

Czech Technical University in Prague
Faculty of Mechanical Engineering
Department of Instrumentation and Control Engineering



Design of a Hexapod Robot

Bachelor Work

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Prague, 2021

I. Personal and study details

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Branch of study: **Information and Automation Technology**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Design and control of spider robot

Bachelor's thesis title in Czech:

Návrh a řízení robota pavouka

Guidelines:

- 1) Design the mechanics of the robot - parts cut from aluminium or 3D printed
- 2) Select suitable actuators for the robot, install and connect the electronic circuits
- 3) Create control software (e.g. Arduino) to allow the robot to walk
- 4) Experimentally verify your design

Bibliography / sources:

Jagannathan Kanniah, M. Fikret Ercan, Carlos A. Acosta Calderon: Practical Robot Design: Game Playing Robots 1st Edition, CRC Press; 1st edition, ISBN-13 : 978-1439810330

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Assignment valid until: _____

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Acknowledgement

I would like to thank my supervisor, doc. Ing. Martin Novák, Ph.D. for his help, knowledge and he provided for me to be able to develop this bachelor work.

At the same time, I would like to thank him and Czech Technical University in Prague for providing me with all the necessary tools and equipment required for this work specially during these difficult times.

I would also like to thank my family for their unconditional support throughout my university life

Octavio Javier Linares Calderon

Abstract

Czech Technical University in Prague

Faculty of Mechanical Engineering

Department of Instrumentation and Control Engineering

Design and control of a hexapod robot

This bachelor work is aimed to design, build and program a hexapod robot which parts can be 3D printed in plastic or laser cut from sheet metal. The evolution and changes in the design of the parts of this robot will be shown in this bachelor work along with the problems faced. In addition, the programming to make it walk will be included.

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Introduction

Robotics is a rapidly growing and popular technical discipline. It integrates fields of mechanical engineering, electrical engineering, information engineering, mechatronics, electronics, bioengineering, computer engineering, control engineering, software engineering, mathematics, among others. Robotics has progressed significantly as a result of its uses in industry. As a result, robotics has remained popular in manufacturing and industry for a long time.

However, robotics has found uses in a variety of industries other than manufacturing during the last decade, including service robotics, medical, entertainment, and education. Computer technology, sensor technology, semiconductor technology, and artificial intelligence advancements all played a role.

Hexapods

An example of a robot that is not used for industrial purposes is a hexapod. A hexapod, as its name indicates by definition, is a six-legged walking robot [1]. While there can be many different types of hexapod robots, the mechanics and movements of most of them are biologically inspired by hexapod insects.

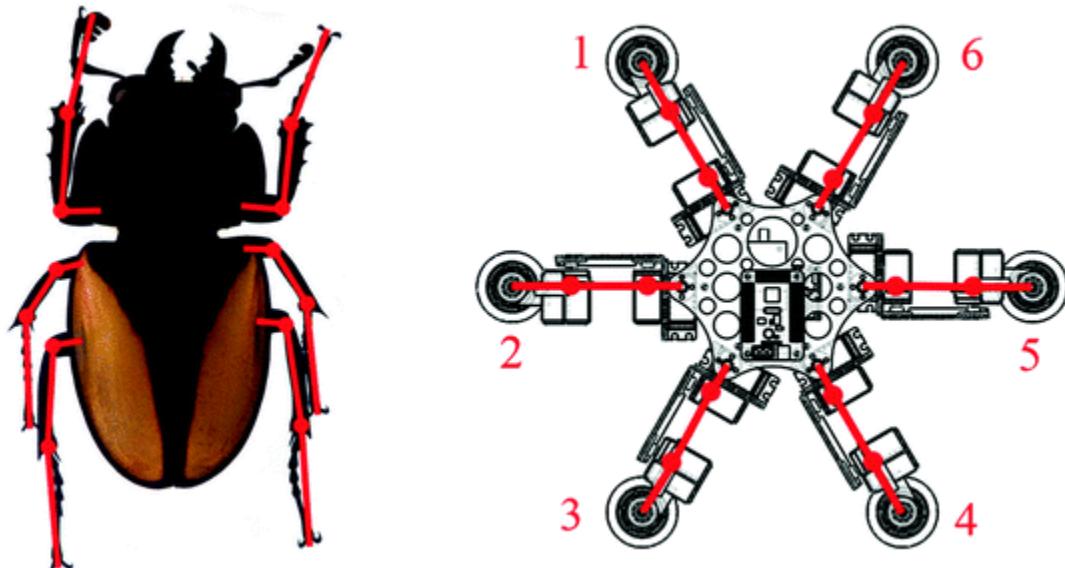


Figure 1: Symmetric configuration [2]

In Figure 1 we can see the two main symmetric configurations for the legs. Laterally symmetric and radial symmetric, respectively. Radial symmetry presents some benefits in comparison. Firstly, each leg is similar to one another and this means they could share exactly the same structure. This makes it easier to mass produce if needed. Another advantage is that each gait programmed

would work in any direction. We can program it even to walk backwards, something that is impossible for real insects.

Hexapod robots are commonly used for research purposes as they allow us to study insect-like locomotion and motor control. These types of robots have great stability as they can be statically stable on three or more legs, giving it great flexibility in the way it can move. This also makes them easier to control as they will remain stable while walking thanks to the number of legs.

While commercially available hexapods and other examples made by different people tend to have similar builds and properties, one of my main inspirations for my design has been the PhantomX AX Metal Hexapod MK-III made and sold by Trossen Robotics.



Figure 2 : PhantomX AX Metal Hexapod MK-III Kit
PhantomX AX Metal Hexapod MK-III Kit [3]

These hexapod kits are the collaborative effort from some of the top talent in the robotics community: Next-Gen AX series DYNAMIXEL robot servos, the ArbotiX-M Robocontroller. The kit includes all the necessary servos and even has its own code which makes it easy and ready to operate. I followed this example and also used eighteen DC servos to give each leg three degrees of freedom in movement. Furthermore, I also decided to use aluminium as the material for the body and legs of my hexapod.

Servos

Servo motors are widely used in robotics. They are DC motors with built-in control electronics. These motors are not meant for continuous rotation, but for a fixed angular rotation instead. By using a potentiometer, that is housed with the motor itself, it receives feedback about its position. Thanks to this, servomotors are easy to program and to manipulate its position, making them really useful in applications involving control of robotic parts such as humanoid limps or in this case, the hexapod's legs.

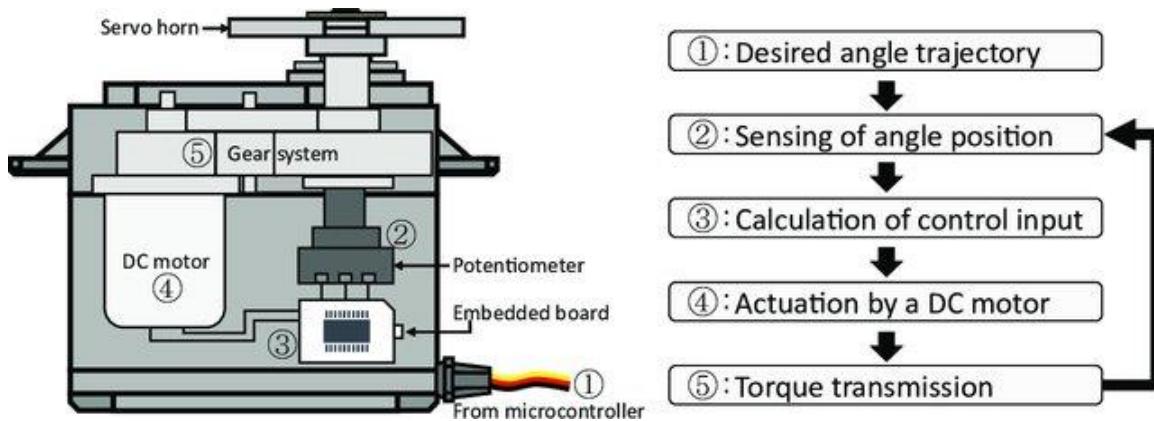


Figure 3 : Schematic of an RC servo moto [4]

For this project, two similar servomotors have been used. Both of them are brushed DC motors and a range of 180°.

