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ΣΠΟΥΔΑΣΤΙΚΗ ΕΡΓΑΣΙΑ

Quadrupedal Bio-inspired Robots: Development & Characteristics

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ΠΕΡΙΛΗΨΗ

Τετράποδα Βιομιμητικά Ρομπότ: Ανάπτυξη και Χαρακτηριστικά

Παπαδοπούλου Νικολέτα Παναγιώτα

Την τελευταία δεκαετία, έχουμε δει σημαντικές προόδους στον τομέα των τετράποδων ρομπότ και πολλές υποσχόμενες προσπάθειες καταβάλλονται για να βοηθήσουν τους ανθρώπους αντικαθιστώντας τους στην εκτέλεση επικίνδυνων, βαρετών ή ανθυγιεινών εργασιών. Αντλώντας έμπνευση από τη φύση, οι μηχανικοί της ρομποτικής έχουν βάλει στόχο να επιτύχουν παρόμοιες δυνατότητες δυναμικής κίνησης σε μηχανές με πόδια μέσω αυτού που ονομάζεται βιο-έμπνευση. Το κίνητρο πίσω από αυτήν την ανασκόπηση είναι η σύνοψη και η εξέταση προηγούμενων ερευνητικών προσπαθειών και η παροχή χρήσιμης καθοδήγησης για μελλοντικές καινοτομίες ρομποτικού σχεδιασμού προς πιο αποτελεσματικά τετράποδα ρομπότ. Τα βασικά χαρακτηριστικά για την υλοποίηση του τετράποδου αρθρωτού συστήματος συζητούνται εστιάζοντας στις μεθόδους ενεργοποίησης και μηχανικού σχεδιασμού ποδιών. Ιδιαίτερα, αυτό το έργο τελευταίας τεχνολογίας διευκολύνει επίσης τον ρόλο του αναγνώστη να κατανοήσει καλύτερα τα ρομποτικά παραδείγματα που υπάρχουν ήδη στην αγορά ή αποτελούν μέρος της ακαδημαϊκής βιβλιογραφίας, συμβάλλοντας σε ερευνητικούς σκοπούς σχεδιασμού.

Λέξεις κλειδιά

Τετράποδα Ρομπότ, Ενεργοποίηση, Μηχανισμός, Σχεδιασμός Ρομποτικού Ποδιού

ABSTRACT

Quadrupedal Bio-inspired Robots: Development & Characteristics

Nikoleta Panagiota Papadopoulou

In the last decade, we have seen major advancements in the area of quadruped robots and many promising efforts are setting out to help humans by replacing them in performing dangerous, dull, or unclean tasks. Drawing inspiration from nature, robotics engineers have set out to achieve similar dynamic locomotion capabilities in legged machines through what is called bio-inspiration. The motivation behind this review is to summarize and consider previous research efforts and provide useful guidance for future robotic design novelties towards more efficient quadruped robots. Essential characteristics for the realization of the quadrupedal system are discussed focusing on actuation and mechanical leg design methods. Particularly, this state of the art project also facilitates the role of the reader gaining a better understanding on the robotic paradigms that already exist in the market or are part of academic bibliography, contributing in design research purposes.

Key Words: Quadruped robots, Actuation, Mechanism, Leg Design

FIGURES CATALOGUE

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1.0 BRIEF HISTORY AND CONCEPTUAL BACKGROUND

1.1 A SHORT INTRODUCTION TO THE EARLY EVOLUTION OF QUADRUPEDS

The early down of biomechanics in the seventeenth century[1] introduced what is now considered one of the most popular research topics in bio-inspired robotics: Legged Locomotion.

While many scientists and researchers devoted their time researching the imitation of walking by the development of machines with legs, Chebyshev introduced the first walking mechanism in 1870. This ahead of its time mechanism resembles the Greek letter lambda and consisted of four bars, primarily converting rotational motion to translation motion with constant velocity. During the following decades a number of efforts were made to design mechanisms that would aim to generate a desired motion profile while operating.

It was not until the 1940s that a number of researchers began to reconsider the real possibilities of using legged robots. Under the notion that machines ought not to be limited on the kinematic mechanisms that provide cyclic movements, came the integration of planning and control systems. In other words, the researching community in the middle of the 20th century is moving towards autonomy. Hirose and Kato’s spider-like quadruped robot[2] was characterized as one of the most significant milestones in the field during 1976. Mimicking nature and drawing inspiration from the long-legged spiders the quadruped under the name **KUMO-1** weighed 14kg and was 1.5 m in length. The walking mechanism presented by the Tokyo Institute of Technology generated motion on each leg from a driving motor and one clutch and in this way a large family of quadrupeds began developing.

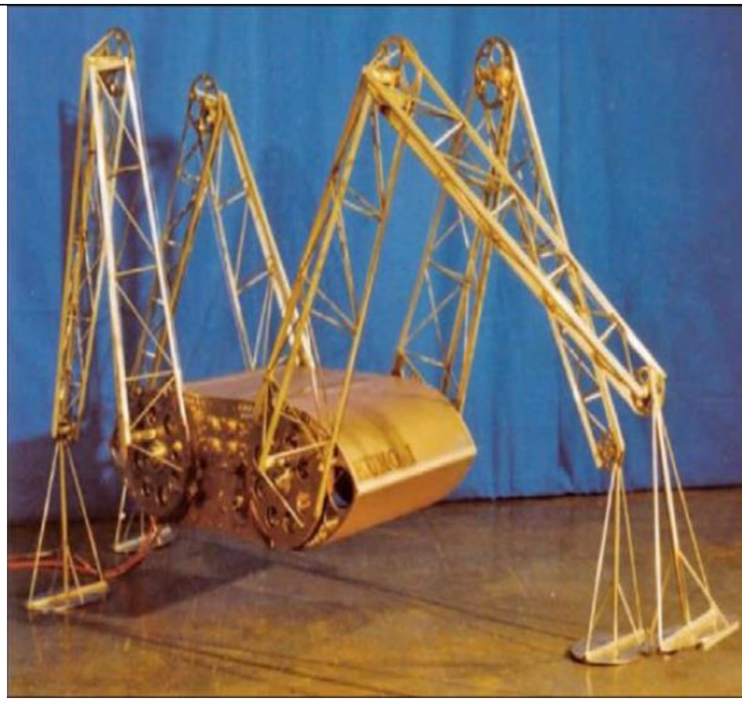


Figure 1-1 KUMO-I as First Quadruped walking robot [2]

1.2 EVOLUTION OF QUADRUPEDAL ROBOTS IN 1980S.

In 1980, Professor Hirose developed the Pre-ambulate Vehicle (PV-II). The PV-II made history of climbing stairs on sensor-based motion control for the first time in the world[2]. The robot, as shown in Figure 1-2, weighed 10 kg and was 0.9 m high based on sensor based motion control making use of toe tactile sensor and attitude sensor. Its leg was based on a three-degree-of-freedom (DOF) pantograph mechanism, which was patented as the **PANTOMEC**.

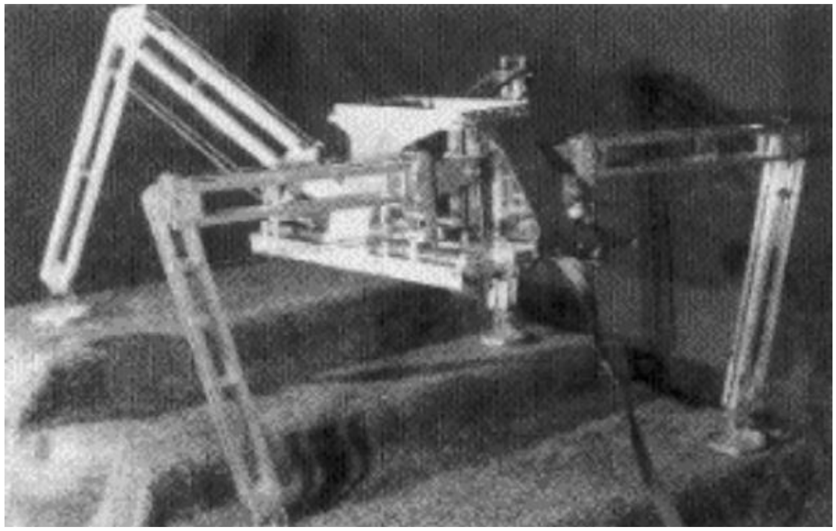
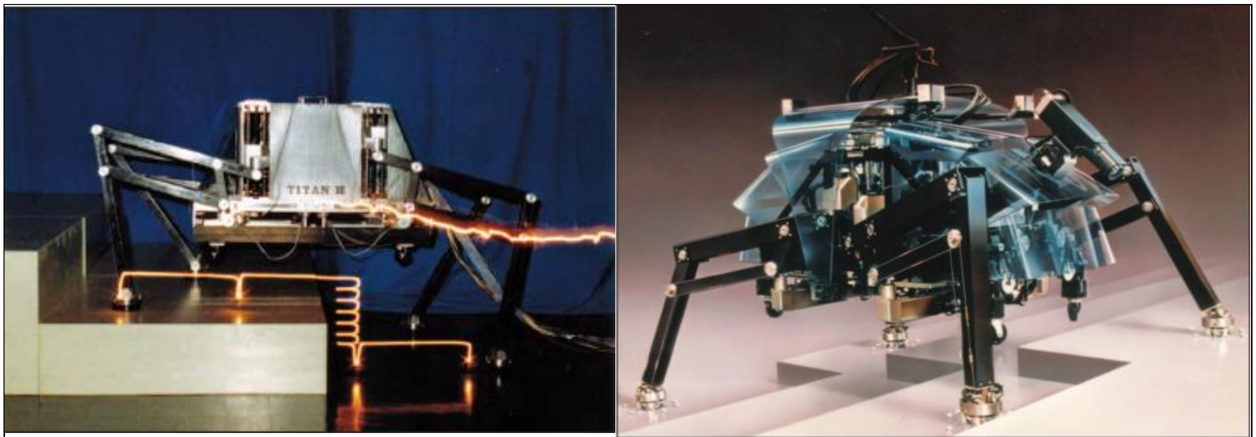


Figure 1-2 PV-II quadruped [3]

A few years later, Hirose began the development of the **TITAN series**[2] and he has been developing the **TITAN-IX** since 2001. It is important to get into more detail of Hirose's astounding contribution as it proved to be highly critical in the development of quadruped robotics.

TITAN-III followed PV-II, as a more prominent form of the later, for the realization of higher terrain adaptability while introducing a newly developed contact sensor (Whisker sensor). Its leg length is 1.2 m and weight is 80 kg. **TITAN-IV** (shown in Figure 1-3), as was developed in 1986 in order to be exhibited at International science exposition held at Tsukuba. The new version of TITAN could exhibit behaviors of transition of a continuous motion from crawl walking to trot by gradually increasing its speed. Then **TITAN-V** and **TITAN-VI** as shownwere mechanisms that served testing purposes with light weight and simple mechanism focusing on dynamic motion. Following, the walking quadruped robot **TITAN-VII** was designed mainly for distribution in assisting construction work at steep slope like moving scaffold.



Out of all, **TITAN-VIII** was the most popular working quadruped robot especially amongst general application purposes and even in colleges and research institutes. It has been designed with a new tethered (tied) driving mechanism considering Gravitational Decoupled Actuation (GDA) with 400 m leg length and 40 kg weight, while also having the innovative features of light weight design and high output power, characteristics of the TITAN series.

Around the same time in 1986, Raibert[3]–[5] and his co-workers at the Massachusetts Institute of Technology (MIT) made the first quadruped with complete dynamic stability. While most of the researchers that were involved in the development of dynamically stable robots started with focusing on statically stable multi-legged robots and later moved on to dynamic systems, Raibert chose to do the opposite. He made a planner and three-dimensional machine that ran and hopped in as the single-legged “kangaroo”. His idea was that by finding a solution to a one-leg problem he could apply this principle to multiple legged systems and eventually made a breakthrough regarding dynamic balance.

The TITAN-XIII is the last model of the TITAN series[6] and sprawling-type quadruped robot driven by tendons as shown in Figure 1-3. Its symmetric design gives it the ability to walk efficiently in any direction by trot gait with 1.38 m/s speed while being battery powered. (More is due to be discussed on the chapter of Sprawling Type articulated legs).

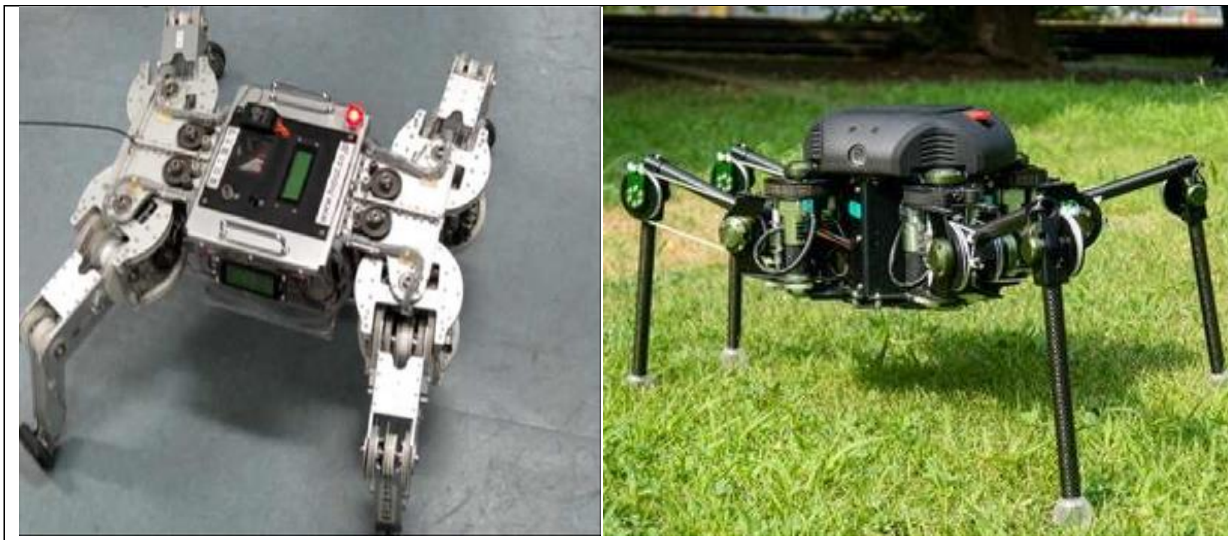


Figure 1-3 TITAN VII and TITAN-XIII [6]

1.3 DEVELOPMENT OF QUADRUPED ROBOTS IN THE EARLY 2000S

Another series of quadrupedal robots under the name TEKKEN[7] following the development of another robot series, Patrush was introduced by Kimura in the early 2000s. The first quadruped created at the Kyoto Institute of technology, had three joints, weighing approximately just 5.2 kg and reaching the speed of 0.6 m/s while controlled in RT-Linux and written in C-language.

In the **TEKKEN series** the robot has a control system that incorporates central pattern generators or CPGs, reflexes and responses as well as a mechanism that makes the most of the control system. TEKKEN, which is equipped with a single mechanism, an unchangeable control method, and modifiable parameters, is capable of achieving walking and trotting on flat terrain, can walk using a free gait on irregular terrain, and is capable of running on flat terrain using a bounding gait. Later, in 2010 the TEKKEN quadruped heavily inspired Maufroy to develop **Koteshu**, also using a neural controller made of a Central Pattern Generator (CPG) and a set of reflexes.

