DECLARAÇÃO

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Título dissertação:

3D Modelling and Design of a Bioloid Compliant Quadruped Leg

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Ano de conclusão: 2011

Designação do Mestrado:

Mestrado em Engenharia Biomédica

Área de Especialização: Biomateriais, Reabilitação e Biomecânica

Escola: de Engenharia

Departamento: de Engenharia Mecânica

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Acknowledgements

To my parents and my brother

First of all, I would like to give special thanks to my supervisor Prof. Dr. Cristina Santos for her professional support, guidance and encouragement throughout the development of this dissertation. I deeply appreciate her many efforts to proofread my dissertation over and over again.

I am extremely grateful to my dissertation co-supervisor, Prof. Dr. José Machado, from the Department of Mechanical Engineering, for all the availability and orientation along the semester which has been fundamental in the elaboration of this project.

To all the researchers from the Robotics Laboratory, with a special thanks to Vitor Mat and Miguel Oliveira, for their extensive knowledge and range of ideas during my work in the Webots™ software.

My greatest acknowledgement goes to my family, my parents and my brother, for all the encouragement and support along the five years as a student. Love and thank for the values, the caring and trust, you are my motivation and my pride.

To my òacademic familyó, with whom I ha thanks for the brotherhood, thanks for all the sharing moments and finally the love.

Big thanks to my friends, for the companionship, the joy, the affection, for their never ending patience, support and encouragement, but mostly for the friendship. You were fundamental during this time. Thanks for listening and accompanying, thanks for being there.

Finally, my thanks go to all those who are not particularly mentioned here. The work presented could not have been made without the support from many individuals.

Abstract

In the growing fields of rehabilitation robotics, prosthetics, and walking robots, the modeling of a real robot is a complex and passionate challenge. On the crossing point of mechanics, physics and computer science, the development of a complete model involves multiple tasks ranging from the 3D modeling of the different body parts, the measure of the different physic properties, the understanding of the requirements for an accurate simulation, to the development of a robotic controller.

In order to minimize large forces due to shocks, to safely interact with the user or the environment, and knowing the ability of passive elastic elements to store and release energy, compliant mechanisms are increasingly being applied in robots applications.

This work aims to the elaboration of an accurate efficient three-dimensional model of the legs of the quadruped Bioloid robot and the development of a world showing the effect on Webots™ simulation software developed by Cyberbotics Ltd. The goal was to design a segment pantograph leg with compliant joints, in order to actively retract the collision and the impact of the quadruped legs with the ground during locomotion. Geometrical and mechanical limits have to be evaluated and considered for the modeling setup.

Finally a controller based on the use of Central Pattern Generators was improved in order to adapt to the novel model and simple tests were performed in the Webots™ rendering a 3D model simulation for the different values of spring-damping coefficients at the legs knee joint. Through the use of a MATLAB® algorithm, the characterization of the joint angles during simulation was possible to be assessed.

Resumo

A modelação de um robot real é um desafio complexo e fascinante na crescente área da Robótica, que engloba desde robots de reabilitação, próteses até à diversidade de outros dispositivos locomotores. No cruzamento da mecânica com a física e as ciências computacionais, o desenvolvimento de um modelo completo envolve várias tarefas que vão desde a modelação 3D das diferentes partes do corpo, a medição das propriedades físicas inerentes, a compreensão dos requisitos para uma simulação precisa bem como a aplicação de um controlador robótico.

A fim de minimizar grandes forças devido a choques, interagir com segurança com o utilizador ou o ambiente e conhecendo a capacidade de armazenagem de energia por parte de elementos elásticos passivos, um sistema de amortecimento demonstra ser uma aplicação de crescente interesse na Robótica.

Este trabalho visa a elaboração de um modelo tridimensional eficiente e preciso das pernas do robô quadrúpede Bioloid a ser reproduzido num mundo no software Webots™ desenvolvido pela Cyberbotics Ltd. O objectivo foi desenhar uma perna pantográfica segmentada tridimensional a ser aplicada em paralelo com um sistema de amortecimento mola de forma a retrair activamente a colisão e o impacto das patas do quadrúpede contra o solo durante a locomoção. Deste modo para uma configuração do modelo bem sucedida são tidos em conta limites geométricos e mecânicos.

Por ultimo, o controlador com base no uso de Central Pattern Generators foi melhorado a fim de se adaptar ao novo modelo e por conseguinte foram realizados testes simples usando o simulador Webots™. Nesta parte experimental é realizada a simulação do modelo permitindo avaliar o comportamento do modelo 3D para diferentes valores de coeficientes de mola e de amortecimento aplicados ao nível do joelho da perna. Através de um algoritmo MATLAB® é possível caracterizar e analisar o comportamento doa ângulos das juntas durante a simulação.

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Abbreviations and Acronyms

DoF	Degrees of Freedom
ODE	Open Dynamics Engine
CoM	Center of Mass
CPG	Central Pattern Generator
SEA	Series Elastic Actuator
MACCEPA	Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator
PAM	Pneumatic Artificial Muscles
PPAM	Pleated Pneumatic Artificial Muscles
VSA	Variable Stiffness Actuator
AMASC	Actuator with Mechanically Adjustable Series Compliance
VSSEA	Variable Stiffness Series Elastic Actuator
$\tilde{l}_0$	normalized length of the first leg segment (thigh/scapula)
$\tilde{l}_1$	normalized length of the second leg segment (shank/upper arm)
$\tilde{l}_2$	normalized length of the third leg segment (foot/lower arm)
$\tilde{l}$[illegible]	normalized distance of the pantograph attachment [illegible]
l_0	absolute length of the first leg segment (thigh/scapula)
l_1	absolute length of the second segment (shank/upper arm), [illegible]
l_2	absolute length of the third leg segment (foot/lower arm)
l[illegible]	absolute length of the pantograph attachment [illegible]

▓▪ ▄▌	leg stiffness of the virtual leg
□	body mass
▌	gravitational acceleration: 9.81 m/s^2
∜	leg angle between ὰ / ὰ or ὰ / ὰ
╛╣	fully extended total length of the leg: 0.21 m
╛ε	length of the leg at touchdown
╛	current leg length
■⁄	relative leg length
♪▪ ▄▌	angle between the leg segment and the virtual leg
♫	angle of attack of the virtual leg
╕▪ ▄▌	leg force
○●	velocity of the center of mass with respect to the coordination system
◄╤	time of contact
Ᵽ	half angle of the virtual leg
▓▓▼▬►░ ▪ ▌	spring constant at the knee joint
╬╬■╪□▬░ ▪ ▌	damping constant at the knee joint

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1 Introduction

This chapter presents the context of the framework, defining objectives to the development, as well as the motivations of the project. This section ends with a brief description of the dissertation structure.

1.1 The work presentation and motivation

The work developed in the present dissertation had the duration of one semester, being developed in the Control, Automation and Robotics Group of the University of Minho, in Guimarães.

