Analysis and Research of Quadruped Robot's Actuators: A Review

Khalid Hussain, Zakarya Omar, Xingsong Wang*, and Orelaja Oluseyi Adewale
School of Mechanical Engineering, Southeast University, Nanjing, PR China
Department of Mechanical Engineering, University of Khartoum, Khartoum, Sudan
Email: khalid@seu.edu.cn, za20119@yahoo.com, * xswang@seu.edu.cn,orhesheywal@yahoo.com

Muhanad Elnour
School of Automation, Southeast University, Nanjing, PR China
Email:engmohannad5@yahoo.com

***Abstract*—As a vital component of quadruped robots, the actuator provides the robot with the primary source of power and torque needed to locomote and determine the application performance, such as load capacity, high-speed locomotion, and jumping agility. Over a recent couple of decades, outstanding work has been done to investigate the actuators adopted by quadruped robots, and numerous inquiries about it have been issued. These examination results are grouped into four classes (electrical actuators, hydraulic actuators, pneumatic actuators, and internal combustion engine actuators) according to actuation and then classified and analyzed. According to this basis, we study and sum up the actuators and their performance and efficiency to the robot locomotion and their design techniques. Finally, we give some recommendations for the development of the actuators used in quadruped robots. This analysis aims to summarize various studies and provide enlightenment for robotic designers to develop efficient actuators for quadruped robots in the future.**

***Index Terms*—quadruped robots, actuators, hydraulic actuators, pneumatic actuators, electrical actuators**

I. Introduction

Nowadays, mobile robots are one of the fastest expanding fields of scientific research. Due to their characteristics, mobile robots can replace humans in many fields. Applications include industrial automation, construction, transportation, medical care, planetary exploration, patrolling, surveillance, emergency rescue operations, reconnaissance, petrochemical applications, entertainment, personal services, and many other industrial and nonindustrial applications. Most of these are already available now.

Legged robots [1] present significant advantages over wheeled robots [2] and tracked robots [3] because they can work in unstructured, dangerous, and perilous conditions[4]. Quadruped robot [5]has surpassed other multi-legged robots in terms of stability [6][7], control difficulty [8], and payload capacity [9]. Therefore, in recent years quadruped robot has progressively become a hot research spot in robotics.

Similar to animals, where muscles and tendons primarily contribute to the energetic efficiency [10][11], actuators determine the basic application performance of the robot, such as walking speed, operational adaptability, and payload capacity [12]. Developing high-performance actuators for legged robots has always been a significant challenge in robotics [13]. The perfect actuator is to minimize friction, inertia, and mass loss while maximizing torque, bandwidth, and power [14]. Therefore, Quadruped robot efficiency is mainly dependent on the performance of the actuator used. However, there is still an important gap between the actuators' performance in the Quad Robots and the current expectations. Especially performance aspects such as energy efficiency, mechanical strength, total energy density, or load-to-weight ratio of the robotic leg in case of shock and impulse are still not satisfactory [15]. Therefore, it is a priority and necessary to carry out mechanical leg analysis and research work. Fig. 1 shows the development of actuation systems in quadruped robots from the past to the future.

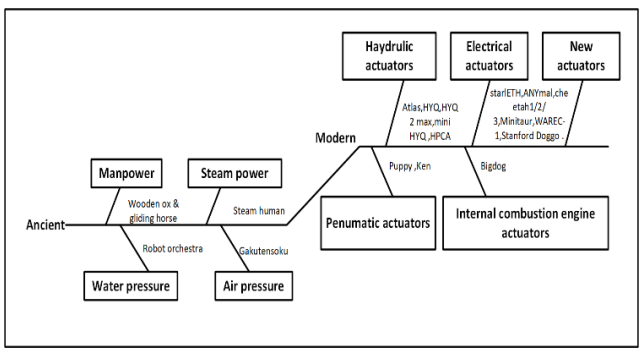

Figure 1. Development of actuators in quadruped robots

In the second section, actuators commonly used by quadruped robots were divided into four types according to the actuation system, and they have been compared and analyzed. Table I shows the characteristics of the actuation methods used by quadruped robots.

