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Quadruped Robots Mechanism, Structural Design, Energy, Gait, Stability, and Actuators: A Review Study

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***Abstract*—Recently developed quadruped robots have more efficient dynamic performance and adaptation to environments than before. They have already been used in the building of infrastructure, Military tracking, and emergency disposal. To predict future work on quadruped robots, it is first necessary to examine the frequently used mechanism and structure of the quadruped robot. The optimization of energy usage is then covered as well. The stability and gait techniques of the quadruped robot are then reviewed, and the benefits and drawbacks in terms of gait movement, environment adaptation, and energy consumption are examined. This paper surveys the quadruped robots' development path, mechanisms, structural design, energy, gait, stability, actuators. Eventually, a summary of the quadruped robots' current and future work is presented.**

***Keywords*—legged robot, mechanism, structural design, gaits, stability, actuator**

I. INTRODUCTION

Currently, mobile robots are gaining a lot of attention from researchers. They are grouped into three types according to the mechanisms they employ to move. Robots with legs have substantial benefits over conventional wheels and tracks vehicles, it can also work in unstructured, difficult, and dangerous conditions [1]. Paved surfaces or something equivalent are required for wheeled vehicles to travel because they are most efficient and quick on them. This mechanism may also be simple as well as lightweight. Although tracked vehicles have greater accessibility in challenging terrains, they are still not always capable of overcoming obstacles and have comparatively high energy consumption. Traditional vehicles continuously leave ruts on the ground, which can be unfavorable in certain situations such as, for example, from the environmental side. It has been noticed that it is possible to conclude that legged locomotion systems give effective mobility in natural terrains, since these vehicles may use independent footholds for each foot, unlike to wheeled vehicles which need to continuous support surface [2]. Thus, these vehicles can move in irregular terrains by changing their legs configuration to adapt to surface irregularities. Furthermore, the feet may create contact with the ground in selected points according to the terrain conditions. Due to these reasons, legs are simply adequate systems for locomotion in irregular terrains. When vehicles move on soft surfaces, such as sandy soil, the capability to use discrete footholds in the ground may also enhance the energy usage, since they deform the terrain less than tracked or wheeled vehicles. As a result, less energy is required and the area of contact between the foot and the ground might be arranged so that there is little ground support pressure. Furthermore, legged vehicles with multiple Degrees of Freedom (DOF) in the leg joints can shift direction without slipping [3]. To introduce a decoupling and dampening impact between the body of the robot and the terrain irregularities, the body height can also be changed because of its payload. Mobile robots can move independently without the aid of outside human operators. A robot is autonomous when the robot itself can specify actions to be taken to perform a task via a perception system. To coordinate all the robot's subsystems, it also requires a cognition unit or control system which comprise the robot. The fundamentals of mobile robotics consist of the fields of locomotion, cognition, navigation, and perception. Understanding the mechanism and applying kinematics, dynamics, and control theory are needed to solve locomotion problems. Perception involves specialized fields such as computer vision and areas of signal analysis and sensor technologies. For achieving the objectives of the mobile robot, cognition

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is responsible for analyzing the incoming data from sensors and taking the appropriate actions. Information theory, artificial intelligence, and planning algorithms are all necessary for navigation. Also, the ability to control walking robots is primarily based on advances in mechatronics and computer technology. The fundamental advances of sensing and vision systems enabled steady control of walking robots [4]. Table I highlights the comparison between wheeled and legged robotic vehicles. From the table, it can be observed that legged vehicles have more advantages compared to wheeled vehicles in terms of capability to cross boundaries, accessibility of terrain, obstacles navigation, performance, and maneuvering [5, 6].

TABLE I. ROBOT COMPARISON: WHEELED AND LEGGED VEHICLE [7]

Technical standards	Wheeled Vehicle	Legged Vehicle
Capability to cross boundaries	X	✓
Accessibility of Terrain	X	✓
Cost Effectiveness	✓	X
Obstacles Navigation	X	✓
Performance	X	✓
Balancing	✓	X
Maneuvering	X	✓
Controlling	✓	X

This paper is organized as follows: Section I is a general review of quadruped robots in terms of their development which allows them to travel through challenging terrain. Section II introduces the most common types of gait mechanism and its difficulties. Section III provides the structural design concepts and optimizing parameters. Section IV shows the present study of optimizing the energy consumption of quadruped robots. In Section V, the study and detail types of gaits of quadruped robot are presented. Section VI introduces the methods of stability utilized by most quadruped robots. Section VII describes the types and features of actuation systems. Finally, Section VIII and IX summarize the review and provide an idea on conclusion and future work of quadruped robots.

