Design of a holonomic five legged robot

Final Report

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Copy 1 of 4

Part 1. Preamble

This report is a description of the work I completed during the year on my final year project, Design of a holonomic five legged robot.

This report contains a copy of my approved project proposal and documentation on the technical parts of my project. These can be found in parts 3 and 4 respectively. The technical documentation contains a detailed recording of the steps taken to overcome design challenges. This includes circuit diagrams, algorithm flowcharts and test results. This section appears on the CD that accompanies this printed report.

This project does not build on any previous project. Instead it is a completely different approach to the holonomic exploration robot problem that was also addressed in earlier years. Although this project has a similar goal to that of previous years, it does not build on these as the locomotion is completely different.

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_________ _________________________

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

LED	light emitting diode
PWM	pulse width modulation

Part 2. Summary

This report documents the development of a robot intended for exploration in unknown terrain by moving holonomically and using legs for locomotion.

What has been done

What has been acieved

Findings

Part 3. Project identification: approved Project Proposal

This section contains the problem identification in the form of the complete approved Project Proposal, unchanged from the final approved version.

1. Problem statement

Motivation. Robots used for exploration need to be highly manoeuvrable to cross terrain not possible for humans and cars. The motivation for this project is to develop a robot using five legs, capable of crossing rough terrain, that can move holonomically. A robot like this can be used to explore autonomously and can also be used to carry supplies or equipment to remote places.

Context. A vehicle is considered holonomic if it does not suffer from a phenomenon called the parallel parking problem [1]. This phenomenon restricts the vehicle to forward and backward movements only, while slightly turning the front wheels. The vehicle is therefore capable of moving in arcs but never sideways. One approach to achieve holonomic movement in vehicles is to swop the cylindrical wheels found on most vehicles for spherical wheels [2]. While this solution solves the parallel parking problem, it introduces a new restriction of only functioning properly on relatively flat surfaces, unless very complicated suspension mechanisms are implemented. This solution is therefore not suitable for any off-road application. This project will extend on this to solve the problem of terrain without sacrificing holonomic movement. LS3 [3] and BigDog [4] are examples of existing legged robots that function in a way that mimics the way four legged animals walk. These robots were both developed by Boston Dynamics to help humans carry loads across terrain that is not accessible by car. They can therefore follow someone on a foot trail as well as being able to navigate to a given location using GPS.

Technical challenge. The aim of this project is to build a five legged holonomic robot which is capable of moving in any direction from a standing position as well as being able to rotate about its own axis. The control system of the robot will consist of a processor calculating all the required joint angles of all the legs to move the legs in a way that the robot moves in the desired direction. The engineering challenge in this project is the development of a control system algorithm that is fast enough to make the robot react in real time while still being thorough enough to ensure that the robot does not damage itself or its surroundings while moving.

Limitations. One of the technical limitations that makes this project challenging is the trade-off considering the length of the robot legs. Longer legs will mean more manoeuvrability for the robot and faster movements but will also mean increased torque required by the servo motors. This causes a larger power consumption and therefore a shorter battery life. It is also easier to construct a larger robot but this will again eventually lead to bigger power requirements.

2. Project requirements

ELO 3: Design part of the project

Mission requirements of the product

A five legged holonomic robot will be built in this project. The requirements of the robot that would determine whether the project is successful can be summarized in the list below.

- The robot should be able to move in any direction from a stationary position.
- The robot should be able to rotate about its own axis while remaining in the same position.
- The robot should be controlled remotely by using a smartphone application.
- The robot should use five legs to execute any of the required movements.
- The robot should be able to move on both smooth and coarse surfaces.
- The robot should be able to move on both flat and slanted surfaces.

Student tasks: design

The tasks that are vital to ensuring that the product meets the mission critical requirements are listed below.

- The mathematical analysis and design for the movement of the legs should be done on paper.
- The design should then be implemented in a graphical mathematics package such as Python for further refinement.
- Once the algorithm design is sound, electronic design can commence in a simulation environment such as LTSpice.
- The design can then be implemented in electronics using a microcontroller and support electronics together with some driving circuitry.
- A smartphone application should be developed to remotely control the robot.
- Each subsystem should be tested for isolated functionality as well as interaction with other subsystems to make sure all requirements are met.

ELO 4: Investigative part of the project

Research questions

The investigative section on this project will focus on the amount of legs of a legged robot and the effect on stability. Do five legs provide more stability when walking on slippery surfaces? Can the robot still work without some of its legs?