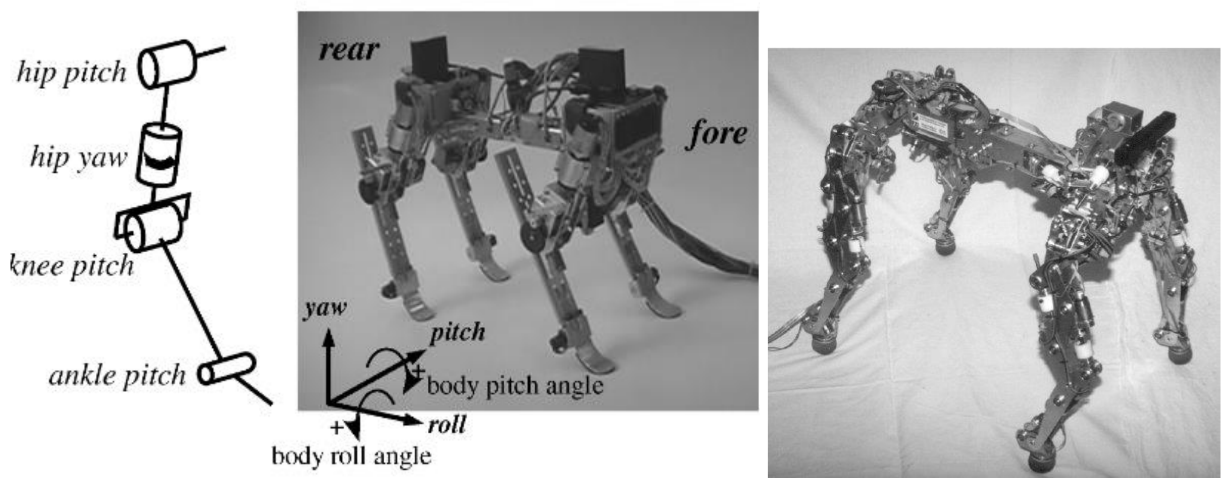


Figure 1-4 TEKKEN[7] **and BISAM** [8]

A biologically inspired four-legged walking machine, **BISAM**[8] (shown in Figure 1-4) was developed by a group of researchers in Karlsruhe Institute of Technology, Germany. Each leg divided into four segments, which consists of three revolute joints, is attached to the main body by a fourth. Its adaptive control architecture, comes from the implementation of a rather basic neuro-oscillator output that also includes sensor information to generate the actual motor actions and is influenced by different levels of reflexes.

The inter-university research program on Intelligent Robotics supported by the Ministry of Education in Tokyo had a really ambitious goal. The research was aiming to bridge the gap between the low level quick/smooth legged locomotion and the high-level vision/sensor based behavior research in very complex environments of quadrupeds. In this respect, **JROB-1**and **JROB-2**[9], [10] were developed, utilizing TITAN-VIII with motor drivers for the body of the robot, color tracking vision, a vision board and a robot interface board. Lastly, the robots were running under the operating system RT-Linux and with the use of the programming language Euslisp[11], the 3D geometric model was implemented.

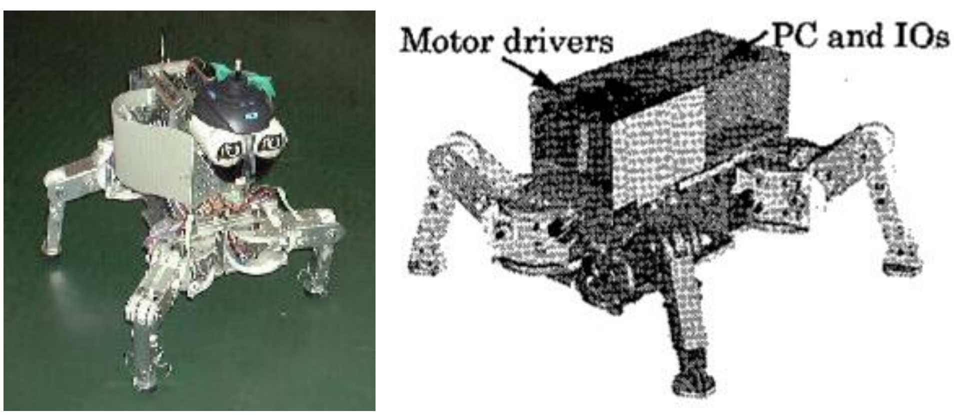


Figure 1-5 J-ROB1[9] **and J-ROB2**[10]

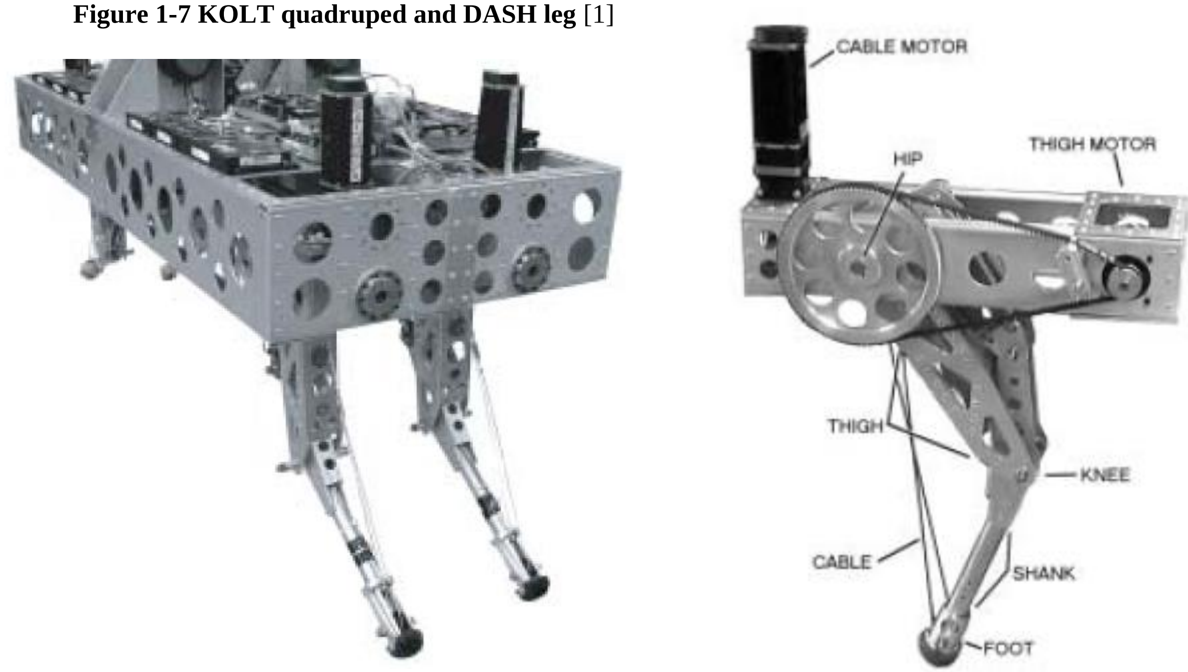
Researches towards automation of the quadruped robot had just started and in 1999, SILO4[12] was designed by the Industrial Automation Institute (CSIC), in Spain for both researching and educational purposes. The four-legged robot had 12 DOF and a focus on gait generation, terrain adaptation, and stability. Later on, in 2005 its designers released the book, "Quadrupedal Locomotion: An Introduction to the Control of Four-legged Robots"[12], analyzing the process of building SILO4.

Figure 1-6 SILO4 [12]

In 2004, researchers both from Stanford University and Ohio State University published, a paper presenting a study on quadrupedal gallop gait[13], [14]. Strong motivation for the research was the fact that body dynamics are primarily influenced by the impulses delivered by the legs. In other words, the successful design and control of single leg energetics is crucial.

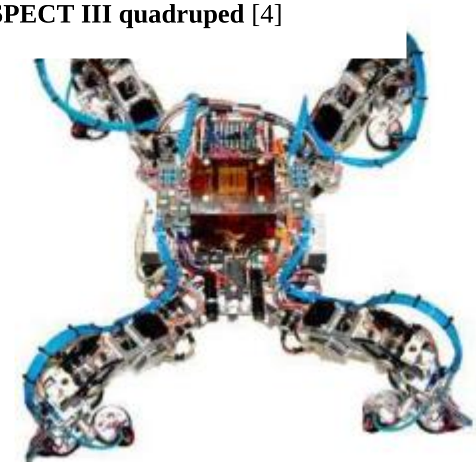
The Stanford Dynamic Articulated Structure for High Performance (**DASH**) [1]is introduced, a single leg mechanism that can reach the speed of 4.15 m/s as shown in Figure 1-7. Interestingly, two intelligent strategies are being developed, being a predecessor of quadruped control. First being the Levenberg–Marquardt on-line learning method and the second, adaptive fuzzy control. The quadrupedal presented by this research, **KOLT**[1] (Kinetically Ordered Locomotion Test) as shown in Figure 1-7 consists of four three-degree-of-freedom DASH legs and its features include high-speed actuation, energy storage, on-line learning control, and high-performance attitude sensing.

Figure 1-7 KOLT quadruped and DASH leg [1]



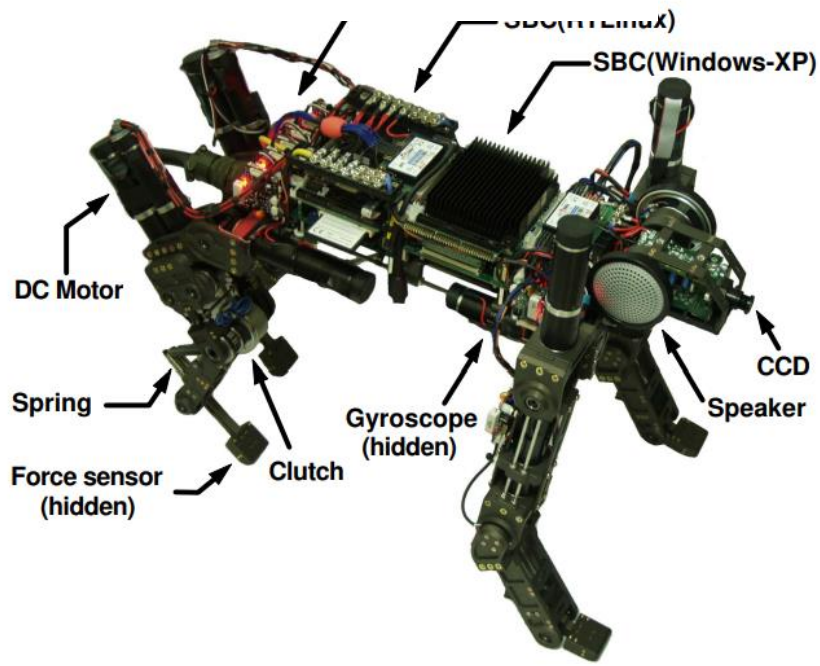
In 2005, the quadruped **MRWALLSPECT-III**[15] is designed, by The School of Mechanical Engineering Sungkyunkwan University in Korea, aiming to create a both walking and climbing robot that would manage to operate in a convex environment. In order to avoid collision between the robot's bottom part and the edge of a corner, the research is focusing on finding the optimal design so that a larger workspace and higher adaptability are guaranteed. Also, by examining the robot's posture, the team managed to propose a new algorithm that determines the appropriate gait for this purpose. **MRWALLSPECT-III** is equipped with an IR sensor, attached either to the leg of the robot or on the top, in order to measure the distance from the next surface of the corner that needs to be avoided. The robot has four legs with each one, bearing three-DOF active joints and a passive ankle joint. The most remarkable feature of this quadruped has to be the three suction pads on each of its legs that are responsible for adhesion to the wall, giving it its wall-climbing novelty. The robot also has two controllers; a single board computer, Pentium-III running on RT-Linux and a second one, that drives the two-DOF scanning module, composed of a CCD camera and an IR (infra-red) sensor.

Figure 1-8 MRWALLSPECT III quadruped [4]



In 2007, a biologically inspired dog-type robot was created by another team of the same university in Seoul, named **AiDIN**[16] (Artificial Digitigrade for Natural Environment) as shown in Figure 1-9. Once again, mimicking living creatures in robotic innovations is seen as fundamental in the control of robots and AiDIN is no exception. The 12-DOF robot is equipped with geared DC motors on the active joints and twelve microcontrollers that communicate with the RT-Linux operating single board computer through a famous protocol, named Controller Area Network (CAN). The AiDIN quadruped presents the Gravity Load Controller (abbreviated as GLC) by using a neural oscillator, similar to a rhythmic pattern generator. Its desired motions are designed in advance and trained. The creation of the oscillator for the control requires two steps: motion planning and building the model of mathematical computing. Firstly motion data is collected from observing the animal to be imitated, in this particular case, a dog. While taking into consideration the mechanical limitations of the robot, the data collected; joint angles of the legs, are modified so as to produce a stable locomotion.The second step is building a mathematical model using the **Recurrent Neural Network** (**RNN**), in order to generate the desired joints angles. Finally the training process is done by a Backpropagation Through Time (BTT) method; a recurrent neural network training technique.

Figure 1-9 AiDIN quadruped [5]



In 2008, the quadruped proposed by Korea Institute of Industrial Technology, was named **qRT**[17] and it presented the novelty of a two-legged and two-wheel robot. With a total number of 12 DOF, weighing about 60 kg, the qRT quadruped speeds up to 1.3 m/s and uses a gasoline engine that drives a hydraulic actuation system controlled by an online method. The robot manages to carry heavy-loads and move fast on uneven terrain and inclined surfaces.

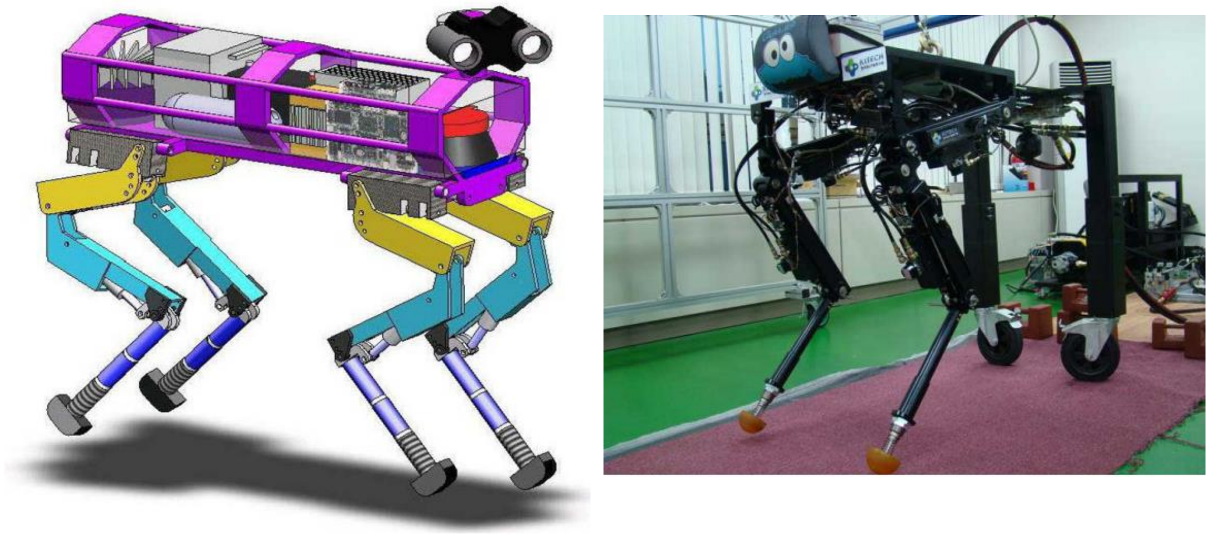


Figure 1-10 Configuration of qRT quadruped [6]

The department of Telecommunication and Control at Sao Paulo University presented a tree-climbing bioinspired robotic platform focusing on non-invasive environmental research, named **Kamanbare**[18], [19] as shown in Figure 1-11. The quadruped climbing robot has 16 DOF with a gait pattern inspired by the maneuvering and grip capabilities of chameleons. Approximately, it weighs 1.3 kg and is controlled by a Linux operating system.

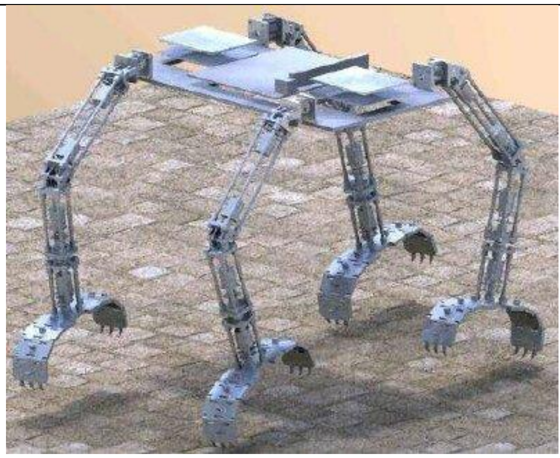


Figure 1-11 Kamanbare quadruped [18]

Hubo Laboratory from the Department of Mechanical Engineering (KAIST) in South Korea, presented in 2009 a lightweight (42kg), frame-type structured quadruped robot that has the ability to walk on even or uneven terrain while also carrying a payload. To reduce the computational burden of the main computer, **Hubodog**[20], as shown in Figure 1-12 utilizes a distributed control system. The communication between the main computer (operating in Windows XP using RTX software) and the subcontrollers of the 12 active joints is possible using the CAN protocol, so that high-speed serial communication is achieved while also receiving sensor information.

