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Abstract

This project consists of two packages, one related to building robots and the other is tracking objects using camera vision. The goal for both is to accurately measure the pose of the end effector and Apriltags. The robots are designed to measure angles for the rotary joint and the other linear distance for the prismatic joint. Solely using the mathematical expressions yield highly inaccurate results, but after adding a compensator through adding constants and variable time delay, the results improved drastically. The rotary robot measures the desired angle within $\pm 1°$, and the the prismatic robot measure within $\pm 0.2cm$. For the camera calibration and tracking, it was observed that the positional and temporal errors were relatively low. But the motion measurements were highly inaccurate. Taking more photographs with higher range of perspective and improve the accuracy in the calibration process. The difference between the plotted position and physical measurement was about 5%. The temporal variation for position is about 3mm.

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1 Introduction

The purpose of this project is to apply the knowledge related to forward kinematics, inverse kinematics, and vision.

2 Theory

This section will outline the mathematical theory utilized in building the robots and tracking pose of the Apriltags.

2.1 Package A: Building (Jann Cristobal)

For this project, there are two main requirements for the robots. The first one is to produce a rotary motion whose output angle can be accurately measured given the user input. The second one is to produce a linear motion whose output distance can be accurately measured given the user input.

2.1.1 Part A: Rotary Joint

For the first robot, the large motors can be controlled precisely to rotate a specific amount. The method used to achieve the requirements is by using gear train. The main take away from using gears is the idea of utilizing mechanical advantage. Gear ratio is calculated as:

$$R = \frac{\omega_A}{\omega_B} = \frac{r_B}{r_A} = \frac{N_B}{N_A}$$

where A is the input gear, B is the output gear, ω is the angular velocity, r is the radius, and N is the number of teeth.

A low gear ratio amplifies the output velocity at the expense of input torque. The opposite is true for a low gear ratio. Clearly, using the proper gear ratio will yield the maximized performance [1].

2.1.2 Part B: Prismatic Joint

For the second robot, the goal is to create a linear motion and measure the distance given by the user. There are several ways to achieve this such as hydraulic, and pneumatic systems. These methods work by manipulating fluid pressure distribution to create a force that results in linear motion.

For this project, the LEGO Mindstorms kit uses electric motors. Thus, linear motion can be achieved by converting rotational motion using linkages and the various gears in the kit. A slider-crank mechanism is one of the methods that can be utilized for this purpose.

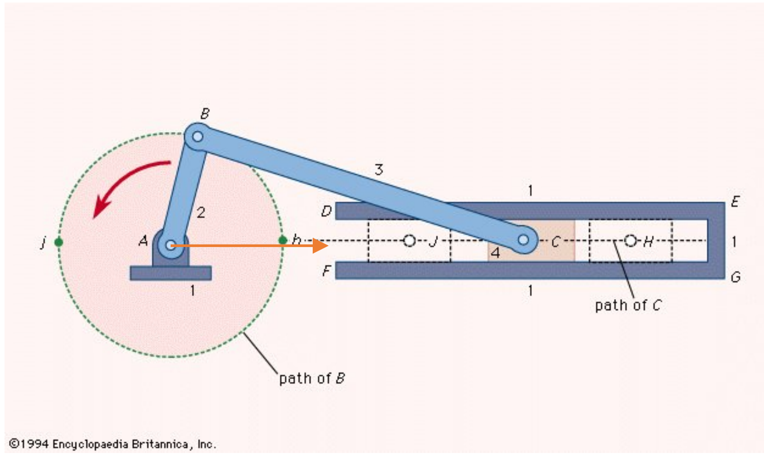


Figure 1: Slider-crank mechanism [2]

Figure 1 above shows how the rotational motion about joint A is converted into a linear motion of joint C. The set of equation that describes this mechanism is given as follow:

$$r_1 = r_2 \cos(\theta_1) + r_3 \cos(\theta_2)$$

$$r_2 \sin(\theta_1) = r_3 \sin(\theta_2)$$

Where the unknown variables θ_1 is the input angle from the motor, and θ_2 is the angle between link 3 and 1. These unknown parameters can be solved given the variable $r_1$which is the distance between joint A and C, and the constant link lengths r_2 and r_3.

2.2 Package B: Vision (Stephanie Chan)

For this project, two different cameras will be compared based on their intrinsic parameters. The intrinsic matrix generated by MATLAB is denoted by K and is shown below.

$$K = \begin{bmatrix} f_x & s & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{bmatrix}$$

S is axis skew, f_x and f_y are the focal lengths, and x_0 and y_0 are the principal point offsets. Skew can be broken down into $f_x \cos\theta$ where θ is the skew angle. A non-zero skew angle results in non-square pixels. An example of a pixel with a non-zero skew angle is shown below in figure 2.

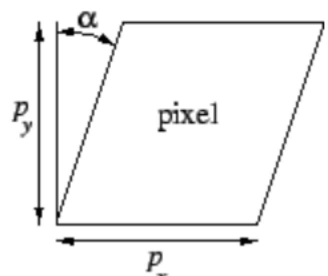


Figure 2: Pixel with a skew angle [3]

Focal length is the distance between the pinhole camera and the image plane. Higher focal length values result in images appearing to be zoomed in, and lower focal length images result in images appearing to be zoomed out. When f_x and f_y differ, the result is a non-square pixel. The greater the difference, the larger the pixel deviation.

Principal point offset is the distance between the principal point and the film origin. A perfectly calibrated camera would have principal point offsets of zero. Non-zero values result in images being shifted up or down, or to the left or right.

The software used for this project is MATLAB. A checkerboard calibration target was used to calibrate the camera. Apriltags were used to measure the accuracy of the system.

3 Design Documentation

This section will show the design process involved in finding a solution for the problem statements.

3.1 Package A: Building (Jann Cristobal)

3.1.1 Part A: Rotary Joint

There were several steps involved in designing and building this robot. The first part was coming up with the structure, and then programming the robot to do the desired tasks.

