CAT LIKE QUADRUPED ROBOT

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This is just a summary of the graduation thesis prepared for MEXT application

Abstract: Quadruped robots are mostly used for hazardous environments that contain obstacles and can be dangerous for humans. Necessity of legged robots are increasing day by day because of their ability of move more flexibly and efficiently on rough terrain than other classical type robots. We present a design of a quadrupedal robot in a small size like a cat. Robot systems include a smart method for leg control, determine the body orientation and global location. This data open doors to enable the quadruped robot to walk over uneven terrain while keeping its balance as well as executing autonomous missions.

Key words: *Quadruped robot, legged robot*

1. INTRODUCTION

Mobile robotic researches mostly focused on wheeled or tracked robots for more than 200 years and reached the limit, and it is relatively difficult to make a fundamental breakthrough. Researchers' focus is shifted to the legged robotics mostly on mobile robot field which robot type requires high flexibility over a terrain. Quadruped robots have some construction and analysis difficulties but have advantages on ease of control and stability with respect to the bipedal robots. In this manner, we developed a quadrupedal robot in a small size to reduce the cost and complexity.

Designing a legged robot is more complicated than a wheeled robot. Process involves deciding and designing various parameters such as leg structure, leg joints and kinematics, actuators, stability and motion control. While designing and deciding; energy consumption, stability, motion speed, cost, locomotion ability criterias should be considered.

2. OBJECTIVE

Cat like quadruped robot project aimed to be developed in order to lay the groundwork for future studies in addition to a quadruped robot design. In this way, project offers a low-cost, easy to build, lightweight and open to development robot to people who want to contribute from different disciplines in the field of rapidly developing legged robotics without needing to worry about the mechatronics. Thus, we aimed to contribute to the innovations in the field of legged robotics by opening a way to develop this platform.

3. TECHNICAL APPROACH

3.1 DESIGN OF QUADRUPED ROBOT

Design of a system started with determining the system requirements and these requirements translated into technical requirements and decisions. The developed system specifications are given in the Table 1.

Description	Value
Weight	About 3.5 kg
Dimensions (L x W x H)	350x 250 x 150 mm
Height	185 mm to 125 mm
DOF per leg	3 active
Walking speed	0.2 m/s
Max speed	0.5 m/s
Actuation	Digital servo motors
Battery	*Li-Ion (15000 mAh)*
Average operation time	*20 min*
Onboard sensors	Accelerometer Gyroscope Magnetometer GPS (UBlox-Neo-M8N)
Onboard computer	Raspberry Pi 3

Table 1 - System Specifications

- In order to be able to improve the robot comfortably in future works, flexibility has been provided in the decisions made in the development of both the mechanical, electronical and software sides of the robot.
- It was designed by using 3 active DOFs in each leg, totalled 12 DOFs so that the robot can easily perform any desired movement.
- It is designed in cat sizes and less than 5 kilograms in weight in order to make the robot easy to carry.
- The selected joint motors are servo motors with UART protocol in order to easily implement the possible microprocessor or motor changes.
- Open source and widely used Raspberry Pi 3 is used as microprocessor of the robot.

- It was designed carefully as modular sub-systems to make the robot mechanically open to changes.

3.1.1 Mechanical Design

Robot's mechanic development managed by using spiral system development model. An interative workflow in followed and finaly design and project is validated. Robot designed as sub-systems to open door to the improvements. These modular sub-systems shown in further paragrapghs of the paper.

Joint actuators are designed with a load bearing that is shown in Figure 1. Modular block named as ServoBlock that bears radial loads to avoid overloading the servo motors.

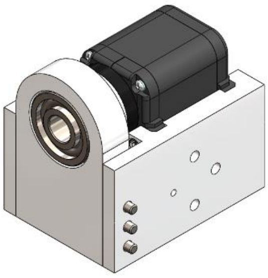


Figure 1 - ServoBlock

Lower leg design and the one leg's design is shown in the Figure 2. Same leg design is used for four legs to increase ease of simulation.

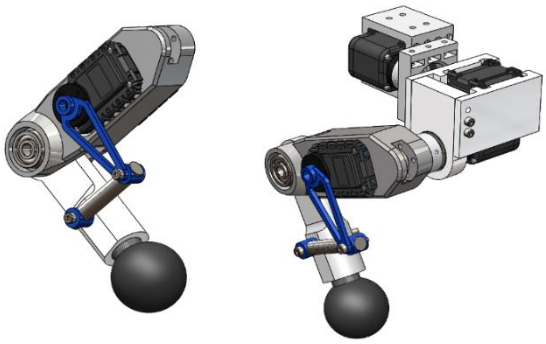


Figure 2 - Left: Lower Leg
Right: One Leg's Design

Body is designed considering possible upgrades and body gives a flat surface on top and at the bottom to easy implementation of tools. The connections are made by using distance nuts and bolts. Electronic box and leg system parts which are inside the body are tangential to the top and bottom of body. This contact makes body stronger.