II. GAIT MECHANISMS

The mechanisms of legged robot locomotion are usually inspired by biological systems and their environments. Humans, animals, insects, and other four-legged creatures provide fundamental understanding of how legged vehicles must be designed and built. Such designs must consider variables such as energy usage and stability, and the difficulties of controlling every additional leg because the stability of the robot improves as the number of legs increases. Each leg requires at least two degrees of freedom, one for moving forward and another for lifting, so its power usage rises. Gait mechanisms, robot control systems, structure, size, sources of power, actuators, and sensors are all elements to consider when building robotic systems. A different of approaches can be used to improve a robot's stability. The mechanisms include Jansen linkage, parallel leg, Klann linkage, pantograph, strider linkage, and others. Mechanisms that are identical replicas of biological animals' joints and links have a high number of DOF, which causes challenges in control algorithms. Furthermore, mechanical complexity is one of the most common causes of malfunctions and significantly raises weight and cost. To solve those challenges, authors suggested the use of legged robots with fewer degrees of freedom and system actuation. The concept depends on the development of robots while maintaining the concept of legs for locomotion. This line supports mechanical simplicity, which raises robustness. It is essential to remember that legged robots are still machines. As a result, the first consideration in their design process should be appropriate physical and mechanical implementation. Habumremyi *et al.* [8] collected the properties of multiple designs that are used for artificial locomotion legs platforms. S. Hirose *et al.* in [9] investigated multiple ideas for use in legged vehicles designs. The concept is to maximize the system's power using "coupled actuation and energy efficiency". The method of "actuator gravitational decoupling" has been used in many robots and could be used not just in system design, but in locomotion posture as well. In some instances, when designing a robot, empirical knowledge of mechanics and physics is used. The equipment was designed with the goal of minimizing a situation that would penalize the efficiency of the robot under consideration.

III. STRUCTURAL DESIGN

To assess the development of a previously designed legged robot, it is observed that electrical and hydraulic actuators are frequently used. The hydraulic actuating has a higher power-to-weight ratio than the electrical actuating type, but the weight of the robot is comparatively increased [10]. Physical specifications and dimensions played a significant role in the building of the mechanical structure. It is difficult to state the precise weight and size of the robot at first. The supply of components in the markets influences the size of the robot. The robot's weight is determined by the actuator mechanism whether it is electrical or hydraulic as well as all electronics onboarded. Choosing the appropriate leg length is an important factor in robot. A large part of the length of the robot's legs is smaller than the size of the robot. Long legs and high proportionally body structure demand more balance and less agility. The number of working joints in each of the robot's legs determines its complexity. Except for Hirose' pantograph leg robot, each actuator adds weight to the robot. The leg of the two-joint mechanism is simple to design and control, and it is frequently used in quadruped robots such as LittleDog, ANYmal, Spot Mini, and others. Toed animals have a three-joint structure in their legs, which provides significant benefits in running speed and energy efficiency. At low speeds, terrestrial animals have symmetric gaits usually walk and trot, whereas fast animals have asymmetric gaits. The feet have an identical phase difference in symmetric gait, so the left and right feet land at the same time. In asymmetric gaits, the trailing foot is set down instantly before a short period of time, and the leading foot is set down soon after the interval. The trailing foot should make a small decelerating motion, then an increased accelerating motion [11]. Each leg's positive and negative work could be balanced. Each leg, in principle, functions like a passive spring, storing strain energy in its muscles and releasing it in an elastic coil. The three-part structure of the MIT Cheetah robot allowed it to achieve a running speed of 6 m/s and cross obstacles with high energy efficiency. Zeng *et al.* [12] presents an overview of how a single leg for quadruped robots is built with high-speed locomotion. The leg has been designed to be lightweight and low inertia, with three joints to mimic quadruped animals. Later, in 2018, the MIT Cheetah mini succeeds to do the first quadruped robot back flipping, indicating a major achievement in the evolution of small electric quadruped robots. The Italian Institute of Technology's developed HyQ robot employs a virtual leg model [13, 14] to improve interaction with the ground, Boston Dynamics presented a LittleDog robot, each of its leg has three Degrees of Freedom (DOF) plus the body's X, Y, Z A high gain servo motor powers each joint [15]. To determine position and joint angles, twenty-two reflection balls are mounted to the torso and legs.

IV. ENERGY

One of the most difficult challenges for legged robot designers is optimizing the consumption of energy. It has been demonstrated that the locomotion efficiency of current robots is very low when compared to either animals in motion or wheel locomotion. As an example, Nagasaki *et al.* [16] performs a simulation of the HRP1 humanoid robot's running gait and concludes that the robot would require actuators that are 28 to 56 times more efficient than those found in the actual humanoid. Aside from this conclusion, they estimated that the energy consumption would be about ten times that of a human in the same gait. It is predicted that in the future, locomotion via artificial legs will be one of the most efficient modes of transportation. As a result, more attention should be placed on this aspect in the development of such systems, specifically using power or energy-based optimization criteria during the design, construction, and exploration stages, as this influences the mechanical structure, type of propulsion, and power supply system. Based on these concepts, several writers investigated the optimization of locomotion structures and gaits using energy criteria. The specific resistance (ρ) is an index that is commonly used to analyze and compare the performance of legged robots. It is defined as to compare the locomotion efficiency of various types of vehicles [17]:

$$\rho = \frac{P}{MgV_{max}} \tag{1}$$

where P is the maximum power of the vehicle, M is its mass, g is its gravitational acceleration, and V_{max} is its maximum velocity. While the specific resistance can also be described as [18]:

$$\rho\ (V_F) = \frac{P(V_F)}{(M_g)(V_F)} \tag{2}$$

A number of authors argued that, in contrast to the utilization of mechanical power to the calculation of "specific resistance", this index might be estimated via electrical power so as to take into consideration Several serious energy losses occur, allowing for a different definition of the specific resistance [18–20].

