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Design and Fabrication of Quadruped Robot

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ABSTRACT

In the current century, there has been an increase in crimes and malicious activities around the world creating a need for a reliable surveillance technology. The areas with such activities rely on fixed surveillance technology which can be easily tampered with. A Quadruped (Four legged) walking robot can access such less secure places and it can also conquer rough terrain, dodge obstacles making it perfect for surveillance and monitoring. Aim behind the project is constructing a robot to carry out task using robotic arm and carry out monitoring in remote areas.

The robot is constructed using open-source software and hardware like Raspberry Pi, Arduino UNO, ESP32, BLDC-motor, ROS etc. This Robot can be used in search and rescue during an unfortunate occurrence of any natural calamity. The motto behind the project is avoiding human risk which is involved in dangerous areas by use of an autonomous walking robot.

The design of a quadruped robot involves careful consideration of its kinematics, dynamics, and control algorithms. Recent advancements in materials, sensors, and actuation have led to the development of highly agile and efficient quadruped robots that can perform a variety of tasks in challenging environments. The objective of this project is to develop a reliable solution that enables the implementation of stable and fast static/dynamic walking on even and uneven terrain. The robot captures/mimics the mobility, autonomy and speed of four-legged living creatures. This also consists of a remote controller and balance sensor embedded on it for detecting terrain changes.

I. INTRODUCTION

Quadruped robots are named as such because they move on four legs, imitating the locomotion of animals like horses, dogs, and insects. These robots are characterized by their exceptional stability, agility, and flexibility in different terrains. Due to their versatility, quadruped robots can be used in a wide range of applications.

The design of these robots typically consists of a body with four legs that have joints and actuators for movement and control. Additionally, quadruped robots may incorporate sensors such as cameras or LiDAR to perceive their surroundings and make decisions accordingly. Some advanced quadruped robots even feature artificial intelligence systems or machine learning algorithms to improve their capabilities and autonomy.

Project Overview

Our project is about saving lives without endangering human lives further than it already is and to make lives easier. We can describe it as having two phases.

Phase 1: Framework-The electrical and mechanical components being placed into the frame.

Phase 2: Movement-To get the robot moving using embedded systems and integral coding.

II. LITERATURE REVIEW

"WORKING PRINCIPLE OF ARDUINO AND USING IT AS A TOOL FOR STUDY AND RESEARCH", Leo Louis. This paper explores the working principle and applications of an Arduino board. This also explores on how it can be used as a tool for study and research works. Arduino board can provide a quick tool in development of VLSI test bench especially of sensors. Main advantages are fast processing and easy interface. Today, with increasing number of people using open-source software and hardware devices day after day, technology is forming a new dimension by making complicated things look easier and interesting. These open sources provide free or virtually low costs, highly reliable and affordable technology. This paper provides a glimpse of type of Arduino boards, working principles, software implementation and their applications.

"Science and Computing with Raspberry Pi", Brian R Kent. The portable Raspberry Pi computing platform with the power of Linux yields an exciting exploratory tool for beginning scientific computing. Science and Computing with Raspberry Pi takes the reader through explorations in a variety of computing exercises with the physical sciences. The book guides the user through configuring your Raspberry Pi and Linux operating system; understanding the software requirements while using the Pi for scientific computing; computing exercises in physics, astronomy, chaos theory, and machine learning.

“Using the ESP32 Microcontroller for Data Processing”, Marek Babuich, Petr Foltynek, Pavel Smutny. This article deals with experiences with the development of applications of the ESP32 microcontrollers and provides a comprehensive review of the possibilities of applications development on this platform in the area of data measurement and processing. Microcontrollers usually connect with IoT modules and other smart sensors and provide data to the superior system. This paper also describes implementation of application with the version of connected OLED display and with ESP32 Wrover development board with integrated display.

“Review on Field Oriented Control of Induction Motor” by Ayman Yousef, Samel Abdel
Maksoud. The field oriented control (FOC) of induction motor provide one of the most suitable and popular speed control technique presently used. The principle of field oriented control is based on the is normally achieved by controlling the armature with constant field current. The Field weakening is employed to increase the speed beyond a base peed. The simplicity and flexibility of control of dc motors have made them suitable for variable speed drive applications. In the field oriented control, a d-q coordinates reference frame locked to the rotor flux vector is used to achieve decoupling between the motor flux and torque. They can be thus separately controlled by stator direct-axis current and quadrature-axis current respectively, like in a dc motor. In this paper, the principle, classification, and the most common of the field-oriented control are presented.

“Bearings: Basic Concepts and Design Applications” By Maurice L. Adams. Bearings: from Technological Foundations to Practical Design Applications provides a modern study of bearing types, design factors, and industrial examples. The major classes of bearings are described, and design concepts are covered for rolling elements, surfaces, pivots, flexures, and compliance surfaces. Fluid film lubrication is presented, and the basics of tribology for bearings is explained. The book also looks at specific applications of bearing technology, including bearings in vehicles, rotating machinery, machine tools, and home appliances. Case studies are also included.

“3D PRINTING TECHNOLOGIES IN VARIOUS APPLICATIONS” by A. Ramya, Sai leela Vanapalli. Industrial adoption of 3D Printing has been increasing gradually from prototyping to manufacturing of low volume customized parts. The need for customized implants like tooth crowns, hearing aids, and orthopaedic-replacement parts has made the life sciences industry an early adopter of 3D Printing. Demand for low volume spare parts of vintage cars and older models makes 3D printing very useful in the automotive industry. It is possible to 3D print in a wide range of materials that include thermoplastics, thermoplastic composites, pure metals, metal alloys and ceramics. Right now, 3D printing as an end-use manufacturing technology is still in its infancy. But in the coming decades, and in combination with synthetic biology and nanotechnology, it has the potential to radically transform many design, production, and logistics processes. 3D printing encompasses a wide range of additive manufacturing technologies. Each of these builds objects in successive layers that are typically about 0.I mm thin. In basic terms there are four categories of 3D printers. Firstly, we have printers that extrude a molten or otherwise semi-liquid material. Secondly, there are printers that solidify a photo curable resin. Thirdly, there are printers that bind or fuse the granules of a powder. And finally, there are printers that stick together cut sheets of paper, plastic or metal.

“MODERN ACCESSIBLE APPLICATION OF THE SYSTEM BLENDER IN 3D DESIGN PRACTICE” , Tihomir Dovramadjiev. In recent years there has been increased interest in systems with a free license. In the field of 3D design a powerful system with a free license is the Blender. With its small volume, not any serious high demands on hardware systems, combined with many advantages and innovations Blender 3D graphics system is gaining more followers. This trend bodes fast nonlinear positive progression, which gives a reason the use of the system open-source Blender in design practice to be considered appropriate and correct.

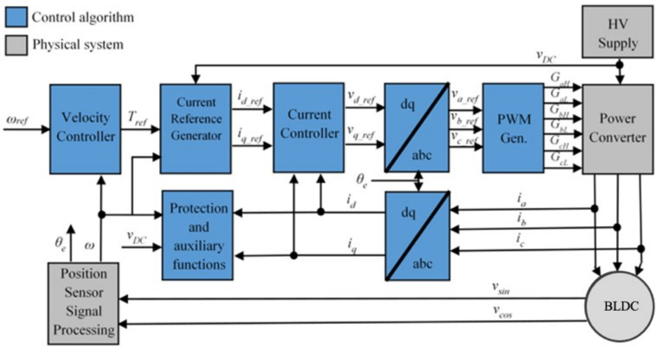
III. PROJECT DESCRIPTION

The different components assembled together make up for the completed model of the Quadruped Robot as a whole. But the project working is based on achieving FOC (FIELD ORIENTED CONTROL).

3-Phase Field Oriented Control

Introduction to FOC

FOC stands for Field-Oriented Control. It is a control strategy commonly used in electric motor control systems, specifically for controlling the speed and torque of three-phase AC induction motors or brushless
(BLDC).



FOC Flowchart

The primary goal of FOC is to accurately control the motor's torque and speed by decoupling the magnetic flux and torque-producing current components. By decoupling these components, the control system can independently regulate them, resulting in more precise control and improved performance.

In FOC, the control algorithm uses mathematical transformations, such as the Park and Clarke transforms, to convert the three-phase AC current and voltage signals into a rotating reference frame. This reference frame aligns with the rotor flux of the motor, simplifying the control calculations.

The FOC control algorithm typically consists of two control loops: the inner current loop and the outer speed or position loop. The inner current loop controls the motor's current by adjusting the amplitude and phase of the current components in the rotating reference frame. The outer loop controls the speed or position by adjusting the reference current based on the desired motor behavior.

FOC offers several advantages over traditional control methods, such as direct torque control or scalar control. These advantages include improved motor efficiency, higher torque and speed control accuracy, reduced torque ripple, and enhanced dynamic response. FOC also allows for smoother motor operation at low speeds and precise control over a wide range of operating conditions.

FOC is widely used in various applications that require precise motor control, such as robotics, electric vehicles, industrial automation, and renewable energy systems. It has become a standard control technique for high-performance motor drives due to its ability to provide efficient and accurate control of AC induction motors and BLDCs.

WORKING PRINCIPLE OF FIELD ORIENTED CONTROL

The field oriented control consists of controlling the stator currents represented by a vector. This control is based on projections that transform a three phase time and speed dependent system into a two coordinate (d and q frame) time invariant system. These transformations and projections lead to a structure similar to that of a DC machine control. FOC machines need two constants as input references: the torque component (aligned with the q coordinate) and the flux component (aligned with d coordinate).

The three-phase voltages, currents and fluxes of AC-motors can be analysed in terms of complex space vectors. If we take i_a, i_b, i_c as instantaneous currents in the stator phases, then the stator current vector is defined as follow:

$$\vec{l}_s = i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}$$

Where, (a, b, c) are the axes of three phase system.

This current space vector represents the three phase sinusoidal system. It needs to be transformed into a two time invariant coordinate system. This transformation can be divided into two steps:

(a, b, c) → (α, β) (the Clarke transformation), which gives outputs of two coordinate time variant system.

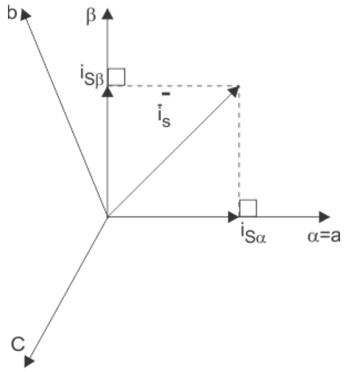
(a, β) → (d, q) (the Park transformation), which gives outputs of two coordinate time invariant system.

The (a, b, c) → (α, β) Projection (Clarke transformation)

Three-phase quantities either voltages or currents, varying in time along the axes a, b, and c can be mathematically transformed into two-phase voltages or currents, varying in time along the axes α and β by the following transformation matrix:

$$i_{\alpha\beta o} = 2/3 \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Assuming that the axis a and the axis α are along same direction and β is orthogonal to them, we have the following vector diagram:



The above projection modifies the three phase system into the (α, β) two dimension orthogonal system as stated below:

$$i_{s\alpha} = i_a$$

$$i_{s\beta} = i_a / \sqrt{3} + 2i_b / \sqrt{3}$$

But these two phase (α, β) currents still depends upon time and speed.

