 and 1.3. The higher the value of the F-numbers the flatter or level the floor. Measurements can be made in multiple ways. A straight edge can be used in small measurement areas, measuring displacement from the edge to the floor, while devices, such as the Dipstick, can be used in larger areas. The common flaw with these methods is the requirement of manual operation. Concrete floors are the primary venue for floor profile measurements. When installing a concrete floor, the general contractor is responsible for certifying that the new floor meets the customer specification for levelness and flatness. For large warehouse spaces and multi-story buildings, this task can be quite onerous.

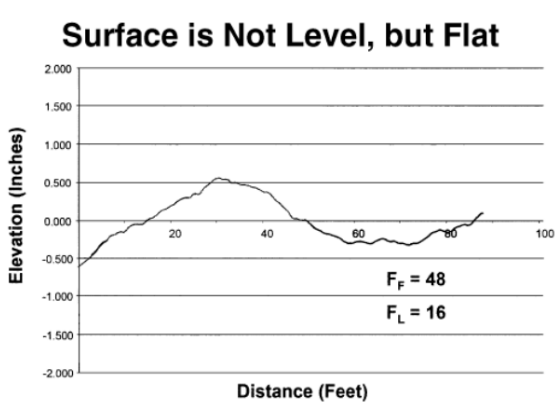


Figure 1.2: Floor Flatness vs Floor Levelness

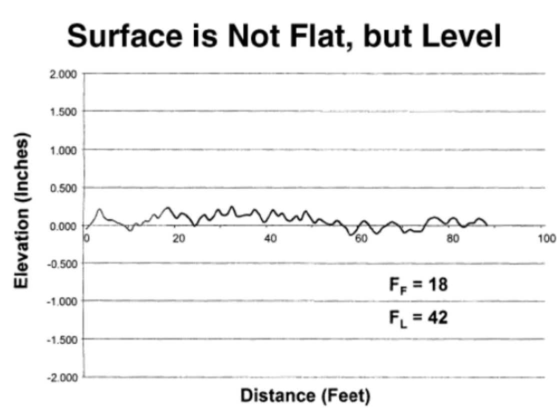


Figure 1.3: Floor Levelness vs Floor Flatness [1]

1.2 Objective

The primary objective of the autonomous floor profiler is to navigate a floor space, measuring the profile as it goes. The data recorded during navigation is converted to displacement values and F-numbers are calculated for each line of measure in the floor space. Since F-numbers are produced from straight line measurements, the critical functions of the device are autonomous operation, outside of user setup, and the ability to travel in straight lines. The autonomous floor profiler cannot consistently perform these functions due to its inability to effectively navigate the floor space. Therefore, the objective of this thesis is to develop and introduce a system of devices for efficient navigation for the autonomous floor profiler. This will be accomplished through a new laser guidance system. The system will include four new devices exclusively for navigation, in addition to the measurement device. This thesis will focus on the addition of the four external navigation devices.

1.3 Thesis Outline

This thesis presents an autonomous floor profiling system as an alternative to labor demanding and time consuming methods in use today.

Chapter 1 gives a brief introduction to floor profiling and F-numbers used in industry. It also discusses the objectives of the thesis.

Chapter 2 outlines existing solutions to this problem and introduces the laser guided autonomous floor profiling system.

Chapter 3 describes in detail the proposed solution including design considerations, components, programming, system setup.

Chapter 4 discusses the procedure for evaluating the proposed system and the results obtained from testing experimentally.

Chapter 5 concludes the research and discusses future work.

2. Solutions

2.1 Dipstick

The Dipstick is a manually operated, walking floor profiler. It has two support feet, 12 inches apart. The device operator walks the Dipstick along lines, taking a slope measurement on each step. The Dipstick is rated to an accuracy of +/- 0.0005” per reading. The cost of this device is $9950 [2].

Figure 2.1: Dipstick floor profiler [2]

2.2 F-Meter

The F-Meter is a manually operated, rolling floor profiler. It was invented by Allen Face and Company. It is marketed as being the fastest floor profiler on the market, ideal for large test areas. The listed sensor accuracy for the F-Meter is +/- 0.002” per reading. The cost of this device is $12,995 [3].

Figure 2.2: F-Meter floor profiler [3]

Outside of cost, the biggest issue with the Dipstick and the F-Meter floor profilers is manual operation. This leads to lost resources, in the form of skilled laborers, and monetary loss. The obvious solution is an autonomous device.

2.3 Autonomous Floor Profiler

An autonomous floor profiler was developed as a senior design project by Adam Meece, Chad Whaley, and Matthew Flowers at the University of Cincinnati in 2016 [4]. The device measures and navigates a floor space autonomously. The measured data is then analyzed by a custom MATLAB script, which produces F-numbers and plots of lines of measure [4].

Figure 2.3: Autonomous Floor Profiler [4]

2.3.1 Design

The major components of the autonomous floor profiler are the robot base, microcontroller, measurement sensors, navigation sensors, and analysis software. The robot base is a Create 2 from iRobot. This provides the body of the device, including power supply, storage, drive motors, and wheels. The microcontroller is an Arduino Mega 2560 R3. This interfaces with the internal Create 2 controller, allowing commands to the Create 2, and all sensors. The floor measurement sensor is a 9-degree of freedom inertial measurement unit consisting of a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. This unit measures the tilt of the device in the direction of travel and the direction normal to travel, simultaneously. Two ultrasonic proximity sensors act as navigation sensors, allowing the device to make navigation decisions based off the proximity to the test area boundaries [4]. Figure 2.4 shows the navigation path of the device.

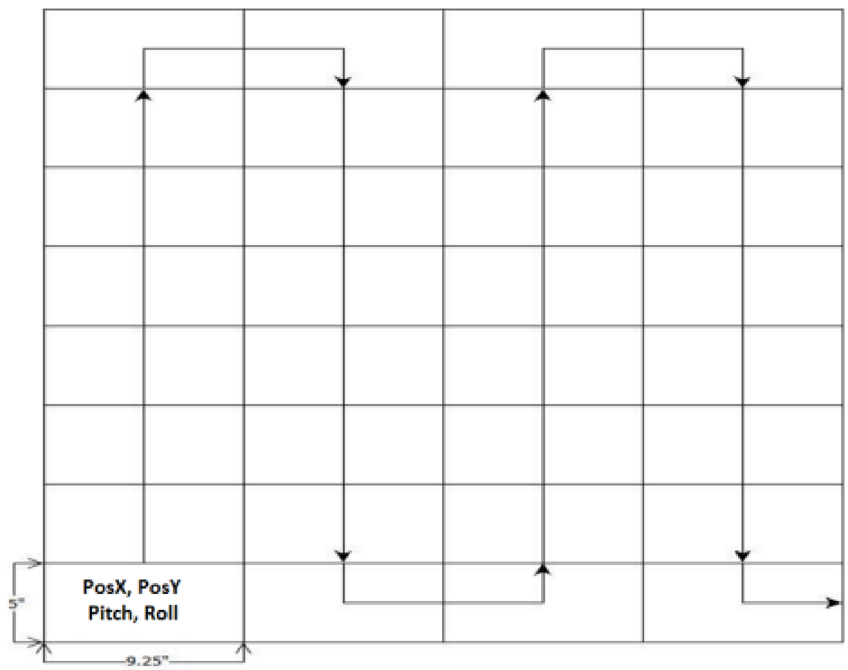


Figure 2.4: Navigation path of the autonomous floor profiler [4]

The navigation algorithm, utilizing the ultrasonic proximity sensors, is represented by the flowchart shown in figure 2.5. The device drives forward until the forward-facing proximity sensor detects the wall. Next, it turns right. If the forward-facing proximity sensor is no longer flagged, the device drives forward 9.25” and turns right again. Then it will drive forward until the next wall is reached, turning left now. It will continue to snake through the test area until the end is reached.

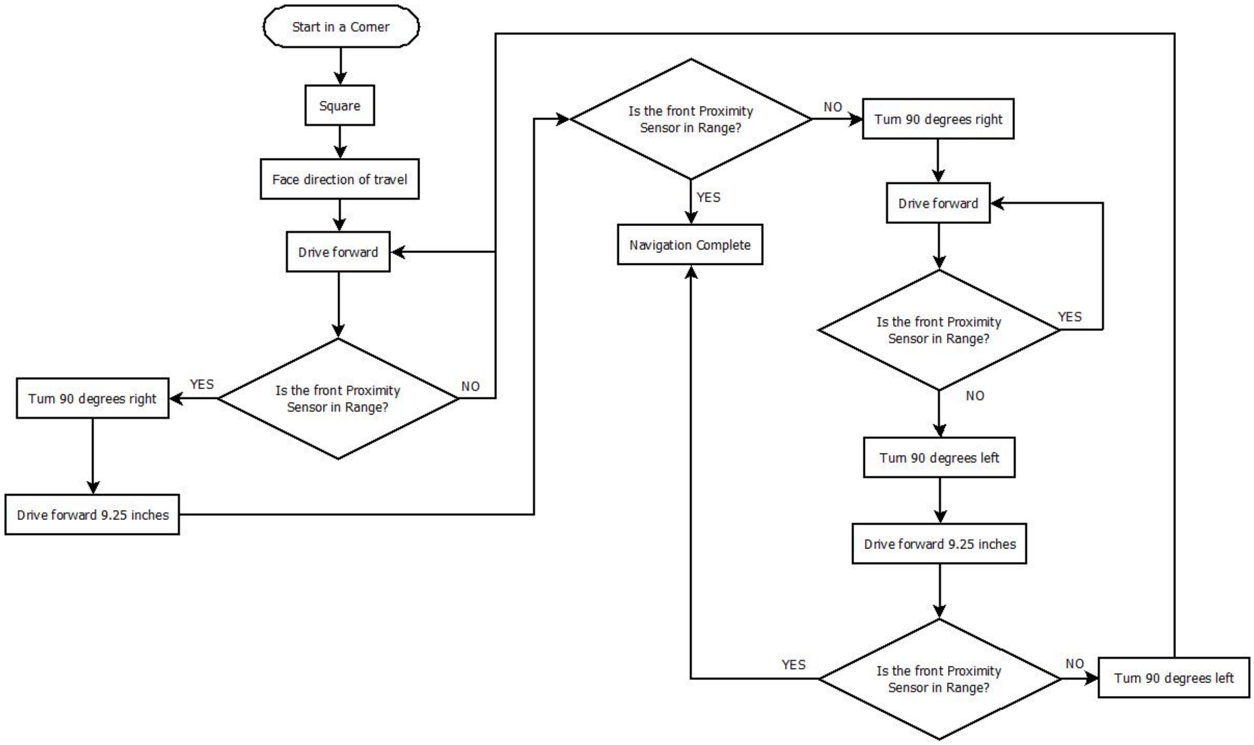


Figure 2.5: Autonomous floor profiler navigation algorithm [4]

Since the points of contact between the device and the ground are 5” in the x-direction and 9.25” in the y-direction, as shown in figure 2.6, the tilt measurements are taken every 5”.

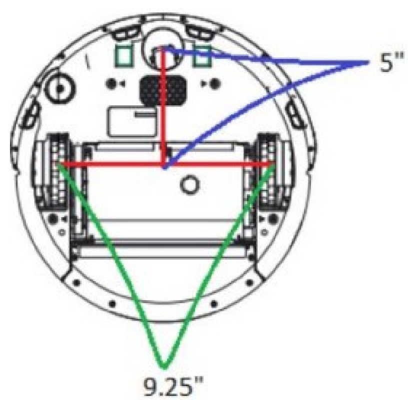
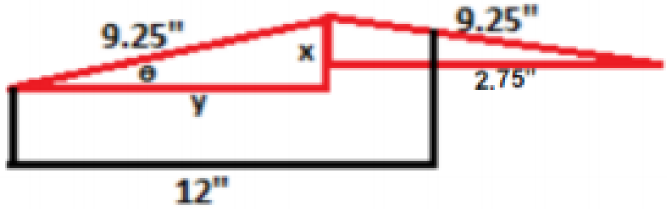


Figure 2.6: Wheel distance measurements [4]

To conform to the F-number standard, the 5” and 9.25” measurements must be converted to 12” measurements [4]. This is accomplished through weighted averaging, shown in figure 2.7.



(9.25/12)*s1 + (2.75/12)*s2 = 12"slope

Figure 2.7: Weighted average example [4]

The 12" slopes are used to calculate displacement every 12". The slopes are used to calculate the floor flatness, F_F, and the displacements are used to calculate floor levelness, F_L. Q is the difference in consecutive slopes, while Z is the difference in elevation across 10-ft [4].

$$Q_n = slope_{n+1} - slope_n \quad , \quad F_f = \frac{4.57}{3 * std(Q) + |mean(Q)|}$$

$$Z_n = elevation_{n+10} - elevation_n \quad , \quad F_l = \frac{12}{3 * std(Z) + |mean(Z)|}$$

Figure 2.8: F-Number calculations [4]

2.3.2 Problems

The fundamental problem with the autonomous floor profiler is the inability of the device to drive in straight lines. While the Create 2 comes with built-in commands for straight driving, the physical limitations of the wheel motors prevents the device from driving straight. Instead, the "drive straight" command causes the device to move in a large radius circle. To remedy this issue, the autonomous floor profiler uses the yaw heading from the inertial measurement unit's gyroscope as a reference point. The device attempts to correct to this heading as it drives along each measurement line. This method is better than no feedback control but still lacks the necessary straightness due to error in initial alignment and sensor drift [4]. These issues can adversely affect the measured floor profile. For example, the gyroscope feedback results in a travel path that oscillates approximately +/- 0.5”. While this value isn’t beyond the scope of human error, it is compounded with the error in alignment and drifting sensor headings, leading to the device ending a measurement line offset from the intended stop point by several inches. Figure 2.9 illustrates this problem.

