**Testing Document**

**Project:** ECSE211 Design Project – Capture the Flag

**Task:** Construct an autonomous robot that can play one-on-one version of the game Capture the Flag

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| Nov. 17, 2017 | Priscilla | All | Compiled tests into one document and updated format to increase readability |
| Nov. 17, 2017 | Priscilla | Beta Demo Tests | Added Sample Calculations |
| Nov, 20, 2017 | Paarth | Final Integration Tests | Added Navigation to Zip line test |
| Nov, 20, 2017 | Paarth | Final Integration Tests | Added Zip line traversal test |

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1. **Component Tests**

**2.1 Best Ultrasonic Sensor**

**Performed by:** Priscilla

**Software used:** Version 1.0

Classes used: Main, Test

**Hardware used:** Minimal Design consisting of the EV3 Brick, 2x EV3 Motors, the Ultrasonic Sensor and a few connector pieces. (See Figure 2.1.1 and Figure 2.1.2 below)

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Left - *Figure 2.1.1: Top View*, Right - *Figure 2.1.2: Front View*

**Purpose:** Determine which ultrasonic sensor(s) to use in the final mechanical design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Place the robot facing parallel to a wall at a distance of 15 cm away
2. Instruct the robot to drive forward for 10 seconds while sampling the sensor value every 0.1 seconds. Display the sensor values on the console
3. Record the sensor values
4. Repeat Steps 1 through 3 for each sensor with three trials per sensor

**Expected Outcomes:** The measured sensor values are expected to have outliers and contain noise. However, the different sensors should have varying levels of noise and thus, precision.

**Results:** See Section “10.1 Ultrasonic Sensor Data” of the *Appendix* for the data collected from each trial

|  |  |  |
| --- | --- | --- |
| **Sensor Number** | **Trial Number** | **Mean (cm)** |
| **1** | 1 | 18.28 |
| 2 | 15.71 |
| 3 | 17.71 |
| Average | 17.23 |
| **2** | 1 | 16.28 |
| 2 | 16.00 |
| 3 | 15.32 |
| Average | 15.87 |
| **3** | 1 | 14.69 |
| 2 | 15.62 |
| 3 | 14.59 |
| Average | 14.97 |

*Sample Calculations, Sensor 1:*

**Observations and Conclusions:** Based on the data collected, Sensor 3 is the most accurate out of the three. All of the data collected from the sensors did contain noise and outliers but one proved to have less than the others. Therefore, this test was a success and Sensor 3 must be used in the final Mechanical Design.

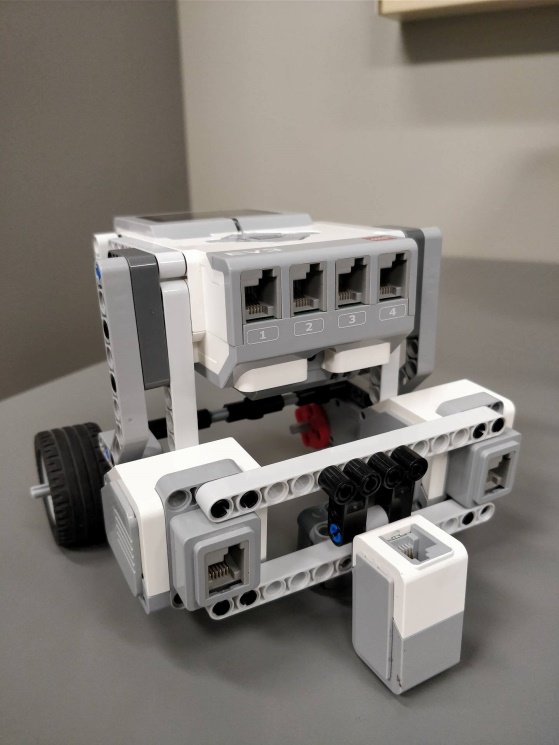
**2.2 Best Light Sensor**

**Performed by:** Priscilla

**Software used:** Version 1.0

Classes used: Main, Test

**Hardware used:** Minimal Design consisting of the EV3 Brick, 2x EV3 Motors, the Light Sensor and a few connector pieces. (See Figure 2.2.1 and Figure 2.2.2 below)

****

Left - *Figure 2.2.1: Top View*, Right - *Figure 2.2.2: Front View*

**Purpose:** Determine which light sensor(s) to use in the final mechanical design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Place the robot on a black surface (Ex. a black poster board placed on the floor)
2. Instruct the robot to drive forward for 10 seconds while sampling the sensor value every 0.1 seconds. Display the sensor values on the console
3. Record the sensor values
4. Repeat Steps 1 through 3 for each sensor with three trials per sensor

**Expected Outcomes:** The measured sensor values are expected to have outliers and contain noise. However, the different sensors should have varying levels of noise and thus, precision.

**Results:** See Section “10.2 Light Sensor Data” of the *Appendix* for the data collected from each trial

|  |  |  |
| --- | --- | --- |
| **Sensor Number** | **Trial Number** | **Standard Deviation** |
| **1** | 1 | 0.0106 |
| 2 | 0.0089 |
| 3 | 0.0096 |
| Average | 0.0097 |
| **2** | 1 | 0.0143 |
| 2 | 0.0148 |
| 3 | 0.0094 |
| Average | 0.0128 |
| **3** | 1 | 0.0112 |
| 2 | 0.0104 |
| 3 | 0.0112 |
| Average | 0.0109 |

*Sample Calculations, Sensor 1:*

Formula used to calculate the standard deviation of the 100 samples of each trial:

**Observations and Conclusions:** Based on the data collected, Sensor 1 is the most precise out of the three. All of the data collected from the sensors did contain noise but one proved to have less than the others albeit not by a very significant amount. Nonetheless, this test was a success and Sensor 1 must be used in the final Mechanical Design.

**2.3 Best EV3 Motors**

**Performed by:** Chaoyi, Priscilla

**Software used:** Version 1.0

Classes used: Main, Test

**Hardware used:** The same minimal design used in Section “2.2 Best Light Sensors”. (See Figure 2.2.1 and Figure 2.2.2 above)

**Purpose:** Determine which EV3 Motors to use in the final mechanical design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Float the motors and display the tachocount on the screen
2. Mark a certain point on the motor
3. Rotate the wheel 5 times using the marking as a guide
4. Record the tachocount
5. Repeat Steps 1 through 4 for each motor with five trials per motor

**Expected Outcomes:** The measured values are expected to vary from motor to motor will some motors being clearly more accurate than others.