Nowadays, Robotics is growing fast and in the most fields, making a significant impact on many aspects of modern life. Locomotive robots are no exception and became an attractive field of research. Walking machines have a major interest in a large range of applications, from industry to healthcare, transportation, military applications, space and sea exploration, providing many advantages over human faculties in many of these situations in terms of safety and effectiveness [1] [2] [3].

Currently, the biomechanical models are very complex and their application in modeling keeps being applied on several areas. In robotics there are several studies and projects mimicking the human and animal behavior to improve the knowledge about their mechanisms and ultimately succeed in the many significant fields, like rehabilitation.

The modeling and design of a robot is a complex and interesting challenge, therefore in order to minimize large forces due to shocks and to safely interact with the user or the environment, the motivation of this work aims to the elaboration of an accurate efficient three dimensional model of a quadruped robot with compliant legs.

The main goal of this project is to improve the leg design of the Bioloid quadruped robot, from a three-dimensional model developed by Filho-Robin [4]. For this purpose a new segmented pantographic robotic leg design was created using the Webots™ simulation software, with passive compliant knee joints associated.

Focusing on a main issue which is the leg retraction, the design features to be implemented are essential for the performance of the quadruped when it contacts the ground. Thus, the use of a well-designed passive compliant system comes as a benefit in order to obtain a successful operative leg. This component is not only useful to store energy and reducing power consumption, it also helps to make a segmented leg safe and robust when facing external perturbations [5].

This project aim to a final leg incorporated in the Bioloid quadruped robot in order to perform a stable and linear locomotion. With the goal of a future real assembling of the developed mechanism, the objective was to achieve a stable simulation of the novel quadruped using a qualified virtual software.

1.2 Bioloid robot presentation

The ROBOTIS® is a well-known, specialized company developer of robotic kits with a wide set of advantageous features, thus it holds an academic interest on research in many fields greatly due to its robustness and versatility. The kit used in this project is named BIOLOID. Figure 1.1 illustrates the dog assembly known as "Puppy".

Figure 1.1 - Puppy BIOLOID robot [6].

The basis of this project was the model created by Fillion-Robin [4], which holds a three-dimensional model that closely resembles a real dog robot, as illustrated in Figure 1.2. Therefore some of the main characteristics (orientations, weight, etc.) presented in the Webots™ world from [4] were maintained.

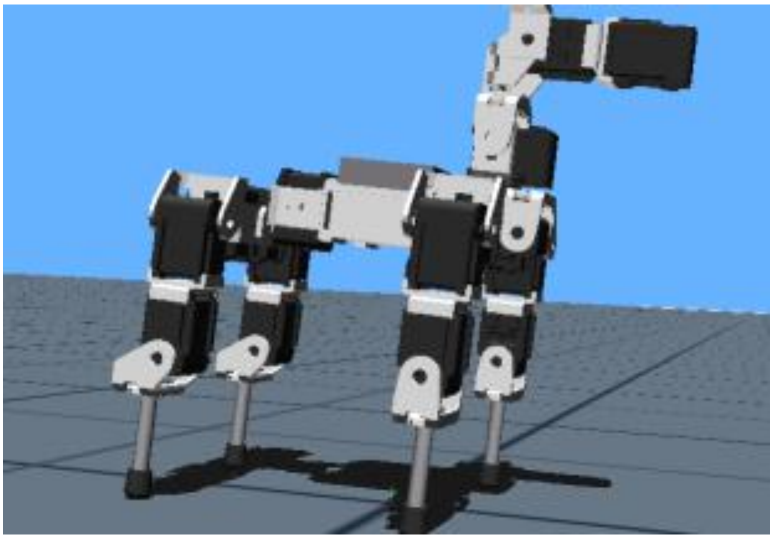


Figure 1.2 - Quadruped robot model rendered in Webots™ [4].

The robot design aim for the development of an accurate leg model and both efficient and robust for a quadruped, using the same Webots™ simulator software to the rendering of a 3D model. The Webots™ platform, developed by Cyberbotics Ltd, in collaboration with the Swiss Federal Institute of Technology in Lausanne, performs a rapid prototyping environment for modeling, programming and simulating mobile robots models, demonstrating the different phases of the reproduction of the motion [4].

Webots reproduces several accurate properties, very important for such models: shape, color, mass, friction or density. The core of this software is based on the robust and powerful physics engine: Open Dynamics Engine (ODE). The two main components of ODE a the rigid body dynamics simulation engine and the collision detection engine, known to be a successful and promising Physics tool, working as a library to provide more realistic simulations [4].

The Bioloid kit used is composed of a collection of mechanically indispensable components to robots performance: high density plastic block shaped parts which are responsible for the interconnection of the elements providing the apparatus cohesion during motion; an actuation controller, the CM5 processor unit; and for the actuation, the Dynamixel AX-12 servomotors.

These units can be assembled together in a single system, however the interactivity of these components with each other carries a considerable level of complexity [4] [7] [8]. The servomotors are chained in a hierarchical series configuration and to control these servo components there is an actuation unit which can be programmed via a supplied program named CodeBlocks. This program is an Integrated Development Environment software that is responsible for the motion generation of the model [9].

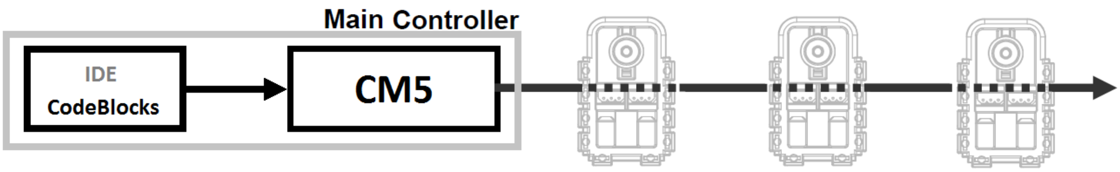


Figure 1.3 – Control process and disposition block diagram for Bioloid motion generation [6].

1.3 Considerations of the model

Despite the good characteristics of the former model, several aspects can be improved. In order for a robotic device to be successful in a known application, it needs to interact safely and efficiently with its user or the environment [4] [10].

As mentioned, on the previous Bioloid quadruped configuration model, some main characteristics were maintained. First of all, the leg presents same degrees of freedom (DoF), where each leg is able to move in three axes, the hip joint can be actuated for pitch and roll and the knee joint that is also actuated for the pitch angle variation, thereby the motion generation can take place only for the sagittal plane. While the hip active joint main actuation is responsible for the protraction and retraction of the leg through the locomotion main control, knee joint has the function of extend and contract the leg. This last mentioned joint also will hold a spring damping system that is responsible for impact absorption during stance phase of the walking cycle.

Secondly, should be emphasized that the configuration of the leg was only change after the knee joint extension, maintaining the trunk, head and upper parts of the limbs as the original model.

