Reiwa 5 (2023) Date submitted:

Fundamental Labs I Report

(School of Science and Engineering, College of Engineering Systems)

☐ 7 System control engineering basic labs
☐ 9 Diodes and transistors
☐ 11 DC motor manufacturing and control
☐ 8 Basics of linear systems using operational amplifier
☐ 10 Basics of logic circuits and computers
☑ 12 Mechanisms and mechanical elements

Submitted by: Lab group____ Student ID No. 202218028 Name PRABHNOOR SINGH SAHNI

Lab partners: (1)________ (2)________
(3)________ (4)________
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	1st week	2nd week	Report submission
Lab date	Month/Day	Month/Day	Received stamp
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Fundamental Labs
Kinematics and Mechatronics

Prabhnoor Singh Sahni

February 12, 2024

Contents

Week 1

LEGO Mindstorms Programming and Mechanism assembly and operation

1.1 Purpose

- Learn basics on kinematics and mechatronics, such as gear and link mechanisms.
- Assemble actual mechanisms, move them, and learn how the mechanisms work.

1.2 Robolab Basic Operation

We begin our experiments by setting up the computer and starting Robolab. Our first program is to rotate a motor.

1.2.1 Assignment 1

1. For rotating a motor, we select the appropriate icon for the motor and make the program according to the instructions given in the Labs text, Figure 1.1. After connecting the motor to the output of the NXT and after connecting NXT to computer. We upload the program and run the NXT. We can confirm the operation of the motor.
2. Now, we make changes to this program to make the motor rotate and stop when we press and release touch sensor. For this purpose, we use the icon for the touch sensor and add it in the program to get

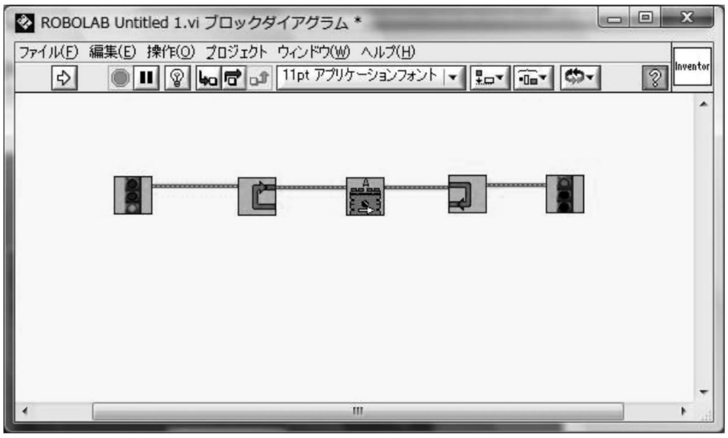

Figure 1.1: Program to rotate a motor eternally

the desired output. Figure 1.2 shows the program in Robolab, and Figure 1.3 shows the motor along with the touch sensor.

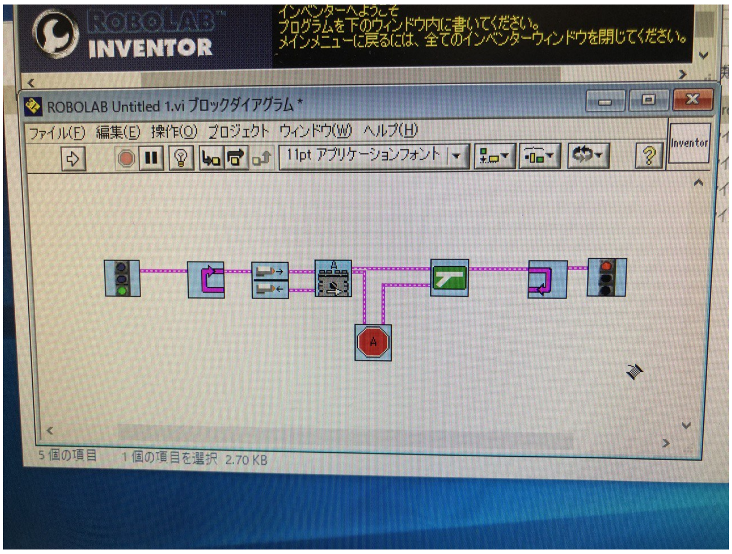

Figure 1.2: Program to rotate motor by using a touch sensor.

3. In the next task, we're supposed to make a motor stop and rotate when an optical sensor is directed to face a bright place and a dark place. For this we use the icon for the optical sensor and connect the appropriate terminals to the stop icon. This is in turn connected to the motor as in Figure 1.4. We were able to confirm the operation of this assignment. We saw that the motor was rotating the optical sensor was directed to

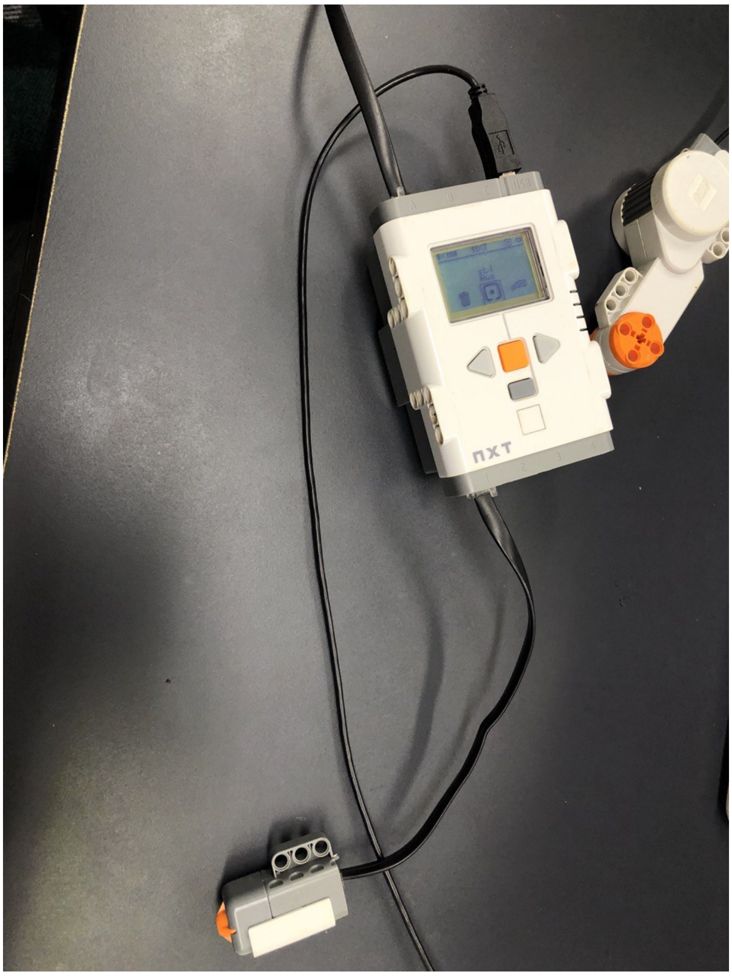

Figure 1.3: The physical components when motor is rotated using a touch sensor.