The first step for designing this robot was determining the gear ratio given the available parts in the Lego Mindstorms kit. The final overall gear ratio that was used is 1:5. The main reason for a having a low gear ratio is because the Lego motors can only measure angles as integers. Thus, having a low gear ratio would increase the accuracy of the output angle (i.e. $1°$ motor angle is equivalent to $0.2°$ output angle). This gear ratio was achieved by arranging the 12-tooth, 20-tooth, 36-tooth double bevel gear, and 28-tooth turn table as shown in figure 3 below.

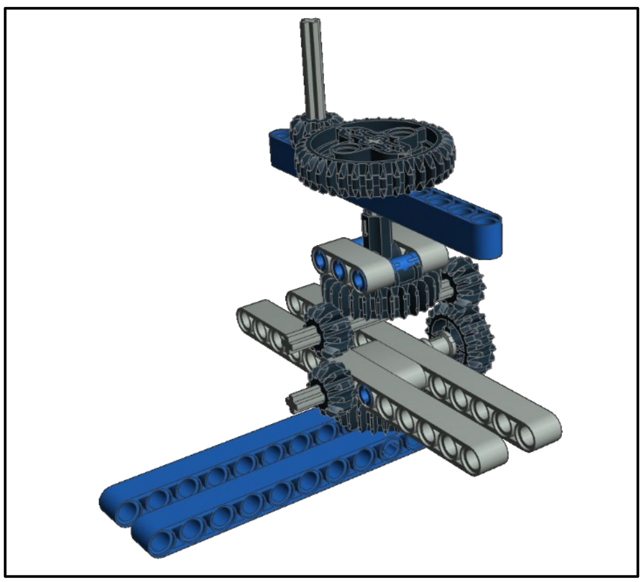


Figure 3: Gear train arrangement

The input shaft spins the 12-tooth gear which drives the 36-tooth gear attached to the 28-tooth turntable. It then drives a 12-tooth gear attached to a 12-tooth gear. Then, it drives the 20-tooth gear attached to a 12-tooth gear which drives the 28-tooth gear turn table.

$$\left(\frac{12}{36}\right)\left(\frac{28}{12}\right)\left(\frac{12}{20}\right)\left(\frac{12}{28}\right)=\frac{1}{5}$$

This arrangement was achieved by first having the main gear train as $\left(\frac{12}{20}\right)\left(\frac{12}{36}\right)$. The rest were added in order to change the direction of motion as well as to fit it within the base structure.

After determining the gear train, the next step was designing the indicator. The initial idea was to have a pencil holder that would draw an arc which could then be measured manually after running the robot. Figure 4 below shows the penholder design.

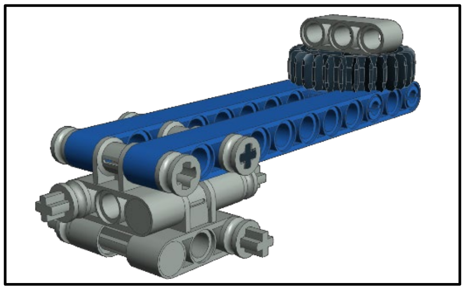


Figure 4: Penholder

The goal for this design was to have some adjustment by utilizing the shafts and pins which can be loosened and tightened with ease. This idea of having a pen holder was later abandoned in favor of a simpler indicating arrow.

After that, the next step was to design the homing mechanism. To do this, two touch sensors are used. One for zeroing the frame and the other for sensing the maximum range allowable, which is $180°$ for this robot. Further illustrations for the positioning of the sensors and how they are activated can be seen in the assembly drawing in figure 5.

The next step was to mount the motors and finish the overall structure. This was done by connecting the beams and the rectangular frames to form a stable base for the robot to stand.

The final design for the whole robot can be seen below in figures 5 and 6.