$$\rho = \frac{E}{Mgd} \tag{3}$$

where E represents the entire electrical energy consumed by the linear displacement d. The authors in [21] proceed to demonstrate a comprehensive model of legged robot energy consumption according to the robot as well as actuator Including mechanical and electrical components, then used to investigate the effect of leg configuration, body weight, speed profile on energy usage, and trajectory of the foot of "SILO4 quadruped robot". A hexapod robot's locomotion characteristics were investigated by Silva and Machado using four calculated measurements of performance using dynamic modelling of the examined mechanism. The average absolute density of energy per unit distance traversed. E_{av}, which determined by taking the absolute value of mechanical power, was the key measure in their study. A Given robot that has n legs and m joints, then the mechanical power represents the product of torque's actuator by angular velocity. The mechanical absolute energy delivered is then averaged over the distance travelled d to determine E_{av} [22]:

$$E_{av} = \frac{1}{d}\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T\left|\tau_{ij}(t)\dot{\theta}_{ij}(t)\right|dt \tag{4}$$

where τ_{ij} denotes motor torque and $\dot{\theta}_{ij}$ denotes "angular velocity" for i^{th} leg as well as j^{th} joint. Power minimization looks to be a critical issue, but very high-power demands may occur for short periods of time. In such situations, the average value may be low, but the peaks are impossible to achieve. As a result, the authors suggested an alternative index, the standard deviation per meter, which evaluates power variability over a complete cycle T and travelled distance d:

$$E_{av} = \frac{1}{d}\sqrt{\frac{1}{T}\int_0^T\left[\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T\left|\tau_{ij}(t)\dot{\theta}_{ij}(t)\right| - \frac{E_{av}}{T}\right]^2 dt} \tag{5}$$

T_L is another alternative optimization method, where the power lost in joint actuators per traveled distance d for an actuated device, expressed as:

$$T_L = \frac{1}{d}\sqrt{\frac{1}{T}\sum_{i=1}^{n}\sum_{j=1}^{n}\int_0^T\left[\tau_{ij}(t)\right]^2 dt} \tag{6}$$

A fourth possible optimization approach considers the forces that occur on the robot's hips per travelled distance d and time needed for travel T, resulting the index mean force on the hips per meter defined as:

$$F_L = \frac{1}{d}\sqrt{\frac{1}{T}\sum_{i=1}^{n}\int_0^T\left\{[f_{ix}(t)]^2 + \left[f_{iy}(t)\right]^2\right\}dt} \tag{7}$$

where, f_{ix} and f_{iy} indicate the forces acting on the hip of the robot's i^{th} leg in the x and y directions, as well. The simultaneous minimization of all indices is required for good system efficiency. (E_{av}, D_{av}, T_L, F_L). Quadruped robots with embedded power sources started to develop as power system manufacturing technology improved. A typical robot is the "BigDog-v2" [23, 24]. A manipulator mounted on the robot's torso can throw things with a dynamic gait, enabling leg-arm collaboration. The Cheetah series robot from MIT [25] are high effective quadruped robots. Energy usage is very close to animal level. First three generations' cost of transportation can approach 0.51 [26], 0.47 [27], 0.45 [28] individually. Four design principles were applied by the researcher to decrease the energy loss in locomotion. The whole power used by the robot is approximately 973 W, and the "cost of transport" is 0.5, which is very close to cost of running of animals. [29].