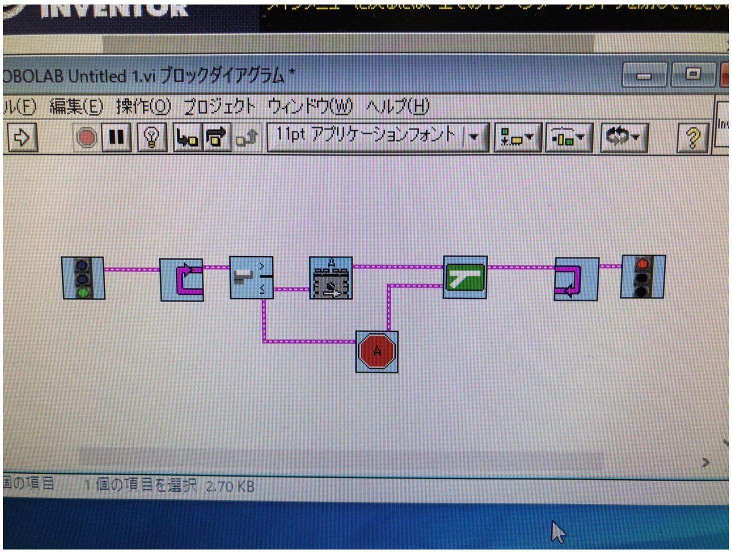

Figure 1.4: Program for rotating motor depending on input from optical sensor

a white paper and the motor stopped when the sensor was directed to the black table.

1.2.2 Assignment 2

In this assignment, we were required to create a program such that when the touch sensor is pressed, the motor starts making reverse rotations. For this purpose, we use the wait for icon of the sensors. The icon for touch sensor waits for the input, and based on that it makes the motor rotate either in forward or reverse direction. We have to use two of these sensors to make sure that the flip between forward and reverse is recurrent. Then we create the program on the computer, which can be seen in Figure 1.6. We can confirm the operation of our motor and touch sensor once we pass the code into the NXT.

1.2.3 Assignment 3

In this assignment we use a distnace sensor and motor to create a program so that when the distance with the wall is near, the motor rotates; when the distance is in the middle, the motor stops and when the distance is far, the motor shows reverse rotations. For this assignment, we have used two distance sensors, a stop icon, two icons for defining constant integer values used to check distance, branches and two motors (one for reverse, other for

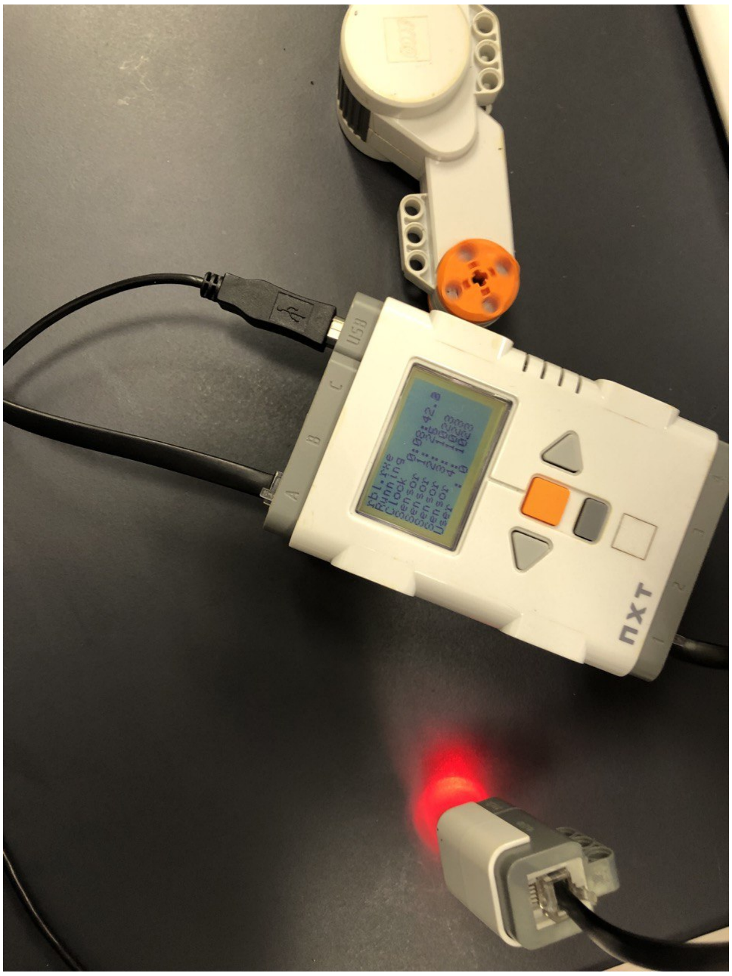

Figure 1.5: Physical components when optical sensor is used as input to rotate motor.

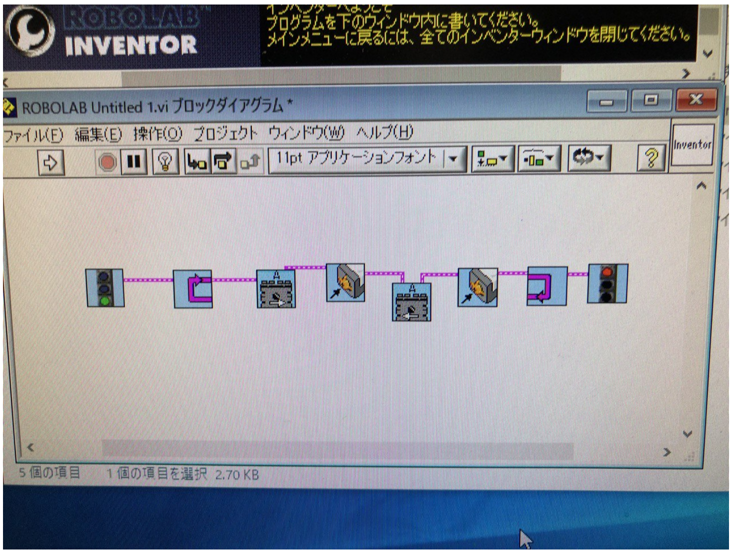

Figure 1.6: Program to rotate a motor either in forward or reverse direction based on the number of times the touch sensor is pressed.

forward). Basically, for the program, we first set particular distance values. Since the sensor gives output in centimetres. We set that if the output is more than 20 cm, the distance is far; if it's less than 10 cm, the distance is near and if it's between 10 cm and 20 cm, the distance is in the middle. Using this logic, we make a flowchart showing the process as in Figure 1.7. And then, using the flowchart it becomes pretty straightforward to create the program on the computer. The program is as in Figure 1.8. We confirm the operation after pushing code to the NXT and running it.

1.3 Rotational velocity and force conversion of flat gear-based systems

In this section we proceed to understand rotational velocity and force conversion in multigear systems. In a multigear system, gears with different numbers of teeth rotate at different speeds. The basic principle is that larger gears (more teeth) rotate more slowly but produce more torque, while smaller gears (fewer teeth) rotate faster but with less torque.