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In the third section, the adopted method for optimizing actuators used by quadruped robots in recent years is presented. In the last section, numerous proposals are made to develop the actuators used in quadruped robots in the future, followed by a conclusion.

TABLE I. TYPICAL ACTUATORS, AS WELL AS THEIR CHARACTERISTICS IN THE ROBOT'S LOCOMOTION

Actuation Method	Types	Characteristics
Electrical actuation	Electronic motor	High actuation bandwidth, high mechanical efficiency, high mechanical stiffness, hard to coordinate motor torque and speed.
Hydraulic actuation	Hydraulic cylinders	High impedance, low energy utilization efficiency, high precision energy control.
Pneumatic actuation	Artificial muscles	High elasticity, excellent flexibility, high nonlinearity.
Chemical fuel	Combustion	High energy density, complex structure, difficult to design and control, energy saving on board.

II. ANALYSIS OF FOUR TYPICAL ACTUATORS USED BY QUADRUPED ROBOTS

This section presents a selection of the most significant robots, classified by type of actuation. Special focus lies on quadruped (four-legged) robots.

A. Electrical Actuators

Electrical actuators are used widely in robotic systems [16]. They are clean (no leaking pressurized fluids), require no extra equipment(no need for fuel tanks, air storage tanks or air filters), No need for exhaust systems so it can operate indoors and can be easily controlled [17].

Boston Dynamics has developed many electrically powered quadruped robots in the last two decades, like Spot and mini spot robot[18]. Hutter et al,2012 proposed StarlETH quadruped robot[19], which employed a series elastic actuator that makes the system well suited for inordinately dynamic movement and torque controllable. Electrical actuators at the main body are linked using a chain and pulley system. This robot's crucial component is its actuator that is implemented in all joints using linear compression springs that decouple the joint from the motor and gear train. This arrangement improves efficiency by using energy storage and ensures validity against impacts. Hutter et al.,2016 also designed another electrically actuated quadrupedal robot called ANYmal[20] that highlights unique versatility and locomotion capacity. As shown in Fig. 2, it's actuators Performance recorded a controlled bandwidth of more than 70 Hz, high capability of disturbance rejection, and impact robustness when be operate using the maximum velocity. ANYmal can perform walking, dynamically trot at moderate speed, and perform remarkable maneuvers to run or crawl very steep stairs.

Figure 2. Anymal robot

MIT Cheetah 2 adopted a traditional proprioceptive actuator design that owns force control, position control, and high impact mitigation capabilities. This layout enabled it to autonomously bound over obstacles [21]and jump at a high speed of 6m/s[22], but it is a range of motion restricted to sagittal plane locomotion. The Minitaur robot designed by Kenneally et al,2016 [23] applies a Direct Driven actuation design. This robot represents a novel class of direct drive (D.D.) legged robots and has mechanical robustness, transparency, high efficiency, increased specific power, and high actuation bandwidth. TITAN-XIII sprawl-type quadrupedal robot implemented in 2016 by S. Kitano et al. [23] capable of energy-efficient and high-speed locomotion. It uses a brushless D.C. motor as a source of actuation for all joints. It has a very high power-weight ratio, almost four times higher than the previously developed sprawl-type quadrupedal robot TITAN-VIII[24]. Dharmawan et al.,2017[25] designed a novel type of piezoelectric actuated robot that applies a piezoelectric actuator as part of a four-bar linkage structure locomotion. The unimorph actuator substitutes the four-bar linkage input link, and motion is produced at the coupler link referable to the actuator deflection. Bled et al.,2018 [26] applies proprioceptive actuation into MIT Cheetah3 to extend the scope of movement on the hips and knees and kidnapping/adduction degrees of freedom. The mechanical structure is designed to empower basic control systems for dynamic motion. It highlights the high-data transfer capability of proprioceptive actuators to oversee physical communication with the ground in addition to the extended range of motion on the hips and knees. The Stanford Doggo[27] robot developed by N. Kau and his group at Stanford University, which applies quasi direct drive brushless D.C. motor as an actuator as shown in Fig. 3. As a result of, it merges the advantages of direct-drive and geared drive actuators.