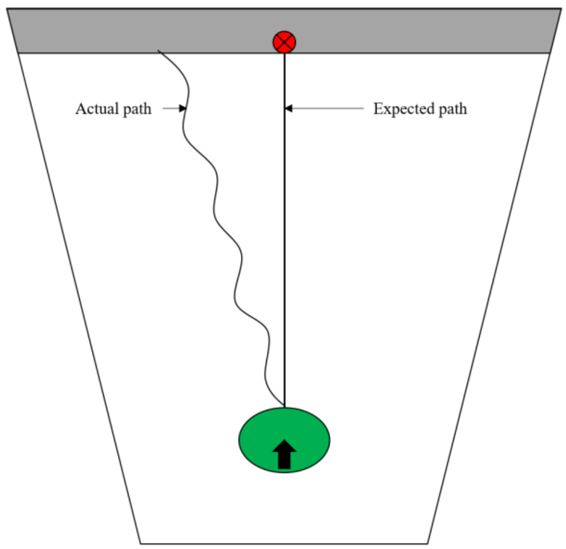
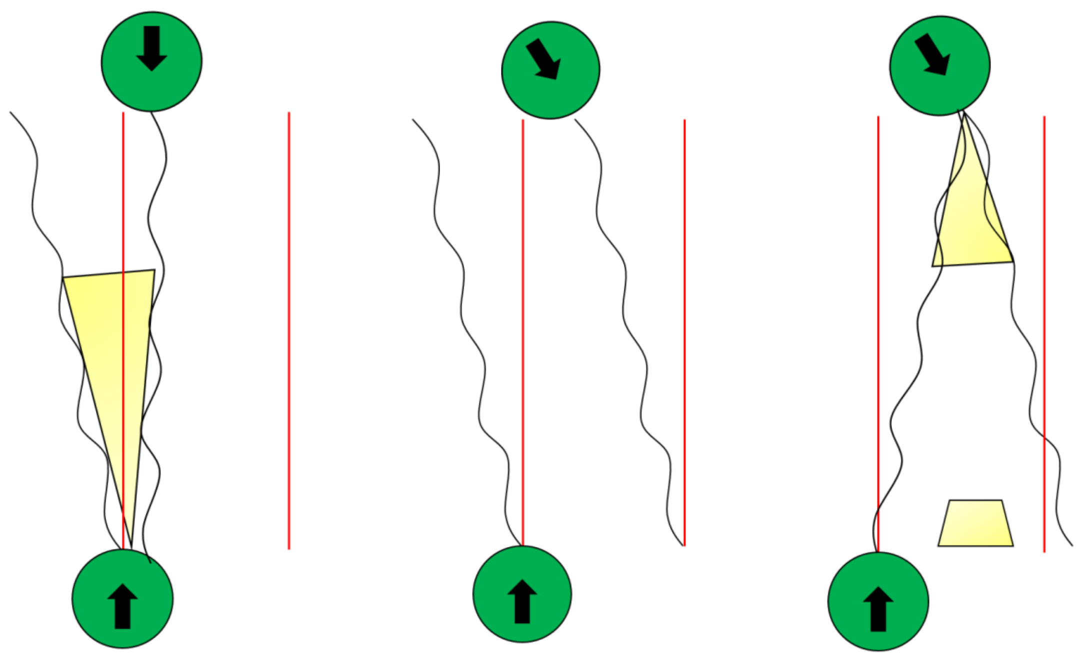


Figure 2.9: Gyroscope navigation issues

From the location that the device stops, it will turn parallel with the wall, drive 9.25”, turn 180° from the gyroscope’s original heading, take a new gyroscope heading, and start a new measurement line [4]. If the original heading was wrong due to misalignment or the sensor heading drifted, the new line will not follow the correct path. This can lead to measurements that overlap previous measurements or leave portions of the floor unmeasured. Either case decreases the validity of the results.

There are three possible scenarios with gyroscope-feedback navigation:

- First, the device could drive over floor that has already been measured, corrupting the recorded data.
- Second, the device drives parallel to the first line with no more than approximately 1” of floor missed at any point along the path.
- Third, the device travels in a new direction, resulting in large portions of floor that are not measured.



Figures 2.10, 2.11, & 2.12: Scenario one, Scenario two, Scenario three, respectively. The yellow areas are the overlapping or missed measurements.

Due to the possibility of corrupted data and missed measurements, a new navigation method is required.

2.4 Laser Guided Floor Profiling System

To correct the lack of straight driving from the autonomous floor profiler, a new system has been developed. The laser guided floor profiling system addresses the concerns from the autonomous floor profiler, adding precision and accuracy to the navigation while maintaining autonomy.

2.4.1 Concept

Since the gyroscope feedback control for the autonomous floor profile introduced error in the form of alignment and drift, lasers are used. Lasers provide both alignment verification and a constant heading, without drift. The system consists of two laser devices for the floor profiler to track on straight line paths and alignment lasers and two peripheral lasers, acting as tripwire stopping points for each line, heading sources for movement between lines, and alignment lasers for setup. The floor profiler navigates the floor space in the same pattern as the Autonomous Floor Profiler.

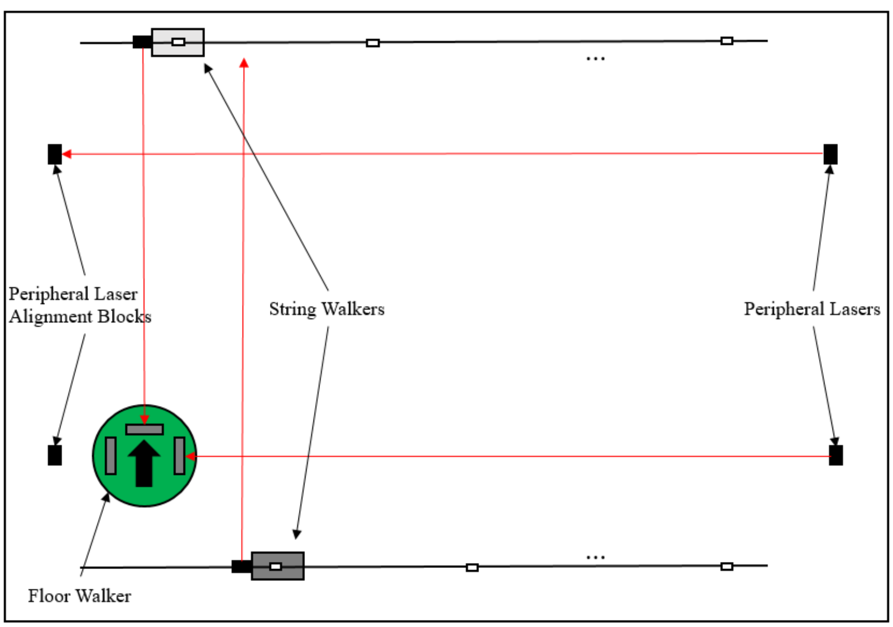


Figure 2.13: Laser Guided Floor Profiling System Layout

2.4.2 Modules

The original autonomous floor profiler has been stripped of the ultrasonic sensors and has been outfitted with a linear photodiode array, oriented in the direction of travel, for straight line laser tracking and two photodiodes, oriented normal to the direction of travel in either direction, for peripheral laser recognition. The laser dot is focused onto the linear photodiode array using a cylindrical, plano-convex, Fresnel lens [5]. This device will be referred to as the Floor Walker.

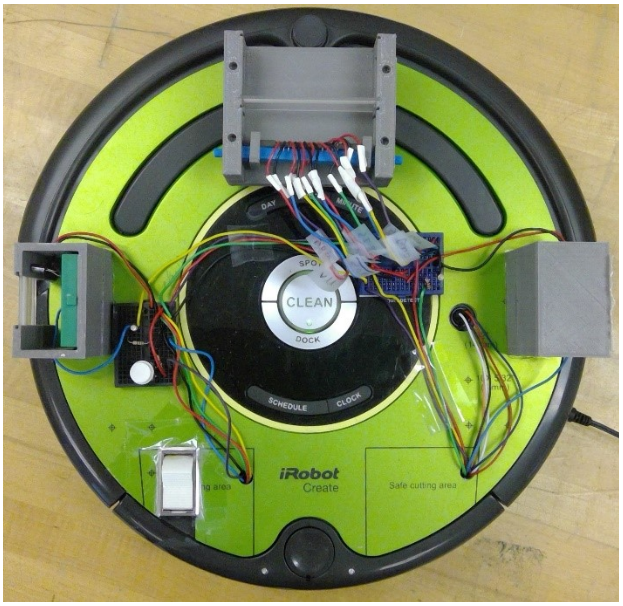


Figure 2.14: Floor Walker [5]

To provide laser guidance and maintain system autonomy, a new device, called the String Walker, has been developed. This device hangs from a line of para-cord, strung along one side of the test area. This will be referred to as the suspension line. The String Walker provides the laser for the Floor Walker to track. It moves along the suspension line to a new position when the Floor Walker has arrived using a spool line attached to a servo within the device. With two of these devices placed on opposite sides of the floor space, as shown in figure 2.13, the Floor Walker will have laser guidance in straight lines across the entire floor space.

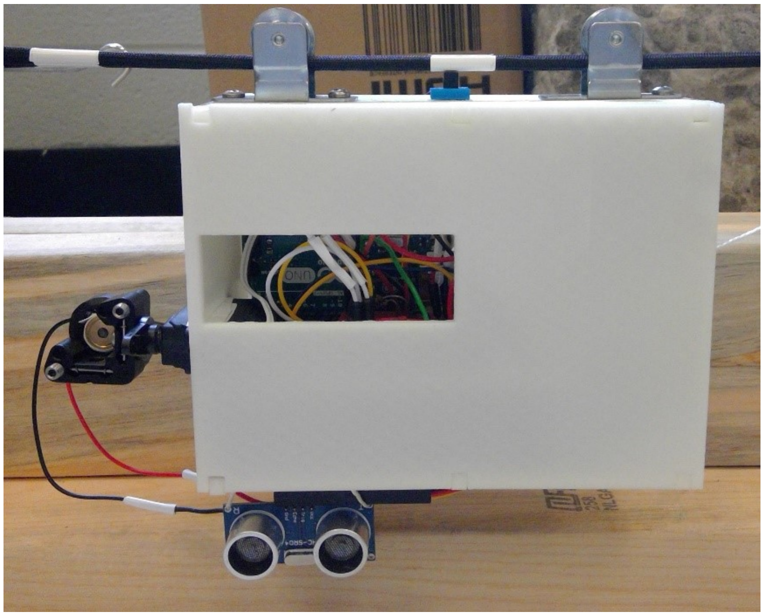


Figure 2.15: String Walker

The peripheral lasers are the final two components added for alignment and navigation. These lasers are oriented perpendicularly to the directions of travel of the Floor Walker. They act as stopping points, laser guidance between lines, and alignment lasers for the Floor Walker. The peripheral lasers have an alignment block opposite the laser diode.

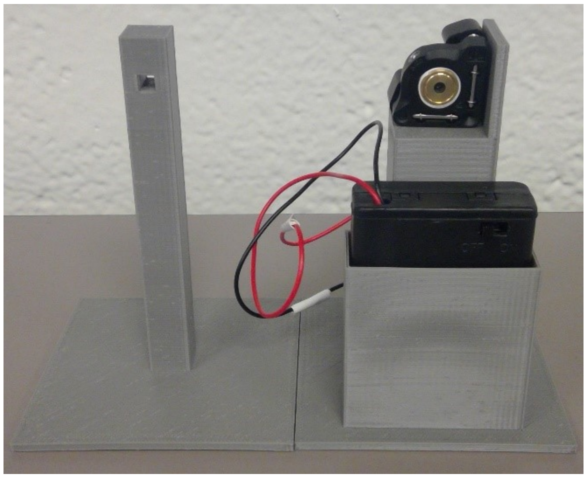


Figure 2.16: Peripheral Laser with Alignment Block

3. System Design

3.1 Components

3.1.1 3D Designs

The String Walkers and Peripheral Lasers are custom devices, therefore the physical enclosure for each was designed and 3D printed to accommodate the desired functionality. The String Walker enclosures consist of a battery compartment, motor mounting clips, microcontroller mounting holes, power supply access holes, sensor mounting locations, spool line access point, and wheel mounting holes. The Peripheral Laser mount consists of a battery compartment and laser mounting platform.