In nature, legged locomotion can be observed in a range of various gaits, which are identified by their different footsteps pattern and contact forces, as discussed by Hildebrand [30]. Minetti and Alexander [31] presented biomechanical experiments, whereby there is a direct relationship between running speed, gait choice, and energy consumption in humans. Meanwhile, Hoyt and Tylor study the same relationship with horses [32]. The results showed that the animals' gaits may change as a function of locomotion speed based on metabolic. Researchers in [33] used an optimum control for motion generation of conceptual models of bipeds and quadrupeds' robots to get the effect of gait mode in robotic systems. The method can generate motions that minimized positive mechanical work, while being subjected to real robot dynamics and locomotion restrictions, such as foot non-penetration and actuator limitations. The results indicate that modifying gait as a function of locomotion speed may significantly improve the mechanical economy by varying forward speed and foot contact sequence. In bipedal locomotion, the ideal behavior is to walk slowly and run quickly, while in quadruped locomotion, the optimal behavior is to walk slowly, trot at intermediate speed, and gallop at high speed. It is worth noting that there was a minor mechanical energy difference between trotting and toelting, which may explain why the toelt is a part of some horses' locomotion repertory. Galloping didn't surpass trotting in simulations, in contrast to biological quadrupeds that belong to the lack of an articulated spine in the initial quadrupedal model as described by Yesilevskiy *et al.* [34]. Smit-Anseeuw *et al.* [35] adopted this approach to investigate the optimal motions for bipedal robot (RAMone), by comparing two different knee joint orientations at forwards and backwards pointing, in addition to two different footfall sequences (walking sequence with a double support phase and a running sequence with an aerial phase). The results showed that the best gait transitions from ballistic walking with instantaneous double-support to spring-mass running is at a speed about 1 m/s. The results also showed, at low speeds, the actuator springs doesn't store elastic energy, whereas at high speeds, the springs conduct almost all the mechanical energy changes throughout the robot. By turning from ballistic walking to spring-mass running, metabolic energy consumption was lowered by 88%. This is corresponding to the studies of metabolic cost of human walking. Selinger *et al.* [36] evaluated people preferred gait in various cost landscapes and defined the relationship between the metabolic cost with particular gait parameter, Also, they demonstrated that, people may constantly modify step frequency to reduce the metabolic energy. Subsequently, Selinger *et al.* [37] have discovered the fundamental characteristics that describe this energetic cost optimization, which also can be substantially replicated using a basic reinforcement learning algorithm, as shown by Simha *et al.* [38]. Gasparri *et al.* [39] defined a problem of optimal control in such a way that robot dynamic factors such as joint impedance, in addition to standard state and control variables, can be optimized. The optimal control problem is handled using a direct method. The locomotion constraints describing periodic change of contact phases with single support and double supports are defined, as well as the robot dynamics and conventional restrictions such as joint limitations. Toeda *et al.* [40] present the relationship between gait generation and energy efficiency based on rat Neuromusculoskeletal model. The musculoskeletal component of the model was built using real anatomical data from rats, while the motor control component was built using physiological principles from the spinal central pattern generator and muscle synergy. They also included posture and speed regulation models at the brainstem and cerebellum levels. Through forward dynamic simulation, the simulated joint kinematics and muscle activity were compared to animal data. The model trotted by varying the phase difference between both forelimbs and hindlimb using muscle-synergy-based motor commands. Furthermore, the speed of each gait varies by changing the extension phase duration and amplitude of the muscle synergy-based motor commands, as well as the values that used as references for the regulation models. It found that the relation between Cost of Transport (CoT) and speed was U-shaped for both generated walking and trotting, and the speeds for the lowest CoT differed through the two gaits. Animal locomotion requires changing gait to adapt to the situations. Despite the unknown of what it is causes animals to choose a particular gait, energy efficiency is a significant issue. According to these reports, the relationship between oxygen consumption and speed for each horse gait is U-shaped, and different gaits have varied speeds at which oxygen consumption is minimized. By shifting gait, the horse may achieve energy-efficient locomotion over a wide speed range. However, the underlying mechanisms that drive U-shaped oxygen consumption and varied speeds for the minimum consumption between different gaits remain unknown.

V. GAIT

Song and Waldron defined the gait in [41] as "the time and the location of the placing and lifting of each foot, coordinated with the motion of the body in its six degrees of freedom, in order to move the body from one place to another". A legged robot's gait is typically characterized using three terms: duty factor, stride, and relative phase [41, 42]. The "stride" is the travelled distance by torso in one gait period. Large animals improve their speed through adjusting their length of stride, whereas small animals concentrate on "stride frequency". The robot that runs at a high stride frequency is much steady, but it is less efficient. "Duty factor" is the ratio of one leg's stance period to one cycle gait. The primary distinction between walking and running is that walking has a duty factor higher than 0.5 and running has a duty factor less than 0.5. In walking, both feet are on ground at the same time, whereas in running gait, both feet are off the ground. Asymmetrical gait, with each leg having the same duty factor and a 0.5 phase difference. The relative phase of one leg is described as the delay divided by the total period. The gait of a quadruped robot could be classified as static or dynamic based on the supporting polygon. Static gait is primarily referred to walking, whereas trotting, bounding, galloping, and other dynamic gaits are examples of dynamic gaits. Galloping and trotting are the two most prevalent gaits use. Fig.1 illustrates typical quadruped robot gait curves in terms of trot, pace, gallop, bound, walk and pronk. From the figure, the stance is represented by "black bars", while the swing is represented by "blank bars" [43].

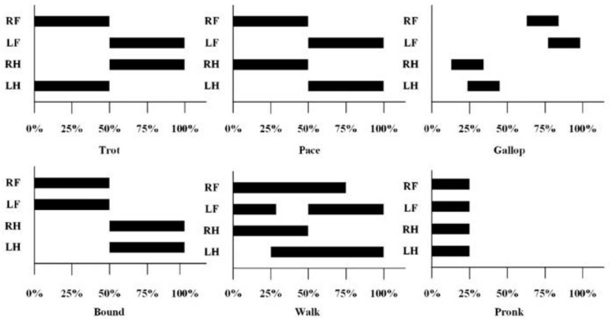

Figure 1. Gait graphs for quadruped robot [44].