In recent years, there are more and more designs of new robots which are biomomimetics copies of animals. Cheetah [11], furthermore named Oncilla, is a robot developed by BioRob (Biologically Inspired Robotics Group) in Switzerland at the École Polytechnique Fédérale De Lausanne (EPFL) that tries to follow this idea. It features complex model of a compliant, pantographic leg with passive dynamics that was designed from observations in small mammals. Taking the Cheetah/Oncilla as an inspiration, the new leg was developed using a pantographic model responsible for the extension and retraction at the knee joint during locomotion.

In the Webots™ world the implementation of the pantographic mechanism introduces a concern in the physics characterization. Thus, the geometrical and mechanical limits regarding the system must be considered in the modeling, in other words, the demanding parallelism condition of the new mechanism must be properly implemented on the physics plugin in order to obtain an accurate and dynamic simulation.

In addition to these modeling parameters, also the control of the robot will held some configuration settings. The servomotors features will be produced as the Dynamixel AX-12 actuation characteristics. Afterwards, the locomotion control of the servos will be carried out by Central Pattern Generators (CPGs). These prove to be adequate by mimicking the animals in the production of rhythmic neural activity to control their movements, through the generation of oscillatory signals for the actuators, enabling stable periodic gaits and also the achievement of complex behavior in different kind of environments [5][12][13][14].

1.4 Structure of the dissertation

The first chapter of this dissertation summarizes the main goals of the work, presenting the project theoretical framework and motivation. In this same chapter is also mentioned which are the achieving goals as well as the practical work and considerations to the developing model, finalizing with a description of the dissertation.

Before the modeling and experimentation it was carried out a study on the compliant systems developed by researchers and a state of the art concerning the passive compliant actuators with applications in locomotion mechanisms, developed in the past few years. This part of the dissertation is presented in the second chapter, addressing the analysis and comparison of these systems.

In chapter number three, is presented the leg design developed for legged robots, distinguishing the different types of structures. Focusing on the pantographic configuration benefits in the leg retraction, the Cheetah, also known as Oncilla, quadruped characteristics are deepen analyzed, incorporating the information about the three-segmentation, structural setup and ultimately the consideration of the compliant mechanism.

The forth part of the body of this dissertation approaches the modeling of the leg. The kinematic analysis of the leg is developed in order to establish limitative parameters for the joints configuration and consequently repercussion in the experimental simulation. Also, the spring-damp coupled system is assessed for the desired retraction.

The practical part of this work is described and analyzed in the fifth chapter, where it is characterized the Webots configuration parameters to be introduced in the modeling as well as the physics plug-in of the new mechanism. This chapter addresses the analysis of the controller of the servomotors for the locomotion step cycle. Ultimately the final model is accomplished and the simulation is carried out. Throughout a MATLAB® algorithm the results were able to be presented and discussed

Finally in the last chapter, the final statements and conclusions are described and some future work considerations are suggested in order to improve the legs performance in a walking gate with a compliance system.

2 Passive compliant actuation systems

In this chapter it is exploited the study of the principal compliant actuators applied along the years in the different walking robots. Firstly, the state of the art of the compliant actuation technologies is presented as well as the functional principles or implementation of each case. Ultimately a brief comparison is done in an effort to distinguish the requirements and features for the different stiffness actuators design

2.1 State of the art of passive compliant actuators

Research in legged locomotion is evolving and new technologies are being explored worldwide with the aim of improving actuator performance [10]. Thereby for the rehabilitation robotics, prosthetics, and walking robots, variable stiffness actuators or adjustable compliant actuators design and implementation are being upgraded. Due to their interesting properties regarding safe human-robot interaction, reducing large shock forces and improving energy-efficient locomotion, they are becoming an inspiration in the Robotics field. The presence of internal elastic elements provides the ability to store and release energy in case of walking/running robots and prostheses of the passive elastic elements [15] [16] [17] [18] [19].

According to Laffranchi study report on compliant actuators [19], first of all the functional principles can be differentiated by their stiffness characterization, which can be fixed or variable. On the following section is presented a comparison of the mechanical design between the different compliant actuators [17].

2.1.1 Actuators with fixed compliance

Actuators with fixed compliance represent the first attempts towards the development of compliant actuation systems, incorporating in its structure an element with fixed passive stiffness. These systems can be implemented following two main approaches, the antagonistic or the series design [19].

A specific case of a fixed passive spring in series configuration with the actuation system (as electric motors or hydraulic systems) is the *Series Elastic Actuator* (SEA), developed by Williamson in 1995 [10], illustrated in Figure 2.1. These actuators employ only one actuator and one elastic element per degree of freedom [15] [19].

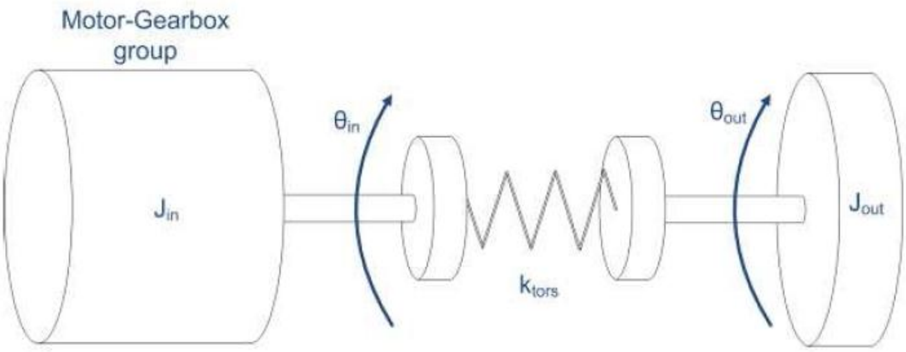


Figure 2.1 - A conceptual schematic of fixed compliance actuator adapted from SEA [19].

The element with the fixed passive stiffness is placed between the rigid actuator and the load These configurations show equilibrium-controlled stiffness, in other words the equilibrium position of the spring is controlled to exert a desired stiffness or force. The compliance is actively changed when the motor position is adjusted based on the deflection of the spring to alter the tension or compression of the spring, in other words, the motor torque of the actuator is proportional to the displacement of the unit and force on the spring.

To obtain variable stiffness, the virtual stiffness of the actuator is adjusted by dynamically variation of the equilibrium position of the spring. The use of series elastic actuators improve the performance of repetitive motion tasks as walking, exhibiting stable behavior while in contact with all environments [10] [15].

The improvements brought by Series Elastic Actuators, such as safety in human-robot interaction, ability to absorb the shocks and enhancement of the force/torque control performance are also applicable for fixed stiffness antagonistic setups. Actually, an antagonistic joint is made of two series elastic actuators displayed antagonistically which transmits the agonist/antagonist forces to the joint [10].