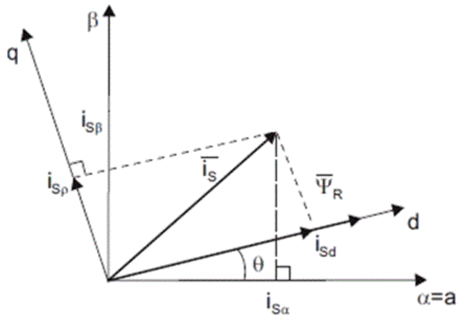
The (α, β) → (d.q) projection (Park transformation)

This is the most important transformation in the FOC. In fact, this projection modifies the two phase fixed orthogonal system (α, β) into d, q rotating reference system. The transformation

matrix is given below:

$$i_{dqo} = 2/3 \times \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\,) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Where, θ is the angle between the rotating and fixed coordinate system. If you consider the d axis aligned with the rotor flux, Figure 2 shows the relationship from the two reference frames for the current vector:



Where, θ is the rotor flux position. The torque and flux components of the current vector are determined by the following equations:

$$i_{sq} = i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta$$

$$i_{sd} = i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta$$

These components depend on the current vector (α, β) components and on the rotor flux position. If you know the accurate rotor flux position then, by above equation, the d, q component can be easily calculated. At this instant, the torque can be controlled directly because flux component (i_{sd}) and torque component (i_{sq}) are independent now.

BASIC MODULE FOR FIELD ORIENTED CONTROL

Stator phase currents are measured. These measured currents are fed into the Clarke transformation block.

The outputs of this projection are entitled $i_{s\alpha}$ and $i_{s\beta}$. These two components of the current enter into the Park transformation block that provide the current in the d, q reference frame. The isd and isq components are contrasted to the references: i_{sdref} (the flux reference) and i_{sqref} (the torque reference). At this instant, the control structure has an advantage: it can be used to control either synchronous or induction machines by simply changing the flux reference and tracking rotor flux position. In case of BLDC the rotor flux is fixed determined by the magnets so there is no need to create one. Therefore, while controlling a BLDC, i_{sdref} should be equal to zero. As induction motors need a rotor flux creation in order to operate, the flux reference must not be equal to zero. This easily eliminates one of the major shortcomings of the “classic” control structures: the portability from asynchronous to synchronous drives. The outputs of the PI controllers are V_{sdref} and V_{sqref}.

They are applied to the inverse Park transformation block. The outputs of this projection are $V_{s\alpha ref}$ and $V_{s\beta ref}$ are fed to the space vector pulse width modulation (SVPWM) algorithm block. The outputs of this block provide signals that drive the inverter. Here both Park and inverse Park transformations need the rotor flux position. Hence rotor flux position is essence of FOC.

The evaluation of the rotor flux position is different if we consider the synchronous or induction motor.

1. In case of synchronous motor(s), the rotor speed is equal to the rotor flux speed. Then rotor flux position is directly determined by position sensor or by integration of rotor speed.
2. In case of asynchronous motor(s), the rotor speed is not equal to the rotor flux speed because of slip; therefore a particular method is used to evaluate rotor flux position (θ). This method utilizes current model, which needs two equations of the induction motor model in d,q rotating reference frame.

CLASSIFICATION OF FIELD ORIENTED CONTROL

FOC for the BLDC motor can be broadly classified into two types: Indirect FOC and Direct FOC schemes.

DIRECT FIELD-ORIENTED CONTROL

- Conventional direct field-oriented control (DFOC) algorithms provide more precision for torque control than scalar schemes, but require sensors for the speed control of the rotor and the magnetic flux to provide the data for the FOC algorithms.
- They also face challenges in the dynamic response and the dependence on measuring the parameters in the motor.

Indirect Field-Oriented Control

Instead an indirect field-oriented control (IFOC)method estimates the phase angle of the rotor magnetic field flux, eliminating the need for additional sensors but adding to the complexity and the computation time of the control system.

CIRCUIT FOR ACHIEVING FOC

To achieve Field-Oriented Control (FOC) in an electric motor control system, a specific circuit configuration is typically used along with appropriate control algorithms. While the exact circuit implementation can vary depending on the motor type and the control system design.

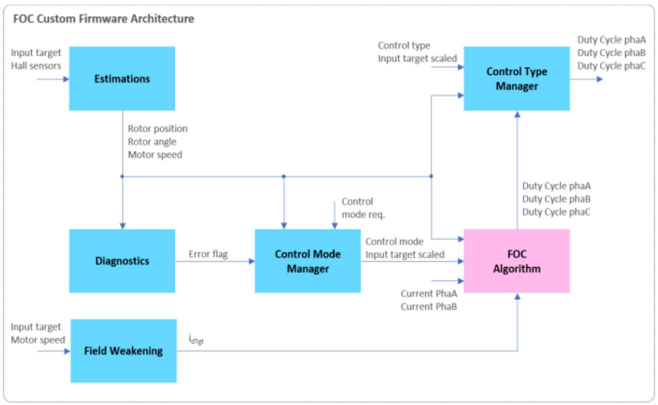
Components used to achieve FOC:-

1. ESP32-WROOM-32U
2. TMC6200-TA
3. AMS 1117 5.0V Voltage Regulator
4. AMS 1117 3.3V Voltage Regulator
5. BSC0921NDIATMA1 MOSFET
6. Decoupling and Filter Capacitors
7. Current Sense Resistors
8. LED Indicators
9. CAN Bus

ESP32-WROOM-32U is the microcontroller where the program is stored. The AS56000 sensor unit which is mounted behind the motor sends the motor angle to the controller using I2C communication protocol. The microcontroller then sends PWM signals to the driver unit, defining the required position of the motor. The TMC6200 driver unit amplifies the low level 3.3V PWM signals to a higher voltage of 12V. The decoupling capacitors are placed near to the TMC6200 for charge pumping, which is the concept of increasing voltage signals through inductance. Bootstrap capacitors give the required strength for the voltage signals. 470nF bootstrapping capacitors have been used in the circuit.

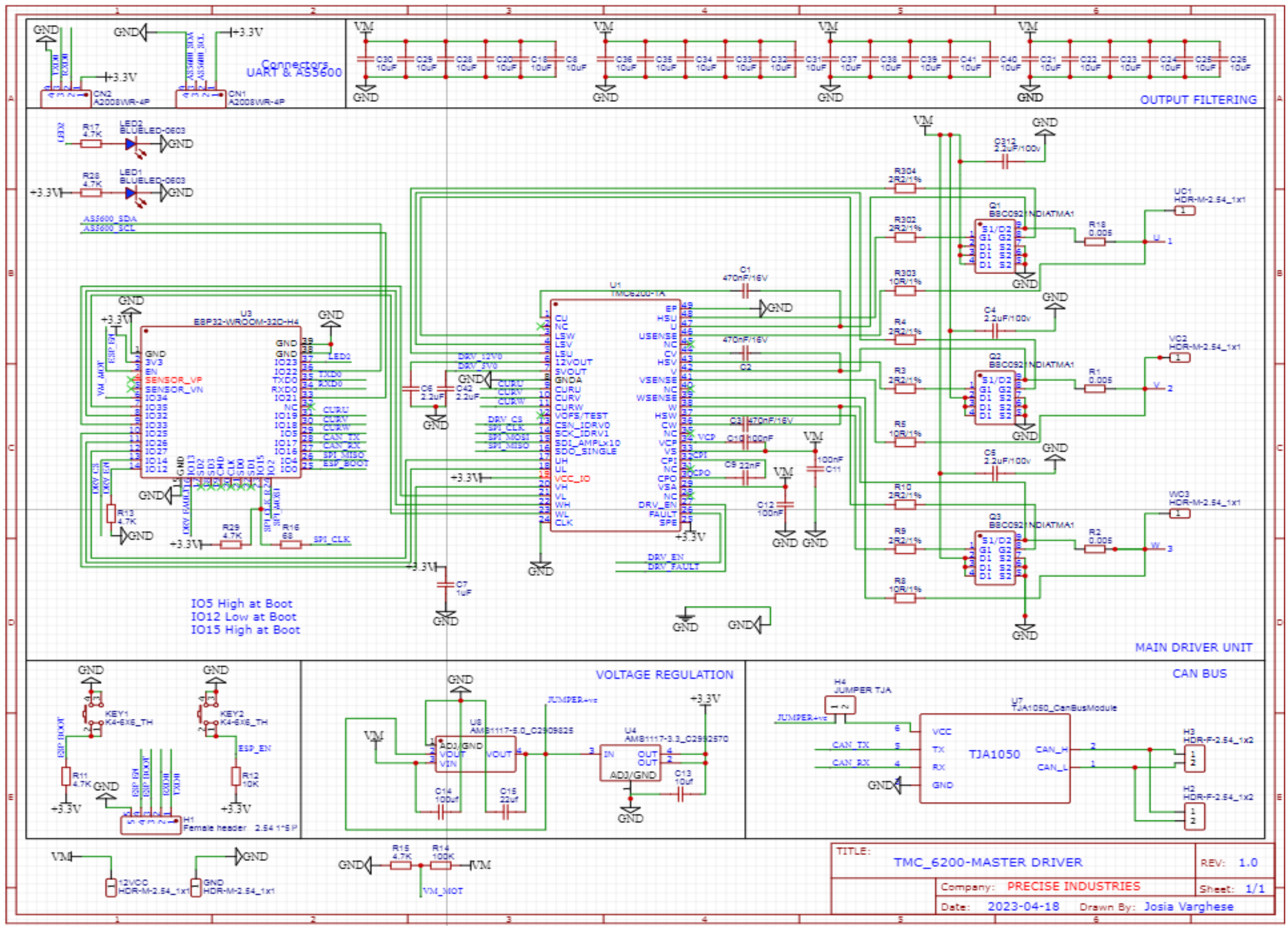
There are 6 PWM signals coming from the microcontroller, each of which is used for position control of the motor. The 6 PWM signals are divided into two parts- HIGH SIDE SIGNALS and LOW SIDE SIGNALS/ENABLES. The high

side signal controls the gate(G1) and the low side signal controls the gate(G2) of BSC0921NDATMA1 MOSFET.
Dual n-channel MOSFETs are used to achieve amplified 3 phase 6 PWM signals. The MOSFET consists of Gate1, Drain1, Source1, Gate 2, Drain2, Source2. The voltage(VM) is connected to the Drain 1 of the MOSFET. The High side signal from the driver is connected to the Gate1 of the MOSFET . When the signals are received by the gate of the MOSFET, the circuit closes and the voltage is induced at Source1 of the MOSFET. The Low Side signals from the driver unit is connected to the Gate2 of the MOSFET . The Source2 of the MOSFET is connected to the ground of the circuit. When the low side signal is passed to the gate2 of the MOSFET, the Drian2 gets a low signal . The continuous switching produces a phase signal at the
S1/D1 pin of the BSC0921NDATMA1 MOSFET. The current sense resistors of 10R is connected to the output of the MOSFET where the BACK-EMF of the motor is monitored and sent to the driver unit TMC6200. The internal current amplification of the TMC6200 allows to debug the BACK-EMF from the motor coil and sends it to the ESP32 Microcontroller.