Many of the motions observed and mathematically formulated of natural gaits were found to be periodic in nature. As a result, motion was classified into two categories, Periodic and Non-periodic, as shown in Fig. 2.

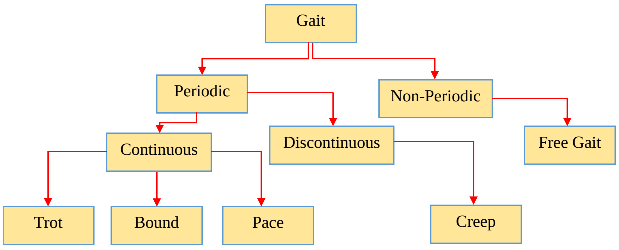

Figure 2. Leg types categorize [45].

The periodic gait is distinguished by continuous gait, in which the torso moves continuously while all legs move at the same time, this usually works for flat terrains. while for rough terrains, animals usually perform a distinct type of "continuous gait" named "wave gait" in slower speed. On sharp irregular terrains, mammals and insects adjust their gait pattern, which is described as safe gait and is distinguished by the sequential movement of the legs and torso [43]. The body moves forward and backward with entire four feet in proper contact with the ground, and then one leg is moved while the three legs remaining in addition to body stay positioned, resulting the gait to be discontinuous. This gait produces uncertain body movement, which is beneficial to a four-legged vehicle, and they are very simple to execute. The pattern of the trot is frequently applied gait in terms of practicality and simplicity. Each leg's swinging time and support segment are similar in the trot gait. ANYmal robot includes a free gait setting in which the leg order does not take a specific shape. The "Froude number" (f_r) is used to analyze and compute the dynamic movement of various quadruped robot configurations. Animals with different sizes use the same "Froude number" in their locomotion. Froude number is dimensionless that linked to inertia force to "gravitational force". (f_r) is described in [46] as:

$$Froude\ No.(f_r) = \frac{mv^2}{l}/mg = v^2/gl \tag{8}$$

where v represents running speed, g represents "gravitational force", then l indicates the distance between the hip joint and the earth The "Cheetah-Cub" run at 6.9 body lengths per second with the highest Froude number $f_r = 1.3$.

A. Configurations of Gaits

1) Trotting gait

This type of gait includes moving opposite legs diagonally simultaneously. This is a rapid movement, and dynamic stabilization is used to maintain a stable state. The body is ballistic and without support twice during each cycle, so if the pace is higher, there is more stability. Fig. 3 shows the example of leg movement during trotting motion cycle. From the figure, β is the duty factor, which in trot gait equal to 0.5 as minimum [43].

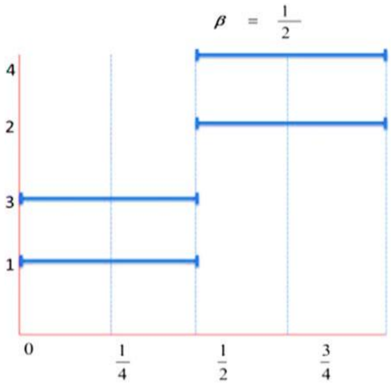

Figure 3. Leg movement during a trotting motion cycle [43].

2) Creeping gait

Because of their steadiness, creeping and crawling gaits are used. Each step requires one leg to be raised; the order in which the legs are raised can result in 6 distinct gaits configurations. Fig. 4(a) represents creeping gait that has the greatest steadiness for travelling along x-axis which referred to as the crawling gait. If the walking direction is in -x, then it takes (e) arrangement. Similarly, the crawl gait is represented by 1234 and 1432 in the -y and y directions, respectively. The 1243 and 1342 creeping gaits, on the other hand, provide medium stability and are ideal for turning [43].

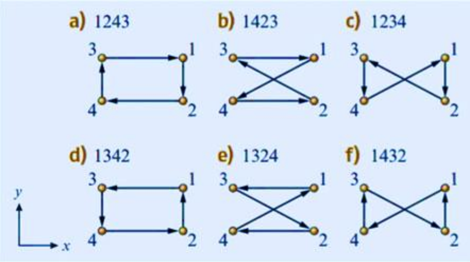

Figure 4. Depiction of different gait sequence [45].

The minimum “duty factor” (β) for static stability gaits for four-legged robots is 0.75, as illustrated in Fig. 5.

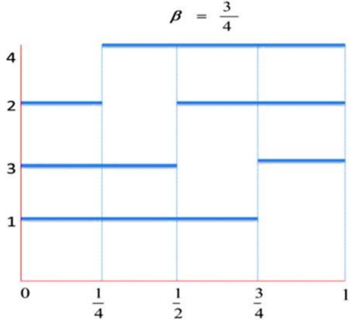

Figure 5. Leg movement during a creeping motion cycle [43].