Figure 3.1: String Walker enclosure

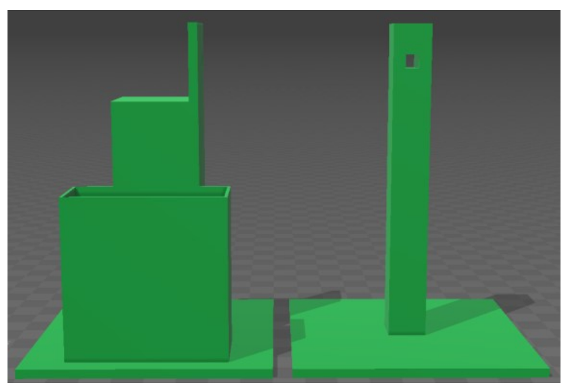


Figure 3.2: Peripheral Laser mount

3.1.2 Motors and Accessories

The String Walker utilizes two servo motor for operation. The first is the drive servo. This motor is a continuous rotation servo, providing 360 degrees of rotation. The EZ-Robot continuous rotation servo is used. The specifications of this servo follow:

- 4.8-7.4 VDC Operating Voltage
- 0.12 sec/60° @ 6V or 108 rpm @ 7.4V Speed
- 6.5 kg-cm @ 6V Torque [6]

These specifications meet the needs of this device. The function of the drive servo is to pull the String walker along the suspension line. This is accomplished by attaching a spool wheel to the servo. The Locked-UP RC Hogshead Winch Spool is used. This spool wheel can hold approximately 20ft of spool line [7]. A spool line is run from the spool wheel to the end of the measurement area. To move, the drive servo turns the spool wheel, winding the spool line and pulling the String Walker along the suspension line.

The second servo is the laser servo. This motor is a standard servo, providing 180 degrees of rotation. The Hitec HS-485HB servo is used. The specifications of this servo follow:

- 4.8-6.0 VDC Operating Voltage
- 0.22 sec/60° @ 4.8V / 0.18 sec/60° @ 6.0V Speed
- 4.8 kg-cm @ 4.8V / 6.0 kg-cm @ 7.4V Torque
- Karbonite gears [8]

These specifications meet the needs of this device. The function of the laser servo to oscillate the laser up and down. This is accomplished by attaching the laser to a mirror mount and attaching the mirror mount to the laser servo. Since the oscillation must be as high frequency as possible, the karbonite gears of this servo are required to alleviate rapid wear and tear.

3.1.3 Sensors

The String Walker has two onboard sensors. The first is an ultrasonic proximity sensor. This sensor is used to detect the Floor Walker. The HC-SR04 is used. The specification of this sensor follows:

- Working Voltage: 5 VDC
- Working Current: 15mA
- Working Frequency: 40Hz
- Max Range: 4m
- Min Range: 2cm
- Measuring Angle: 15 degree
- Trigger Input Signal: 10uS TTL pulse
- Echo Output Signal: Input TTL lever signal and the range in proportion [9]

This sensor is used to detect the Floor Walker in the range of 6”-40”, therefore it meets the required specifications of this device.

The second sensor included in the String Walker is an IR proximity sensor. This sensor is used to detect a transition from black-to-white on the suspension line. When the sensor is detecting the black line, it returns approximately 5V, while returning approximately 0V when detecting white. The sensor used is the QRD1114. This consists of an IR LED and a phototransistor [10]. This sensor requires a current limiting resistor on the LED and a pull-up resistor on the phototransistor [11].

3.1.4 Laser

When selecting the lasers, the biggest concerns were beam divergence and cost of the laser module. The String Walkers are meant to be cost effective alternatives to current floor profiling methods, therefore, the lasers needed to be inexpensive. Alternatively, to keeps the system accurate, the laser module needed to have a small divergence at a distance and less divergence mean more cost. Keeping these considerations in mind, the Quarton Laser Module - VLM-650 is used. This module has the following specifications:

- Wavelength: 650 nm
- Output power: Class IIIa – less than 5mW.
- Beam Divergence (Half Angle): 0.5 mRad
- Operating Voltage: 2.6-5 VDC [12]

This laser module has a beam divergence of 1 mRad (Full Angle), which equates to a dot diameter of 0.12" at 10-ft. The cost of this laser module is $19.60, making is both cost effective and relatively low beam divergence. For these reasons, this laser module meets the requirements of this device.

In addition to laser modules, laser mounts are required. The diameter of the laser module is 10.5mm [12] and precise alignment is necessary. Therefore, optical mirror mounts are used as laser mounts. These are small enough to hold the laser module and have alignment screws for optimal system alignment. The mirror mounts used are Newport M05-R mounts. The mounting hole is 0.5" in diameter, which is adequate [13]. Additionally, these mirror mounts have versatile mounting holes, allowing mounting through either vertical or horizontal holes.

3.1.5 Microcontroller

Microcontrollers are well suited for interfacing sensors and actuators. In this case, a microcontroller is used to make decisions related to device movement based on sensor inputs. An Arduino Uno R3 with an ATmega328P microcontroller is used due to the ability for fast prototyping, simple interface, abundance of I/O ports, 5V operating voltage (same as sensors and servos), low cost, and low computation levels required in this device. The specifications of the Arduino Uno R3 follow:

- Microcontroller: ATmega328P
- Operating Voltage: 5V
- Input Voltage: 7-12V
- Digital I/O Pins: 14 (6 PWM output)
- PWM Digital I/O Pins: 6
- Analog Input Pins: 6
- DC Current per I/O Pin: 20 mA
- DC Current for 3.3V Pin: 50 mA
- Flash Memory: 32 KB
- EEPROM: 1 KB
- Clock Speed: 16 MHz [13]

3.1.6 Power Sources

Three main factors were considered when choosing a power supply for the String Walker. First, the ideal input voltage range for the Arduino Uno R3 is 7-12V. Next, the String Walker needs to maintain operation for the duration of the floor profiling. This is more difficult to quantify since the floor space is variable. Lastly, the load on the battery will vary with load on the servo motors. The stall current of the servos is not listed, so a safe estimate of 1A per servo is assumed. This estimate comes from personal experience with standard servos. For these reasons, a 12 V, 3000 mAh lithium ion battery with a maximum output current of 3A is used. The input voltage range for the servos is 4.8-7.4V, while the battery supplies 12V. To provide an appropriate input voltage to the servos, voltage regulators are required. 5V regulators are used to step the voltage down from 12V to 5V. The peripheral lasers are powered by three AA batteries in series for a total voltage of 3.5V. The power supplies for the String Walkers and peripheral lasers have power switches built-in. These are the switches for powering the devices on or off.

3.2 Implementation

The initial design of the String Walker included all the components listed above, except the voltage regulators and laser servos. The initial design had a steady laser that was not connected to the oscillating laser servo, and the drive servo received power directly from the Arduino Uno R3, as shown in figure 3.3.

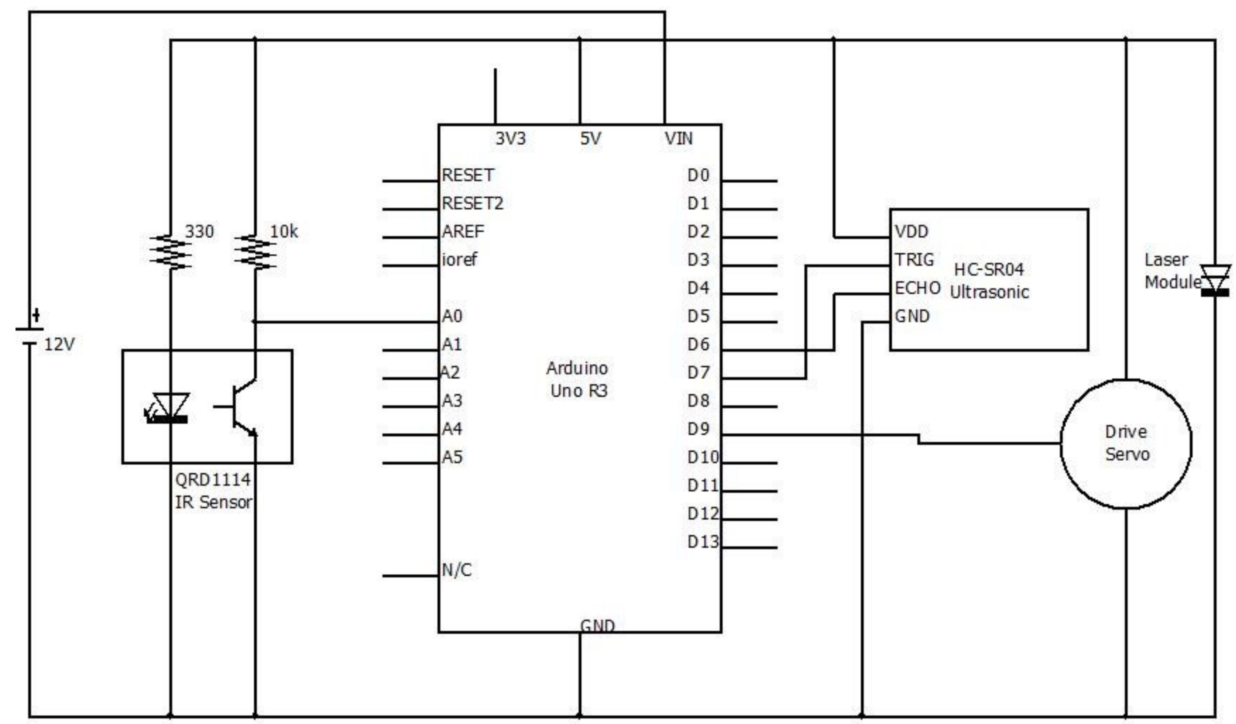


Figure 3.3: Initial String Walker Circuit Diagram

3.2.1 Initial Design Issues

There were two notable flaws with the first implementation. First, there is no hardware solution for setting the alignment of the system without triggering the device to move by tripping the ultrasonic sensor. Second, if the laser beam is not parallel to the optical axis of the lens on the Floor Walker, which focuses the laser onto the navigation sensor, the light will be focused away from the Floor Walker sensor. This issue is exacerbated by the nature of the system, which is to measure floor profiles. This means that the Floor Walker will be moving over slopes throughout the test area, changing the orientation of the lens and the optical axis. When this occurs, the laser signal to the Floor Walker is lost, causing it to deviate from its course.

3.2.2 Final Design

The problems in the initial design are addressed with the addition of an initialization pushbutton and oscillating the laser up and down to improve the odds of the laser beam being parallel to the optical axis. The oscillating laser will provide heading inputs to the Floor Walker consistently, despite the various slopes the Floor Walker will move over, but it does not provide constant headings. This leads to the Floor Walker deviating from the measurement line between laser headings. This issue is resolved by feeding gyroscope headings to the Floor Walker between laser headings. Additionally, the addition of a laser servo to oscillate the laser pushed the current draw over the capacity of the Arduino Uno R3. Therefore, the servos are powered directly from the battery through 5V regulators. The final design incorporates the solutions to the issues discovered in the initial design. The final circuit diagram is shown in figure 3.4. The cost per String Walker is approximately $240 and the cost per peripheral laser is around $57. This puts the cost of both String Walkers and both peripheral lasers around $493.

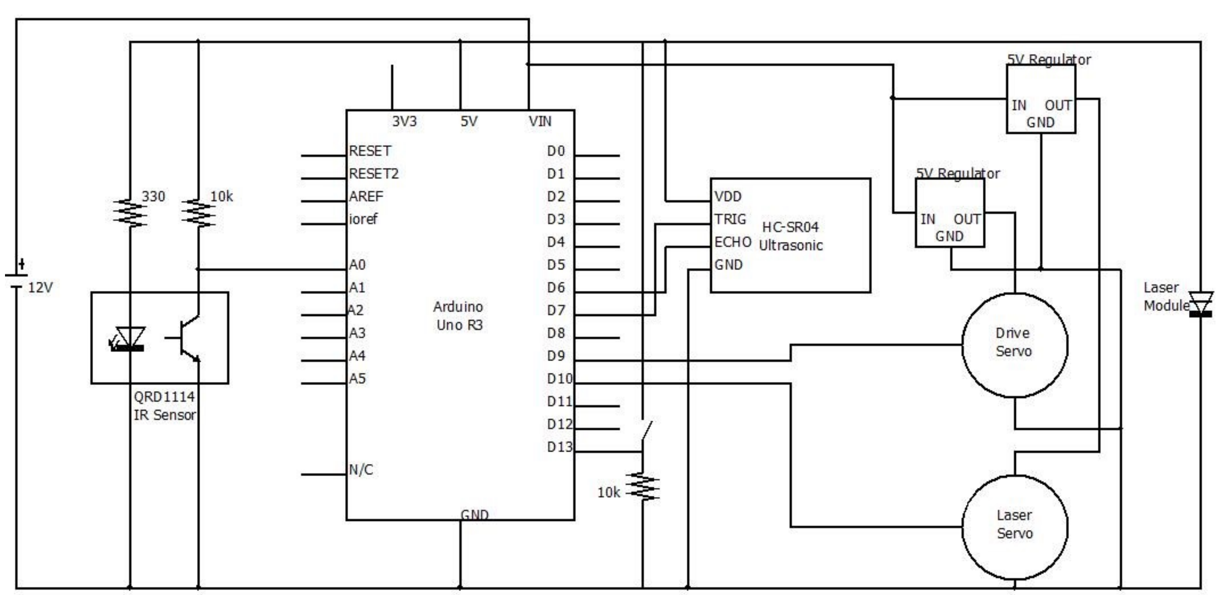


Figure 3.4: Final String Walker Design Circuit Diagram

Power analysis for the String Walker was conducted for each mode of operation:

- Idle mode – The device is powered on but only the pushbutton input is being monitored.
- Laser-tracking mode – In this mode, the laser servo is in constant use and the ultrasonic proximity sensor is constantly being checked, all other components are idle.
- Driving mode – In this mode, the drive servo is in use and the IR sensor is constantly being checked, all other components are idle.