FOC Custom Framework Architecture

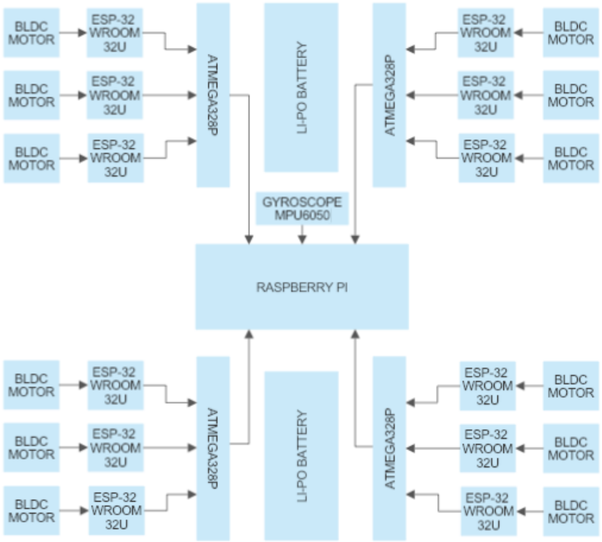
Below is the schematic diagram of the circuit designed to achieve FOC in the motor.



Circuit Diagram for Achieving FOC

HARDWARE AND SOFTWARE DESCRIPTION

The block diagram below shows the framework of the Quadruped Robot consisting of the basic hardware components with the necessary drivers and power supply required for the working.



Block Diagram for Quadruped Robot Structure

MECHANICAL HARDWARE DESCRIPTION

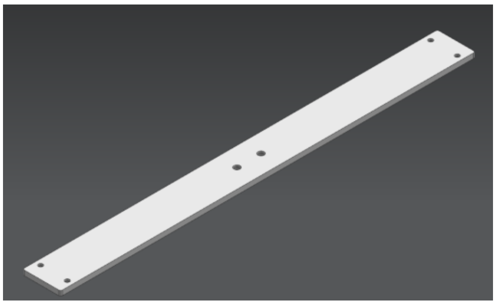
Mechanical hardware refers to the physical components and structures used in mechanical systems and applications. These additives are generally designed to offer support, enable motion, transmit forces, or carry out specific capabilities within a mechanical device. The main mechanical components of the robot are described below.

Parts of the Chassis

The chassis is frame which hosts the mechanisms upon which the entire body rests. It is basically
like the skeleton of Quadruped Robot. The chassis of the robot is entirely made up of three parts

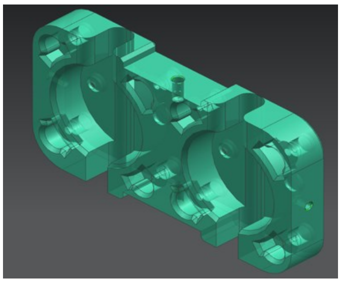
- the aluminium bar,
- the end support, and
- the centre support.

Aluminium Bar



Aluminum Bar

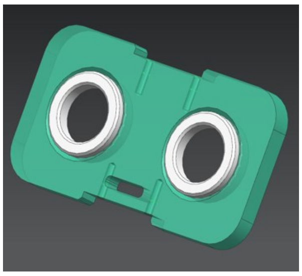
Center Support



Isometric View of Center Support

The centre support hubs the planetary gear mechanism which is used for torque conversion for the motor which controls or rotates the shoulder. This is made from PLA material through 3D printing. The part has been 3D printed to reduce the cost and the weight of the part. It consists of holes to hold the motor holder, which is done my means of screws fastened into it.

End Support



End Support

The end support holds the other end of the shoulder support which is inserted into the bearing, which reduces the frictional losses during rotation and gives a smooth rotation. The ball bearings inserted into the slots have an inner diameter of 25mm and outer diameter 36mm. The top end and bottom is screwed to the aluminum rods which fixes the whole chassis into one complete structure.

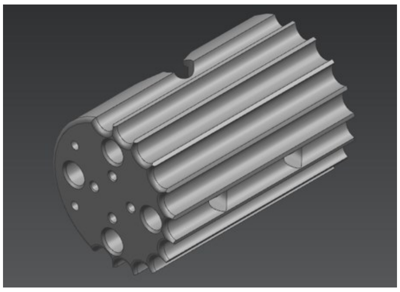
Parts of The Limbs

The limbs are locomotion components which causes the movement of the ‘Quadruped Robot’, which are connected through a series of complex mechanisms involved in actuation of different parts of the limb. There are four such limbs which are connected across the chassis with the centre support and end support acting as the connectivity points.

Typically each limb has a three degree of freedom(all three rotational). This is achieved using three BLDC motors supporting each rotation at the limb dissection.
The limb can be further broken down into three parts

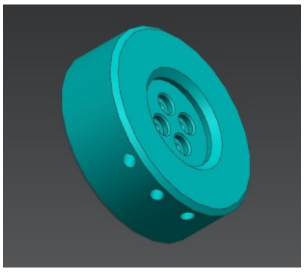
- the shoulder,
- the arm, and
- the leg

The Shoulder

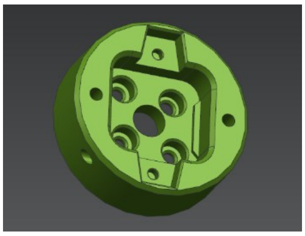


Shoulder

The shoulder is the part of the robot which connects the chassis to the limbs with one end of the shoulder connected to the center support through planetary gear assembly and the other end is connected to the end support of the chassis using shoulder support. The shoulder is driven using an 810kv BLDC motor. A planetary gear assembly is used for amplification of the torque produced by the BLDC motor.



Motor Cover



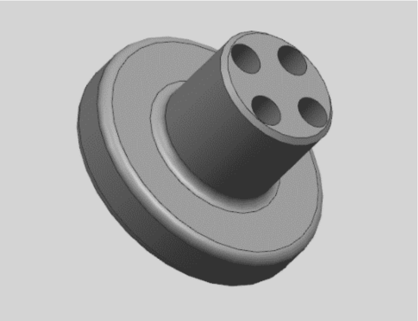
Shoulder Motor Holder

The planetary gear assembly consists of an 18 teeth sun gear fixed to the motor coupler at the flat end and with the gear structure at the centre, and three 18-teeth planetary gears revolving around the sun gear with a 54-teeth ring gear housing the entire gear mechanism.

The shoulder support is connected to the planetary gear mechanism using a coupler made of aluminium to ensure rigidity in the structure and to sustain the load of the planetary mechanism and the shoulder support. The planetary mechanism and the shoulder support are 3D printed using a PLA plastic filament with infill ranging from 20-40%, based on the load being applied on the component.

Shoulder-Planetary Coupler

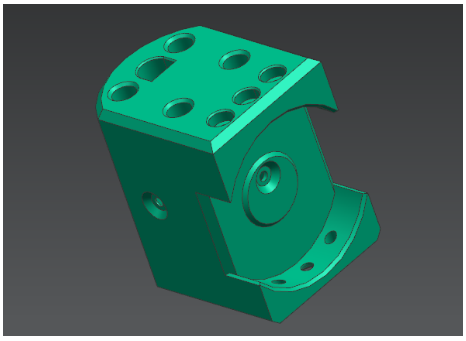
The shoulder support also accommodates the motor holder of the arm, which is used to twist the leg at the point of hinging.



Shoulder Support

The Arm

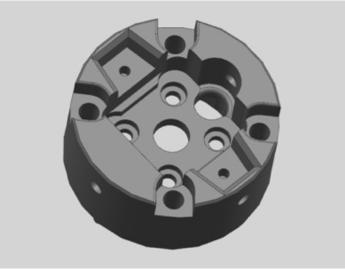
The arm is connected to the shoulder through means of a coupler made out of PLA plastic with 30% infill and with a resolution of 0.12 mm, which gives a smoother curves to maintain the structure without any defects and perfect insertion of BLDC motor coupler.



Arm Coupler

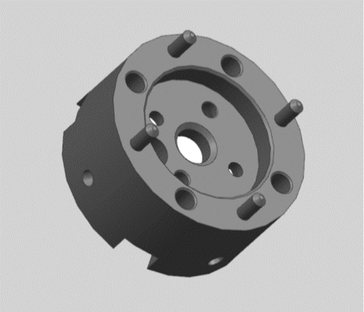
Arm holds the leg in place and it acts as the hinge point of the leg. It is made of a PLA plastic material with a 40% infill, which is given for strength and better heat handling. The arm acts as the housing for the u-link assembly, and the 360kv motor used for lifting the leg which is hinged at the other end of the arm.

To the end of the arm is an arm closure which is made of PLA plastic which holds the motor and a magnetic encoding sensor(AS5600) which is used to measure the angle of rotation of the BLDC motor. The arm enclosure has pin like protrusions which are provided for desired coupling with the arm.



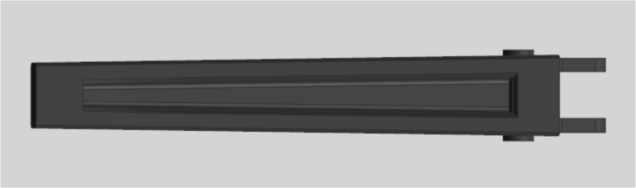
Arm Closure with Slot for AS560

Arm

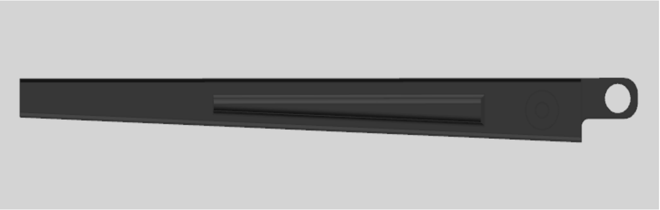


Arm Closure

The Leg



Front View of the Leg



Side View of the Leg

The leg is the point of the of the entire body rest upon. The legs are made out of PLA plastic with 50% infill. The infill of such order is to make the part stronger and to increase the impact absorption caused by the movement of the rob

The leg is hinged at two points at the top end, one to the u-link and the other to the arm. Slots are provided at the topmost point of the leg to accommodate ball bearings which are placed to reduce and friction and give a smooth movement to the leg.

PARTS OF THE LINEAR ACTUATOR

The linear actuator enables the conversion of the rotational motion from the motor into linear motion, providing the necessary actuation for the leg movement in the quadruped robot.

The motor, which is connected to the lead screw, provides rotational motion. The motorcover, typically made of aluminium, serves as a protective housing for the motor and helps in mounting it securely. A cylindrical coupler connects the motor cover to one end of the lead screw. It ensures that the rotational motion of the motor is transmitted to the lead screw.

The other end of the lead screw is fixed, allowing it to rotate along with the cylindrical coupler. The rotation of the lead screw causes the attached ACME bolt to move along the threading of the lead screw. The ACME bolt is connected to the u-link assembly, which comprises the u-link itself. The u-link is secured in a fixed position to prevent its rotation along with the lead screw. This is achieved using two joint bearings, which allow only linear movement. At the top end of the u-link, where the leg is hinged, a ball bearing is placed within the slot. This reduces friction and facilitates smoother movement of the leg. As the lead screw rotates, it moves the u-link along its axis, pushing or pulling the leg up or down, depending on the direction of rotation. By controlling the rotation of the lead screw, the leg can be precisely positioned and moved according to the desired motion pattern.

LEAD SCREW

A lead screw is a type of mechanical power transmission used in machines for high-precision actuation. It converts rotational motion into linear motion. Other names for a lead screw (or leadscrew) are power screw and translation screw.

Lead screw is a power transmission linkage used in modern machines. It can generate very high forces with

a small moment, thus providing a large mechanical advantage. It can be thought of as a wedge wrapped around a cylindrical rod.