3) Bouncing gait

Support in the bound alternates between sets of legs, with the fore and hind limbs working together to move the body forward in a bound gait, bound’s gait phase is the shortest which allows the leg to be frequently contact with ground. As a result, the bound adapts itself well to impediment avoidance and movement. Later, a simulation analysis in Fig. 6 shows that some basic planar quadruped bounding designs for dimensionless body inertia numbers less than one and duty factor (β) less than 0.5, are always passively stable [43].

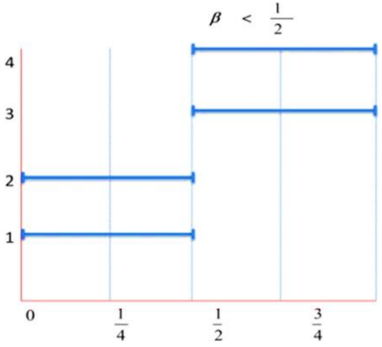

Figure 6. Leg movement during a bouncing motion cycle [43].

4) Waving gait

This kind of gait provides the most steadiness on x-axis, and the duty factor varies between 0.75 ≤ β < 1 which is the duty factor of the wave gait. It is typically similar to “static stability”, one leg is elevated and the other three legs on the ground, generating an elliptical solution to calculate β. This movement is uniform and symmetrical, indicating stability.

Sutyasadi *et al.* [47] suggested a control algorithm that ensures quadruped robot gait tracking performance. The quadruped robot is unsteady during dynamic gait motions such as trotting. In addition to parameter errors and unmodeled dynamics, the quadruped robot is constantly subjected to disturbances. Cheetah is a fast robot, built by Boston Dynamics as shown in Fig. 7(a). This tethered robot can reach speeds of more than 45 km/h. Later, Boston Dynamics developed Wildcat, the world’s quickest untethered quadruped robot. It weighs 154 kg, powered by an engine that works on methanol driving all its hydraulic actuators, able to run at 32 km/h in an open area with care and balance. For locomotion, it used a range of different gait patterns such as, bounding, galloping, and trotting, among others. Spot, the latest dog-like untethered quadruped robot built by Boston Dynamics, is shown Fig. 7(c). It takes a different approach to dynamic robot control than the company’s prior releases, BigDog and LS3. The robot measures approximately 1.1 m × 0.5 m × 0.84 m (L × W × H) and has a top pace of 5.76 km/h. The robot weighs 30 kg in total and can handle a 14 kg load. All of the joints are operated by a battery and have electric actuation. The walking and trotting gaits of the robot are omnidirectional. In 2015, the same lab built the MIT Cheetah-2 [48]. The researcher successfully implemented an algorithm for robots to accomplish unrestricted running at speeds ranging (0 to 4.5 m/s) in regular way. The robot has the ability to run in a grassy, treadmill, and uneven terrain. The robot can leap over 400 mm high hurdles when run with 2.5 m/s. “Boston Dynamics Corporation” created BigDog-1st [49]. BigDog integrates fifty sensors including gyroscope, a stereo vision camera, joint position, ground contact, ground weight, LIDAR, Light detection, and joint force among others. Four degrees of freedom has each leg of the robot all are hydraulically actuated, absorb and release energy from one step to the next. It can trot at 0.8 m/s and can walk on 35 ° inclined surface, driven by a 15 hp using engine of gasoline and has a PC104 processor and the Quenix real-time operating system mobile. Kolter *et al*. optimized robot motion using the differential symbolic strategy gradient technique. The “LittleDog” used this technique to climb the stairs. Authors in [50] suggested a reinforcement technique based on “Actor-Critic” to achieve quadruped robot suspension restore while in [51], the authors used reinforcement technique to make the “AnYmal” robot faster in simulation. The technique directly used a network to execute functions using the joint actuator’s data and applies the unpredictability from dynamics model of the rigid body to simulated model. WRAP1 is a bionic four-legged robot used to investigate dynamic and static locomotion in irregular terrain [52]. The WRAP1 weighs approximately 60 kg and has 12 degrees of freedom. Later, the 2nd generation of BigDog was presented in 2008, as shown in Fig. 7(b) which can drive 130 m constantly without needing to assist [49].

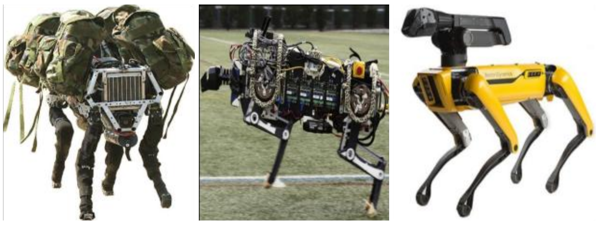
(a) (b) (c)

Figure 7. The quadruped robot (a) MIT Cheetah, (b) 2nd Generation of BigDog, (c) Spot [7].