2.1.2 Actuators with variable compliance

The actuators that possess a variable compliance are able to regulate passively the physical compliance, having the capability of regulation of position, stiffness, wide of range of stiffness and very important energy storage facility. Such brings out the benefit of the variable stiffness implementation comparing to the actuators with fixed passive compliance, it shows a similarity to the muscle-tendons apparatus, which assume a rigid configuration during contraction and compliant configuration during relaxation. This type of actuator can be categorized also in two main groups - in the first one, the compliance is placed in series between the actuator and the load and in the second one, it is set antagonistically, as it is schematized in Figure 2.2 [15] [19] [20].

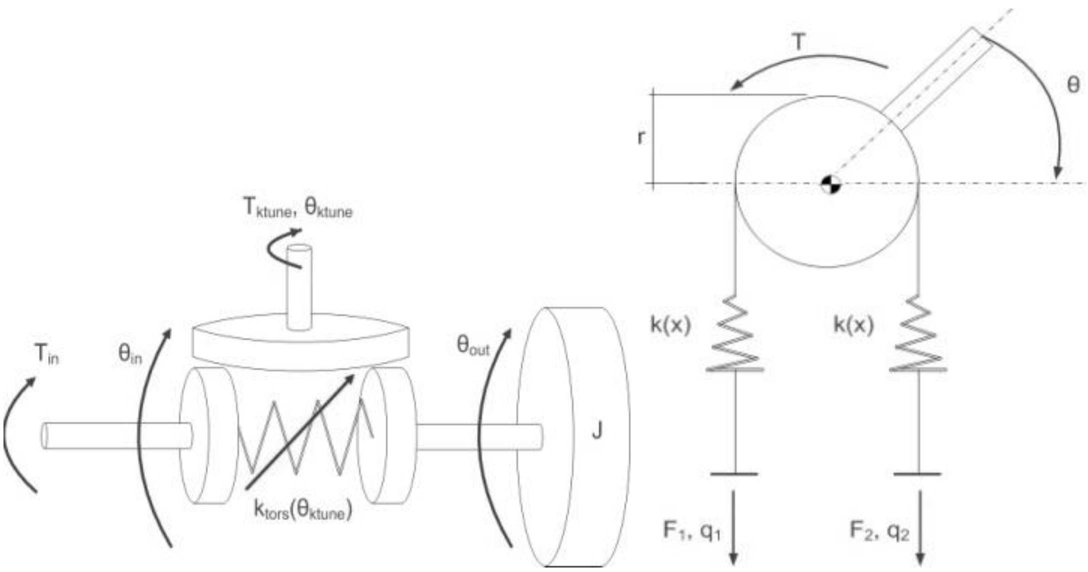


Figure 2.2 - Serial and antagonistic variable compliance actuation schemes respectively [20].

2.1.2.1 Series configuration

One of the main accomplishments of this type of variable stiffness actuator is the use of two actuators to set the equilibrium position of the joint, independently from the stiffness tuning. In the series configuration of actuators there are two ways to achieve the stiffness variation: one is through structure-controlled stiffness, which during operation can modulate the effective physical structure of a spring and achieve variations in stiffness and stored energy by adjusting the material properties (modulus, moment of inertia and/or effective beam length); the second way is through mechanically-controlled stiffness, which also adjusts the effective physical stiffness of the system, however, adjusts stiffness by varying the points where a compliant element is attached to the structure, as a result alters the tension or preload of the spring [15][19].

An example of the structure-controlled stiffness design is the *Jack Spring actuator*™ developed by Hollander, Sugar and their team [21]. In this new type of actuator, a helical spring is used as the compliant element and the lead of the Jack Spring changes under an applied axial load. The external force can act in both directions. Both compliance and equilibrium position adjustments of the Jack Spring™ mechanism is achieved by adding or subtracting the number of active coils, see Figure 2.3 [15].

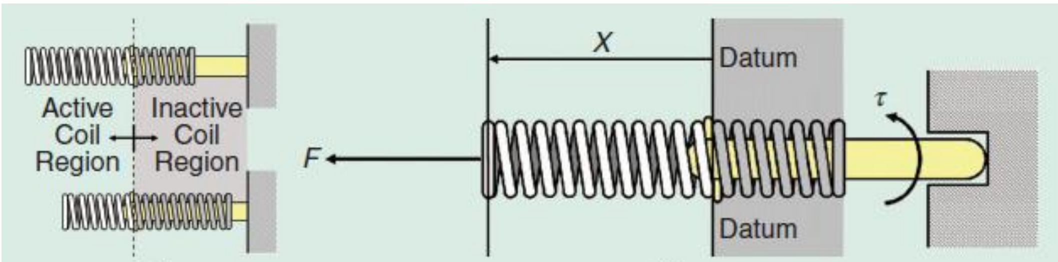


Figure 2.3 - Jack Spring™ Actuator's active and inactive reg [15].

The *Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator* (MACCEPA) developed by Van Ham et al. [18] is a application of the mechanically-controlled stiffness design, requiring only one compliant element (see Figure 2.4). The complete actuator behaves as a torsion spring where the spring characteristics and equilibrium position can be controlled independently during operation. The variation of the compliance is based on the variation of the length of the lever arms and uses only one passive element. Some advantages of MACCEPA actuator can be outlined: the actuator can be built with independently controllable torque and stiffness, it has a significantly simple design and presents a linear angle-torque characteristic. On the other hand, has drawbacks regarding energy efficiency and the servomotors require some space in the structure [15] [17].

A new model of this actuator was proposed and the lever arm of the setup is new replaced by a profile disk. Therefore the torque-angle curve and consequently the stiffness-angle curve can be modified by choosing an appropriate shape of a profile disk. The advantages of the new setup are that the design is simple, can use linear springs and the control of equilibrium position and pretension are independent. The actuator shows both a large joint angle and stiffness range [18] [22].

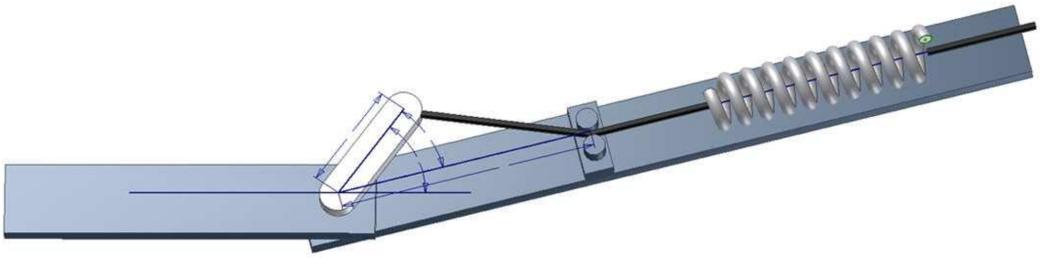


Figure 2.4 - MACCEPA actuator working principle [18].