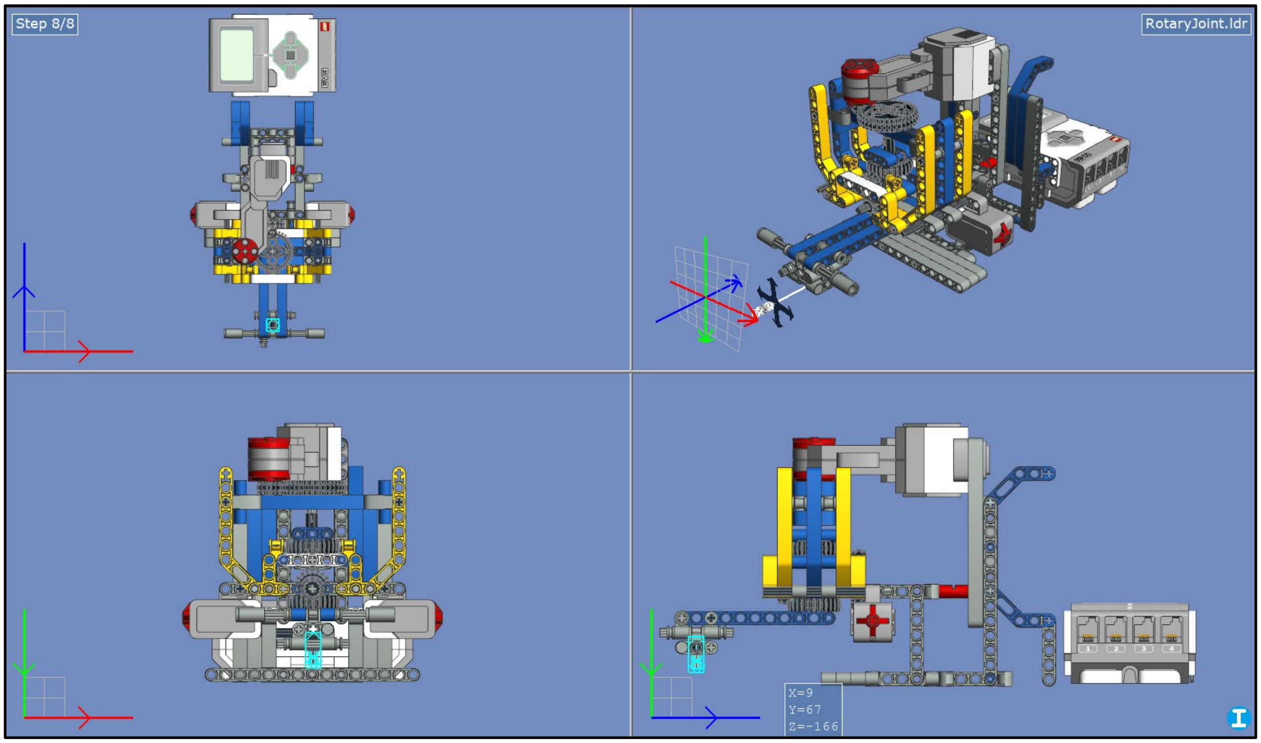


Figure 5: Three-View Drawing for the Rotary Robot

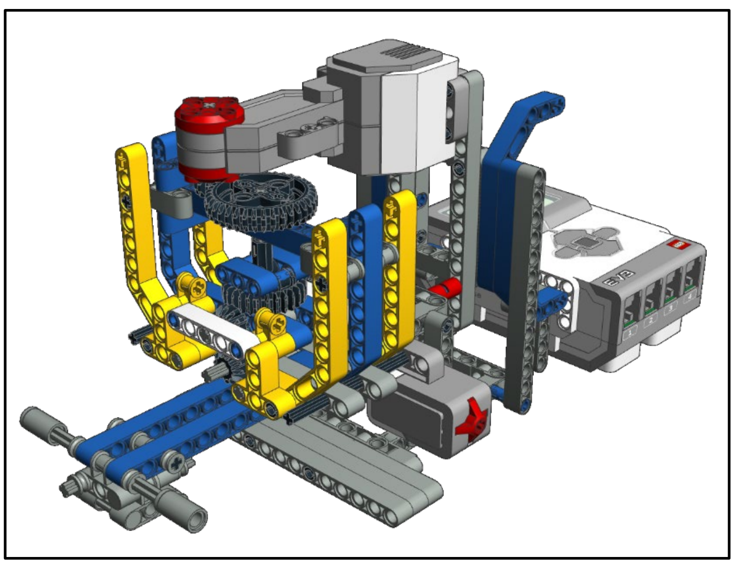


Figure 6: Isometric view for the Rotary Robot

After building the structure, the next step was to program the robot to do the required task of measuring the desired angle as inputted by the user. The pseudo code or logic is as follows:

1. The user is asked for the desired angle.
2. Checks if the angle is within the range of 0 to 180 degrees. If not, the prompt shows up again asking for an angle within the range.
3. If the angle is within the range, the required motor angle is calculated using the gear ratio.
4. Motor starts in the direction towards the zero position.
5. Once homed, the motor angle reader is reset, then the motor turns the direction of increasing angle.
6. Motor angle is continually read. Once it matches the required motor angle, and the mechanism has been homed prior, the motor will stop.
7. If the motor angle does not match the required angle, it will continue past the desired angle until it reaches the maximum limit of 180 degrees.
8. Then, the process will restart from home until the required angle is found with respect to the zero-position.

3.1.2 Part B: Prismatic Joint

Starting with the structural designing and building, similar to the rotary robot, the first step was to pick a gear ratio which is crucial for doing the math later. For this robot, the overall gear ratio is 1:25 between the input and output. The reason for having a low gear ratio is similar to the previous, which is to increase the accuracy for reading small angles. To achieve this gear ratio, the 8 tooth, 24 tooth, and worm gears were used. The worm gear is used to change direction. The gear train is arranged as:

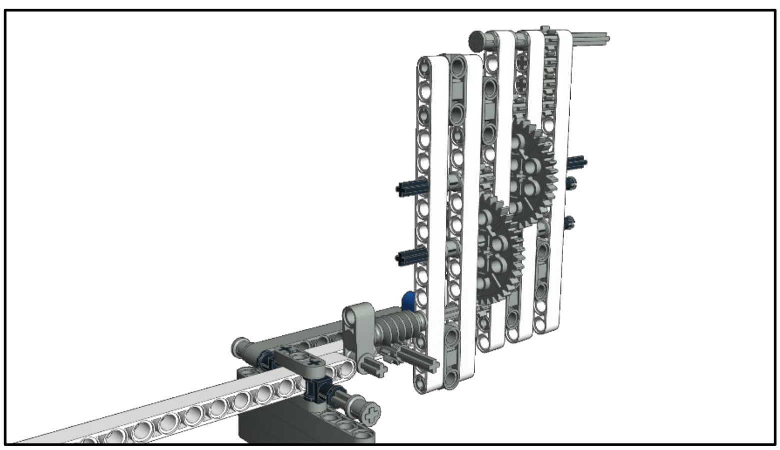


Figure 7: Gear Train for the Prismatic robot

The input shaft spins the 8-tooth gear which drives the 8-tooth gear attached to the 8-tooth gear. It then drives a 40-tooth gear attached to a 8-tooth gear. Then, it drives the 40-tooth gear attached to a 8-tooth gear which drives the 8-tooth gear.

$$\left(\frac{8}{8}\right)\left(\frac{8}{40}\right)\left(\frac{8}{40}\right)\left(\frac{8}{8}\right) = \left(\frac{1}{25}\right)$$

The next step was to figure out how to convert rotation to translational motion. As discussed in the theory portion, the method chosen is a slider crank mechanism. Figure 8 below shows how the mechanism will be implemented using the Lego beams, cranks shafts, and gears.