It may travel over mud, icy environment, or even a forest, and regain balance after skidding down a slope or being kicked by someone. The main purpose of this robot is to serve as a mule for US troops, but the BigDog project was cancelled due to high noise caused by a gasoline-powered engine. After that it was ruggedly renamed as “LS3” or also named “Alpha Dog”, after his precursor BigDog. The LS3 is specifically intended for military purposes and can work in different environments. It has 12 joints in its legs, and all hydraulic actuators are powered by a gas or diesel engine. To identify the path that will track the user, a stereo vision system and LIDAR are combined. [53]. In a manually labelled dataset, the total reliability of the accurate tracking rate is around 98.8 %. Kimura *et al*. [54] Yesilevskiy *et al*. [34] used a CPG controller to operate a trotting Tekken robot in rough terrain. The authors in [55] suggested a “CPG controller” for repetitive motion control for quadruped robots. The controller built according “Wilson-Cowan neural oscillator”, and it can generate various gaits and varies the robot’s motion in a steady manner. Igarashi [56] organized trajectory according to ZMP stability and experienced trotting gait of the “TITAN” robot on unknown ground and body posture automatically arranged. Xu [57] used the technique of prediction to acquire ZMP and CoG, allowing robots to successfully walk in the presence of unperceived disturbances.

VI. STABILITY

Stability is defined as an equilibrium position that can be measured and experienced by properly positioning the legs. Static and dynamic stability are the two forms of stability, and it is critical in legged robots.

A. Static Stability

The stability of the robot maintains it balanced so that it does not fall over when standing, i.e., the center of gravity is inside the ground contact frame. To illustrate, consider a tripod robot that forms a triangular area. As a result of its stable construction, the robot remains stationary, and its CoG is in a triangle. This area is known as a “support polygon” [58, 59], which represents the projection of a robot’s support points to area on which positioned. At least, three legs should be contact ground. The Zero Moment Point that is presented in [60] is a modification of center of gravity approach that includes the inertia force, in addition, it considers the most frequently utilized static stability control approach. ZMP stability criterion control method was used to perform static walking in the Alof robot [61].

B. Dynamic Stability

A quadruped robot’s stability is mostly determined by its body movements [62]. For instance, a one leg of robot is stable since the robot is running but will fall down whenever stop, it is hard to control but it moves fast and effectively [43, 63]. As a result, majority of quadruped robots utilizing this type of stability since static is inefficient, because as it mentioned, three legs must be contact the ground at least, walking is slow, while “dynamic stability” allows for a range of 0 to n of legs. To attain an effective model, there should be dynamic stability in addition to static stability, which means that rather than one leg is lifted, it should two legs lifted instead to save energy while remaining slightly less stable than static. The ability to maintain stability has prompted an increase in research on efficient dynamic stability, as in the HyQ series [64–66], and “ANYmal” [67, 68] that have weight less than 30 kg and can carry payload. While “SCalf series” [69–71] uses the same technique [72–75]. Raibert [76] used this technique to attain “dynamic stability” in robots with one leg and suggested theory of virtual leg, to make it include bipedal and quadruped robots. Bledt *et al.* [28] and Di Carlo *et al.* [77] supposed the robot as a single rigid body to attain stability under different patterns gaits.

VII. ACTUATORS

In general, quadruped robots are divided into three types based on actuation [78]: hydraulic actuators, pneumatic actuators, and electrical actuators. Electric actuators have high control accuracy, but they cannot withstand heavy loads. Because of their nonlinear characteristics, pneumatic actuators are challenging to control [79]. Hydraulic actuators are extensively used because of their high power, but the vibration is a little stronger. Mechanical leg motion is characterized by a series of dynamic events. One of the main challenges in robotics research has always been the actuator systems to get an efficient dynamic legged robot. Most quadruped robots are powered by a single sort of actuator. Each actuation’s assembly has benefits and disadvantages. The best actuator should be chosen based on the main function and requirements. To improve the robustness and effectiveness of the “HYQ quadruped robot”, hydraulics in addition to electrical actuators are embedded. Quadruped robots that are hydraulically actuated, like “Scalf-1”, “LS3”, and “BigDog”, have efficient carrying capability as well as locomotion. ANYmal as shown in Fig. 8(c) is powered by special torque actuators to make it has sufficient dynamic performance and mobility climbing. Furthermore, for indoor applications, most four legged robots electrically actuated, for instance “ANYmal, Spot, and LittleDog”. Semini develops hydraulic Quadruped (HyQ) [64, 80] in 2010, as shown in Fig. 8(a). The robot has eight hydraulic actuators and four electronic actuators. HyQ robot which is also hydraulically actuated intended to execute a variety of tasks, such as running [81]. Also, it successfully navigated various terrains through a “stereo vision camera” [82, 83]. The same researcher presented two improved versions of HyQ called HyQ2max and HyQ2cetaur [84]. HyQ2-max improves factors such as reliability, output torque, robustness, joint angle. In “HyQ2max”, one set of hydraulically arms with 6 DOF actuator is incorporated. Hutter created Star1ETH, a medium-sized canine as shown in Fig. 8(b) [85, 86]. A high-quality series of elastic actuators are installed in star1ETH, which gives similar performance to our “tendons” and muscles in terms of storing a significant amount of energy temporarily. “WildCat” is a four-legged robot that is hydraulically actuated, still holds the title as the fastest quadruped robot with speed reach to 25.7 km/h [87]. The overall features of described quadruped robots are summarized in Table II.

