Engineering Quadruped Locomotion: Actuation Systems, Kinematics, and Efficiency

Chirag Nere[1], Dr. Vaijanti Despande[2], Prof. Jahida Subhedar[3]

[1]Department of Mechatronics, Symbiosis Skills and Professional University Pune, India
[2]Professor, Dept. of Mechatronics Engineering, Symbiosis Skills and professional University , Maharashtra, India
[3] Professor, Dept. of Mechatronics Engineering, Symbiosis Skills and professional University , Maharashtra, India

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Abstract - *The paper explores the intricate relationship between actuation systems, kinematics, and efficiency in quadrupedal locomotion. By analyzing the complex interplay of these factors, the research contributes to the advancement of quadruped robotics, enhancing their mobility and overall performance. The study delves into novel actuation approaches, considering both mechanical design and control strategies. Additionally, it investigates the impact of kinematic configurations on locomotion patterns, and terrain adaptation. The paper emphasizes the pivotal role of efficiency in ensuring sustainable and effective quadrupedal movement. Ultimately, this research serves as a comprehensive guide for designing, engineering, and optimizing quadrupedal actuation systems, paving the way for improved robotic mobility across various applications.*

The quadruped research consists of a motor drive used which is an Odrive setup connected with a 900KV BLDC motor in combination of AS5600 magnetic encoder and which is controlled by a microcontroller Arduino DUE. This testing rig is a more simplified version of quadruped and its actuation system, the sensor and BLDC motors are held by a 3D printed setup.

A precise control is possible for a quadruped robot on difficult terrains giving each leg of a quadruped robot property of shock absorber. The robot is more energy efficient as we are using harmonic gear boxes and there are less losses. Durability and reliability combination of harmonic and series elastic drive reduced the stress on the system. As the harmonic gearbox has zero backlash the durability of the robot increases. One of the main reasons for SED is Adaptability of a quadruped robot on various terrains and dynamic environment enhancing more stability in a quadruped robot.

Key Words: Quadruped robot, Actuation system, series elastic drive, Harmonic Gear box.

1.INTRODUCTION

Driven by nature's locomotion principles, legged robotics research is experiencing a transformative phase. Contrasting early rigid, kinematically-controlled walking machines, the field is embracing increasingly compliant systems, opening up novel avenues for exploration. Leveraging their mechanical softness, manifested through back-drivability and low system inertia, these platforms seamlessly engage with their surroundings. They adeptly handle collisions during ground contact, and their inherent safety facilitates harmonious human-robot cooperation. Drawing inspiration from nature's efficient muscle and tendon compliance, springs in robotics emulate non-linear oscillations, mirroring biological energy-efficient mechanisms.

1.1 Literature Review

StarlETH is based on four identical legs that are arranged in an X configuration. With linear dimensions of about 0.6 m and a total weight of 23 kg, it has the size of a medium-sized dog. Every leg has a total of 3 degrees of freedom, one each for hip abduction/adduction, hip flexion/extension, as well as knee flexion/extension. The robot's design is based on earlier studies that we conducted to optimize a planar running leg. We put emphasis on keeping the inertia of the moving segments minimal by concentrating all actuators at the main body through the use of chain and cable pulley systems. This is beneficial to ensure fast swing leg motion and to reduce impact losses at the intermittent ground contact.[3] The lightweight main body is fabricated as a carbon fiber sandwich monocoque with aluminum front and back connectors. It contains well protected all electronic parts that are cooled through active air circulation.

The key elements of StarlETH are the high compliant series elastic actuators that are implemented in all joints using linear compression springs in a pre-compressed setup (antagonistically at the hip joints). Springs decouple the motor (Maxon EC-4pole 200W) and gearbox (Harmonic Drive CSG-14, 1:100 reduction) from the joint. [3]This setup ensures robustness against impacts, allows for energy storage to improve the efficiency, and provides full torque controllability. All joint angles, motor angles, and spring deflections are precisely measured in every joint. The lightweight ball feet are based on air filled racquet balls that provide amble cushioning with minimal weight while having a high contact friction coefficient. To detect changes in the contact force, we tightly integrated force sensing resistors (FSR). The proprioceptive sensor equipment is completed with a X-sense MTi IMU that includes an accelerometer.