Table 3.1 shows the power consumption of the String Walker in various modes of operation. The table contains current, power consumption, and battery life based on the 12V, 3000mAh battery. The battery life of the device ranges from 35 hours in a constant idle mode to 10.7 hours in a constant driving mode. The estimated battery life on normal operation is approximately 11.75 hours. The table also includes the current and power consumption if either the laser or drive servos stall. As expected, these values are much higher than normal operation.

Normal Operation	**Current Draw (mA)**	**Power (mW)**	**Battery Life (hrs)**
Idle	84.66666667	375.0833333	35.43307087
Laser Tracking	250	749.3166667	12
Driving	280.5	890.675	10.69518717
Weighted Avg	255.0833333	772.8763889	**11.76086246**
Stall Operation	**Current Draw (mA)**	**Power (mW)**	
Laser Tracking	591.6666667	3448.483333	
Driving	698.8333333	4704.008333	
Total	1290.5	8152.491667	

Table 3.1: Power analysis of the String Walker

3.3 Programming

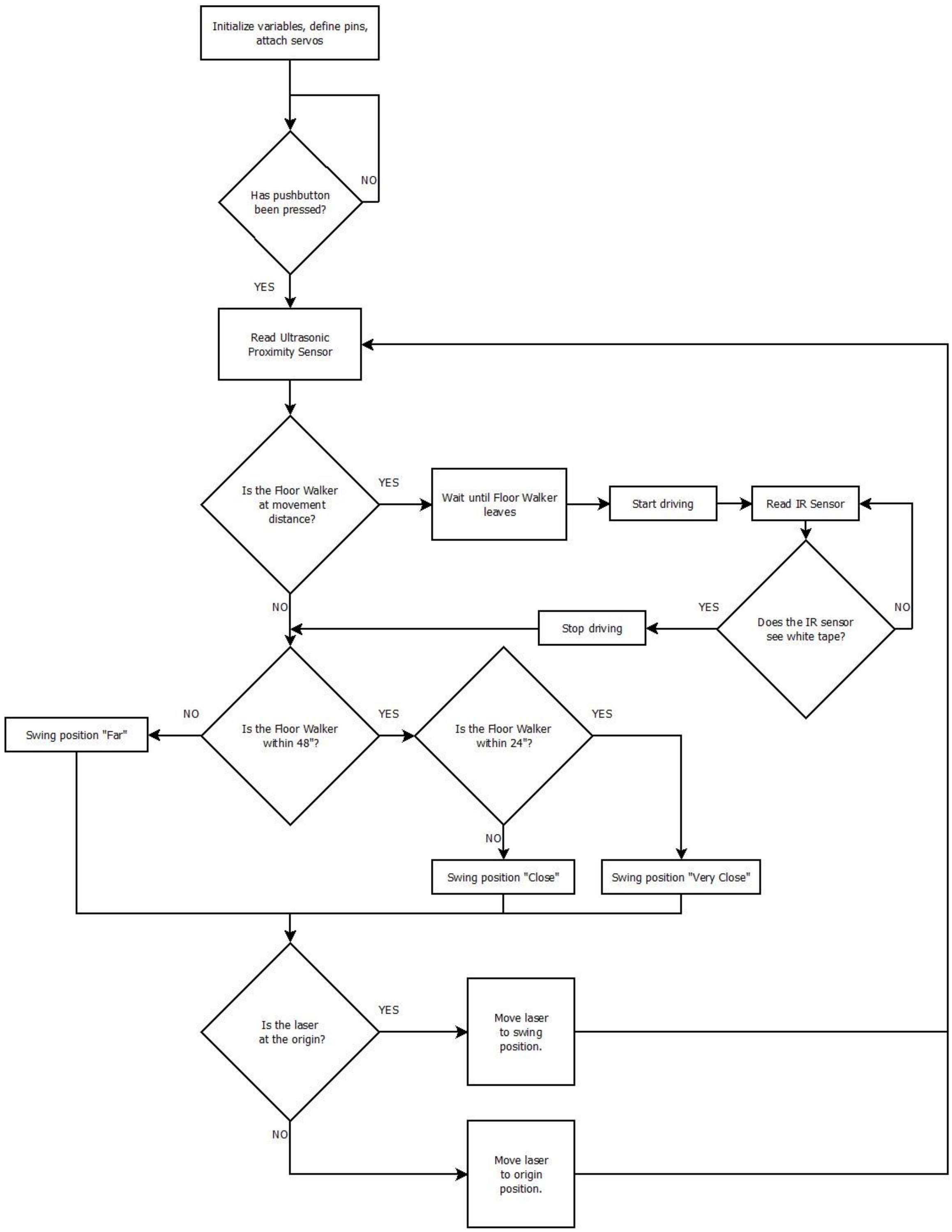


Figure 3.5: String Walker Program Flowchart

The String Walker program starts by initializing all variables, defining I/O pins, and attaching the servo motors. Next, it waits until the pushbutton has been pressed. This allows the user to align the system.

After the pushbutton has been pressed, the String Walker monitors the ultrasonic proximity sensor. It checks the distance to the Floor Walker. If the Floor Walker is not detected within 48", the laser swing angle is set to its long-distance value. Otherwise, the String Walker checks to see if the Floor Walker is within 24". The laser swing angle is set to the close-distance value if the distance is between 48 and 24", while it is set to the very-close-distance value if the distance is less than 24". The long-distance value is smaller to keep the movement of the laser at a distance to a minimum, while up-close, the value is larger to ensure that the laser sweeps the entire sensor on the Floor Walker. The laser continually oscillates between the origin and the swing angle until it is time to move.

If the ultrasonic sensors detect the Floor Walker within 6", the String Walker movement function begins. The String Walker will continue to monitor the ultrasonic sensors until it detects the Floor Walker outside of 6". Waiting for the Floor Walker to depart is a stop condition for the String Walker. If the Floor Walker remains within 6", the String Walker will be stationary.

Next, the drive servo starts pulling the String Walker to the next measurement line. While driving, the String Walker is monitoring the IR sensor, mounted on top of the device. The suspension line for the String Walker is black, therefore the IR sensor returns a value near 5V when it detects the line. At intervals of 18.5" are white strips of tape on the suspension line. This interval is determined by the width of the wheel base of the Floor Walker, 9.25". Each String Walker will move two measurement lines at a time. When the IR sensor detects white, it returns a value near 0V. Using this information, the String Walker will navigate. It stops moves when the IR sensor detects black and stops when the IR sensor detects white. Upon stopping, the device will resume checking the ultrasonic sensors.

The String Walker will loop through this program indefinitely. When the entire test area has been measured, the Floor Walker will be stopped within 6” of one String Walker, which will be stationary. The other String Walker will be in line with the first with the laser oscillating. The stop position of the system is shown in figure 3.6.

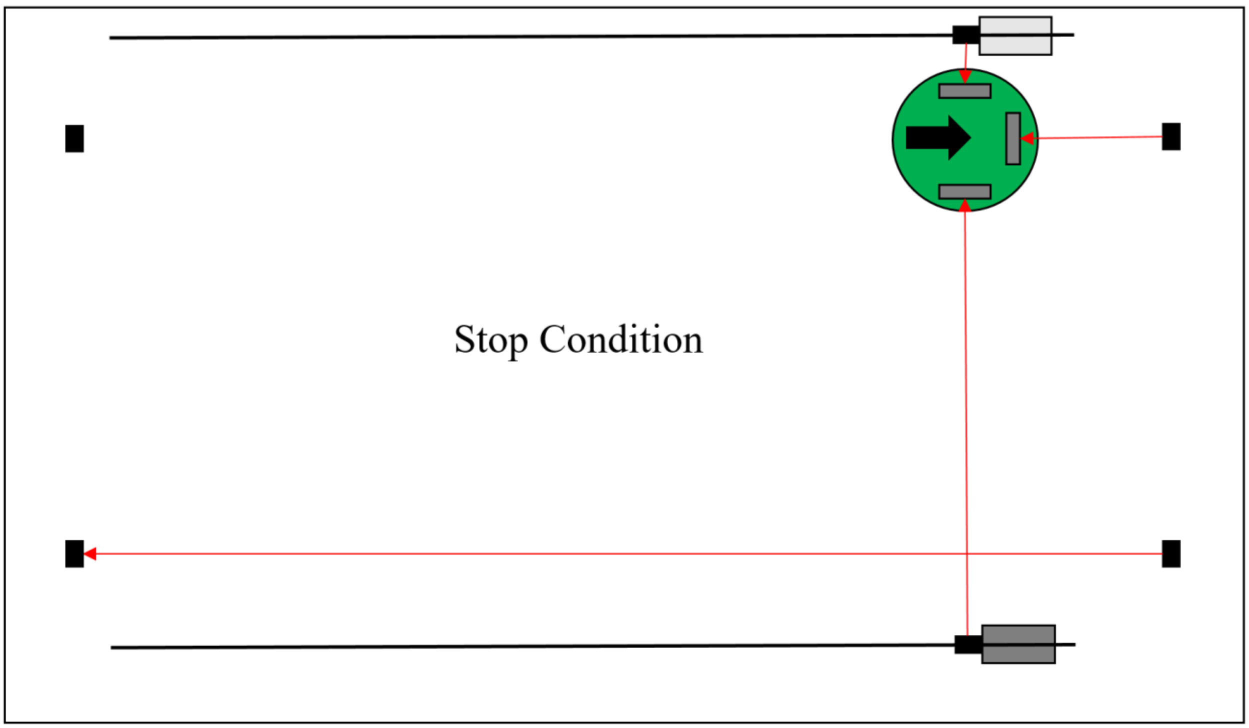


Figure 3.6: System stop position

3.4 System Setup

The system is configured as shown in figure 3.7. The suspension lines run parallel to each other with the desired distance between lines. String Walker 1 is positioned on the first measurement line with the spool line strung as shown in figure 3.8. String Walker 2 starts on the second measurement line, 9.25” from the first measurement line. The spool line is run as shown in figure 3.8. The peripheral lasers are mounted with the beam parallel to the suspension line as shown in figure 3.7. The distance from the beam to the front of the String Walker is 10”. The Floor Walker starting position is in the lower left corner of the test area. It will be aligned with String Walker 1 and the peripheral laser as shown in figure 3.7. Once all devices are in position, the lasers are aligned using the mirror mount alignment screws. After alignment, the system is ready.

