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# Development of the Design and Control of a Hexapod Robot for Uneven Terrain

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**ABSTRACT**

In the Indonesian Search and Rescue Robot Contest in 2021 and 2022, the robot still cannot work well when passing through uneven obstacles. The change in uneven terrain from the previous year was a difficulty for the robot in passing it. This research was conducted to develop mechanical design and movement control design for the robot, so that the robot can be more optimal when moving through uneven terrain. The design of the hexapod robot is done by reducing the dimensions of the existing robot and determining the Center of Gravity point. The movement of the robot is also designed by determining the angular position of the AX-18A servo with respect to the terrain the robot travels through. The movement algorithm applied to the robot is the tripod gait algorithm. The robot control on the debris field and irregular floor is done by applying a proximity sensor to minimise the robot from hitting the wall on the field. The robot also has an IMU sensor that will work in measuring the slope on the up-and-down floor terrain (slope), so that the movement of the robot can be adjusted when passing through the terrain with the slope read by the sensor. The results of the research conducted show that the robot can be redesigned through 3D design through solidworks by determining the Center of Gravity (CoG) point. The robot has been able to pass through 3 objects tested, namely debris terrain, irregular floor terrain, and up and down floor terrain. The success rate of the robot when passing through debris terrain and irregular floor terrain is 100% with an average time of 9.7 seconds and 10.1 seconds. The success rate of the robot when passing through the up-and-down floor terrain is 80% with an average time of 22.9 seconds.

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## 1. INTRODUCTION

Indonesia is an archipelago with a high risk of disaster [1]. According to their causes, disasters are divided into two types: natural disasters and non-natural disasters [2]. Natural disasters are those caused by natural events. Non-natural disasters are disasters caused by non-natural events (human behavior, disease and endemics) [3][4]. Natural disasters that are common in Indonesia include landslides, earthquakes and eruptions [5][6]. Meanwhile, non-natural disasters, which are common in Indonesia, include fire disasters [7][8]. The SAR team, supervised by the National Search and Rescue Agency, conducts search and rescue operations for disaster victims [9].

The need for the development of technology that can be of assistance to people in the process of evacuation of disaster victims [10]. Robotics is one of the technologies that can be of help to people with these problems [11][12][13]. Robots can be divided into two types on the basis of how they are powered, namely wheeled robots and legged robots [14][15]. Wheeled robots can move by utilizing the motor's rotation connected to the wheel as the driving mechanism, whereas legged robots rely on a servo motor for propulsion [16][17]. When moving across irregular terrain, robots with legs are more manoeuvrable than robots with wheels [18][19]. The National Achievement Center and Indonesian Ministry of Education, Culture, Research and Technology work together to conduct an annual competition activity called the Indonesian Robot Contest. Indonesian Robot Contest has different competition divisions including the Indonesian Search and Rescue Robot Contest division. The aim of this division is to put out a candle fire and save a doll that represents a victim. This task involves fighting fires and rescuing people during a fire emergency.

A hexapod robot is a type of legged robot that has 6 legs, with each leg having 3 joints on each side of the leg [20][21]. Based on their shape, hexapod robots can be divided into two types: the rectangular type and the hexagonal type [22]. Rectangular type hexapod robot uses 6 legs on the robot, with 3 legs each on the right and left sides of the robot body [23]. On the other hand, in the hexagonal type, the 6 legs of the robot are distributed all over the body of the robot [24]. In this research, the robot to be designed is a hexapod robot of the rectangular type.

In the Indonesian Search and Rescue Robot Competition in 2021 and 2022, there are several terrains that hexapod robots still have difficulty traversing, namely debris terrain, irregular ground terrain, and slope terrain. While moving through these terrains, the robot still encountered obstacles and got stuck in the terrain. In fact, in the uneven terrain, the robot's body state is not balanced when climbing or descending the terrain, so the robot can fall forward or backward. This is due to the less than ideal design of the robot's mechanics. In addition, the process of controlling the movement of the robot's legs is not good, which causes the robot's movement to be unstable when crossing the terrain. The time taken by the robot to cross the terrain is also a problem for the robot. The longer the robot takes to cross uneven terrain, the more the robot's overall time will be affected in each match. As a result, the match points earned will also be lower.

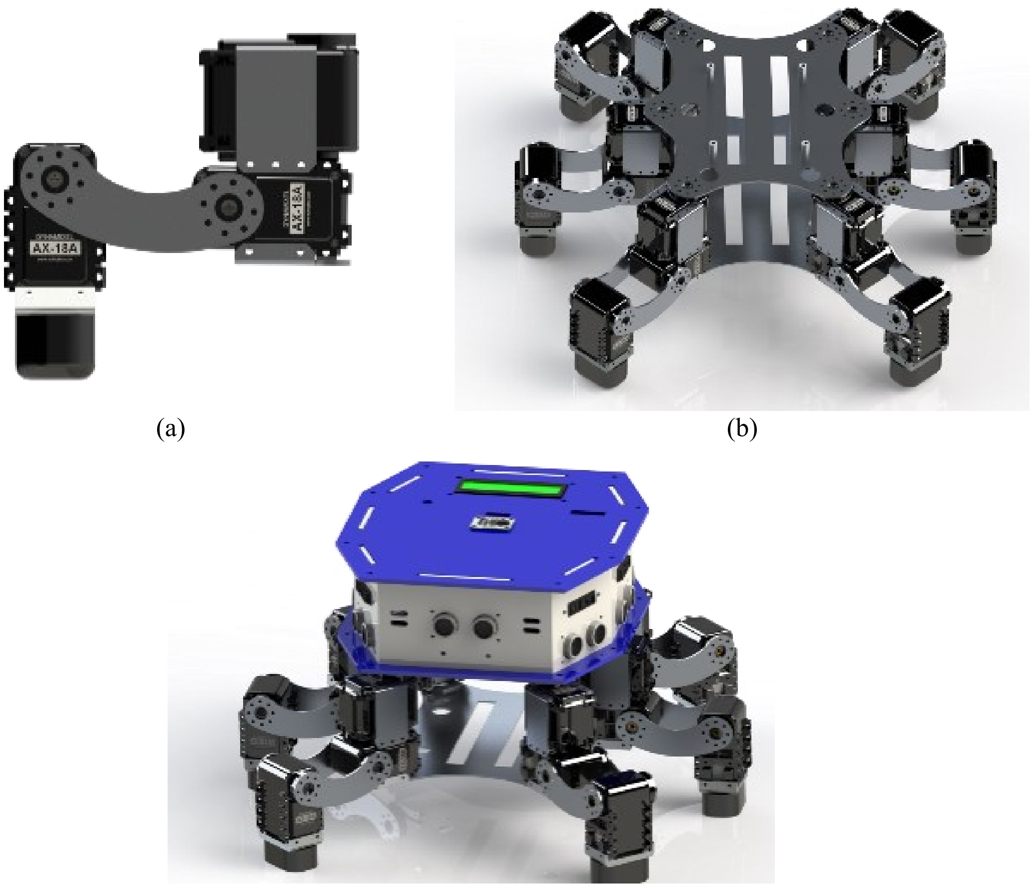
From the problems encountered with the hexapod robot, it is necessary to develop the mechanical design and motion control of the robot as it traverses the terrain. The design of the robot mechanics will be done by applying the concept of Center of Gravity (CoG). The application of the CoG to the robot is done by knowing the balance point of the robot when passing through uneven terrain, namely the up and down terrain. By determining the CoG point, the weight point of an object can be determined so that its stability can be maintained [25]. The implementation carried out on the robot is intended to test the robot's performance in traversing uneven terrain based on the design development carried out and the robot's designed movement pattern in traversing uneven obstacles by testing the robot's movement on uneven terrain. The robot will be tested on 3 different types of terrain based on the terrain in the guidebook for the Indonesian Search and Rescue Robot Contest in 2021 and 2022. The tests that will be performed on the robot include uneven terrain (hollow terrain), debris terrain, and up and down terrain (slope) [26].

