Lab Report 00: Robot Actuation and Sensing

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ABSTRACT

This lab investigated the robot's sensing and actuation through sensor unit testing and the implementations of ripple and tripod gait on a hexapod. The performances of gaits were evaluated in terms of displacement in x and y directions over 10 and 30 seconds. The results showed that the tripod gait outperformed the ripple gait by moving 400% farther in x direction while maintaining extremely stable.

I. INTRODUCTION

The concept of robots existed for a century but has continuously evolved. Modern robots are no longer defined as rigid mechanical systems but embodied intelligences capable of learning, perceiving, and adapting. In [1, Ch. 1], a robot is defined as "an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals." And "actuation" and "sensing" are two essentials in the study of robotics because they connect robots to the physical world.

Specifically, robots rely on effectors and actuators to have an effect in environments. Effectors are devices that drive robots to act following the given commands, and actuators are the underlying mechanisms that enable the effector to function [1, Ch. 3]. For example, an agricultural robotic harvesting system uses a gripper powered by motors to harvest crops [2]. In this configuration, the gripper functions as the effector, while the motors serve as actuators. Other types of actuators include hydraulics and pneumatics, but motors are the most commonly used [1, Ch. 4].

DC motors convert electrical energy into mechanical energy and provide torque; however, their high rotational speed often results in insufficient torque for most robotic tasks. Therefore, gears are commonly used to modify speed and torque [1, Ch. 4]. Additionally, while DC motors excel at continuous rotation, many robotic tasks require accurate positioning. By integrating sensors and controllers with appropriate gear reduction, servo motors can control speed, torque, and position precisely and are therefore better suited for robotic manipulation [1, Ch. 4], [3].

In all cases, actuation requires energy to power the effector. Nevertheless, passive actuation uses potential energy or a robot's inherent mechanical properties. For instance, McGeer's passive walker used gravity as an energy source to enable walking through its mechanical design [4].

"Sensing" is also critical for providing the information a robot needs to achieve its goals. A robot senses its internal state through proprioceptive sensors, such as a battery monitor, and senses external state through exteroceptive sensors, such as a light-level detector [1, Ch. 7]. However, sensor outputs typically cannot be used directly without additional processing. Uncertainties in the physical world—arising from sensor noise, effector errors, internal-state errors, and insufficient understanding of external states—prevent robots from taking ideal actions [1, Ch. 7], [5], [6]. Therefore, processing is necessary to transform raw sensor outputs into intelligent responses, also known as the signal-to-symbol problem [1, Ch. 7].

Consider a voice-recognition robot as an example. A microphone acquires raw audio, signal processing separates speech from background noise, mid-level processing extracts audio features, and finally the processed audio is compared with a database to identify the person.

Given the complexity of producing meaningful responses from sensor outputs, researchers have developed several approaches: action-oriented perception, expectation-oriented perception, task-driven attention, and perceptual classes [1, Ch. 7]. Another approach is to fuse outputs from multiple sensors to obtain redundant information and improve accuracy, though this can introduce additional uncertainties requiring more advanced methods.

The objective of this lab is to explore robot sensing and actuation by implementing two typical gaits—tripod and ripple—and collecting readings from sensors attached to the robot.

II. METHODS

Specifically, a hexopod robot was used in this lab. The robot has 18 bus servos, and each leg has three bus servos, which control different degrees of freedom [Fig. 1]. From the robot's center, the innermost servos control forward and backward motion; the middle servos control upward and downward motion; and the outermost servos control the claws extending inward and outward. In addition, the robot contains an ultrasonic sensor (sonar) at the front to detect distance through echolocation, which uses sound reflected off objects to locate the robot in an environment [1, Ch. 9]. The robot also includes other sensors not used in this lab, such as accelerometers and gyroscopes, which track acceleration and angular velocity.

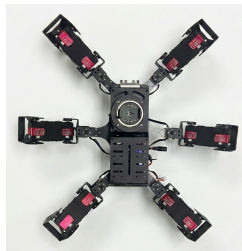

Fig. 1. Spider Pi's picture from top view taken in the laboratory.

Before implementing the gait algorithm, several values needed to be determined, including each servo's ID, its "default position" (the position the robot returns to after resetting), and its direction of motion. The ultrasonic sensor's output unit was also unknown. Therefore, the lab began with repetitive testing to collect these information.

Servo IDs range from 1 to 18, so we systematically changed servo positions using different IDs and matched each ID to its corresponding physical servo. Next, default positions were read and recorded immediately after resets. Finally, to determine each servo's motion direction, we modified position values slightly above and below the default and observed how the motion changed.