Student tasks: experimental work

The experiments that will be conducted to address the research questions above are listed below.

An experimental setup to test the ability of the robot to move on a variety of surfaces is required.

- The robot will be placed on both smooth and coarse flat surfaces to perform the same manoeuvres.
- The robot should be able to perform these manoeuvres with a similar degree of difficulty and in similar time.

Another experimental setup is required to test the robot's ability to handle small obstacles and bumps.

- The robot will be placed on a surface with bumps and small obstacles such as rocks.
- It should be able to execute the same set of manoeuvres mentioned in the experimental setup above in similar time.

3. Functional analysis

The functional analysis of the system can be shown best in a flow diagram. This can be seen in Figure 1 below.

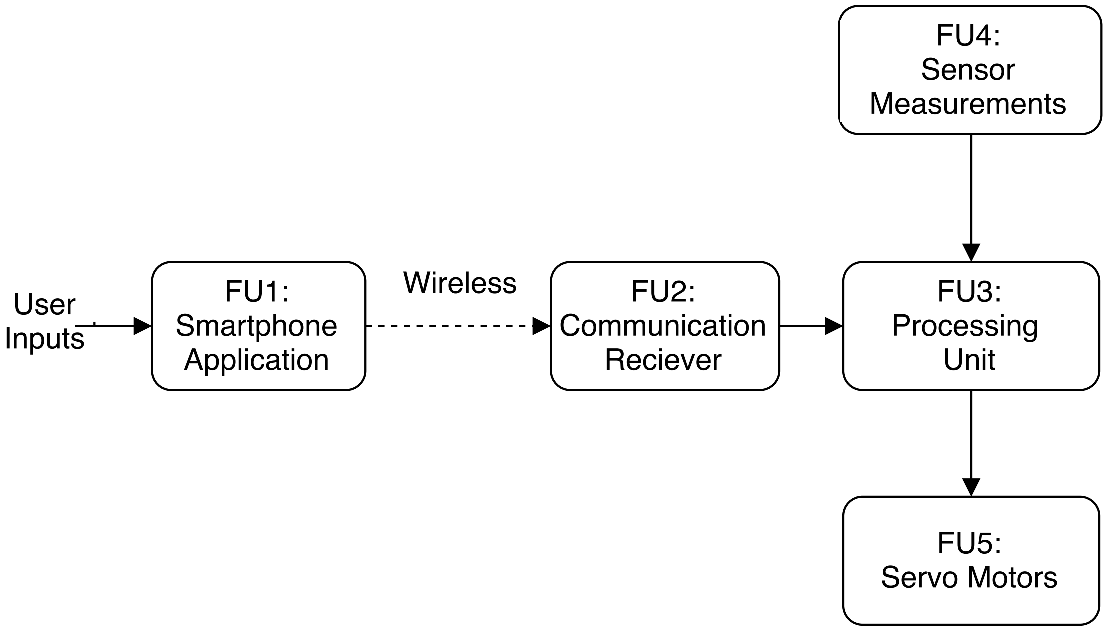

Figure 1. Functional block diagram of the product.

In Figure 1 above, the process is shown to begin with the input from the user into a smartphone application. This consists of a user interface on the screen of the smartphone that the user can interact with. The user interface will allow the user to make the robot translate as well as rotate. This information is sent to the microcontroller on the robot via wireless technology. The robot analyses this combination of translation and rotation commands and breaks it into a separate vector for each of the legs. The final position of each leg as well as the route to each individual leg destination is computed next. This makes use of a process called inverse kinematics. The manoeuvres requested by the user can be realized through a series of movements with servo motors installed on the joints of the robot legs. In order to make a limb move, the exact required angle of each joint is calculated and communicated to the servo. This process is repeated continuously to make the robot react to the varying inputs of the user.