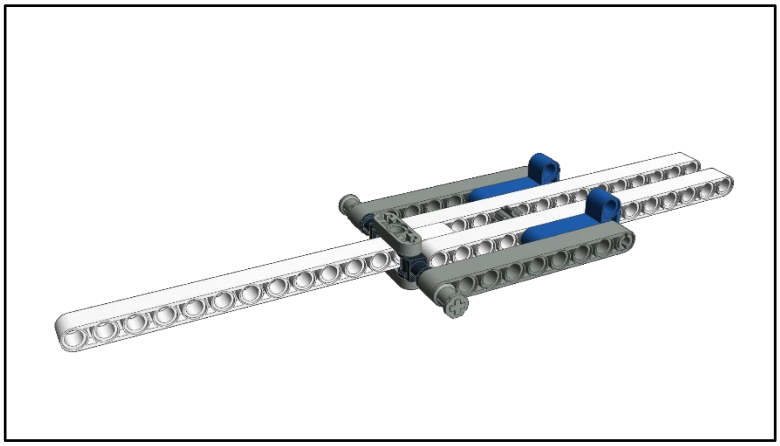


Figure 8: Slider crank design for the prismatic robot

There are several parameters for this mechanism. The equations that relate all these parameters are:

$$r_1 = r_2 \cos(\theta_1) + r_3 \cos(\theta_2)$$

$$r_2 \sin(\theta_1) = r_3 \sin(\theta_2)$$

Where fixed lengths $r_2 = 2.4\ cm$, $r_3 = 6.4\ cm$, variable link length r_1, unknown angle θ_1 , and θ_2.

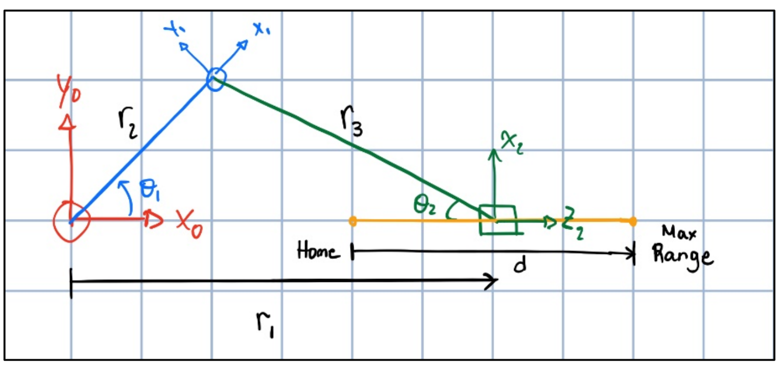


Figure 9: slider crank parameters

If we set r_1 to be a specific value, we are left with two unknowns, θ_1 and θ_2. They can be solved since there are two equations that can be related to one another. Due to the nature of solving for angles using trigonometry, there are two possible set of answers for any given r_1. What this means physically, is that one solution will have elbow up as shown in figure 9, and the other will be elbow down which will be mirrored off of the $x_0 - z_0$ plane.

The next step is the homing mechanism. Since the touch sensor was already used for the first robot, the ultrasonic sensor was used as a way to home the mechanism. The way this works is by positioning the sonic sensor a known distance away from the homed position and using that value to set the measurements with respect to that position.

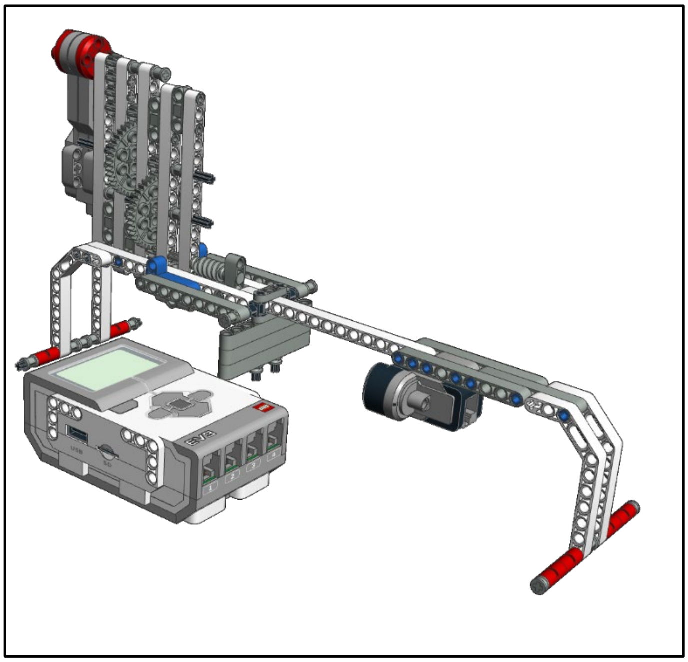


Figure 10: Ultrasonic sensor a zero mechanism.

As seen on figure 9, when the slider crank is homed, i.e., $\theta_1 = 180°$, the sonic sensor will measure a distance of 7.6 cm away from its current position. Thus, whenever it detects the stack of beams at that distance, the system knows that it is homed. The ultrasonic sensor can also be used to determine whether the distance has reached the maximum value when it reads 3.1 cm. The range of linear motion is 4.8 cm from the zero position to max when measured using a ruler, which means there are some errors when it comes to using the ultrasonic for measuring distances. Although this is the case, it is accurate enough to always know when it is homed or has reached max distance.

The final design for the structure of the prismatic robot can be seen in figure 11 and 12 below.