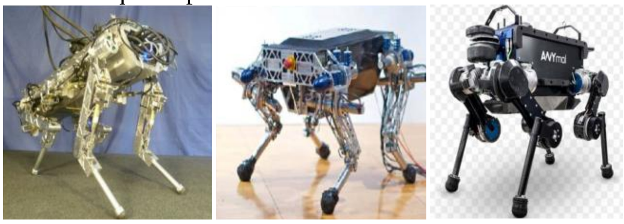
(a) (b) (c)

Figure 8. Quadruped robots (a) HyQ, (b) Star1ETH, (c) ANYmal [7].

TABLE II. FEATURES OF DESCRIBED QUADRUPED ROBOTS

Name of robot	Dimension (m)	Type of gait	Velocity (m/s)	Weight (kg)	Payload (kg)	DOF per Leg
HyQ	1 _ 0.5 _ 0.98 (L _ W _ H),0.68(l)	Trot	2	80	-	3
MIT cheetah	-	Trot-running	6.1	33	-	3
Cheetah	1.7(H)	Gallop	12.5	-	-	3
Star1ETH	0.6(L),0.49(l)	Bound	1	23	25	3
SPOT	1.1 _ 0.5 _ 0.84 (L _ W _ H)	-	1.6	30	14	3
Big Dog _2	1.1 _ 0.3 _ 1 (L _ W _ H)	Bound	3.5	109	154	4
LittleDog	0.3 (L)	-	0.25	2.85	-	4
ANY mal	-	Free gait	1	30	10	3
Wild cat	1.17(H)	Trot, bound	8.8	154	-	
SCALF-I	1 _ 0.4 _ 0.68 (L _ W _ H)	Trot	1.8	123	80	3

VIII. CONCLUSION

Quadruped robots have made substantial progress after years of development. However, there are still considerable gaps between them and four-legged animals. As a result, greater attention should be paid to the optimization of such systems, and various optimization methods are required to improve their design and construction. Following are several conclusions that can be made from this review:

- The locomotion effectiveness of available robots is quite low in comparison to living animals or wheeled vehicles, and they still have significant constraints, such as slow speeds, difficulty in construction, and the need for complex control algorithms.
- Mechanisms are heavy because they require many actuators to move numerous DOF legs, which requires a lot of energy.
- Appropriate gait selection is required to adapt to terrain and locomotion circumstances.
- Electric actuators have high control accuracy but cannot withstand heavy loads due to their nonlinear characteristics, while pneumatic actuators are challenging to control. Hydraulic actuators are extensively used because of their high power but are affected by vibration.
- The mobile robot’s robustness is improved by using high precision controller and joint actuators. Joint actuators play an essential role in robot complexities.
- Next is the weight and cost. The main function is to ensure that the torque generation to weight ratio of the joint actuators is high. The power output to weight ratio of hydraulic and pneumatic actuator are significant, fast reaction time, and simple to implement.
- Features such as identifying, remembering, and gaining knowledge from the surroundings should be supported and implemented to assist the mobile robot in achieving greater autonomy.
- A cognitive robot, which is concerned to be a robot with mental behavior, is the future work of a mobile robot that can response to complicated tasks in the real world.
- Artificial intelligence, networking, cooperative work, autonomous driving, and emotion expression are getting attention which can be applied in different sectors like health care, manufacturing industry, robotic services, and product distribution.

IX. FUTURE WORK

To make the robot adapt to different terrains, the robot’s structures ought to be multifunctional and adaptable. During the design process, it is essential to integrate the specifications of numerous bionic stuffs to improve specific functions. Then a mechanism that outperforms the initial bionic object can be created. Furthermore, to meet the requirements of locomotion and to show the importance of optional foothold, in day/night complex environments, 3D environment constructing technologies with swift refresh rates based on multiple data sources combination, real-time foothold selecting and optimization processes, gait organizing, and smoothing transition methods are needed. To enhance the quadruped robot’s mobile manipulation capacity, manipulators and coordinated control of torso movements are required. Regarding the advancement of autonomous driving, artificial intelligence, cooperative work, and perception, four-legged robots will be used in a variety of areas like underground, exploration, health care, and so on. Future work should also concentrate on assisting the robot in recognizing, memorizing, and learning its environment. Recognizing where the robot has been previously will boost the efficiency of environment comprehension. Recognizing also implies that the robot could memorize the required information about its surroundings. Finally, with the advancement of intelligence algorithms and deep learning, quadruped robots will adjust to their surroundings by training ahead of time and learning in real time.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Alarazah Hussein Abdulwahab: Data collection and writing. Ahmad Zhafran Ahmad Mazlan: Review and editing. Ahmad Faizul Hawary: Review and editing. Nabil Hassan Hadi: Data validation; all authors had approved the final version.

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