## 2. METHODS

The robot design system is carried out by the design of the robot hardware, the design of the robot design and the design of the robot control.

### 2.1. System Design

The system design is carried out on the robot by designing the robot design and the robot hardware system. The robot design is designed using SolidWorks software by designing a mechanical system on the legs and frame of the robot [27]. The robot leg system designed is a leg with a 3 DoF (Degree of Freedom) system. The degree of freedom is the number of directions in which the joints in a robot arm can move. The design of the robot is also carried out on the robot frame by determining the placement of the legs based on the type of rectangular hexapod robot. Figure 1 shows the results of the design of the hexapod robot.




(a) (b)

(c)

**Figure 1**. Design results on (a) legs (b) frame (c) robot

In addition to robot design, robot hardware design is also carried out. Robot design is done by creating a system block diagram. In the diagram there are input, processing and output components. The input components on the robot consist of IMU sensors, HC-SR04 ultrasonic sensors, GP2Y0A21 sensors and buttons. Meanwhile, the output component is an actuator, namely a servo. In this system, the robot processing component consists of two microcontroller boards, namely Arduino Due and Open CM-9.04A. Arduino Due will act as a controller of the input components in the form of buttons and sensors used on the robot. Meanwhile, the Open CM-9.04 board is used as the controller component for the output component, namely the servo. These two microcontroller boards are configured by implementing serial communication. Arduino Due sends commands in the form of byte data types that contain the condition of the motion mode to be executed. Then the Open CM 9.04A microcontroller board executes the results of the robot motion command according to the motion design in the form of angular positions on each servo joint. This system is powered by a lithium polymer battery with an output voltage of 12V. This voltage powers the Open CM microcontroller board and each of the 18 servos. In addition, this power source is also stepped down to 5V. This 5V will be used to power the Arduino Due microcontroller board and input components in the form of ultrasonic sensors, Sharp GP sensors, and IMU BNO055 sensors. Figure 2 shows the results of the system block diagram design.

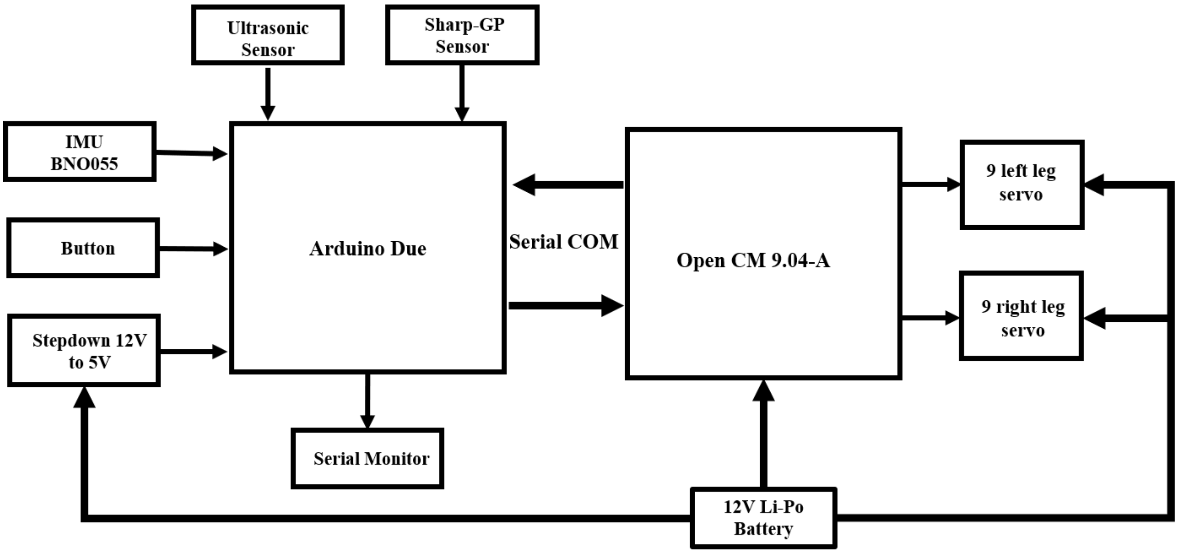



**Figure 2**. System block diagram design results

### 2.2. Control System

The control system of the robot is based on the movement of the robot's legs. The robot leg motion control is designed by applying the tripod gait motion algorithm. The tripod gait algorithm is a hexapod robot motion algorithm that is often used because the three robot legs make the robot more stable when it moves [28][29]. This algorithm works in two steps, which are repeated. In the first step, the robot's right leg (front, back) and left leg (middle) move forward. Then the left robot leg (front, back) and the right robot leg (middle) move backwards. In the second step of the robot step, the left robot leg (front, back) and the left robot leg (middle) move forward. Then the right robot leg (front, back) and the left robot leg (middle) move backwards. Figure 3 shows the motion pattern of the robot with the tripod gait algorithm.