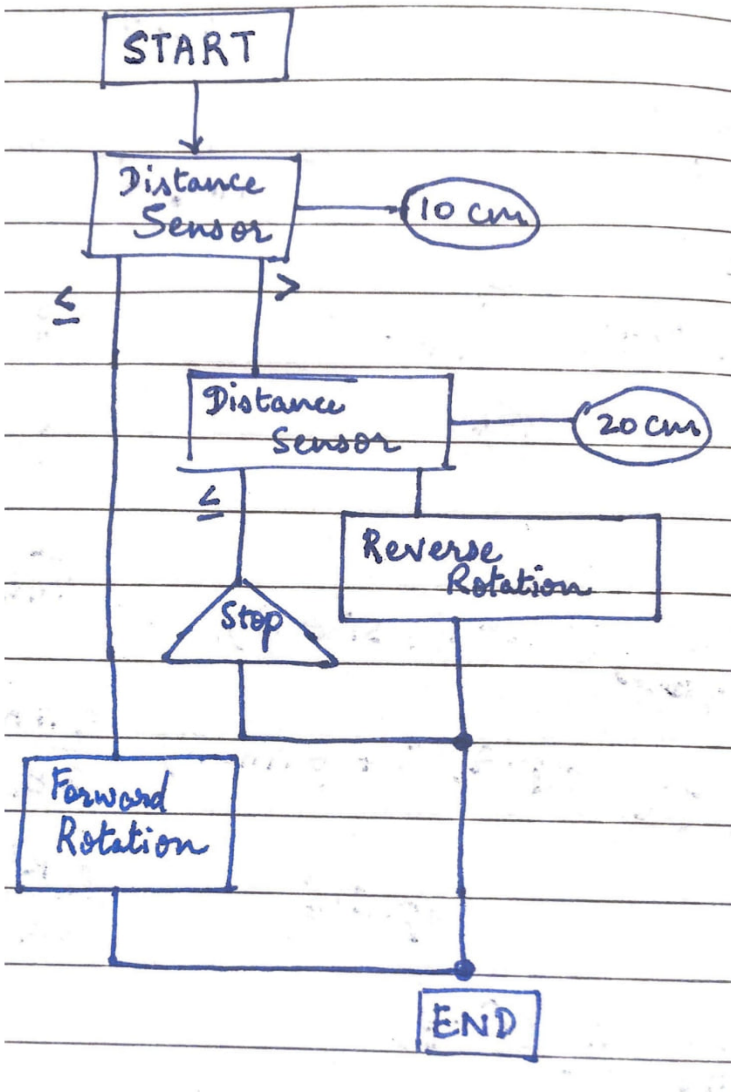

Figure 1.7: Flowchart explaining the process of motor rotation through distance sensor. It shows that the program starts by checking the data from the distance sensor. If data is less than or equal to 10 cm, it moves to rotating the motor. If it's more than 10 cm, it goes through another check to determine if it's more than 20 cm. Depending on this output, it either stops or rotates the motor.

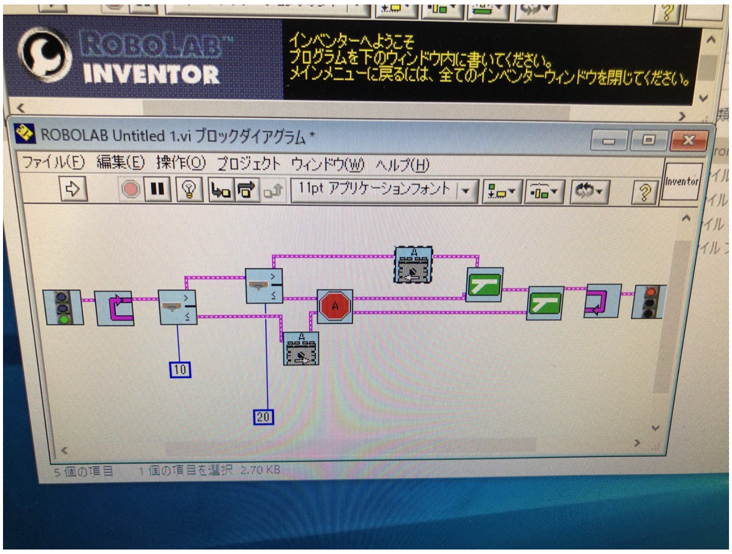

Figure 1.8: Program to rotate a motor when distance is near, stop when distance is middle and reverse rotations when distance is far.

1.3.1 Assignment 4

In the three assignments described, there are differences in rotational velocity and force depending on the configuration of the gears and their sizes.
In the first experiment when we are independently rotating the gears the rotational speeds and force are also independent. Now, in the second experiment we drive the small gear with motor, while the larger gear. Let the properties denoted by "1" represent the smaller gear and those denoted by "2", the larger gear.
Case 1: **Motor on small gear**
Let time go from t=0 seconds to t=t seconds. In this time,

$$\text{(Distance covered by a teeth of gear 1)} = \text{(Distance covered by a teeth of gear 2)}, \tag{1.1}$$

$$= 2\pi r_2. \tag{1.2}$$

This shows that Gear 1 does $\frac{r_2}{r_1}$ rotations in t seconds and Gear 2 does 1 rotation. Thus,

$$\omega_1 = \frac{r_2}{r_1}\frac{1}{t} rot/s, \tag{1.3}$$

$$\omega_2 = \frac{1}{t} rot/s, \tag{1.4}$$

$$\frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} \tag{1.5}$$

$$\Rightarrow \omega_1 = \frac{r_2}{r_1}\omega_2 \tag{1.6}$$

$$\text{or } \omega_2 = \frac{r_1}{r_2}\omega_1. \tag{1.7}$$

where ω is angular velocity.
Now, moving to torque, we know that Torque $\tau = \mathbf{r} \times \mathbf{F}$. Thus, (considering only magnitudes),

$$\tau_1 = r_1 F, \tag{1.8}$$

$$\tau_2 = r_2 F, \tag{1.9}$$

$$\Rightarrow \tau_2 = \frac{r_2}{r_1}\tau_1. \tag{1.10}$$

The term $\frac{r_2}{r_1}$ is called the reduction ratio and its inverse, $\frac{r_1}{r_2}$ is called the reciprocal reduction ratio. The **reduction ratio** refers to how much the rotational speed or torque is decreased (or increased) from the input to the output. Case 2: **Motor on big gear**
Just like Case 1, we have:

$$(\text{Distance covered by a teeth of gear 1}) = (\text{Distance covered by a teeth of gear 2}), \tag{1.11}$$

$$= 2\pi r_2. \tag{1.12}$$

This shows that Gear 1 does $\frac{r_2}{r_1}$ rotations in t seconds and Gear 2 does 1 rotation. Thus,

$$\omega_1 = \frac{r_2}{r_1}\frac{1}{t} rot/s, \tag{1.13}$$

$$\omega_2 = \frac{1}{t} rot/s, \tag{1.14}$$

$$\omega_1 = \frac{r_2}{r_1}\omega_2. \tag{1.15}$$

Also,

$$\Rightarrow \tau_1 = \frac{r_1}{r_2}\tau_2. \tag{1.16}$$

1.3.2 Assignment 5

Now, unlike our two gear system in last assignment, we prepare a three gear system. Since we know the reduction ratio and the relationship between two gears from the previous assignment, we can directly use those results to understand this problem.
Consider the three gears denoted by "1","2" and "3". Let ω be angular velocity and r be radius.

$$\omega_2 = \frac{r_1}{r_2}\omega_1, \tag{1.17}$$

$$\omega_3 = \frac{r_2}{r_3}\omega_2, \tag{1.18}$$

$$\Rightarrow \omega_3 = \frac{r_1}{r_3}\omega_1. \tag{1.19}$$

$$\tag{1.20}$$

Also,

$$\tau_2 = \frac{r_2}{r_1}\tau_1, \tag{1.21}$$

$$\tau_3 = \frac{r_3}{r_2}\tau_2, \tag{1.22}$$

$$\Rightarrow \tau_3 = \frac{r_3}{r_1}\tau_1. \tag{1.23}$$

We can see that Gear 1 and Gear 3 are rotating in the same direction. Gear 3 rotates as if Gear 2 does not exist. Its angular velocity and torque depends completely on Gear 1.