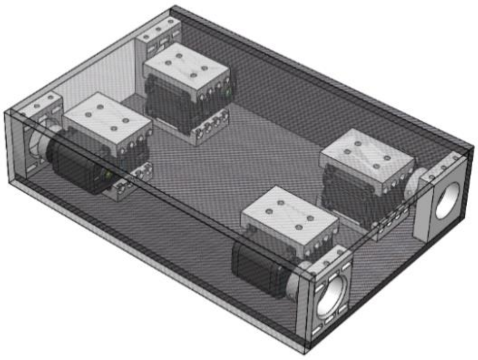


Figure 3 - Body of the Robot

Figure 4 shows whole assembly of the robot. Robot has four legs with forward-backward configuration that found reduces slippage between feet and ground and improves motion performance in general [Zhang et al. 2015]. Each leg has three active degree of freedom that shown in Figure 4 and Figure 5. Quadruped robot has 12 active DOF totally. All the legs have same design for simplicity of modelling simulation, control and manufacturing.

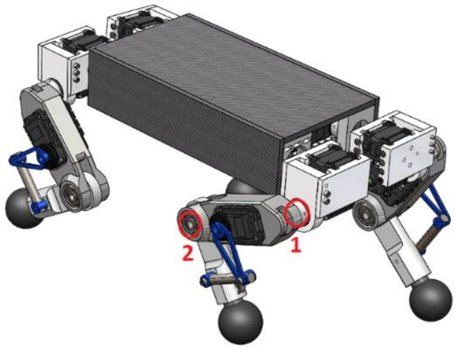


Figure 4 - Designed Quadruped Robot and Hip, Knee Joints

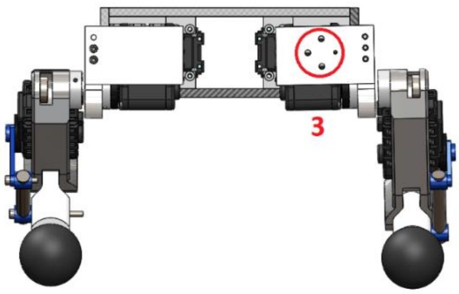


Figure 5 - Lateral Movement Joint

3.1.2 Electronical Design

I. Actuator Selection

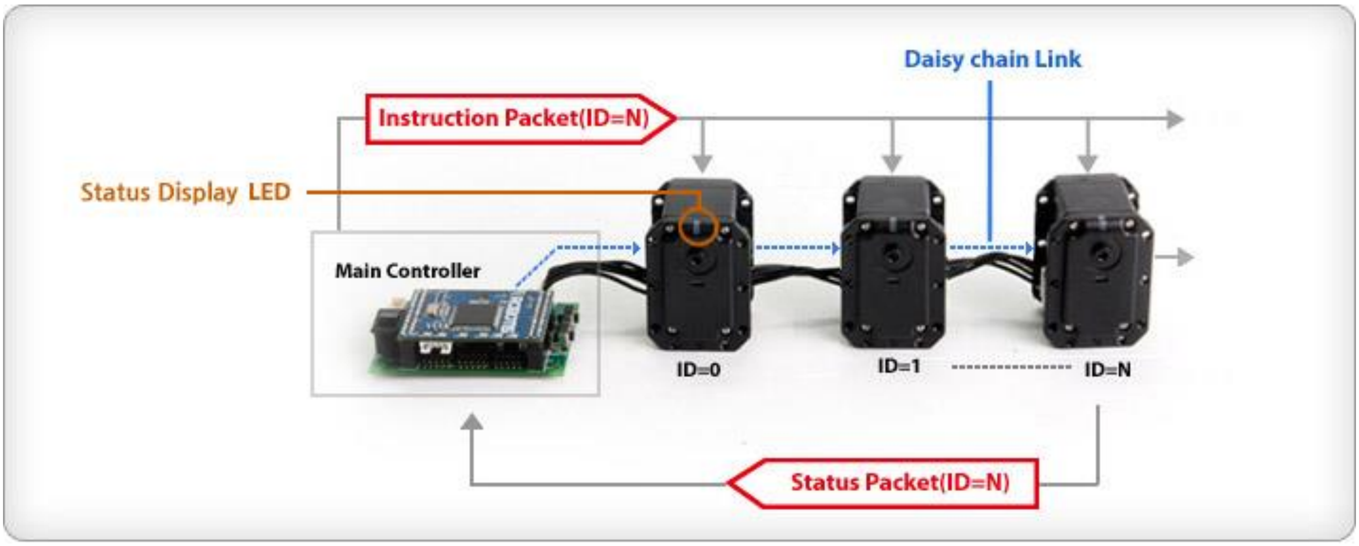


Figure 6 - Dynamixel AX12A and Communication

A robot is a machine with moving parts that accomplish a certain task. Motions are generated by actuators so, actuators are one of the most important components of the robot. True actuator selection effects system efficiency, and the suitability for the requirements of the robot. Dynamixel AX12 servo motor is selected because, control of the motor is easy and servo motors can give position and torque feedback to the system with an affordable price. Without using any external position torque sensor, encoder or driver circuit, system will be controlled easily. On the other hand, servo motors with UART communication is selected to have flexiblity on processor or computer selection. Any computer or microprocessors supports half-duplex asyncrhonous serial communication.