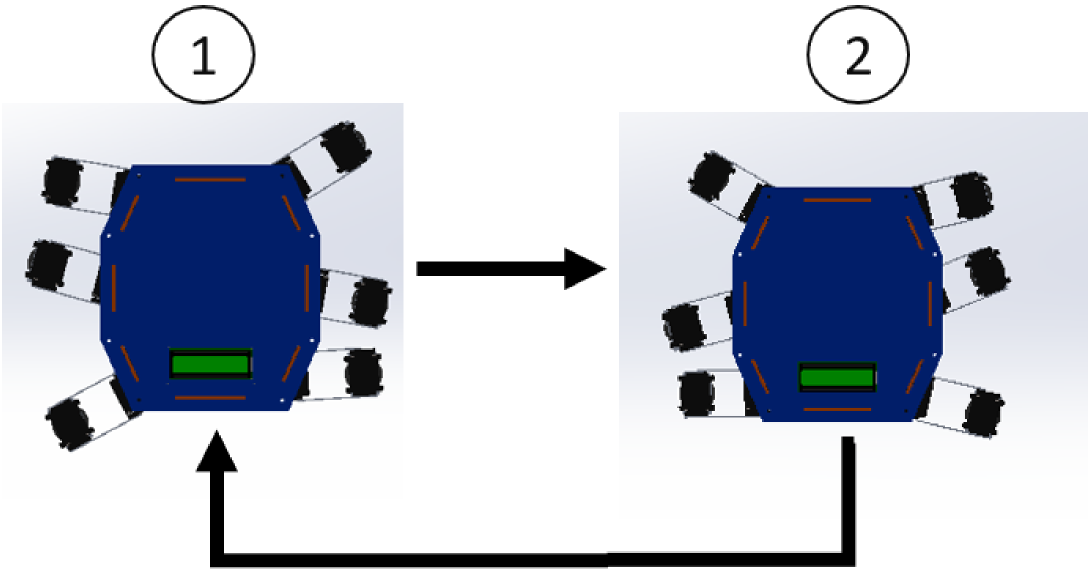



**Figure 3**. Robot movement pattern with tripod gait algorithm

### 2.3. Robot Algorithm for Uneven Terrain

The design of the robot control system algorithm for uneven terrain involves the design of a flowchart consisting of three different types of uneven terrain, namely debris terrain, uneven ground terrain and slope terrain.

#### 2.3.1. Debris Field Flowchart

The flowchart starts by initializing the input and output components on the robot. Then, when all the initializations have been completed, the system enters the state of pressing the start button on the robot. When the start button is pressed, the robot enters the sensor reading state. When the robot enters the predetermined sensor state, it will move according to the designed debris movement mode, i.e. right or left. If the robot is not in all conditions, it will move in straight debris mode. Once the entire robot body is out of the debris field, the walking system is complete. Figure 4 shows the results of designing a robot trajectory when passing through a debris field.