1.3.3 Assignment 6

In order to achieve a very large deceleration ratio we want to make sure that the terms do not get cancelled. So if we can make the gears not touch by their teeth, but instead have same characteristics as the source gear (one driven by motor). We can do this by keeping two or more gears on top of each other, i.e. two gears driven by same motor. See Figure 1.9.

$$\omega_1 = \frac{r_2}{r_1}\omega_2, \omega_4 = \frac{r_3}{r_4}\omega_3; \tag{1.24}$$

$$\text{we know, } \omega_3 = \omega_2. \tag{1.25}$$

$$\text{Thus, } \omega_4 = \frac{r_3 r_1}{r_4 r_2}\omega_1. \tag{1.26}$$

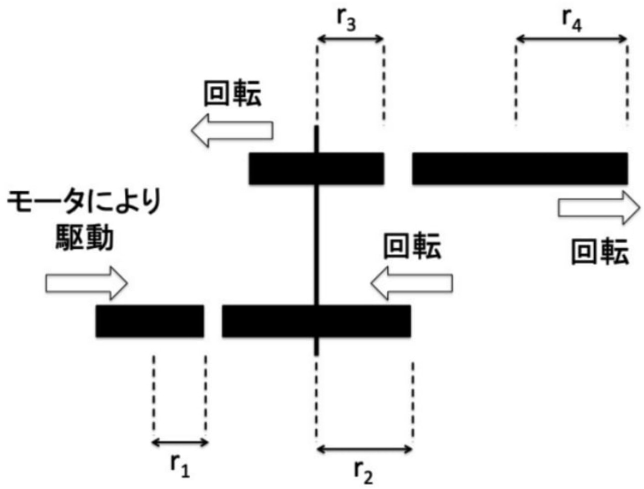

Figure 1.9: Multiple Flat Gear system

Also for torque, using a similar approach we get:

$$\tau_4 = \frac{r_4 r_2}{r_3 r_1} \tau_1 \tag{1.27}$$

Hence, we have achieved a large deceleration/reduction ratio where the terms do not get cancelled. This type of system has many uses.

1.3.4 Assignment 7

"Backlash" refers to the amount of clearance or play between mating gears. It is the relative motion or movement between gears when they change direction of rotation, particularly when transitioning from driving to coasting or vice versa. Generally, there is no problem when the gears are continuously rotating in some direction. The problem arises when the direction of rotation is reversed or changed.

When the motion is reversed, the clearance between the gear teeth causes a brief moment where the gears disengage before they engage again in the opposite direction. This can lead to several issues.

- Backlash can introduce inaccuracies and imprecision in the movement of mechanical systems.
- It can cause mechanical wear and tear.
- It has an overall impact on performance.

1.4 Bevel gear, worm gear-based rotational direction conversion

For this section, we assembled a mechanism consisting of a motor, bevel gear and worm gear based on the instructions provided. The final assembled structure is as shown in Figure 1.10.

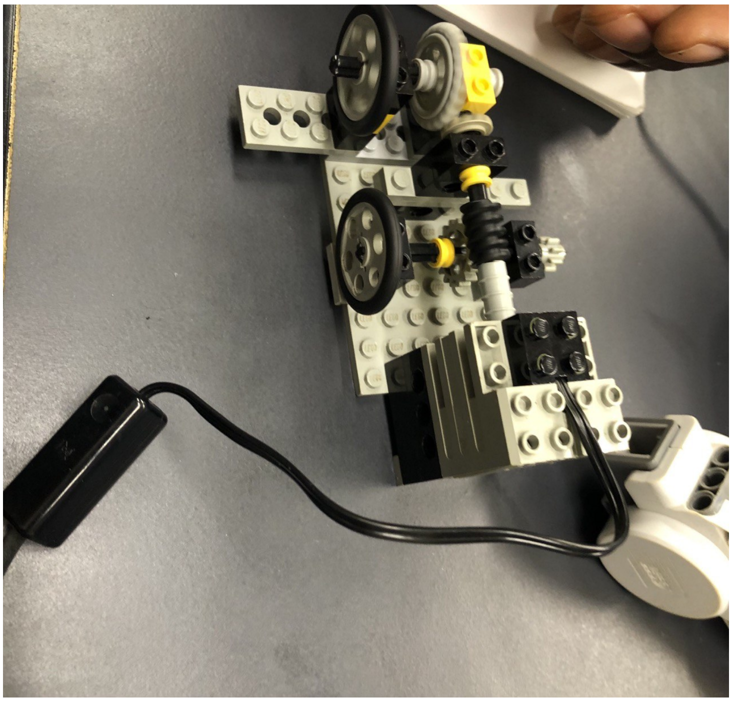

Figure 1.10: Bevel gear, worm gear-based rotational axis conversion mechanism

1.4.1 Assignment 8

When we do not know the properties like radius or angular velocity in a physical system, how does one find the recution ratio? Reduction ratio is an intrinsic property of gears. Thus, another measure of the reduction ratio can be by using number of teeth. We see that the reduction ratio or deceleration ratio, given by $\frac{r_2}{r_1}$ can also be written as

$$\frac{n_2}{n_1}$$

where n is the number of teeth in the gear. This is true because the number of teeth on a gear is directly proportional to the radius.

For our system, for the bevel gear, since the two gears had 12 and 24 teeths. Thus $n_1 = 12$ and $n_2 = 24$. So reduction ratio $= \frac{n_2}{n_1} = 2$.
Now, for the worm gear. A worm gear has n teeth. So it will have n rotations. Let the angular velocity of the worm gear in our system be denoted by ω_3, then

$$\frac{\omega_4}{\omega_3} = \frac{1}{n}, \tag{1.28}$$

$$\omega_4 = \frac{1}{n}\omega_3. \tag{1.29}$$

Also,

$$\frac{\tau_4}{\tau_3} = \frac{r_4}{r_3} \tag{1.30}$$

$$= \frac{n_4}{n_3} \tag{1.31}$$

$$= n(\text{because } n_3 = 1 \text{ and } n_4 = n). \tag{1.32}$$

$$\Rightarrow \tau_4 = n\tau_3. \tag{1.33}$$

Thus reduction ratio is n=16 (for worm gear).