2.1.2.2 Antagonistic configuration

In Antagonistic-controlled stiffness configuration two actuator units with non-adaptable compliance and non-linear force-displacement characteristics are coupled antagonistically, working against each other. By controlling both actuators and using nonlinear springs, the compliance and equilibrium position of this antagonistic setup can be changed. In order to obtain adaptable compliance, it is required the nonlinearity of the springs in the two actuators, while the resulting spring characteristic is linear. This design is biologically-inspired, following the concept of a joint actuated by two muscles arranged in an antagonistic manner [15].

The antagonistic design setups can be implemented using three different arrangements "Simple", "Cross coupled" and "Bidirectional" (Figure 2.5). In an antagonistically actuated joint are used two driving elements which by co-contraction regulates the stiffness of the joint and the angular displacement.

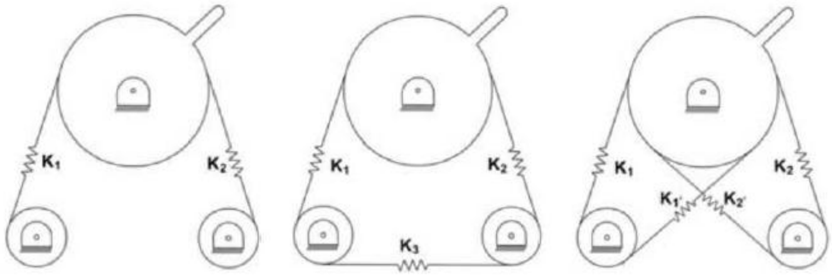


Figure 2.5 - The Simple, Cross-coupled and Bi-directional antagonist setups [19].

In the case of the “Simple” antagonistic arrangement, the control of the compliance system can be performed by electric motors or more biologically inspired by pneumatic muscle actuators, which compliance is an inherent characteristic of the actuator.

The McKibben muscle [23] is the most well-known design of *pneumatic artificial muscles* (PAMs), that when pressurized contracts the muscle axially while expanding radially. The compressibility of air makes them inherently compliant, behaving in a spring-like fashion. However, one of the disadvantages is the substantial threshold of pressure, introduced by friction, which makes it difficult to control. The improvement of this mechanism is pleated PAM (PPAM) [24] which overcomes significantly the threshold of pressure. In this design, the angle and length of the lever arms can be altered to compensate for the non-linearity of the force-angle characteristic of the muscles in order to implement a more linear behavior of the joints torque and angular displacement [17].

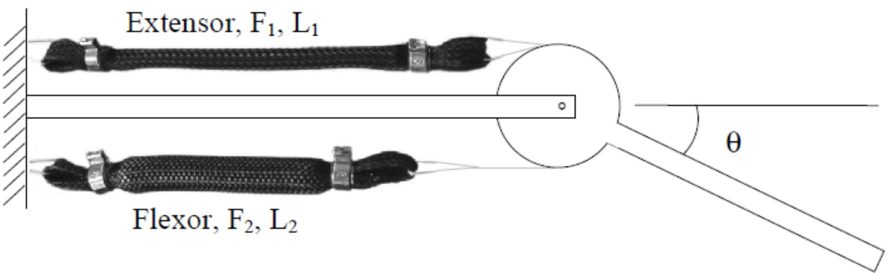


Figure 2.6 – Schematic of a rotational joint actuated by an antagonist pair of McKibbens [23].

However, in the “Simple” antagonistic approach using electrical actuation, differently from pneumatic actuation, the compliance is not an inherent property of the actuator and therefore requires additional compliant passive elements like springs between the actuators and the load. An example of this case of actuation is presented by *Migliore* [25], see Figure 2.7. Migliore is responsible for designing the “biological inspired joint describes the development and physical implementation of a servo-actuated robotic joint that uses antagonistic series-elastic actuation with a nonlinear spring mechanism. These mechanisms form a real-time mechanical feedback loop through independent control of both joint angle and joint stiffness [15] [17].

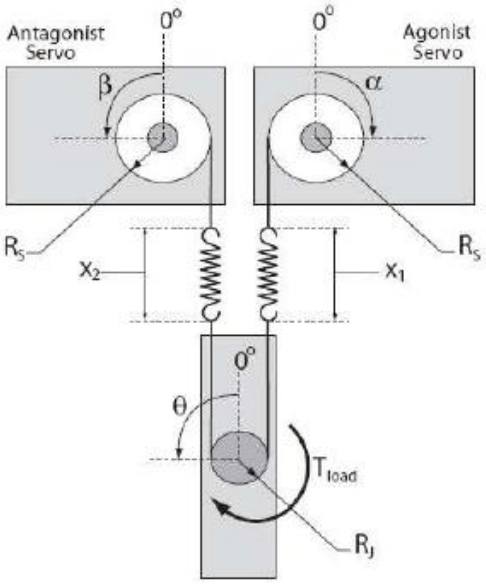


Figure 2.7 - Schematic of the Migliore's actuator [25]

A specific case of the cross-couple layout is the *Variable Stiffness Actuator* (VSA), presented in 2004 by Bicchi and Tonietti (Figure 2.8). A timing transmission belt (tensioned by springs) connects nonlinearly the main shaft to three actuator pulleys, two are connected to position-controlled back drivable DC motor (pulleys 2 and 3 in Figure 2.8 – Variable Stiffness Actuator CAD views and schematic mechanism of the antagonistic pair Figure 2.8) and one connected to the link (pulley 1). The antagonist motion of the driving actuators changes the apparent angle between the spring axis and the belt and this permits the stiffness adjustment. Summarizing, it consists of elastic actuators in series, which can modulate the position and stiffness of the system by acting on the springs' rest length [17] [19] [24].

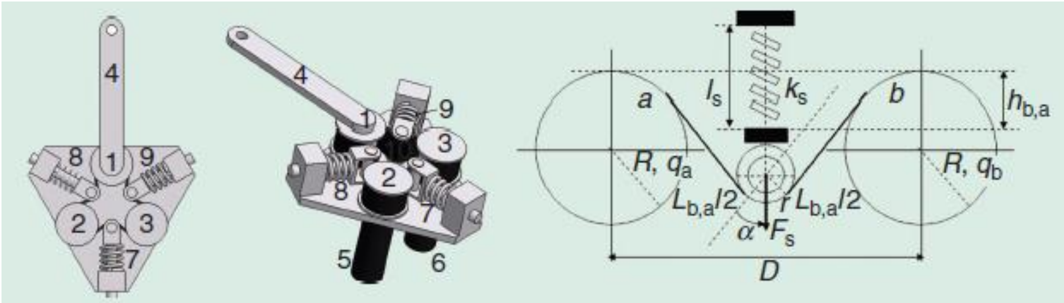


Figure 2.8 – Variable Stiffness Actuator CAD views and schematic mechanism of one of the antagonistic pairs [19].