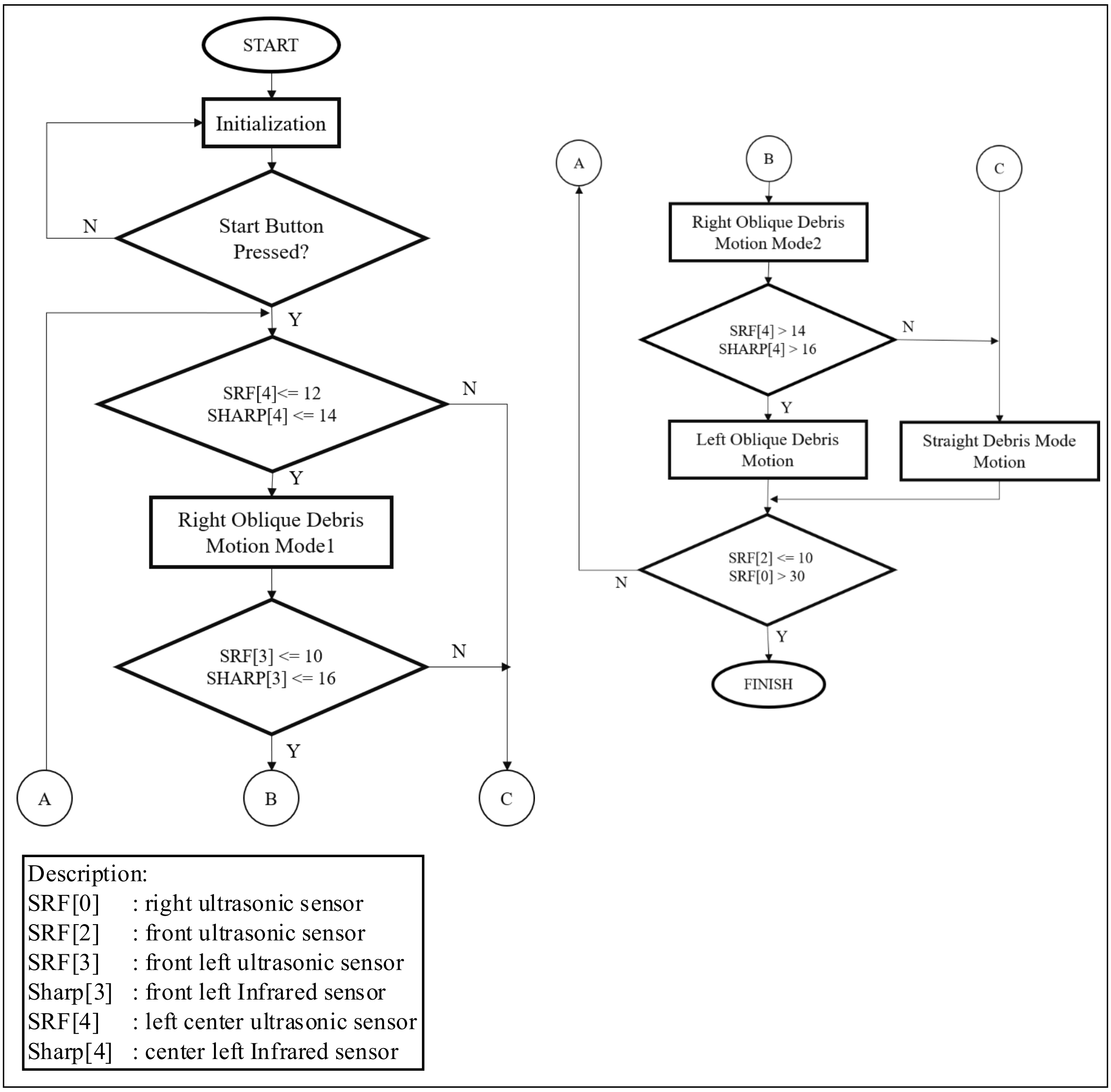



**Figure 4**. Robot flowchart design on debris field

### 2.3.2. Flowchart of Irregular Floor Field

The flowchart starts by initializing the input and output components on the robot. Then, when all the initializations have been completed, the system enters the state of pressing the robot start button. When the start button is pressed, the robot enters the sensor reading state. The robot will move based on the results of the sensor reading condition according to the designed irregular terrain movement mode, namely right oblique left oblique and straight movement. If the robot is not in all conditions, it will move in straight motion mode. There is one condition when the whole robot body has left the terrain, then the system is complete. Figure 5 shows the results of designing a robot flowchart for traversing an uneven terrain.

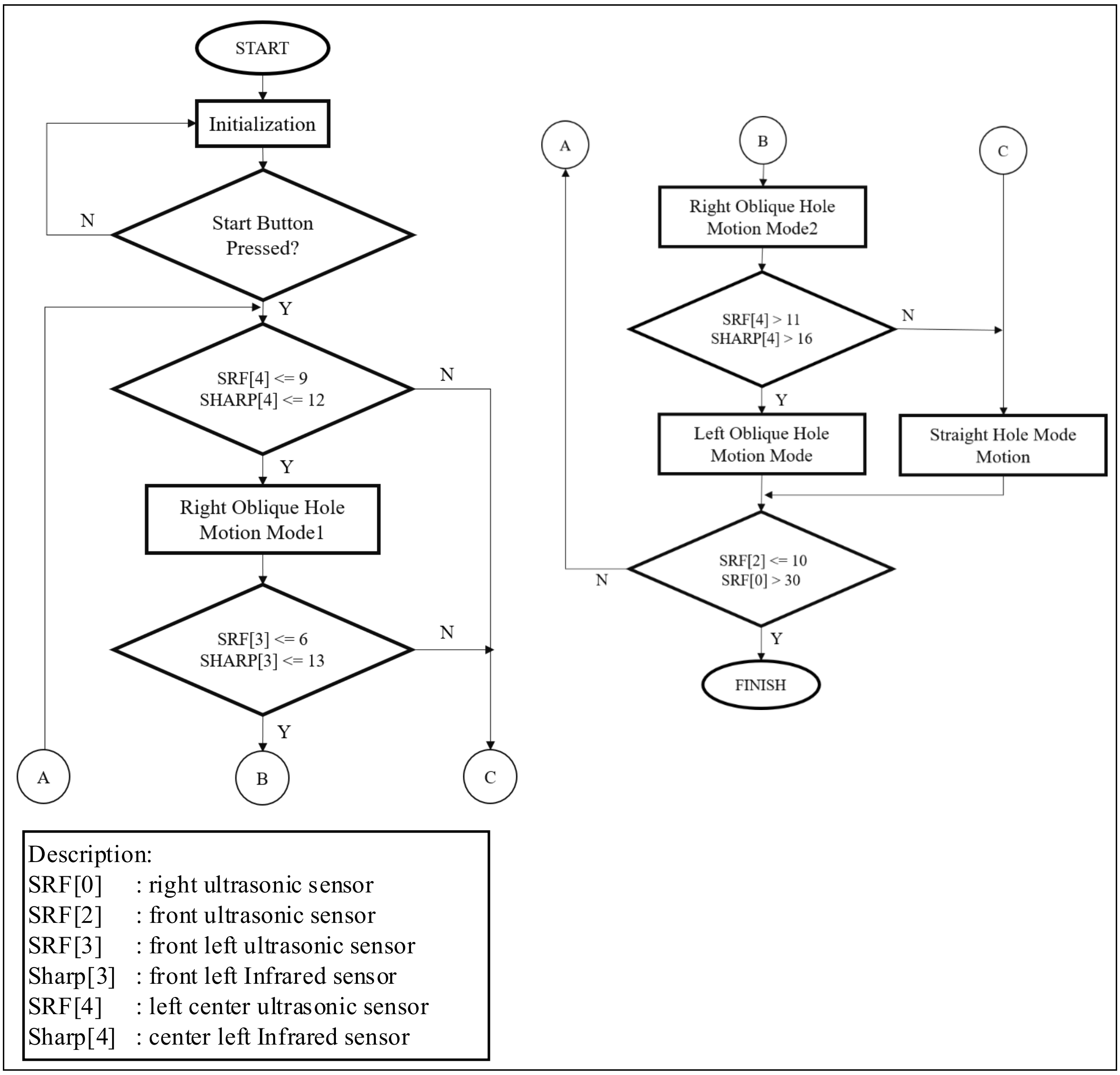



**Figure 5**. Robot flowchart design on irregular floor meanders

### 2.3.3. Flowchart of Up and Down Floor Terrain

The flowchart starts by initialising the input and output components on the robot. Then the robot enters the start button pressing state. When the start button is pressed, the robot enters the index_mission state. The index_mission consists of 4 missions that read the IMU sensor states and perform movements on the designed robot. The tilt reading on the IMU sensor is performed in three states, namely when the robot is climbing the terrain, when the robot is at the top of the terrain and when the robot is descending the terrain. In each index_mission there is also a timer variable that is incremented in each mission that is performed. This timer variable is used as a condition parameter to switch from one mission to another after the counter up has been met. The robot will perform missions sequentially until it reaches index_mission 4, at which point the robot will stop and the system will be complete. Figure 6 shows the results of the flowchart design as the robot traverses the up and down terrain (slope).