**Results:**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Motor** | **Trial 1** | **Trial 2** | **Trial 3** | **Trial 4** | **Trial 5** |
| **1** | 1804° | 1787° | 1802° | 1791° | 1805° |
| **2** | 1814° | 1796° | 1792° | 1800° | 1802° |
| **3** | 1799° | 1795° | 1802° | 1801° | 1796° |
| **4** | 1810° | 1805° | 1798° | 1801° | 1800° |
| **5** | 1801° | 1803° | 1796° | 1799° | 1793° |
| **6** | 1794° | 1802° | 1799° | 1795° | 1801° |

\*The expected value is (5 Rotations)\*(360°/Rotation) = 1800°

|  |  |  |
| --- | --- | --- |
| **Motor** | **Average Value** | **Standard Deviation** |
| **1** | 1797.8° | 8.2° |
| **2** | 1800.8° | 8.3° |
| **3** | 1798.6° | 3.0° |
| **4** | 1802.8° | 4.8° |
| **5** | 1798.4° | 4.0° |
| **6** | 1798.2° | 3.6° |

*Sample Calculations, Motor 1:*

**Observations and Conclusions:** Based on the average values, Motor 2 has the most accurate data followed by Motors 3 and 5. From the sample standard deviation values, Motors 3, 5 and 6 are the most precise. The motors are preferred to be precise rather than accurate. Therefore, Motors 3, 5 and 6 are the best out of the given resources. The mechanical design must be changed to use Motors 3 and 6 for movement and Motor 5 for the pulley.

1. **Odometer Tests**

**3.1 Odometer Accuracy**

**Performed by:** Chaoyi

**Software used:** Version 1.0

Classes used: Main, Test, Odometer, Display

**Hardware used:** Version 1.0

**Purpose:** Determine if the odometer is accurate enough for the integrated design.

**Procedure:**

In this test, the robot will follow this algorithm:

Wait for button press

for i in range (0,4):

Go forward for 2 tiles

Turn right by 90°

Go forward for 2 tiles

Turn right by 153.435°

Go forward for 2.236 tiles

Turn left by 108.435°

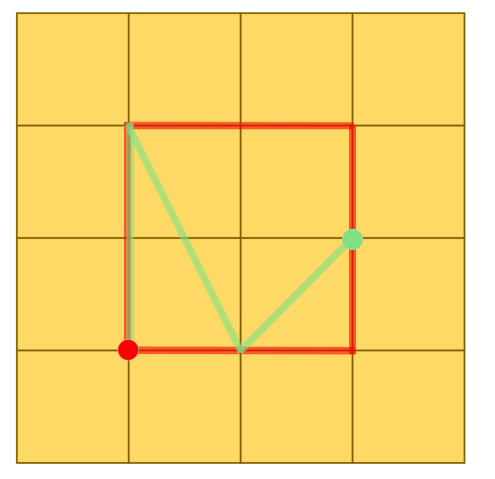
Go forward for 1.414 tiles

Turn left by 45°

Stop

Then, with the battery fully charged, follow these steps:

1. Place the robot at the starting position (X, Y, θ) = (0, 0, 0°) and run the software
2. Observe the robot to ensure it is following the red path and then the green path specified below. The start point is in red and the end point is in green.



1. The robot’s final position should be (X, Y) = (2, 1) or (60.96cm, 30.48cm). Measure the robot’s actual position (X, Y) and record the (Xf, Yf) displayed on the robot’s screen.
2. Repeat Steps 1 through 3 four more times for a total of five trials.

**Expected Outcomes:** The odometer is expected to have a Euclidean error distance which is less than 2cm. If the error is greater than this value, the test will be considered unsuccessful.

**Results:**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Trial** | **1** | **2** | **3** | **4** | **5** |
| **Xf(cm)** | 60.57 | 59.96 | 59.96 | 60.56 | 60.56 |
| **Yf(cm)** | 29.62 | 29.49 | 30.00 | 29.44 | 30.11 |
| **X (cm)** | 57.96 | 59.96 | 57.96 | 57.46 | 58.96 |
| **Y (cm)** | 28.98 | 28.48 | 28.48 | 27.98 | 27.48 |
| **ɛ (cm)** | 2.69 | 1.01 | 2.51 | 3.43 | 3.08 |
| **ɛ mean (cm)** | 2.54 | | | | |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** The average of the Euclidean error is 2.54cm. This value is greater than the needed 2cm error. According to the Euclidean error which was greater than expected, this test was unsuccessful. A correction technique must be implemented in the software in order to correct the odometer.

1. **Localization Tests**

**4.1 Ultrasonic Localization Accuracy**

**Performed by:** Younes

**Software used:** Version 1.0

Classes used: Main, Test, Odometer, Ultrasonic Localization

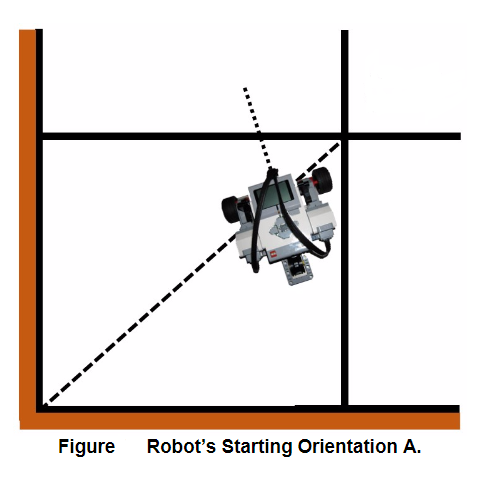
**Hardware used:** Version 1.0

**Purpose:** Determine if the ultrasonic localization is accurate enough for the integrated design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Place the robot in any orientation on the diagonal line between the starting corner and the next tile intersection as shown below. Launch the software



*(Supplied by client)*

1. The robot will perform ultrasonic localization using falling edge and once localized, the robot’s final orientation should be 0°. Measure and record the robot’s actual orientation.
2. Repeat Steps 1 and 2 four more times for a total of five trials.

**Expected Outcomes:** The final angle is expected to be no more than ±2.5° than from the 0° orientation. A final angle of more than ±2.5° from the expected will be considered an unsuccessful test.

**Results:**

|  |  |
| --- | --- |
| **Trial** | **θerr** |
| **1** | -7.0**°** |
| **2** | 10.0**°** |
| **3** | 6.0**°** |
| **4** | -8.0**°** |
| **5** | 2.0**°** |
| **Mean** | 0.6**°** |
| **Standard deviation** | 7.9**°** |

*Sample Calculations:*

**Observations and Conclusions:** The standard deviation of the error was 7.9**°** and the average value was 0.6**°.**The results show that the robot cannot always reliably localize to exactly 0°, which means that it will be difficult to navigate to the zip line. The average value is close to the expected however, the standard deviation is far too large. Therefore, further improvements are needed for the ultrasonic localization in order to ensure it is accurate enough to mount the zip line.