4. Specifications

Mission-critical system specifications

SPECIFICATION (IN MEASURABLE TERMS)	ORIGIN OR MOTIVATION OF THIS SPECIFICATION	HOW WILL YOU CONFIRM THAT YOUR SYSTEM COMPLIES WITH THIS SPECIFICATION?
The robot should be able to move in a given direction in 30 degree increments from a stationary position.	Proving that the robot can move straight forward, left, backwards and right (directions spaced 90 degrees apart), will prove that the robot is holonomic.	The robot will be placed on a grid on the floor and instructed to move in one of the chosen directions at a time.
The robot should be able to rotate 90 degrees without translating the centre of the body by more than 5% of the body diameter.	Rotating 90 degrees proves that the robot does not suffer from the parallel parking problem. 5% of the robot diameter can still be considered negligible and prove that no translation is required to rotate.	The robot will be placed on the grid on the floor and instructed to rotate. The translation of the centre of the body will be noted.
The time it requires to complete a manoeuvre should not vary more than 25% between smooth and rough surfaces.	A variation of less than 25% in time can still be considered to be a similar time. This proves that the robot can move over different surfaces with similar difficulty.	The robot will be instructed to complete a specific set of movements on a flat smooth surface and the time to completion will be recorded. Various obstacles will be placed in the way of the robot (small blocks, sand, etc.), and the robot will be instructed to repeat the specific set of instructions and the time difference will be noted.
The robot should be able to walk at a speed of at least 100mm/s.	100mm/s is a reasonable speed for the scale of the robot. This proves that all of the subsystems function together well.	The robot will be instructed to walk at maximum speed in a straight line for one meter. The time to completion will be measured.

The robot should be able to walk on a surface with a 10% incline without falling over.	An incline of 10% proves that the robot platform is stable while not putting too much strain on the servo motors.	The robot will be placed on a slanted surface and instructed to translate and rotate. It should not fall over while performing these manoeuvres.

Table 1. Mission-critical system specification

Field conditions

REQUIREMENT	**SPECIFICATION (IN MEASURABLE TERMS)**
The robot should be in range of the wireless smartphone controller.	For wireless communication to work reliably, the user with the smartphone should be less than 10m from the robot.
To prevent falling over, the robot should walk on surfaces close to horizontal.	The robot should not be operated on surfaces with an incline of more than 10%
The robot should stay dry to protect electronics.	The robot should never be operated near water or wet surfaces.
The robot should work in normal temperature conditions for South Africa.	The robot should be operated in the temperature range 10^{o}C to 40^{o}C.

Table 2. Field conditions

Functional unit specifications

SPECIFICATION	**ORIGIN OR MOTIVATION**
FU1. The smartphone application should communicate commands from the user interface to the robot at a frequency of at least 10 Hz.	The robot should be in constant communication with the smartphone application to update the trajectory vectors. An update frequency of 10 Hz will update the robot fast enough to make the robot feel responsive.

FU2. The inverse kinematics calculator of the robot should be able to calculate the joint positions correctly to move each leg to the desired location.	The joints should all be calculated correctly in order for the robot to make the correct set of movements to walk.
FU3. The servo motor angles should all be within 5 degrees from the calculated values.	The servo angles have to be accurate in order to make the robot walk predictably. A tolerance of 5 degrees can still be considered accurate for hobbyist servo motors.

Table 3. Functional unit specifications

5. Deliverables

Technical deliverables

DELIVERABLE	DESIGNED AND IMPLEMENTED BY STUDENT	OFF-THE-SHELF
Microcontroller for control of the robot.		X
Control code for inverse kinematics and servo control.	X	
Android application with a user interface for control of the robot.	X	
Wireless module for communication between the smartphone interface and the robot		X
Circuits implemented on PCB for interfacing all hardware with the microcontroller.	X	
Servo motors for movement of the joints.		X
Robot body and legs.	X	
Simulations on all implemented software and analogue design	X	

Table 4. Deliverables

Demonstration at the examination

1. The robot will be placed on a grid on the floor and the examiners will be shown that the robot is capable of holonomic movement.
2. The centre of the robot will be noted on the grid and the examiners will see that the robot is capable of rotating around its centre without translating.
3. The robot will execute a specific set of movements while the time to completion is being recorded.
4. Small obstacles will be placed in the way of the robot to make movement more challenging. This includes small blocks to step over as well as a change in surface such as sand.
5. The robot will repeat the set of movements over the obstacles while the time to completion is measured again.

6. The examiners will see that the robot is capable of moving with similar effort over various surfaces.

6. References

[1] J. Reeds and L. Shepp, “Optimal paths for a car that goes both forwards and backwards”, *Pacific Journal of Mathematics*, vol. 145, 1990.

[2] K. Tadakuma, R. Tadakuma and J. Berengeres, “Development of holonomic omni-directional vehicle with omni-ball: Spherical wheels”, *Intellegent Robots and Systems*, vol. 2007, 2007.