1.4.2 Assignment 9

There is a force applied on the worm gear. This force has two components, $fcos(\theta)$ and $fsin(\theta)$ since it is applied at an angle θ. Now, due to contact, there also exists a friction force (f'), opposite to the motion. Let μ be the coefficient of friction.
We notice that in this motion there are two conditions– not rotating and rotating,let's discuss them in detail.
Not Rotating Condition
The gear does not rotate when the force on the worm gear is unable to overcome the force of static friction.

$$fsin(\theta) \leq f' = \mu N = \mu fcos(\theta) \tag{1.34}$$

$$\text{Thus, } tan(\theta) \leq \mu \tag{1.35}$$

where N is the normal force.
See Figure 1.11.
Rotating Condition
The gear will rotate when the force is large enough to overcome the force of friction.

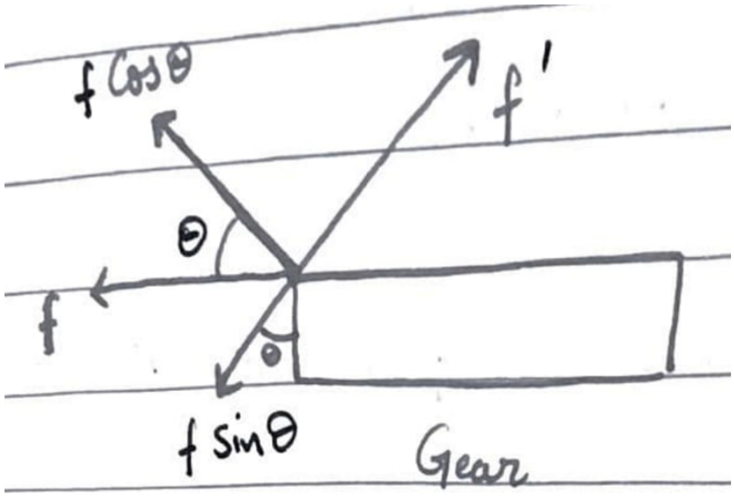

Figure 1.11: Free Body Diagram of a worm gear illustrating the various forces.

$$fsin(\theta) \geq f' = \mu N = \mu fcos(\theta) \tag{1.36}$$

$$\text{Thus, } tan(\theta) \geq \mu \tag{1.37}$$

Lastly, as we know $0 \leq \mu \leq 1$, thus, if $\theta = 45°$ the gear will rotate regardless of μ. Thus, we can understand the role of friction and angle played in the rotation of the worm gear.

Week 2

Parallel four-link mechanism and Motion Conversion

2.1 Parallel four-link mechanism

This week we begin by understanding the working of a parallel four-link mechanism. The parallel four-link mechanism is a mechanical system comprising four rigid links connected by revolute joints, forming a closed-loop structure. This mechanism offers advantages such as symmetrical motion, predictable kinematics, and efficient power distribution.

2.1.1 Assignment 10

Here, we will derive the coordinates of the hand position of the parallel four links. From Figure 2.1, we can see that:

$$\vec{OD} = \vec{OA} + \vec{AB} + \vec{BD}, \tag{2.1}$$

$$x = L_1 cos(\theta_1) + L_2 cos(\theta_2) + L_3 cos(\theta_1 + \pi) \tag{2.2}$$

$$y = L_1 sin(\theta_1) + L_2 sin(\theta_2) + L_3 sin(\theta_1 + \pi) \tag{2.3}$$

We now substitute from the identities for sum of angles of Cos and Sin.

$$x = (L_1 - L_3) cos(\theta_1) + L_2 cos(\theta_2) \tag{2.4}$$

$$y = (L_1 - L_3) sin(\theta_1) + L_2 sin(\theta_2) \tag{2.5}$$

2.1.2 Assignment 11

In this section, we analyze the tip operation of a parallel four-bar linkage, focusing on its behavior when the angles between the links are set to 90°.

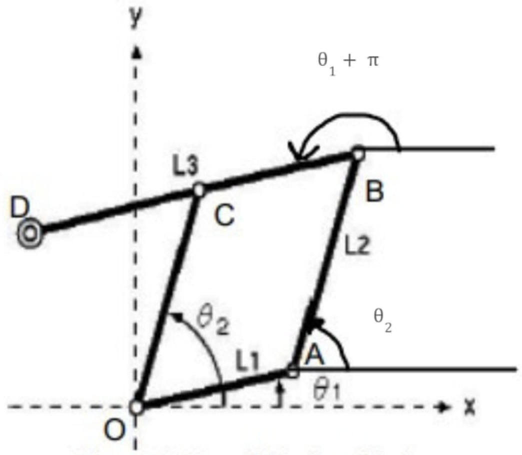

Fig. 14: Parallel four links

Figure 2.1: Parallel four links diagram

We begin by setting all angles in the parallel four-bar linkage to 90°, effectively transforming the linkage into a rectangular shape. See the part labelled as base in Figure 2.2. Using graph paper, we record the path traced by the tip of the linkage when rotating only the top gear from this orientation. Similarly, we record the path when rotating only the bottom gear.
We can see the path labelled in Figure 2.2 as "Only Top Gear", which is obtained when rotating only the top gear. We look at the path relative to the base and we can understand the characteristics. Also, we are able to realise the position of the centre of the arc that is drawn when tracing this path. We can see the position of the centre right at the joining of the link. It is at the joint closest to the pencil. This position is labelled in the figure. Further, we see the arc traced by the rotation of only the Bottom Gear, marked in Figure 2.2 as "Only Bottom Gear". The centre of this circle can be realised by looking at the entire structure and relating the centre of the circle of the arc of the rotation of only the top gear. We look at the intersection of the two arcs and with that we're able to find the centre of the second circle.

Why is the range of this not a proper circle?

There is interference between the base and the links, and this causes the range to be an "improper" circle.