II. Controller Selection

Controller is another most important component of the robot. Controller will calculate motor angles for each axis of motors and send command to the motors, read data from sensors and keep the robot stable. On the other hand, it should be common to make easy for future works who wants to develop this project. Controller needs to have enough computing power to work on image processing too.

Raspberry contributes a platform that gives opportunity to develop projects easily and this platform is quite common. Because of this reason, Raspberry Pi can be selected as controller. A PID controller will be implemented on the raspberry pi for controlling the robot. Also, Raspberry Pi has GPIO pins that user can connect sensors and read data from them. There are some models of Raspberry, Pi 3 model is selected for this project because of the being fastest model while development of the project.

III. Sensor Selection and Data Filtering

Robot have accelerometer, gyroscope, magnetometer and GPS sensors. A position detection algorithm is used to determine the robot position with respect to recieved data from sensors. The self-balancing reflexes will be calculated by taking feedback from these sensors. Some of the IMU sensors considered and LSM303D is selected because of its cost effectiveness and having accelerometer, gyroscope and magnetometer in a one package.

A complementary filter is used to overcome this noise problem. Complementary filter is a basic method that uses accelerometer and gyroscope data to obtain angle [1]. After some tests, high pass filter and low pass filter coefficients are selected as 0,98 and 0,02 which are implemented to the formula shown at Figure 8. The method of complementary filter is shown at 7.

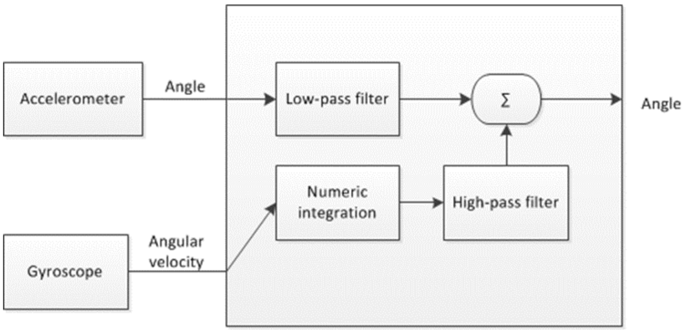


Figure 7 - Complementary Filter Scheme

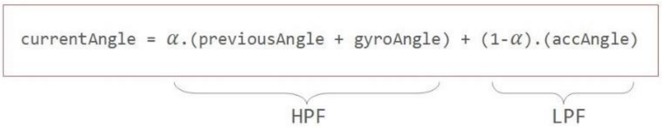


Figure 8 - Complemantry Filter Formula

UBlox Neo-6M GPS is used in this project. GPS is used to determine the location of the robot. Mission planning capability is planned as entering the GPS coordinates and creating a route between these GPS coordinates. To obtain global position of the robot, Global Positioning Sensor (GPS) is used.

3.1.3 Tests and Simulations

I. Strenght Tests

Designed components are tested by using Solidworks Simulation. The worst case is considered for all cases. Whole assembly designed to resist 10g shock. Robot weight is calculated as 2.8 kilograms. This means, all components can resist 400N without reaching plastic deformation. Some of the simulations are shown in the Figure 9.

II. Quarter and Full Model Simulations

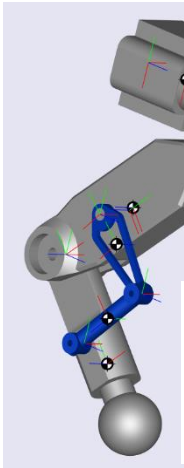


Figure 8- Quarter Model of Robot

Quarter model of the robot is required to simulate walking gait, locomotion algorithm, required joint torque verification and develop PID controller to self-balancing capability [2]. For these reasons, a CAD model is designed on the MATLAB Simulink with a simplified version of the quadruped robot. Simplified leg is shown at Figure 10.

Mathematical model of the robot is required to simulate controller, locomotion algorithm and even to see required joint torques. For these reasons, a CAD model is designed on the MATLAB Simulink as shown at which is a simplified version of the