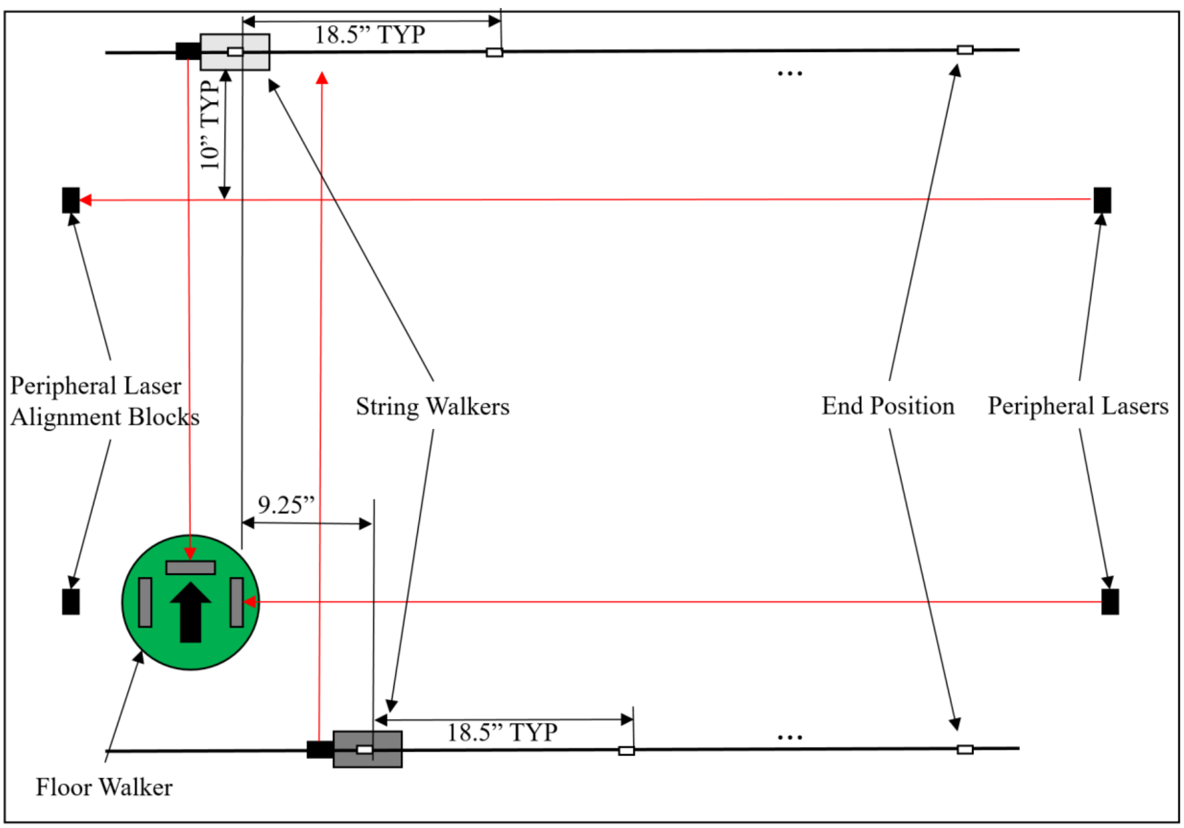


Figure 3.7: System configuration

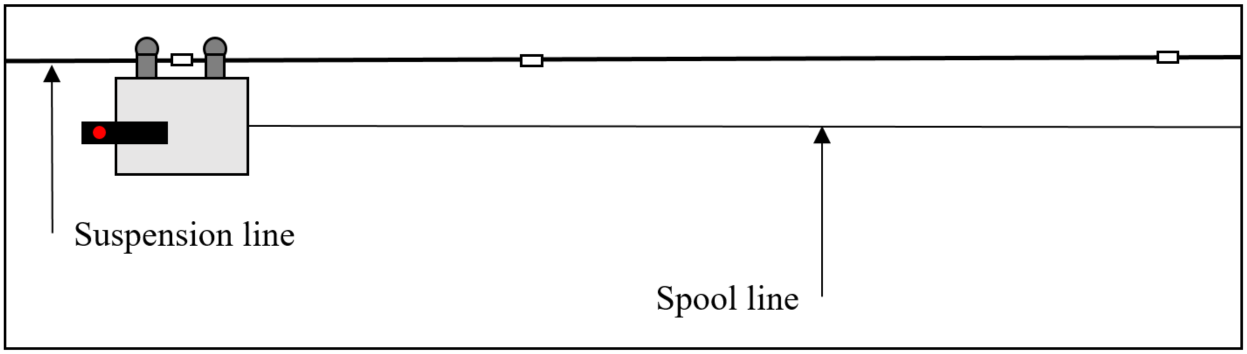


Figure 3.8: Spool line and Suspension line illustration

4. Results

4.1 System Analysis

4.1.1 Procedure

The results are obtained from experimental testing with consistent procedures. The testing is designed to determine straightness from three methods of navigation, gyroscope feedback, laser guidance, and laser-gyroscope combination navigation.

1) Start the setup by obtaining or creating 10 continuous feet of white paper. Draw a straight line from one end of the paper to the other. Mark the line in 4” increments, starting at 0” and ending at 120”.
2) Setup the String Walker at one end of the line, ensuring enough distance between the end of the line and the String Walker to accommodate the Floor Walker.
    a. Align the String Walker with the line by turning the device on and rotating it back and forth on the suspension line making sure the laser remains on the line from start to finish.
    b. Steady the String Walker on the suspension line and press the pushbutton.
3) Place the Floor Walker opposite the String Walker with the back at the edge of the paper strip. Use the oscillating laser and straight line to align the Floor Walker
4) Once aligned, attach a marker to the back of the Floor Walker. Ensure that the marker is placed directly in the center, using the laser and straight line.
    a. The marker must be placed in the same position for every trial.

5) Turn the Floor Walker on by pressing the center pushbutton and flipping the white switch.

6) Allow the Floor Walker to drive to the String Walker. Once the Floor Walker has driven to the end of the paper strip and before it reaches the String Walker, stop it.

7) Starting at 0”, measure the displacement from the straight line to the line drawn by the Floor Walker with a measuring tool. Take measurements every 4”. Displacement to the right of the straight line is negative, to the left is positive.

8) Run as many trials as desired, replacing the white paper every five trials to avoid cluttering.

The experimental setup is shown in figure 4.1.

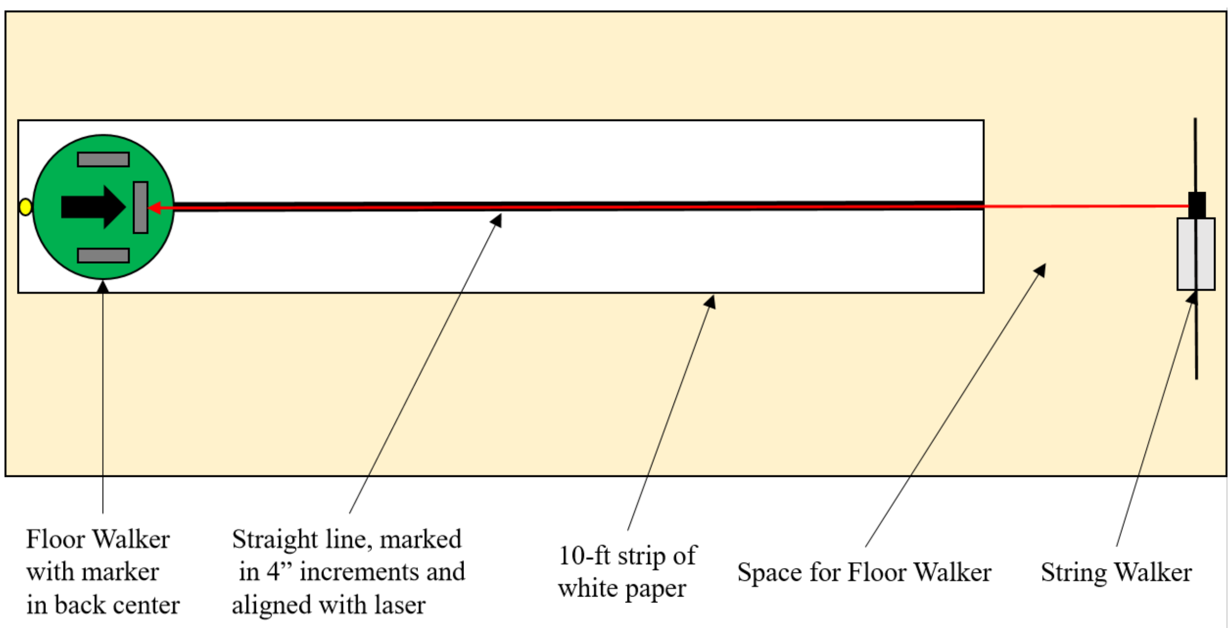


Figure 4.1: Experimental Setup

4.1.2 Gyroscope

Figures 4.2-4.4 show fifteen trials of Floor Walker displacement from the straight-line path using the gyroscope-feedback navigation method. This method is the original navigation method from the autonomous floor profiler. The graphs are split into three groups of five trial. They cover the entire 10-ft path. The graphs include the displacement, Gaussian distribution, standard deviation, and mean for all five trials in each group. Figure 4.5 shows the total Gaussian distribution, standard deviation, and mean for all trials. Table 4.1 includes the mean and standard deviation for all trials.

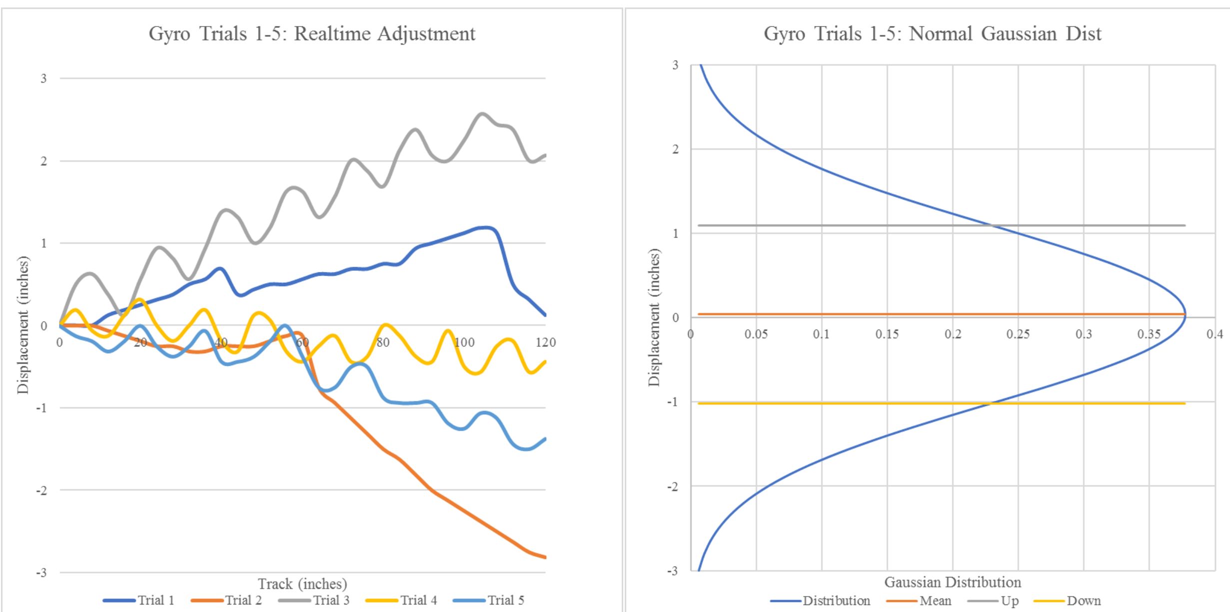


Figure 4.2: Gyroscope feedback, straight-line driving, trials 1-5, displacement and Normal Gaussian distribution. The mean displacement is 0.0383” and the standard deviation is 1.058”.

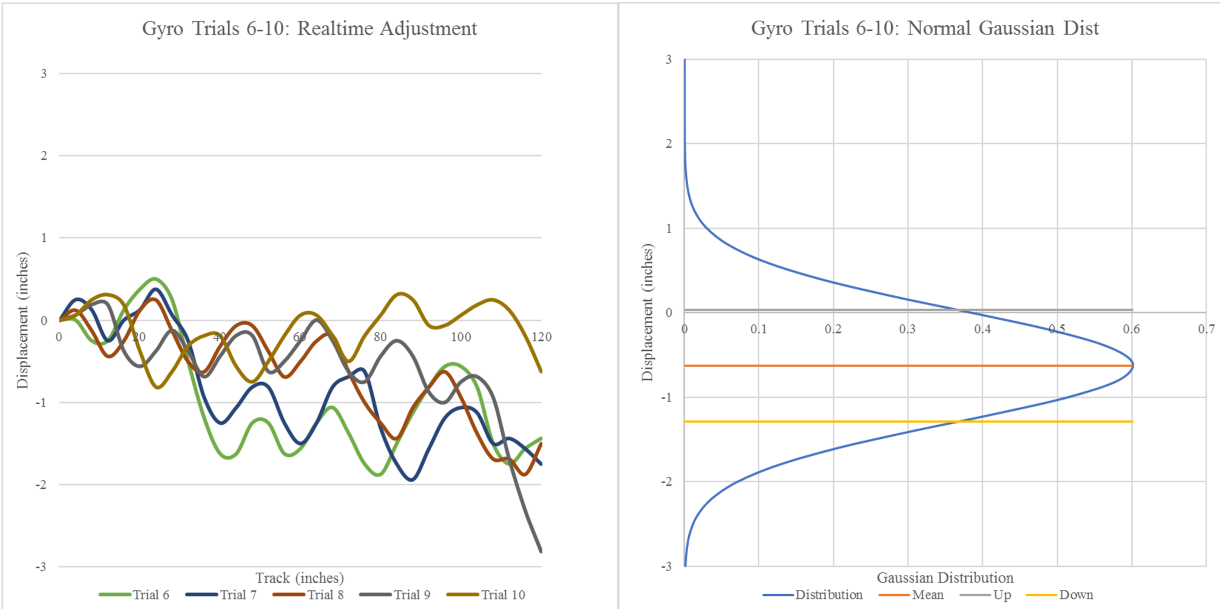


Figure 4.3: Gyroscope feedback, straight-line driving, trials 6-10, displacement and Normal Gaussian distribution. The mean displacement is -0.63” and the standard deviation is 0.664”.

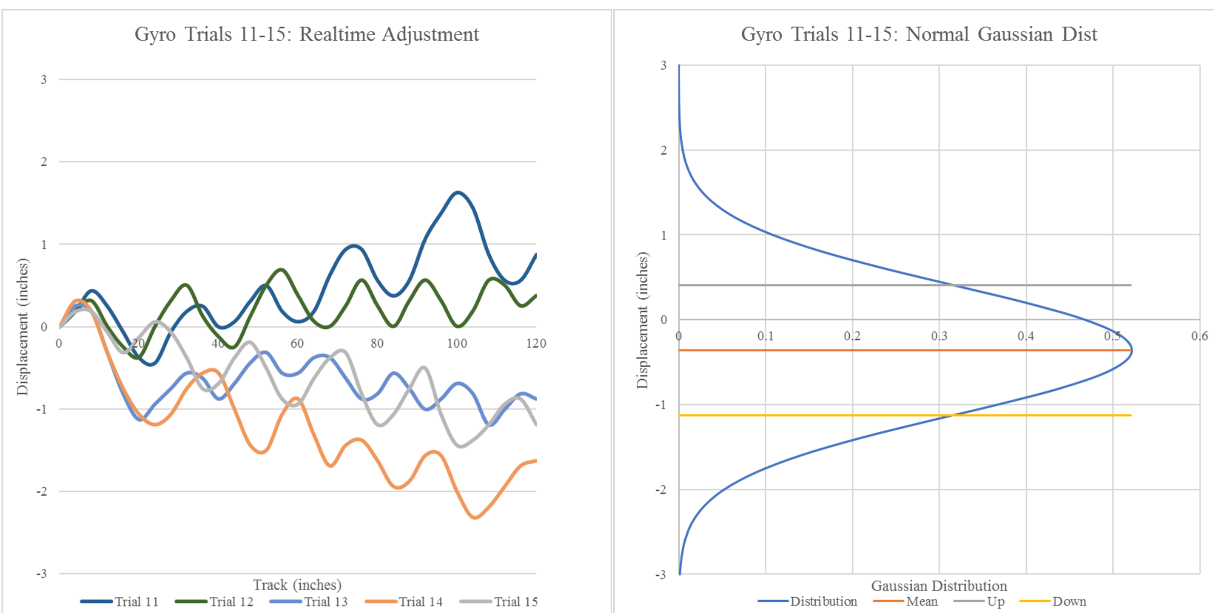


Figure 4.4: Gyroscope feedback, straight-line driving, trials 11-15, displacement and Normal Gaussian distribution. The mean displacement is -0.359” and the standard deviation is 0.765”.