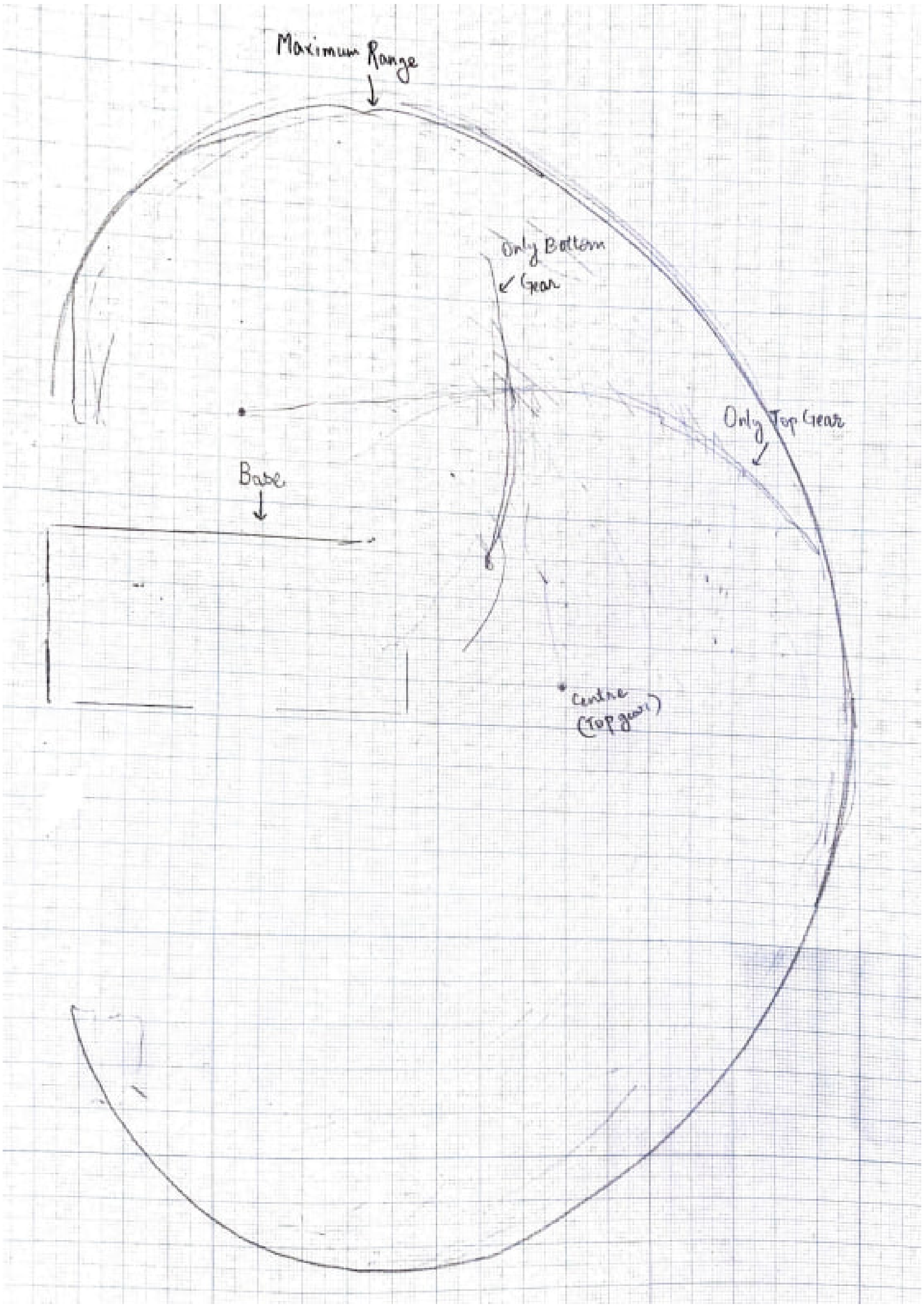

Figure 2.2: Record of the tip operation of the parallel four links on a graph paper.

2.1.3 Assignment 12

When using such a mechanism, there are numerous benefits. Yes, it is indeed possible to place only one motor which will enable us to drive both the gears. The obvious advantage is that this mechanism does not need a second motor, as already established. Further, By placing the motor on a base that is separate from the link joints, there is greater flexibility in motor selection. Motors can be chosen based on their specific performance characteristics without being limited by size and weight constraints imposed by the link joints.
A crucial advantage in this mechanism is of efficient power distribution. Separating the motor from the link joints allows for better distribution of power within the mechanism. This can lead to reduced energy consumption, as power can be transmitted more directly to the gears without the added weight and inertia of the motor affecting the movement of the link joints.
Moreover, it also provides us with a greater range of motion because there is only one motor. It also helps in cable management as only one cable can be used to connect to the motor. This improve efficiency. Since the arm does not have a motor, the centralised power delivery system will not fail. It reduces failure.

Disadvantages of Placing Motor on link-joint sections

Firstly, mounting the motor directly on the link joint sections adds additional weight and inertia to the mechanism. This can result in slower response times and reduced efficiency, especially in applications requiring rapid or precise movements.
The space available on the link joint sections may be limited, making it challenging to install larger or more powerful motors. This limitation can restrict the performance capabilities of the mechanism and limit its potential applications.
Placing the motor on the link joint sections increases the risk of interference with the movement of the mechanism. The motor's size and positioning may restrict the range of motion or cause unwanted friction or obstruction, leading to reduced reliability and performance.

"non-parallel" four-link Mechanism

To transform the parallel four-link mechanism into a non-parallel configuration, we can modify the lengths of the links such that they are no longer parallel. Rotating this modified mechanism will result in a different motion compared to the original parallel configuration. Specifically, the trajectory of the tip or end effector will vary, potentially leading to different kinematic behaviors and applications. Experimentation with different link lengths and configurations can provide insights into the versatility and adaptability of four-link mechanisms for various engineering tasks.

2.1.4 Assignment 13

In a parallel four-link mechanism, the motion of the link tips tends to be symmetrical when rotating the top and bottom gears. This symmetry arises from the geometric arrangement of the links and joints, resulting in predictable and balanced movement patterns.
Moreover, the range of movement of the link tips remains relatively consistent across different configurations of the parallel four-link mechanism. This is because the parallel arrangement of the links constrains the motion within a certain range, providing stability and predictability in operation.
Advantages of the Parallel Four-Link Mechanism:
The parallel arrangement of the links in the four-link mechanism facilitates predictable kinematics, making it easier to design and control. Symmetrical motion patterns and consistent range of movement contribute to the reliability and stability of the mechanism in various applications.
Lastly, the geometric simplicity of the parallel four-link mechanism simplifies design and analysis processes. Engineers can leverage symmetrical motion characteristics and consistent range of movement to optimize performance and address specific requirements without the added complexity associated with non-parallel configurations. It allows for better and simpler calculation.

2.2 Motion Conversion

In this section we examine mechanisms for converting rotational motion into other forms of motion, like reciprocal or straight line motion.

2.2.1 Assignment 14

We have created the following three mechanisms for converting rotational motion of a motor into different types of reciprocating motion.

- Oscillation Mechanism (Figure 2.3)
- Cam Mechanism (Figure 2.4)
  A cam mechanism consists of a cam and a follower. The cam is a specially shaped component mounted on a rotating shaft, while the follower rides on the cam's surface. As the cam rotates, it imparts

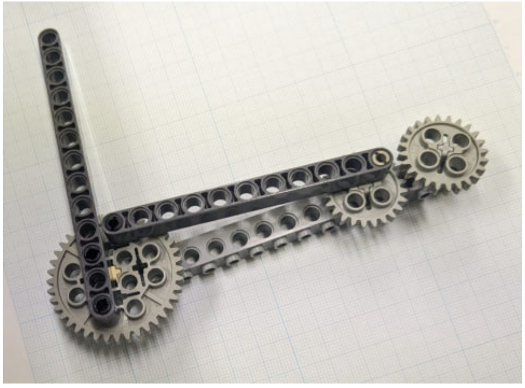

Figure 2.3: Figure illustrating the mechanism created for showing reciprocating oscillation motion.

motion to the follower, converting rotary motion into reciprocating or oscillating motion.

- Slider Crank Mechanism (Figure 2.5)
  A slider-crank mechanism comprises a crank, connecting rod, and slider. The crank provides rotary motion, transmitting it to the connecting rod, which, in turn, imparts linear motion to the slider.