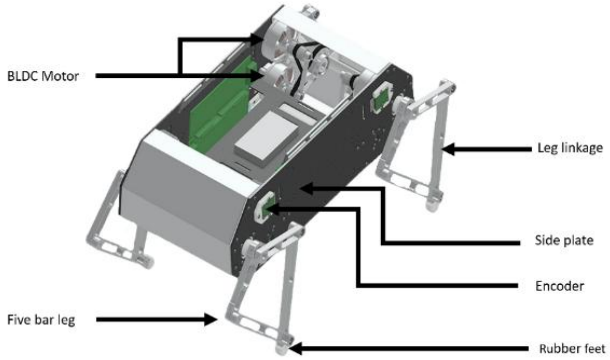

Figure 3. Stanford doggo robot

This robot's leg is a five-bar leg that adds more degrees of freedom to the robot than the robots using the conventional two-bar leg. Fig. 4 shows Stanford's leg design for doggo robot.

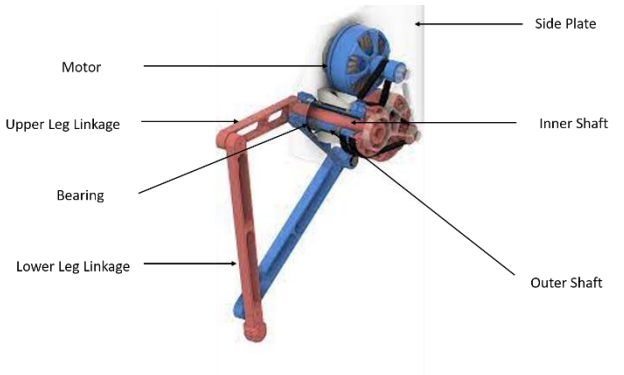

Figure 4. Leg design of Stanford doggo robot

The quadruped robot SpotMini[18]was developed by Boston Dynamics in 2019; it employs an electric motor actuator. SpotMini is the calmest robot that Boston dynamics have built recently and can go for about 90 minutes using a battery, depending on the application. SpotMini inherits all the flexibility of its elder comrade, Spot, by adding the capability to handle and pick up objects using its five degrees of freedom arm and beefed up perception sensors. The common feature of the actuators mentioned above robots is that it is clean, easy to control and quiet that why it is a perfect choice in the small robots.

B. Hydraulic Actuators

The classical methodology of electric motors with high reduction ratios gearbox as utilized in most robot legs does not satisfy the Low impedance force controllability and High impact robustness. Robots using such actuators are restricted to slow and steady mobility to prevent impulsive forces[28]. The hydraulic actuation has a quicker response, greater output power, higher power density and greater bandwidth than electrical actuation[29]. Hydraulic actuators are commonly used for robots with high payload requirements [30].

Marc Raibert and his colleagues developed many robots at CMU Leg lab. MIT Leg lab (Raibert's Quadruped[31]) and later at Boston Dynamics (WildCat, Spot, LS3)[32].on other side, Great effort and funds were allocated to design some hydraulic quadrupeds and to create a Chinese version of BigDog. Some Chinese research centers and universities developed their robot (e.g., Baby Elephant[33], Scalf [34], Beijing Institute of Technology (BIT) quadruped[35], National University of Defense Technology (NUDT) quadruped[36]). Korean have developed a few hydraulic quadruped robot designs within the Jinpoong project. Military grants fund the majority of this research, and thus, there are no available publications about those robot's designs.

The Legged System lab of the Istituto Italiano di Tecnologia (IIT) has developed three hydraulic quadruped robots (HyQ[37], MiniHyQ[38], HyQ2Max[39]) and Efforts are still underway to develop graceful rugged robots for outdoor applications. Semini et al.,2011 introduced (HyQ)[37] a hydraulically powered quadruped robot. The hydraulic actuator allows the robot to achieve powerful and dynamic motions that are hard to perform with the custom electrically operated robots. C. Semini continued using a similar actuation method for his next robot HyQ2Max[40].this robot can perform jogging, crawling over uneven/flat landscape, self-righting, and balancing.