Servo Motor Features

Model:	Towerpro Servos MG995
Dead Band:	0.100 ms
Control System:	+Pulse Width Control
Working Frequency:	20ms period / 50hz (Analog Control)
(RX) Required Pulse:	3.0 ~ 5 Volt Peak to Peak Square Wave
Operating Voltage:	4.8 ~ 6 V DC Volts
Operating Temperature Range:	-0 to + 55 Degree C
Operating Speed (4.8v):	0.200 sec/60° degrees at no load
Operating Speed (6v)	0.160 sec/60° degrees at no load
Stall Torque (4.8v):	9.4kg/cm
Stall Torque (6v):	11kg/cm
Motor Type:	Brushed Motor
Potentiometer Drive:	Direct Drive
Bearing Type:	Output Bearing
Gear Type:	Brass & Aluminum Gears
Case Material:	Plastic
Programmable:	NO
Connector Wire Length:	32.0cm (12.6 inch)
Dimensions:	40.7×19.7×42.9mm
Weight:	55 grams (2.64 oz)

Figure 4 ; MG995 Servo Motor specifications [5]

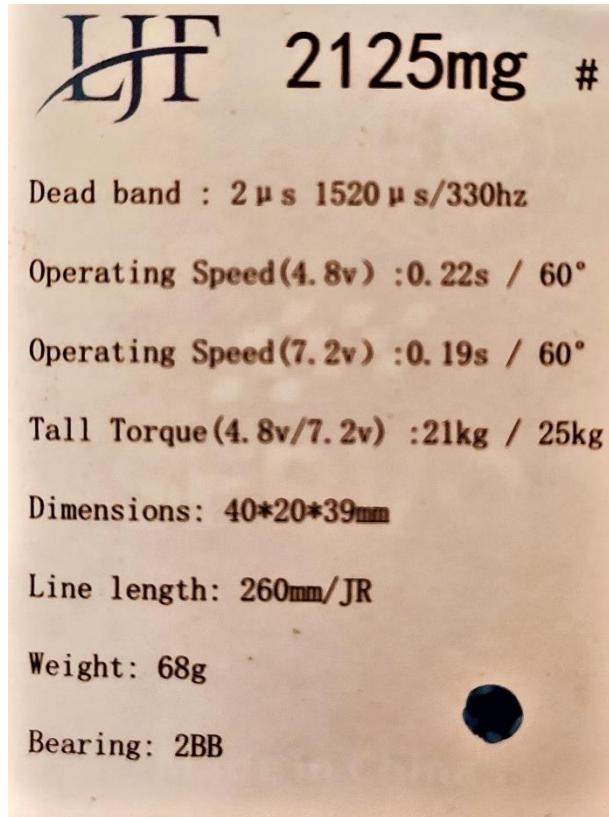


Figure 5 ; LJF 2125mg Specifications

For this project I was provided with twelve MG995 servos and six 2125mg servos to distribute and use for the legs. As we can see from the tables above, both servos are very similar in regard to their physical dimensions, but the main difference is in the 2125mg having more than double the stall torque. Both servos also have the same cables to connect to the Arduino board that will be used for this project (Ground, voltage and signal).

Arduino

In order to control the multiple servos of the hexapod robot, an Arduino Mega 2560 microcontroller board was provided by my supervisor. The board has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button and can be powered simply by a computer with a USB cable or with an external AC-to-DC power adapter.

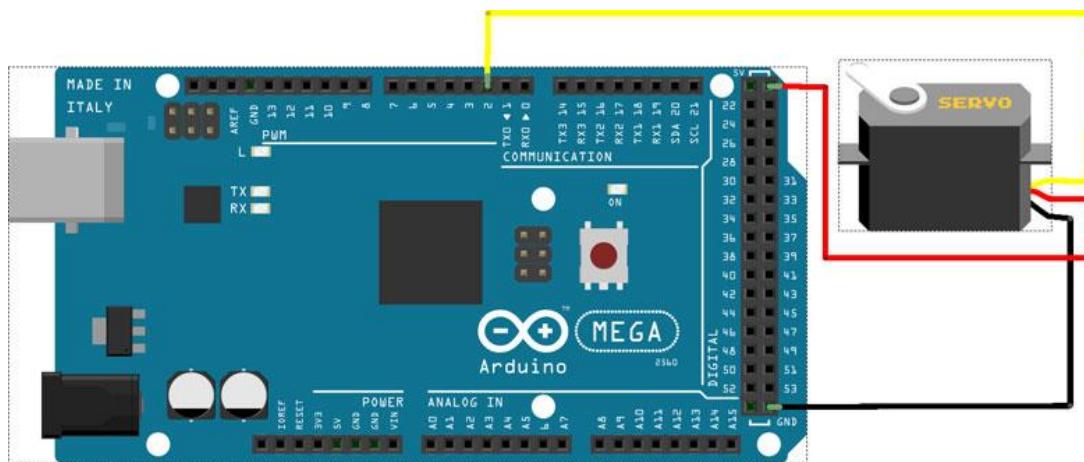


Figure 6 : Arduino Board connected to single servo [6]

However, this Arduino doesn't have enough ports to be able to connect all of the eighteen servos to it. For this reason, a Mega sensor shield v2.0 has to be connected to the main board. This shield helps expand the capacity as it has

32 PWM ports available for connecting the servos and 15 input ports for analog signals.

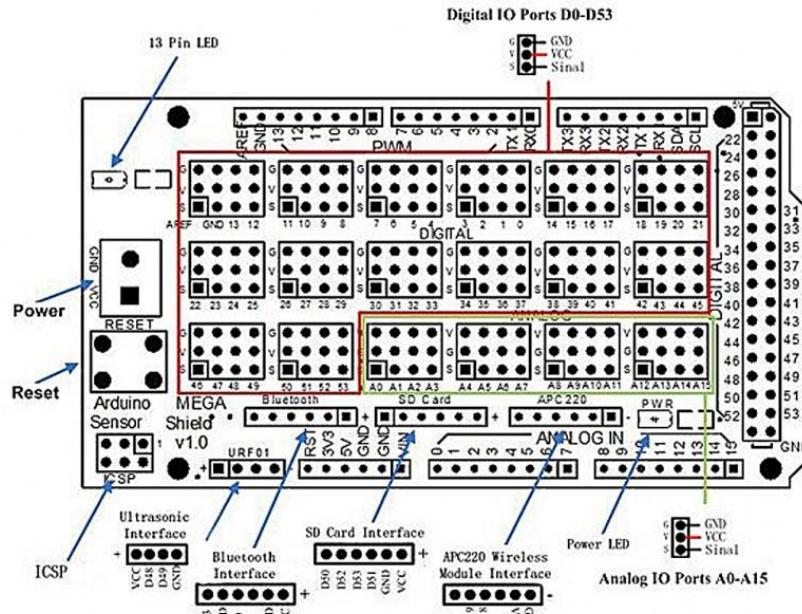


Figure 7 : Mega sensor shield v2.0 [7]

Arduino has its own integrated development environment, Arduino IDE, which uses the programming language C++ to create the “sketch” that is then processed and compiled to machine language when it is uploaded to the Arduino board. From this IDE you can also access the serial monitor which can be used mainly to interact with the Arduino board through the computer for real-time monitoring and debugging. [8]

Kinematics

Kinematics are used to describe the motion of systems of joined parts such as an engine, a robotic arm or in this case, the robotic legs of the hexapod. Often described as the “geometry of motion”, it consider the geometrically possible motions of a body, or system of bodies, without considering the forces involved or the causes of this motion. Kinematics can be divided into two main types, when describing the motion of the robotic legs. Forward kinematics and inverse kinematics.

Forward Kinematics

In order to determine the position and orientation of the robot's end actuator, in this case the tip of the hexapod's leg, the forward kinematic equations must be established.

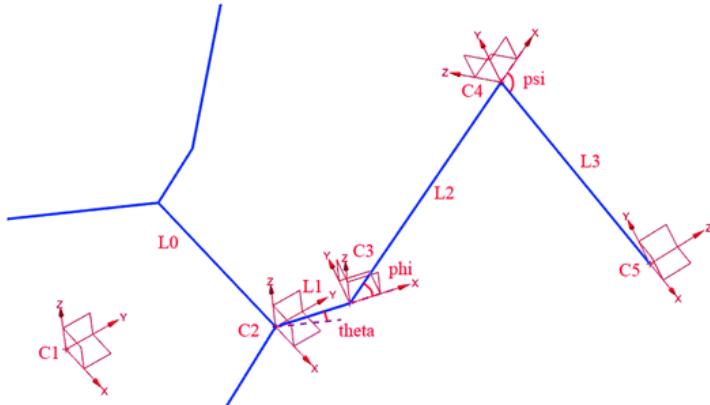


Figure 8 : Coordinates established for leg [9]

For the example seen in Figure 8, the coordinate system has been established at the center of the robot's body, C1, and this has been chosen as the frame of reference. At the same time, the homogeneous transfer matrix for C5 will be calculated. The three variables, theta, phi and psi, represent the angles of rotation of the servo motors for hexapod's leg being analyzed. The angular displacement between the body frame and the coxa, the coxa and the femur, and the one between femur and tibia respectively. As the other factors, the different lengths of the hexapod's leg sections are known, it is possible to proceed with the calculations of homogeneous transfer matrix.

$$\frac{1}{5}T_6 = \frac{1}{2}T_6 \bullet \frac{2}{3}T_6 \bullet \frac{3}{4}T_6 \bullet \frac{4}{5}T_6 = \begin{bmatrix} X & X & X & \#14 \\ X & X & X & \#24 \\ X & X & X & \#34 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where alphabet X is used to stand for the part that we don't care.

$$\begin{aligned} \#14 &= \frac{L0 + [L1 + L3 \cos(\varphi + \psi) + \cos \varphi](\cos \theta - \sqrt{3} \sin \theta)}{2}, \\ \#24 &= \frac{\sqrt{3}L0 + [L1 + L3 \cos(\varphi + \psi) + L2 \cos \theta](\sin \theta + \sqrt{3} \cos \theta)}{2}, \\ \#34 &= -L3 \sin(\varphi + \psi) - L2 \sin \varphi \end{aligned}$$

Figure 9 : Calculation of homogeneous transfer matrix [9]

$$P_6 = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} \#14 \\ \#24 \\ \#34 \end{bmatrix} = \begin{bmatrix} f(\theta, \varphi, \psi) \\ g(\theta, \varphi, \psi) \\ h(\varphi, \psi) \end{bmatrix}$$

Figure 10 : Position vector of the end actuator

Once the homogeneous transfer matrix has been calculated it is possible to write down the equations that will be necessary to calculate the position of the hexapod's end actuator.