[3] B. Dynamics. (2012). Ls3 - legged squad support systems. Accessed 2017-04-12, [Online]. Available: `http://www.bostondynamics.com/robot-ls3.html`.

[4] M. Raibert, K. Bankespoor, G. Nelson and R. Playter. (2008). Bigdog, the rough-terrain quaduped robot. Accessed 2017-04-12, [Online]. Available: `http://www.bostondynamics.com/img/BigDog-IFAC-Apr-8-2008.pdf`.

Part 4. Main report

1. Literature study

1.1 Background and context

1.2 Application of background to this project

In this section of the report, a brief overview of the existing research that is relevant to this project will be given, as well as a short discussion on how this existing research will be used to aid in the design of a five legged holonomic robot during the course of this project.

Legged vehicles are preferred to wheeled vehicles for exploration and rescue in remote areas because of their ability to cross rough terrain quickly with a severely reduced risk of getting stuck. The price to pay for this superior drive-train is far more complex electronics and movement algorithms [1]. Instead of just driving the wheel motors and steering, each limb actuator of each leg has to be controlled to move to a calculated position.

Inverse kinematics is the mathematical process used to calculate the required angles of the limbs of a structure to reach a specific set of coordinates. This is used extensively in this project because of its ability to easily transform desired Cartesian coordinates into the required actuator angles. In the paper [2], a method is discussed for solving the inverse kinematic equations involved in a seven degrees of freedom robotic arm. This method takes into account specified minimum and maximum values for each actuator and degree of freedom in order to avoid self-collision. This method can be applied to any system with a specified degrees of freedom and can therefore be simplified to solve the inverse kinematic equations for the system designed in this project.

To obtain the Cartesian coordinates desired at any given time, the method described in [1], namely Sine pattern methods is used. In [1], the method was applied to a quadruped robot. In the case of this project, the method is expanded to make it suitable for use on a robot with five legs. Adaptation is required because the method relies on the symmetry of a quadruped robot to schedule the lifting of the legs. Since the same symmetry does not exist in a robot with five legs, a different scheduling technique is investigated. This method will rely on information from the current position of the legs, the limits of leg movement, as well as the current horizontal tilt of the robot.

In the conference paper [3], motion planning of omnidirectional robots is discussed and a sophisticated yet simple and efficient method of route planning is proposed. This method is based on vehicles that use three omnidirectional wheels in combination to form a resultant force vector in the desired direction. These type of vehicles differ largely in terms of locomotion when compared to the holonomic legged design used in this project, but there are a few key similarities. Both these designs can move holonomically, therefore they have the ability to move in a straight line while rotating, move in an arc without rotating, or any combination of the two. These similarities mean that some of the methods discussed and applied in [3] can be used to aid in the design of the algorithm used in this project.

A team from Instituto Tecnologico de la Laguna in Mexico designed a hexapod robot [4] similar to the robot designed in this project. The purpose of the hexapod was to investigate its potential for use in exploration of areas that are hard to reach by any commonly used means of transportation. Legged vehicles are more suited to cross rough terrain, but rough terrain complicates the design of the drive-train. In applications where the surface is smooth or close to smooth, open loop control can be applied where the leg is simply moved to the desired position and it is assumed by the designer that the robot foot is making contact with the ground at this point, and therefore supporting part of the distributed robot weight. When the robot is crossing rough terrain, where the surface consists of mainly bumps and holes, this assumption could be false. In such a scenario, the robot could lift another leg while under the impression that its weight is being supported by the other legs. If this is not the case, the robot could fall over and possibly damage itself or be unable to rectify itself. To avoid this problem, closed loop control should be used in the height positioning of the legs. This involves having a sensor in the system that could provide feedback on the state of the foot. The hexapod in [4] used miniature resistive force sensors attached to the bottom of each foot of the robot. The robot therefore has the ability to take analogue measurements from these sensors and determine the weight distribution of the individual feet of the robot. This data is used to confirm that all robot feet are making contact with the surface and correct the situation if this is not the case. This type of feedback is also useful when the robot is operated on slanted surfaces because of the effect that the center of gravity has on a slanted surface. A feedback sensor will be included in the design of the five legged holonomic robot in this project.