**4.2 Light Localization Accuracy**

**Performed by:** Priscilla

**Software used:** Version 1.0

Classes used: Main, Test, Odometer, Light Localization

**Hardware used:** Version 1.0

**Purpose:** Determine if the ultrasonic localization is accurate enough for the integrated design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Place the robot at a starting position (X, Y, θ) = (x, y, 0°) where x and y are unknown to the robot and launch the software
2. The robot will perform light localization and once localized, the robot’s final position should be (X, Y, θ) = (1, 1, 0°). Measure the robot’s actual final position (Xf, Yf).
3. Repeat Steps 1 and 2 four more times for a total of five trials

**Expected Outcomes:** The Euclidean error distance is expected to be less than or equal to ±2 cm relative to the expected final position. A Euclidean error distance of more than ±2 cm from the expected will be considered an unsuccessful test.

**Results:**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Trial** | **1** | **2** | **3** | **4** | **5** |
| **XF(cm)** | 29.78 | 30.18 | 29.98 | 29.28 | 29.68 |
| **YF(cm)** | 29.98 | 30.48 | 28.98 | 29.48 | 30.18 |
| **ε(cm)** | 0.86 | 0.30 | 1.58 | 1.56 | 0.85 |
| **ε Mean (cm)** | 1.03 | | | | |
| **ε Std. Dev. (cm)** | 0.54 | | | | |

Where X = 30.48cm, Y = 30.48cm

*Sample Calculations:*

Trial 1:

**Observations and Conclusions:** The results show that the robot can reliably localize to the (1, 1) position. Since the value of the error plus one standard deviation is still within the error tolerance (1.57cm < 2cm), the test is considered to be a success. No further improvements are needed for the light localization before integration with the rest of the design.

**4.3 Updated Light Localization Accuracy**

**Performed by:** Chaoyi

**Software used:** Version 1.2

Classes used: Main, Test, Odometer, Light Localization

**Hardware used:** Version 1.1

**Purpose:** Determine if the orientation after localizing falls within the margin of error needed to mount the zip line.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place the robot at starting position where all values are random and unknown to the robot but such that when it rotates 360°, the light sensor passes the four gridlines of an intersection. Launch the software
2. The robot will perform light localization and once localized, the robot’s final position should be (X, Y, θ) = (1, 1, 0°). Measure the robot’s actual final position, (Xf, Yf, θf).

**Expected Outcomes:** The Euclidean error distance is expected to be less than or equal to ±2 cm relative to the expected final position. In addition, the final angle is expected to be no more than 15° (since the acceptable margin of error was found to be 17° in Section “6.1 Mounting Margin of Error”) than from the 0° orientation. A final angle of more than 15° or a Euclidean error distance of more than ±2 cm from the expected will be considered an unsuccessful test.

**Results:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Trial** | **Xf (cm)** | **Yf (cm)** | **θf (°)** | **ε (cm)** |
| **1** | 29.60 | 29.20 | 19 | 1.55 |
| **2** | 29.10 | 30.00 | -8 | 1.46 |
| **3** | 29.00 | 30.20 | 6 | 1.51 |
| **4** | 29.40 | 29.20 | 4 | 1.67 |
| **5** | 29.40 | 29.00 | 10 | 1.83 |
| **6** | 29.60 | 29.40 | -9 | 1.39 |
| **7** | 29.20 | 29.90 | 12 | 1.41 |
| **8** | 28.90 | 30.30 | 3 | 1.59 |
| **9** | 29.20 | 29.30 | 18 | 1.74 |
| **10** | 29.70 | 29.50 | -6 | 1.25 |
| **11** | 30.00 | 30.10 | 20 | 0.61 |
| **12** | 29.30 | 29.50 | -7 | 1.53 |
| **13** | 29.50 | 30.20 | 19 | 1.02 |
| **14** | 29.70 | 29.40 | 11 | 1.33 |
| **15** | 29.60 | 29.10 | -2 | 1.64 |
| **16** | 29.80 | 30.10 | 21 | 0.78 |
| **17** | 29.10 | 29.70 | 6 | 1.59 |
| **18** | 29.40 | 30.00 | -5 | 1.18 |
| **19** | 30.20 | 28.90 | 13 | 1.60 |
| **20** | 29.60 | 29.60 | 10 | 1.24 |

\*The expected final position, (X, Y), was (1, 1) or (30.48 cm, 30.48 cm)

|  |  |  |
| --- | --- | --- |
|  | **ε (cm)** | **θ (°)** |
| **Mean** | 1.40 | 10.45 |
| **Standard Deviation** | 0.31 | 6.04 |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** Fifteen of the twenty tests satisfy the criteria for a test to be successful (e.g. the mean Euclidean distance error must be less than ± 2 cm and the mean angle or *θ* error must be less than 15°). Our tests indicate that the mean Euclidean distance error is 1.40 cm and the mean *θ* error is 10.45°. As these errors fall within the error range for the expected outcome, the testing is successful overall. However, the angle error plus one standard deviation is greater than the target margin of error so the navigation must be improved for the final demo.

1. **Navigation Tests**

**5.1 Navigation Accuracy**

**Performed by:** Mahad

**Software used:** Version 1.0

Classes used: Main, Test, Odometer, Navigation

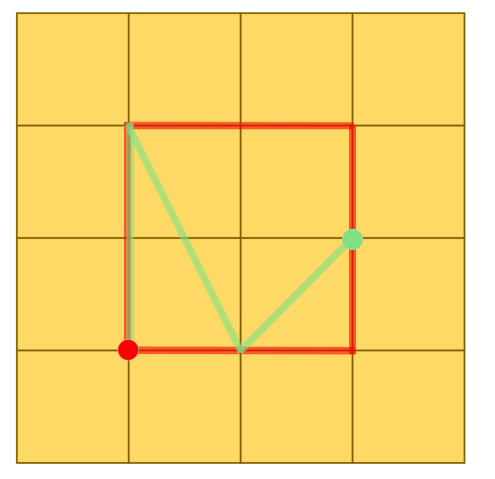
**Hardware used:** Version 1.0

**Purpose:** Determine if the navigation is accurate enough for the integrated design.

**Procedure:**

With the battery fully charged, follow these steps:

1. Launch software, place robot at starting position (X, Y, θ) = (1, 1, 0°) and press a button to begin
2. Observe the robot to ensure it is following the green path specified. Start point in red, end point in green:



1. The robot’s final position should be (X, Y, θ) = (3, 2, 0°) or (91.44cm, 60.96cm, 0°). Measure the robot’s actual position and orientation (Xf, Yf, θf) using a ruler and a protractor and compare with the expected final position and orientation.

**Expected Outcomes:** The final position is expected to have a Euclidean error distance which is less than 2cm and an angle error of less than 2.5°. If the errors are greater than these values, the test will be considered unsuccessful.