Inverse Kinematics

While we can apply forward kinematics to determine the robot leg's (end effector) position and orientation in terms of the joint variables, it's leg length and the angular displacements of the servo motors. Inverse kinematics are used to solve the opposite problem. Finding out the value of these joint variables in terms of the robot leg's position and orientation. [10]

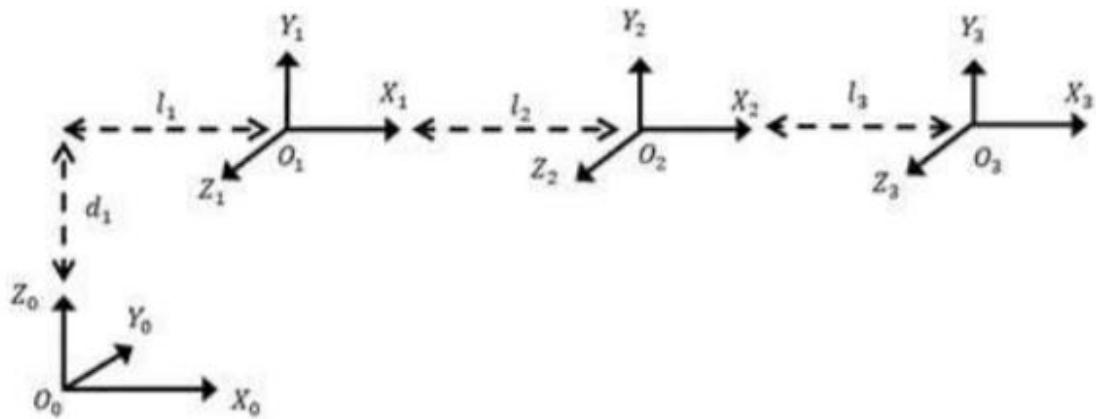


Figure 11 : Frame coordinate of hexapod leg [11]

Figure 11 shows an example of another hexapod leg's frame of coordinate system. This example will be solved using the Denavit-Hartenberg convention, a commonly used convention for selecting frames of reference in robotic applications. In this convention, each homogeneous transformation A_i is represented as a product of four basic transformations that work with four quantities: a_i , α_i , d_i , and θ_i . These parameters are associated with link i and joint I and they are commonly called: link length, link twist, link offset, and joint angle, respectively. [12]

$$[{}^0T]^{-1} = \begin{bmatrix} c\theta_1 & s\theta_1 & 0 & -l_1 \\ 0 & 0 & 1 & -d_1 \\ s\theta_1 & -c\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ((8)$$

It can obtain, that:

$${}^0T[{}^0T]^{-1} = [{}^0T]^{-1} {}^0T {}^1T {}^1T {}^2T {}^2T {}^3T \quad ((9)$$

$${}^0T[{}^0T]^{-1} = {}^1T {}^2T {}^3T \quad (10)$$

Figure 12 : Inverse kinematics equations [11]

$$\begin{aligned}
 & \begin{bmatrix} \dots & \dots & \dots & p_x c\theta_1 + p_y s\theta_1 - l_1 \\ \dots & \dots & \dots & p_z - d_1 \\ \dots & \dots & \dots & p_x s\theta_1 - p_y c\theta_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 & = \begin{bmatrix} \dots & \dots & \dots & c(\theta_2 + \theta_3)l_3 + c\theta_2 l_2 \\ \dots & \dots & \dots & s(\theta_2 + \theta_3)l_3 + s\theta_2 l_2 \\ \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)
 \end{aligned}$$

From this calculation it gets:

$$\theta_1 = \text{Atan2}(p_y, p_x) \quad (12)$$

Figure 13 : Inverse kinematics equations

Through the algebraic approach of decreasing the forward kinematic equation, as it can be seen in Figure 12 ((9), we eventually obtain an equation that depends only on the position (p_y, p_x) in order to calculate the joint angle. This same method can be applied to any of the hexapod's legs.

Designing the hexapod

This project of designing and building a hexapod robot started with the instructions from my supervisor to design a hexapod robot using Autodesk Inventor software. The design was to be similar to another hexapod that was shown to me on a video and the all the parts had to be designed so that they could be 3D printed. Furthermore, it had to be designed to work using the Arduino Mega 2560 board to control it and using MG995 as these were the servos that were available for the project.

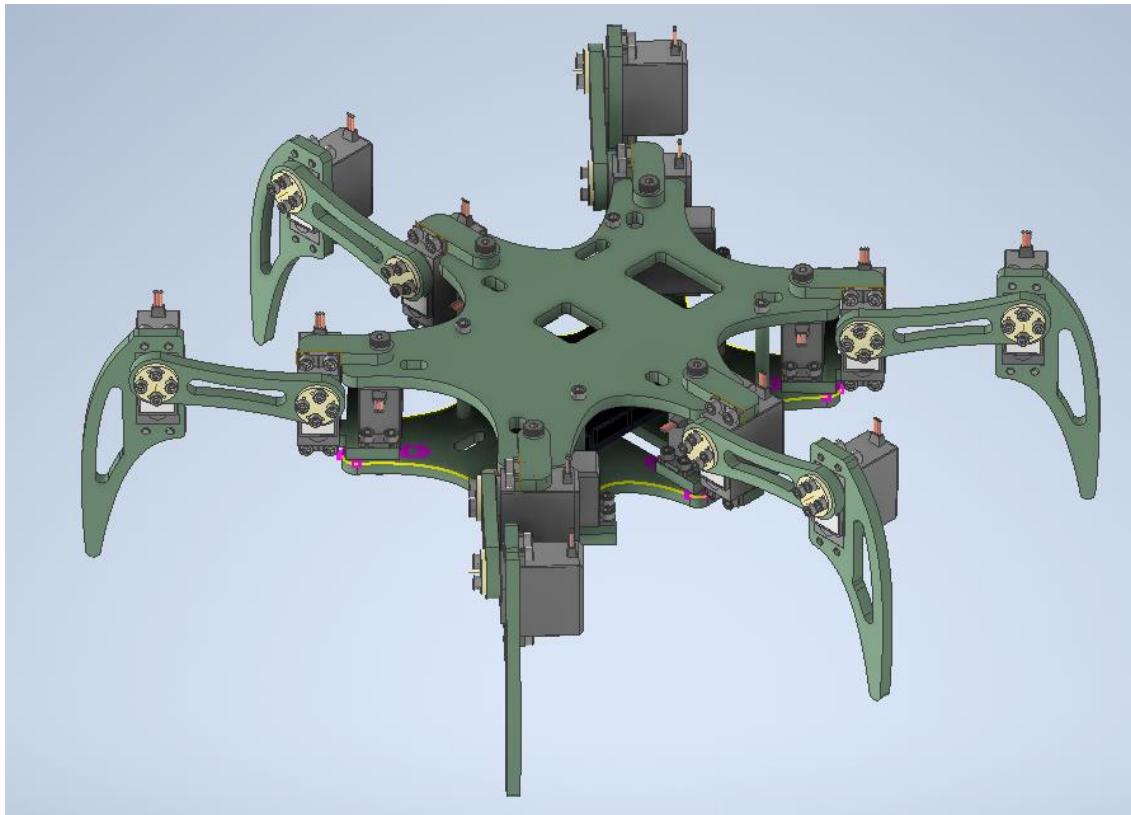


Figure 14 : First design of the hexapod

Having no experience with 3D printing, this first design was inspired by the simplest designs I was able to find as inspiration from other projects online. The parts of this first design were all flat so that they would be easy to 3D print while trying to keep the weight light by cutting several pieces of the material. In this first design the Arduino board would fit inside the main body of the hexapod.

However, after sending this first design to my supervisor, he told me that while a design like this would be functional it would be very unstable as it was using the servo motors as support for the weight. I was then recommended to change the legs' design using something more stable like a servo bracket.