HyQ2Max[40]Compared to HyQ[37]is more powerful, more rugged and have new locomotion skills with self-righting capability. This robot employed a hydraulic actuator to obtain significant joint requirements for the new machine. MiniHyQ quadruped robot designed by Khan et al., 2015 [38] considered the smallest and lightest hydraulically actuated quadruped built so far. An entirely torque-controlled robot has reconfigurable leg designs, wide-ranging joint scope of movement, and a locally available reduced force pack. It's portable by one person because it is weight is only 35kg (24kg plus pump unit). Barasuol et al.,2018,[41]presented (ISA) a hydraulic Integrated Smart Actuator established by IIT in cooperation with Moog. The ISA consist of a 3D printed body containing a hydraulic cylinder, servo valve, sensors for position/pressure/temperature/load, overload protection, and communication and control devices. The key advantage of this actuator is handling some major problems of hydraulic actuation of legged robots by (1) high-performance control as a result of building in controllers running inside integrated electronics (2) using low-leakage servo valve reduced the energy losses (3) compactness thanks to 3D printing of metal. Z.Hua et al.[42] designed the hydraulic passive compliance operator (HPCA) for four-wheel hydraulic robots. It consists of an accumulator and a piston chamber connected to the hydraulic cylinder to store shock forces between the robot's legs and the ground. HPCA showed it has higher energy efficiency and independence of accumulator physical parameters.

All these robots' common feature is high power density, high payload, and quick response compared with the electrical actuators. However, on the other hand, it has problems of control difficulty, oil leakage and cleaning difficulties.

C. Pneumatic Actuators

Several pneumatic robots can perform extremely dynamic tasks. Some of them are built with McKibben muscles, and others with pneumatic cylinders. In this section, we presented the most relevant of these robots and their characteristics.

Aschenbeck et al.,2006 have developed Puppy[43], a canine-motivated quadrupedal robot actuated by Festo air muscles. The little dog is providing a ground for the application and control of pneumatic muscles in quadruped robots. The Festo air muscles were mounted in antagonistic pairs, and they have been controlled with closed-loop position feedback using pulse width modulation. The legs and spine have been assembled and successfully tracked trajectory angles during walking. The two legs can raise a payload of 13.5 kilograms, almost twice the whole robot weight.

The Hirose laboratory in Tokyo Institute of Technology established Airhopper, a quadrupedal robot that is mainly created to carry supplies over hazardous environments, disaster areas, uneven terrain or isolated areas[44]. It is a hybrid leg-wheel robot with a dimension of 1.29m x 1.2m x 0.6m (LxWxH) and a mass of 34.6kg. Legs are built with a four-bar linkage that is actuated by pneumatic cylinders and connected to an electrically driven wheel. The robot can perform a high vertical jump that lifts its feet 0.85m above the ground thanks to it is lightweight. [45]. Narioka et al.,2012 have presented the quadruped robot 'Ken'[46], which has a lightweight and moderate body shape for achieving quick movement. pneumatic artificial McKibben muscles were used as actuators, providing a high frequency and wide motion of limbs, also solved the problems of overheating. Heim et al. [47] designed a quadrupedal robot that uses pneumatic actuators to power the robot's joints. The pneumatic actuator depends on its high performance; it can provide the desired power and torque while keeping the robot lightweight and compact.

The common features of abovesaid actuators are that it is quiet, clean, and compact design, so it is mainly used for quick and accurate systems.

D. Combustion Engine Actuators

For large robots, the combustion engine is commonly preferred referable to their massive output power. A combustion engine is typically driven by fossil fuels like a gasoline engine, where gasoline and air (as an oxidizer) are compressed into cylinders. At an ideal point, a spark is created by a spark plug, which combusts the mixture generating heat energy and pressurized gases. The reaction pushes the piston back, creating linear or rotational movement. The combustion engine can combust fuel externally or internally, known as external combustion engines and internal combustion engines. This section shows the most relevant of these robots.BigDog [48] is a quadruped robot developed at Boston Dynamics in 2008; this robot can go in an outdoor landscape that is extremely steep, rough, uneven, sloppy, snowy, and wet for traditional vehicles. As shown in Fig. 4 Its actuator is a two-stroke water-cooled internal combustion engine that produces about 15 hp. The engine actuates a pump to circulate hydraulic oil through a system of manifolds, accumulators, filters, and other plumbing to the robot's leg actuators. Low friction hydraulic cylinders are used, and two-stage servo valves are used to regulate it. Big dog highlights high energy density, long working time, low weight and small size. The hydraulic system actuated by a combustion engine is a perfect solution for the actuation system of large quadruped robots.