2.2.2 Assignment 15

Now, we will discuss the Paucellier exact straight line motion mechanism. The diagram for such a mechanism is illustrated in Figure 2.7. In this assignment we prove geometrically that the point Q in Figure 2.7 moves in a straight line.
See Figure 2.7, we can see many different triangles. Here, $\Delta OBC, \Delta PBC, \Delta QBC$ are isosceles triangles. Therefore, $OPFQ$ is a straight line.

$$\begin{aligned} OP \cdot OQ &= (OF - PF) \cdot (OF + PF), &(2.6)\\ &= OF^2 - PF^2, &(2.7)\\ &= (OC^2 - CF^2) - (PC^2 - CF^2), &(2.8)\\ &= OC^2 - PC^2 = \text{ constant.} &(2.9) \end{aligned}$$

Also, we see that ΔOPD and ΔOHQ are similar triangles. Thus, from property of similar triangles, we have:

$$\frac{OP}{OD} = \frac{OH}{OQ}, \tag{2.10}$$

$$OD \cdot OH = OP \cdot OQ = \text{ constant.} \tag{2.11}$$

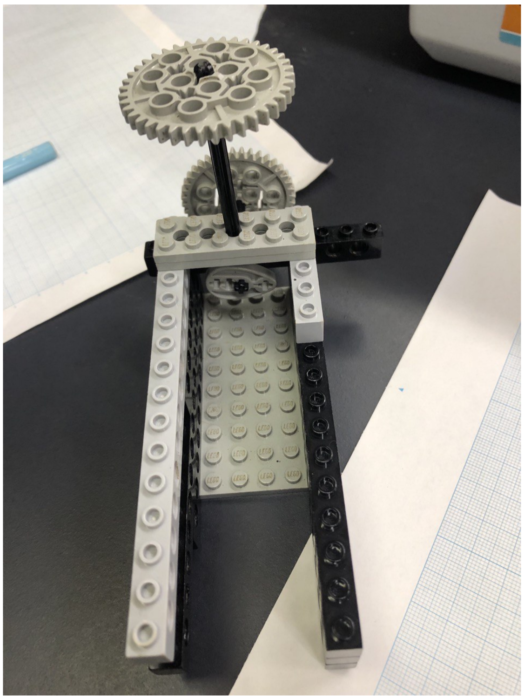

Figure 2.4: Figure illustrating a Cam Mechanism.

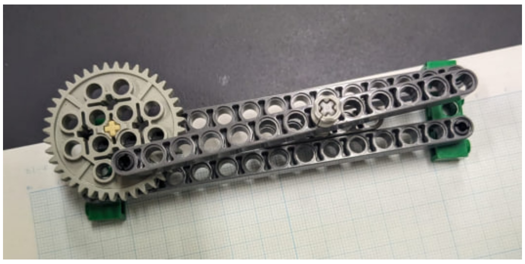

Figure 2.5: Figure illustrating a Slider-Crank Mechanism.

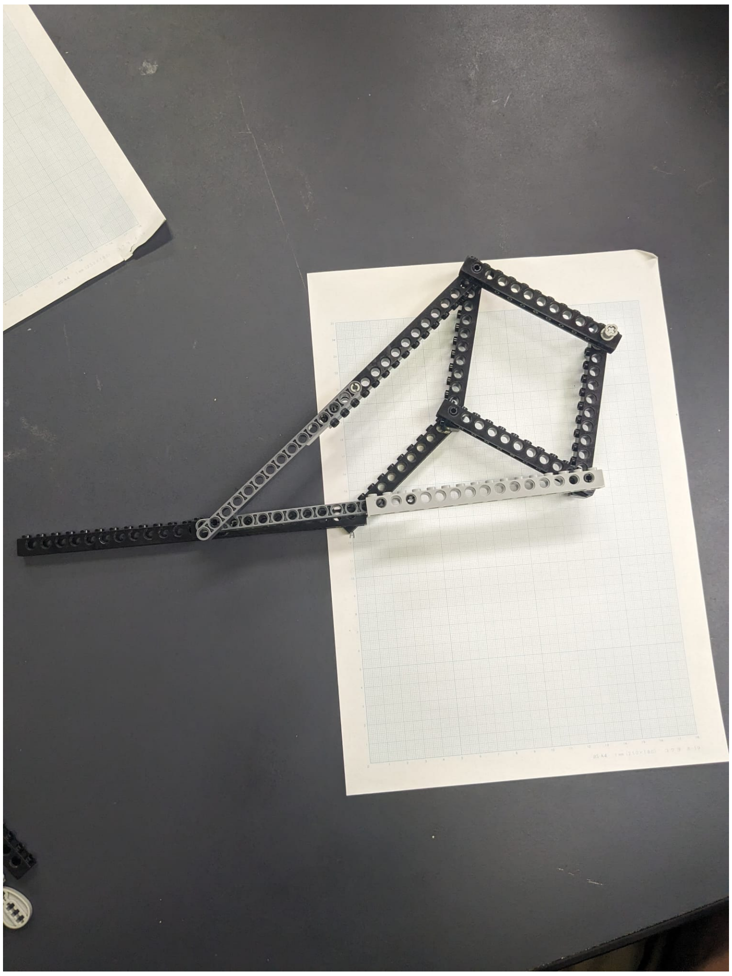

Figure 2.6: Physical structure of the Paucellier exact straight line motion Mechanism

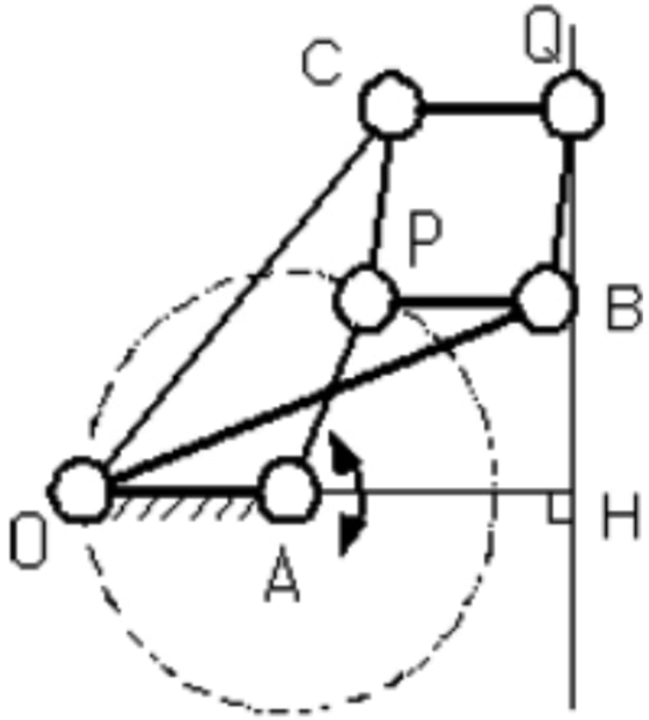

Figure 2.7: Figure illustrating Paucellier exact straight line motion mechanism.

Hence proved, point Q in Figure 2.7 will move in a straight line.

2.2.3 Assignment 16

In this assignment, we make use of the Paucellier straight line mechanism and record the path of point Q on graph paper as in Figure 2.8. We can confirm its operation and verify that the point Q does indeed move in a straight line.