Figure 15 : Servo bracket [13]

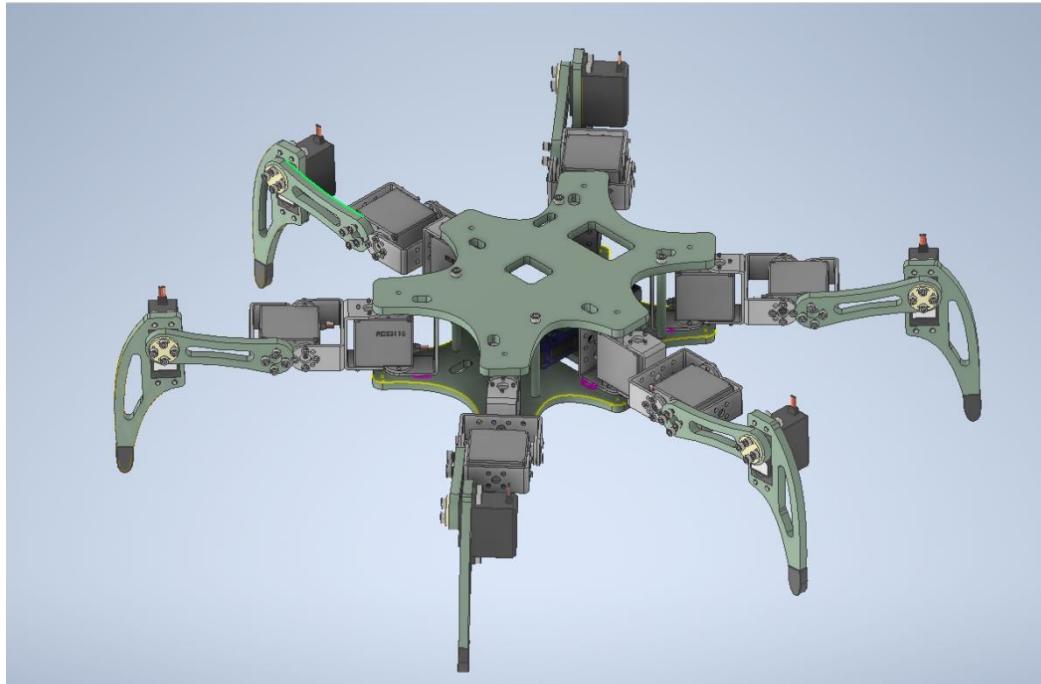


Figure 16 : Second design of the hexapod

For the second version of the hexapod, the legs were attached to the main body with the servo brackets and rubber tips were added to the feet of the robot so that the 3D printed plastic legs wouldn't slip on the ground. While this design was deemed more stable than before by my supervisor, he pointed out that the last servo from each leg was still being used as support for the weight of the robot and that it wouldn't be stable enough. The next recommendation was to design some frames for the servos and find the way make the legs more stable.

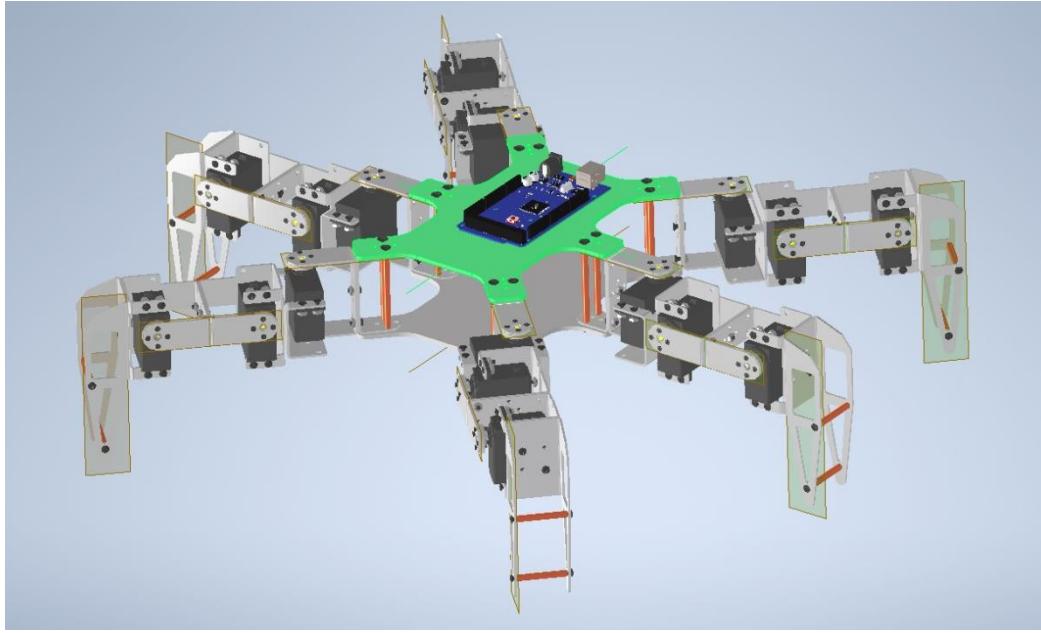


Figure 17 : Third design of the hexapod

Given the option to design the hexapod to either be 3D printed in plastic or to laser cut the parts from sheet aluminium or steel, I decided to change the material to sheet aluminium as it is a light metal that would still be strong to be able to walk and support the weight without getting damaged. Using aluminium was also a good option in order to keep the legs from getting too bulky as metal sheet is much thinner than 3D printed plastic parts would need to be. This design is also focused on using as few different parts as possible so that, if needed, parts could be mass produced or in case a different servo motor with a different frame had to be used. This time, I was also told by my supervisor that at least six of the servo motors could be replaced with stronger ones that had a much higher torque, servo motors 2125mg. While the overall size of these servos was the

same as the MG995 servos, the holes for the screws where slightly shifted and they required a different frame for them to fit. Metal spacers where also included in this design to strengthen the hexapod's leg's tips so they wouldn't bend as it walks. The Arduino board was moved to the top plate of the main body so that it would be easier to access and to leave space inside the body for any other possible components, like a power bank or a battery.

Building the hexapod

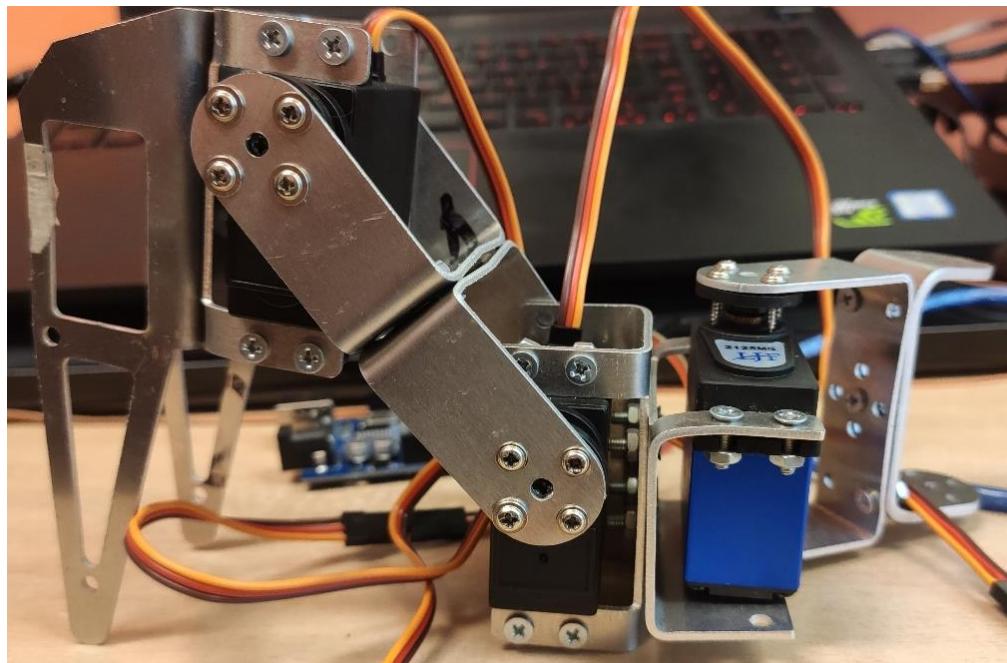


Figure 18 : First leg built

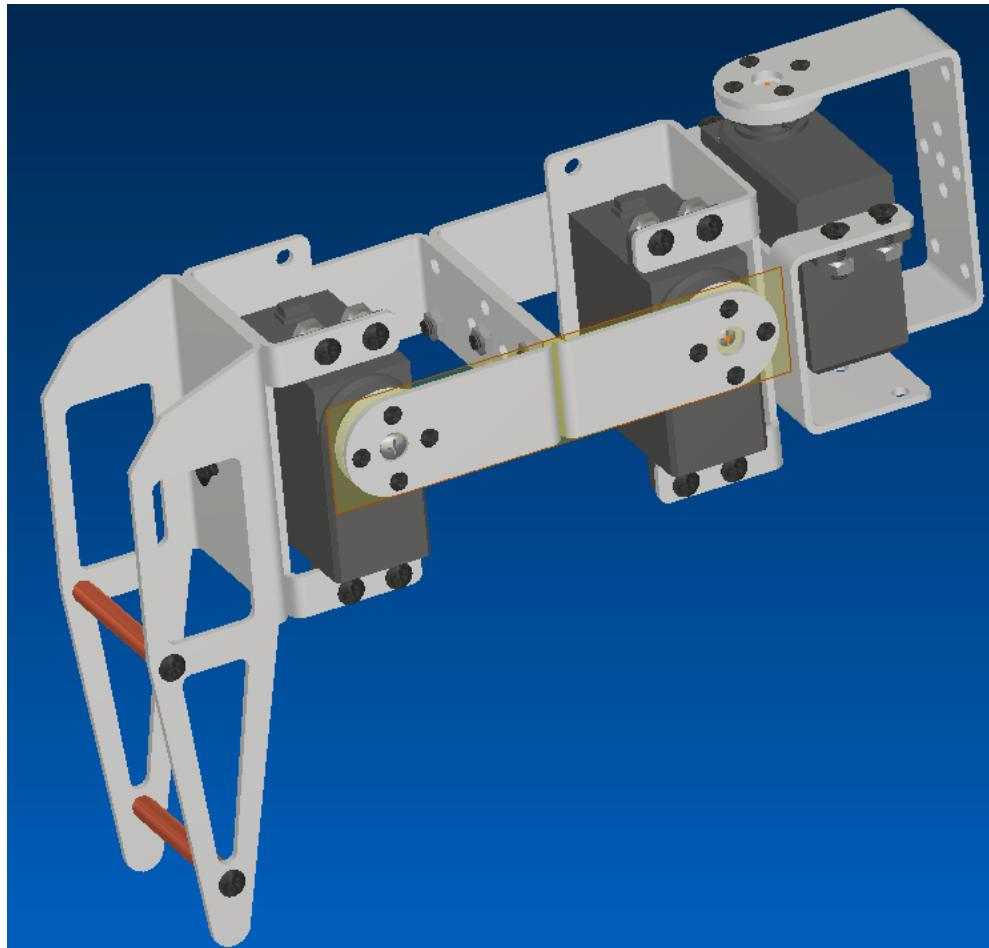


Figure 19 : Model of the first leg

As the third design of the hexapod robot was accepted as correct by my supervisor, it was possible to start building it. As the parts had to be sent to a company to lasercut them, it was recommended by my supervisor to only make one leg first to make sure that the design was correct and everything would work in real life. The main problem with the assembly of this first leg was that parts

had not been ordered to be bent and it was a really complicated task to do as there was also no access to proper equipment due to the covid lockdowns. However, although the parts were not bent completely accurate, it was still possible to assemble the leg as seen in Figure 18. The only problem in the design was the position of the holes for the screws that would secure the servos to its bracket.