If the robot is operating on a slanted surface without it being aware of this and the centre of gravity shifts over the lowest foot making contact, the robot could fall over even when all of its legs are making contact with the surface. In a paper on reactive robot navigation [5], it is proposed that the use of a digital inclinometer can aid in solving this problem. The sensor provides information on the current tilt of the robot in two dimensions. This sensor in combination with the feedback sensors on the robot feet can be used to ensure that the robot levels itself automatically to avoid tipping over. The data collected from this sensor can also be used to collect information on the terrain. In the journal article [5], this data is used for hill climbing as well as finding valleys in unexplored areas. In order to enable the robot designed in this project to walk on slanted surfaces, a digital inclinometer will be used. Some of the reactive navigation techniques discussed in [5] will also be implemented to aid the robot in navigating on slanted planes.

In a paper on the effects of slippery surfaces on biped robots [6], methods on avoiding falling over of a biped robot is investigated. Since these robots have to balance themselves to stay upright, an unforeseen slippery patch on a surface could be fatal for the robot. If it were possible to foresee a slippery surface, slowing down the walking gait and increasing foot surface would help increase the traction of the robot, and therefore lower the risk of slipping. Since a five legged robot is inherently stable and there is no balancing required, slippery surfaces may influence the traction of the robot but there is very low risk of falling over on level surfaces that are slippery. It is therefore suitable to just slow down movements on slippery surfaces to increase the traction where possible.

2. Approach

This section outlines the initial approach to solve the functions shown in the functional block diagram. The functional block diagram of the project can be found in Figure 1

2.1 Design alternatives

2.2 Preferred solution

3. Design and implementation

3.1 Background

A large part of the design of a legged robot depends on the design of a simple leg - more specifically the degrees of freedom that a single leg has. The degrees of freedom that a single leg has is determined by the amount of dimensions that the leg can make a controlled movement in, independently from any other dimensions. There are two common underlying designs in robot leg design - these are for two and three degrees of freedom respectively.

Figure 2 shows an example of a common design that has two degrees of freedom. The design therefore contains two joints in one leg. In this example, the first joint is positioned vertically to form the hip op the robot leg. This allows for the side to side motion required for walking. The second joint is positioned horizontally to allow the lowest limb to move up and down. The two degrees of freedom controlled by this leg design is therefore the horizontal angle of the leg and the height of the foot. These two (and only these two) parameters therefore can be controlled completely independently.

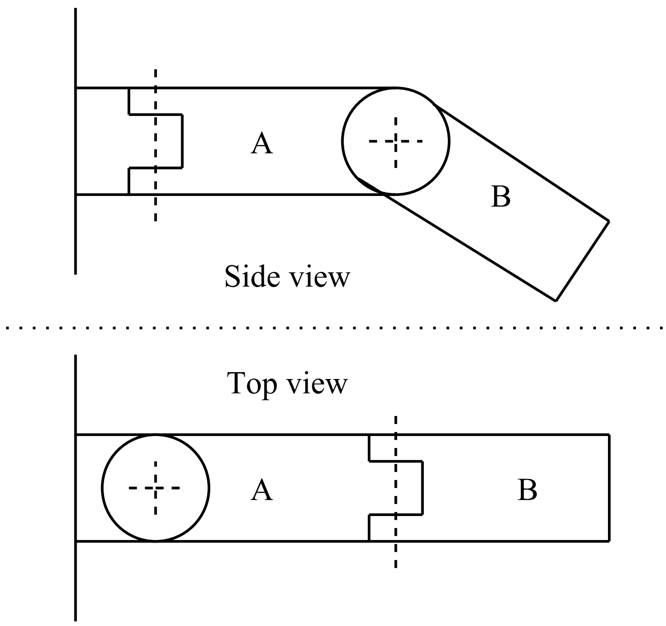

Figure 2. Example of a leg design with two degrees of freedom.

An example of a robotic leg with three degrees of freedom can be seen in Figure 3. This design is similar to that of the leg with two degrees of freedom seen in Figure 2, with the only addition being a second horizontal joint further down from the first. This additional limb means that the horizontal distance from the foot to the hip can be controlled as well as the height of the foot. These two controlled parameters together with the horizontal leg angle which can also be controlled independently as in the case of the two degrees of freedom design means that this design has a total of three degrees of freedom.