To determine the ultrasonic sensor's output unit, the robot was placed at three known distances (10 cm, 20 cm, and 30 cm) from a wall, measured with a ruler. To improve reliability, we ran 10 trials for each distance and kept surroundings clean to reduce noise.

The second part of the lab was the implementation of ripple and tripod gaits [Fig. 2]. Ripple is characterized by moving a pair of legs on opposite sides simultaneously, followed by the next pair, and so forth. Tripod is characterized by always having three legs in contact with the ground while the other three legs lift and propel the robot body in the desired direction [1, Chap. 5].

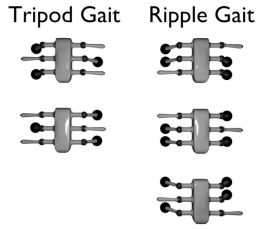

Fig. 2. Illustration of tripod and ripple gait, in which light circles indicate feet touching the ground [1, Chap.5].

However, unlike the traditional ripple gait illustrated in Fig. 2, we were inspired by a traditional Chinese sport—dragon boat racing—in which people use paddles on both sides of the boat to generate forward motion by rowing backward against the water.

Specifically, we separated the ripple gait into two phases. In the first phase, the robot sequentially swings the front and middle pairs of legs forward and the back legs backward. Before swinging, each pair of legs lifts slightly to break contact with the floor to prevent distorting the robot's body due to friction, then lowers after swinging. In the second phase, the robot pushes downward and swings backward the front and middle legs to generate forward force, resembling how a dragon boat moves. Then, the back legs push down slightly and extend the outermost servo, providing additional forward motion. These phases repeat to form the gait cycle. For larger movements, the push-and-extend magnitudes are increased and motor speed is higher.

To implement the tripod gait, the robot first lifts three legs while the other three form a tripod on the ground. While in contact with the ground, the tripod legs rotate backward to generate forward force on the robot body. Meanwhile, the lifted legs rotate forward in the air and are then lowered back onto the ground. The same process is repeated for the other three legs to form one gait cycle. For the version with larger movements, the forward rotation angle is larger.

Then, the lab evaluated the performance of ripple and tripod gait respectively by measuring the displacement in both the x and y directions over 10 seconds and 30 seconds. For each gait, both the small and large versions were run for three trials to improve the reliability of the measurements.

Fig. 3. Set up of the ruler system built for measuring robot's distance traveled in both x (vertical) and y (horizontal)

To accomplish this, we adopted two measurement approaches. The first approach measured displacement by using sensor in x direction and ruler in y direction; a ruler was also used to measure the x direction for comparison with sensor-based measurements. The second approach relied solely on a ruler to measure both the x and y directions using the setup shown in Fig. 3.To maintain accuracy, we ran the test in an empty space without obstacles that could potentially interrupt the robot while moving. We also ensured the robot started from the same initial position by marking the floor with tape to improve measurement reliability [Fig. 4].

Fig. 4. Robot starting positions marked by tapes

III. RESULTS

As shown in Fig. 5, at a testing distance of 10 cm, the ultrasonic sensor produced readings of 105, 112, 108, 105, 106, 113, 105, 109, 102, and 101(μ = 106.6, **σ** = 3.92). At 20 cm, the readings were 210, 214, 213, 211, 212, 213, 213, 210, 214, and 212 (μ = 212.2, **σ** =1.48). At 30 cm, the readings were 308, 307, 307, 308, 312, 306, 308, 312, 307, and 307 (μ = 308.2, **σ** = 2.10). The sensor output and actual distance formed an almost perfect linear relationship (with slopes of approximately 10.66, 10.61, and 10.27 for 10, 20, and 30 cm respectively), which confirms millimeter units.

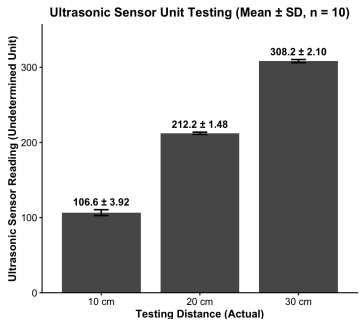

Fig. 5.Ultrasonic sensor unit testing results at distances of 10 cm, 20 cm, and 30 cm. Bars represent the mean of readings from 10 trials per distance. The error bars represent the standard deviation.