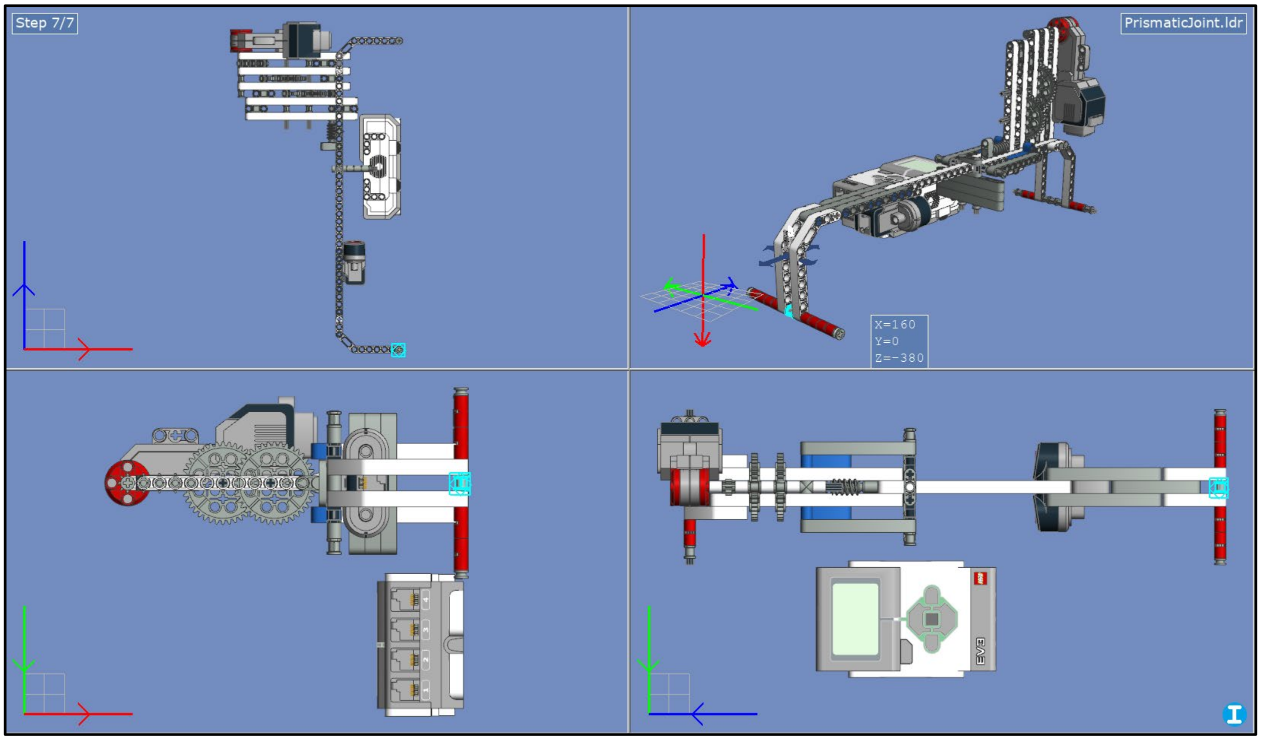


Figure 11: Three view drawing for the prismatic robot.

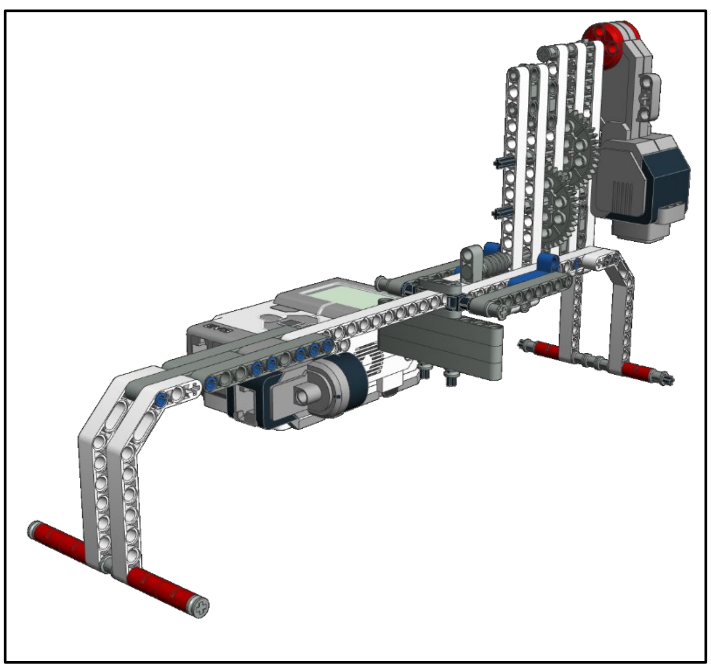


Figure 12: Isometric view for the prismatic robot.

After building the structure, the next step was to program the robot to do the required task of measuring the desired angle as inputted by the user. The pseudo code or logic is as follows:

1. The user is asked for the desired distance.
2. Checks if the distance is within the range of 0 to 4.8cm. If not, the prompt shows up again asking for a distance within the range.
3. If the distance is within the range, the required r_1 link length is calculated.
4. The angle θ_1 for joint A is then calculated using the above equation.
5. Then, the required motor angle is calculated using the gear ratio.
6. Motor start in the direction towards the zero position.
7. Once homed, the motor angle reader is reset, then the motor turns the direction of increasing distance.
8. Motor angle is continually read. Once it matches the required motor angle, and the mechanism has been homed prior, the motor will stop.
9. If the motor angle does not match the required angle, it will continue past the desired angle until it reaches the maximum limit of 4.8 cm.
10. Then the process will restart from home until the required angle is found with respect to the zero-position.

3.2 Package B: Vision (Stephanie Chan)

Several factors in the intrinsic matrix determine how accurately a camera can capture images. These factors include skew, focal length, and principal point offset [3]. Table 1 below includes the intrinsic calibration constants for both Stephanie's camera and Jann's camera.

Table 1: Intrinsic Camera Parameters

Camera Parameters	Stephanie's Camera	Jann's Camera
Skew	0	0
Focal Length (x) [pixels]	3755.59291132048	1374.64865068782
Focal Length (y) [pixels]	3750.30930109363	1373.02071981653
Principal Point Offset (x) [pixels]	2225.88373612818	965.538333995719
Principal Point Offset (y) [pixels]	1724.03225751081	558.859582289156

This table shows the comparison between the two camera parameters between both members.

Skew affects whether there are any barreling or pin-cushioning distortion effects. Both cameras have a skew factor of zero, meaning there is no distortion due to skew.