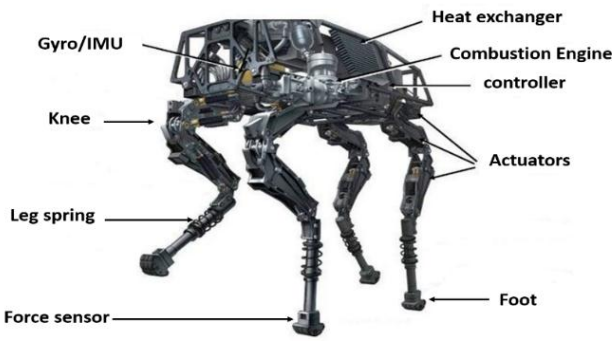

Figure 5. Bigdog robot

III. Recently Used Approaches to the Optimization of Legged Robot's Actuation Systems

A wide variety of robots have been developed in recent years. All types of actuators have been employed to Quadruped robots, and Table II listed the important robots in the last decades and their highlights and drawbacks.

As presented in Table II every robot has it is characteristics according to the type of actuation and the robots that use electrical actuation is shown to be the best from the aspect of quiet and ease of control. Robots use combustion engine actuators shows that it is the best in the aspect of the payload. However, is not friendly with the environment. Hydraulically and pneumatically driven robot also shows some advantages as high speed and long working period.

TABLE II. ACTUATORS OF THE MOST SIGNIFICANT ROBOTS IN THE RECENT YEARS AND THEIR HIGHLIGHTS AND DEFICIENCIES

Name	Year	Actuation method	Mass (Kg)	Highlights	Deficiencies
Stanford Doggo	2019	Brushless DC motor	0.27	high vertical jumping, high jumping agility,	limitations in specific force
SpotMini	2019	Brushless DC motor	25	very calmest, very agile	Light payload, short working period
MIT Cheetah 3	2018	proprioceptive actuation	45	Simple control strategies, high bandwidth,	Short working period, light payload. not suited for all environments
HyQ2Max	2017	hydraulic actuation	80	Robust against impulsive loads, provide high power	Noisy, heavy
Minitaur	2016	D.D Motor	0.25	Transparency, High specific power, high-actuation bandwidth, and mechanical robustness/efficiency	limitations in specific force
Ken	2012	pneumatic artificial muscles		high frequency, wide stride motion of limbs, no overheating, lightweight	Light payload, slow locomotion
HyQ	2011	Hydraulic actuation	80	provide high power, robust against impulsive loads	Noisy, need a lot of maintenance
BigDog	2008	internal combustion engine, hydraulic cylinders		High payload, high power output, long working period	Difficult to control, very noisy, exhaust emissions

Hybrid actuation systems were used and developed to get more advantages in one system and to avoid drawbacks. J. Cho et al.,2017 proposed a Pneumatic-Electric Hybrid Actuation System for Cheetaroid quadrupedal robot[61]. This actuator provides a switchable stiffness. The simulation shows that using this semi-active pneumatic actuator will reduce the robot's CoT by more than 50% compared to that without this actuator.

The research for optimizing and developing the actuators used by quadruped robots continued and increased during the last years, and Fig. 6 shows the percentage of research during the last six years.

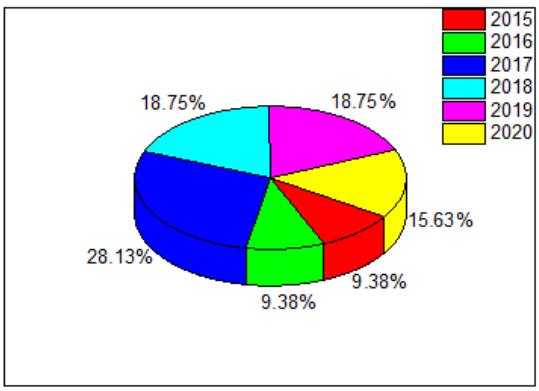

Figure 6. Studies of Quadruped robot's actuators during the last 6years

IV. DISCUSSION AND CONCLUSIONS

This study aims to provide a compact manuscript that facilitates the comparison between the several types of actuation systems used in legged robots and their highlights and limitation. The main areas involved in this field are electrical actuators, hydraulic actuators, pneumatic actuators, and chemical fuel actuation, as listed in Table1. Combining with the recent technological development, the most important research can be summarized as five aspects, which are agile, Strong, efficient, eco-friendly, and Quiet. Although these aspects indicate that every actuator has it is advantages and disadvantages when compared with each other. According to the robot's application, the legged robots' designers should trade-off between the highlights and deficiencies of all actuation systems and select the suitable actuator.