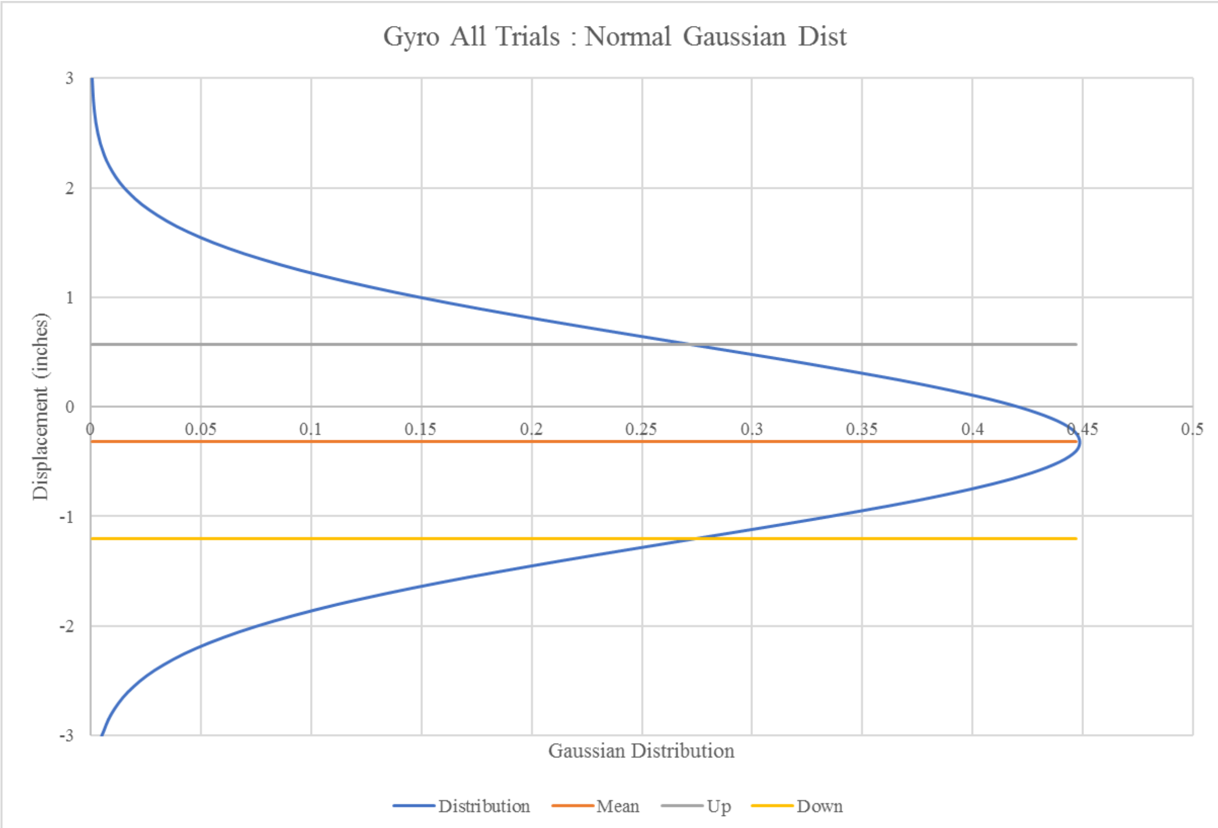


Figure 4.5: Standard deviation and mean for all gyroscope trials. The mean displacement is -0.317" and the standard deviation is 0.765".

Trial	Mean, μ	Standard Deviation, σ^2	$\mu + \sigma^2$	$\mu - \sigma^2$
1	0.5444	0.336832355	0.881	0.21
2	-1.006	0.978647391	-0.03	-1.98
3	1.4274	0.727154885	2.155	0.7
4	-0.1714	0.234374458	0.063	-0.41
5	-0.6028	0.457505835	-0.15	-1.06
5 Trial	**0.0383**	**1.057885785**	**1.096**	**-1.02**
6	-0.9294	0.705097714	-0.22	-1.63
7	-0.8629	0.664179125	-0.2	-1.53
8	-0.6411	0.589510061	-0.05	-1.23
9	-0.5827	0.647262204	0.065	-1.23
10	-0.1331	0.322126697	0.189	-0.46
5 Trial	**-0.63**	**0.663588405**	**0.034**	**-1.29**
11	0.4536	0.494671135	0.948	-0.04
12	0.2036	0.262282812	0.466	-0.06
13	-0.6371	0.338781674	-0.3	-0.98
14	-1.2177	0.662174861	-0.56	-1.88
15	-0.5968	0.461151781	-0.14	-1.06
5 Trial	**-0.359**	**0.765196801**	**0.406**	**-1.12**
Total	**-0.317**	**0.888981035**	**0.572**	**-1.21**

Table 4.1: Gyroscope navigation trial data

The overall standard deviation is 0.89” and the overall mean is -0.317”. This indicates that approximately 68% of the time the Floor Walker is in the range 0.572” – (-1.21)” relative to the desired straight-line. The worst displacement measured at the 10-ft mark was nearly 3” from the centerline. This is due to the difficulty of alignment and sensor drift. If the device were to continue this trajectory for a longer test line, the displacement would be greater. For instance, if the line were 50-ft the displacement would be close to 15”. This would cross over the next measurement line in the test area and corrupt the results of the profile.

4.1.3 Laser

Figures 4.6-4.8 show fifteen trials of Floor Walker displacement from the straight-line path using the laser-tracking navigation method. This method replaces the gyroscope navigation method in the autonomous floor profiler. The graphs are split into three groups of five trial. They cover the entire 10-ft path. The graphs include the displacement, Gaussian distribution, standard deviation, and mean for all five trials in each group. Figure 4.9 shows the total Gaussian distribution, standard deviation, and mean for all trials. Table 4.2 includes the mean and standard deviation for all trials.

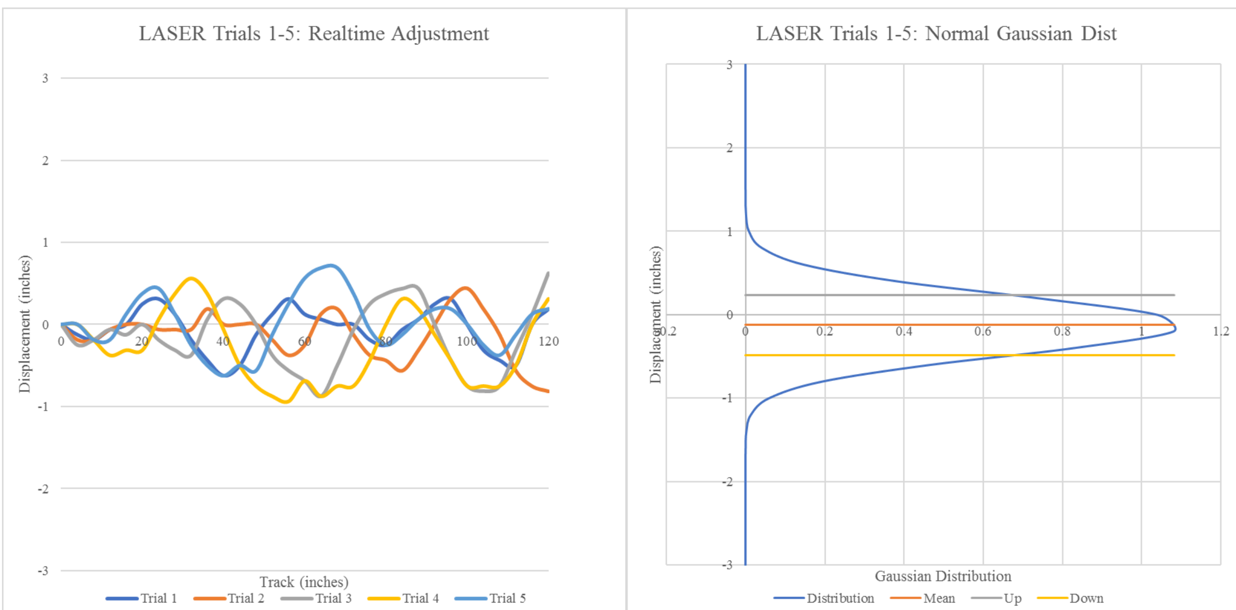


Figure 4.6: Laser-tracking, straight-line driving, trials 1-5, displacement and Normal Gaussian distribution. The mean displacement is -0.125" and the standard deviation is 0.362".

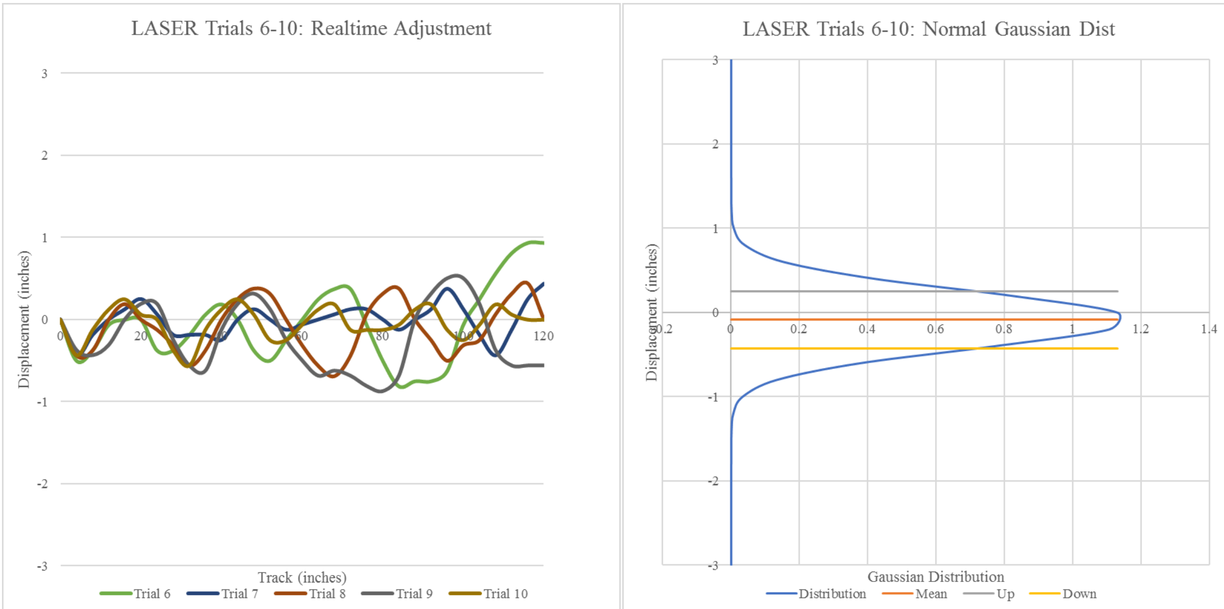


Figure 4.7: Laser-tracking, straight-line driving, trials 6-10, displacement and Normal Gaussian distribution. The mean displacement is -0.088” and the standard deviation is 0.342”.

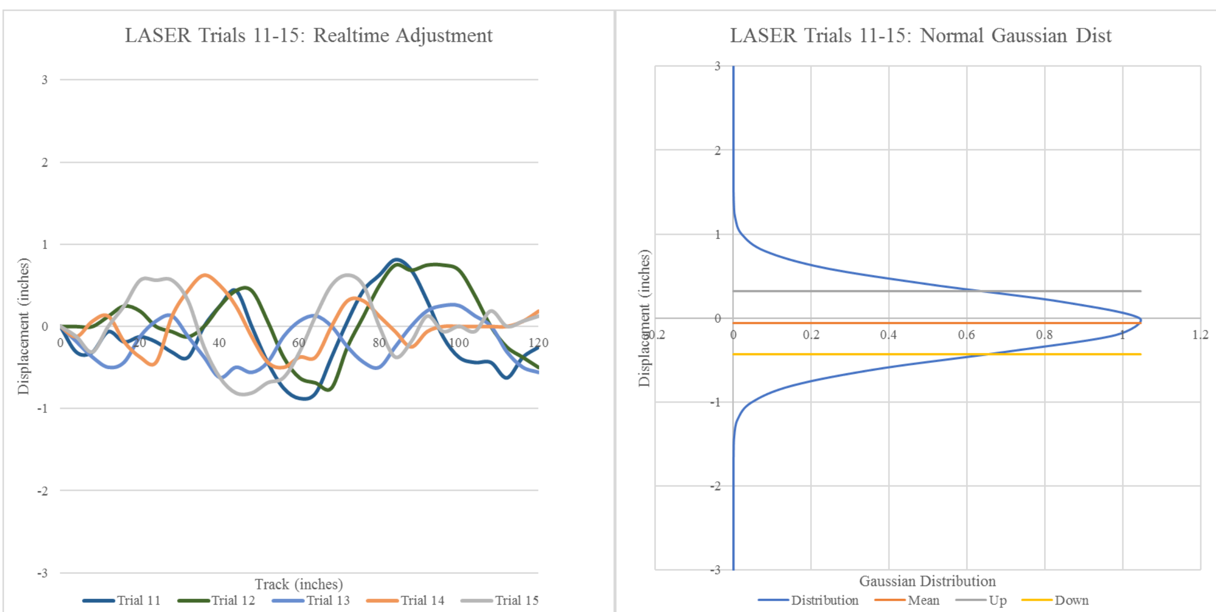


Figure 4.8: Laser-tracking, straight-line driving, trials 11-15, displacement and Normal Gaussian distribution. The mean displacement is -0.056” and the standard deviation is 0.38”.