Looking at focal length, Stephanie's camera parameters are approximately 3 times greater than Jann's camera parameters. Focal length is the distance between the pinhole and the image. Greater differences in the focal length x and y values create a distorted image. Stephanie's focal length values for x and y differ by 5 pixels, while Jann's focal length values differ by 1 pixel. This indicates that Jann's camera is more accurate.

Concerning principal point offset, Stephanie's camera parameters are approximately 2 to 3 times greater than Jann's parameters. A larger positive principal point offset shifts the image to the right and up. Considering all five intrinsic parameters, it can be concluded that Jann's camera gives a better performance.

The following scene calibration procedure was conducted with the Apriltags.

1. Four Apriltags were positioned on a flat surface (floor). A camera was set up to point at the Apriltags.
2. The positions of the Apriltags were measured in relation to each other.
3. The MATLAB file, ***setup_script.m***, was run. The script produced two figures. Figure 13 shown below is the raw bitmap image, and figure 14 is the processed schematic version.

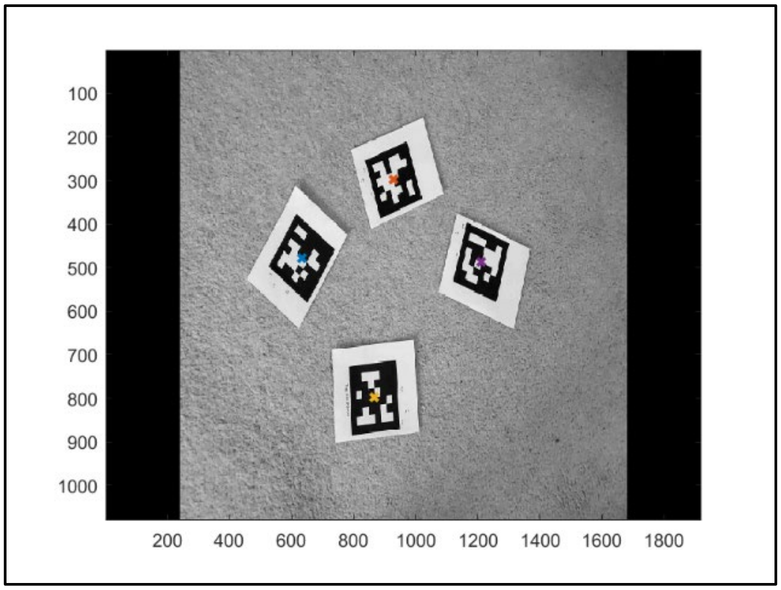


Figure 13: Raw bitmap image.

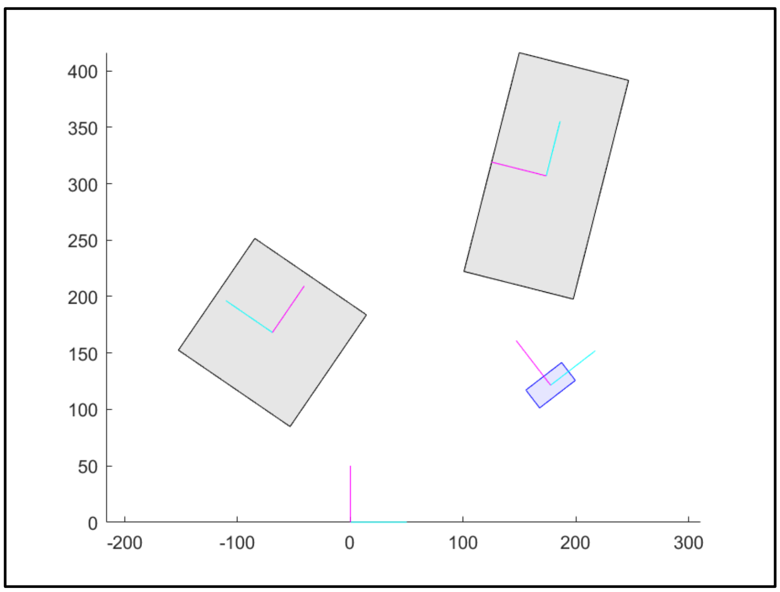


Figure 14: Processed schematic.

A requirement of this project is to measure positional and rotational accuracy. To measure positional accuracy, the distance between the Apriltags was measured using a ruler and compared to the distance given in the processed schematic image provided by MATLAB. To measure rotational accuracy, the origin tag was rotated 90 degrees and the rotated measurements were compared to the original measurements. Thus, we can determine how well the camera detects images positionally and after rotations.

4 Project Operations

This section will discuss the results of how well the systems performed.

4.1 Package A: Building (Jann Cristobal)

1. Assess the accuracy and repeatability of the manipulator motion in response to commanded motion.

Without doing any adjustments in hardware or compensation in software to the final design, it appears that solely relying on the math will not yield the desired results. The accuracies of the robots are low. Some factors that contribute to this include friction, high gear tolerance, and bending.

2. Is that motion biased?

Both robots have motion bias. For the rotary robot, the indicator appeared to be lagging behind the desired angle by about 5 degrees. For the prismatic robot, the inaccuracies increased as the distance required reached the maximum value. The physical measurement lags as large as 1.2cm behind the desired distance for the maximum value.

3. How repeatable is your homing mechanism and software?

The repeatability of the homing is excellent. Once the program was finished, the rotary robot always zeros the system. For the prismatic robot, the only time it fails is towards the end of a long day of testing. This may be due to the ultrasonic sensor itself, because the zero value would sometimes go from 7.6 cm to 7.4 cm sonic sensor reading. This issue can easily be fixed either by restarting the EV3 or recalibrating by deconstructing and reconstructing the hardware.

4. Are there any changes to the software or hardware design that can improve the performance?

In terms of hardware design changes, it is possible to improve performance by using lubricant to reduce friction, reducing the number of gears and direction changes to reduce gear tolerance, and having more support structure to reduce bending. In terms of software, slowing down the motor speed allows for a more accurate reading of the angles and compensators were added in order to correct for the motion bias. For the rotary robot, it was compensated by adding 5 degrees to the desired arm angle. For the prismatic robot, a time delay was calculated based on experimental values. There is not one equation that works for the whole range of motion, but by using a switch statement, correlation for key ranges were experimentally determined.