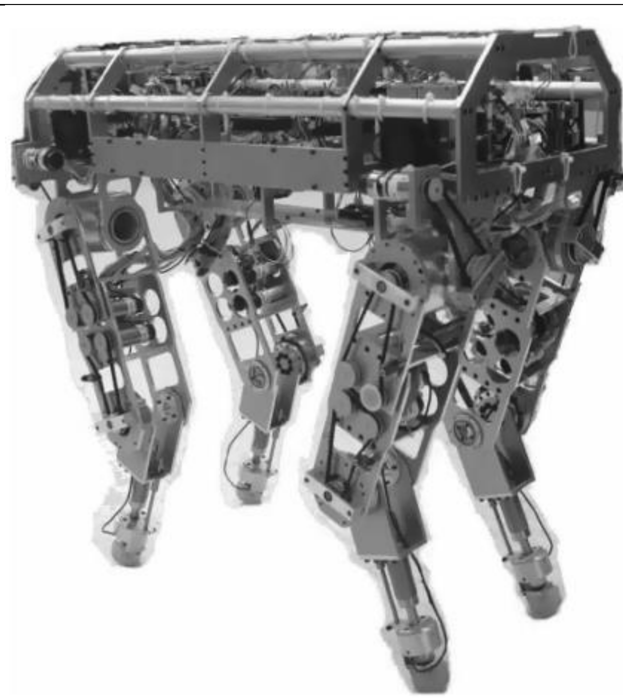


Figure 1-12 Hubodog quadruped [20]

In 2013, Toyota Technological Institute's control system Laboratory created a robotic platform to explore quadruped locomotion dynamics, introducing **Robocat-1**[21] as shown in Figure 1-13. An electrical actuated quadrupedal robot that each leg of, has 2 active DOFs deployed; in its hip and knee joints, bearing an overall weight of 6.85 kg. Powered by AC servo motor units which additionally include encoders and harmonic gears, Robocat-1 has gyro sensors for the measurement of the robot's orientation and calculates the GRF (Ground Reaction Force) response through FSR (Force Sensing Resistor) modules.

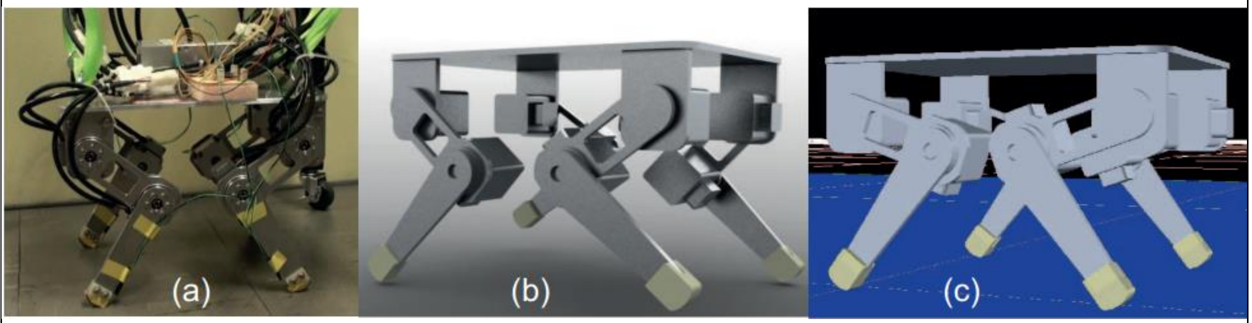


Figure 1-13 a) Actual quadruped robot RoboCat-1. b) RobotCat-1 CAD model. c) RoboCat-1 simulation model in OpenHRP3 [21]

Harbin Institute of Technology in China presented in 2014 a quadruped robot named **MBBOT**[22], as shown in Figure 1-14 . This bio-inspired quadruped was designed with an interesting approach: Each leg consists of four identical hydraulic-rotational joints with actuators and a prismatic spring located between the ankle joint and foot, so as to imitate the functionality of the muscle and tendon of the mammal. MBBOT has a number of sensors, including displacement sensors, 3-component force sensor in the feet and Inertial Measurement Units (IMU). The robot can reach the speed of 0.83m/s on the treadmill, weighing 100kg. In the same year other researchers from China, particularly from Shanghai Jiao Tong University developed a quadruped, also known as '**Baby Elephant**'. This 130kg robot can carry heavy loads of up to 30kg while also maintaining a maximum speed of 0.5m/s. The elephant-like quadruped consists of 4 serial-parallel hybrid mechanism legs, that use a hydraulic actuator (Hy-Mo), developed specifically for this project.

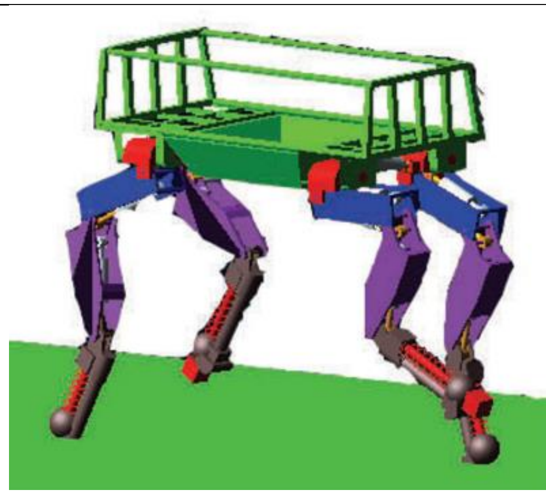


Figure 1-14 Model of MBBOT in simulations [7]

1.4 CONTEMPORARY QUADRUPED ROBOTS

1.4.1.1 HyQ

In 2010, the Department of Advanced Robotics from the Italian Institute of Technology developed a highly versatile, hydraulically powered quadruped named **HyQ** [23] as shown in Figure 1-15, setting the goal to create a platform that would have the ability to navigate successfully through rough terrain and perform dynamically complex tasks. Therefore, the quadruped in question bears 3 DOFs on each leg. The hybrid quadruped combines the usage of 8 hydraulic actuators and 4 brushless DC electric motors in total. The first ones are to be used for achieving high velocity, high power-to-weight ratio, and robustness against torque peaks. The later, are chosen for the hip joints of the robot, where compact dimensions are of higher importance.

HyQ quadruped, also features three different types of sensors on each active joint: a relative optical encoder responsible for joint control, an absolute magnetic encoder used for the robotic joint's initialization and finally, a force/torque feedback sensor that allows the dynamic control of the quadruped in difficult terrain. Moreover, the quadruped weighs approximately 91kg and has a maximum trotting speed of 2-3 m/s. Following, Dr. Semini and his team proceeded in using stereovision camera and IMU[24] (Inertial Measurement Unit) data for goal-oriented navigation on unknown rough terrain.

A more thorough analysis of the **HyQ quadruped robot series** from the perspective of leg design and actuation will be further discussed in chapter *2.1.2.1*.

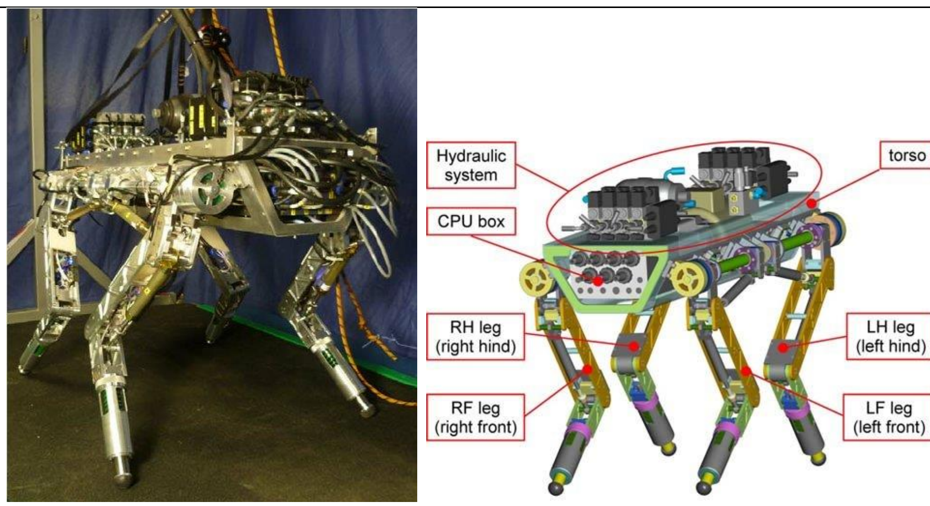


Figure 1-15 Hydraulic quadruped robot HyQ

Picture of HyQ and CAD model of the robot body with the onboard hydraulic system including the explanation of the key robot parts and components [25]

1.4.1.2 StarlETH

The quadruped made in the Swiss Federal Institute of Technology, is named **StarlETH**[26], [27] (Springy Tetrapod with Articulated Robotic Legs). The robot is of lightweight construction in order to achieve fast locomotion, weighing around 23kg and reaching the velocity of 1 m/s. Star1ETH as shown in Figure 1-16 has 3 DOF in each leg, a series of highly elastic actuators in order to replicate the way muscles and tendons behave. Moreover, the robot is allowed high fidelity joint torque control and protection from the impact loads, due to mechanical springs that separate the motors and overall gearbox from the joints. The kinematic data obtained by encoders mounted on the quadruped, alongside the IMU, allow estimation of position and maneuvering regardless of additional perception or an additional motion capture system. Lastly, pressure sensors are added at the compliant ball feet, so as to provide feedback regarding the contact situation of the robot.

Robotic Systems Lab from the ETH institution also designed **ANYmal**[28]. A multipurpose quadruped specifying in commercial and industrial operations that have the potential of being used for example, in applications of oil and gas sites inspection with additional features such as accurate localization, navigation and mapping.

A more thorough analysis of both **StarlETH** and **ANYmal** from the perspective of leg design and actuation will be further discussed in chapter *2.1.2.1*.

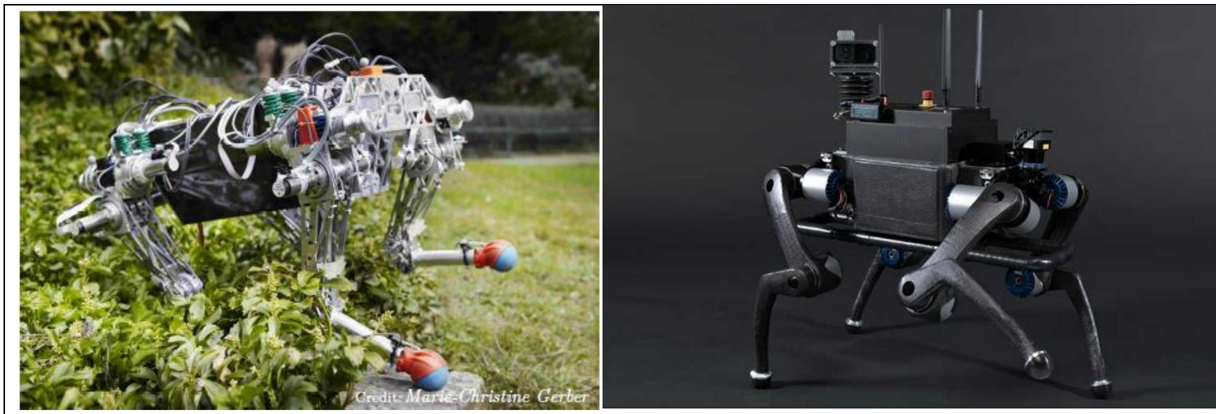


Figure 1-16 StarlETH [26] **and ANYmal**[28] **quadrupeds**

1.4.1.3 MIT Cheetah

Supported by the Defense Advanced Research Program (DARPA), the Massachusetts Institute of Technology (MIT) developed a highly efficient quadruped robot named **MIT Cheetah**[29] in 2013. The running MIT Cheetah can reach up to 6 m/s on the treadmill and has 12 DOF; 1 DOF for ab/adduction and 2 DOFs for both shoulder/hip and knee. The 33kg quadruped is highly efficient[30], with a total power consumption from the battery pack being 973W, resulting in a 0.5 CoT[1]; rivaling the CoT indicator of animals of equivalent scale.

This quadruped was developed with a hierarchical control architecture achieving high speed trot while using the proprioceptive[2] feedback and the programmable leg-compliance without the use of the robot’s body force sensory feedback. The proprioceptive force-control actuator in

[1] *CoT* stands for Cost of Transport

[2] Proprioception is the awareness of the body in space. It is the use of joint position sense and joint motion sense to respond to stresses placed upon the body by alteration of posture and movement.[68]

the form of low-level individual leg controller enables high bandwidth response to external disturbances. To achieve highly dynamic locomotion with various gait-patterns, a high level controller consisting of a gait pattern modulator with proprioceptive leg TD detection and a leg trajectory generator gives the parameters of the kinematics and kinetics of the robot's running motion. To avoid the deterioration of force-control performance, this FPGA/RT control architecture is realized without any mechanical springs/dampers installed on the legs. Instead, the control loop frequency is largely increased.

Moreover, this control setup employs a stance-trajectory design intended to adjust impulse at each foot-end in the stance phase according to the *Equilibrium-point hypothesis*[3] *when the quadruped runs*. The equilibrium point trajectory follows the simple sinusoidal wave, of which amplitude is the control variable adjusting the impulses exerted to the ground. Lastly, a smooth swing-trajectory designed is implemented by using the Bézier curve for desirable swing-leg dynamics.

Later, in 2015 **MIT Cheetah-2**[31] was developed proposing a novel impulse planning algorithm in order to give the ability to the quadruped to achieve untethered running, whilst being able to change the running speed. With velocities ranging from 0 to 4.5 m/s not only can MIT Cheetah-2 perform in regulated environments like treadmills but also grassy fields without re-tuning or re-optimization of the control parameters.

[3] The *Equilibrium point hypothesis* introduced by Bizzi[68] in 1992, proposes that animals might exert proper force on the environment by controlling the equilibrium point of their limbs' virtual compliant system to have a penetration depth into a contact surface. Then, the instantaneous difference between the actual position on the ground and the equilibrium position in the designed trajectory generates the requisite GRFs (Ground Reaction Force) without solving complex inverse dynamics problems. Therefore, the stance-phase trajectory has to be designed from a different standpoint than the swing-phase.

MIT’s most recent quadruped robot was introduced in 2019, under the name **Mini Cheetah**. This quadruped is a lightweight, low-cost, and high performance partially open source quadruped robot. It weighs 9kg and can run up to 2.45 m/s while also having the ability to demonstrated highly dynamic behaviors including trot, trot-run, bounding, and pronking (spring into the air) and successfully land 360◦ backflips from standing. Similarly to ANYmal quadruped, Mini Cheetah utilizes SEAs (series-elastic actuators), with each actuator containing an electric motor, single stage planetary transmission, and power electronics. In order to achieve the low-cost “factor”, Mini Cheetah bears motors originally designed for remote control drones and airplanes instead of custom-built actuators like its predecessors. The four identical legs of the robot were made to achieve wide range of motion and minimize limb mass and inertia.

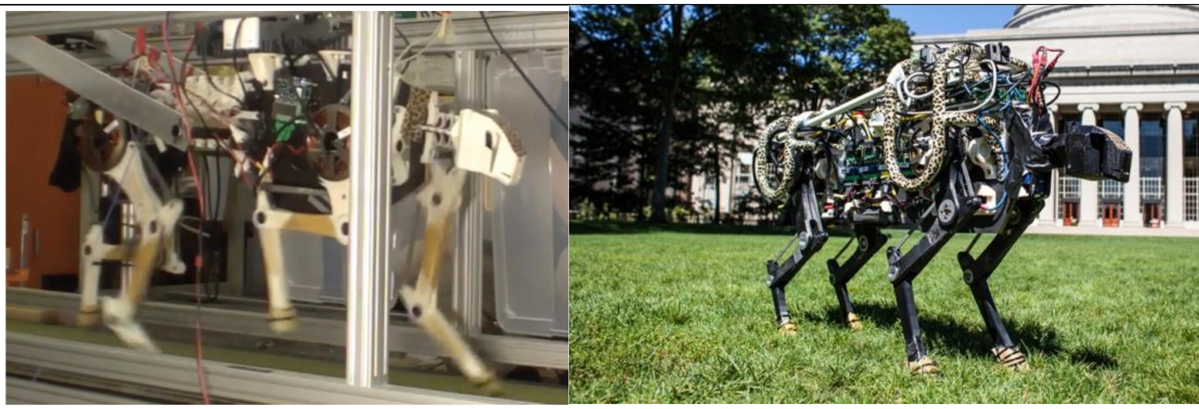


Figure 1-17 MIT Cheetah and MIT Cheetah-2 [31]

Figure 1-18 Mini Cheetah[32]

1.4.1.4 Boston Dynamics Quadrupeds

Arguably, Boston Dynamics Corporation (BDI), Massachusetts-based robotics firm, is considered to be one of the most influential and important pioneers in the field of robotics and especially in quadrupedal locomotion. Being also funded by the USA Defense Advanced Research

Project Agency (DARPA), the company in 2008 set out to develop a new breed of rough-terrain four-legged robots that capture the mobility, autonomy and speed of living creatures.