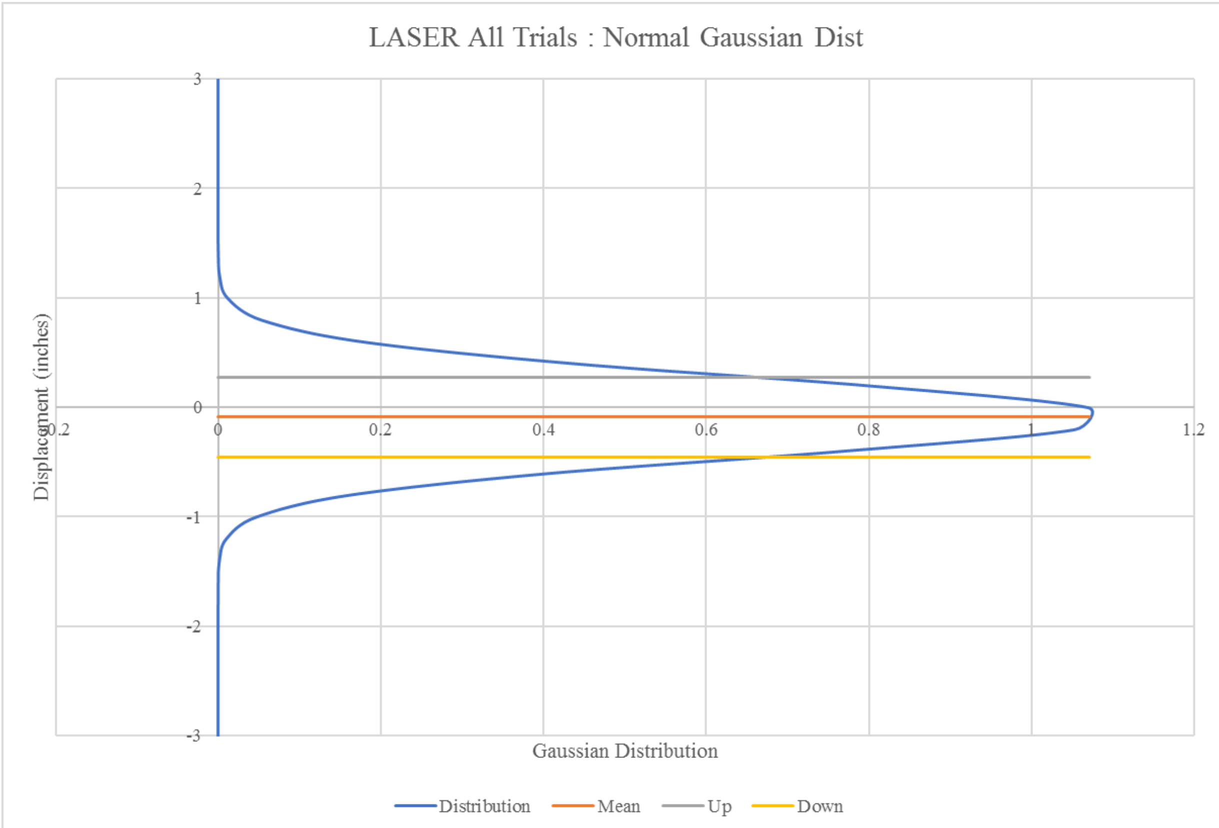


Figure 4.9: Standard deviation and mean for all laser trials. The mean displacement is -0.09” and the standard deviation is 0.362”.

Trial	Mean, μ	Standard Deviation, σ^2	$\mu + \sigma^2$	$\mu - \sigma^2$
1	-0.0605	0.252249892	0.192	-0.31
2	-0.131	0.285023891	0.154	-0.42
3	-0.1532	0.395233288	0.242	-0.55
4	-0.2883	0.432044739	0.144	-0.72
5	0.0081	0.341125219	0.349	-0.33
5 Trial	**-0.125**	**0.361518415**	**0.237**	**-0.49**
6	-0.0585	0.463902484	0.405	-0.52
7	-0.0101	0.198974674	0.189	-0.21
8	-0.0907	0.314645342	0.224	-0.41
9	-0.2379	0.399539602	0.162	-0.64
10	-0.0423	0.195969401	0.154	-0.24
5 Trial	**-0.0879**	**0.341567247**	**0.254**	**-0.43**
11	-0.1331	0.421134561	0.288	-0.55
12	0.0766	0.422021608	0.499	-0.35
13	-0.1935	0.268637373	0.075	-0.46
14	-0.006	0.276496496	0.27	-0.28
15	-0.0242	0.405567795	0.381	-0.43
5 Trial	**-0.056**	**0.37802371**	**0.322**	**-0.43**
Total	**-0.0897**	**0.361776826**	**0.272**	**-0.45**

Table 4.2: Laser navigation trial data

The overall standard deviation is 0.362” and the overall mean is -0.09”. This indicates that approximately 68% of the time the Floor Walker is in the range 0.272” – (-0.45)” relative to the desired straight-line. The worst-case displacement at 10-ft is nearly 1”. This improvement over the gyroscope navigation method is due to ease in alignment and lack of sensor drift. Where the gyroscope navigation was prone to alignment errors, the use of the String Walker with peripheral lasers makes the laser navigation alignment simple and reliable. In all cases, the displacement from the centerline is consistent. This implies that even at longer distances the device will remain near the centerline. The size of the standard deviation is due to the lack of constant laser signal.

The oscillating laser provides frequent signals to the Floor Walker over all distances and floor pitches, but not a constant signal. This results in periods of time where the Floor Walker is driving without navigation data, resulting in error.

4.1.4 Laser-Gyroscope Combination

Figures 4.10-4.13 show fifteen trials of Floor Walker displacement from the straight-line path using the laser-gyroscope hybrid navigation method. This method replaces both the gyroscope and individual laser navigation methods in the autonomous floor profiler. The graphs are split into three groups of five trial. They cover the entire 10-ft path. The graphs include the displacement, Gaussian distribution, standard deviation, and mean for all five trials in each group. Figure 4.9 shows the total Gaussian distribution, standard deviation, and mean for all trials. Table 4.2 includes the mean and standard deviation for all trials.

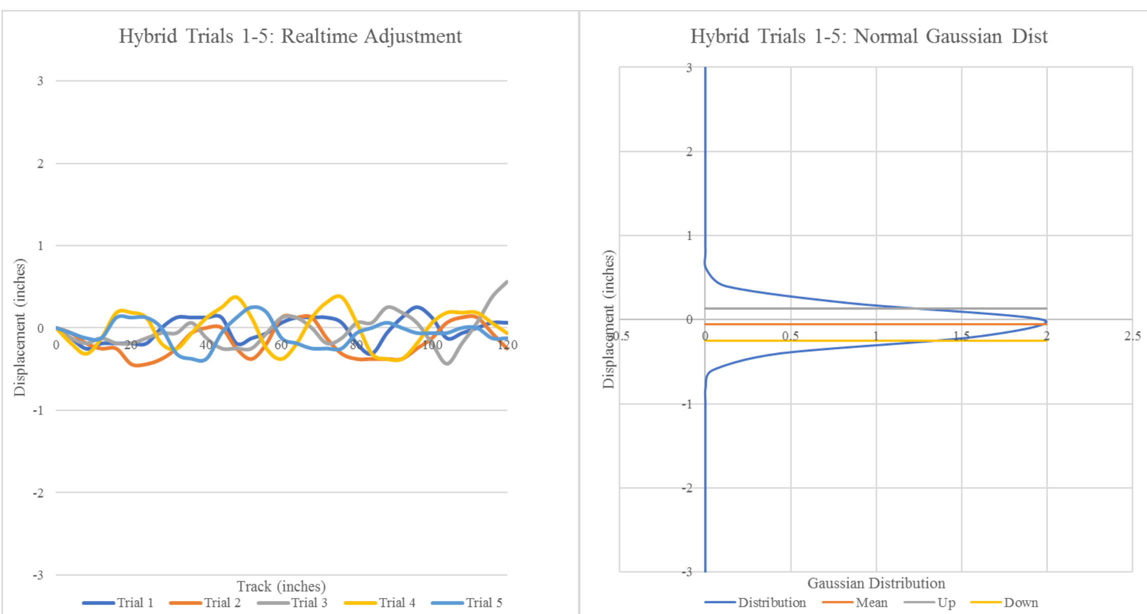


Figure 4.10: Laser-Gyroscope Hybrid, straight-line driving, trials 1-5, displacement and Normal Gaussian distribution. The mean displacement is -0.059” and the standard deviation is 0.193”.

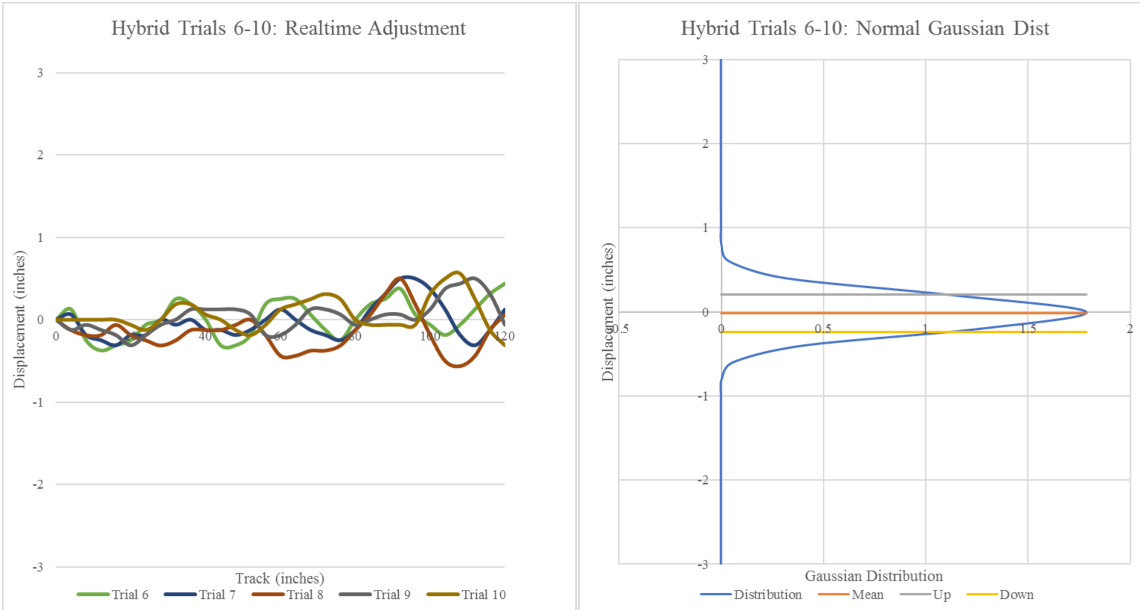


Figure 4.11: Laser-Gyroscope Hybrid, straight-line driving, trials 6-10, displacement and Normal Gaussian distribution. The mean displacement is -0.015” and the standard deviation is 0.223”.

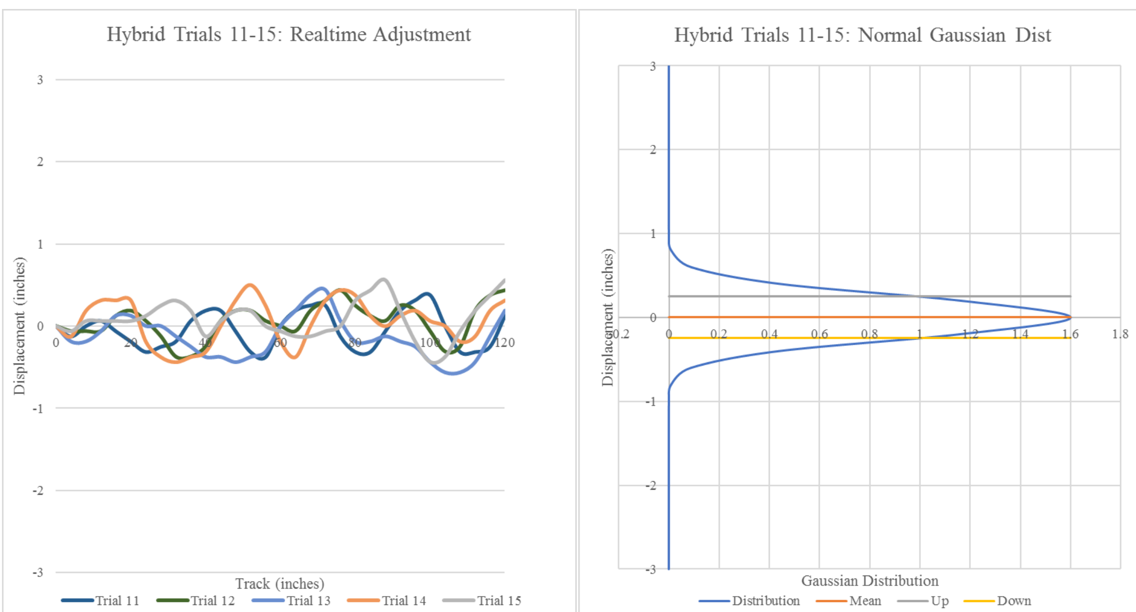


Figure 4.12: Laser-Gyroscope Hybrid, straight-line driving, trials 11-15, displacement and Normal Gaussian distribution. The mean displacement is 0.0016” and the standard deviation is 0.249”.