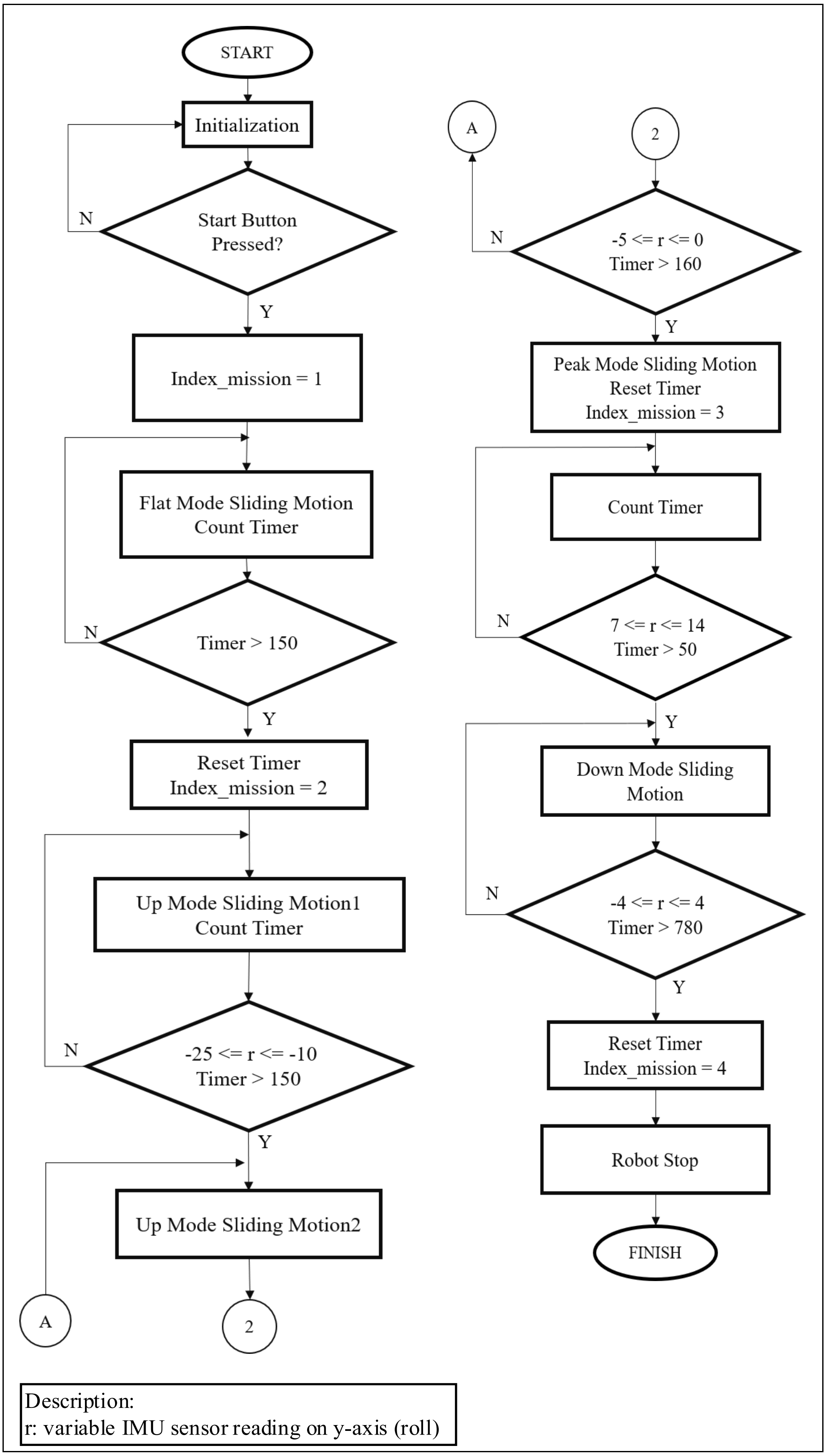



**Figure 6**. Design of robot flowchart on slope terrain

## 3. RESULT AND DISCUSSION

This test is carried out on the results of the robot design development and the robot control test when driving over uneven terrain. Robot design development is carried out by making sketches of the robot's mechanics and body. The robot is designed by determining the center of gravity point. The purpose of determining this point is to make the robot more stable when walking over uneven terrain. The controls designed for this robot will be tested on rubble terrain, uneven terrain and up and down terrain (slope). The robot is tested on the basis of the parameters of the robot's success in traversing the terrain and the robot time obtained when the robot traverses the terrain.

### 3.1. Testing Center of Mass on Robot Design

A design is made on the robot frame to determine the shape of the robot to be built. The robot legs that have been previously arranged are assembled with the lower and upper frames on the robot to form the mechanical hexapod robot. The dimensions of the hexapod robot are shown through the design with a display as shown in Figure 6. The overall dimensions of the robot, measured from the tip of the robot's foot, are 319.64 mm long and 324.45 mm wide. The design process is also carried out on the head of the robot. The robot head contains a printed circuit board and sensors used on the hexapod robot. The design of the robot head also takes into account the mechanical part of the robot leg. The robot head is designed to fit the size of the robot leg mechanics so that the size of the robot remains ideal and the balance of the robot is better. Figure 7 shows the results of the mechanical design on the hexapod robot.