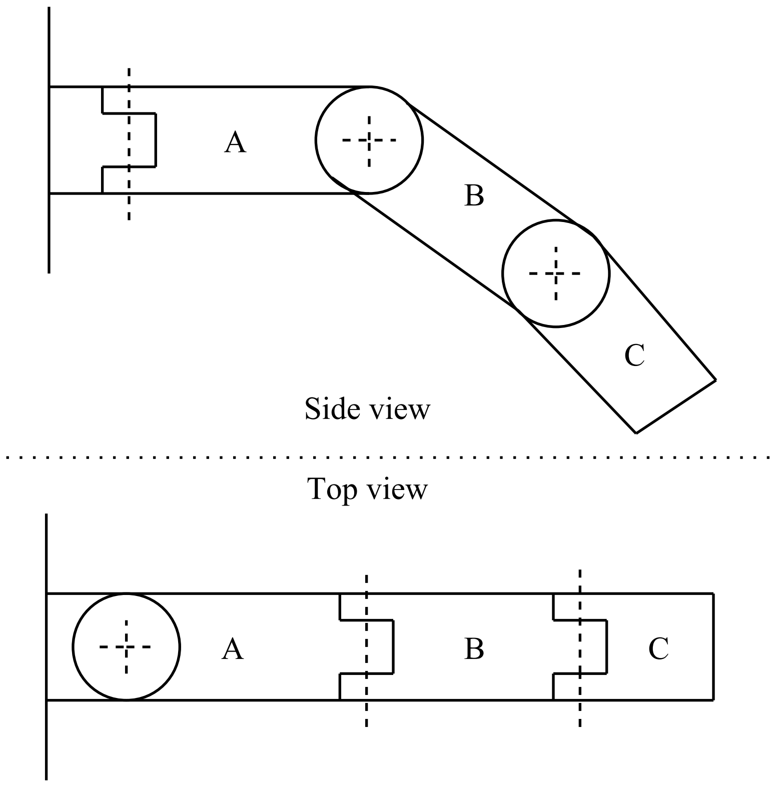

Figure 3. Example of a leg design with three degrees of freedom.

The overall shape of the robot and, more specifically, the placement of legs around the robot will greatly influence the robot's performance when moving forward in a straight line, moving sideways and moving over obstacles.

A popular design in hexapod robots is placing the legs in groups of three on opposite sides. This means that the legs are all aligned in a similar direction while the body is usually a long rectangular shape, similar to that found on insects. The advantage of this design lies mainly in the ability to move forward very quickly since the legs are placed optimally for forward motion. While holonomic movement is possible, it is usually much slower than forward or backward motion. This design is usually more suited to robots with an even number of legs due to the symmetry of the design. An example of such a configuration is illustrated in Figure 4.

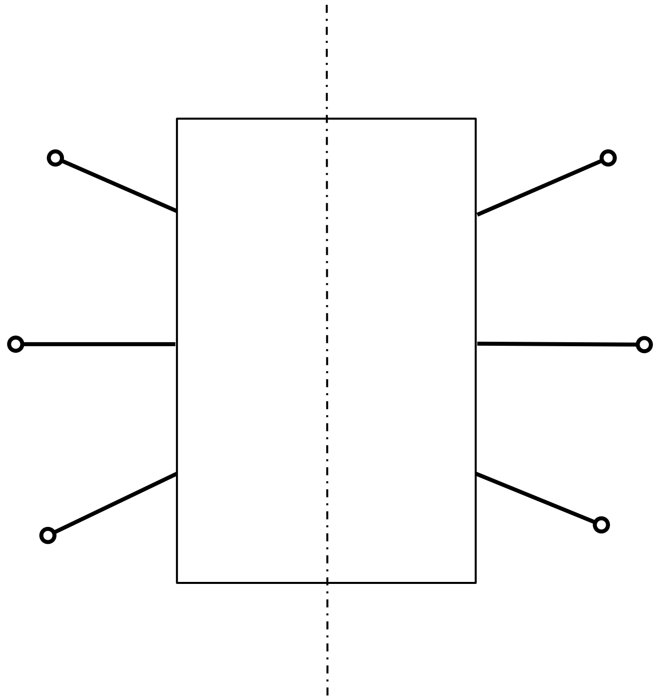

Figure 4. Example of a symmetric hexapod robot chassis.