So, the quadruped named **BigDog**[33] was introduced in 2005, a 109kg robot driven by a hydraulic pump that delivers high-pressure oil to the actuators of the robot's leg actuators as shown in Figure 1-19. The actuators are low-friction hydraulic cylinders regulated by two-stage servo-valves of aerospace quality. Every leg of BigDog has a redundant leg architecture, has four active DOFs and a fifth passive one. The robot is equipped with a heat-exchanger, in order to reduce loss of efficiency due to overheating of the hydraulic oil and fifty sensors are integrated, like: joint position, ground contact, joint force sensors, ground load, a gyroscope, a LIDAR (Light Detection and Ranging) and a stereo vision camera. An onboard computer that contains a PC104 Pentium processor performing both low-level and high-level control realizes the control of the robot. Low-level onboard control regulates the positions and forces at the joints whilst, high-level control is responsible for functions, operation of the legs, provision of stability on rough terrain, and reflex responses to external disturbances. BigDog is adaptive to rough ground changes through terrain sensing and posture control. Lastly, a gait-coordinator algorithm that regulates inter-leg communication attains stable gait and so, the process for the transition of the robot's state is initiated. The next chapter for BigDog was not so fortunate however. Initially intended for military use, aiming to help with loads transportation of up to 400 pounds, when tested by US Marines, its potential possibility of being utilized in the army was challenged by the limitation that the robot is very noisy and hence, can be easily detected[34].

Figure 1-19 BigDog and LS3 Quadrupeds by Boston Dynamics[35]

Boston Dynamics presented in 2009 the quadruped named as **Legged Squad Support System (LS3)** [35], also known as Alpha Dog as shown in Figure 1-19. The LS3 bears significant resemblance to its predecessor, BigDog and has the form of a horse. The quadruped, is capable of tracking certain visual and oral commands and uses GPS (Global Positioning Systems), integrated computer vision and LIDAR in order to detect and generate the path to guide itself, whilst following the human operator through unidentified and rough environment.

LittleDog as shown in Figure 1-20 is the quadruped that followed in 2011, also created by Boston Dynamics. This robot was designed for research reasons regarding the development of algorithms that can reliably navigate over rough, irregular terrain which requires active selection of footholds and robot posture to overcome obstacles, comparable to the size of the robot's leg. Bearing three actuated DOFs in each leg, the robot weighs only 2.85 kg and is capable of traveling at speeds of over 25 cm/s. Each leg of the quadruped has incorporated encoders that measure the angles of the actuated joints, a potentiometer that produce analog signals corresponding to the length of the lower leg and strain gauges in order to measure the lateral forces applied to the foot of the robot. Lastly, LittleDog is equipped with an IR (Infra-Red) proximity sensor that has the purpose of detecting objects in front of the robot. The LittleDog API (Application Programming Interface) and data-logging systems were introduced to allow rapid and safe algorithm development, experimentation and allows users to perform a variety of control tasks. The API by formatting data from LittleDog's internal sensors, controls the joint coordinates relative to the robot's body and provides reasonably synchronous access to data from both the robot and the motion-capture system.

Figure 1-20 Little Dog quadruped [2]

Boston Dynamics introduced the fastest untethered quadruped robot in the world in 2013, named **Wildcat**[36] as shown in Figure 1-21, funded by DARPA. The total weight of the robot is 154 kg, and powered by a methanol burning engine that drives all hydraulic actuators, Wildcat can run up 32 km/h in outdor environment and successfully using a variety of gait patterns for locomotion like trot, gallop and bound, etc.

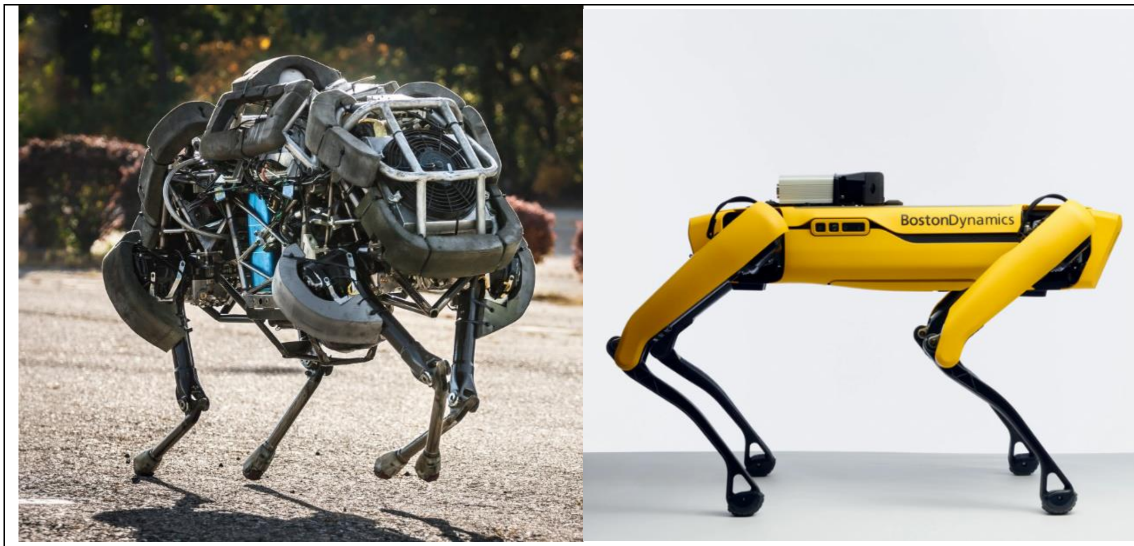


Figure 1-21 Wilcat Quadruped and Spot by Boston Dynamics[35], [37]

Perhaps Boston Dynamic's most recognized by the public and latest quadrupedal robot **Spot Mini**[38] as shown in Figure 1-21, often referred as "Spot", presents a new approach to dynamic robot control. The untethered dog-like robot can run up to 5.76 km/h with its dimensions being 1.1 m×0.5 m×0.84 m (L×W×H). Spot weighs only 30kg and has the capability of carrying 14kg of load. All the joints of the robot are electrically actuated and Spot, being powered by battery is meant for sensing and inspection in remote or hazardous environments. It is self-charging, allowing it to autonomously perform routine or on-demand data collection without human interaction[39]. Its built-in dock detection and tablet interface allows it to return home to charge at the push of a button or call of a task, without requiring operator directions. The Spot has an inbuilt 3D vision system with simultaneous localization and mapping (SLAM), providing depth information, enabling the robot to navigate its surroundings, and avoid obstacles.

Besides its basic capabilities, the bioinspired Spot leverages hardware to further improve safety, communications and behaviour on remote sites being able to climb, descend stairs, balance, and adjust to physical disturbance. The Spot becomes a most light-footed robot that can work in the office, home, and outdoor using its 5 DOF sensor arm. Interestingly enough, in 2019, Spot was utilized by Massachusetts State Police in two unnamed incidents for evaluating the robotic dog's capabilities in law enforcement applications, especially for remote inspection of potentially dangerous environments. Also, in 2021 Spot was reported being used by French army were part of a project by the École Militaire Interarmes school at a French army camp Saint-Cyr Coëtquidan for reconnaissance[40].

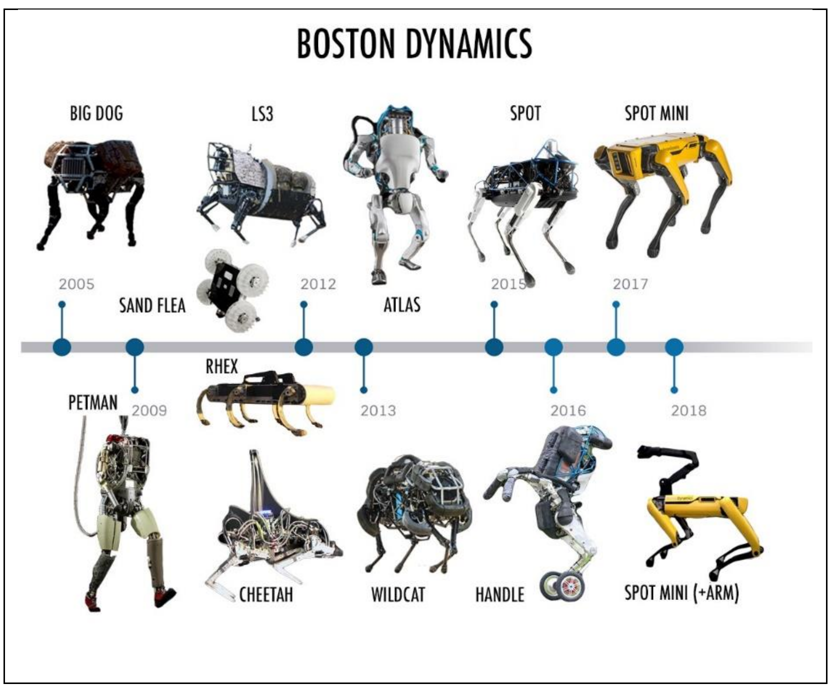


Figure 1-22 Brief Timeline of Boston Dynamics Corporation Robots

***This photo was sourced from an unofficial Boston Dynamics Reddit post:

https://www.reddit.com/r/BostonDynamics/comments/fa67ts/boston_dynamics_robotics_timeline/

1.4.1.5 Ghost Robotics Minotaur

The **Minitaur**[41], developed at the University of Pennsylvania in collaboration with Ghost Robotics, is a quadruped robot with symmetrically driven 5-bar linkages used as directly driven legs, meaning there are no gears or other mechanisms between the legs' drive motors and the legs themselves. This leads to an increased power efficiency as compared to motors with gears which may only have a maximum of 90% efficiency. This lead to the Minitaur being able to bound at a speed of 1.5m/s and jump about 50 cm vertically. The precise nature of the Minitaur allows for control across a variety of terrains while also being able to make small and precise movements.

This medium-sized robot features powerful outrunner motors that allows it to not only is able to perform running tasks, but also jump over complex terrain. Each leg is driven by two of these motors that allow it to run at speeds reaching 2.0 m/s, and jump to a vertical height of 0.48m

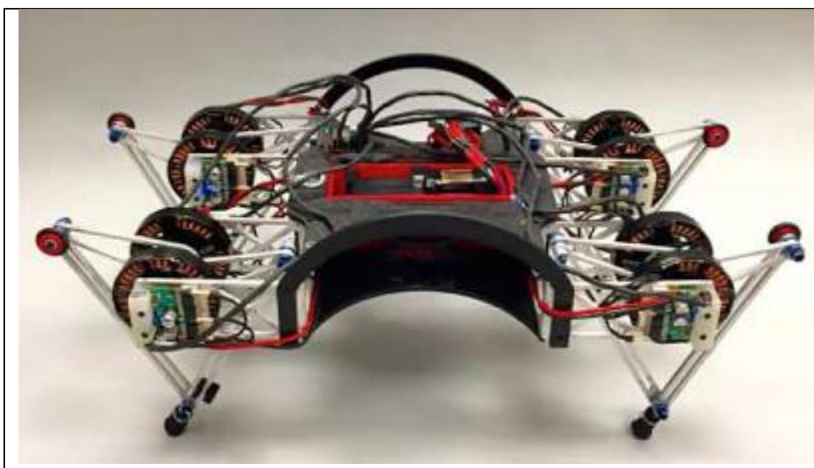


Figure 1-23 Minitaur quadruped [41]

1.5 OPEN SOURCE QUADRUPEDS

In this chapter, are being discussed some of the most recognized attempts for the creation of **Open Source** benchmark platforms in the field of quadrupedal locomotion research. Collaboration is at the core of open source robotics, enabling a diverse community of developers, researchers, and enthusiasts to work together, share insights, and collectively improve robotic technologies. Through this collaboration, a rapid exchange of ideas accelerates the development of cutting-edge solutions while maintaining transparency in the source code. In this way, thorough inspection is possible, leading to enhanced reliability and security in robotic systems. Furthermore, the cost-effectiveness of open source robotics allows for broader accessibility, enabling startups and educational institutions to experiment, learn, and contribute to the field. The Open Source model in robotics fuels a cycle of continuous development, learning, and innovation, pushing the boundaries of what robots can achieve and how they can positively impact various industries and everyday life. Below, we discuss a number of Open Source robotic builds in the field of quadrupedal locomotion that combine these three key characteristics: low-cost, easiness in replication and high performance.

1.5.1.1 Stanford University Open Quadrupeds

In this scope, the Department of Mechanical Engineering of Stanford University presented in 2019 **Stanford Doggo**[42] and in 2021 **Stanford Pupper**[43].

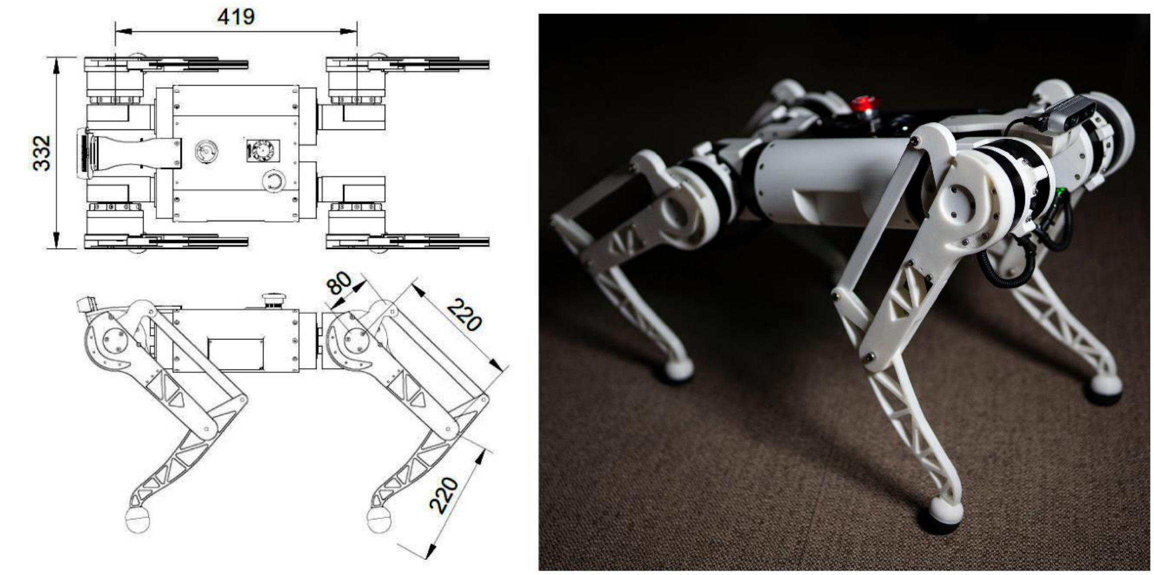
Stanford Doggo is driven by quasi direct drive (QDD) actuation and the four-legged robot is capable of demonstrating characteristics of dynamic locomotion; steady velocity during running, jump height, and vertical jumping agility. The mechanical design of Stanford Doggo utilizes a belt drive as a lightweight QDD transmission to increase the effective torque while maintaining low reflected inertia and transparency to enable sensitive control. The hardware and software to replicate this robot is open-source, requires only hand tools for manufacturing and assembly, and costs less than $3000.

Stanford Pupper is another effort aiming to make legged robotics research more accessible, cost-effective, and comparable across institutions. The Open Source quadruped robot is simple and easy to build with its components coming from off the shelf sources, making the lightweight robot an accessible, reliable platform that enables fast iteration. Pupper can be built from the ground up in under 8 hours for a total cost under $2000, with all components either easily purchased or 3D printed.

Figure 1-24 The Stanford Pupper and Stanford Doggo[42], [43]

1.5.1.2 PADWQ

This open source dynamic quadruped robot presented in 2021, **PADWQ**[44] (pronounced pa-dook) features 12 DOFs, driven by QDD actuators with high control bandwidth. Additionally it bears an onboard depth sensor and a GPU-equipped computer allows for movement in uncertain terrains. The quadruped is made of off the shelf components and 3D printed plastic making it affordable to reproduce. In order to ensure the rigidity of the robot's legs, a finite elements analysis is conducted on PADWQ and a number of walking tests.