Another important design based on the same principle of antagonistic design is the *Actuator with Mechanically Adjustable Series Compliance* (AMASC) developed by Hurst et al. The working principle is based still on the antagonistic setup of two nonlinear springs (Figure 2.9). The advantage is that just one actuator is used to control the equilibrium position and the compliance by changing the pretension of both nonlinear springs. The AMASC reduction ratio of the pulleys varies proportionally with the spring deflection to obtain the quadratic relationship. The pulleys are also used to uncouple the control of compliance and equilibrium position [17] [26]. A linear version of this actuator is the VSSEA, (Variable Stiffness Series Elastic Actuator) developed by Thorson et al., in 2007 [27].

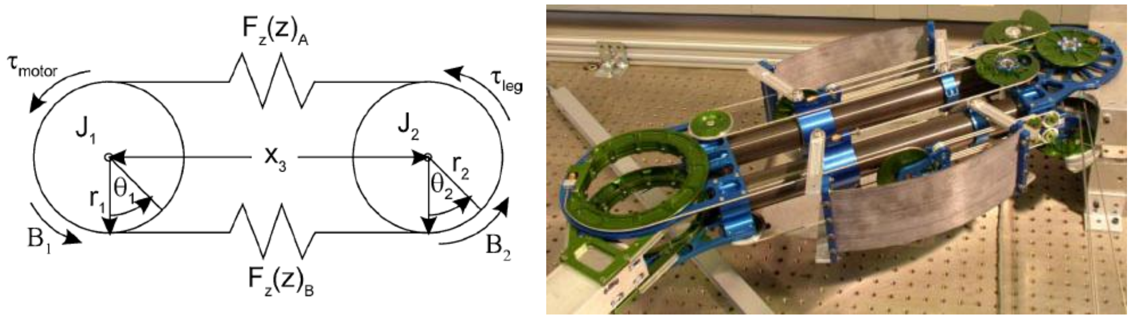


Figure 2.9 - Simplified schematic overview of the AMASC [19] [26].

2.2 Comparison of the passive compliant actuators

In the previous section, the configurations of the actuation systems were presented and simplified to their basic functionalities. From the beginning this devices can be classified in two main groups, the fixed and the variable compliance actuation systems. Each of these two categories can be implemented following series or antagonistic designs.

Van Ham *et al.* in [15] did a complete overview and classification of adaptable passive compliant actuators classifying the various designs [18]. He provides an overview of some of the properties for the different groups of controllable stiffness actuators, Table 2.1.

Table 2.1 - An overview of some of the properties for the different compliant actuators [15].

	SEA	Jack Spring	MACCEPA	Antagonistic
Minimum spring number	1	1	1	2
Linear springs	Yes	Yes	Yes	No
Always total spring length	Yes	No	Yes	Yes
Preload/Pretension in equilibrium position	No	No	Yes	Yes
Completely stiff setting possible	No	Yes	No	No
Vary compliant setting possib	Yes	Yes	Yes	No
Infinite bandwidth for shock absorbance	Yes	Yes	Yes	Yes
Infinite bandwidth for chosen compliance	No	Yes	Yes	Yes
Independent control stiffness equilibrium position	No	Yes	Yes	Yes/ No
Possibility to vary linearity of t stiffness curve	Yes	Yes	Yes	No

Within each group, there are distinctions, and the described designs might be optimized for a specific application. Besides the named functional parameters, other design criteria may be taken into account as the complexity of the design, cost, speed of the stiffness variation, maximum torque, and size of the complete system [15].

There are obvious advantages that passive compliant actuators with variable stiffness offer when compared with compliant actuators with a fixed passive stiffness. The decision between choosing adaptable or fixed compliant design is dependent on the range of compliance that is needed and the load allowed by the device. Therefore, depending on the application, adaptable compliant actuators are favorable for larger stiffness range being able to regulate the required stiffness and torque range and consequently the energy storage, on the other hand, if weight is important and a small range of required stiffness values are desired than a fixed compliant actuator is better [17][18].

In the first concept, the fixed compliance actuators are based on adjusting the equilibrium controlled stiffness through the position of springs. These actuators demonstrate an advantage when compared to variable stiffness due to the compact design and the simplicity to control presenting more stability to repetitive motions, however, constantly requires energy to regulate its actuator position.

In addition, while in series configuration is required one actuator and one compliant joint, the antagonistic designs extra work is needed to adjust the stiffness because they need at least two actuators and two compliant elements per degree of freedom. The main difference between the fixed stiffness design performance, SEA, which possesses a series configuration, and the antagonistic designs from AMASC is that the last can vary its stiffness while the SEA cannot. Also, the AMASC has mechanical energy storage, tunable compliance and low friction. [15][19][26][28].

Inside the antagonistic actuator configurations in contrast to VSA design, AMASC equilibrium position and compliance can be set more or less independently, each one by a dedicated servo motor that can be dimensioned appropriately.

Comparing the performances of the designs equipped with springs with PAM setup is not easy because the calculation of the energy consumption of compressed air is not obvious or trivial. Similarly to artificial muscles in which the spring and motor are combined in one element, the pressurized air is both responsible for the compliance and force generation. The maximum range of motion is limited by the maximum contraction and rest length of the muscle [17].

Opposing the mentioned two types of variable compliance actuators with a series configuration, the Jack Spring allows adaptable compliances and actively tunes the intrinsic stiffness of the spring, and on the other hand, the mechanically controlled stiffness, mentioned MACCEPA, is an actuator with independently controllable compliance and equilibrium position [15]. Also, the MACCEPA actuator has a second advantage that is the fact that the construction is much more straightforward when compared to the other designs because the construction of quadratic springs is difficult and the MACCEPA actuator uses one simple linear spring. It has both a large joint angle and stiffness range, although the actuator shows some drawbacks in the energy storing capabilities and the servomotors require some considerable space [17] [18].

Recently, advances in material technology have introduced new substances, making it possible to build structurally strong articulated mechanisms that are compact and lightweight. Examples of such materials that can be used to develop novel actuators are shapememory alloys, electrorheological fluids, electrostrictive and magnetostrictive materials, and electroactive polymers [15].

2.3 Applications of passive compliant actuators

As it has been said, compliant actuators are implemented in walking and running robots inspired by nature. Therefore some compliant actuators were developed to specific locomotive machine applications.

For the most well-known, the series elastic actuator [10], in 1998, Pratt set Flamingo, a planar bipedal walking robot with fixed stiffness. Afterwards Sugar [29] developed in 2002 a novel selective compliant actuator that consists of a spring attached in series to a linear actuator driven by a DC servomotor and the equilibrium position of the spring is controlled to exert a desired force [10] [24] [29]. In 2009 [30] a new mechanical design was developed, a bipedal walking robot named M2V2 with 12 actuated DoF in the lower body: three at each hip, one at each knee, and two at each ankle [30]. Fixed compliance actuators have also a role in rehabilitation robotics as in ankle prosthetics [31], which used a SEA that employs parallel compliance (Figure 2.10).

Figure 2.10 ð Examples of SEA application. Spring flamingo [32], M2V2 bipedal [30] and ankle-foot prosthesis [31] respectively.