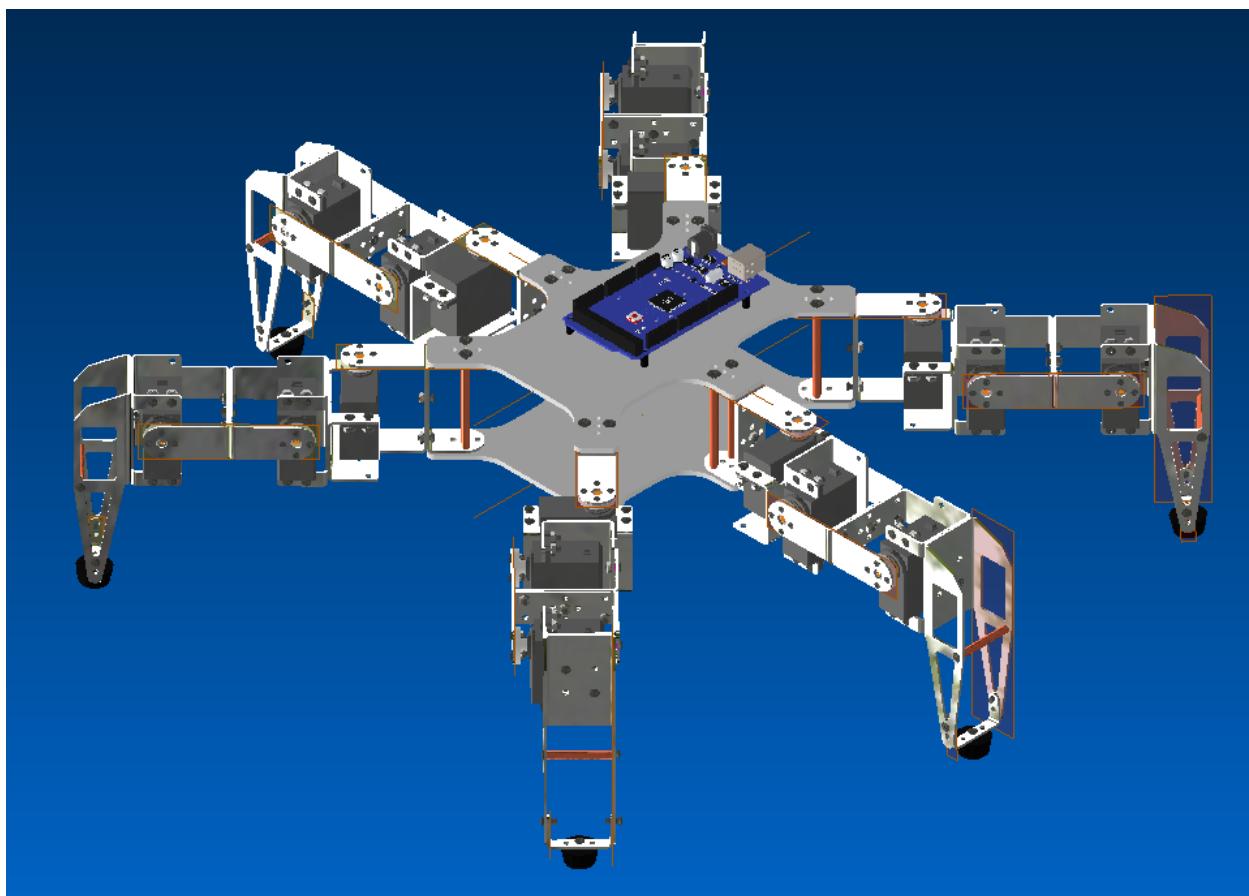


Figure 20 : Fourth hexapod design

As the test of the first leg had gone well, the leg was able to move properly. The holes for the screws on the servo brackets were moved to fit properly with the servo motors and the metal spacer at the tip of the legs was replaced with a small bracket where rubber tips could be attached. This design also allows for the possibility to replace the bracket and attach any other piece if required in the future. This time the parts were bent by the same company that cut them so there was no problem at all when assembling the whole hexapod together.

The first time I built the hexapod placing the stronger 2125mg servo motors at the base of the legs. However I realized later that the joint requiring the greater stall torque to stand up was the joint closer to the end of the leg. As it is the joint further away from the main body of the hexapod and the one that has to lift the most weight. Another important problem was that the servos were not getting enough power for all of them to work at the same time. I was using an external 5v 4amp AC to DC converter connected to the Arduino Mega Sensor shield but the servos were not able to hold the weight of the whole robot with this low power. The last problem faced with this first built was that the rubber tips I was able to find at the hardware store were too big and robot could

get a good grip when trying to walk, making the legs slip and causing the hexapod to fall down.

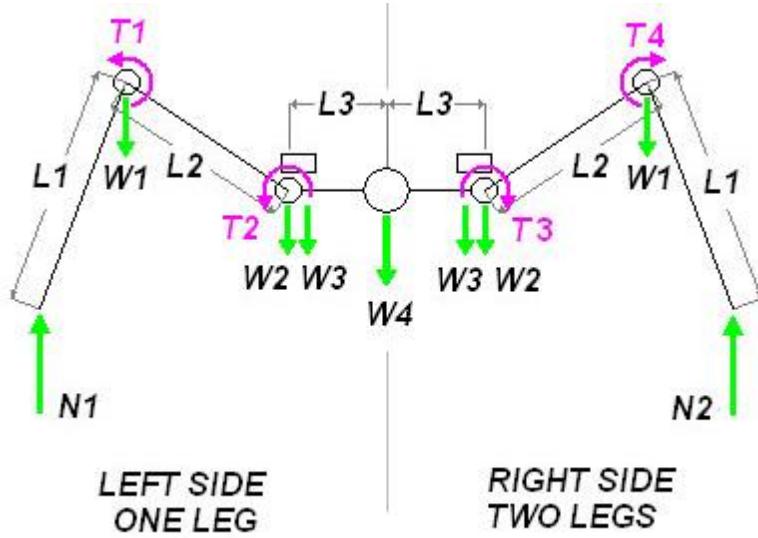


Figure 21 : Distribution of torques and forces [14]

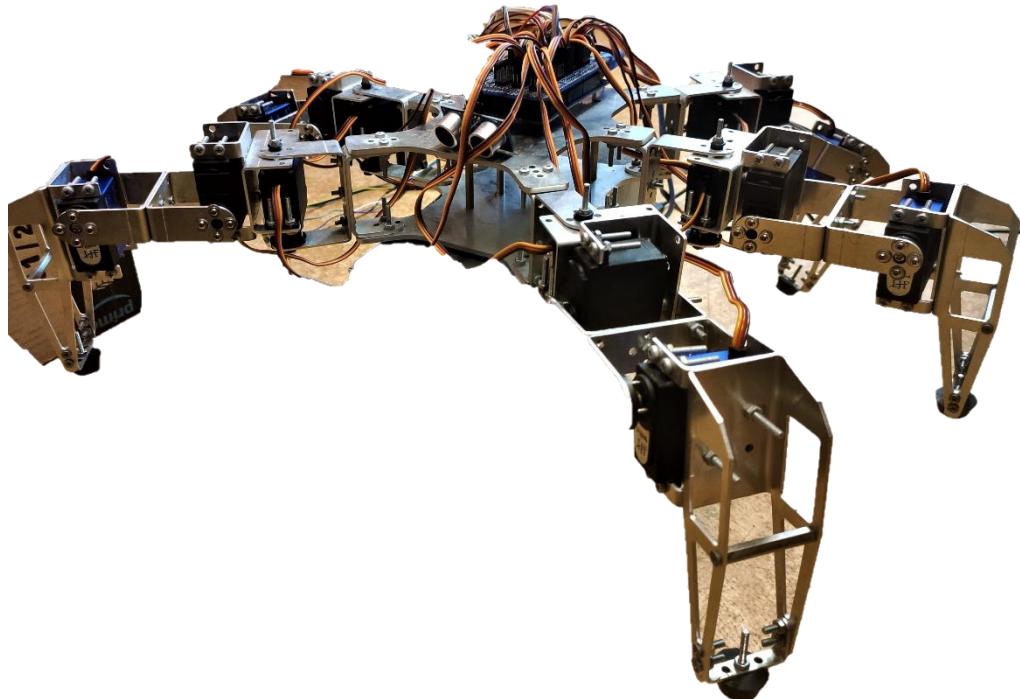


Figure 22 : Final version of the hexapod

After replacing AC to DC converter for a switching power supply with a higher amperage of 18 amps, the hexapod was able to stay up on its feet when placed on the floor with all the servos on. Using a switching power supply also offers the benefit of converting AC to DC more efficiently. The rubber tips were replaced with the smallest ones I could find so that they don't slip as much as before on flat surfaces. Finally, the last big change done to the hexapod was flipping the middle servo, on each leg, upside down so that the whole hexapod would be a bit taller and not hit the ground when bending down the legs.