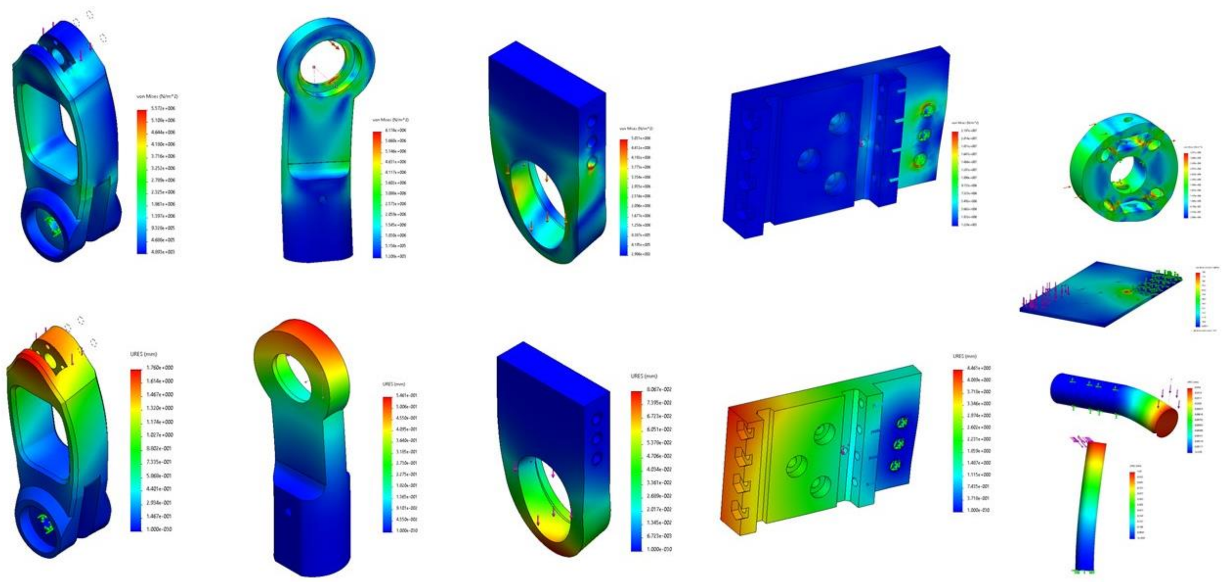


Figure 7 - Strenght Test of Robot's Parts

SpyCat robot. Under normal circumstances, the controller of the robot repeats one leg's locomotion algorithm all over the legs with a certain order and phase difference between each of them [2].

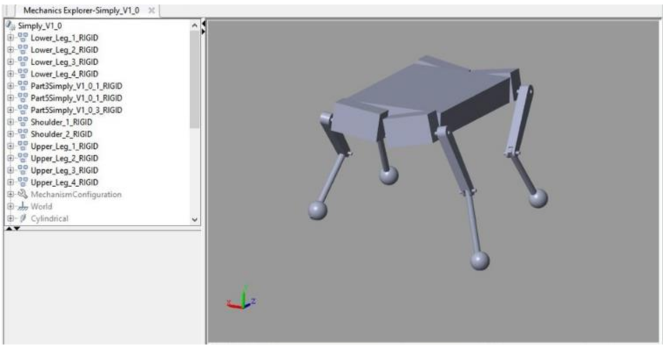


Figure 9 - Full Model of Robot

3.1.4 Software Design

I. Body Orientation Determination

The most basic way to determine the pitch angle and roll angle of the body is using only the accelerometer. There will be always constant gravitational acceleration roughly 9.81m/s^2. The quadruped robot won't accelerate other greater accelerations; thus, it can be used to determine pitch angle and roll angle by following equations.

$$Pitch_{angle} = \tan^{-1} \frac{a_x}{\sqrt{a^2{}_y + a^2{}_z}}$$

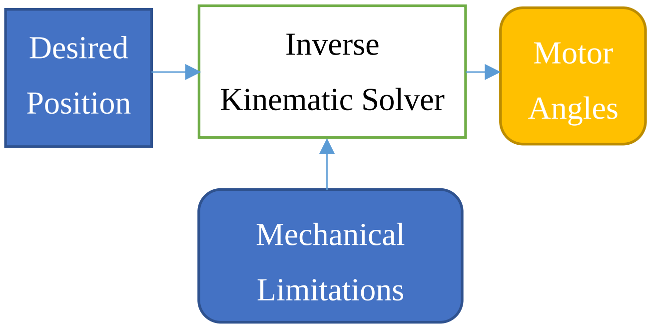
Equation 1 – Body Pitch Angle

$$Roll_{angle} = \tan^{-1} \frac{a_y}{a_z}$$

Equation 2 – Body Roll Angle

II. Kinematic Solver

In this part of study, inverse and forward kinematic analysis of quadruped robot is investigated. Denavit-Hatenberg method is used for forward dynamics and analytical solutions is used for inverse kinematics. [3] A python script obtains the angular positions of joints of each legs with respect to transfered kinematic equations.



III. Main Control Loop

First thing to control robot is the control signal that comes from either control interface or from a remote controller. All commands are sent to the controllers via different channels. After taking this command, command transformed into leg coordinates. Gait generation and control library takes role to create a desired gait points and send these coordinates into inverse kinematic solver. This library calculates the required motor angles to reach the desired coordinates.