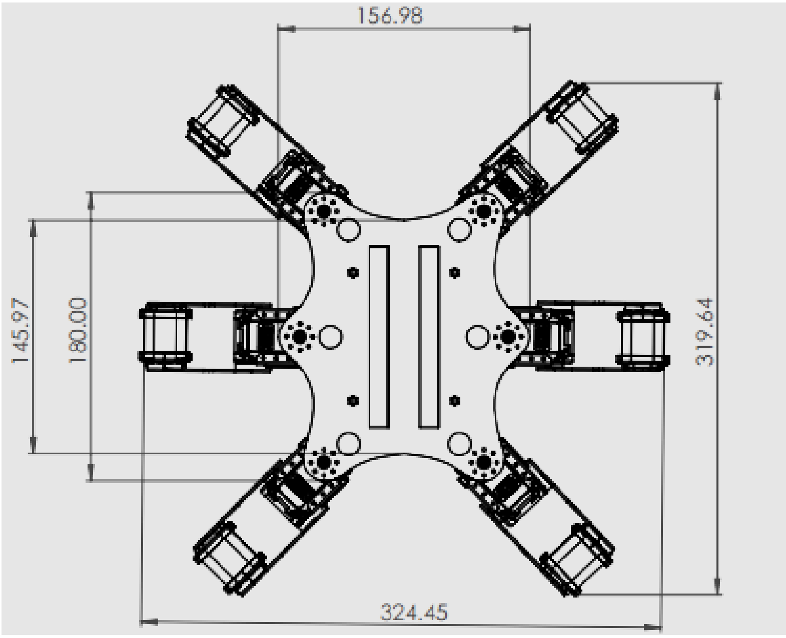



**Figure 7**. Mechanical design of hexapod robot

The center of gravity point can be obtained from a feature in the Solidworks software. This feature can be activated when the assembly performed on the design is complete. The robot frame is designed using aluminium sheet material with a thickness of 1.5mm. Meanwhile, the robot head is designed using acrylic material with a thickness of 3mm. The determination of this material is done in order to be able to determine the point of CoG (Center of Gravity) or the center of load of the robot [30]. The load point of this robot can be used to determine the position of the BNO055 sensor placement. To obtain the CoG coordinate point on the robot, it is necessary to select from the Solidworks 2018 menu, namely Mass Properties. Then select the initial coordinate point on the robot part. This coordinate will provide a starting point for determining the robot's CoG measurement point. From the results of setting the reference coordinate system, the initial reference point of the CoG point can be obtained. Using the mass properties menu, the CoG point on the robot is at the x, y, z coordinate point (0 -2.7 7.2) cm from the reference point. Figure 8 shows the results of determining the CoG point and Figure 9 shows the results of the CoG coordinate value in Mass Properties.