(**a**) Overall Dimension (**b**) The assembled robot

Figure 1-25 The PADWQ quadruped[44]

1.5.1.3 D'Kitty by ROBEL

D'Kitty[45] is not a conventionally built quadruped. Funded by Google, the platform after the name ROBEL (Robotics Benchmarks for Learning with Low-Cost Robots) introduced the four-legged robot that simplifies learning agile legged locomotion tasks. With over 14000 training hours of on-hardware reinforcement learning, the low-cost, modular robot is easy to replicate, maintain and is robust enough to provide rigorous comparison between learning algorithms. D'Kitty offers a low barrier to entry with a cost of $4200, and an assembly time of less than 6 hours. However it need to be noted that the low-cost robot sacrificies performance to facilitate its accessibility. The servomotors that D'Kitty bears are too slow for dynamic moving, with a maximum speed of only 8 rad/s. In comparison, Stanford Pupper[43] servos that was mentioned above, reach velocities of 16 rad/s. As far as the transparency is concerned, the D'Kitty servos have a current control mode similar to the actuators on Pupper, but D'Kitty servos have high-reduction multi-stage gear trains with high nonlinear friction which impedes accurate torque control.

Figure 1-26 D'Kitty Quadruped by ROBEL[45]

1.5.1.4 SOLO-12Open Source Quadruped

The **SOLO-12 [70]** quadruped is open-source torque-controlled legged robot platform. The SOLO by PAL Robotic's project was launched in 2016, under the aegis of the Open Dynamic Robot Initiative in response to there being a low number of affordable advanced robotic platforms for learning at the time. Only weighing 2.2 kg, the four-legged robot follows this actuator module: a high-torque brushless DC motor and a low-gear-ratio transmission suitable for impedance and force control. The large range of motion that is a result of eight identical actuator modules and foot contact sensors make Solo suitable for locomotion in uncertain terrains. Solo reduces the build complexity by relying more heavily on 3D printed parts. The robot's dynamic capabilities, such as jumping and recovering from falls, make it ideal for testing complex algorithms and pushing performance limits. Its low weight facilitates easy transportation to different locations, promoting further developments. PAL Robotics' extensive R&D experience allows them to provide valuable advice on research with SOLO 12. Researchers can explore a wide range of areas, including animal-based limb movement, various terrains, reinforcement learning, dynamic locomotion, environment manipulation, and integration of advanced communications technology. PAL Robotics offers both a ready-assembled SOLO 12 robot and a SOLO 12 KIT, containing all necessary parts for users to build their own robot, with various accessories and components available as well. The full 8-DOF quadruped Solo built costs approximately 6300€.

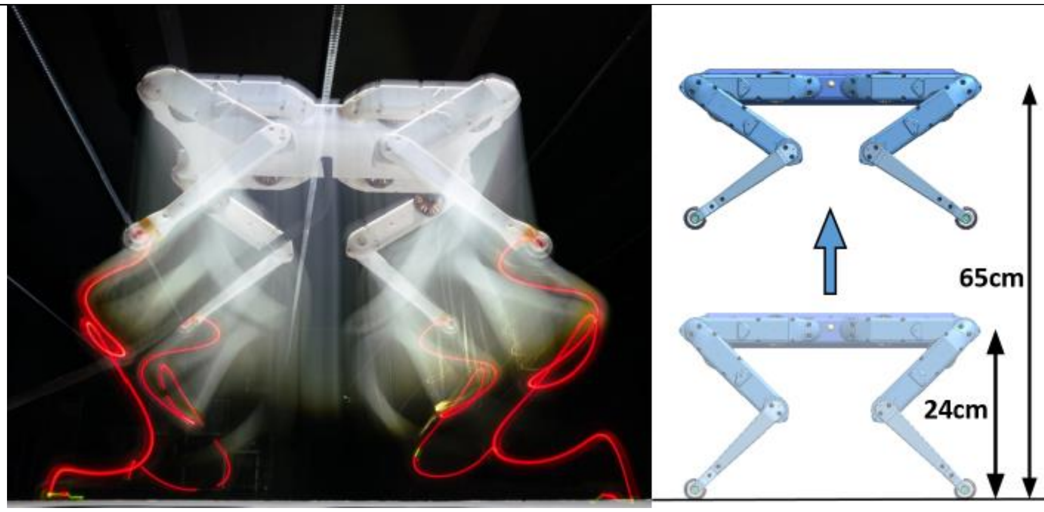


Figure 1-27 Quadruped robot SOLO-12 jumping [70]

1.5.1.5 Spotmicro quadruped robots family

Drawing inspiration from the Spotmini, the Korean engineer of **Spotmicro**, Deok-Yeon Kim designed the open source robot following the aesthetic of the of Boston Dynamics quadruped. Unlike its inspiration, Spotmini employs off the shelf components like Arduino Mega and servo motors (12 DOFs in total) and 3D printed parts. The project is open for robot enthusiasts to replicate in the Thingiverse platform however, the code for the robot is not provided making the Spotmicro a non-completed attempt since its creator was required to join the military in his country for two years and is absent from development.

Figure 1-28 Spotmicro Open Source Quadruped[47]

The Spotmicro robot sparked great enthusiasm in the community, especially as Spotmini's recognition from the public increased. Other quadrupeds emerged providing more information regarding the build and development of the novel effort in low-cost robots. SpotmicroAI platform provides the files for the 3D printed parts of the robot, instructions and a materials list (including electronics, sensors, necessary hardware tools), using either NVIDIA Jetson Nano or a Raspberry Pi 4 and a spotmicro repository in GitHub where instructions regarding a simulator with 12-point Bezier Curve gait for the robot can be found. Spot Mini Mini is a part of the Spotmicro - OpenQuadruped collaborative community that has created a reliable and versatile simulator in order to facilitate users that aim to creating the low-cost robot, with a repository with detailed instructions and "HOWTOs" about the project.

Figure 1-29 OpenQuadruped and Spot mini mini

1.6 APPLICATIONS OF QUADRUPED ROBOTS TODAY

Quadruped robots have demonstrated their remarkable versatility and usefulness across various industries and applications. Due to their high robustness and agile nature, these robots find significant applications in fields such as search and rescue operations in disaster areas after earthquakes,tsunami, landslides or avalanche where they can navigate challenging terrains and access areas not easily accessible to humans. Additionally, four legged robots are utilized in. In industrial environments by being employed for inspection and maintenance of infrastructure, pipelines, and complex machinery. Furthermore, quadruped robots are used in the field of entertainment and research, contributing to the development of lifelike animatronics and supporting humanitarian efforts for demining of former war zones. With ongoing advancements in robotics in over 3 decades, these versatile quadrupedal machines are bound to expand their utility, enabling humans to tackle an ever-increasing array of challenges efficiently and safely.

2.0 MECHANISM

The mechanics of multilegged robots define the fundamental characteristics of the robotic system, such as movement, workspace, and singularity, much like the skeletal system of mammals does. The biological skeleton has motivated the structure of several multi-legged robots mechanisms and their type synthesis is more complicated than that of simple serial or parallel robotic mechanisms. For a given motion pattern (gait), a legged robot can have its kinematic mechanisms with **serial, parallel or hybrid** topologies, as shown in Figure 2-1 and therefore, the uncertainty of topological states increases the difficulty of the type synthesis of multi-legged robots[48].

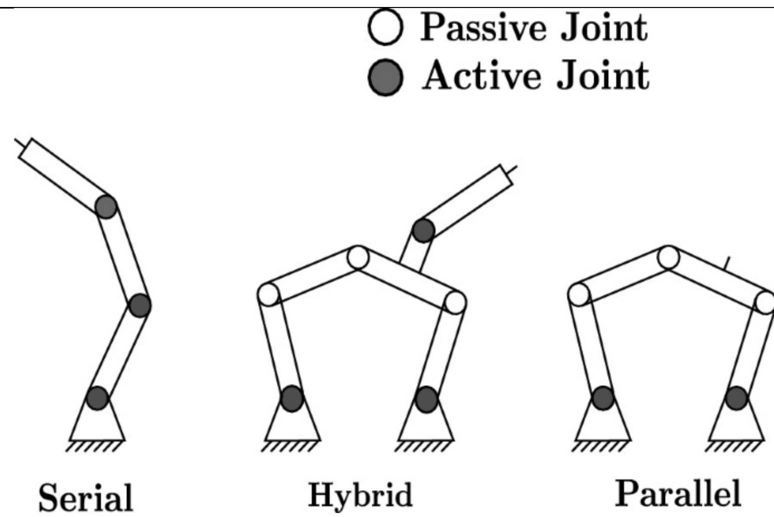


Figure 2-1 Basic Kinematic Topologies [70]

In general, **serial kinematic mechanisms** (SKMs) have larger workspace and dexterity, whereas **parallel kinematic mechanisms** (PKMs) bare higher stiffness and payload capacity.

Only a small number of multilegged robots use pure serial or parallel topologies, with serial topologies exhibiting great performance regarding dynamic control. For example, **ANYmal** [57],[58] (as shown in Figure 2-11) and **HyQ2Max**[55] (as shown in Figure 2-7)quadruped robots have pure serial leg mechanisms. Whereas, PKMs are typically used for leg structures of high-payload mobile robots. The serial parallel hybrid mechanism has greater rigidity than the SKM with the same DOF and a larger workspace than the PKM with the same DOF[48]. For some disaster rescue tasks, multilegged robots need both static and dynamic gaits for proper foothold and responsive locomotion respectively. Furthermore, although contemporary researchers primarily focus on performance analysis and on the design of specific quadrupeds, the actuation and control systems of robotic machines should be protected from potentially harsh environments and taken into consideration during type synthesis[48]. A hybrid leg mechanism can be a suitable solution[49]. It is clear that a systematic approach is needed to determine all types of configurations of walking robots, thereby allowing the development of the most promising designs. A number of four possible designs can be seen in Figure 2-2.

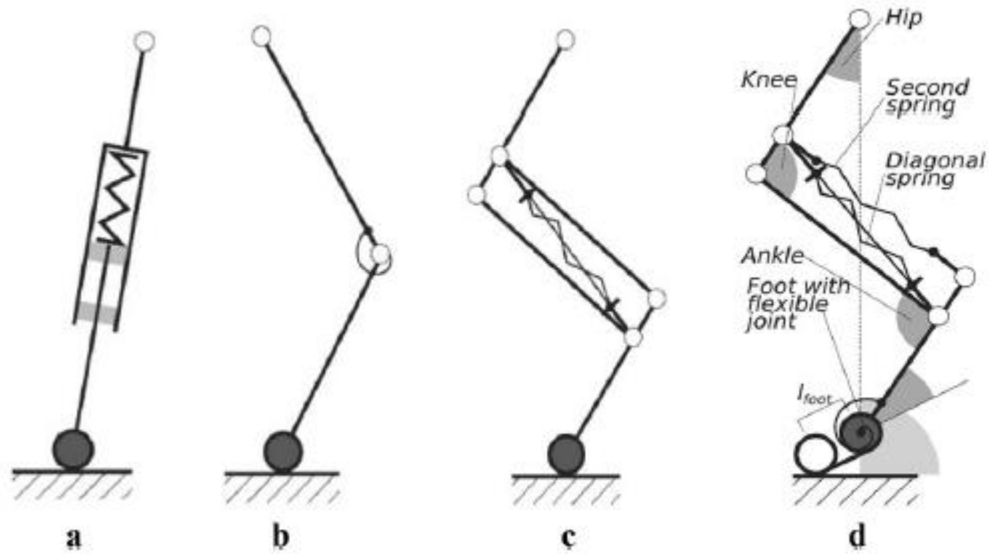


Figure 2-2 Possible designs for compliant legs: a) Telescopic-prismatic; b)Two-segment; c) Three-segment; d) Four-segment[50]

2.1 LEG ARCHITECTURE

It is maybe best to discuss the type synthesis of quadruped robots through the classification of the nature of the leg's segmentation and the number of degrees of freedom. In the next section, we introduce three different types of legs through the prism of actuation: Prismatic, Articulated (both Mammal and Sprawling types) and finally Redundant leg structures.

2.1.1 Prismatic Legs

With the term leg segmentation, we refer to the number of joints and links of the robotic leg composition. Figure 2-2 displays different designs for legged robots. The simplest case of legged robot systems is that of a prismatic leg design, applying a sliding or telescopic mechanism alongside with an actuated rotary hip joint. This particular type of leg design depicts early quadruped robots with such legs, such as Raibert's MIT Quadruped robot[51] and Scout II robot[52].

The **MIT Quadruped** robot actuates its legs by hydraulic pistons, as shown in Figure 2-3. The robot's prismatic leg is driven by a hydraulic actuator in series with an air spring. It is able to actively protract, retract, adduct and abduct, as well as shorten and lengthen its legs. Drawing inspiration from Raibert's design, Ahmadi and Buehler designed "ARL Monopod II"[53], a motor-ball screw-type prismatic leg as shown in Figure 2-3. This alternative approach of a leg design, is driven by a linear motor-ball screw-spring mechanism for compliant drive. The periodic drive of the motor supports a quasi-static vertical oscillation between the weight and the leg spring. Instead of using a hydraulic actuator and an air spring this design uses an electric ball screw and a helical compression spring in order to better simulate an animal's Achilles tendon. Finally, Scout II designed by Poulakakis[52] uses an electrical hip actuator and passive compliant prismatic legs as shown in Figure 2-4. With no active actuators, the leg achieves the telescopic movement through its spring. The passive – active leg design allows for a lightweight and compact distribution with low inertia while also ensuring enough rigidity to withstand repeated loads, achieving fixed lengths and complying operation.

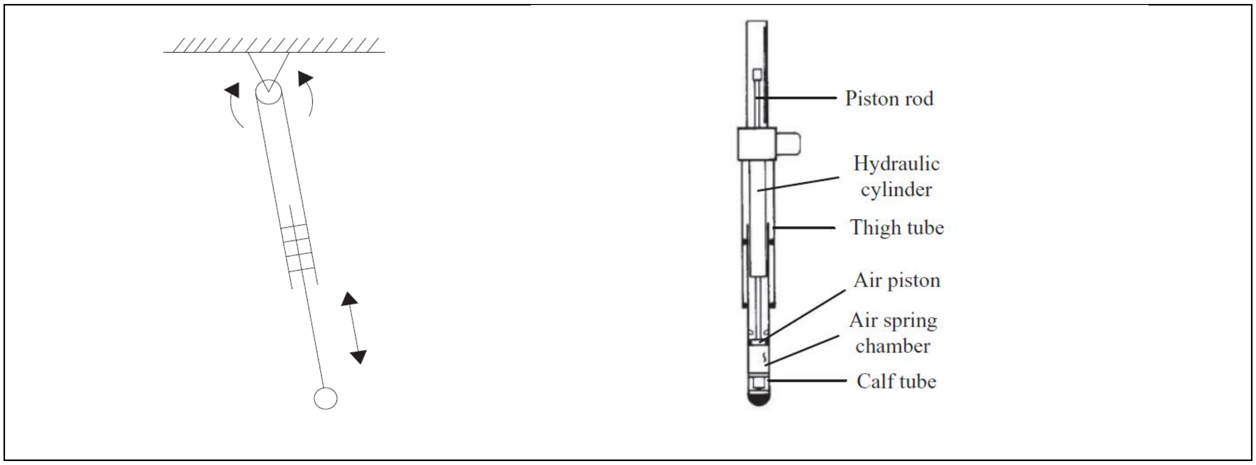


Figure 2-3 Left to Right: Prismatic legs topology and Hydraulic prismatic leg [54]

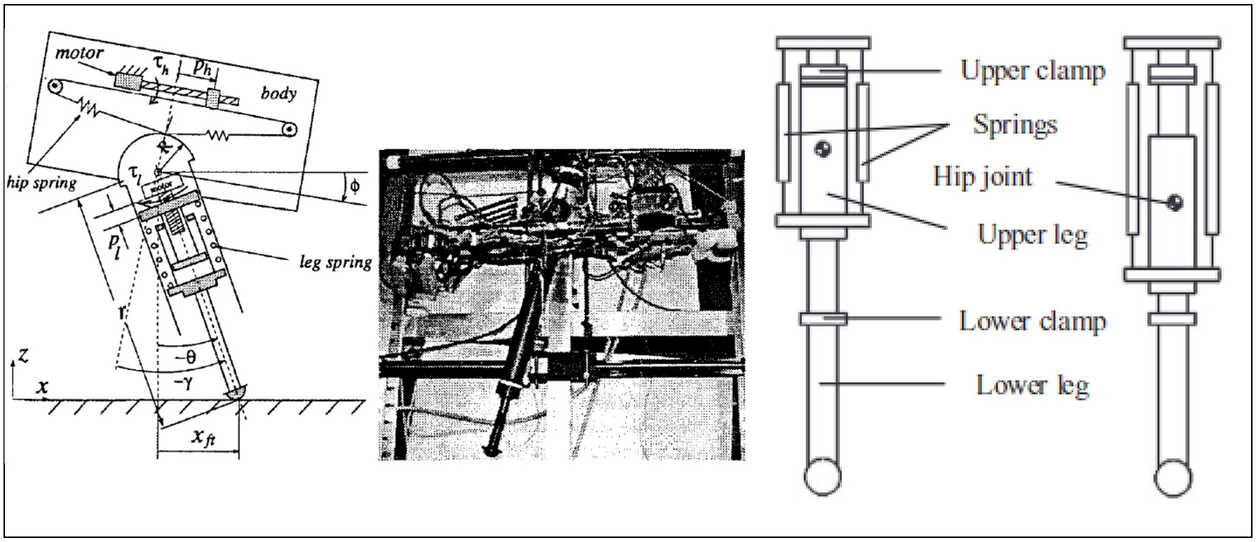


Figure 2-4 Motorized scew-type prismatic leg, MIT quadruped, Passive active prismatic leg [54]

2.1.2 Articulated Legs

An alternative to prismatic legs is the segment of articulated leg. It incorporates a comparable function to the knee or elbow joint of the animal leg and has great biomimetic characteristics. Two-segment articulated legs as shown in Figure 2-2, opposed to prismatic compliant legs, offer self-stable running for a wider range of forward running velocities and encourage stability against changes in the leg's angle of attack and the robot's apex height.