Fig.1[1]Spot robot Boston dynamics

Boston Dynamics developed the latest dog-like untethered quadruped robot named Spot, as shown in fig.1 [1]. It is a new approach to dynamic robot control compared to BigDog and LS3, previously released by the company. The robot is about 1.1 m x 0.5 m x 0.84 m(L x W x H) and can run 5.76 km/ h. The total weight of the robot is 30 kg, and is able to carry14 kg load. All the joints are electric actuation and powered by a battery. The robot has Omni-directional walking and trotting gaits. The Spot is built with a 3D vision system with simultaneous localization and mapping (SLAM), providing depth information, enabling the robot its surroundings, and avoiding obstacles. Spot's built-in computers are fully dedicated to robot locomotion and navigation. The robot is remotely controlled by human operators while also navigating and performing some tasks autonomously. The robot is dynamically controlled, which can easily climb, descend stairs, balance, and adjust to physical disturbance. The Spot becomes a light-footed robot that can work in the office, home, and outdoors using its 5 DOF sensor arm.

1.2 Methodology/Experimental

Actuation system:

Actuation system in a quadruped robot plays a crucial role for the movement of a quadruped. This system comprises mechanisms and components responsible for generating motion in a quadruped robot. The methodology mainly comprises analysis of types of actuators, gear box , and encoders of the actuation system. The research phase involves dealing with exact configuration of motor, gearbox, and encoder.

For motors, we classify the motors based on their KV which is Kilovolts or how much a motor is capable of handling load. Torque is also an distinguishing feature which differentiates the motor. Some of the major ratios to be considered are weight to power, RPM to torque, Torque to KV, and RPM to KV. While researching the actuators conclusion was obtained that ideal specifications for a quadruped robot are as follows:

Specification	Cubemars AK80-9	MJBOTS QDD100
Voltage	24V	44V
Current	12A	-
Torque	18Nm	16Nm
Weight	485g	485g
RPM	245rpm	416rpm
Type of Gearbox	Planetary	Planetary

Now, the major research are revolves around the type of gear box system use in the actual there are two types of gear boxes:

1. Planetary gearbox
2. Harmonic gearbox

Planetary Gearbox: Gearbox which is an epicyclic type of gearbox which has a sun gear and planet gear. The sun gear is stationary and planet gear surrounds it and rotates around it.

Harmonic Gearbox: Harmonic Gearbox also known as Strain wave gearbox consist of a Spline with external teeth which is deformed by an elliptical to engage contact of internal spline with the outer spline which is a solid ring. Thus, the harmonic gearbox has Zero backlash which makes it more precise and accurate.

Series elastic drive, one of the major aspects for a quadruped was to tackle the problem of stiffness of a quadruped. A quadruped robot has to replicate the acrobatics of a four-legged animal. Hence the quadruped robot needs to manage the stiffness and the

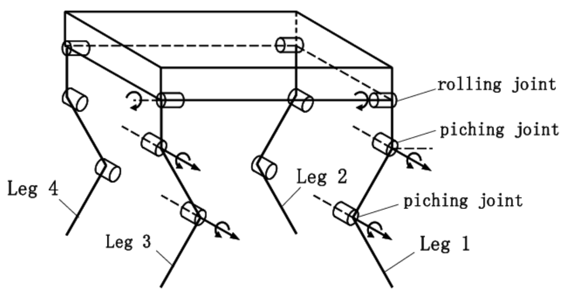

Fig 2. [2]Kinematics of a quadruped robot

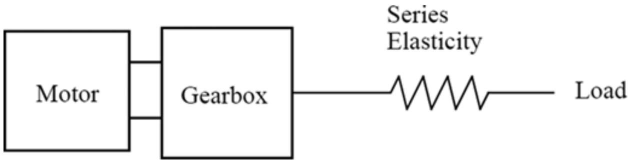

Fig. 3 Block diagram for series elasticity

The series of high standard elastic actuators are installed in Star1ETH, which have similar behavior as our ten-don and muscles to keep a large amount of energy temporarily. The robot is incorporated with IMU, which gives the kinematic information from the joint. Another versatile quadruped robot is designed for the robotic system at Star1ETH Zurich called ANYmal, as shown in Fig.4

Fig. 4 Anymal Robot

Experimental Setup for this research comprises a 3D printed rig for holding BLDC motor and a magnetic encoder AS5600 on the other end. Initially the testing rig of AS5600 magnetic encoder which is shown in figure fig. 5

Fig. 5 Encoder rig

The testing rig described below features a Brushless DC (BLDC) motor paired with an AS5600 Magnetic encoder, forming a crucial setup for evaluating series elastic drive systems. This innovative rig is supported by a custom-designed 3D printed structure, which provides stability and precision during testing procedures. The BLDC motor, known for its efficiency and controllability, serves as the powerhouse of the setup, driving the series elastic drive mechanism with precision and consistency. The AS5600 Magnetic encoder enhances the functionality of the rig by accurately measuring the motor's rotational position and velocity, enabling precise control and feedback mechanisms. Together, these components create a versatile testing platform that enables researchers and engineers to assess the performance and capabilities of series elastic drive systems, contributing to advancements in various fields such as robotics, automation, and motion control.