The lead screw used is a 4 start M8 screw with 2mm pitch.

In applications such as screw jacks and mechanical presses, it is used to create large forces. They also find use in applications needing extremely precise motion transfer and control, such as linear actuators and linear stages.

As the sliding contact area between the screw and the nut is high, a lead screw has more friction losses compared to other alternatives such as gear trains and chain drives. This characteristic generally limits a lead screw’s use to light- and medium-duty applications.

Working

- A lead screw works in one of two ways:
- The shaft is stationary, and the power is supplied to the nut.
- The shaft rotates and transfers power to the nut.

In the first case, manually applied force or a motor rotates the nut. This pushes the nut along the shaft’s axis. Ultimately, the torque applied to the nut is transformed into linear motion.

In the second case, the nut’s rotational motion is restricted, and the screw shaft rotates. The nut moves 4g the screw axis in the process. Thus, the torque on the screw shaft converts into linear motion of the nut.

ADVANTAGES OF LEAD SCREWS

- Lead screws are cheap and reliable as they only have a few parts
- They require little to no maintenance.
- Smooth and quiet operation
- Capable of lifting heavy loads
- Some power screws have self-locking properties.
- Low-pitch screws can give highly precise measurements, which are vital in machine tool applications

DISADVANTAGES OF LEAD SCREWS

- Not suitable for applications with a very high torque demand.
- In comparison to other mechanical power transmission methods, leadscrews have a high wear rate.
- They have relatively poor efficiency

ACME NUT

An ACME nut, additionally known as an ACME screw or ACME thread, is a sort of threaded fastener generally used in linear motion programs. It capabilities a trapezoidal thread profile, which sets it apart from well-known V-fashioned threads like the ones found on traditional screws or bolts.

The ACME thread profile consists of an imperative ridge flanked by flat or slightly rounded aspects, resulting in a wider and greater robust thread form compared to conventional threads. This design presents numerous advantages in linear actuation systems, consisting of increased load-sporting ability, better durability, and improved resistance to put on and tear.

ACME bolts are regularly paired with ACME nuts, that have corresponding threads to have interaction with the bolt. When the ACME bolt rotates, the nut moves linearly alongside the thread, bearing controlled linear movement. The nut used is a 4-start M8 nut with 2mm pitch.

POS05 JOINT BEARING

POS5 bearing is Rod End PilloBall Insert Type, Right Handed Thread Self Lubricating, Chrome Steel Protective coated for corrosion resistance

POS05 rod-end bearings, also called Heim joints or spherical rod ends, are articulating joints that are attached to the ends of tie rods, steering links, and cylinders to provide a transfer of motion and force between two points. CM-M5 bearing consist of a spherical swivel with a cylindrical bore through which a bolt may pass pressed into a housing that has a threaded shank. Rod end bearings are used in applications such as steering linkages, agricultural machinery, and textile manufacturing equipment, among others.

U-LINK

A U-Link is used for linear actuation of the limb of the quadruped robot through means of a lead screw along with the acme bolt and coupler. It is hinged to the lead screw coupler which is in turn attached to the acme drill nut.

The U-link plays a crucial role in bearing the weight of the entire structure, and as mentioned, it is made of aluminium material to provide sufficient strength and support. The u-link assembly includes a lead screw and an acme bolt, which are responsible for transmitting and converting rotational motion into linear motion. These components are attached to an aluminium coupler.

U-Link

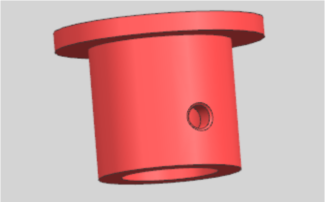
To facilitate smooth rotation of the leg and minimize friction, ball bearings are incorporated into the slots provided on the arm. The ball bearings help in reducing the contact area between the rotating parts, thereby minimizing friction and preventing excessive heat generation that could deform plastic components. Additionally, washers are used to ensure proper alignment and spacing between the ball bearings and the M4 Allen screws that secure the leg. This helps to maintain stability and prevent unwanted movements.

By employing ball bearings and washers in the u-link assembly, the aim is to ensure smooth and efficient movement of the leg while minimizing friction and preventing potential heat-related issues. These design considerations contribute to the overall functionality and longevity of the quadruped robot's leg mechanism.

Usually, belt drives are used for this type of actuation, but this is a unique actuation mechanism designed by us for the movement of the legs. This is machined using a JV100 CNC machine and programmed in Mastercam 2022.

ACME COUPLER

ACME coupler serves as a connector between the ACME nut and the joint bearings, allowing for the transmission of linear motion. The ACME nut is typically threaded and designed to engage with the ACME bolt or lead screw, while the joint bearings provide a pivoting or hinged connection between the u-link and the rest of the leg mechanism.

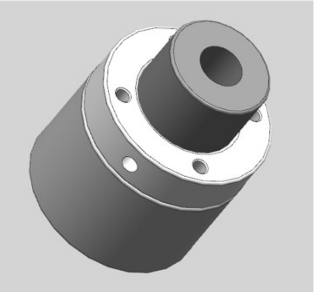


ACME Coupler

The ACME coupler is a component that bridges the gap between the ACME nut and the joint bearings on the u-link. It ensures proper alignment and connection, enabling the transfer of linear motion from the ACME nut to the u-link and subsequently controlling the leg movement.

MOTOR-LEAD CONNECTOR

The "Motor-Lead Connecter" refers to the connector that holds the lead screw in place and facilitates its rotation. It serves as the interface between the motor and the lead screw, allowing the motor's rotational motion to be transmitted to the lead screw effectively.



Motor-Lead Connector

The Motor-Lead Connecter is typically designed to securely attach the lead screw to the motor shaft. It ensures a tight and rigid connection between the two components, minimizing any slippage or misalignment during operation.

The Motor-Lead Connecter is crucial for maintaining the synchronization between the motor and the lead screw, as any disconnection or looseness could lead to inaccurate or unreliable leg movements.

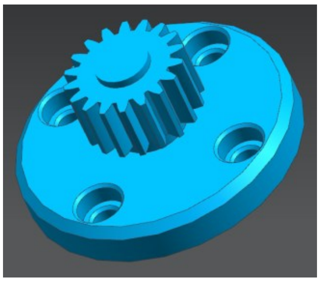
Planetary Mechanism Parts

The planetary gear mechanism, also known as an epicyclic gear system, is a gear arrangement commonly used in various applications, including robotics, automotive systems, and machinery. It consists of three main components: a sun gear, planet gears, and ring gear. Let's explore the functioning and benefits of the planetary gear mechanism:

SUN GEAR

The sun gear is a central gear located at the center of the mechanism. It is typically connected to a power source, such as a motor or engine.

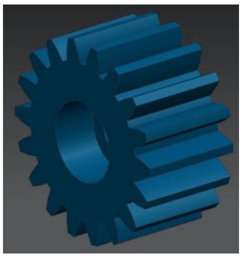
An 18 teeth sun gear is being used, which s been 3D printed using ABS plastic with 40% infill and 0.12mm resolution. The sun gear is the driver of the planetary gear mechanism. It is attached to the planetary motor coupler, made out of aluminium and is fixed using M3 screws rigidly screwed onto the coupler.



Sun Gear

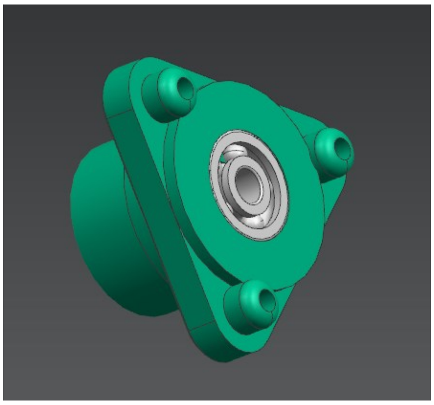
5.1.4.2 Planet Gear

Multiple planet gears surround the sun gear and are evenly spaced around it. These gears are connected to an internal carrier or planet carrier, which holds them in place while allowing them to rotate.



Planet Gear

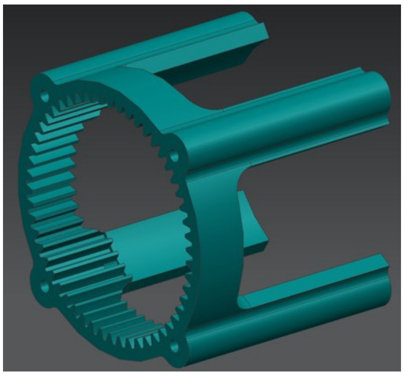
Three 18 teeth planet gears revolve the sun gear. These three planet gears are inserted with ball bearings to avoid any friction during rotation and keep the gears rigidly in position and avoid play in the mechanism. The three planet gears are screwed on the planetary drive using M3 screws. The planetary drive is fixed to a drive holder which is made to rotate smooth using a ball bearing and the end is fixed to a coupler.



Planetary Drive

RING GEAR

The ring gear is the outermost gear in the system and surrounds the planet gears. It meshes with the planet gears and provides the outer support and housing for the mechanism.



Ring Gear

The ring gear is has 54 teeth and is made out of ABS plastic using a 3D printer. It has 40% infill and is made in 0.12 resolution. The ring gear is fixed rigidly to the centre support using a 70mm M3 Allen bolt and the planet gears rotate inside the ring gear on its teeth.

Functioning of the Planetary Gear Mechanism:

The planetary gear mechanism operates based on the interaction and movement of the sun gear, planet gears, and ring gear. The most common uses of the planetary gear mechanism are mentioned below:-

1. Speed Reduction: By fixing the ring gear and allowing the sun gear to rotate, the planet gears rotate around the sun gear while also rotating on their own axes. This arrangement creates a gear reduction effect, resulting in the output shaft rotating at a slower speed than the input shaft.
2. Speed Increase: By fixing the sun gear and rotating the ring gear, the planet gears rotate in the opposite direction while also spinning on their axes. This setup causes the output shaft to rotate at a faster speed than the input shaft, resulting in speed increase.
3. Torque Amplification: When the sun gear provides the input torque, the planet gears transmit the torque to the ring gear. Since the planet gears are engaging with both the sun gear and the ring gear, the output torque is increased in comparison to the input torque. Torque amplification is the main use of the planetary mechanism employed in the Quadruped Robot.

BEARINGS

A bearing is a machine element that constrains relative motion to only the desired motion and reduces friction between moving parts. The design of the bearing may, for example, provide for free linear movement of the moving part or for free rotation around a fixed axis; or, it may prevent a motion by controlling the vectors of normal forces that bear on the moving parts. Most bearings facilitate the desired motion by minimizing friction. Bearings are classified broadly according to the type of operation, the motions allowed, or to the directions of the loads (forces) applied to the parts.

The main purpose of bearings is to prevent direct metal-to-metal contact between two elements that are in relative motion. This prevents friction, heat generation and ultimately, the wear and tear of parts. It also reduces energy consumption as sliding motion is replaced with low-friction rolling.

They also transmit the load of the rotating element to the housing. This load may be radial, axial, or a combination of both. A bearing also restricts the freedom of movement of moving parts to predefined directions as discussed above.

BALL BEARINGS

Ball Bearings are mechanical assemblies that consist of rolling spherical elements that are captured between circular inner and outer races. They provide a means of supporting rotating shafts and minimizing friction between shafts and stationary machine members.