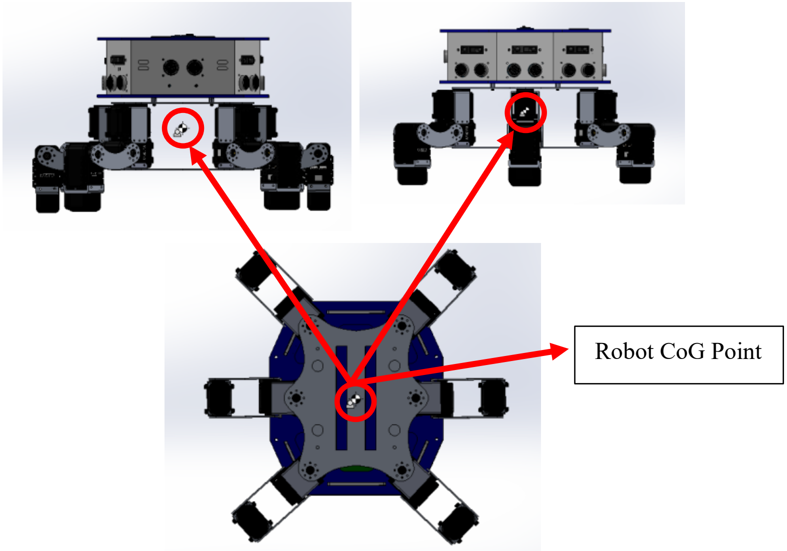



**Figure 8**. The result of determining the CoG point

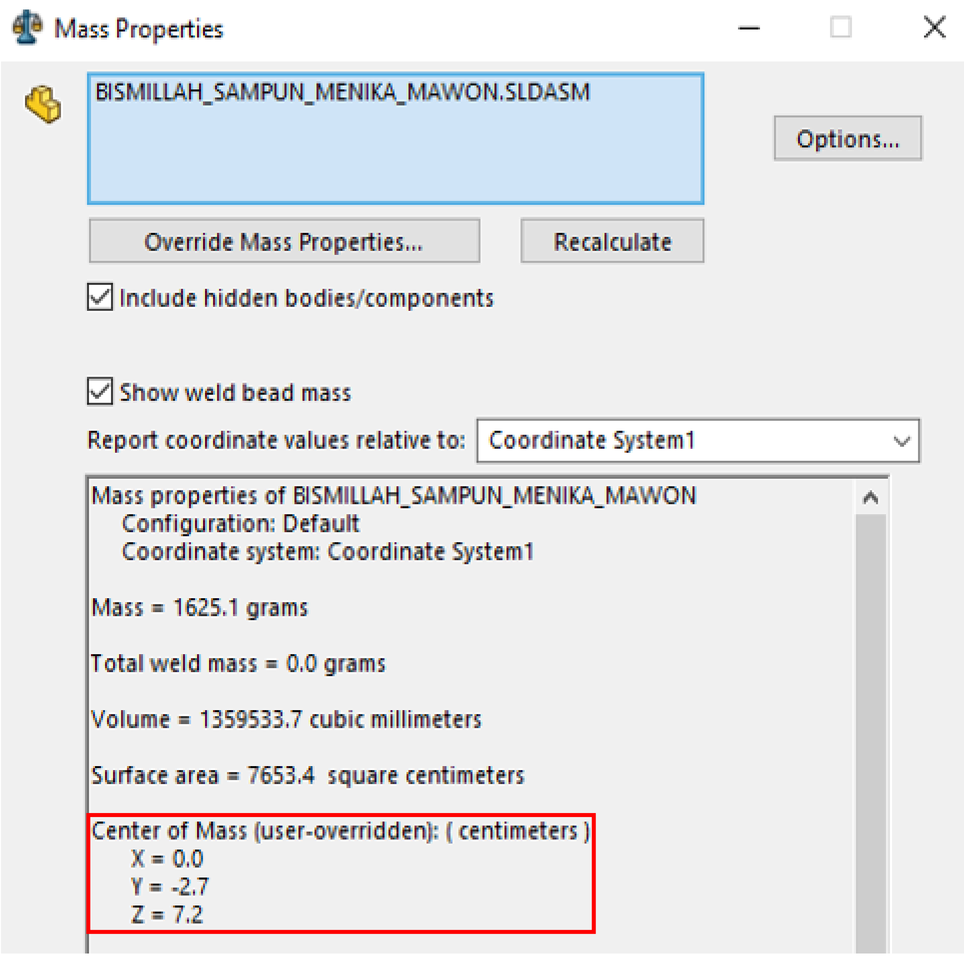


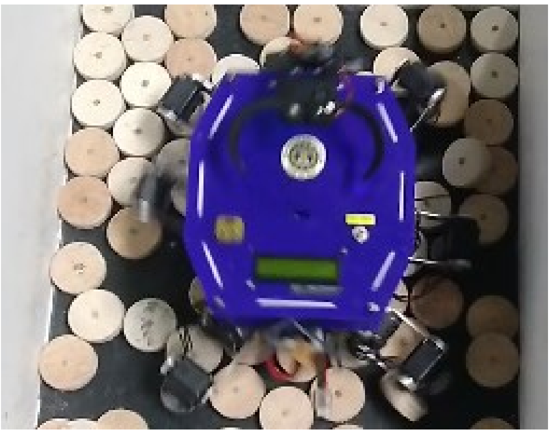

**Figure 9**. CoG coordinate value results on mass properties

### 3.2. Testing the Robot on Debris Fields

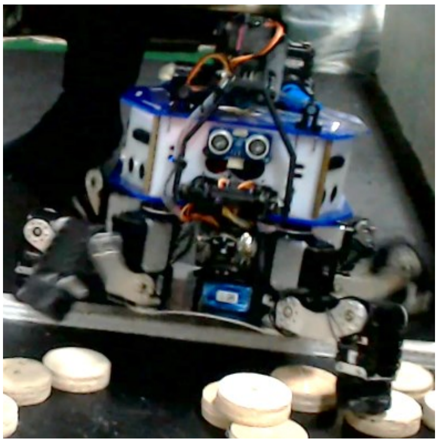
The first tests were carried out on the hexapod robot in the debris field. This algorithm is set up to apply the designed movements and a combination of distance sensor readings to the robot, namely the HC-SR04 sensor and the Sharp GP2Y0A21. Table 1 shows the results of testing the robot in the debris field and Figure 10 shows the appearance of the robot as it passes through the debris field.

**Table 1.** Testing the robot on debris terrain

| Testing | Test Parameters | | |
|---|---|---|---|
| | **Success/Failure** | **Robot Motion Position** | **Time (seconds)** |
| 1 | Success | Center | 9 |
| 2 | Success | Center | 8 |
| 3 | Success | Right- Center | 8 |
| 4 | Success | Right-Left | 12 |
| 5 | Success | Right-Left | 11 |
| 6 | Success | Right- Center | 11 |
| 7 | Success | Right - Center | 9 |
| 8 | Success | Center | 9 |
| 9 | Success | Right - Center | 9 |
| 10 | Success | Right - Left | 11 |
| Time Average | | | 9.7 |



(a)



(b)

**Figure 10**. Robot moving through debris field (a) top view, (b) front view

After testing the robot's movement, it can be determined that the robot's success rate in passing through the debris field is as follows.

$$\text{Success Rate} = \frac{\text{Total Successful}}{\text{Number of Tests}} \times 100\%$$

$$\text{Success Rate} = \frac{10}{10} \times 100\%$$

$$\text{Success Rate} = 100\%$$

Throughout the experiment there are conditions where the robot's movement is not always straight, so it may hit the wall and take the robot longer to traverse the terrain. Table 1 shows that in the 4th, 5th and 10th robot trials the robot did not move straight on the terrain. The robot's motion state is tilted to the right and then to the left with a time of 11 and 12 seconds. The hexapod robot was tested 10 times on the rubble terrain. After testing the movement of the robot, it can be seen that the success rate of the robot is 100%. The result of the calculation of the average time obtained when testing the robot through the debris field is 9.7 seconds.

### 3.3. Testing the Robot on Irregular Floor Terrain

The second test carried out on the hexapod robot is a test on uneven ground. The robot algorithm is created by applying the movements made and the existing distance readings on the robot, namely HC-SR04 and Sharp GP2Y0A21. The robot movement algorithm is combined with the sensor reading conditions so that when the robot moves, it has the potential to hit the wall. Table 2 shows the results of testing the robot on irregular terrain and Figure 11 shows the appearance of the robot as it traverses irregular terrain.

**Table 2.** Testing the robot on irregular floor terrain

| Testing | Test Parameters | | |
|---|---|---|---|
| | **Success/Failure** | **Robot Motion Position** | **Time (seconds)** |
| 1 | Success | Right-Center | 9 |
| 2 | Success | Left- Right | 11 |
| 3 | Success | Right - Center | 9 |
| 4 | Success | Right - Center | 9 |
| 5 | Success | Right | 11 |
| 6 | Success | Right - Center | 10 |
| 7 | Success | Right | 11 |
| 8 | Success | Right - Center | 10 |
| 9 | Success | Left - Right | 11 |
| 10 | Success | Right - Center | 10 |
| Time Average | | | 10.1 |

(a) (b)

**Figure 11**. Robot traversing uneven terrain (a) top view, (b) front view

After testing the robot's motion, it can be obtained that the success rate of the robot when passing through irregular floor terrain is as follows.

$$\text{Success Rate} = \frac{\text{Total Successful}}{\text{Number of Tests}} \times 100\%$$

$$\text{Success Rate} = \frac{10}{10} \times 100\%$$

$$\text{Success Rate} = 100\%$$

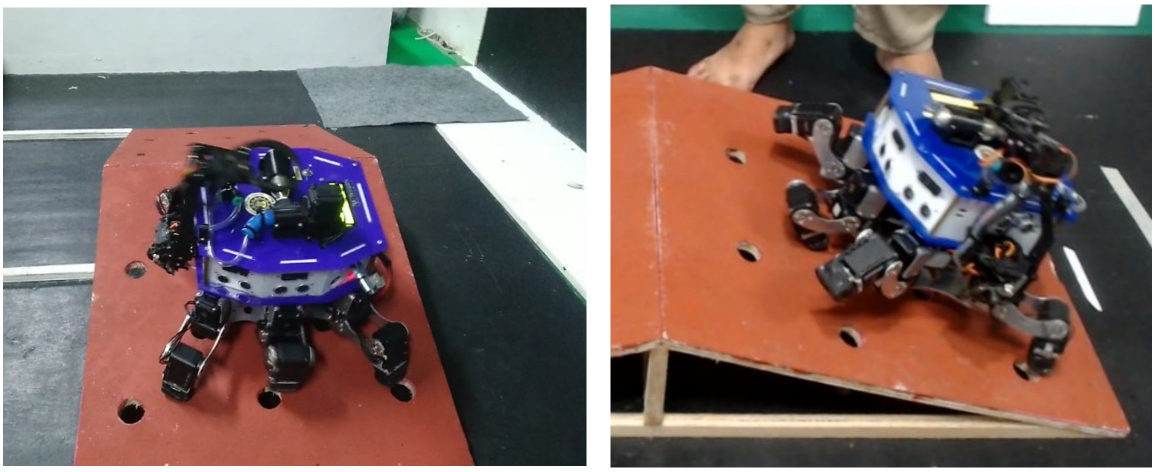
The tests carried out on the hexapod robot show that the robot can move well on irregular floor terrain. However, there are some conditions where the robot is still not able to move well in tests 1, 3, 4, 6, 8 and 10. In this condition, the robot can consistently walk well in the middle of irregular terrain. The hexapod robot was tested 10 times for walking on irregular floor terrain. After all the tests had been carried out, the success rate of the robot in traversing irregular floor terrain was 100%. The result of the calculation of the average time obtained when testing the robot over irregular floor terrain is 10.1 seconds.