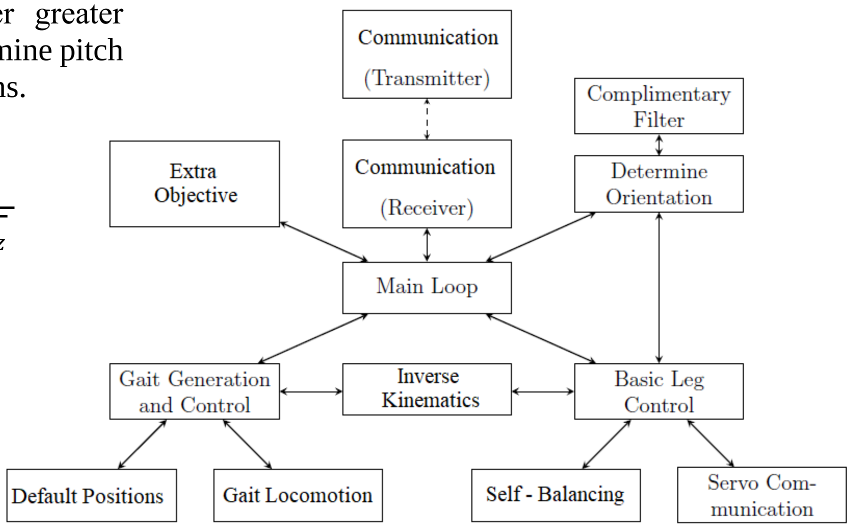


Figure 10- Basic Control Scheme of the Robot

Another library is always checking the sensor positions, and GPS positions and determines the body orientation and accelerations. By using these data, a self-balancing algorithm keeps the robot balanced.

The basic control scheme in the matter of controller is shown in Figure 12.

IV. Control Interface

Robot planned to have ability of autonomous operation. An interface is created on C# for usage as ground station intergace to see data of robot such as velocity, location, motor positions. Interface planned for autonomus mission planning. The created software is using USB port to communicate. with robot. Figure 11 shows designed interface.

Figure 11 – Control panel of SpyCat

3.2 DEMO STUDIES ON QUADRUPED ROBOT

3.2.1 Manufacturing Mechanics

FDM 3D printing is used in the parts of the robot since its low cost with respect to CNC or other manufacturing methods. Figure 12 shows the some of the parts, Figure 13 shows all required parts of the robot.

Figure 12 – 3D printing of the robot parts

Figure 13 – All parts of the robot

Gait and default positioning (such as sitting standing) are tried while robot is hanging to the platform first. Real tests are done after ensuring the algorithms and positions. 20x20 sigma profiles are used to build the hanging platform as shown in the Figure 14.

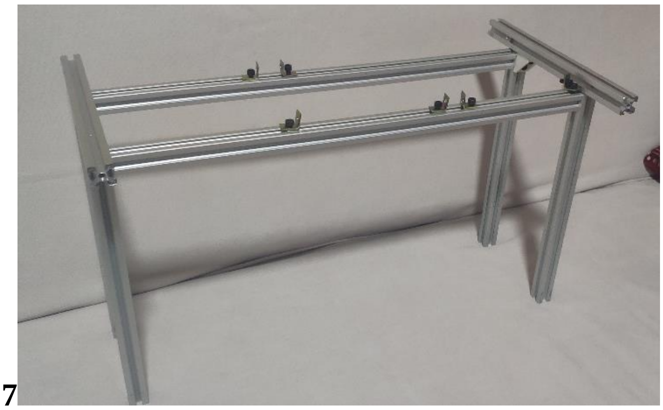


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Figure 14 – Hanging platform

Figure 15 shows hanging platform and SpyCat's final mechanical assembly together.

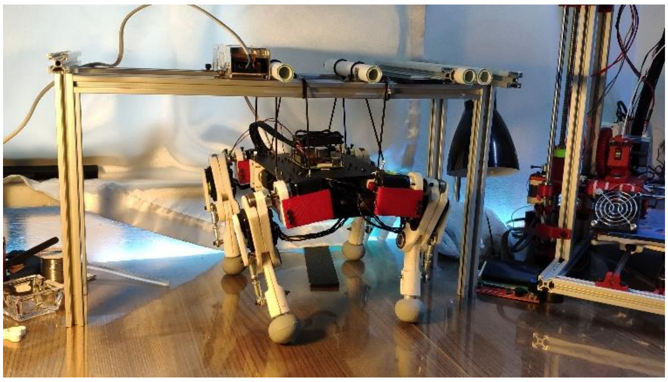

Figure 15 – Final hanging platform and SpyCat robot

3.2.1 Manufacturing Electronics

For motor – microprocessor communication a cheap and DIY solution is designed and manufactured. [4] Designed PCB layout and wiring diagram are shown in the Figure 18 and Figure 19.

Power Distribution board for motors are shown in Figure 18.