According to the type of their configuration, articulated legs can be divided in either mammal-type or sprawling-type leg structures[6], as shown in Figure 2-5. The key difference in these two types falls into the positioning and placement of the leg relatively with the rest of the robot’s body. In the case of mammal-type, the leg is positioned vertically, downward from the hip joint in most cases. On the other hand, sprawling-type indicated that the first leg segmentation is positioned in the horizontal direction.

It appears that mammal-type robots exhibit higher velocities of walking speed, smaller footprint that makes it easier to navigate in narrower spaces and lower driving torque. The latter, is the outcome of almost no joint torque when in stance phase and small torque when the leg is bent. Interestingly enough, sprawling-type robots exhibit more stability since the gravity can be adjusted in lower positions and the body itself serves as support for the robot while standing. Therefore, sprawling-type leg robots have both wider range of motion while maintaining higher security. Figure 2-5 shows the two different types of topologies of articulated legs.

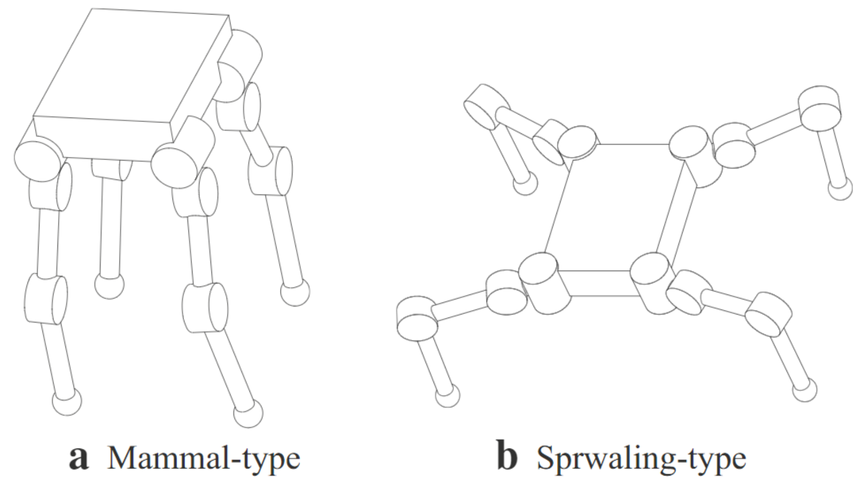


Figure 2-5 Topologies of robots with articulated legs [6]

2.1.2.1 Mammal Type articulated legs

Recognized proposals of quadrupedal robots with articulated mammalian-type leg designs were discussed in the chapter of *1.4.1.4*. **Wildcat** quadruped robot, **LS3**, **Spot** and **SpotMini** were all developed employing two-segment articulated legs. However, the specifications of these robots are yet to be published; information of the mechanisms and structure can only be derived from online videos published by the company.

It is important to mention that, both Wildcat and the LS3 quadruped (mentioned in 1.4.1.4) are powered by a two-stroke gasoline engine-hydraulic pump electric servo cylinder. Due to its higher power density than a four-stroke engine, two-stroke engines are employed and are equipped with hydraulic energy storage tanks in order to avoid slow response and oil pressure fluctuations. Additionally, the articulated quadruped Spot robot is driven by battery-motor-hydraulic pump-electric servo hydraulic cylinder. With the energy supply mode changed, the noise issue that arises when the robot is operating can be successfully reduced, resolving a major problem Boston

Dynamics faced with *BigDog in 2005.* The quadruped SpotMini is also driven by battery-motor. Removing the hydraulic pump and the electric servo has proved to bring more flexibility to the structural design. Moreover, SpotMini's knee motor is placed at the hip joint driving the knee joint by traction mechanism. Subsequently, the inertia of the leg is reduced as well as the noise of the mechanism. SpotMini has been known as Boston Dynamic's quietest quadruped robot.

Semini developed the **HyQ**[23], [25] quadruped robot, which bears articulated legs, and so did its successors, the improved **HyQ2Max**[55] quadruped robot and the lightweight **MiniHyQ**[56]. As shown in *Figure 2-6*, the HyQ quadruped uses electro-hydraulic articulated legs. The main advantages of this design choice are high speed and high torque of the hydraulic system and the compact structure of the electric actuator. In other words, the drive system provides high speed, high power-to-weight ratio, and robustness against torque peaks required for hip flexion/expansion joint and knee joint but also enables compactness of the Hip Abduction/Adduction (HAA) joint structure. The HAA joints are consisted of a tubular structure and a number of ball bearings that distribute the loads, achieving a firm connection between the leg and the body. The thigh of the robot leg has parallel ribs that connect through links and a passive prismatic reduces the leg's ground impact.

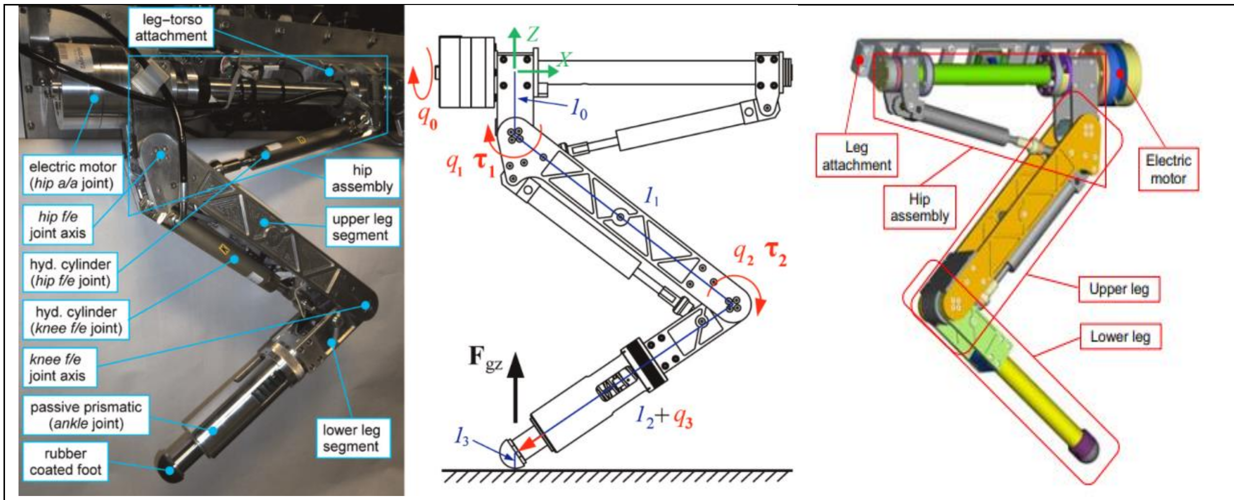


Figure 2-6 HyQ quadruped articulated leg. [23]

In 2015 the quadruped **HyQ2Max**[55] is introduced, heavily based on the morphology, torque control and hydraulic actuation technology of HyQ. This robot has a wider range of motion, higher joint torque, achieves higher velocities of locomotion, can handle higher payload, its design is more robust and finally, it is self-righting. Similar to HyQ, each leg of HyQ2Max has three joints: Hip Abduction/Adduction (HAA), Hip Flexion/ Extension (HFE) and Knee Flexion/Extension (KFE) as shown in Figure 2-7. As we can see in the picture, between HAA and HFE, there is a 0.1-meter sideways offset. The Hip Abduction/Adduction (HAA) joint utilizes a double vane rotary actuator and can output rotational motions directly; The KFE joint is actuated by a single-blade rotary hydraulic cylinder combining with a four-bar linkage as transmission. This linear actuator facilitates the need for the knee joints to produce large torques in one direction (leg extension) and much smaller torques in the other (leg retraction).

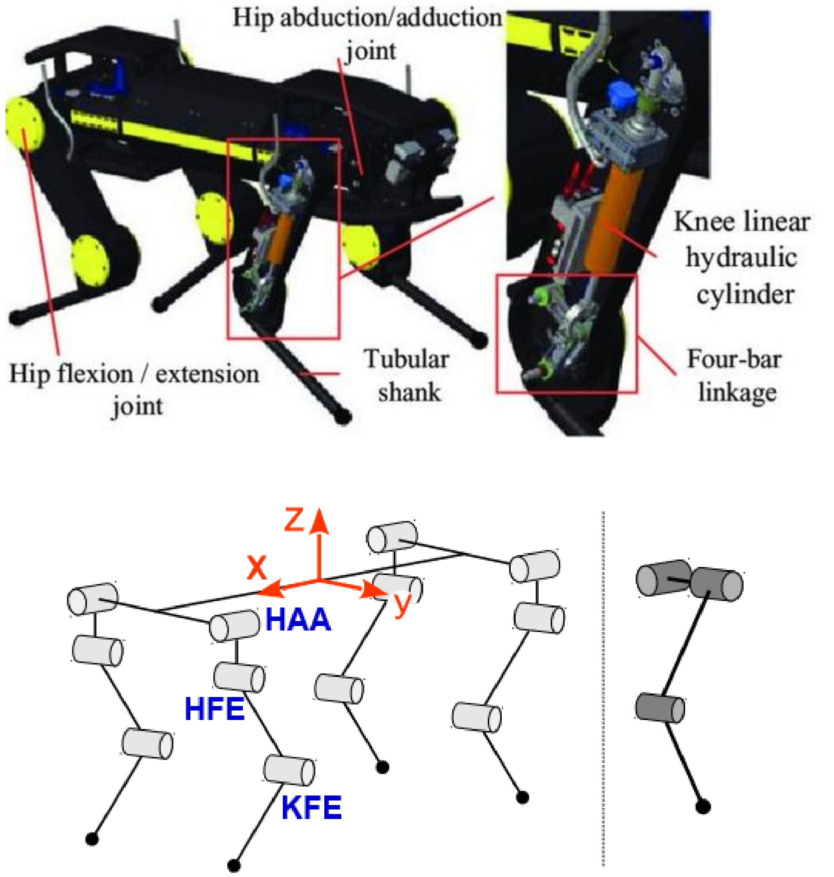


Figure 2-7 HyQ2Max: Hydraulically driven quadruped robot.[55]

In the same year, 2015, **MiniHyQ**[56] is presented. What this four-legged robot achieves is a lightweight proposal with carefully selected “miniature” hydraulic actuators that reach a wider range of joint movement while also reducing the weight distribution in the legs. Both linear hydraulic actuators and rotary hydraulic actuators are driving the hip joints of the robot. The electric pump is powered by the onboard vehicle battery and in order to reduce the weight of the legs as much as possible a centralized manifold is placed in the torso. As a result, the electric pump can provide 13 L/min flow rate and 20 MPa of pressure in each leg successfully instead of using distributed manifolds on each leg. The articulated leg of MiniHyQ consists of three active DOFs per leg: HAA, HFE and KFE. The two later leg joints are responsible for generating main tasks of straight walking and running movement of the robot while the Hip Abduction/Adduction joint is responsible for the balance of MiniHyQ. As stated in the published paper[56], a rotary hydraulic actuator has wide range of motion and constant torque, although it is heavier than a linear actuator. With the intention of decreasing the weight of the robotic leg instead of using rotary hydraulic actuator in both HFE and KFE joints, a linear actuator is chosen in the Knee Flexion/Extension joint reducing the leg inertia significantly.

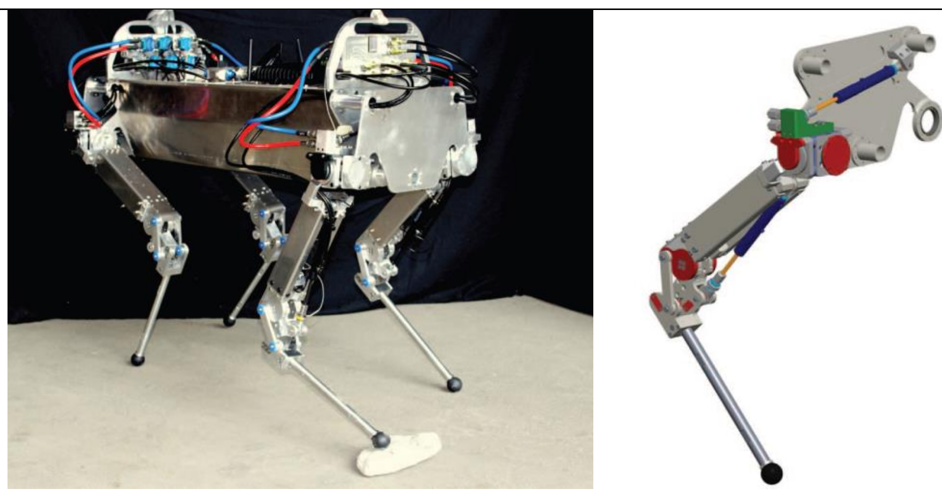
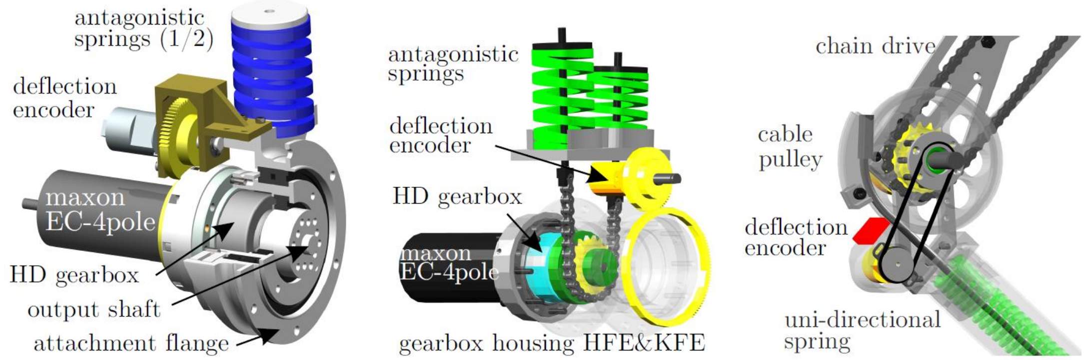


Figure 2-8 MiniHyQ: Photo of the quadruped and CAD design of the Leg which consist of 3 active DoF i.e., HAA, HFE and KFE.[56]