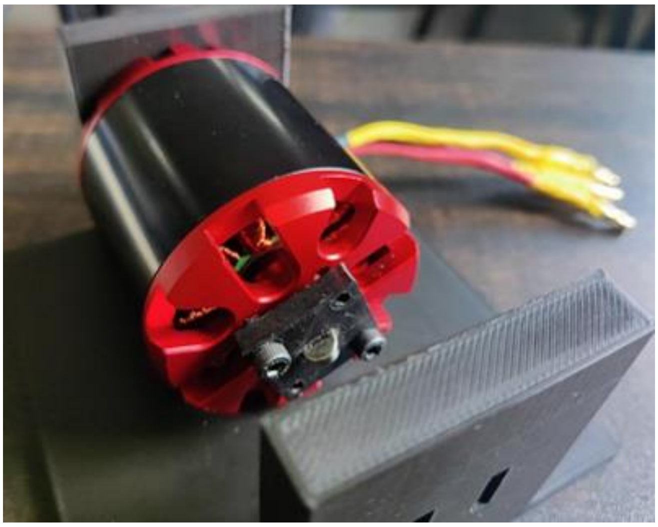

Fig. 6 Motor and Encoder testing rig

The 3D printing rig comprises two supporting walls, each serving a specific purpose within the setup. One wall is designed to securely hold the BLDC motor in place, providing a stable foundation for its operation. This wall is meticulously engineered to accommodate the motor's dimensions and mounting requirements, ensuring optimal alignment and minimal vibration during testing. The second supporting wall is dedicated to housing the magnetic encoder of the AS5600. Positioned adjacent to the BLDC motor, this wall is strategically placed to facilitate precise alignment between the motor's shaft and the encoder, enabling accurate measurement of rotational position and velocity. Together, these two walls form the backbone of the testing rig, providing essential support and stability for the BLDC motor and AS5600 encoder, respectively. Their robust construction and precise design ensure reliable performance and accurate data collection, making them indispensable components of the overall setup for testing series elastic drive systems.