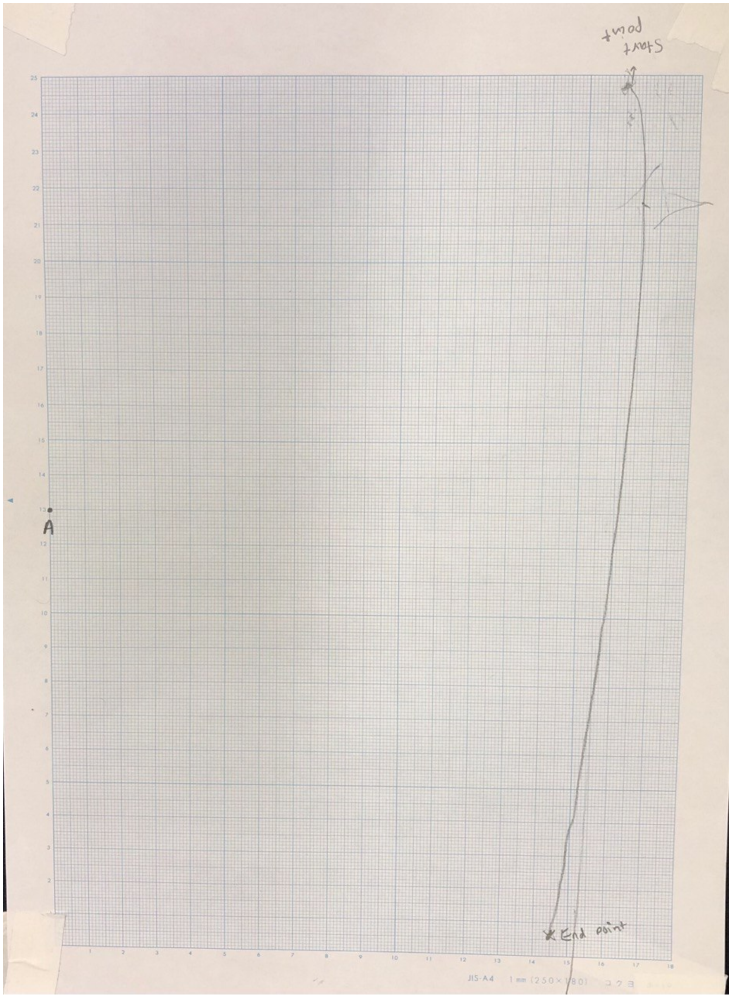

Figure 2.8: Path of point Q of the Paucellier straight line motion mechanism.

2.3 Motion control using sensor

2.3.1 Assignment 17

Using the aforementioned types of sensor and the motor, we build a mechanism for rotating a long beam by 90°. We use two touch sensors, and the principle that when the motor rotates the long beam from 0° to 90°, at the end of 90° we put a touch sensor, which gets pressed by the beam. This sensor then triggers the motor to rotate backwards. Now, the beam again completes moving from 90° back to 0° where it hits another touch sensor. This, then triggers the motor to again change directions. And just like this the beam keeps on rotating, and changing direction every 90°. We can look at the physical mechanism in Figure 2.9 and the program for this mechanism can be seen in Figure 2.10.

2.4 Conclusion

The series of experiments provided valuable insights into the fundamentals of Kinematics and Mechatronics. We covered the parallel four-link mechanism, motion conversion mechanisms, gear systems, reduction ratio, and practical experiments with motors and gears. We learned about how these concepts affect rotational velocity and force transmission in mechanical systems, providing valuable insights into engineering applications. We understood a lot of new things and it added to our knowledge base and provided us with experience with Robolab and making mechanisms using LEGO Mindstorms.

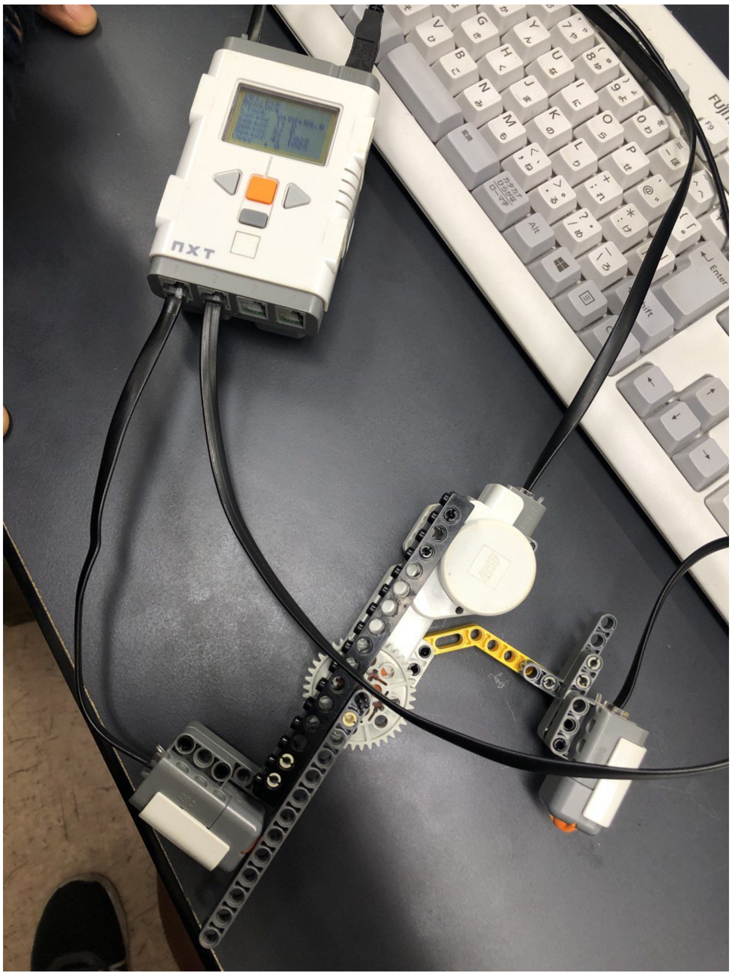

Figure 2.9: Physical structure of the mechanism for rotating a long beam by 90°.

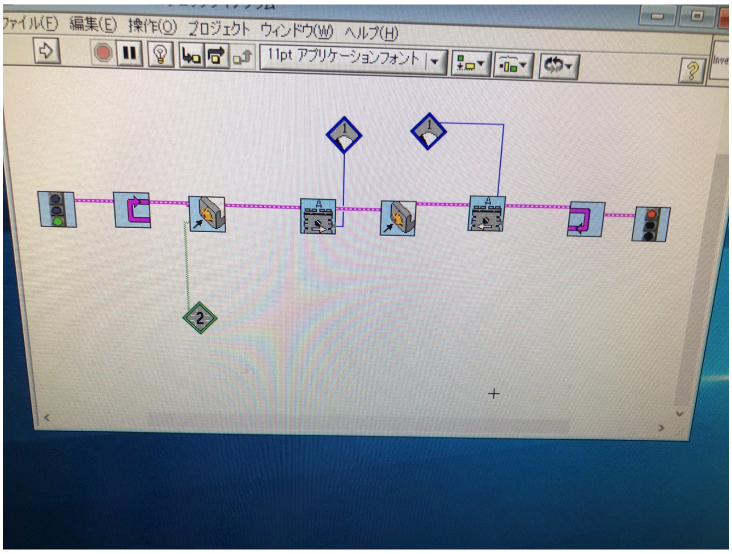

Figure 2.10: Program for a mechanism for rotating a long beam by 90°.

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