4.2 Package B: Vision (Stephanie Chan)

1. Evaluate the precision and accuracy of the image analysis software.

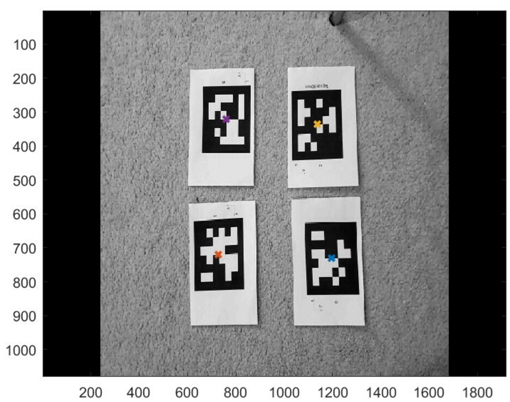
To evaluate the precision and accuracy of the image analysis software, the physical Apriltag measurements were compared to the positions given by the software. Measuring the middle of the origin tag to the edge of the adjacent tag using a ruler resulted in 19.6 cm. The distance described by the image analysis software was 20.6 cm. This positional difference of 1cm is approximately 5% of the distance. This indicates the software is not very accurate.

2. Is there much temporal variation in the reported positions (with no motion)?

To analyze temporal variation, three trials were performed with the camera and Apriltags in the same position. Table 2 show below summarizes the positions of each tag relative to the origin tag in millimeters. Figure 15 (a) and (b) show the raw bitmap image and processed schematic for trial 1.

Table 2: Apriltag positions for temporal variations.

Trial	**Tag 1**	**Tag 2**	**Tag 3**	**Tag 4**
1	(0,0)	(145.404, -5.77579)	(151.916, -145.665)	(5.23686, -173.812)
2	(0,0)	(144.451, -3.24762)	(151.838, -142.313)	(4.85116, -171.932)
3	(0,0)	(144.662, -3.53489)	(152.004, -142.701)	(5.16585, -172.493)



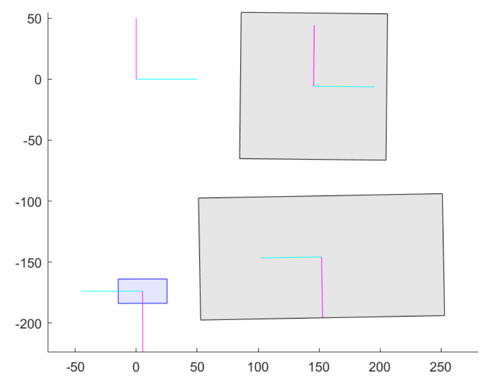


Figure 15: (a) raw bitmap image for trial 1 and (b) processed schematic for trial 1.

Overall, there is relatively low temporal variation across the three trials. The greatest variation is approximately 3mm in the y direction of tag 3. Since the experiment was not conducted in ideal conditions, the variation could also be due to the camera shifting a few millimeters or the Apriltags being blown a few millimeters to the side by wind.

3. How uniform is the motion measurement throughout the field of view?

To determine how uniform the motion measurement is throughout the field of vision, 3 trials were conducted with the Apriltags in constant positions and the camera at different angles and distances. Figures 16, 17, and 18 below are the raw bitmap images and processed schematics for each trial.

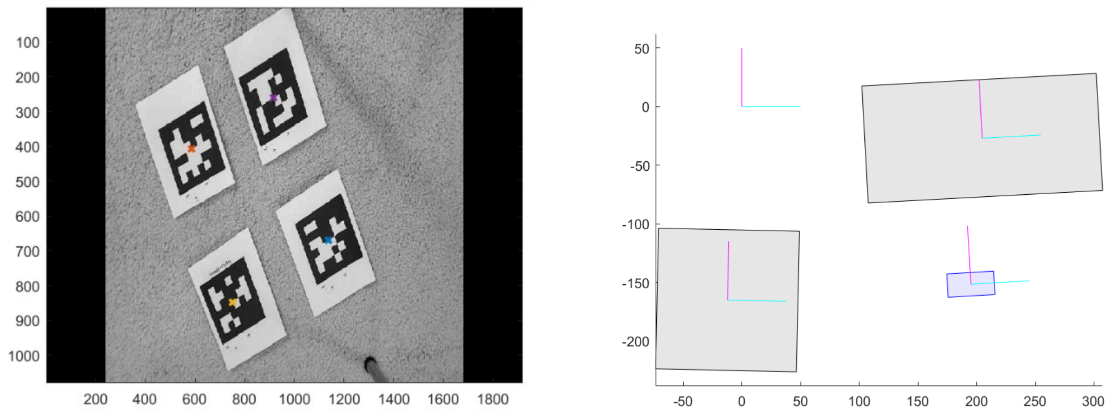


Figure 16: (a) raw bitmap image for motion trial 1 and (b) processed schematic for motion trial 1.

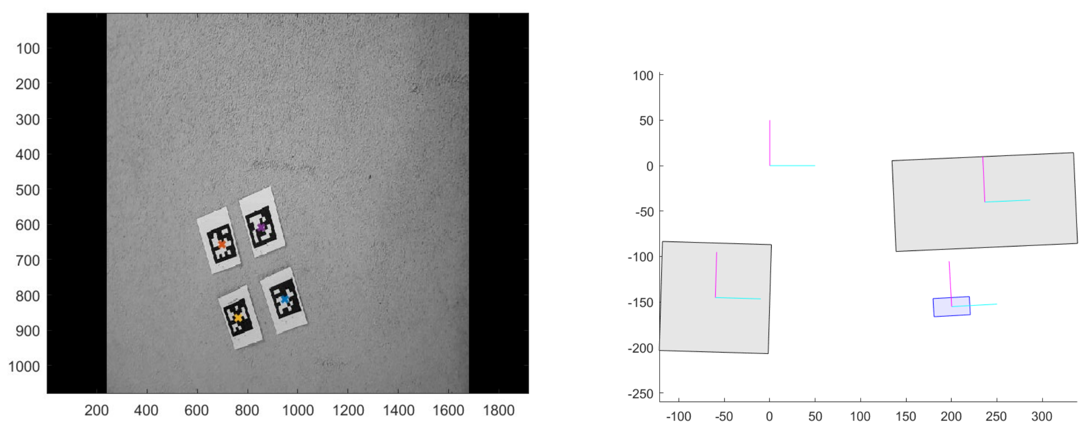


Figure 17: (a) raw bitmap image for motion trial 2 and (b) processed schematic for motion trial 2.