Next, as shown in Fig.6, when given 10 seconds, the small ripple gait moved 75, 69, and 71 millimeters (μ = 71.7, **σ** = 3.1) in x direction when measured by ruler and 87, 82, and 82 millimeters (μ = 83.7, **σ** = 2.9) when measured by the sensor. The robot moved 9, 8, and 12 millimeters (μ = 9.7, **σ** = 2.1) in y direction. The large ripple, on the other hand, moved 141, 135, and 143 millimeters (μ = 139.7, **σ** = 4.2) in x direction when measured by ruler and 174, 182, and 177 millimeters (μ = 177.7, **σ** =4.0) when measured by the sensor. The robot moved 71, 71, and 72 millimeters (μ = 71.3, **σ** =0.6) in the y direction. On the other hand, under 30 seconds, the small ripple gait moved 337, 334, and 342 millimeters (μ = 337.7, **σ** = 4.0) in x direction when measured by ruler and 327, 329, and 323 millimeters (μ = 326.3, **σ** = 3.1) when measured by the sensor. The robot moved 23, 27, and 23 millimeters (μ = 24.3, **σ** = 2.3) in y direction. Alternatively, the large ripple moved 561, 566, and 553 millimeters (μ = 560.0, **σ** =6.6) in x direction when measured by ruler and 523, 517, and 510 millimeters (μ = 516.7, **σ** =6.5) when measured by the sensor. The robot moved 210, 211, and 208 millimeters (μ = 209.7, **σ** =1.5) in the y direction.

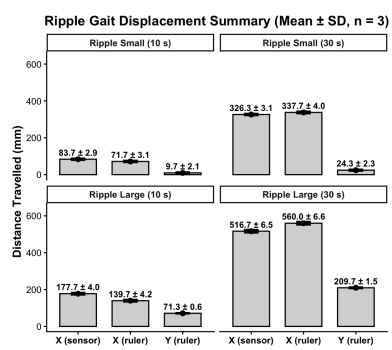

Fig. 6. Ripple gait testing with different conditions illustrated. Bars represented the average displacement of that condition with the standard deviation error bars.

The same conditions and tests were also run for the tripod gait. Under 10 seconds, tthe small tripod gait moved 425, 417, and 430 millimeters (μ = 424.0, **σ** = 6.6) in the x direction when measured by ruler and 422, 409, and 415 millimeters (μ = 415.3, **σ** = 6.5) when measured by the sensor. The robot moved 27, 32, and 26 millimeters (μ = 28.3, **σ** = 3.2) in the y direction. The large tripod, on the other hand, moved 960, 957, and 972 millimeters (μ = 963.0, **σ** = 7.9) in the x direction when measured by ruler and 903, 910, and 915 millimeters (μ = 909.3, **σ** = 6.0) when measured by the sensor. The robot moved 43, 42, and 55 millimeters (μ = 46.7, **σ** = 7.2) in the y direction.

On the other hand, under 30 seconds, the small tripod gait moved 1502, 1492, and 1484 millimeters (μ = 1492.7, $\boldsymbol{\sigma}$ = 9.0) in the x direction when measured by ruler and 1492, 1479, and 1510 millimeters (μ = 1493.7, $\boldsymbol{\sigma}$ = 15.6) when measured by the sensor. The robot moved 63, 58, and 52 millimeters (μ = 57.7, $\boldsymbol{\sigma}$ = 5.5) in the y direction. Alternatively, the large tripod moved 2983, 3001, and 2990 millimeters (μ = 2991.3, $\boldsymbol{\sigma}$ = 9.1) in the x direction when measured by ruler and 1766, 1812, and 1784 millimeters (μ = 1787.3, $\boldsymbol{\sigma}$ = 23.2) when measured by the sensor. The robot moved 62, 65, and 59 millimeters (μ = 62.0, $\boldsymbol{\sigma}$ = 3.0) in the y direction [Fig. 7].

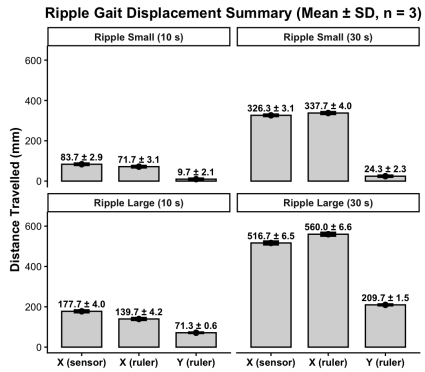

Fig. 7. Tripod gait testing with different conditions illustrated. Bars represented the average displacement of that condition with the standard deviation error bars.

IV. DISCUSSIONS

Results showed astonishingly large deviations across groups. In Fig. 8, the percent differences between small and large ripple gaits given the same time are huge. Within 10 seconds, the difference in the x direction is 94.88%, and 637.93% in the y direction. There were also noticeable differences between sensor readings and ruler measurements. For example, the x-direction sensor reading for small ripple under 10 seconds had a 16.73% difference compared to the ruler measurement. Additionally, the effect of 20 additional seconds was non-negligible—the robot moved more than 300% farther in the x direction and 150% farther in the y direction when given 30 seconds compared to 10 seconds. Several reasons explain these deviations. First, the large gait increases push and extension extent, as well as servo motor speed, so the robot travels farther in both directions.