An alternative design approach is to space the legs evenly around the robot chassis. The robot chassis would normally be round or a polygon with the same number of sides as legs. In the case of a five legged robot, the legs would be positioned $\frac{360^o}{5} = 72^o$ apart. This equally spaced design approach has the disadvantage of not being particularly fast in any given direction but the advantage that it can manage the maximum speed in any given direction. Figure **??** shows an example of a circular body with five equally spaced legs.

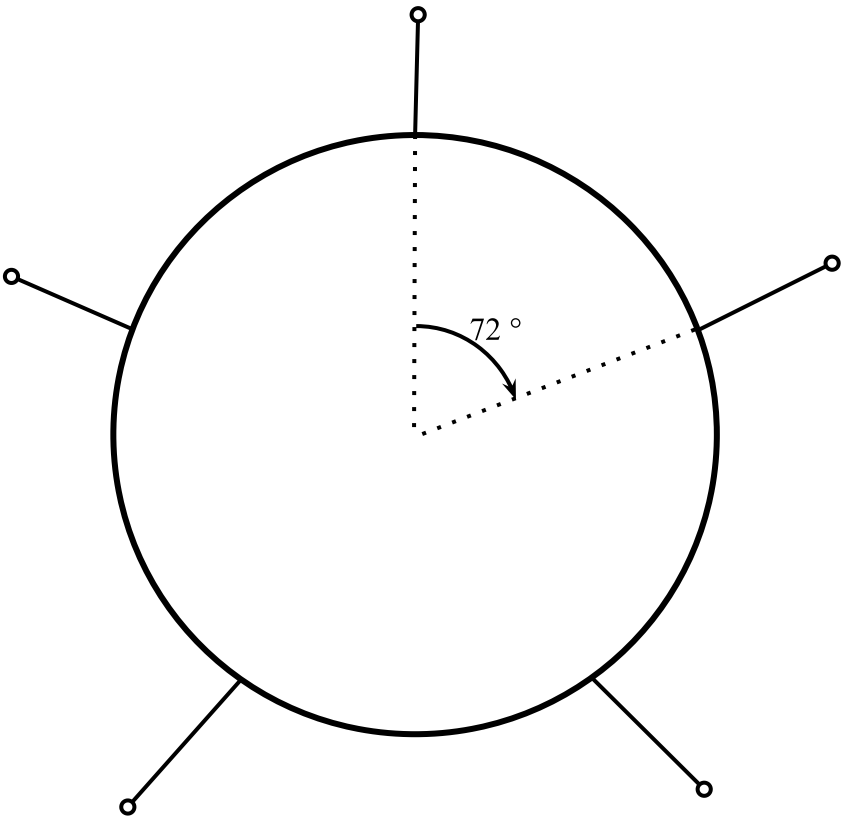

Figure 5. Example of a robot chassis with equally spaced legs.

Choosing actuators for the movement of the legs will determine how well the robot functions, how complicated the implementation is, how battery life is impacted and what type of feedback is required. The three types of motors considered is geared DC motors, stepper motors and servo motors.

Geared DC motors are simple to implement mechanically because small motor assemblies can often have a high torque output because of the integrated gearbox. The disadvantage of using a gearbox is that it can make the response sluggish if the reduction ratio is too high. Motor speed can easily be controlled by using pulse width modulation (PWM) to control the current through the motor. It is much more difficult to control motor position. In order to make a functioning control system with this type of motor, some feedback is required on the current position (shaft angle) of the motor. This can be implemented with a rotary encoder or in the case where the shaft never makes a full rotation, a potentiometer. The control system can then apply the voltage necessary to the motor in order to reach the required angular position. It will be necessary to apply negative voltages to the motor in some cases to make it reverse. The simplest way to achieve this is by implementing the motor control circuit with an H-bridge.

Stepper motors move in discrete steps and it is therefore much simpler to keep track of shaft angle and calculate the steps required to reach a given angle if the current angle is known. In order to know where it is when turned on, servo motors are often implemented with a 'home' position it can use as reference. This requires some sensor used to determine if the arm is in a specific position or not. A homing routine is used when initializing the robot wherein the robot moves a limb with unknown position in a specific direction while continuously polling the homing sensor for change. As soon as the sensor senses the presence of the arm, movement is seized and the current position is determined to be the home position. All movements can then be calculated from this reference position

The design with three degrees of freedom has the advantage of being able to lift a leg without altering the horizontal position of the leg. This means that the robot is able to walk without altering the height of the body of the robot. This means that the robot is able to much better cross rougher terrain because of the ability to alter the height the robot feet as the terrain requires. With the design that has two degrees of freedom, the foot height is a function of the horizontal extension of the leg. With this design the main advantage is the simplicity - both mechanically and in software. The cost and power consumption will also be much lower because of the reduced amount of actuators.