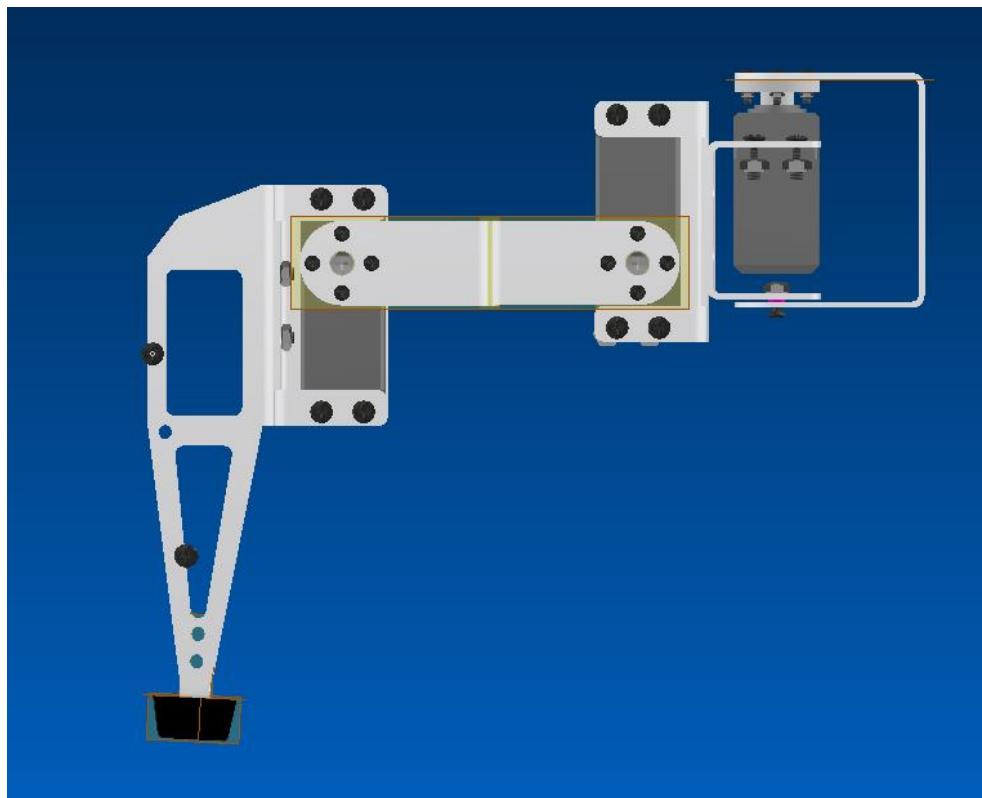


Figure 23 : Modified model of the leg

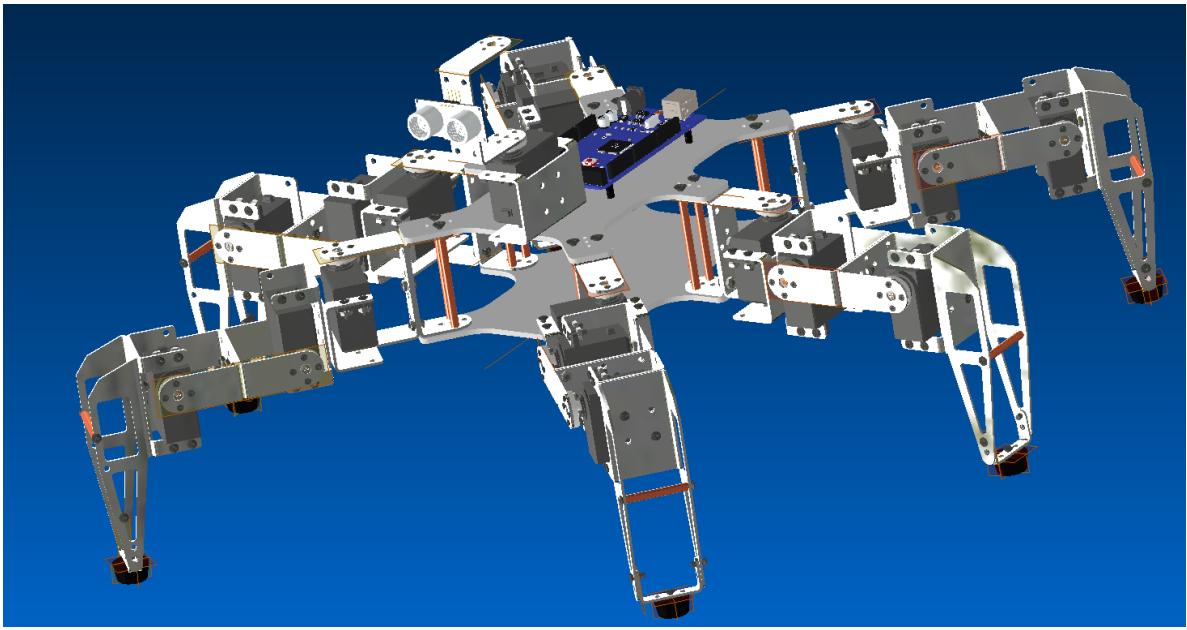


Figure 24 : Final model of the hexapod

Programming the hexapod

All the programming of the hexapod has been done through the Arduino IDE in C++ language. The code can easily be divided into the different functions or loops. To control the hexapod, two joystick modules have been connected and programmed to start the different functions. Joysticks operate like two potentiometers that are connected together inside the housing of the module. One of them controls the X axis and the other control the Y axis. Each of them acts like a sensor that varies the voltage as they are pushed in one

direction. This can then be read by the Arduino board as a signal with a value that goes from 0 to 1023.

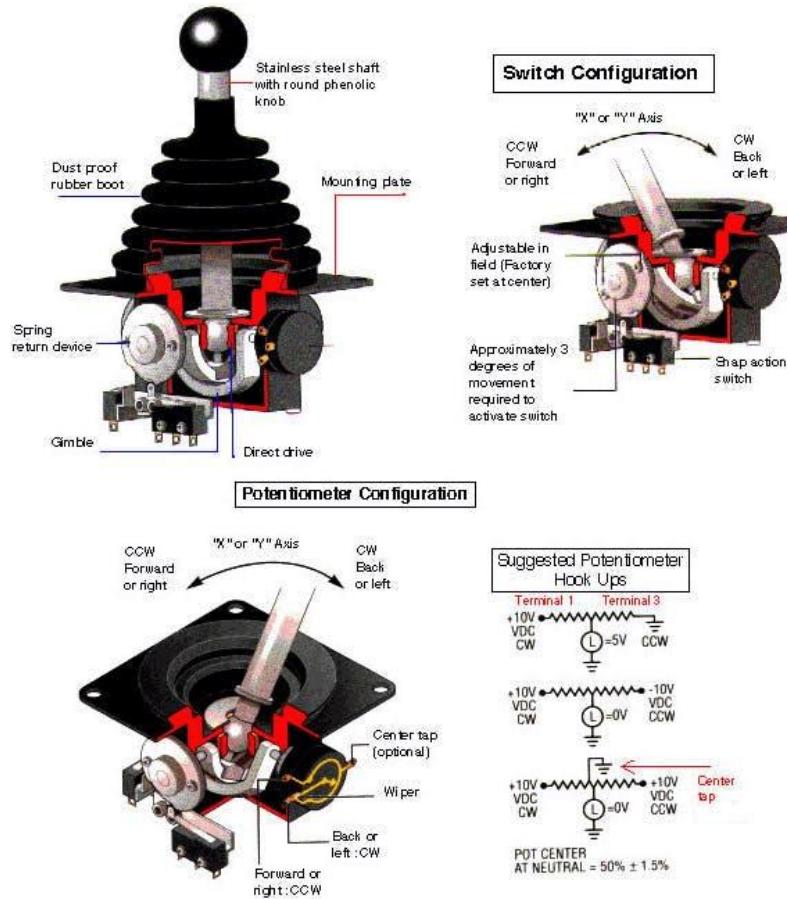


Figure 25 : Circuit of a joystick [15]

The other important component that will be used to control the hexapod will be an ultrasonic sensor. This component employs SONAR to determine its distance from an object in front of it. It has a working range from 2 cm to 4 cm.[16]