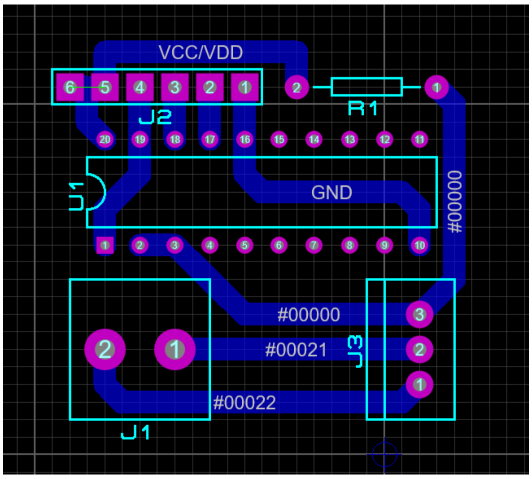

Figure 17 – Motor Communication PCB

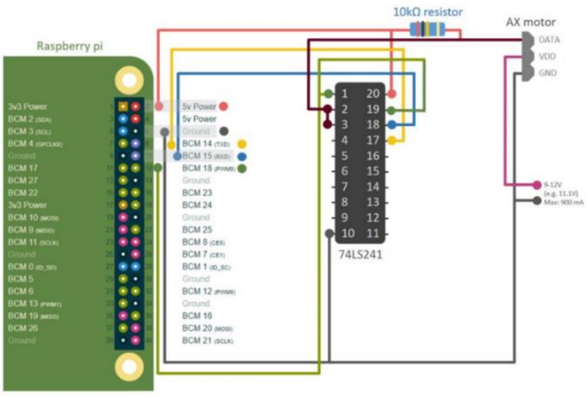

Figure 16- Motor Communication Electronics Wiring Diagram

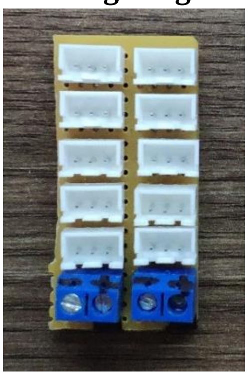

Figure 18 – Power distribution board

3.2.2 Gaiting and Movement Studies

Robot shall be used at many different terrain conditions. So, three main gait type is selected, and their gaiting calculations were made. They are;

- High gaiting at rough terrains
- Normal gaiting for normal terrains
- Fast gaiting for smooth terrains

These are just selected type of gaits. Gait creation library is open to any parameters that comes from user for many scenarios.

Rough terrain requires overcome obstacles and more stability. In order to achieve this kind of gait characteristic gait stride should be small to increase stability of movement, robot shall be erected to have high height and on the other hand, leg jump should be high to overcome obstacles. So, a gait with stride length of 60mm, height of 190mm and jump of 50mm is selected as an example.

Gait creator creates such gait and sends package to the IK solver. IK solver finds an analytical solution for angular angles of motors for each to reach desired position. These motor angle data sent to related motors and movement of the robot is observed and position feedback was taken from every motor. Measured and desired angles fit to expectations. The maximum error is -0.90mm.

Figure 19 shows the desired and real path of the end point of leg. Expectations of simulation and real gaiting is shown in Figure 20.

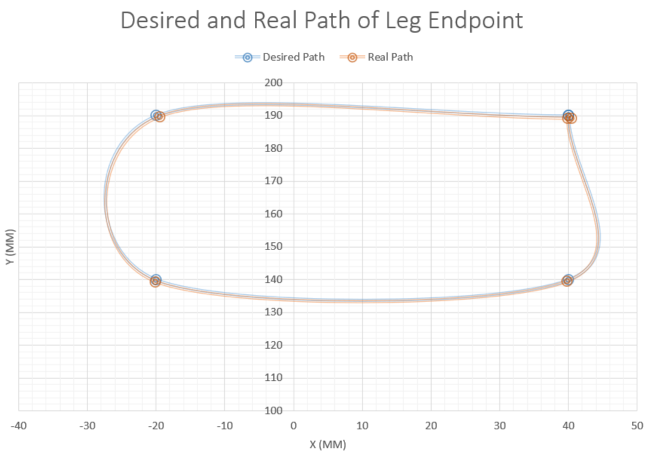

Figure 19 – Desired and measured path of leg end point

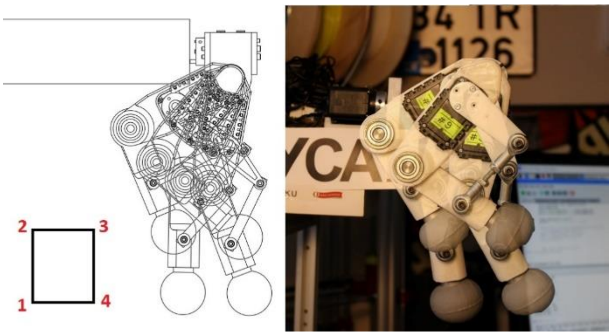

Figure 20 – Comparison of target and real trajectory for rough terrain scenario

A path was created for normal hubbly terrains such as top of the soil. In order to create this kind of scenario, gait parameters took average values which are stride length of 100mm, height of 170mm and jump length of 20mm. The maximum end-effector position error is 1.24mm which fits to expectations.

Figure 21 shows the desired and real path of the end point of leg. Expectations of simulation and real gaiting is shown in Figure 22.