**Results:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Trial** | **Xf (cm)** | **Yf (cm)** | **θ (°)** | **ε (cm)** |
| **1** | 89.04 | 59.76 | -6.00 | 2.68 |
| **2** | 92.74 | 60.26 | -2.00 | 1.48 |
| **3** | 91.44 | 60.76 | 2.00 | 0.20 |
| **4** | 92.54 | 59.66 | 1.00 | 1.70 |
| **5** | 91.64 | 61.86 | -1.00 | 0.92 |
| **Mean** | | | -1.00 | 1.40 |
| **Standard Deviation** | | | 3.39 | 0.92 |

\*The expected final position, (X, Y), was (3, 2) or (91.44cm, 60.96 cm)

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** Three out of our five tests satisfy the criteria for a test to be successful (e.g. the mean Euclidean distance error must be less than ± 2 cm and the mean angle or *θ* error must be less than ± 2.5°). Our tests indicate that the mean Euclidean distance error is 1.40 cm and the mean *θ* error is -1.0°. As these errors fall within the error range for the expected outcome, the testing is successful overall. The navigation lab is based on the odometer test, which is not perfect according to the result of odometer test. However, the Euclidean distance error and the *θ* error don’t seem to change much. This indicates that our navigation method is quite satisfactory.

**5.2 Updated Navigation Accuracy**

**Performed by:** Chaoyi

**Software used:** Version 1.2

Classes used: Main, Test, Odometer, Navigation

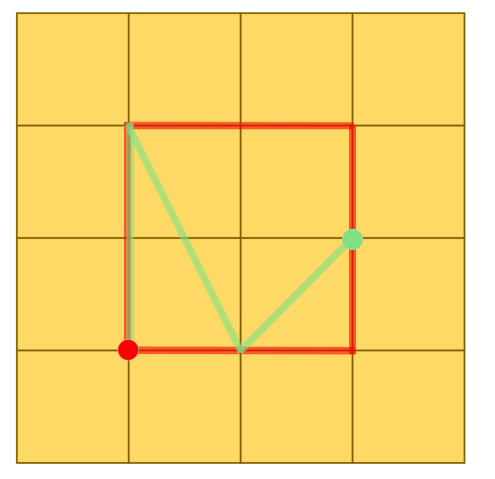
**Hardware used:** Version 1.1

**Purpose:** Determine if the orientation and position after navigating falls within the margin of error needed to mount the zip line.

**Procedure:**

With the battery fully charged, follow these steps:

1. Launch software, place robot at starting position (X, Y, θ) = (1, 1, 0°) and press a button to begin
2. Observe the robot to ensure it is following the green path specified. Start point in red, end point in green:



1. The robot’s final position should be (X, Y, θ) = (3, 2, 0°) or (91.44cm, 60.96cm, 0°). Measure the robot’s actual position and orientation (Xf, Yf, θf) using a ruler and a protractor and compare with the expected final position and orientation.
2. Repeat Steps 1 through 3 nineteen more times for a total of 20 trials

**Expected Outcomes:** The Euclidean error distance is expected to be less than or equal to ±2 cm relative to the expected final position. In addition, the final angle is expected to be no more than 15° (since the acceptable margin of error was found to be 17° in Section “6.1 Mounting Margin of Error”) than from the 0° orientation. A final angle of more than 15° or a Euclidean error distance of more than ±2 cm from the expected will be considered an unsuccessful test.

**Results:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Trial** | **Xf (cm)** | **Yf (cm)** | **θf (°)** | **ε (cm)** |
| **1** | 90.20 | 59.00 | -2.00 | 2.32 |
| **2** | 89.10 | 60.50 | 1.00 | 2.38 |
| **3** | 90.00 | 60.70 | 3.00 | 1.46 |
| **4** | 90.40 | 59.70 | 2.00 | 1.63 |
| **5** | 89.40 | 59.50 | -1.00 | 2.51 |
| **6** | 90.60 | 59.90 | -4.00 | 1.35 |
| **7** | 90.20 | 60.40 | 2.00 | 1.36 |
| **8** | 89.90 | 60.80 | 3.00 | 1.55 |
| **9** | 89.20 | 59.80 | 2.00 | 2.52 |
| **10** | 90.70 | 60.00 | 1.00 | 1.21 |
| **11** | 91.00 | 60.60 | -1.00 | 0.57 |
| **12** | 90.30 | 59.00 | 4.00 | 2.27 |
| **13** | 90.50 | 60.70 | -3.00 | 0.98 |
| **14** | 89.70 | 59.00 | 2.00 | 2.62 |
| **15** | 90.60 | 59.60 | -2.00 | 1.60 |
| **16** | 89.80 | 59.00 | -4.00 | 2.56 |
| **17** | 90.10 | 60.20 | 5.00 | 1.54 |
| **18** | 90.40 | 60.50 | 1.00 | 1.14 |
| **19** | 91.20 | 59.40 | -3.00 | 1.58 |
| **20** | 90.60 | 60.10 | 2.00 | 1.20 |

\*The expected final position, (X, Y), was (3, 2) or (91.44cm, 60.96 cm)

|  |  |  |
| --- | --- | --- |
|  | **ε (cm)** | **θ (°)** |
| **Mean** | 1.72 | 2.40 |
| **Standard Deviation** | 0.61 | 1.19 |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** Thirteen of the twenty tests satisfy the criteria for a test to be successful (e.g. the mean Euclidean distance error must be less than ± 2 cm and the mean angle or *θ* error must be less than 15°). Our tests indicate that the mean Euclidean distance error is 1.72 cm and the mean *θ* error is 2.40°. As these errors fall within the error range for the expected outcome, the testing is successful overall. However, the Euclidean distance error plus one standard deviation is greater than the target margin of error so the navigation must be improved for the final demo.

1. **Zip Line Tests**

**6.1 Mounting Margin of Error**

**Performed by:** Chaoyi

**Software used:** Version 1.2

Classes used: Main, Test, TraverseZipLine

**Hardware used:** Version 1.1

**Purpose:** Determine the margin of error for which the robot is still successfully able to mount, traverse and dismount the zip line.

**Procedure:**

With the battery fully charged, follow these steps:

1. Starting with a perfect orientation, place the robot at the intersection just before the base of the zip and launch the software
2. Observe whether the robot successfully mounts
3. Observe whether the robot successfully traverses the zip line
4. Observe the qualitative behaviour of the dismount
5. Repeat Steps 1 through 4 for two more trials
6. Record any notable behaviour and the angle tested
7. If the trials are successful, increase the orientation error by 1° and run the test again

**Expected Outcomes:** The robot should successfully mount the zip line given it starts at the ideal position and up to a margin of error of 10° to allow for error during navigation and localization. The traversal should be smooth and the robot should remain on the zip line for its entire length. The dismount should controlled (i.e. the robot should not drop) and the robot should come to a complete stop.