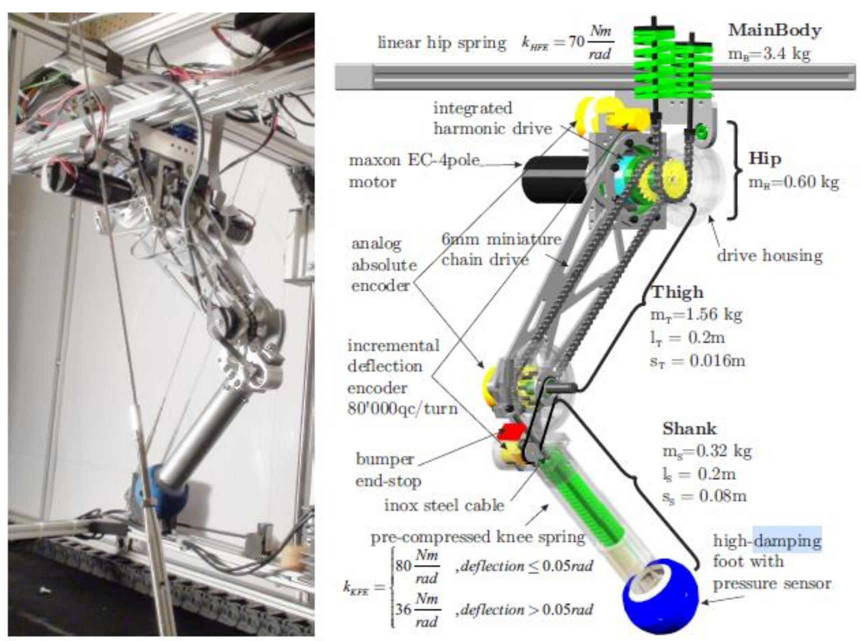
Hutter and his team developed the **StarlETH** [26], [27] and **ANYmal**[57], [58] quadruped robots with articulated legs in 2013 and 2017 respectively. A Series Elastic Actuator (SEA) drives the mechanical leg of StarlETH. Creating the following structure: What realizes the compliant output of the joint and the upward movement of the joint motor is a compact design with a micro-drive chain/cable pulley and a linear compression spring, as shown in *Figure 2-9.* Subsequently, joint mobility is significantly higher than what could be achieved with a design based on linear actuators. The robot's leg is fully extendable and retractable while the hip joint has a big swing angle, although the cabling of StarlETH is limiting to the abduction angle range. Aiming to resolve the "**damping dilemma**[4]" as stated in Hutter's published paper "StarlETH & Co."[26] the design of the robot benefits from the non-linear spring damping characteristics. During stance phase of the quadruped both damping and linear, torque/deflection ratio are relatively reduced. At the same time, the need for both high damping and no oscillation during flight phase is satisfied. Finally, the robotic leg is made from thin parallel joints whose interstice allows the drive chain mechanism to be installed and protected. The shank is a cylindrical tube, and the elastic elements of the knee joint are arranged inside.

[4] Damping Dilemma [26]: the joint should have low damping during stance phase (to maximally support the vertical mass-spring oscillation that characterizes most running gaits) and high damping during swing phase (in order to quickly control the position of the foot point to maintain and balance a locomotion gait).



(a) HAA (mixed) (b) HFE (inverse) (c) KFE (classic)

Figure 2-9 ScarlETH: Compliant Joints a) HAA joint; b) HFE and KFE joints; c) Chain drive connecting to knee joint and photo of ScarlETH articulated leg.[26]



(a) Single leg test bench (b) CAD visualization

Figure 2-10 ScarlETH: Mechanical System Description of the SEA principle for HFE and KFE joints.[26]

As far as the quadruped **ANYmal**[57], [58] is concerned, its joint unit deploys series elastic actuators with highly integrated electronics, sensors, and joint axle bearings for advanced interaction. Hence, the robotic legs of ANYmal do not require additional sensors, and joint axle bearings. Moreover, high torque motors and harmonic drive gears in series with a rotational spring support the robot. Joint output position and spring deflection are measured using absolute position sensors providing high accuracy and great torque resolution. The joint arrangement of ANYmal is chosen mammalian with a HAA joint, a HFE joint and finally a KFE joint. Contrasted with the previous robot of the team, StarlETH and other quadrupeds like MIT Cheetah, HyQ and BigDog likewise, ANYmal has its legs built in with an offset, allowing necessary space for undisrupted rotation.

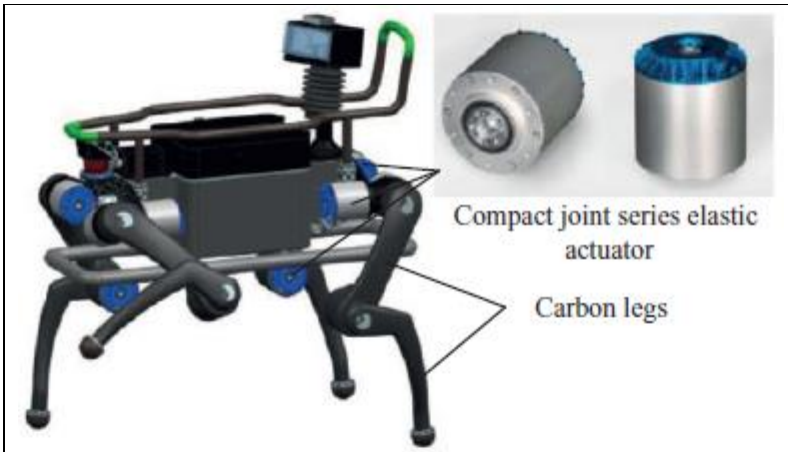


Figure 2-11 ANYmal: SEA-driven quadruped robot [57]

2.1.2.2 Sprawling Type articulated legs

By introducing the TITAN series (mentioned above in *1.1*), the Tokyo Institute of Technology created a recognizable work and a very good example in the direction of sprawling-type articulated legs, with the quadrupeds using this type of leg. Their most recent four-legged robot **TITAN-XIII**[6] features a lightweight and compact mechanical leg for high speed, energy efficiency, with high stability, wide range of motion, and ease of maintenance (shown below in Figure 1-3).

TITAN-XIII's leg bears the unique design of a wire-driven mechanism that includes a brushless direct current (DC) motor, a planetary gear set, two synthetic fiber cables, and input and output pulleys. In order to compensate for this design expansion, a coaxial tensioner shaft is installed as the input pulley to the wire-driven mechanism. By using the wire-driven mechanism to transmit power to each axis, the inertia is reduced since the motors can be placed at the base of the leg, with this particular architecture allowing for easier disassembly and therefore, easier maintainability. Furthermore, as a transmission and reduction mechanism to drive the hip yaw joint a timing belt mechanism is utilized, which is composed of small timing pulley, big pulley, and a timing belt (as can be shown in **Error! Reference source not found.**). Lastly, the connection b etween the two links of the leg has been taken into account, with an offset between them ensuring the avoidance of collision between the two links during parallel folding and expanding the range of motion of the quadruped.

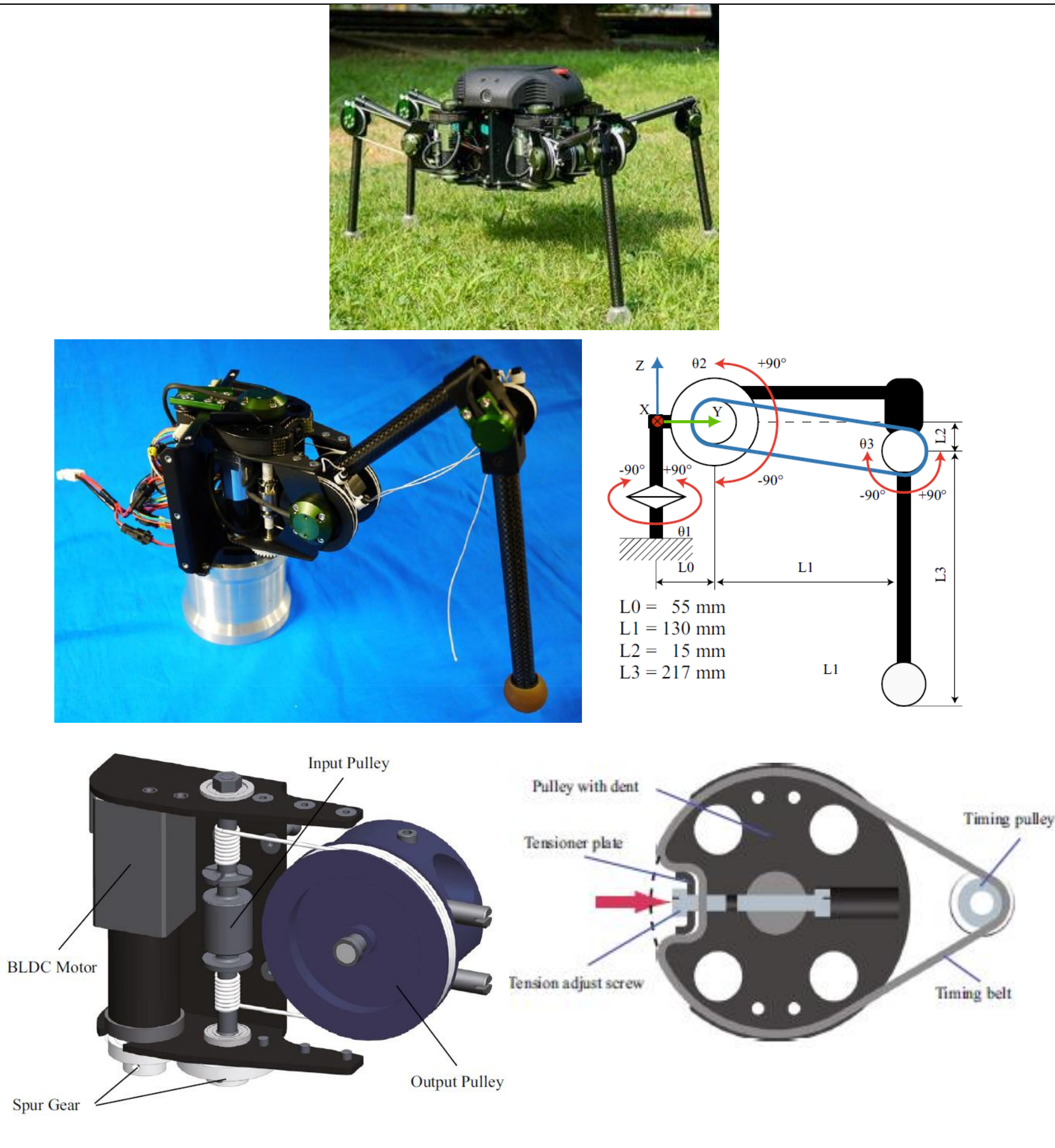


Figure 2-12 TITAN-XIII: (middle) Photo & Basic structure (down) Wire driven leg mechanism & Pulley CAD figure [6]

2.1.3 Redundant Legs

Redundant articulated legs is the extension of the articulated leg architecture with one or more rotating joint additional to the design (shown in *Figure 2-13*). In 2001, Dr. Hartmut Witte[59] suggested that for a three-segment leg model applied in small mammals, during the contact of the leg with the ground the most proximal and distal segments are held in parallel most of the time. This biological behavior inspired the pantograph leg design for legged robots, and proposed a **pantograph structure**, which extracts main mammalian leg features, such as three-segmentation, segment alignment, and compliant elements. Robots like Cheetah-cub[50], [60] and MIT Cheetah are designed to mimic nature and bare the three-segment “pantograph” leg model and have better biomimetic and kinematic properties in geometric topography.

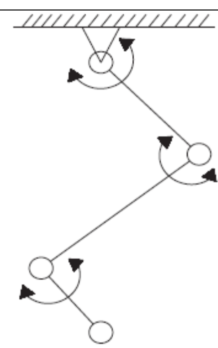


Figure 2-13 Topology of redudant articulated legs [59]

In the case of the **Cheetah-cub series**[50], [60] of quadruped robots with redundant articulated legs the mechanical leg design is bio-mimicking the cat legs. Two leg designs were proposed: a first design with a three-segment, SLP leg. In addition, a second, four-segment ASLP leg, with in-series elastic elements (as shown in *Figure 2-14*). The leg configuration based on a spring-loaded pantograph mechanism allows for very good leg compliance and very low leg stiffness.

The inertia of the leg is reduced by the placement of both RC servo motors proximally. The hip/shoulder actuator is directly mounted between body and leg and the knee actuator is attached to the body's center. The role of the knee actuator is only to retract the leg (by pulling on a cable) and not to extend the leg (leg extension is solely due to the antagonistic, gravity-loaded springs). The cable mechanism comes from the knee motor and is connected to the lower end of the diagonal spring through the idler pulley at the hip joint. In order to facilitate the separation of the knee and hip motor movements a low radius idler pulley is utilized, also allowing the proximal mounting of both actuators. The ankle joint is passively driven by a biauriculate spring element; it smooths the impacts impacts of the ankle joint when touching the ground, and realize the passive compliance of the leg, so that the robot's self-stability and maximum speed are improved.

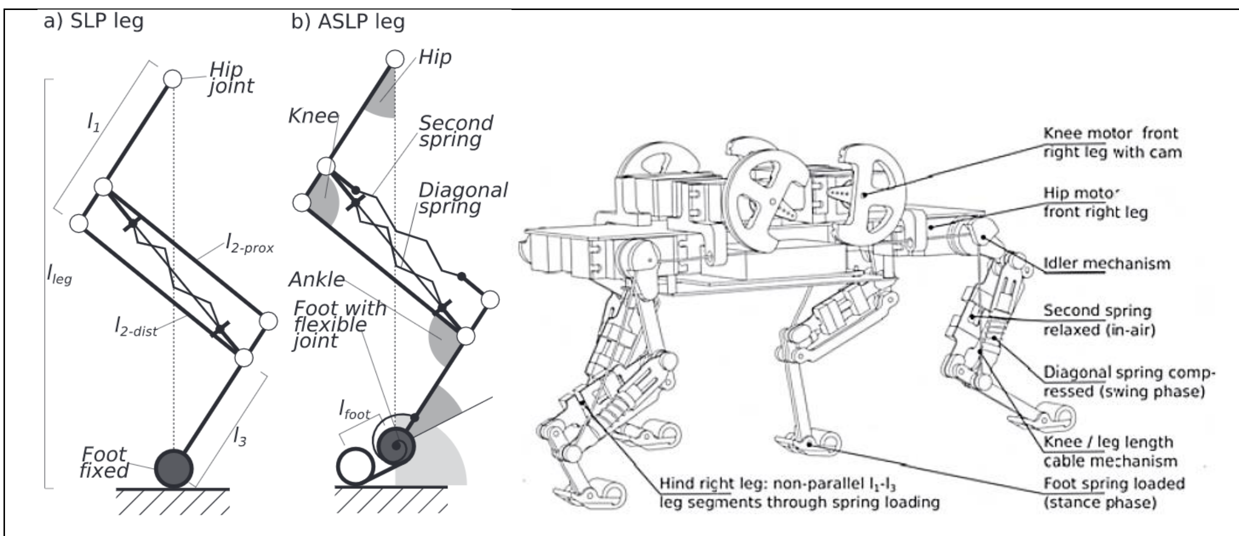


Figure 2-14 Cheetah-cub quadruped: a) SLP, b) ASLP leg structure & Quadruped Schematic[50]

3.0 ACTUATION

In the previous chapter, a number of dynamic legged robotic systems were discussed, often focusing on the demanding requirements like the ability of accurate velocity control, low impendance force controllability and high impact robustness. It is only common place then, that the decisions taken regarding the actuation of the robot places unique demands on the both the performance specifications and passive mechanical characteristics of the actuator and legged locomotion introduces unique challenges to the process of actuator design. It is possible to define metrics for guiding the design process for these individual requirements. Yet, it is not clear how to design an actuator to satisfy many conflicting requirements given the numerous couplings among them.

For example, dynamic gaits such as running, require high stride frequency and low duty factor. From the theory of momentum conservation, the relationship between the total vertical impulse F_z, gravity G and T is the period of cyclic locomotion, can be written as:

$$\int_0^T F_z \, dt = GT \tag{1}$$

From the equation (1) above it is shown that with the increase of the ground reaction force, the duty factor decreases. Correspondingly, the increase of ground reaction force comes with the increase of speed. Biological muscles might be considered an ideal actuator – capable of compliant yet high-power operation in a compact form factor. To bring an example, maximum reaction force of a dog’s leg is around 2.6 times its bodyweight when the dog is running with a velocity of

9m/s[61]. In order to satisfy the condition of high output torque, different types of high power density actuators have been created. In the next chapters three categories of actuation technologies are going to be discussed, which are vastly used in legged dynamic locomotion, namely: Hydraulic actuators, Quasi-direct drive actuators (QDD) and finally Serial Elastic Actuation.