Figure 4.13: Standard deviation and mean for all hybrid trials. The mean displacement is -0.0243” and the standard deviation is 0.224”.

Trial	Mean, μ	Standard Deviation, σ^2	$\mu + \sigma^2$	$\mu - \sigma^2$
1	-0.0202	0.143216134	0.123	-0.16
2	-0.1633	0.185593411	0.022	-0.35
3	-0.0383	0.199973171	0.162	-0.24
4	-0.0101	0.226794354	0.217	-0.24
5	-0.0645	0.154309622	0.09	-0.22
5 Trial	**-0.0593**	**0.192578214**	**0.133**	**-0.25**
6	0.0101	0.222871187	0.233	-0.21
7	-0.0262	0.21344323	0.187	-0.24
8	-0.1593	0.228863949	0.07	-0.39
9	0.0363	0.184296692	0.221	-0.15
10	0.0625	0.193127903	0.256	-0.13
5 Trial	**-0.0153**	**0.223194135**	**0.208**	**-0.24**
11	-0.0444	0.21486677	0.171	-0.26
12	0.0544	0.216356104	0.271	-0.16
13	-0.1371	0.249707165	0.113	-0.39
14	0.0524	0.262344796	0.315	-0.21
15	0.0827	0.230809354	0.313	-0.15
5 Trial	**0.0016**	**0.249288138**	**0.251**	**-0.25**
Total	**-0.0243**	**0.224367133**	**0.2**	**-0.25**

Table 4.3: Hybrid navigation trial data

The overall standard deviation is 0.224” and the overall mean is -0.0243”. This indicates that approximately 68% of the time the Floor Walker is in the range 0.2” – (-0.25)” relative to the desired straight-line. The worst-case displacement at 10-ft is just over 0.5”. This method is greatly improved over both the gyroscope and laser navigation methods on their own. The benefits of the laser navigation method are included but the issue of not having a constant laser signal is resolved by filling the gaps in laser headings with gyroscope headings. The hybrid method prioritizes the laser input but when the laser is not detected, the gyroscope heading is used. This prevents the device from veering off course between laser headings. In all cases, the displacement from the centerline is consistent and smaller than both the gyroscope and laser navigation methods. Like the laser navigation method, at longer distances the device will remain near the centerline.

The standard deviation of the hybrid method is very small compared to the original gyroscope navigation but it is not zero. The deviation from the centerline is within acceptable tolerances, however, when considering the Dipstick. Since the Dipstick is manually operated, it is prone to human error. It is easy to imagine the Dipstick operator not placing the device exactly on the line they are aiming for. Additionally, the Dipstick is positioned on two circular feet, reducing the precision of placement. This deviation may be very small, no more than a quarter of an inch, but still an error. Furthermore, an operator may not place the device identically on the same measurement line on multiple trials and different operators may place the device differently, compounding the error. The laser-gyroscope hybrid navigation system has a standard deviation of less than a quarter of an inch, which is comparable to the expected error using the Dipstick.

4.2 String Walker Analysis

4.2.1 Laser Oscillation Angle

The laser oscillation angles were selected based on the ability of the Floor Walker to read the laser input at various distances and the ability of the laser to effectively impact the sensor at various distances. The frequency of oscillation remains constant throughout the navigation process, despite the angle of oscillation. This frequency is approximately 8 Hz.

While the frequency remains the same, the speed that the laser passes the Floor Walker at various distances changes. For instance, the laser movement at 12-inches with a 1° oscillation angle is 0.209", resulting in a laser movement speed of 0.838"/second. The same angle at 120" results in a laser movement of 2.09" and a laser movement speed of 8.38"/second. These values increase with increased angles.

$$d_{12"} = 2 * \tan(1/2°) * 12" = 0.209"$$

$$Speed_{12"} = d_{12"} * \frac{8Hz}{2} = 0.838"/second$$

$$d_{120"} = 2 * \tan(1/2°) * 120" = 2.09"$$

$$Speed_{120"} = d_{120"} * \frac{8Hz}{2} = 8.38"/second$$

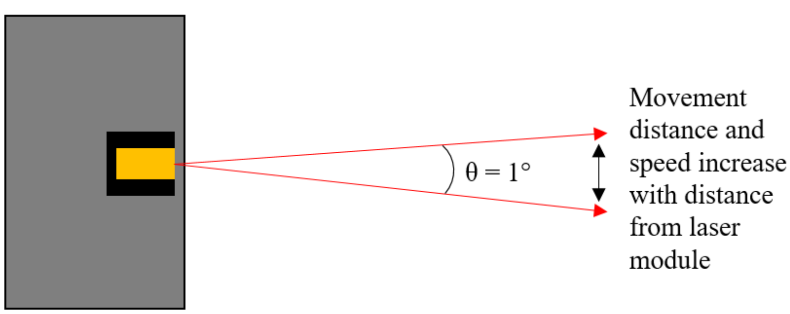


Figure 4.14: Laser oscillation illustration

Due to the distance and speed considerations, various angles were tested and quantified to optimize the system performance. Table 4.4 shows the results of these tests. The table includes the tested angle, the distance from the String Walker to the Floor Walker, the number of times the Floor Walker detected the laser in 10 seconds, the distance and speed the laser moved at various distances for each angle, and the range each angle will useful.

Angle (degrees)	Distance (ft)	Laser Count (10 sec)	Laser Movement (in)	Laser Speed (in/s)	Range (ft)
3	10	25	6.284615866	25.13846346	0-2
	8	32	5.027692693	20.11077077	
	6	34	3.770769519	15.08307808	
	4	33	2.513846346	10.05538539	
	2	35	1.256923173	5.027692693	
	1	36	0.628461587	2.513846346	
2	10	30	4.189212044	16.75684817	2-4
	8	34	3.351369635	13.40547854	
	6	36	2.513527226	10.0541089	
	4	34	1.675684817	6.70273927	
	2	35	0.837842409	3.351369635	
	1	0	0.418921204	1.675684817	
1	10	34	2.094446501	8.377786002	4-10
	8	38	1.6755572	6.702228802	
	6	39	1.2566679	5.026671601	
	5	42	1.04722325	4.188893001	
	4	33	0.8377786	3.351114401	
	2	0	0.4188893	1.6755572	

Table 4.4: Laser oscillation angle test results

From this table, the larger the angle and the larger the distance from String Walker to Floor Walker, the faster and further the laser moves. This becomes an issue for the Floor Walker to detect the laser. Also, if the angle is too small, the laser will not impact the sensor at all. This leads to the useful range for each angle. The 3° angle is used from 0-2-ft, the 2° angle is used from 2-4-ft, and the 1° angle is used from 4-10-ft. The keeps the laser movement speeds low enough for detection as well as increasing the laser movement distance at close ranges to ensure sensor impact.

4.2.2 Movement Distance

One of the critical functions of the String Walker is autonomous movement. This is accomplished by using a drive servo for movement and an IR sensor for detecting where to stop. This movement must be precise to ensure accurate measurement lines across the test area. When the String Walker moves, it will drive 18.5”, then stop. To test this, the device was powered on and the initial laser position was recorded. The device was flagged for movement, and the position of the laser was recorded when it stopped. The difference of these positions is the movement distance. 15 trials were performed.

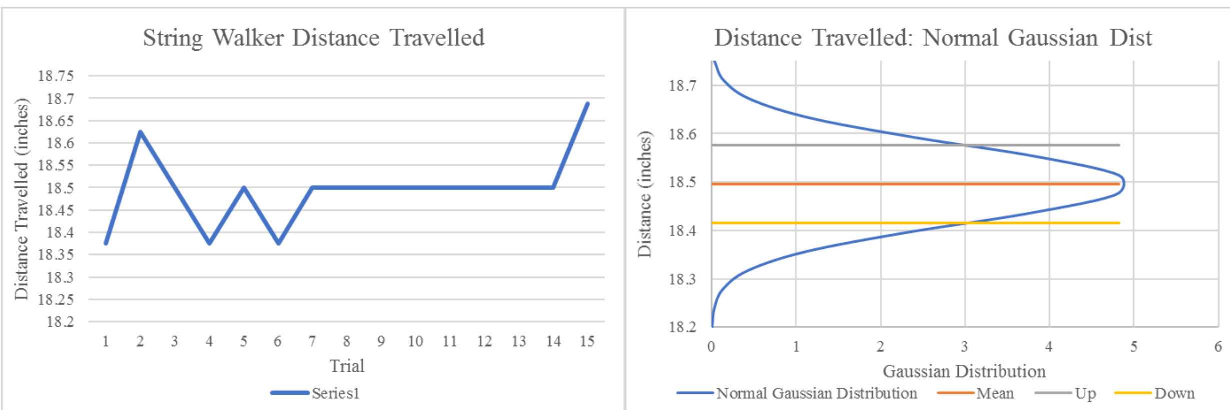


Figure 4.15: String Walker distance travelled, trials 1-15, distance and normal Gaussian distribution. The mean displacement is -0.059” and the standard deviation is 0.193”.

Trial	Start Position (in)	End Postion (in)	Distance (in)
1	35.375	17	18.375
2	35.375	16.75	18.625
3	35.375	16.875	18.5
4	35.375	17	18.375
5	35.375	16.875	18.5
6	35.375	17	18.375
7	35.375	16.875	18.5
8	35.375	16.875	18.5
9	35.375	16.875	18.5
10	35.375	16.875	18.5
11	35.375	16.875	18.5
12	35.375	16.875	18.5
13	35.375	16.875	18.5
14	35.375	16.875	18.5
15	35.375	16.6875	18.6875
		Mean	18.49583333
		Standard Deviation	0.080579498
		Mean+	18.57641283
		Mean-	18.41525383

Table 4.5: String Walker distance travelled test results

All trials started at the same point and travelled to the next measurement line, 18.5” from the first. The average distance travelled by the String Walker is 18.496” with a standard deviation of 0.081” across 15 trials. The device will stop movement after 18.42”-18.58”, 68% of the time. The minimum distance travelled is 18.375”, while the maximum is 18.6875”. If combined with the standard deviation from a straight-line path using the laser-gyroscope hybrid navigation method, the deviation from a straight-line would be approximately 0.3”. One can argue that the error with this method could be comparable to the expected error using the Dipstick.

5. Conclusion and Future Work

5.1 Conclusions

The proposed laser-gyroscope hybrid navigation system for the automated floor profiler has been tested as whole by measuring displacement from a straight-line using the Floor Walker and String Walker, as shown in section 4.1. The test indicates that the system can utilize laser guidance to autonomously navigate and profile a floor. The Floor Walker maintains a standard deviation of 0.224” from the straight-line as it is guided through the test area by the String Walker and peripheral lasers. This is a vast improvement over the original gyroscope navigation, which has a standard deviation of 0.765”. Additionally, the system maintains its autonomy by operating without user interference for the duration of the measurement process.

The oscillation angles and travel distance of the String Walker have been tested as mentioned in section 4.2. The String Walker intelligently adjusts oscillation angles based on distance to the Floor Walker to provide a navigation signal to the Floor Walker. The device move across the test area in consistent increments to provide accurate measurement lines for floor profiling.

5.2 Future Work

While the addition of a laser guided navigation system makes the autonomous floor profiler more precise, there are some areas for improvement;

- The addition of a topographic floor profile map, similar to a contour map, to the data analysis software would provide a better big picture perspective of the test area.

- The current autonomous floor profiler is built off an iRobot Create 2 platform. The points of contact for the Create 2 are 5” apart, front to back, and 9.25” apart, side to side. This requires a method of forming the recorded data into 12” data points. The method used previous is weighted averaging. A new robot platform with points of contact 6” or 12” apart would make the data analysis simpler and remove error from weighted averaging.
- A study exploring the variations in Dipstick measurement would be useful for analyzing the effectiveness of the autonomous floor profiler. The study would require multiple operators measuring a test area multiple times. Comparisons would be made on variations in measurement across the trials for each operator and variations in measurement across operators.

In summary, the research conducted in this thesis is a proof-of-concept of a laser guided navigation system for an autonomous floor profiler that maintains the autonomy of the device while providing precise and accurate navigation through a floor space. This system makes the autonomous floor profiler a possible competitor to devices such as the Dipstick and F-meter.

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