Actuators used by quadruped robots still suffer from huge limitations since some of them are noisy, low speeds, and complicated to control. Moreover, today's structures are heavy, and they need many actuators to move multiple DOF legs, to which one should add large energy consumption. It is expected that in the future, actuators used for quadruped robots may become more efficient and optimized, which can compete with other classical transportation means. However, several aspects

must be improved and optimized in their present state of development, as stated previously.

CONFLICT OF INTEREST

The authors declare that no conflict of interest.

AUTHORS CONTRIBUTIONS

KH and XW conceived the study design. ZO developed the research strategy and wrote the first draft. ME and OOA revised the second drafted manuscript. KH, XW, ZO, and ME contributed to the development of the selection criteria and data extraction criteria. All Authors read, provided feedback, and approved the final manuscript.

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Xingsong Wang (corresponding author) received his B.S. and M.S. degrees from Zhejiang University, Hangzhou, China, in 1988 and 1991, respectively, and the Ph.D. degree from Southeast University, Nanjing, China, in 2000, all in mechanical engineering. From June 2000 to December 2000 and from September 2001 to March 2002, he was a Visiting Scientist with Concordia University, Montreal, QC, Canada. From 2007 to 2008, with Purdue University, West Lafayette, IN, USA, in the School of Mechanical Engineering. He is currently a Full Professor with the School of Mechanical Engineering and the Department Head of the Department of Mechatronics, Southeast University. He is the author of over 140 technical papers and 30 Chinese patents. His current research interests include control theory with applications in precision computer numerical control machine tools, advanced mechatronics with biomedical engineering applications, tendon-sheath transmission theory with applications in rescue robots, and Mecanum-wheel-based automatic guided vehicle system design.(email: xswang@seu.edu.cn)

Khalid Hussain obtained his B.S. degree from the department of mechanical engineering, University of Khartoum in 2014.he is currently pursuing master's degree with the school of Mechanical Engineering, Southeast University, Nanjing, China. His research interests include mechatronics systems, Robotics, Autonomous Vehicles, and Intelligent control systems.

Zakarya Omar received the B.S. degree in Mechatronics Engineering from UTeM, Melaka, Malaysia, in 2014.He is currently pursuing the M.S degree at the School of Mechanical Engineering, Southeast University, Nanjing, China. His major research interests include design and control of mechatronic systems, servo systems, robust control, and robots. (email: za20119@yahoo.com)

Orelaja OluseyiAdewale was born in Oyo state, Nigeria in 1976; He receives Higher National Diploma (HND) in Mechanical engineering from The Polytechnic Ibadan in Oyo state Nigeria in the year 2000, He then proceeded for his Post Graduate Diploma (PGD) from Federal University of Technology Akure, Ondo State Nigeria and graduated in the Year (2004), He obtained his Masters Degree (M.sc) in Mechanical engineering from the Federal University of Agriculture Abeokuta in the year (2013). He is currently pursuing the Ph.D. degree with the School of Mechanical engineering, Southeast University, Nanjing, People Republic of China. His research interests are: Vibration, Control, Robotic, Industrial Production and Mechatronics. He is also a member of professional bodies such as COREN, PDNIM, MnimeChe, MNSE.(email:orhesheywal@yahoo.com).

Muhanad Elnour obtained his B.Sc. From Omdurman Islamic University, Sudan in field of electric and electronic engineering, and the M.Sc. In Mechatronics Engineering from school of mechanical engineering at Sudan University of Science and Technology, Sudan, and currently is Ph.D. Candidate at South East University, China, research interests include Artificial intelligence and Image Processing. (email: engmohannad5@yahoo.com)