Due to the much greater flexibility of the design with three degrees of freedom and the ability to cross rougher terrain, this will be the platform implemented in the final design.

Since this robot is being designed specifically for holonomic movement and has an odd number of legs, another design might be more suited.

3.2 Theoretical analysis and modelling

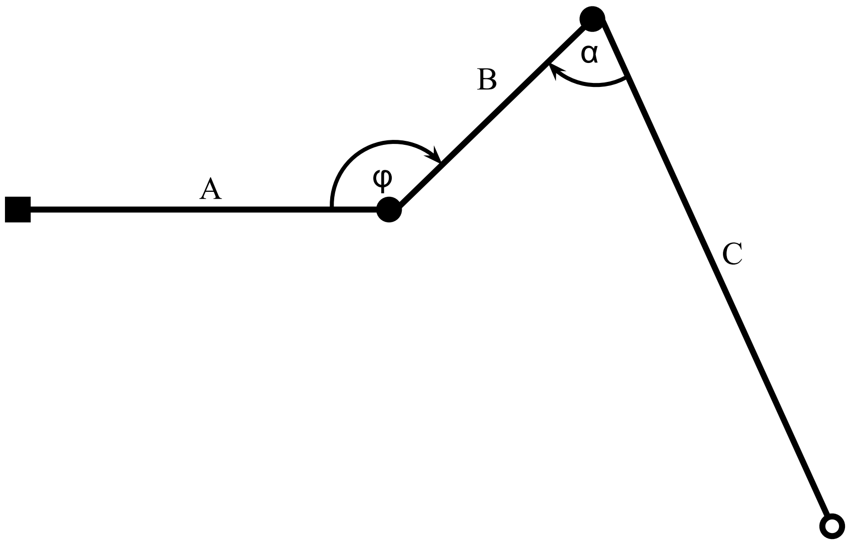

Figure 6. Simulation results for the network.

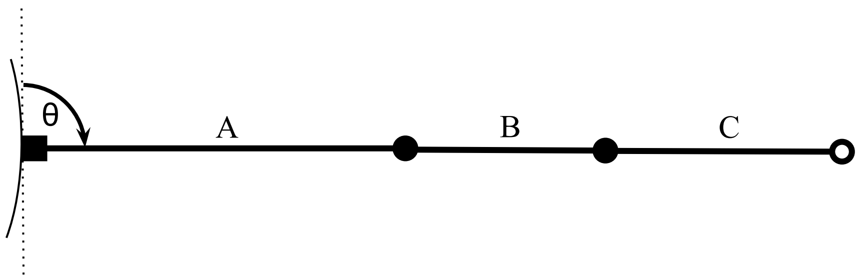

Figure 7. Simulation results for the network.

3.3 Simulation

3.4 Optimisation

3.5 Hardware design

3.6 Hardware implementation

3.7 Software design

3.8 Software implementation

3.9 Design summary

4. Results

4.1 Summary of results achieved

Description of requirement or specification (intended outcome)	**Actual outcome**	**Location in report**
Mission requirements of the product		
1	2	3
Field conditions		
1	2	3
Specifications		
1	2	3
Deliverables		
1	2	3

4.2 Qualification tests

5. References

[1] A. Hidayat, A. N. Jati and R. E. Saputra, “Autonomous quadruped robot locomotion control using inverse kinematics and sine pattern method”, *IEEE*, 2017.

[2] J. Oh, H. Bae and J.-H. Oh, “Analytic inverse kinematics considering the joint constraints and self-collision for redundant 7dof manipulator”, *IEEE*, 2017.

[3] P. Jain, “Odometry and motion planning for omni drive robots”, *IEEE*, 2014.

[4] J. Ollervides, J. Orrante-Sakanassi, V. Santibanez and A. Dzul, “Navigation control system of walking hexapod robot”, *IEEE*, 2012.

[5] R. C. Arkin and W. F. Gardner, “Reactive inclinometer-based mobile robot navigation”, *IEEE*, vol. 2, 1990.

[6] J. H. Park and O. Kwon, “Reflex control of biped robot locomotion on a slippery surface”, *IEEE*, 2001.