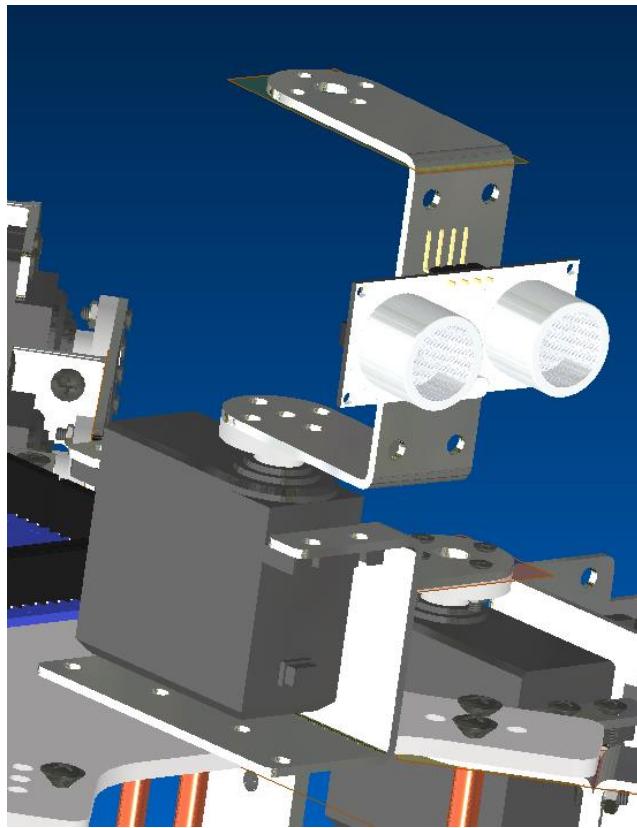
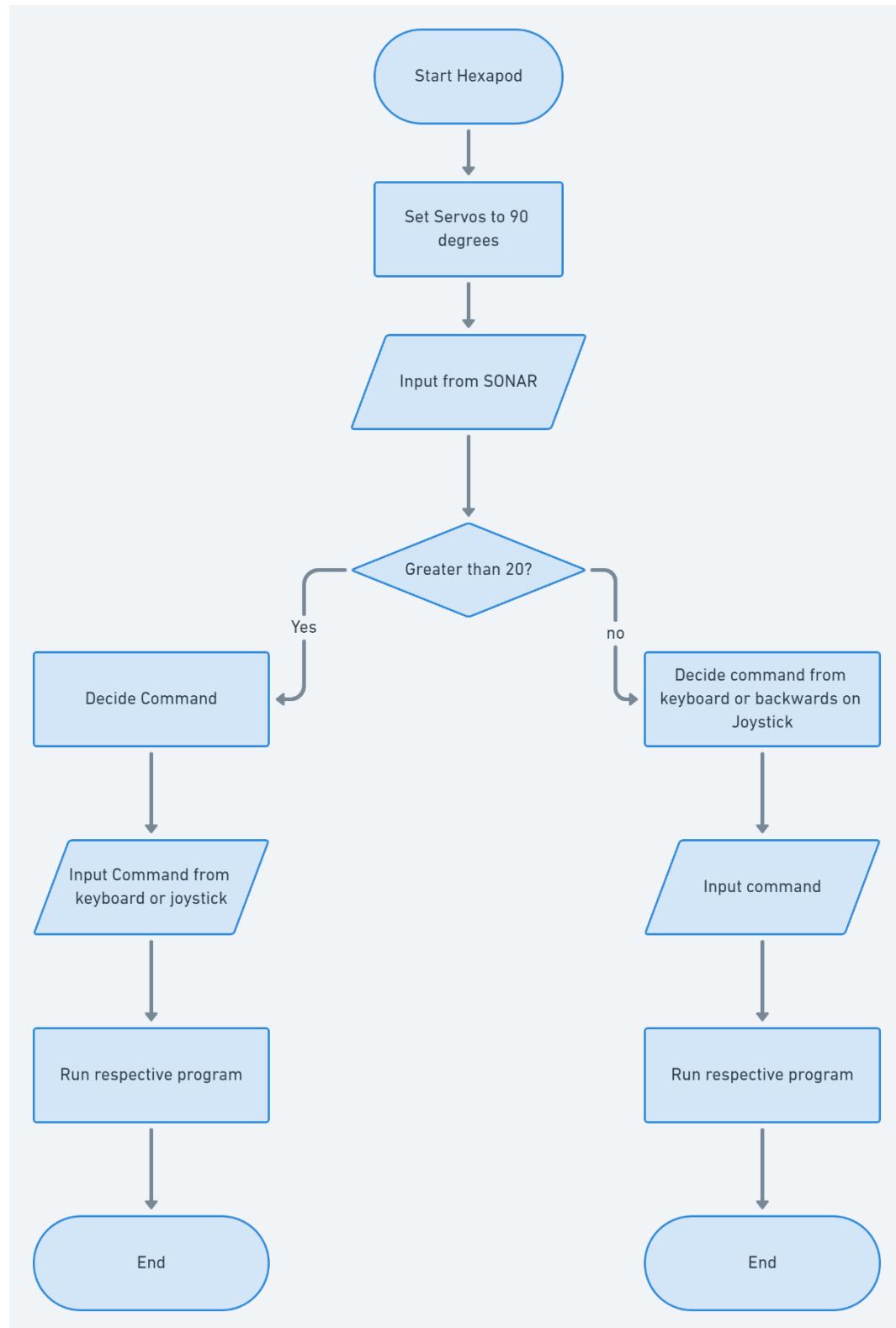


Figure 26 : Head of the hexapod

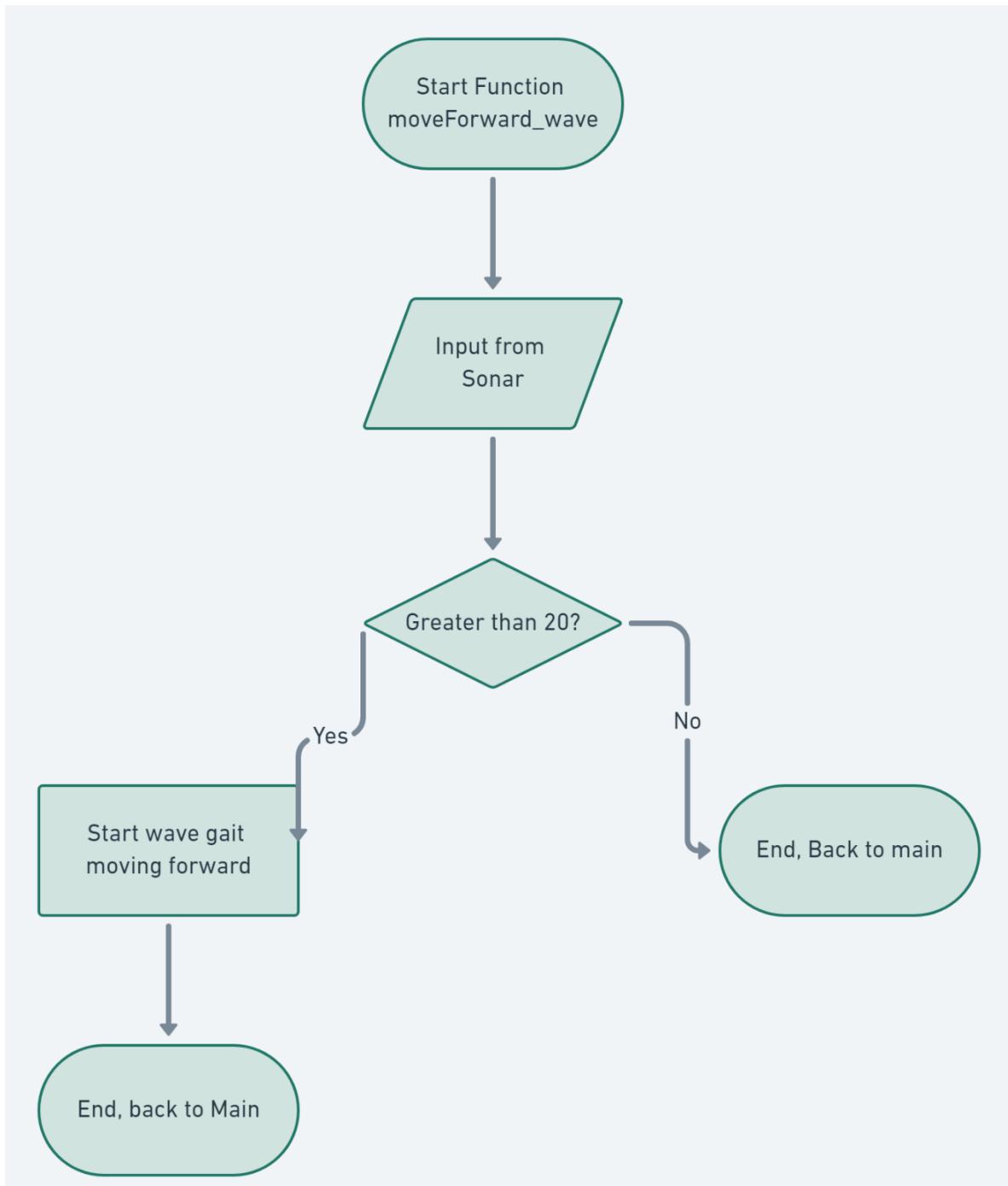
Code and functions

While the setup part of the code can be ignored, the first important part in programming the hexapod is the main Void loop.