Ball bearings are used primarily in machinery that has shafts requiring support for low friction rotation. There are several configurations, most notably shielded or sealed. Ball bearings are standardized to permit interchangeability.

Ball bearings are also known as rolling element bearings or anti-friction bearings. Considerations include

- First choice for high speeds or high precision apps
- Large range of standardized forms
- Handle radial and axial loads with specific configurations.

The inner diameter, outer diameter and thickness in the respective order, of the different bearings used are mentioned below along with where they are being used:-

3×8×4 – Planet gears
4×8×3 – Legs
4x10×4 – U-link
11×25×6 – Arms
25×36×8 – Centre support, End support and Planetary drive holder

3D Printed Parts

3D Printed Parts

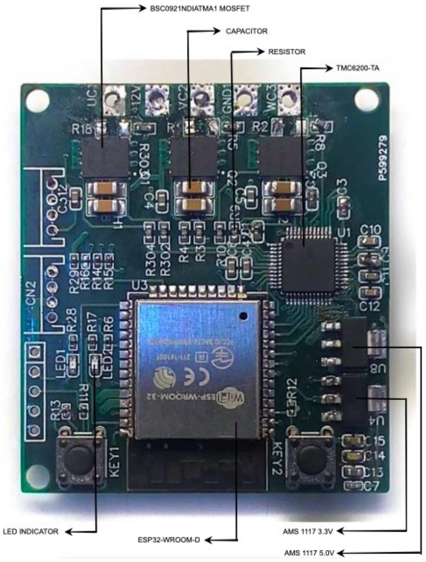
3D printing is an evolution of printing technologies, capable to produce or reproduce freestanding sophisticated structures in one piece. 3D Printing is one of the Additive layer fabrication processes. The 3D printing process happening inside the machine consists of two stages, (1) The direct transfer from software data to printed structures, (2) by repeatedly positioning the print head in all three directions in space in order to print layer by layer the whole object. First, the design is made by a CAD system, and then the areas are printed through a compilation of two-dimensional slices representing the 3D object to consequently print layer by layer until the object is completed. The second stage of the manufacturing process can also be subdivided into two basic steps "coating and fusing", throughout these steps, the material is laid over a surface, and by the action of a source of energy the layers are created. The source of energy and the raw materials vary depending on the used technology.

The 3D printer used is Ender 3 S1 pro, which works through Sterio-lithography.

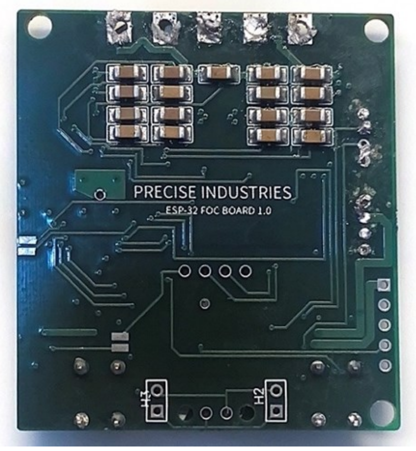
GENERAL ELECTRONIC HARDWARE DESCRIPTION

COMPONENTS ON FIELD ORIENTED CONTROL PRINTED CIRCUIT BOARD(FOC-BOARD)

FOC can be achieved in the Quadruped Robot using a multilayer PCB designed to control the BLDC motors to rotate in a desired direction and at a precise and accurate rate with a very fast response time. The PCB is equipped with many SMD components which control different aspects of the PCB such as voltage regulation, switching times, signal modulation, charge pumping, etc.



Front View of the PCBzz



Back View of the PCB

SMD (Surface Mount Device) refers to electronic components that are designed to be mounted directly onto the surface of a printed circuit board (PCB) during the assembly process. SMD devices have become widely used in modern electronics due to their small size, ease of automated assembly, and improved manufacturing efficiency compared to through-hole components.

SMD components are typically smaller in size compared to through-hole components. They are available in various package types, such as SOT (Small Outline Transistor), SOIC (Small Outline Integrated Circuit), QFN (Quad Flat No-Lead), TSSOP (Thin Shrink Small Outline Package), and many more. These packages have different shapes, dimensions, and pin configurations.

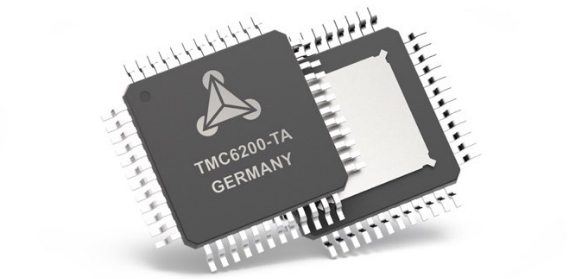
SMD components are soldered directly onto the surface of the PCB using solder paste and reflow soldering techniques. This allows for more compact and densely populated PCB designs, which is particularly advantageous in miniaturized electronic devices. They require specific PCB footprints and are not compatible with traditional through-hole soldering methods. PCB designers must ensure that the PCB layout and pad designs are suitable for the chosen SMD components. Dams are made on the PCB to restrict soldering of metal on the surface of the PCB rather than on the pins provided for the SMD components to be soldered.

Various types of electronic components are available in SMD packages, including resistors, capacitors, integrated circuits (Ics), diodes, transistors, voltage regulators, and more. Almost all types of components used in electronic circuits have SMD equivalents. These components offer several advantages, such as reduced board space requirements, improved high-frequency performance, better thermal characteristics, and automated assembly compatibility. They also facilitate miniaturization and cost-effective mass production.

However, SMD assembly requires specialized equipment and techniques, including stencil printing for applying solder paste, pick-and-place machines for component placement, and reflow ovens for soldering. Repair and rework of SMD components can be more challenging than through-hole components.

TMC6200-TA

The TMC6200 is a high-power gate-driver for PMSM servo or BLDC motors. Using six external MOSFETs and two or three sense resistors, it integrates the full high voltage part of a PMSM drive system for 12V, 24V or 48V, including in-line current sense amplifiers with programmable amplification. It can drive a wide range of motors from Watt to Kilowatt. Software controlled drive strength allows in-system EME optimization. Programmable safety features like short detection and overtemperature thresholds together with an SPI interface for diagnostics allow robust and reliable designs. With the TMC6200, a minimum number of external components is required to build a rugged drive with full protection and diagnostics.



TMC6200-TA

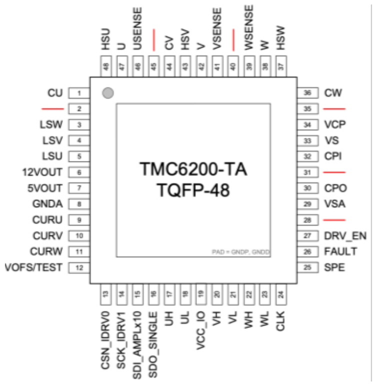
The TMC6200 scores with integration of the complete high-voltage part for FOC controlled PMSM drivers. Its versatile interface matches simple BLDC drives with minimum requirements on the µC PWM, as well as advanced PMSM control algorithms. The small form factor and easy-to-use package of the TMC6200 keeps costs down and allows for miniaturized layouts. Extensive support at the chip, board, and software levels enables rapid design cycles and fast time-to-market with competitive products. High integration and reliability deliver cost savings in related systems such as power supplies and cooling.

A CPU with internal BLDC or sine wave PWM unit drives the gate control lines based on encoder or hall sensor feedback. The current sensor outputs become sampled by the µC integrated.

ADC. Use of SPI is not required, unless more sophisticated diagnostics is desired.

The TMC6200 is a MOSFET gate driver for three phase PMSM and BLDC motors. Internal break-before-make timing is provided for the ease-of-use in combination with simple microcontrollers for PWM generation. Integrated current sense amplifiers eliminate costly sense amplifiers required for FOC controllers (recommended use for applications up to 10A, use external precision amplifiers for higher current with low sense resistor values), while bringing the benefit of in-line current sensing. A complete set of protection and diagnostic functions makes the power stage more rugged than a discrete setup.

The TMC6200 supports six control lines for the MOSFET drivers. High-side and low-side outputs can be individually controlled, or by an individual enable pin plus polarity pin, using internal BBM circuitry. An SPI interface or standalone configuration is supported. The SPI interface is a bit-serial interface synchronous to a bus clock. For every bit sent from the bus master to the bus slave another bit is sent simultaneously from the slave to the master. Communication between an SPI master and the TMC6200 slave always consists of sending one 40-bit command word and receiving one 40-bit status word.

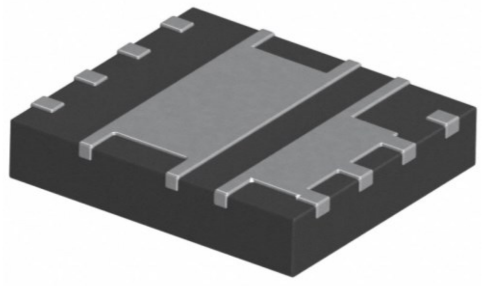


Pinouts of TMC6200-TA

BSC0921NDIATMA1

The BSC0921NDIATMA1 is a Dual N-Channel OptiMOSTM MOSFET manufactured by Infineon Technologies. MOSFET stands for Metal-Oxide-Semiconductor Field-Effect Transistor, which is a type of transistor commonly used in electronic devices and power applications.

The BSC0921NDIATMA1 is a dual N-Channel MOSFET, meaning it has two independent N-Channel transistors in a single package. This configuration allows for more efficient switching and control in certain applications. The OptiMOSTM technology used in the MOSFET offers improved performance in terms of low conduction and switching losses, resulting in higher efficiency and reduced power dissipation.



BSC0921NDIATMA1 MOSFET

Here are some general characteristics and features of the OptiMOSTM MOSFET:

- Power Handling Capability: MOSFETs are commonly used in power applications due to their ability to handle high currents and voltages. However, to determine the specific power handling capability of the BSC0921NDIATMA1, you will need to refer to its datasheet or technical specifications provided by Infineon.
- Low On-Resistance: MOSFETs typically have low on-resistance, which means they can effectively minimize power losses and improve overall system efficiency.
- Low Conduction Losses: OptiMOSTM MOSFETs are designed for high efficiency, providing low conduction losses. This characteristic helps minimize power dissipation and enhances overall system performance.

- Fast Switching Speed: The BSC0921NDIATMA1 MOSFET offers fast switching speeds, enabling efficient control of the connected load, such as motors or other high-power devices. This feature is particularly crucial in applications requiring precise and rapid switching.
- Gate Drive Compatibility: OptiMOSTM MOSFETs are designed to be compatible with standard gate drive voltages, making them suitable for various control circuits and microcontroller-based systems.
- Thermal Management: Efficient thermal management is vital for high-power applications. OptiMOSTM MOSFETs typically feature low thermal resistance and are designed to handle high operating temperatures effectively.
- High Current Handling: It is designed to handle relatively high currents, making it suitable for applications requiring significant power levels.