**Results:**

|  |  |  |  |
| --- | --- | --- | --- |
| **Angle of Error (°)** | **Trial 1** | **Trial 2** | **Trial 3** |
| **0** | S/S/S | S/S/S | S/S/S |
| **1** | S/S/S | S/S/S | S/S/S |
| **2** | S/S/S | S/S/S | S/S/S |
| **3** | S/S/S | S/S/S | S/S/S |
| **4** | S/S/S | S/S/S | S/S/S |
| **5** | S/S/S | S/S/S | S/S/S |
| **6** | S/S/S | S/S/S | S/S/S |
| **7** | S/S/S | S/S/S | S/S/S |
| **8** | S/S/S | S/S/S | S/S/S |
| **9** | S/S/S | S/S/S | S/S/S |
| **10** | S/S/S | S/S/S | S/S/S |
| **11** | S/S/S | S/S/S | S/S/S |
| **12** | S/S/S | S/S/S | S/S/S |
| **13** | S/S/S | S/S/S | S/S/S |
| **14** | S/S/S | S/S/S | S/S/S |
| **15** | S/S/S | S/S/S | S/S/S |
| **16** | S/S/S | S/S/S | S/S/S |
| **17** | S/S/S | S/S/S | S/S/S |
| **18** | F/NA/NA | F/NA/NA | S/S/S |

\*The format of the results is: Mounting/Traversal/Dismounting

S denotes success

F denotes failure

NA denotes the robot failed at an earlier stage and did not make it to that point

**Observations and Conclusions:** As shown in the results, the robot was able to mount, traverse and dismount the zip line up to and including an error margin of 17°. As this is much greater than the target margin, this test was successful.

1. **Beta Demo Integration Tests**

**7.1 Navigating to the Zip Line**

**Performed by:** Chaoyi, Paarth, Ismail, Younes

**Software used:** Version 1.3

Classes used: Main, WifiConnection, Test, Odometer, Localization, Navigation

**Hardware used:** Version 1.1

**Purpose:** Given the starting corner and a point to navigate to via Wifi, determine whether the robot can accurately navigate to the point.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place robot at starting position with a random orientation and record the corner and orientation that is used. Launch the software
2. Choose a destination to travel to and transmit this to the robot along with the corner via the Wi-Fi connection. Be sure to record the expected final destination
3. Observe the localization and navigation to ensure it is running properly
4. Measure and record the robot’s actual final position using a ruler. Compare this value with the expected values

**Expected Outcomes:** The final position is expected to have a Euclidean error distance which is less than 2cm. If the error is greater than this value, the test will be considered unsuccessful.

**Results:**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Trial** | **Corner** | **Starting Orientation (°)** | **X (cm)** | **Y (cm)** | **Xf (cm)** | **Yf (cm)** | **ε (cm)** |
| **1** | 0 | 280 | 30.48 | 121.92 | 30.20 | 120.90 | 1.06 |
| **2** | 0 | 175 | 152.40 | 60.96 | 152.00 | 60.40 | 0.69 |
| **3** | 0 | 140 | 91.44 | 91.44 | 91.10 | 90.80 | 0.72 |
| **4** | 0 | 215 | 60.96 | 182.88 | 60.00 | 182.50 | 1.03 |
| **5** | 0 | 60 | 121.92 | 152.40 | 121.30 | 152.80 | 0.74 |
| **6** | 1 | 80 | 30.48 | 121.92 | 30.80 | 121.40 | 0.61 |
| **7** | 1 | 125 | 152.40 | 60.96 | 153.00 | 60.20 | 0.97 |
| **8** | 1 | 100 | 91.44 | 91.44 | 91.80 | 90.80 | 0.73 |
| **9** | 1 | 135 | 60.96 | 182.88 | 61.50 | 182.30 | 0.79 |
| **10** | 1 | 200 | 121.92 | 152.40 | 122.70 | 151.90 | 0.93 |
| **11** | 2 | 15 | 30.48 | 121.92 | 31.10 | 122.40 | 0.78 |
| **12** | 2 | 40 | 152.40 | 60.96 | 152.90 | 61.30 | 0.60 |
| **13** | 2 | 340 | 91.44 | 91.44 | 92.10 | 91.80 | 0.75 |
| **14** | 2 | 100 | 60.96 | 182.88 | 62.00 | 183.50 | 1.21 |
| **15** | 2 | 310 | 121.92 | 152.40 | 122.60 | 153.20 | 1.05 |
| **16** | 3 | 255 | 30.48 | 121.92 | 29.90 | 122.30 | 0.69 |
| **17** | 3 | 355 | 152.40 | 60.96 | 151.80 | 61.20 | 0.65 |
| **18** | 3 | 25 | 91.44 | 91.44 | 91.10 | 91.60 | 0.38 |
| **19** | 3 | 190 | 60.96 | 182.88 | 60.50 | 183.40 | 0.69 |
| **20** | 3 | 215 | 121.92 | 152.40 | 121.20 | 152.70 | 0.78 |

|  |  |
| --- | --- |
| **ε Mean (cm)** | 0.79 |
| **ε Standard Deviation (cm)** | 0.20 |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** The mean of the ε was 0.79cm and the standard deviation was 0.20cm. Since the average error with one standard deviation is still much below the target, this test is a success. Therefore, the zip line should be integrated and tested.

**7.2 Traversing the Zip Line**

**Performed by:** Chaoyi, Paarth, Mahad, Younes

**Software used:** Version 1.3

Classes used: Main, WifiConnection, Test, Odometer, Localization, Navigation, TraverseZipLine

**Hardware used:** Version 1.1

**Purpose:** Given the starting corner and the location of the zip line, determine whether the robot can successfully mount, traverse and dismount the zip line.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place robot at a starting position with a random orientation and launch the software
2. Transmit the starting corner and the location of the zip line via the Wifi to the robot
3. Observe the robot as it localizes and travels to/aligns with the zip line to ensure it is running as it should
4. Observe and record the qualitative success of the mount, traversal and dismount of the robot

**Expected Outcomes:** The robot should successfully mount the zip line. The traversal should be smooth and the robot should remain on the zip line for its entire length. The dismount should controlled (i.e. the robot should not drop) and the robot should come to a complete stop. If any of the behaviour is not as described, the trial will be considered unsuccessful. In order for the test to be successful, the robot should make it to the other side of the zip line over 85% of the trials.

**Results:**

|  |  |  |  |
| --- | --- | --- | --- |
| **Trial** | **Mounting** | **Traversal** | **Dismounting** |
| **1** | S | S | S |
| **2** | S | S | S |
| **3** | S | S | S |
| **4** | S | S | S |
| **5** | S | S | S |
| **6** | F | N/A | N/A |
| **7** | S | S | S |
| **8** | S | S | S |
| **9** | S | S | S |
| **10** | S | S | S |
| **11** | S | S | S |
| **12** | S | S | S |
| **13** | F | N/A | N/A |
| **14** | S | S | S |
| **15** | S | S | S |
| **16** | S | S | S |
| **17** | S | S | S |
| **18** | S | S | S |
| **19** | S | S | S |
| **20** | S | S | S |

\*S denotes success

F denotes failure

N/A denotes the robot failed at an earlier stage and did not make it to that point

**Observations and Conclusions:** As shown in the table, the robot only fails to mount the zip line for 2 out of the 20 trials. Since the success rate was 90% (above the target of 85%), this test was successful. Therefore, a point to travel to after dismounting the zip line should be added.