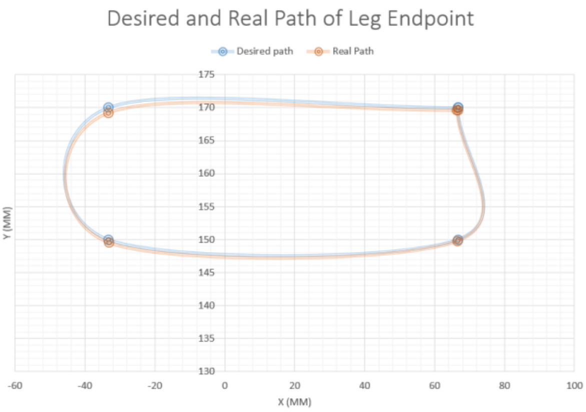

Figure 21 – Desired and measured path of leg end point

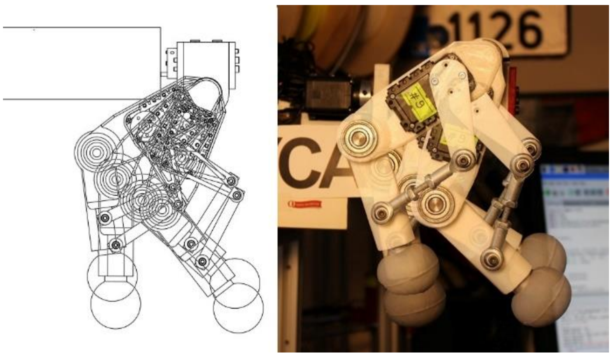

Figure 22 – Comparison of target and real trajectory for normal terrain scenario

Finally, a path was created for flat and smooth terrains such as asphalt. In order to create this kind of scenario, gait parameters took average values which are stride length of 190mm, height of 150mm and jump length of 10mm. The maximum end-effector position error is 1.24mm which fits to expectations again.

In a same manner, Figure 23 shows the desired and real path of the end point of leg. Expectations of simulation and real gaiting is shown in Figure 24.

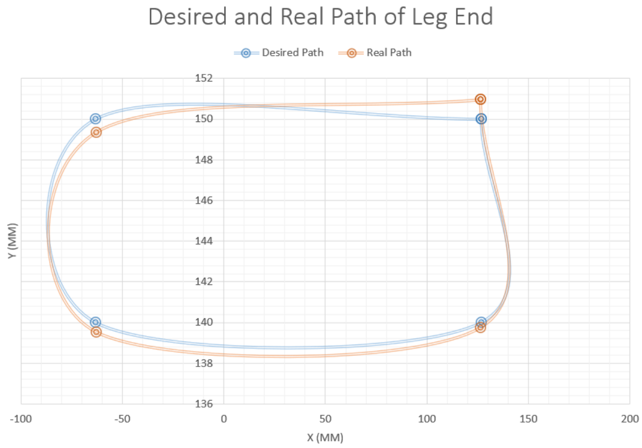

Figure 23 – Desired and measured path of leg end point

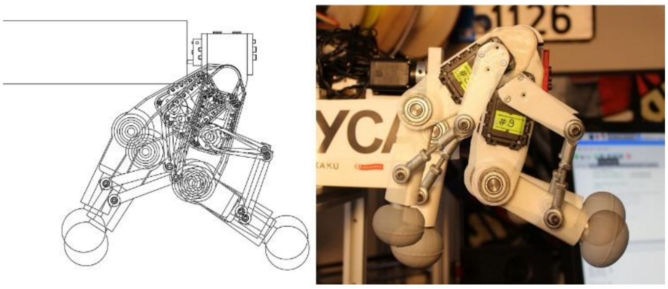

Figure 24 – Comparison of target and real trajectory for smooth terrain scenario

Studies were done for default positioning such as sitting, standing, bending to left or right side. These tests are done while the robot is on its foot to proof that the robot motors are enough to give motion to robot.

- Figure 27 shows standing movements
- Figure 26 shows the standing to default position from bended to right position movements