Table 5. 1 Specifications of BSC0921NDIATMA1 MOSFET

Product Attributes	**Attributes Values**
Category	Discrete Semiconductor Products Transistors FETs, MOSFETs FET, MOSFET Arrays
Manufacturer	Infineon Technologies
Series	OptiMOS
Package	Tape & Reel (TR) Cut Tape (CT) Digi-Reel®
Product Status	Active
Technology	MOSFET (Metal Oxide)
Configuration	2 N-Channel (Dual) Asymmetrical
FET Feature	Logic Level Gate, 4.5V Drive
Drain to Source Voltage (V_{dss})	30V
Current – Continuous Drain (I_d) @ 25°C	17A, 31A
Rds On (Max) @ I_d, V_{gs}	5mOhm @ 20A, 10V
V_{gs}(th) (Max) @ I_d	2V @ 250µA
Gate Charge (Q_g) (Max) @ V_{gs}	8.9nC @ 4.5V
Input Capacitance (C_{iss}) (Max) @ V_{ds}	1025pF @ 15V
Power – Max	1W
Operating Temperature	-55°C ~ 150°C (TJ)
Mounting Type	Surface Mount
Package / Case	8-PowerTDFN
Supplier Device Package	PG-TISON-8

PCB Design

Several components have been used on the PCB, both in through-hole and surface mount packages. The PCB's component placement is crucial for:

1. Effective PCB signal and power track layout
2. Considering thermal impacts that arise from components heating up during typical operation. Any one area of the board cannot experience an excessive temperature increase. Components should be positioned properly, and heat sinks should be included (components that absorb heat and enable it to be dissipated away from the component that generated it).
3. Ergonomic factors where a user would have to access a portion of the PCB to control components (like switches) or for testing and evaluation needs.

The PCB used is a multilayer PCB consisting of 4 layers.
1. first layer is the top layer.
2. second layer is the ground plane.
3. third layer is the VCC power plane, and
4. the fourth layer is the bottom layer.

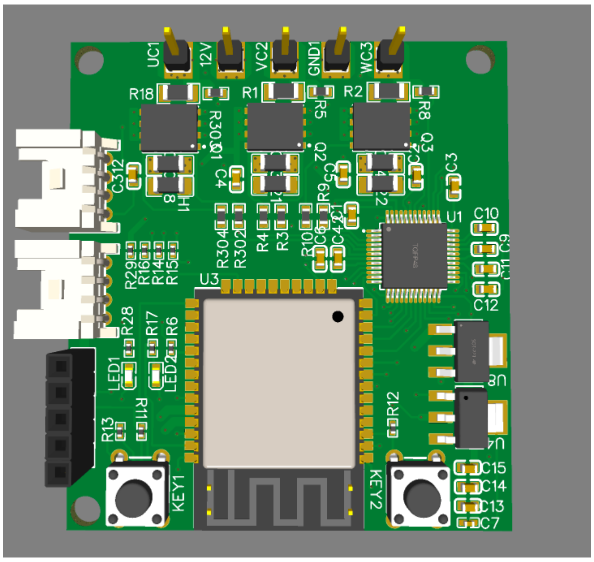
Mechanical description of the PCB
- Length- 48mm
- Width- 53mm
- Thickness- 1.6mm

Routing description
- Routing width- 0.254mm
- Routing angle- 45 degrees
- Routing conflict- round track

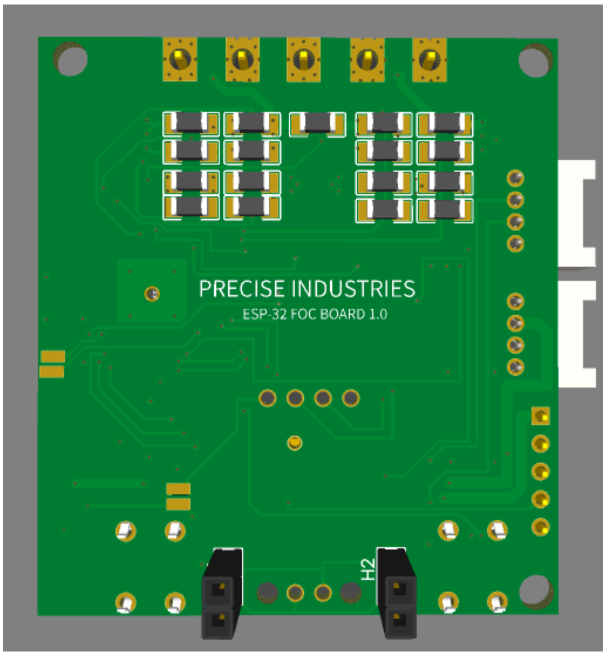
Via description

Via refers to a plated hole that provides a conductive connection between different layers of the PCB. It allows electrical signals or power to pass through the PCB from one layer to another, enabling interconnections between the various components and traces on the board.
- Diameter of the via-0.635mm
- Drill diameter of the via- 0.305

The via is multi-layered



Completed Top View of the PCB



Completed Bottom View of the PCB

I. INVERSE KINEMATIC ANALYSIS OF THE QUADRUPED ROBOT

INTRODUCTION

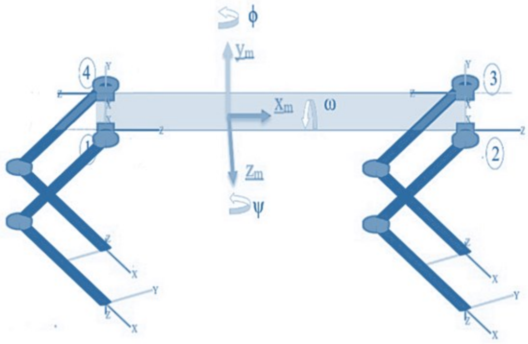
When analysing parallel mechanisms kinematically, it's common to establish closed-loop equations that relate the joint variables of the mechanism. To also determine the connection between the joint variables and the cellular platform's function and orientation, one can use the cellular platform's function expressed through person serial chains.

In this chapter, we will discuss the kinematic analysis of a parallel manipulator that has a restricted motion plane. This manipulator consists of a shifting platform linked to two serial chain legs. The role of the serial chain is to actively and passively constrain the end-effector. The passive kinematic joints of the serial chain provide reaction forces that restrict the end-effector's motion within the serial chain workspace. On the other hand, each active joint induces controllable force on the end-effector. The overall kinematics of the parallel manipulator depend on the kinematics of each sub-chain.

A huge trouble encountered in fixing inverse kinematic equations is that of more than one answers. The truth that a manipulator has a couple of solutions can purpose troubles, because the gadget has as a way to choose one. There are usually multiple sets of joint variables in an effort to yield a particular Cartesian configuration. The standards upon which to base a selection range, but an inexpensive desire will be the closest solution or the allowable joint movement variety. The period closest solution means the solution that minimizes the quantity that every joint is required to move to attain the favoured position and orientation in Cartesian space.

KINEMATIC ANALYSIS

The quadruped robot is a robotic system that consists of a rigid body and four legs with three degrees of freedom (each leg has the same structure). The links of legs are connected to each other by rotary joints. The physical model of the quadruped robot is shown Fig 6.1. The parameters of robot are given in Table 6.1.



The Physical Model of the Quadruped Robot

Table 6. 1 Table of Parameters of Robot

Physical Dimensions	The Length of Robot	L=410mm
	The Width of Robot	W=250mm
	The Length of Side Swing Joint	L1=75mm
	The Length of Hip Joint	L2=180mm
	The Length of Knee Joint	L3=120mm
Coordinate Systems	The Coordinate System of center of Body	$[x_m, y_m, z_m]$
	The Main Coordinate System of Each Leg	$[x_0, y_0, z_0]$
	The Coordinate System of Side Swing Joint	$[x_1, y_1, z_1]$
	The Coordinate System of Hip Joint	$[x_2, y_2, z_2]$
	The Coordinate System of Knee Joint	$[x_3, y_3, z_3]$
	The Coordinate System of Endpoint of Leg	$[x_4, y_4, z_4]$
Variables	The Yaw Angle of Robot	φ
	The Pitch Angle of Robot	ψ
	The Roll Angle of Robot	ω
	The Angle of Side Swing Joint	θ_1
	The Angle of Hip Joint	θ_2
	The Angle of Knee Joint	θ_3

As shown in Figure 1, depending on the leg's coordinates, the robot body can have different configurations. For this reason, the kinematic equation between the rotational movements (φ, ψ, ω) around the centre of body's coordinate system (x_m, y_m, z_m) and the coordinate system of each endpoint of leg (x_4, y_4, z_4) is investigated. Initially, to determine the position and orientation of the robot centre of body in the workspace, the transformation matrix is obtained in Eq.5 using the rotation matrices (Eq. 1, Eq. 2, Eq. 3, Eq. 4).

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\omega) & -\sin(\omega) & 0 \\ 0 & \sin(\omega) & \cos(\omega) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_y = \begin{bmatrix} \cos(\phi) & 0 & \sin(\phi) & 0 \\ 0 & 0 & 0 & 0 \\ -\sin(\phi) & 0 & \cos(Q) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_z = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 & 0 \\ \sin(\psi) & \cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{xyz} = R_x \, R_y \, R_z$$

$$T_m = R_{xyz} \times \begin{bmatrix} 1 & 0 & 0 & x_m \\ 0 & 1 & 0 & y_m \\ 0 & 0 & 1 & z_m \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The kinematic equation the centre of body's coordinate system (x_m, y_m, z_m) and The Main Coordinate System of each leg (x_0, y_0, z_0) is given by the transformation matrices given in Eq.6, Eq.7, Eq.8, Eq.9. The positions and orientations of each leg can be calculated according to the position and orientation of the robot's body.

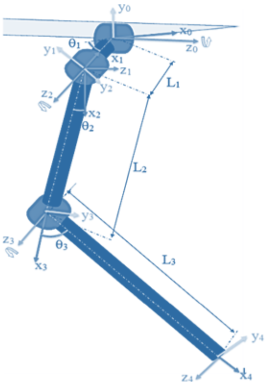
$$T_{rightback} = T_m \times \begin{bmatrix} \cos(\pi/2) & 0 & \sin(\pi/2) & -L/2 \\ 0 & 1 & 0 & 0 \\ -\sin(\pi/2) & 0 & \cos(\pi/2) & W/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{rightfront} = T_m \times \begin{bmatrix} \cos(\pi/2) & 0 & \sin(\pi/2) & L/2 \\ 0 & 1 & 0 & 0 \\ -\sin(\pi/2) & 0 & \cos(\pi/2) & W/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{leftfront} = T_m \times \begin{bmatrix} \cos(-\pi/2) & 0 & \sin(-\pi/2) & L/2 \\ 0 & 1 & 0 & 0 \\ -\sin(-\pi/2) & 0 & \cos(-\pi/2) & -W/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{leftback} = T_m \times \begin{bmatrix} \cos(-\pi/2) & 0 & \sin(-\pi/2) & -L/2 \\ 0 & 1 & 0 & 0 \\ -\sin(-\pi/2) & 0 & \cos(-\pi/2) & -W/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward kinematics of robot, deals with the relationship between the positions, velocities and accelerations of the robot links. Inverse kinematics is the process of finding the values of the joint variables according to the positions and orientations data of the endpoint of robot. In other words, in order to move the robot endpoint to the desired position, it is necessary to determine the rotational values of the joints with inverse kinematic analysis. The forward and inverse kinematics of analysis one leg of a quadruped robot are described in detail. The legs are in different orientations with each other but in the same structure, so it is sufficient to investigate the forward and inverse kinematics analysis of a single leg. Fig. 2 shows the coordinate systems and the angular positions of the right front leg joints. The Denavit-Hartenberg parameters for forward kinematics of the leg are given in Table 2.