**7.3 Navigating to the Enemy Flag**

**Performed by:** Chaoyi, Paarth

**Software used:** Version 1.3

Classes used: Main, WifiConnection, Test, Odometer, Localization, Navigation, TraverseZipLine

**Hardware used:** Version 1.1

**Purpose:** Given the starting corner, the location of the zip line and a point to navigate to, determine whether the robot can successfully navigate to the point after dismounting the zip line.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place robot at a starting position with a random orientation and launch the software
2. Transmit the starting corner, the location of the zip line and a point to navigate to via the Wifi to the robot
3. Observe the robot as it localizes and travels to/aligns with the zip line to ensure it is running as it should
4. Observe of the mount, traversal and dismount of the robot to ensure it is running as it should and record whether the robot successfully crosses the zip line
5. Measure and record the robot’s actual final position (Xf, Yf) after localizing and navigating to the predetermined point. Compare this value with the expected values

**Expected Outcomes:** The final position is expected to have a Euclidean error distance which is less than 2cm. If the error is greater than this value, the test will be considered unsuccessful.

**Results:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Trial** | **Crossed**  **Zip Line** | **Xf (cm)** | **Yf (cm)** | **ε (cm)** |
| **1** | Yes | 123.10 | 151.80 | 1.32 |
| **2** | Yes | 122.80 | 151.50 | 1.26 |
| **3** | No | N/A | N/A | N/A |
| **4** | Yes | 123.00 | 152.10 | 1.12 |
| **5** | Yes | 122.60 | 151.00 | 1.56 |
| **6** | Yes | 122.70 | 151.50 | 1.19 |
| **7** | Yes | 122.50 | 151.10 | 1.42 |
| **8** | Yes | 123.90 | 151.30 | 2.27 |
| **9** | Yes | 124.20 | 150.40 | 3.03 |
| **10** | Yes | 123.50 | 152.00 | 1.63 |
| **11** | No | N/A | N/A | N/A |
| **12** | Yes | 122.80 | 151.70 | 1.12 |
| **13** | Yes | 122.00 | 151.50 | 0.90 |
| **14** | Yes | 123.30 | 150.80 | 2.11 |
| **15** | Yes | 122.30 | 151.00 | 1.45 |
| **16** | Yes | 123.30 | 149.80 | 2.94 |
| **17** | Yes | 122.60 | 152.20 | 0.71 |
| **18** | Yes | 122.90 | 151.90 | 1.10 |
| **19** | Yes | 124.20 | 151.70 | 2.39 |
| **20** | Yes | 122.40 | 151.30 | 1.20 |

\*The expected final position, (X, Y), was (4, 5) or (121.92cm, 152.40 cm)

N/A denotes the robot failed at an earlier stage and did not make it to that point

|  |  |
| --- | --- |
| **ε Mean (cm)** | 1.60 |
| **ε Standard Deviation (cm)** | 0.67 |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** The mean of the ε was 1.60cm and the standard deviation was 0.67cm. Since the average error with one standard deviation is above the target, this test is unsuccessful. However, it should be noted that out of the 18 trials that made it across the zip line, over 60% fell within the margin of error after navigating to the final position. Therefore, the navigation after zip line traversal must be improved for the final competition.

1. **Flag Capture Tests**

Due to time constraints, the flag capture logic was unable to be completed

1. **Final Integration Tests**

**9.1 Navigating to the Zip Line**

**Performed by:** Chaoyi, Younes

**Software used:** Version 1.4

Classes used: Main, WifiConnection, Test, Odometer, Localization, Navigation

**Hardware used:** Version 1.1

**Purpose:** Given the starting corner and a point to navigate to via Wifi, determine whether the robot can accurately navigate to the point.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place robot at starting position with a random orientation and record the corner and orientation that is used. Launch the software
2. Choose a destination to travel to and transmit this to the robot along with the corner via the Wi-Fi connection. Be sure to record the expected destination
3. Observe the localization and navigation to ensure it is running properly
4. Measure and record the robot’s actual final position using a ruler. Compare this value with the expected values

**Expected Outcomes:** The final position is expected to have a Euclidean error distance which is less than 2cm. If the error is greater than this value, the test will be considered unsuccessful.

**Results:**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Trial** | **Corner** | **Starting Orientation (°)** | **X (cm)** | **Y (cm)** | **Xf (cm)** | **Yf (cm)** | **ε (cm)** |
| **1** | 0 | 280 | 30.48 | 121.92 | 29.90 | 119.80 | 2.20 |
| **2** | 0 | 175 | 152.4 | 60.96 | 151.90 | 59.90 | 1.17 |
| **3** | 0 | 140 | 91.44 | 91.44 | 91.00 | 90.00 | 1.51 |
| **4** | 0 | 215 | 60.96 | 182.88 | 59.90 | 180.90 | 2.25 |
| **5** | 0 | 60 | 121.92 | 152.4 | 121.20 | 151.40 | 1.23 |
| **6** | 1 | 80 | 30.48 | 121.92 | 32.50 | 120.30 | 2.59 |
| **7** | 1 | 125 | 152.4 | 60.96 | 152.90 | 59.70 | 1.36 |
| **8** | 1 | 100 | 91.44 | 91.44 | 91.70 | 90.00 | 1.46 |
| **9** | 1 | 135 | 60.96 | 182.88 | 61.40 | 180.70 | 2.22 |
| **10** | 1 | 200 | 121.92 | 152.4 | 122.60 | 150.00 | 2.49 |
| **11** | 2 | 15 | 30.48 | 121.92 | 31.10 | 121.30 | 0.88 |
| **12** | 2 | 40 | 152.4 | 60.96 | 153.50 | 60.10 | 1.40 |
| **13** | 2 | 340 | 91.44 | 91.44 | 93.20 | 90.20 | 2.15 |
| **14** | 2 | 100 | 60.96 | 182.88 | 61.90 | 181.80 | 1.43 |
| **15** | 2 | 310 | 121.92 | 152.4 | 122.50 | 151.80 | 0.83 |
| **16** | 3 | 255 | 30.48 | 121.92 | 29.90 | 121.20 | 0.92 |
| **17** | 3 | 355 | 152.4 | 60.96 | 151.70 | 60.60 | 0.79 |
| **18** | 3 | 25 | 91.44 | 91.44 | 91.00 | 90.80 | 0.78 |
| **19** | 3 | 190 | 60.96 | 182.88 | 60.40 | 181.70 | 1.31 |
| **20** | 3 | 215 | 121.92 | 152.4 | 121.10 | 151.30 | 1.37 |

|  |  |
| --- | --- |
| **ε Mean (cm)** | 1.52 |
| **ε Standard Deviation (cm)** | 0.59 |

*Sample Calculations:*

*Trial 1:*

**Observations and Conclusions:** The mean of the ε was 1.52cm and the standard deviation was 0.59cm. This average error is due to the Light Localization. It was found that the Light localization works 60-70% of the time from the data given in terms of the final orientation. This is good enough to integrate the zip line, however, the success rate is going to be low.