On the other hand, antagonistically displayed series elastic actuators were implemented in a robotic leg mechanism as illustrated in Figure 2.11, which transmit the agonist/antagonist forces to the joint [19].

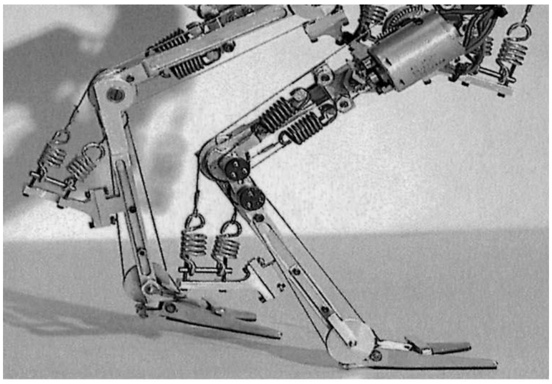
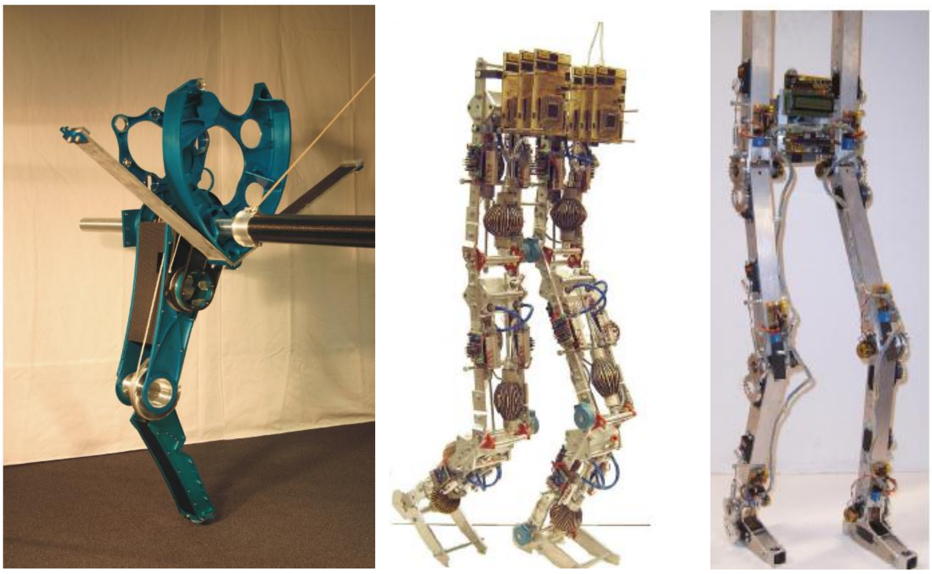


Figure 2.11 ð Robot legs with antagonistic elastic actuators [12].

Other configurations that allow both joint stiffness control and series pretension, such as the AMASC actuator [26]. Hurst and his team designed the biped robot with Mechanically Adjustable Series Compliance (BiMASC) which incorporates tuned mechanical leg springs, see Figure 2.12.a) [33].

Alternatively, Beyl and Vanderborght [34] [35] presented Lucy (Figure 2.12.b)), a two dimensional walking robot with two articulated legs, powered by pleated pneumatic artificial muscle (PPAM) to actuate 6 DoF (ankle, knee and hip joint) [34] [35].



a b c

Figure 2.12 – a) One of the BiMASC's [33], b) Biped walking robot Lucy assembly actuated by PPAM's [34], c) Biped walking robot Veronica ac

Biped Veronica Actuated with MACCEPA actuators (Variable joint Elasticity RObot with a Neuro-Inspired Control Approach) illustrated in Figure 2.12.c), similar to Lucy, however uses a novel control approach, can be adapted at will by systematically setting the equilibrium positions and compliance values of the different joints, resulting in a variety of semi-passive gait patterns [18] [34].

After the analysis of the different designs of compliant actuator systems, for the project of Bioloid, weight has an important part and the stiffness values required to accomplish the load support by the legs are small, the fixed compliant actuator type proves to be the most adequate to be applied for this application. Also, presents a major advantage in stability matters (in repetitive motions as the locomotion cycle) due to its compact design and simple control.

3 Quadruped leg configuration

The aim of this section is to study the various concepts that are taken into account to enable the compliance factor applicable on the robot in terms of the configuration of the leg to a successful retraction. Thus, basic consideration for a leg design can be outlined as follows: the leg should generate an approximately straight-line trajectory for the foot with respect to the body and the leg should have an easy mechanical configuration, towards building a robust and feasible robot [1] [36] [37] [38] [39] [40].

3.1 Legged Robots

A good design is important when it comes to any robot. In the locomotion study and design most legged robots mimic animals in structure. Although many challenges remain, some concepts from biologically inspire robotics aiming to eventually benefit the design of autonomous robots with some of the desirable properties of biological behavior, such as adaptability, robustness, versatility, and agility. A good design would mean: simple control, reduced dynamic effects, high stability, power equilibrium, simplified movement and low cost.

Over the time, taking the inspiration from biology based on scientific observation on legged animals, legged robots in combination with innovative engineering has been witnessing a significant increase in the interest and efficiency, resulting in several artificial walking machines

[12] [39] [41] [42]. The rising interest in legged systems is to expand the understanding of human and animal locomotion, perhaps in cases of high mobility and agility [2] [43] [44]. Basically, taking into account the features of the animal locomotion, there is a need to design and develop a highly flexible and sophisticated walking machine to mimic the muscular behavior [42] [45].

Although the locomotion in legged animals is very simple, research and previous efforts resulted in a number of legged robots with wide variation in shape, size and complexity [42].

In the development of legged machines it must be taken into account several points, which influence the technical features of these systems. As the most important variable of these parameters, it can be listed:

- mechanical structure – determines the walking machine posture, energy efficiency, range of walking speed and types of gaits which can be later implemented
- leg configuration – choice of number of legs, their kinematic structure, joint design solution
- actuating and drive mechanisms – choice of motors type, evaluation of their power, design of motor placement and evaluation of methods of motion transmission from motors to the legs joints to perform an autonomous navigation.
- power consumption in relation to the machines weight, payload, motion conditions – soft, hard terrain, inclined terrain, etc.
- method of walk – speed of motion, balance, number of legs supporting the body during walk, etc. [2] [45] [46].

3.2 Robotic leg mechanism

As mentioned different disciplines (engineering, biology, zoology and computer science) have been involved to discover the complexity of natural locomotion behavior and is a growing field in biomechanics. The promising approach of biologically inspiration aims to use the observed natural principles of locomotion for the efficient design and control of walking machines [47].

In small mammalian quadrupeds, two types of so called effectors are distinguished, muscles and glands. Relevant for the actuation of the locomotor system are the skeletal muscles together with the tendons. In fact, small mammals present similarities to a pantograph mechanism, which is more or less rectangular (see Figure 3.1), during rotation around the legs joints at the trunk. In the stance phase the generation of displacement of the animal is conducted by a spring-mass system. The springs are muscles, the more stiff show a higher compliance factor that offers the possibility to elastically store more energy. The study of pantograph mechanism and implementation will be further addressed [47] [48].