The Coordinate System of Leg Joints

Table 6. 2 The Parameters of Denavit-Hartengerg

Link	α_{i-1}	a_{i-1}	d_i	θ_i
0-1	0	L1	0	θ_1
1-2	$-\frac{\pi}{2}$	0	0	$-\frac{\pi}{2}$
2-3	0	L2	0	θ_2
3-4	0	L3	0	θ_3

Each transformation matrices ($T_0^1, T_1^2, T_2^3, T_3^4$) are given and the forward kinematic matrix (T_0^4) is also given. The elements of the forward kinematic matrix of a leg are given in Table 3.

$$T_0^1 = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & -L_1\cos(\theta_1) \\ \sin(\theta_1) & \cos(\theta_1) & 0 & -L_1\sin(\theta_1) \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_1^2 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ -1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^3 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & -L_2\cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2) & 0 & -L_2\sin(\theta_2) \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^4 = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & -L_3\cos(\theta_3) \\ \sin(\theta_3) & \cos(\theta_3) & 0 & -L_3\sin(\theta_3) \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^4 = T_0^1 \, T_1^2 \, T_2^3 \, T_3^4 = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}$$

Table 6. 3 Elements of the Forward Kinematic Matrix

$m_{11}=\cos(\theta_2)\cos(\theta_3)\sin(\theta_1) - \sin(\theta_1)\sin(\theta_2)\sin(\theta_3)$
$m_{12}= -\cos(\theta_2)\sin(\theta_1)\sin(\theta_3) - \cos(\theta_3)\sin(\theta_1)\sin(\theta_2)$
$m_{13} = -\cos(\theta_1)$
$m_{14} = L_2\cos(\theta_2)\sin(\theta_1) - L_1\cos(\theta_1)$ $+ L_2\cos(\theta_2)\cos(\theta_3)\sin(\theta_1)$ $- L_3\sin(\theta_1)\sin(\theta_2)\sin(\theta_3)$
$m_{21} = \cos(\theta_1) \sin(\theta_2) \sin(\theta_3) - \cos(\theta_1) \cos(\theta_2) \cos(\theta_3)$
$m_{22} = \cos(\theta_1) \cos(\theta_2) \sin(\theta_3) + \cos(\theta_1) \cos(\theta_3) \sin(\theta_2)$
$m_{23} = -\sin(\theta_1)$
$m_{24} = L_3 \cos(\theta_1) \sin(\theta_3) - L_2 \cos(\theta_1) \cos(\theta_2)$ $- L_3 \cos(\theta_1) \cos(\theta_2) \cos(\theta_3)$ $- L_1 \sin(\theta_1)$
$m_{31} = \cos(\theta_2) \sin(\theta_3) + \cos(\theta_3) \sin(\theta_2)$
$m_{32} = \cos(\theta_2) \cos(\theta_3) - \sin(\theta_2) \sin(\theta_3)$
$m_{33} = 0$
$m_{34} = L_2 \sin(\theta_2) + L_3 \cos(\theta_2) \sin(\theta_3) + L_3 \cos(\theta_3) \sin(\theta_2)$
$m_{41} = 0$
$m_{42} = 0$
$m_{43} = 0$
$m_{44} = 0$

After obtained the transformation matrices and forward kinematic matrices required for the inverse kinematic solution of the Quadruped Robot, the inverse kinematic analysis is performed using analytical methods. Equations expressing the angular position of joints ($\theta 1$, $\theta 2$, $\theta 3$) are obtained and given below. There are nonlinear equations in the solution of inverse kinematics problems. For every mathematical expression computed, there may not be a physical solution. Also, there may be more than one solution for the legs endpoint to go to the desired position. For this reason, the legs of the robot (1 and 3) and the leg of the robot (2 and 4) have been realized in the same kinematic structure but in different configurations.

$$\theta_1 = -\text{atan2}(-y_4, x_4) - \text{atan2}\sqrt{x_4{}^2 + y_4{}^2 - L_1{}^2}\ , -L_1\ )$$

$$\theta_2 = \text{atan2}\left(x_4\ , \sqrt{x_4{}^2 + y_4{}^2 - L_1{}^2} \right) - \text{atan2}(L_3 \sin(\theta_3), L_2 + L_3 \cos(\theta_3))$$

$$\theta_3 = \text{atan2}(-\sqrt{1 - D^2}, D) \text{ (Legs for 1 and 3)}$$

$$\theta_3 = \text{atan2}(\sqrt{1 - D^2}, D) \text{ (Legs for 2 and 4)}$$

$$D = (x_4{}^2 + y_4{}^2 - L_1{}^2 + z_4{}^2 - L_2{}^2 - L_3{}^2) / (2L_2L_3)$$

II. ASSEMBLY

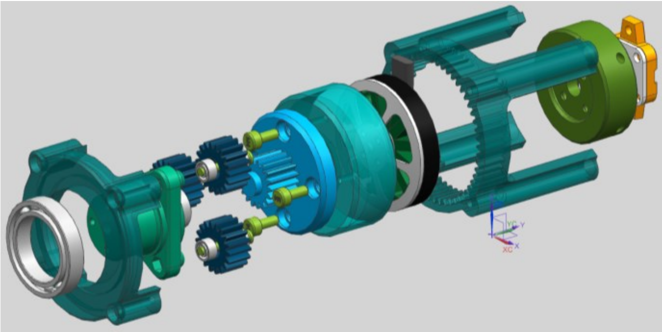
The assembly of the Quadruped Robot is a conjunction of various concept assemblies involved in it. These assemblies all together makes for the movement of different parts of the robot. The different assemblies involved in the robot are:

1. Planetary gear assembly
2. Linear actuation assembly
3. Leg assembly
4. Body assembly

Let's explore each assembly in more detail:

PLANETARY GEAR ASSEMBLY

This assembly consists of a set of gears arranged in a planetary configuration. It is often used in the joints of the robot's legs to provide torque multiplication, speed reduction, and precise motion control. The planetary gear assembly helps in achieving compact and efficient power transmission within the robot.



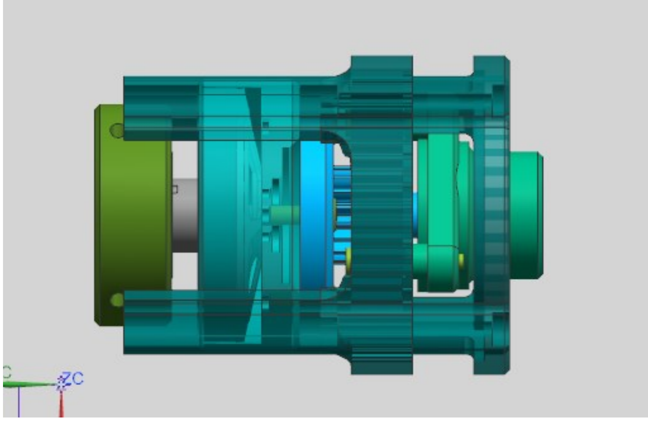
Planetary Gear Assembly

The sun gear, which serves as the driver of the mechanism, is attached to the planetary motor coupler. The coupler is typically made of aluminium and is fixed securely to the sun gear using M3 screws. This connection ensures that the rotational motion of the motor is transferred to the sun gear.

The three planet gears are inserted with ball bearings to reduce friction and provide smooth rotation. The ball bearings keep the gears rigidly in position and minimize any play or movement within the mechanism. The planet gears are secured onto the planetary drive using M3 screws. The planet gears rotate around the sun gear and engage with the teeth of the ring gear.

The planetary drive, with the planet gears attached, is fixed to a drive holder. The drive holder allows smooth rotation of the planetary drive and ensures proper alignment of the gears. A ball bearing is used in the drive holder to facilitate smooth rotation.

The ring gear, which surrounds the planet gears, is fixed rigidly to the centre support. A 70mm M3 Allen bolt is commonly used to secure the ring gear to the centre support. The centre support provides stability and acts as a housing for the planetary gear mechanism. The planet gears rotate inside the ring gear, engaging with its teeth.

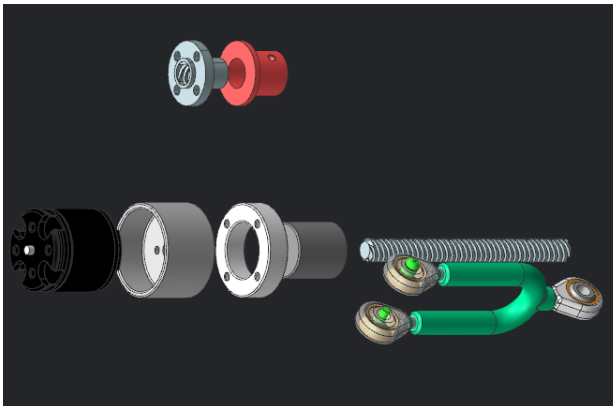


Planetary Gear Mechanism

By assembling these components, the planetary gear mechanism enables torque amplification. The ball bearings, screws, and couplers ensure proper alignment, reduced friction, and reliable operation of the mechanism.

LINEAR ACTUATION ASSEMBLY

This assembly enables linear motion in the robot's legs, allowing them to extend and retract. As mentioned earlier, it typically involves a lead screw, ACME bolt, u-link, joint bearings, and a coupler. The rotation of the lead screw translates into linear motion of the u-link, controlling the leg movement.



Linear Actuation Assembly

With the motor connected to the lead screw, the rotational motion of the motor is transmitted to the lead screw via the cylindrical coupler and motor cover. The motor cover not only serves as a protective housing for the motor but also ensures secure mounting and alignment.

On the other end of the lead screw, the ACME bolt is attached. As the lead screw rotates, the ACME bolt moves along the threading, either advancing or retracting. The u-link assembly, which includes the u-link and the attached ACME bolt, is designed to allow linear movement without rotation. This is achieved by using two joint bearings that hold the u-link in a fixed position.

At the top end of the u-link, where the leg is hinged, a ball bearing is placed within the slot. This ball bearing helps to reduce friction and enables smoother movement of the leg as the u-link is pushed or pulled by the rotation of the lead screw. By controlling the rotation of the lead screw, the position of the u-link and, subsequently, the leg can be precisely adjusted. This control allows for coordinated leg movements and the execution of desired motion patterns in the quadruped robot.

Linear Actuator

Overall, the assembly of the motor, lead screw, u-link, and associated components provides a mechanism for translating rotational motion into linear motion, enabling controlled leg movement in the quadruped robot.

LEG ASSEMBLY

The leg assembly includes the mechanical structure and components responsible for supporting and moving each leg of the quadruped robot. It comprises multiple segments, connected through joints or hinges. The leg assembly also incorporates sensors for feedback and balance control during locomotion.

Leg Assembly

The shoulder is driven by an 810kv BLDC motor. This motor provides rotational motion for the shoulder movement. The shoulder support, which holds the planetary gear mechanism, is connected to the motor using an aluminium coupler. This coupler ensures rigidity in the structure and supports the load of the planetary mechanism and the shoulder support. The shoulder support also accommodates the motor holder of the arm. This motor holder is used to twist the leg at the point of hinging, allowing additional degrees of freedom in leg movement.

The arm is connected to the shoulder assembly using a coupler. This connection allows for the transmission of rotational motion from the shoulder to the arm. The arm serves as the housing for the u-link assembly. The u-link assembly, as previously described, includes the u-link, ACME bolt, joint bearings, and ball bearings. It controls the vertical movement of the leg. The arm is driven by a 360kv motor, which provides lifting motion for the leg. The motor is hinged at the other end of the arm and rotates to raise or lower the leg.