Main loop:



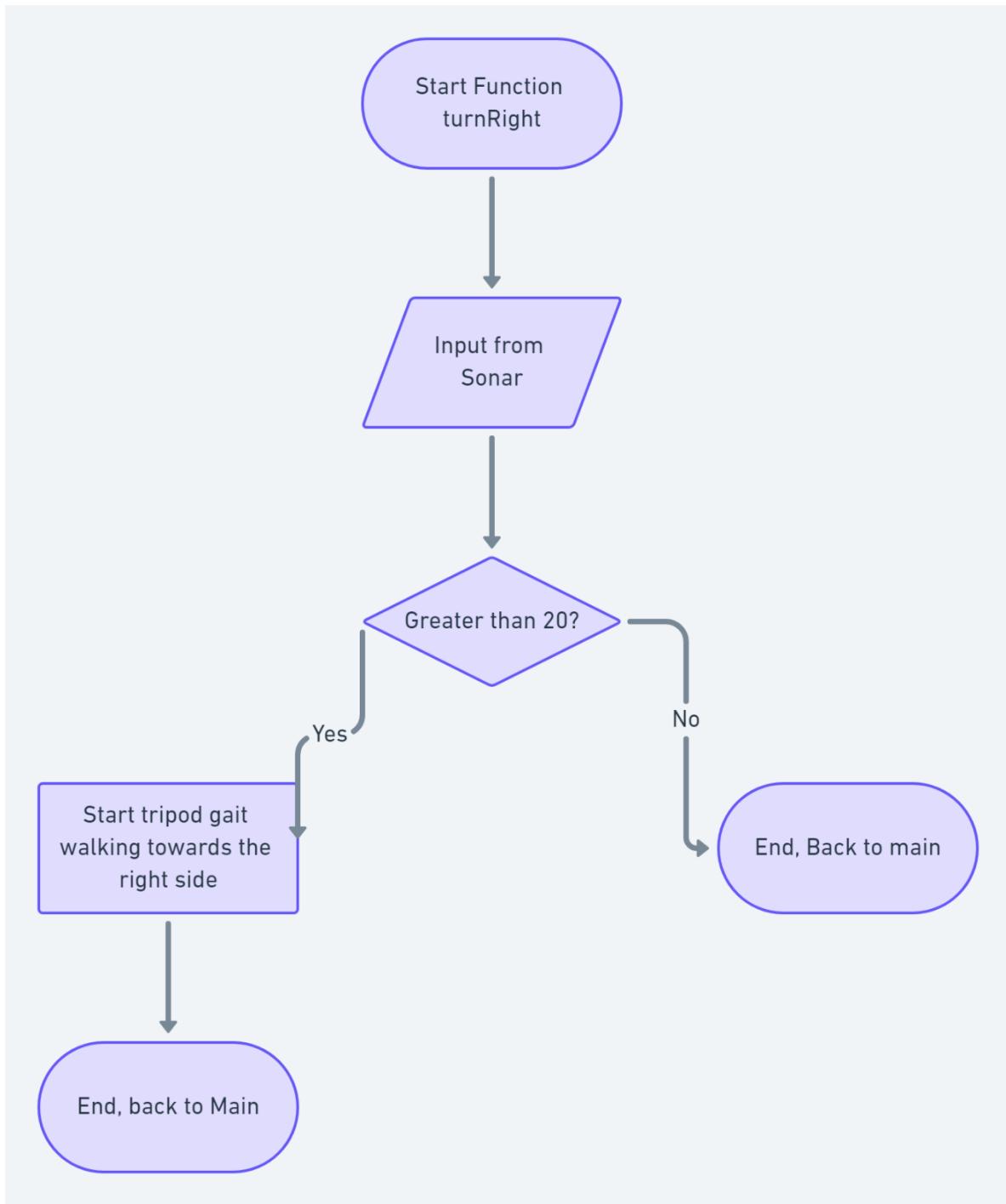
Move forward function



The `moveForward_wave` function starts wave gait that will make the hexapod start walking towards the front. The wave gait will move one leg at a time while the other five legs remain on the ground. It is the slowest but the most stable of the commonly used gaits. Similarly, the `moveBackwards_wave` function will

mirror the movements programmed in this loop so that it walks at the same speed in the opposite direction

Turn right function



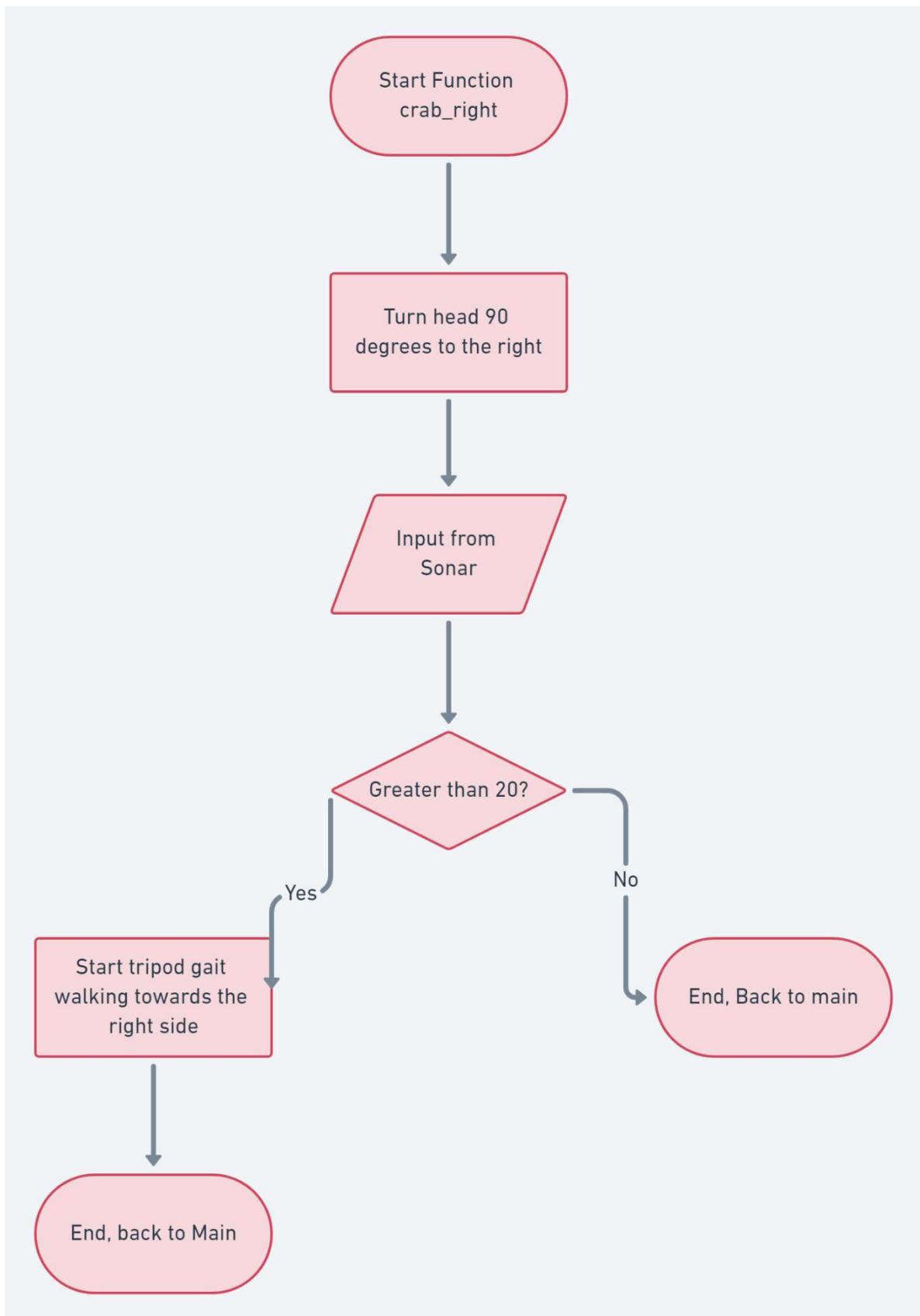
The void turnRight() and turnLeft() start a tripod gait that will make the hexapod spin around in the respective direction. A tripod gait is when three legs of the hexapod move at the same time while the other three legs support the weight. It is much faster than the wave gait and is quite stable but not as much as the wave gait.

Reset

The void reset() function will lower the hexapod's body down to the ground by moving three legs at a time and then will push itself up with all six legs. This will bring it up to its starting position where all servos are set to 90 degrees

Crab walk function

The void crab_right() and the void crab_left() functions will make the hexapod start a tripod gait that makes it move sideways in the direction the name states respectively



Conclusions

The results of this bachelor work show that this hexapod robot designed and programmed by me is capable of walking in different directions and react to its environment thanks to the ultrasonic sensor. Several programming and designing challenges were solved and in the end it was possible to build a functional hexapod robot.

However, some factors should still be pointed out. To begin with, the rubber tips available are still not the best solution as the hexapod would still slip a little when trying to walk. This could be solved with rounder and smaller rubber tips as they would have a better grip and wouldn't be as affected by the angle at which they are pressed against the ground. The other big problem is that the servos were still struggling to keep the hexapod up while walking. Replacing the weaker servos with other servos with higher torque would solve this problem but the situation with covid has made it really difficult to access the lab or have personal contact with my supervisor.

All in all this is a project that can be labeled as successful and with room to improve. The hexapod could be powered by a battery or a power bank so it wouldn't have to be plugged all the time. Furthermore, other modules could be added for the hexapod to have more sensors or to be controlled wirelessly via

bluetooth. A real controller could be used or even an app from a mobile phone. Another limb could be added to allow the hexapod to interact more with the environment. For example, it could move objects in front of it with an arm or pick up small objects.

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