3.1 HYDRAULIC ACTUATION

Hydraulic actuators are naturally robust against impulsive loads, provide high power, and force density. Thanks to fast valve units in combination with load cells for force measurement or pressure-based force estimation, hydraulic actuators provide also high performance torque control and are driven by a pressurized fluid such as mineral or synthetic oil or water; this particular part of their design allows hydraulic actuators to retain robustness against impact. For these reasons many noticiable efforts in the field of robotic quadrupeds have utilized this type of actuation such as BigDog, LS3 , the robots of the HyQ series, Cheetah and ATLAS.

On the other hand, hydraulic actuation poses some limitations. To begin with, hydraulic actuators are often bulky and heavy which places limitations regarding experiment conduction. During experiments, appropriate safety and human resources are required. Additionally, this type of actuation is commercially widespread in industrial applications, such as excavators and bulldozers. When it comes to smaller scale implementations and more significantly in the field of quadrupedal robots, hydraulics are only found in niche markets.

With the aim of actuating a hydraulic robot, a combustion engine is necessary to pump the actuators. It needs to be noted that, while using a combustion engine it is difficult to conduct indoor experiments, because of the noise and the exhaust fumes. Normally for indoor experiments an external electric pump is used to supply hydraulic power to the robot by means of two hydraulic hoses. These hoses can negatively affect the dynamics of the robots, causing unpredictable disturbances and restricting the working range of the robot in a circumference around the pump. Besides, the fluid viscosity loss and internal leakage of the servo valve, makes hydraulic actuators susceptible to energy inefficiency[62]. Finally, although hydraulic actuation facilitates the construction of high DOF machines, often lack versatility necessary to perform a wide range of joint movement. It is because of limited joint range of motion and its torque limits.

3.2 QUASI-DIRECT DRIVE (QDD)

With contemporary advancements in the field of electric actuators, the power mass density of available servomotors has seen a significant increase (continuous up to 7 kW/kg, 3-5 kW/kg)[63], even exceeding this certain ability of biological muscles (Max. 0.3 kW/kg). However, the high power is available only at high speed with relatively low torque compared to muscles. Torque density can be improved by gear reduction but at the same time, this increases the actuator's passive impedance meaning; reflected inertia, friction and damping[63]. The outcome is no other than limitations in bandwidth and compromising of transmission or the so called "transparency[5]" which is of great importance in high speed force control[64]. Moreover, the friction that occurs in gears is highly nonlinear resulting in limitation of force control performance because of the mechanical impedance of the gear train, causing non-desirable force in fast dynamics. So it becomes clear that a critical tradeoff in EM actuators seems to be the compromise between high torque density and low actuator impedance. The joint mechanical impedance is proportional to the square of the reduction ratio. Joints with high reduction ratios do not have back drivability. Without this ability, it is difficult to obtain high bandwidth torque control

The team of the Cheetah robot series set out to create a mechanical system that would be able to withstand high ground reaction forces followed by high impacts on the ground by designing a novel "proprioceptive electric actuators" for legged locomotion. This effort showcased that with the correct design approach, electric motors demonstrated remarkable results with high-torque-density (mass-specific torque) and very low gear reduction to improve the load capacity and low-speed efficiency. These actuators with very low reduction ratios are named quasi-direct drive (QDD) actuators[65] and are able to obtain notable "transparency". In addition, the torque control (which is based on the current control of the electro motor) can be performed in high bandwidths, since the output torque is equivalent to the regulation of the motor's current. Therefore, each actuator has one position sensor, no force or torque sensors, and relatively simple transmission. There are two important evaluation indices for electric motors that are directly linked to the gap

[5] Transparency: A characteristic which means the reflected inertia of the actuator is much smaller than the output inertia

radius of the motor. The first one is peak specific torque K_{ps} for instantaneous performance and thermal specific torque K_{ts} for steady performance[66], can be seen in Figure 3-1 & Figure 3-2:

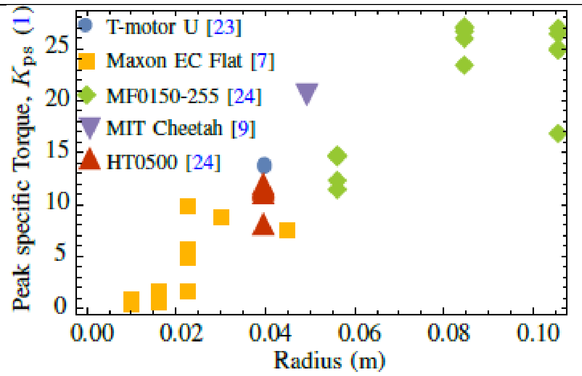


Figure 3-1 QDD actuation: Peak Specific Torque against gap radius for a selection of legged robot actuators. [66]

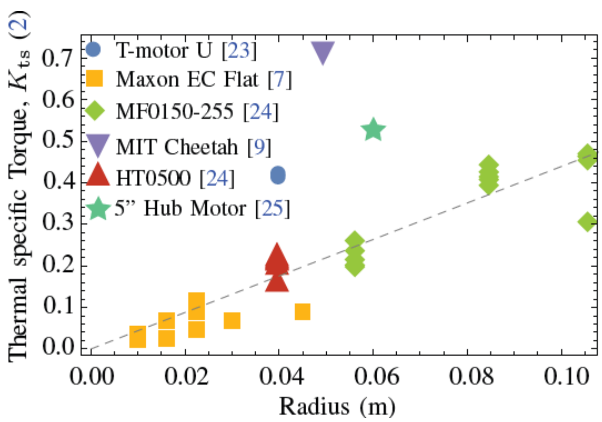


Figure 3-2 QDD actuation: Thermal specific torque against gap radius for a selection of legged robot actuators.[66]

We need to underline however, that the proprioceptive electric actuator technology with low gear reduction ratio cannot satisfy the actuation requirements of larger scale legged robots, despite the fact that QDD actuators have been successfully employed for small-legged robots as the quadruped robots of the Cheetah series.

3.3 SERIAL ELASTIC ACTUATION (SEA)

Series elastic actuators (SEA) combine a conventional highly geared electric motor, a spring and spring displacement sensors at the output. High quality force control is achieved through low impedance and friction and consequently, SEAs apt for in unstructured environments. Series Elastic Actuators replace stiff load cells (which are delicate, expensive, and induce chatter) with a significantly compliant elastic element (which is robust, inexpensive and stable). As shown in Figure 3-3, SEAs bring great resemblance topologically with any motion actuator with a load sensor and closed loop control system[67].

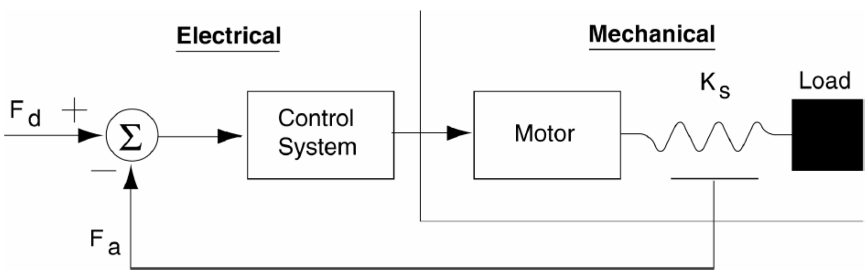


Figure 3-3 Schematic diagram of a Series Elastic Actuator[67]

This type of actuators diminish the effects of friction and inertia by using active force sensing and closed loop control. Moreover, by measuring the compression of the compliant element, the force on the load can be calculated using Hooke's Law. Accordingly, the output torque can be controlled by spring deflection. A feedback controller calculates the error between the actual force and the desired force, applying appropriate current to the motor to correct any force errors. In the meantime, the elastic element can store energy and increase peak power while the spring and servo motor do work in the same direction. Besides, the compliant element can protect the gearbox from being damaged during impact.

Series Elasticity allows for greatly increased control gains by introducing significant compliance between the actuator's output and the load and the torque control case becomes a position control case. In *Figure 3-4*, a characteristic SEA control architecture is shown. We see both the inner torque and outer position control loops; a PID controller friction compensation, and a feed-forward term for the torque control loop.

However, substantial delay and limited bandwidth in the position control appear as drawbacks of SEA actuators, particularly in cases of high velocity locomotion in legged robots. Quadrupeds that utilize SEA actuators have weaker actuation performance to complete dynamic maneuvers like high-speed running which have been demonstrated on the MIT Cheetah robots and the hydraulic robots from Boston Dynamics.

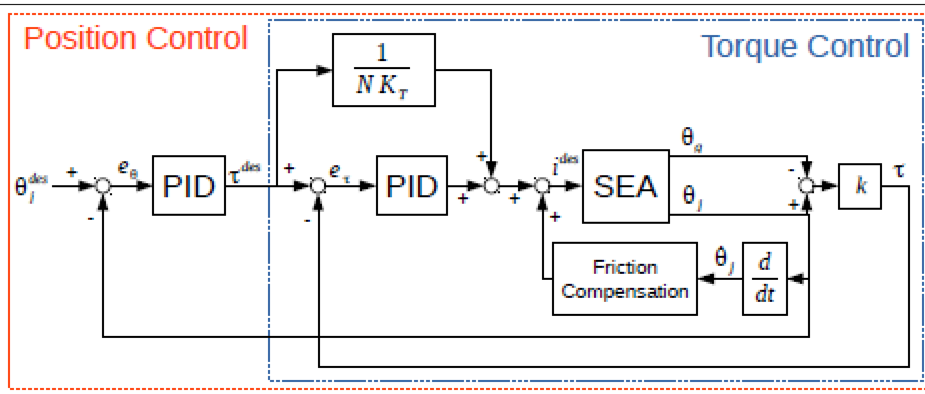


Figure 3-4 SEA block diagram[57]

Block diagram of the cascaded joint position and torque control loop. The SEA block represents the physical actuator unit including field oriented control (FOC) to apply the desired current i^{des}

4.0 CONCLUSIONS

Bionic inspiration is still the driving force behind quadrupedal robotic design and development. In the chapters above, a number of four-legged robots were discussed, that date all the way back to the middle of the 20th century until todays' current milestones in the robotics filed presented by Boston Dynamics (Spot), the Swiss Federal Institute of Technology (StarlETH), the Italian Institute of Technology (HyQ series) and so on. The fundamental focus remained the different topologies of the mechanical structure and the available solutions regarding actuation that contemporary quadruped robots offer. At the same time, novelty suggestions in the field were discussed, posing particular interest for future implementations in the realm of Open Source projects.

4.1.1 Mechanism Structure Design

The complexity in dynamic movement of robots that are exposed to rapid ground contact is obvious. The robotic mechanical structure is challenged by a number of factors like high ground reaction forces and thereby high stress and stress concentrations throughout the leg. At the same time, the mechanical leg ought to have at least three DOFs in order to cover a wide range of motion in 3D space and at the same time, ensure agility.

In the process of mechanical leg structure, it is crucial to balance the relationship between agility and overall structural quality. For instance, the increase of structure thickness functions as a solution to high stress on the robot's legs but this would result in high inertia that limits the rapid swing of the leg and consequently, reducing the agility of the quadruped. In contrast, increasing the actuator power solves the problem to some extent but at the same time, the increased actuator weight could prove to increase the overall inertia and also affect the agility of the leg. The solution to this challenge would be to reduce the leg's inertia. Commonly used methods to reduce leg mass and inertia are structural topology optimization, structural bionics, design to optimize transmission mechanisms, and use of materials with high specific stiffness and specific strength.

4.1.2 Actuators

Locomotion based on dynamic events like impact, rapid leg swing and high force interaction with challenging and unexplored terrain has been one of the most prevalent challenges in robotics research. The demands for actuator systems that have been specifically designed for dynamic legged robots need to require some mechanical standards and specifications. The ideal actuator is to maximize torque, bandwidth, and power while minimizing friction, inertia, and mass loss. The complex relation between them and the contradictory requirements perplexes the actuator design.

More often than not, electromagnetic actuators are combined with gearbox to employ high gear ratio and therefore, ensure maximum positional accuracy and stiffness. However, increasing the gear ratio will amplify the impact loads and increase the overall mechanical impedance of the system, while reducing the high gear ratio will increase friction losses and reduce the overall mechanical strength of the system. The rapid interaction with the ground limits the force control capability since a very high impact load is generated at the end actuator. Conventional actuators with high gear ratio do not reduce the effects of the high mechanical impedance of the actuator system resulting from the high impact load. In order to ensure dynamic interaction of the quadruped the minimization of mechanical impedance pays a critical role. Series Elastic Actuators and Proprioceptive Actuation propose solution to this problem.

In the case of SEA, mechanical impedance is lessen by connecting the spring element in series with a high impedance actuator. This structure results in lower filter vibration load, greatly reduced peak value of the gear force, conversion of the force control problem into a position control problem and stable force control easier to implement while also giving the opportunity to energy storage.

Proprioceptive actuation is a method proposed aiming to reduce high-impact forces by introducing completely different actuator structures. PA protects the system from high-impact forces by replacing springs, stiffness adjustment mechanisms, and force/torque sensor with a lightweight structure of low inertia. In order to compensate for the low-output torque due to reduced gear ratio, the actuator uses a large radius stator and rotor to meet torque density requirements. In comparison to SEA, the proprioceptive actuator proves to demonstrate higher bandwidth force control without contact force feedback.

Finally, hydraulic actuators exhibit higher output power, higher power density, higher bandwidth, faster response, and stronger anti-interference ability compared with electromagnetic actuators. Hydraulic actuators can be divided in two categories: rotary and linear. The first, utilized by quadrupeds like HyQ2Max and MiniHyQ discussed earlier, show complexity and of high quality and are usually placed on the hip of the mechanical legs. The later, used by Boston Dynamic's BigDog, WildCat and the Italian HyQ have a simpler linear structure, are lightweitght and contribute in reduction of the leg mass and inertia while maintaining a more stable run and control.

5.0 FUTURE REASERCH

The objective of this study is to offer a compact text that facilitates an overall view of quadruped robots while taking into account the contemporary efforts towards dynamic quadrupeds. The focus areas are locomotion, structural design, and actuators but there are many other components to be considered towards improving robustness. While multilegged robots have achieved impressive progressions in the recent decades, the biomimetic technology and development we have available is still far from being comparable to mammalian movement. Wires, connectors, computers, bearings, sensors, motors, linkages all should be designed to withstand recurrent and thermal, radiational, chemical and mechanical stains. Moreover, minimizing complexity is a critical step to achieve breakthroughs in ground locomotion. Extracting the fundamentals from the animals is the challenge to bio-inspiration for modern robotics engineers. In the future, we expect the development of more novel mechanisms with serial-parallel coupling, topologies that facilitate rigid-flexible combination and breakthroughs in actuation dynamics.

Many efforts towards these directions have been registered recently and a great number of open source projects can be found for people in interest of realizing them. However it needs to be noted that the Open Source community should benefit from further development in the future. The performance of four legged robotic projects will be significantly improved through enhancing the materials of the robots available in the Open Source community. More powerful actuators, advanced sensors like LIDAR and stereo cameras are needed in order to enhace the safety of the robots, prevent collisions as well as mitigate falls and ultimately protect both the robot and its environment. Quadruped robots could be further developed to have better autonomy and navigation capabilities by implementing advanced SLAM (Simultaneous Localization and Mapping) techniques, path planning algorithms, and obstacle avoidance systems. Moreover, the implementation of machine learning and artificial intelligence techniques could play a substantial role. For example, reinforcement learning could be used towards “teaching” the robot to complete complex tasks, making it efficient in specific scenarios. Another problem that need to be addressed is that of energy efficiency and battery life. Developing energy resourceful gaits is crucial for quadrupeds that require extended periods of operational time.It is also essential to consider the adaptability of the robots in real-world environments. Up until now, low cost open source quadruped robots are mainly focusing on educational and research purposes. By making them affordable more researchers, hobbyists, and educational institutions can contribute on real-world applications, while practical applications would drive the development of Open Source quadruped robots in areas like search and rescue, disaster response, agriculture, construction, and exploration. Amongst them, Spot Mini Mini, part of the Open Source SpotMicroAI family has drawn our attention. This MIT licensed robot project combines the development and build of the robot with a reliable and versatile simulator that can be employed for Reinforcement Learning tasks. The field of legged robotics is interdisciplinary and advancements in fields like materials science, AI, control systems, and biomechanics all contribute to the development of better quadruped robots. The possibilities are vast, and the development of open-source quadruped robots has the potential to impact numerous industries and areas of research.

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