At the end of the arm, an arm enclosure made of PLA plastic is present. This enclosure holds the BLDC motor and houses a magnetic encoding sensor (AS5600) used to measure the angle of rotation of the motor. The arm enclosure features pin-like protrusions that facilitate desired coupling with the arm, ensuring a secure connection. The linear actuator is first placed into the arm through the bottom end and is fixed on the top end using an arm enclosure. The arm enclosure is fixed to the arm using M4×25mm Allen bolts.

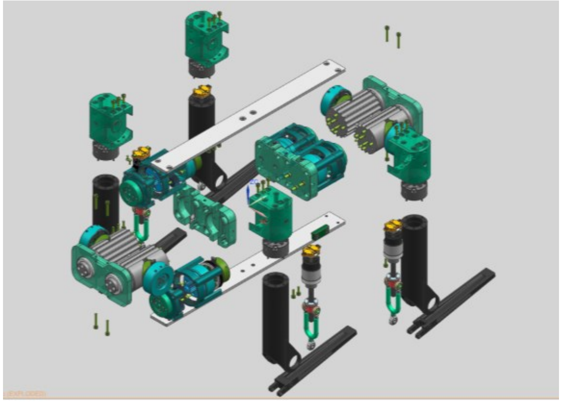
The leg is hinged at two points: one to the u-link assembly and the other to the arm. These hinges are done through means of ball bearings. Slots are provided at the topmost point of the leg to accommodate ball bearings. These ball bearings reduce friction and enable smoother leg movement and hence provide flexibility and allow controlled movement of the leg.

By integrating these components and connections, the quadruped robot achieves the desired range of motion and control in its shoulder, arm, and leg assemblies. The motors, couplers, support structures, and enclosures work together to enable coordinated movement and precise control of the robot's limbs.

BODY ASSEMBLY

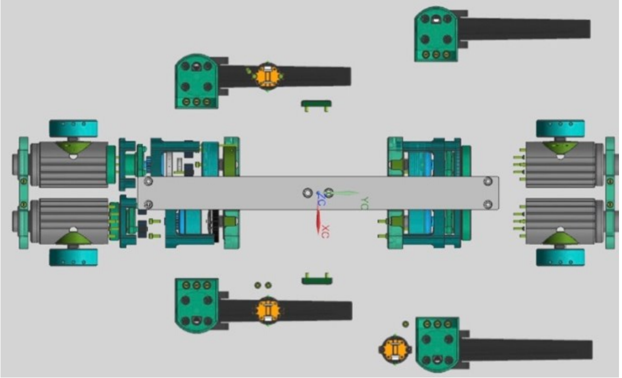
The body assembly forms the central structure of the quadruped robot, housing various components, including the power source, control system, sensors, and communication modules. It provides support and protection for the internal components and ensures stability and balance during robot movement.

The final step in assembling the quadruped robot involves connecting all the independent part assemblies together to form the complete body assembly. Here is a breakdown of the process



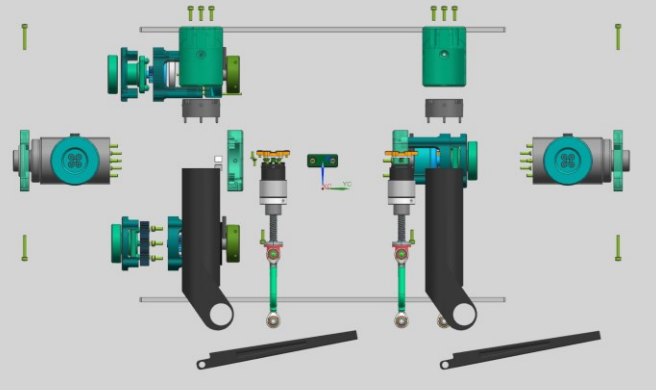
Body Assembly

The planetary gear mechanism assembly is connected to the shoulder using a planetary-to-shoulder coupler. This coupler ensures a secure connection between the two components. The planetary end of the mechanism is inserted into the chassis center support using the motor holder. This motor holder supports the motor that drives the planetary mechanism. The shoulder end of the mechanism is connected to the chassis end support using the shoulder support. This connection provides stability and support for the shoulder assembly. Repeat this process for all four shoulder assemblies, fixing them securely onto the chassis using the aluminum to reinforce and strengthen the structure as needed.



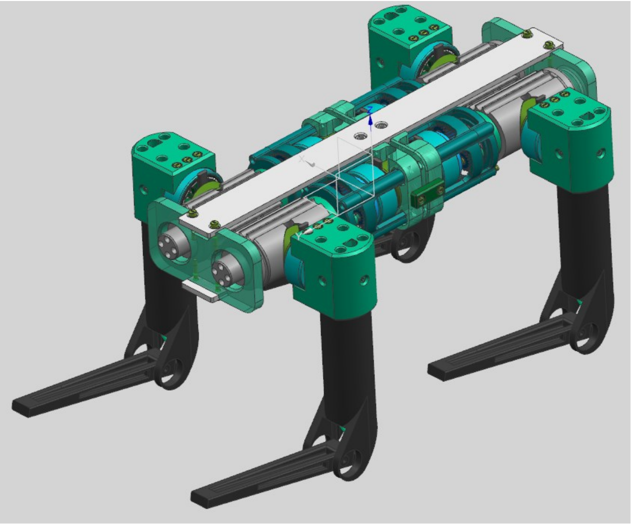
Top View of Body Assembly

The chassis consists of a framework made of aluminum bars that provide the main structure and support for the robot. The end support is securely attached to one end of the chassis using appropriate fasteners. It acts as a mounting point for the shoulder assemblies and helps maintain the stability of the robot. Similarly, the center support is fixed to the chassis at the appropriate location, providing a mounting point for the planetary gear mechanism assembly. It ensures proper alignment and support for the mechanism.



Side View of the Body Assembly

A motor is fixed on each shoulder assembly using a motor holder. The motor provides the driving force for the respective shoulder movement. Inside the motor holder, an AS5600 magnetic encoder is placed. This encoder measures the position of the motor and provides position data to the microcontroller or control system for precise control of the robot's movements.



Assembled Quadruped Robot

The arm coupler is placed on the motor coupler, which is connected to the motor positioned on the shoulder assembly. This connection allows for the transmission of rotational motion from the motor to the leg. The assembled leg, consisting of the linear actuation assembly, is inserted into the slot provided in the arm coupler through the arm closure end.

The leg is fixed in place using an M4 screw, ensuring a secure attachment.

These assemblies work together in harmony to achieve coordinated movement, balance, and control in the quadruped robot. Each assembly has its specific functions and contributes to the overall performance and capabilities of the robot.

III. RESULT

The project ‘QUADRUPED ROBOT’ is fabricated using the various concepts and experimentally tested for the various parameters.

By giving input to the program and calibrating it for an output, the following example results are obtained.

Table 8. 1 Example Results from the Program

$[x_4, y_4, z_4] = [0,- 0.65, 0]$ $[x_m, y_m, z_m] = [0, 0, 0]$			θ_1	θ_2	θ_3
ϕ ψ ω	Leg Number	1	7.5883°	28.7493°	–29.7695°
		2	11.5735°	–33.0804°	100.5692°
		3	11.5735°	33.0804°	–100.5692°
		4	7.5883°	–28.7493°	29.7695°
$[x_4, y_4, z_4] = [-0.05, -0.55, 0]$ $[x_m, y_m, z_m] = [0, 0, 0]$			θ_1	θ_2	θ_3
ϕ ψ ω	Leg Number	1	9.7298°	49.8269°	– 53.8359°
		2	– 47.7890°	– 30.1490°	67.8506°
		3	– 31.9917°	59.6929°	– 69.4310°
		4	31.8200°	– 36.8724°	82.0530°
$[x_4, y_4, z_4] = [-0.15, -0.7, 0.05]$ $[x_m, y_m, z_m] = [0.1, 0.2, -0.3]$			θ_1	θ_2	θ_3
ϕ ψ ωz	Leg Number	1	– 51.7965°	30.1317°	–35.2716°
		2	–48.0254°	– 34.7341°	99.7991°
		3	34.9428°	62.5980°	– 105.322°
		4	43.2869°	– 25.3487°	59.5477°

The findings of this experiment are given below.

Mobility:

- The quadruped robot demonstrated agile and versatile mobility, capable of walking, trotting, running, and turning with ease.
- It showcased smooth and coordinated movements, enabling it to traverse various terrains and obstacles.

Stability and Balance:

- The robot exhibited excellent stability, maintaining its balance even during dynamic movements and on uneven surfaces.
- It demonstrated the ability to recover from disturbances and maintain its posture while in motion.

Motion Control:

- The integration of motor and encoder systems allowed for precise control over the robot's leg movements.
- The robot achieved accurate and repeatable leg positioning, enabling precise step placement and gait control.

Speed and Efficiency:

- The quadruped robot achieved satisfactory speed and efficiency in its locomotion, reaching a maximum velocity of 0.37 meters per second.
- It showcased energy-efficient movements, optimized for longer operational durations.

Control System:

- The implemented control system effectively coordinated the movements of all four legs, ensuring synchronized and balanced locomotion.
- The robot responded promptly to user commands or autonomous control inputs, exhibiting reliable and robust control behaviour.

Payload and Load Bearing:

- The robot demonstrated the capability to carry additional payloads, such as sensors or objects, without compromising its stability or locomotion performance.
- Load-bearing tests showed that the robot could handle a maximum payload of 4.37 kilograms without any adverse effects.

Safety Features:

- The design incorporated safety features to protect the robot and its surroundings, such as collision detection and emergency stop mechanisms.
- These safety features ensured the robot's safe operation in various environments and minimized the risk of accidents.

CONCLUSIONS AND FUTURE WORK

By utilizing 3D-printed parts and affordable smart BLDC motors, the robot offers a cost-effective alternative to its more expensive counterparts. Its maximum leg length of 41cm is commendable for its small size, providing a decent range of motion similar to higher-priced options. With 12 degrees of freedom (DOF), the robot can position its body in six DOF, allowing for various movements and poses.

However, to enhance the robot's capabilities, several improvements are needed. First, the addition of odometry and control for self-balancing would greatly enhance its stability and locomotion. These features would enable the robot to navigate its surroundings more effectively and maintain balance during movement.

Additionally, the robot requires an onboard computer and a battery for standalone operation. This would eliminate the need for an external control system and increase its autonomy. Faster communication with the motors is also necessary to ensure precise and responsive movements.

While the robot currently relies on ROS (Robot Operating System) for control, it is suggested that the control system be ported to a more open and high-performance language to accommodate future onboard computers. This change would provide better computational capabilities and allow for more advanced algorithms and control systems to be implemented.

If these improvements are implemented, the quadruped robot has the potential to become a competent and cost-effective option in its domain. While it may not push the boundaries of performance, it offers a more affordable alternative with most of the essential features found in pricier quadruped robots.

The improved accessibility provided by this robot would be particularly advantageous for educational purposes. Students would have the opportunity to engage with this type of robot at an earlier stage, fostering a better understanding of its functionality and inspiring new ideas in the field. In research settings, a more accessible and affordable robot would facilitate more aggressive testing of robot algorithms and control systems, as the lower repair costs would make experimentation more feasible. Furthermore, the affordability would allow for the exploration of scenarios involving multiple robots, such as robot collaboration or hive control.

Overall, the proposed enhancements would make the quadruped robot more versatile and attractive for both educational and research purposes.

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