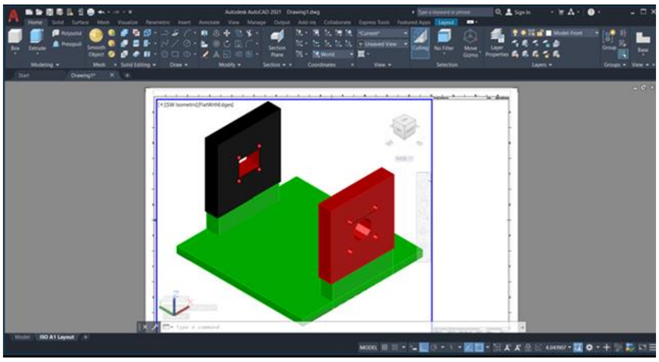

Fig. 7 3D CAD Modeling of testing Rig

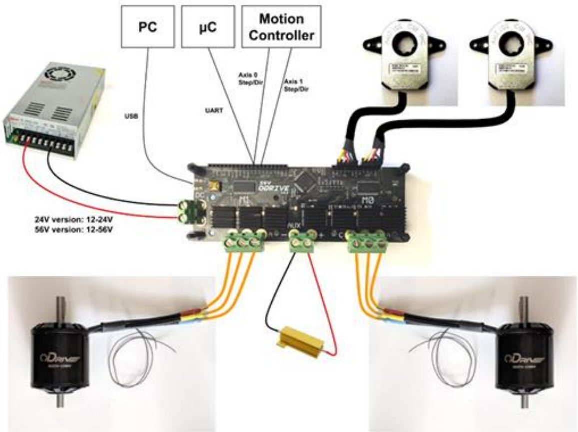

Fig. 8 Odrive, Encoder and BLDC motor setup

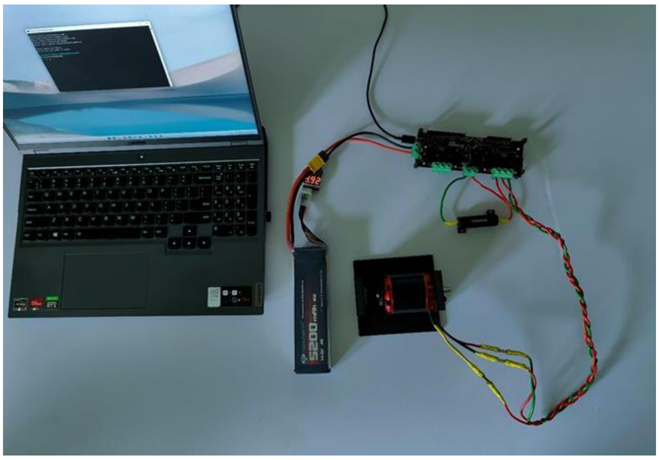

Fig 9. Physical setup for ODrive and Single Bldc Motor

2. Results and Discussion

In a wide array of actuators after selection of actuators with desired need and outcome here is a comparison table regarding actuators.

	Project	Commercial	Project	Project	Commercial	Project	Commercial	Commercial	Project
	Zurich, Switzerland	Zurich, Switzerland	USA	South Korea	USA	Suwon, South Korea	China	China	USA
Manufacturer	Swiss Federal Institute of Technology	ANYbiotics	MIT	Pusan Institute Of Technology	Boston dynamics	Sungkyunkwan University & AIDIN Robotics	Weilan	Unitree	MJBOTS
Product	StarlETH	ANYmal	MIT Cheetah	Padwq	Spot	AiDIN-VI	Alpadog	Go1	QUAD A0
Actuator	Springs decouple Maxon EC-4pole	Self developed (Rotational Series Elastic Actuator)	Mini cheetah	RMD X8 pro	Self Developed (Quasi-Direct Drive)	Self developed (Series Elastic Actuator)	-	Unitree Actuator	QDD100 beta2 Servo
Pay load	25 kg	10 kg	-	-	14 kg	25 kg	3 kg	3kg	
Gear housing	Harmonic Drive CSG-14	Harmonic	Planetory gear	Planetory gear		Harmonic	-	-	Planetary
Weight	23kg	30kg	9 kg	12.7kg	32.7kg	43 kg	24 kg	12kg	9.5 kg
Power	200W	280W	690W	188W		696 W			400W
Battery capacity	-	650Wh	120Wh	57.72+93.24	605Wh	13800 mAh	23 Ah	6000 mAh	-
Torque Control Bandwidth	-	70hz	-	-	-	-		-	-
Operating Duration		2 hrs		1 hrs	1.5 hrs	2 hrs	5.7 hrs	-	-
Maximum torque	-	-	-	-	-	350 Nm		-	-

The above comparison of quadruped is done on differentiating factors:

1. Actuators: An Actuator of a quadruped is a deciding factor for comparison because the factors such as speed, torque, power is based on an actuator. (refer fig.1) The actuators used here are from companies such as Cubemars(RMD X8 pro), Unitree actuator, Mjbots (QDD100 beta 2 servo)

2. Payload: Payload is a factor which tell us the amount of weight which can be carried by a robot excluding the weight of its own. This is an differentiating factor because it should be capable of carrying accessories such as Lidar sensor, Vision cameras, Robotic Arm.(refer fig. 4)

3. Gear housing: Mostly there are two types of gear box used: planetary gearbox and harmonic gearbox. Harmonic Gearboxes are used on high end robots because of their zero backlash feature and accurate movements in the robots kinematics.

4. Commercial or Research Robots: This is a differentiating factor because the commercial robots are used for on field use and others are used as a hobby project and for understanding the mechanics of quadruped.

2.1 Limitation

Some of the limitation of Quadruped robot are:

1. Vulnerability to slipping on slippery surfaces.
2. Inability to effectively traverse dense vegetation.
3. Challenging navigation on unstable or shifting ground.
4. Higher energy consumption compared to wheeled robots.

3. CONCLUSIONS

In this research we can conclude that combination of actuator with SED (Series Elastic drive) and Harmonic gearbox a quadruped can work with more efficiency.

Series elastic actuators play an important role for a quadruped robot to have natural and more precise movement like a 4 legged animal. Series elastic actuators provide a better movement of quadrupeds such as Crawl, Walk, Trot, Creep.

With help of this combination various improvements are achieved. A precise control is possible for a quadruped robot on difficult terrains giving each leg of a quadruped robot property of shock absorber. The robot is more energy efficient as we are using harmonic gear boxes and there are less losses. Durability and reliability combination of harmonic and series elastic drive reduced the stress on the system. As the harmonic gearbox has zero backlash the durability of the robot increases. One of the main reasons for SED is Adaptability of a quadruped robot on various terrains and dynamic environment enhancing more stability in a quadruped robot.

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