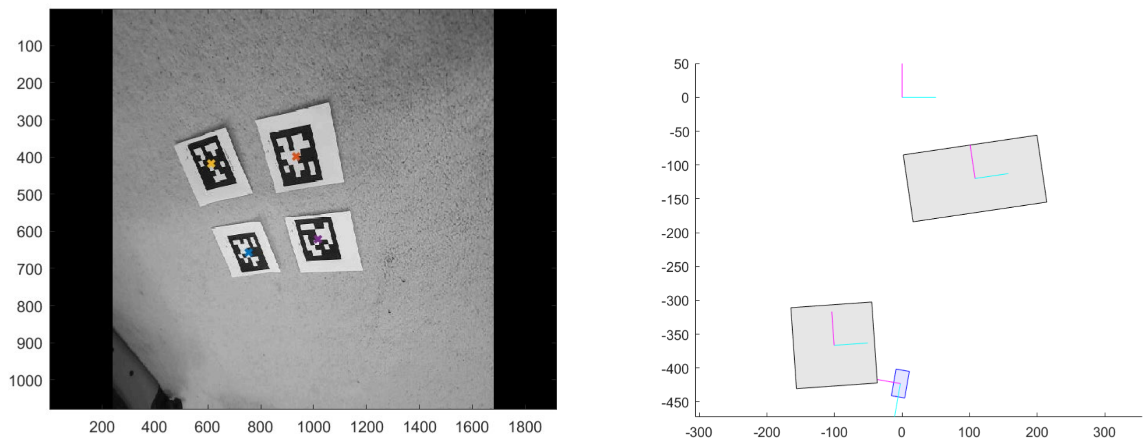


Figure 18: (a) raw bitmap image for motion trial 3 and (b) processed schematic for motion trial 3.

Although the position of the camera has changed, the position and distance between the tags and origin should have remained constant. The distances given in the different schematics can be compared and the uniformity of motion measurement can be determined. Table 3 below summarizes the positions of the tags relative to the origin tag.

Table 3: Apriltag positions for motion measurements.

Trial	**Tag 1**	**Tag 2**	**Tag 3**	**Tag 4**
1	(0,0)	(204.785, -26.9285)	(195.137, -151.5)	(-12.2043, -164.989)
2	(0,0)	(236.703, -40.0624)	(200.252, -155.137)	(-59.9088, -145.133)
3	(0,0)	(107.961, -119.883)	(-2.557, -422.976)	(-100.626, -366.526)

The positions of the tags vary greatly between each trial. For trial 3, the camera was positioned on the opposite side which resulted in the greatest differences in position. From this experiment, it can be concluded that the motion measurement throughout the field of vision is highly inaccurate.

5 Conclusion

Overall, the building and vision projects were successful in terms of accomplishing the required tasks in the problem statements. For building the robots, the mathematical theories used to achieve the requirements were adequate. The errors resulting in motion bias were due to factors not considered when building kinematic models. These include factors such as friction, tolerances, and bending. In terms of the reliability of the homing mechanism, both robots performed exceptionally. In order to improve performance, a time delay was added to the software to compensate for the motion bias. At the end, the rotary joint measured the desired angle within $\pm 2°$, and the prismatic joint measured within $\pm 0.2cm$. After calibrating the camera for the vision project, it was observed that the positional and temporal errors were relatively low. On the other hand, the motion measurements were highly inaccurate. To improve precision and accuracy, the camera could be recalibrated using more images. Taking a greater number of calibration images at various angles and distances would improve the accuracy and consistency of the system.

6 References

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AER 627: Intro to Space Robotics, Laboratory Report Evaluation

Student Name(s): Jann Cristobal					
Lab Number: 1	**Section: 02**		**TA: Joel Moore**		
Component	**Excellent**	**Good**	**Satisfactory**	**Needs Improvement**	**Grade**
Analysis (Grades are tailored to each problem set)					
Completeness					
Clear, concise, legible					
Understanding of Theory					/5
Design Documentation Assignment					
Chosen design explained clearly with appropriate figures and other details (/2)					
Completeness, design rigor and rationale. (/2)					
Technical writing and organization (/2)					/5
Operational Assignment					
Presentation of results (figures, organization, completeness) (/2.5)					
Working hardware demonstration (/1.5)					
Technical writing and organization (/1)					/5
Overall:					/15
Comments:					

AER 627: Intro to Space Robotics, Laboratory Report Evaluation

<table>
<tr><td colspan="6">Student Name(s): Stephanie Chan</td></tr>
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<tr><th>Component</th><th>Excellent</th><th>Good</th><th>Satisfactory</th><th>Needs Improvement</th><th>Grade</th></tr>
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<tr><td>Completeness</td><td></td><td></td><td></td><td></td><td rowspan="3">/5</td></tr>
<tr><td>Clear, concise, legible</td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Presentation of results (figures, organization, completeness) (/2.5)</td><td></td><td></td><td></td><td></td><td rowspan="3">/5</td></tr>
<tr><td>Working hardware demonstration (/1.5)</td><td></td><td></td><td></td><td></td></tr>
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<tr><td colspan="5">Overall:</td><td>/15</td></tr>
<tr><td colspan="6">Comments:</td></tr>
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