**9.2 Traversing the Zip Line**

**Performed by:** Mahad, Younes

**Software used:** Version 1.4

Classes used: Main, WifiConnection, Test, Odometer, Localization, Navigation, TraverseZipLine

**Hardware used:** Version 1.1

**Purpose:** Given the starting corner and the location of the zip line, determine whether the robot can successfully mount, traverse and dismount the zip line.

**Procedure:**

When performing the test, do 20 trials with 5 trials starting in each corner.

With the battery fully charged, follow these steps:

1. Place robot at a starting position with a random orientation and launch the software
2. Transmit the starting corner and the location of the zip line via the Wifi to the robot
3. Observe the robot as it localizes and travels to/aligns with the zip line to ensure it is running as it should
4. Observe and record the qualitative success of the mount, traversal and dismount of the robot

**Expected Outcomes:** The robot should successfully mount the zip line. The traversal should be smooth and the robot should remain on the zip line for its entire length. The dismount should have controlled (i.e. the robot should not drop) and the robot should come to a complete stop. If any of the behaviour is not as described, the trial will be considered unsuccessful. For the test to be successful, the robot should make it to the other side of the zip line over 85% of the trials.

**Results:**

|  |  |  |  |
| --- | --- | --- | --- |
| **Trial** | **Mounting** | **Traversal** | **Dismounting** |
| **1** | S | S | S |
| **2** | F | N/A | N/A |
| **3** | S | S | S |
| **4** | S | S | S |
| **5** | S | S | S |
| **6** | F | N/A | N/A |
| **7** | S | S | S |
| **8** | F | N/A | N/A |
| **9** | S | S | S |
| **10** | F | N/A | N/A |
| **11** | S | S | S |
| **12** | S | S | S |
| **13** | F | N/A | N/A |
| **14** | S | S | S |
| **15** | F | N/A | N/A |
| **16** | S | S | S |
| **17** | S | S | S |
| **18** | S | S | S |
| **19** | F | N/A | N/A |
| **20** | S | S | S |

\*S denotes success

F denotes failure

N/A denotes the robot failed at an earlier stage and did not make it to that point

**Observations and Conclusions:** As shown in the table, the robot only fails to mount the zip line for 7 out of the 20 trials. This is logical data as this is consistent with our Navigating to the Zip line test conclusion. Since the success rate was 65%, this test was a failure. Therefore, more tests should be conducted to have a higher success rate.