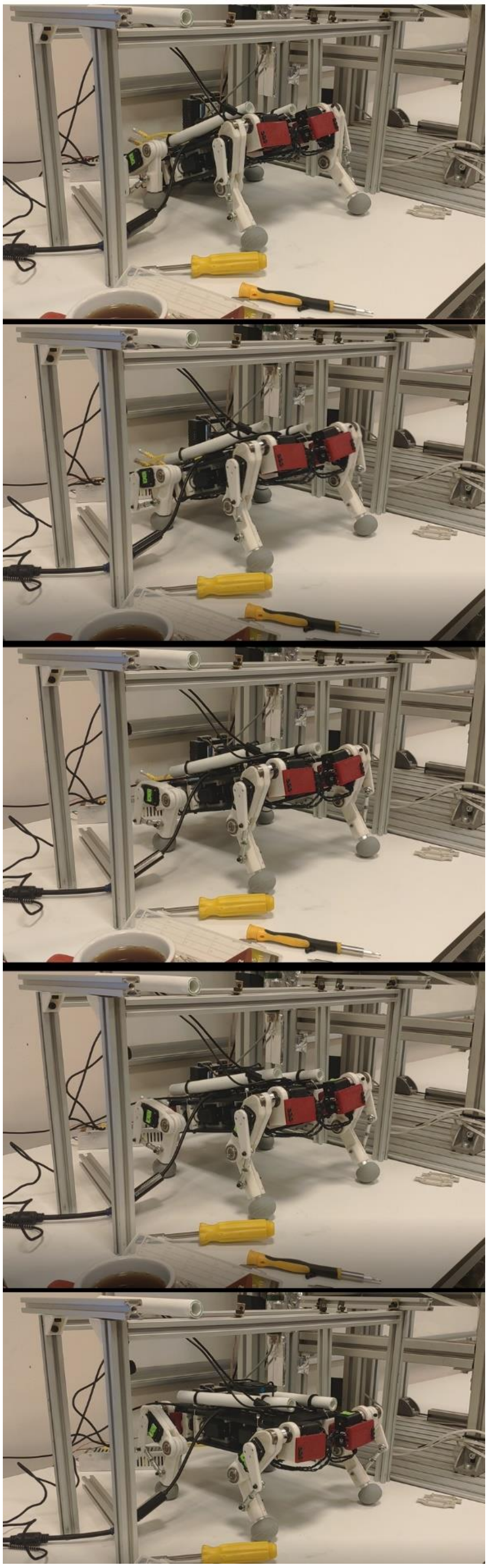

Figure 25 – Standing movements

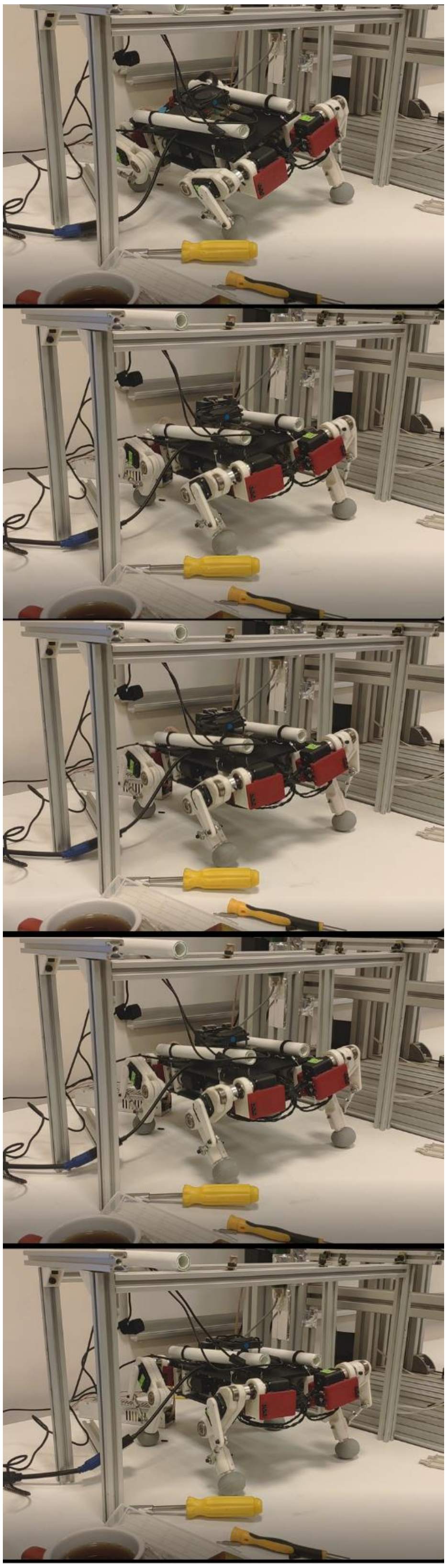

Figure 26 – Standing to default position from bended to right position

CONCLUSION

In this project the design of a quadruped robot, strength test of mechanical parts, manufacturing, kinematic analysis, sensor data filtering, body orienteation determination, quarter and full model simulations in Matlab, controller interface for monitoring sensor data and plan autonomous mission, gaiting and balancing studies had been carried out. An iterative design methodology convert design into low-cost and modular structure. Leg configuration is selected as forward-backwards since Zhang et al. found this configuration reduces slippage between feet and ground and improves motion performance in general. CAD model verification is done with strength tests and optimizing parts for 3D printing. Inverse and forward kinematic analysis studies was carried out using D-H method. Also, Robo-Analyser software was used, for performing the analysis in software. A Basic complementary filtering algorithm used to filter data. Sensory data translated into body orientations successfully for whole body control and balance. Robot obtained using theoretical translated into simulated analysis in Matlab to validate the studies and tune PID controller. Finally, demo studies were carried out on gaiting and movements. Proposed at the end position's results of the manipulator were almost same.

ACKNOWLEDGEMENTS

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