### 3.4. Testing of the Robot on Up and Down Terrain (Slope)

The third test carried out on the robot is the up and down terrain (slope) test. Testing on this terrain is structured with algorithms that use a combination of compiled movements and IMU sensors. The IMU will be in charge of the detection of the slope of the terrain the robot is driving on. This allows the robot to switch the mode of movement in both uphill and downhill conditions. Table 3 shows the results of testing the robot on the up and down terrain, Figure 12 shows the condition of the robot going up the up and down terrain and Figure 13 shows the condition of the robot going down the up and down terrain.

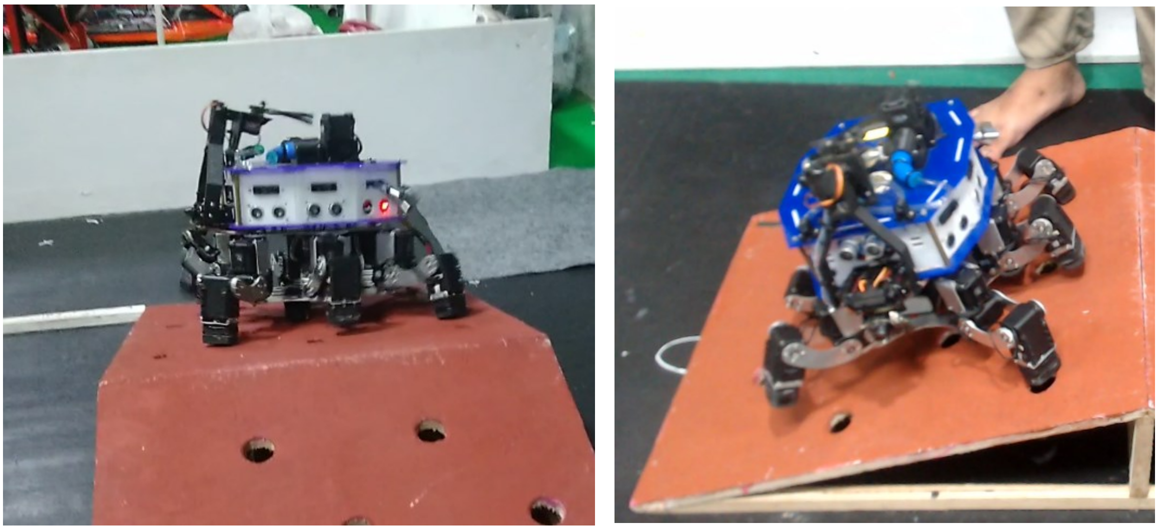
**Table 3.** Testing the robot on up and down floor terrain (slope)

| Testing | Test Parameters | | |
|---|---|---|---|
| | **Success/Failure** | **Robot Motion Position** | **Time (seconds)** |
| 1 | Success | Straight | 22 |
| 2 | Failure | Right-Back | 26 |
| 3 | Success | Straight | 24 |
| 4 | Failure | Right-Back | 24 |
| 5 | Success | Right | 22 |
| 6 | Success | Straight | 21 |
| 7 | Success | Straight | 22 |
| 8 | Success | Straight | 23 |
| 9 | Success | Straight | 22 |
| 10 | Success | Straight | 23 |
| Time Average | | | 22.9 |



(a) (b)

**Figure 12**. Robot moving up and down the floor terrain (a) side view, (b) front view



(a) (b)

**Figure 13**. Robot moving down the floor terrain up and down (a) side view, (b) front view

After testing the robot's motion, it can be obtained that the success rate of the robot when passing through the up and down floor terrain is as follows.

$$\text{Success Rate} = \frac{\text{Total Successful}}{\text{Number of Tests}} \times 100\%$$

$$\text{Success Rate} = \frac{8}{10} \times 100\%$$

$$\text{Success Rate} = 80\%$$

Robot testing on up-and-down terrain shows that overall the robot can move well through the terrain. Overall, the tests of the robots carried out on the up and down terrain show that in some tests there are conditions where the robot's movement is not completely straight, causing the position of the robot's footrest not to rest on the terrain floor. The position of the robot's foot which is off the ground will cause the robot to stop and not be able to walk to complete the ground. On the basis of 10 tests carried out on the robot, the success rate of the robot in traversing the up and down terrain is 80%. The average result of the acquisition of the time needed for the robot to pass the terrain with up and down floor is 22.9 seconds.

## 4. CONCLUSIONS

Design development can be done by making designs through Solidworks software. The design also applies the determination of the center of gravity point by Solidworks software to determine the balance point of the robot so that it can be more balanced and walk well when passing through uneven terrain, especially on the slope. The robot has successfully performed movements by applying the tripod gait algorithm. The motion modes that have been arranged on the robot include debris field motion mode, irregular ground field motion mode, and up-and-down ground field motion mode (slope). Based on the tests conducted, the success rate of the robot in traversing the debris field and irregular ground field is 100%. Meanwhile, the success rate of the robot in passing through the up-and-down ground terrain (slope) is 80%. The time obtained when testing on each terrain is quite efficient. In the debris field the average time obtained is 9.7 seconds, while in the irregular ground field the average time obtained is 10.1 seconds. The robot takes a long time to cross the up and down terrain (slope) with an average of 22.9 seconds.

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