1. **Appendix**

**10.1 Ultrasonic Sensor Data**

Sensor 1 Values Sensor 2 Values Sensor 3 Values

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Trial 1** | **Trial 2** | **Trial 3** |  | **Trial 1** | **Trial 2** | **Trial 3** |  | **Trial 1** | **Trial 2** | **Trial 3** |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 15 | 15 |  | 4 | 13 | 15 |  | 13 | 15 | 15 |
| 15 | 15 | 15 |  | 15 | 13 | 15 |  | 13 | 15 | 15 |
| 15 | 15 | 15 |  | 15 | 13 | 15 |  | 13 | 15 | 15 |
| 15 | 15 | 15 |  | 15 | 2 | 15 |  | 13 | 15 | 15 |
| 15 | 15 | 15 |  | 15 | 13 | 15 |  | 13 | 15 | 13 |
| 15 | 15 | 15 |  | 15 | 13 | 15 |  | 13 | 15 | 13 |
| 15 | 15 | 15 |  | 15 | 13 | 15 |  | 13 | 15 | 13 |
| 14 | 15 | 16 |  | 15 | 13 | 15 |  | 13 | 15 | 13 |
| 14 | 15 | 16 |  | 15 | 13 | 15 |  | 13 | 15 | 13 |
| 14 | 15 | 2 |  | 15 | 15 | 15 |  | 15 | 15 | 2 |
| 14 | 15 | 16 |  | 15 | 15 | 15 |  | 15 | 15 | 16 |
| 14 | 15 | 16 |  | 14 | 15 | 15 |  | 11 | 15 | 16 |
| 14 | 16 | 16 |  | 14 | 15 | 15 |  | 14 | 15 | 16 |
| 14 | 16 | 16 |  | 14 | 15 | 13 |  | 14 | 14 | 16 |
| 14 | 16 | 16 |  | 14 | 15 | 13 |  | 14 | 14 | 16 |
| 16 | 3 | 16 |  | 16 | 15 | 13 |  | 14 | 14 | 16 |
| 16 | 15 | 16 |  | 16 | 15 | 13 |  | 14 | 14 | 16 |
| 16 | 15 | 16 |  | 16 | 5 | 13 |  | 14 | 57 | 16 |
| 16 | 15 | 16 |  | 16 | 15 | 13 |  | 14 | 14 | 16 |
| 16 | 15 | 15 |  | 16 | 15 | 45 |  | 14 | 14 | 15 |
| 16 | 15 | 15 |  | 16 | 15 | 15 |  | 14 | 14 | 15 |
| 16 | 15 | 15 |  | 16 | 15 | 15 |  | 14 | 14 | 15 |
| 16 | 15 | 15 |  | 16 | 15 | 15 |  | 14 | 14 | 15 |
| 16 | 15 | 15 |  | 16 | 15 | 15 |  | 14 | 14 | 15 |
| 16 | 15 | 15 |  | 16 | 15 | 15 |  | 14 | 14 | 15 |
| 16 | 16 | 15 |  | 16 | 16 | 15 |  | 16 | 4 | 15 |
| 16 | 16 | 15 |  | 7 | 16 | 15 |  | 16 | 15 | 15 |
| 213 | 16 | 15 |  | 43 | 16 | 17 |  | 16 | 17 | 15 |
| 15 | 16 | 15 |  | 15 | 27 | 17 |  | 16 | 17 | 15 |
| 15 | 16 | 15 |  | 15 | 16 | 17 |  | 2 | 17 | 15 |
| 15 | 15 | 15 |  | 15 | 15 | 17 |  | 13 | 17 | 15 |
| 15 | 15 | 15 |  | 15 | 15 | 17 |  | 13 | 17 | 15 |
| 15 | 15 | 148 |  | 15 | 15 | 17 |  | 13 | 17 | 5 |
| 15 | 15 | 14 |  | 15 | 15 | 17 |  | 13 | 17 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 17 |  | 13 | 17 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 17 |  | 13 | 17 | 14 |
| 15 | 101 | 14 |  | 15 | 15 | 14 |  | 13 | 15 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 15 | 15 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 15 | 15 | 14 |
| 13 | 14 | 14 |  | 13 | 14 | 14 |  | 15 | 15 | 14 |
| 13 | 14 | 14 |  | 13 | 14 | 14 |  | 15 | 15 | 14 |
| 13 | 14 | 14 |  | 13 | 14 | 14 |  | 15 | 15 | 14 |
| 13 | 14 | 14 |  | 13 | 14 | 10 |  | 15 | 15 | 14 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 148 | 15 |  | 15 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 11 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 40 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 13 | 14 | 13 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 2 | 14 | 14 |  | 13 | 14 | 15 |  | 15 | 15 | 13 |
| 14 | 14 | 14 |  | 14 | 14 | 15 |  | 14 | 15 | 13 |
| 14 | 14 | 14 |  | 14 | 14 | 15 |  | 14 | 15 | 13 |
| 14 | 35 | 14 |  | 14 | 35 | 14 |  | 14 | 14 | 28 |
| 14 | 14 | 14 |  | 14 | 14 | 14 |  | 14 | 14 | 14 |
| 14 | 14 | 14 |  | 14 | 14 | 14 |  | 14 | 14 | 14 |
| 14 | 14 | 14 |  | 14 | 14 | 2 |  | 14 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 14 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 14 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 14 | 14 | 14 |
| 15 | 15 | 14 |  | 168 | 15 | 14 |  | 15 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 15 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 15 | 14 | 14 |
| 15 | 15 | 14 |  | 15 | 15 | 14 |  | 15 | 14 | 14 |
| 15 | 15 | 16 |  | 15 | 15 | 16 |  | 15 | 16 | 16 |
| 15 | 15 | 16 |  | 15 | 15 | 16 |  | 15 | 16 | 16 |
| 15 | 15 | 16 |  | 15 | 15 | 16 |  | 2 | 16 | 16 |
| 15 | 15 | 16 |  | 14 | 15 | 30 |  | 15 | 16 | 16 |
| 15 | 15 | 16 |  | 14 | 15 | 15 |  | 15 | 16 | 16 |
| 200 | 15 | 16 |  | 14 | 15 | 15 |  | 15 | 16 | 16 |
| 13 | 15 | 16 |  | 14 | 15 | 15 |  | 15 | 16 | 16 |
| 13 | 15 | 16 |  | 14 | 15 | 15 |  | 15 | 16 | 16 |
| 13 | 15 | 16 |  | 14 | 15 | 15 |  | 15 | 16 | 16 |
| 13 | 14 | 16 |  | 14 | 14 | 15 |  | 14 | 16 | 16 |
| 13 | 14 | 15 |  | 14 | 14 | 15 |  | 14 | 16 | 15 |
| 13 | 14 | 15 |  | 14 | 14 | 15 |  | 14 | 16 | 15 |
| 13 | 14 | 15 |  | 5 | 14 | 15 |  | 14 | 15 | 15 |
| 13 | 14 | 15 |  | 14 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 13 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 14 | 15 |  | 15 | 14 | 15 |  | 14 | 15 | 15 |
| 15 | 15 | 15 |  | 15 | 15 | 15 |  | 15 | 15 | 15 |
| 15 | 15 | 17 |  | 15 | 15 | 17 |  | 15 | 32 | 17 |
| 15 | 15 | 17 |  | 16 | 15 | 17 |  | 15 | 17 | 17 |
| 15 | 15 | 17 |  | 16 | 15 | 17 |  | 15 | 17 | 17 |
| 15 | 15 | 17 |  | 16 | 15 | 17 |  | 15 | 17 | 17 |
| 15 | 15 | 17 |  | 16 | 15 | 17 |  | 15 | 17 | 17 |
| 15 | 15 | 17 |  | 16 | 15 | 17 |  | 52 | 17 | 17 |
| 15 | 15 | 15 |  | 16 | 15 | 15 |  | 15 | 15 | 15 |
| 15 | 15 | 15 |  | 16 | 15 | 15 |  | 15 | 15 | 15 |
| 15 | 15 | 15 |  | 16 | 15 | 15 |  | 15 | 15 | 15 |
| 15 | 15 | 173 |  | 16 | 15 | 15 |  | 15 | 15 | 7 |
| 15 | 15 | 15 |  | 16 | 15 | 15 |  | 15 | 15 | 15 |
| 15 | 15 | 15 |  | 16 | 15 | 15 |  | 15 | 15 | 15 |

**10.2 Light Sensor Data**

Sensor 1 Values Sensor 2 Values Sensor 3 Values

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Trial 1** | **Trial 2** | **Trial 3** |  | **Trial 1** | **Trial 2** | **Trial 3** |  | **Trial 1** | **Trial 2** | **Trial 3** |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.13 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.13 | 0.15 |
| 0.14 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.15 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.16 |  | 0.16 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.19 | 0.15 |  | 0.14 | 0.14 | 0.15 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.14 |  | 0.14 | 0.14 | 0.13 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.14 |  | 0.14 | 0.14 | 0.13 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.14 |  | 0.14 | 0.14 | 0.13 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.14 |  | 0.14 | 0.14 | 0.13 |
| 0.14 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.14 |  | 0.14 | 0.14 | 0.13 |
| 0.17 | 0.15 | 0.16 |  | 0.15 | 0.16 | 0.18 |  | 0.14 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.17 | 0.14 | 0.16 |  | 0.18 | 0.16 | 0.18 |  | 0.15 | 0.12 | 0.13 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.13 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.13 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.13 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.14 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.14 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.14 | 0.16 |  | 0.14 | 0.12 | 0.14 |
| 0.15 | 0.14 | 0.14 |  | 0.18 | 0.15 | 0.16 |  | 0.14 | 0.14 | 0.14 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.14 | 0.16 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.15 | 0.16 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.16 | 0.13 |  | 0.16 | 0.16 | 0.16 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.17 | 0.13 |  | 0.17 | 0.16 | 0.16 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.17 | 0.13 |  | 0.17 | 0.16 | 0.16 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.17 | 0.13 |  | 0.17 | 0.16 | 0.15 |  | 0.13 | 0.15 | 0.12 |
| 0.15 | 0.17 | 0.15 |  | 0.17 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.15 | 0.17 | 0.15 |  | 0.17 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.15 | 0.17 | 0.15 |  | 0.17 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.12 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.13 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.15 | 0.14 | 0.14 |
| 0.14 | 0.14 | 0.15 |  | 0.14 | 0.16 | 0.15 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.16 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.14 | 0.14 |  | 0.14 | 0.14 | 0.16 |  | 0.12 | 0.14 | 0.14 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.14 | 0.16 |  | 0.12 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.15 | 0.16 |  | 0.12 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.15 | 0.16 |  | 0.14 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.15 | 0.16 |  | 0.14 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.15 | 0.16 |  | 0.14 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.14 |  | 0.15 | 0.15 | 0.16 |  | 0.14 | 0.12 | 0.15 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.16 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.16 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.12 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.14 |
| 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.15 |  | 0.15 | 0.15 | 0.14 |