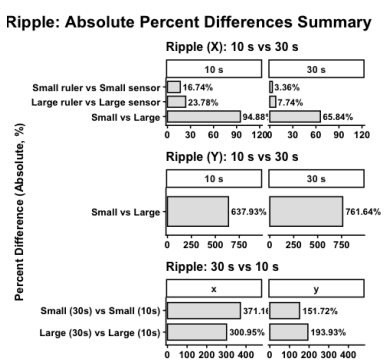

Fig. 8. Ripple gait testing results and comparison with percent differences.

However, this also introduced more unsteadiness that distorted the robot's direction, explaining why the larger gait moved much farther in the y direction. Secondly, distortions in the y direction caused the sensor to no longer detect distance parallel to the x direction, reducing accuracy.

On the other hand, the tripod gait also had large deviations but presented a different pattern. In Fig. 9, the robot moved more than 100% farther in the x direction when using a large gait, and drifted 64.71% in the y direction for 10 seconds but much less for 30 seconds. Unlike the ripple gait, sensor readings and ruler measurements in the x direction were not as different—only 2.09% for the small gait and 5.90% for the large gait at 10 seconds. However, there was a large deviation when using the large gait for 30 seconds. When given more time, both gaits

moved the robot more than 200% farther in the x direction, and 32.86% farther for the large gait and 103.56% farther for the small gait in the y direction.

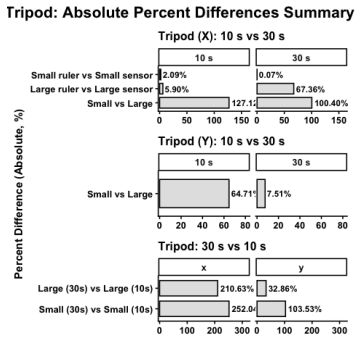

Fig. 9. Tripod gait testing results and comparison with percent differences.

One significant difference between the tripod gait and ripple gait is their steadiness. The tripod gait was more stable and symmetrical while moving, which produced less distortion in the y direction and thus explains why differences between sensor readings and ruler measurements were minor compared to the ripple gait. However, when using a large gait for 30 seconds, the difference between ruler and sensor measurements was substantial. This is likely because the longer operation time combined with amplified rotational drift caused the robot body to deviate more, which reduced the accuracy of distance estimation by the ultrasonic sensor.

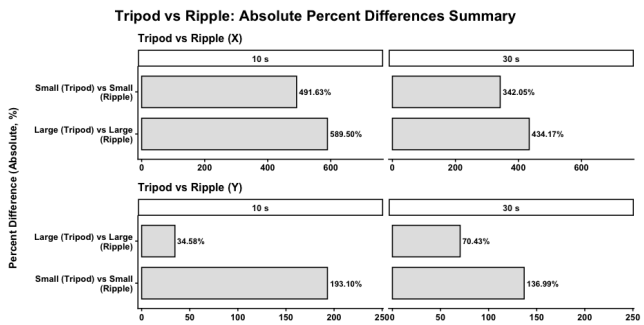

Fig. 10. Performance comparison of the tripod gait and ripple gait.

Overall, the tripod gait outperformed the ripple gait to a surprising extent, moving the robot in the x direction by an average of almost 400% more [Fig. 10]. Several factors explain this. First, the tripod gait has a shorter movement cycle, allowing more iterations given the same time and thus greater total displacement. Second, the tripod gait moved more symmetrically and stable which kept the robot mostly along the x direction, whereas the ripple gait substantially distorts and drifts due to the friction. There are also other uncertainties that contribute to the deviations. For instance, the unstable sound wave spreading can affect the echolocation which brings errors to the sensor reading; human eye observation can bring minor errors when measuring displacement by ruler; and different test timings with unequal battery voltage can also affect servo's performance.

V. CONCLUSIONS

In conclusion, this lab explored how sensors and actuators work on a robot platform and how to effectively manipulate them to enable robot locomotion while gathering valuable insights from the sensor. Specifically, this lab calibrated the sensor's reading through rounds of testing, emphasizing the importance of processing the sensor's raw output to useful information. Additionally, this lab implemented and evaluated ripple and tripod gait by testing the distance traveled of them given different amounts of time. The results and discussion underscore the trade-offs between gait complexity and stability—the ripple gait's reliance on sequential leg movements caused friction-related inefficiencies, while the tripod gait's constant three-leg ground contact provided consistent forward propulsion.

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