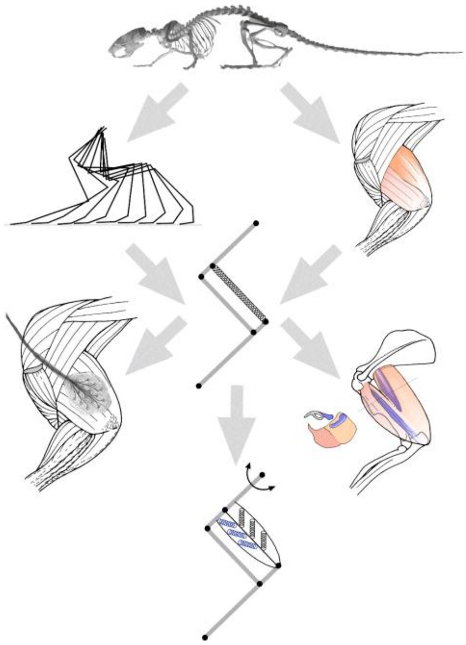


Figure 3.1 - Concept of the "pantograph leg" of small mammals [48].

There are several characteristics and principles that can be extracted from mammalian locomotion, in order to implement a stable and adaptive walking in the new leg:

¶ The limbs of mammals are almost segmented shaped and present the same configuration in terms of functionality, both in fore-limb and hind-limb, therefore the construction may be the same (see Figure 3.2).

¶ The progression is mainly due to the displacement of the proximal segment (scapula or femur) being the leg drive.

¶ Two segments (first and third - femur/foot) operate almost parallel during retraction of the limb, as in a pantograph mechanism.

¶ High limb compliance is a general principle for small mammals, and this help the self-stabilization of the limb, i.e., the stable locomotion of the animal, in presence of external disturbance without the necessity of a sensory feedback [12] [48].

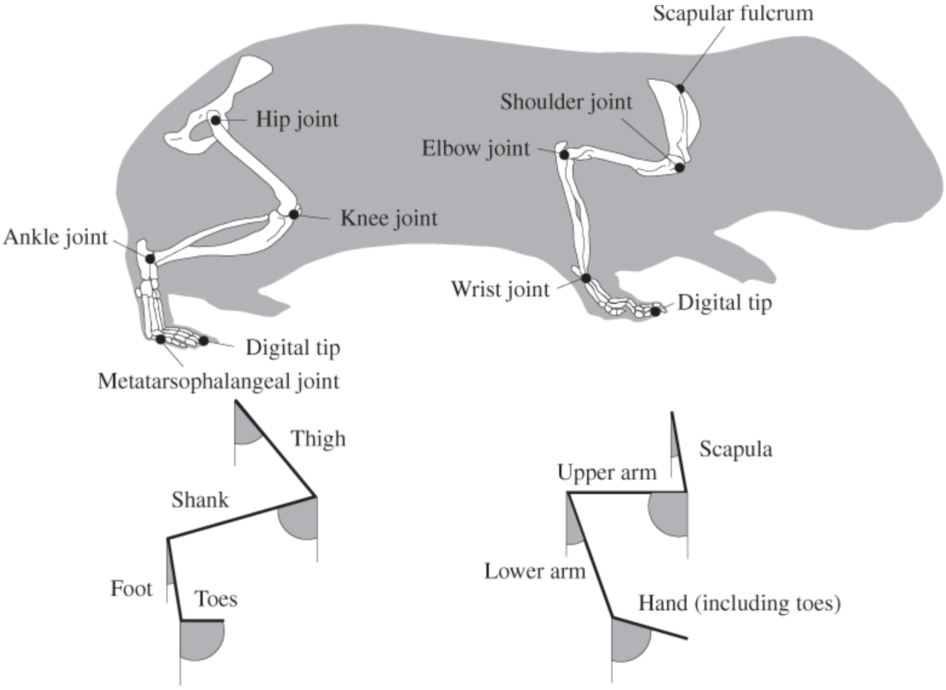


Figure 3.2 - The tri-segmented limb abstraction for small mammals. The limbs are segmented in three parts ðFore-limbs/Hind-limbs : scapula/femur, humerus/shank and lower arm/foot [12].

Considering the number of segments in the use of a two-segment leg, compression directly translates into joint flexion which in turn results in a higher joint torque and, consequently in an increased leg force (Figure 3.3).

Three-segmented limb in a z-configuration are typical presented in front and hind limbs of mammals. The additional segment adds a degree of freedom in which the Internal joint angles and the three segment lengths work together in the foundation of this configuration.

The additional degree of freedom in tri-segmented limbs imposes the risk of structural instability for z-shaped legs in case of a very dynamic motion, where the compression may result in different situations (e.g. bifurcation). However the triple linkage of the leg shows a higher effective energetic and mechanical advantage.

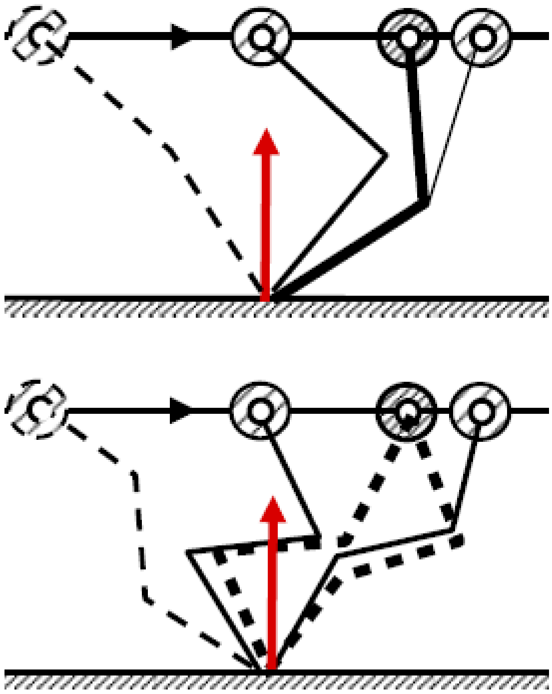


Figure 3.3 ô Schematic description of a bi-segmented system configuration with a single joint and a tri-segmented with a par of joints respectively [49].

The highly mentioned ôôpantographic be the synchronous movement of the two joints of the tri-segmented leg, insures that this instability does not occur, i.e. the first and third segment operate in matched motion, where the angles are always equal [19][49][50][51][52].

There are constraints on the possible combinations of joint angles and segment lengths that are relevant for leg physics. The relative length of limb segments is of special relevant in the leg design. Another advantage for small animals with three-linkage limbs is the equally long segmentation which indeed contributes to a lesser degree to progression. The benefits of this configuration are a large working range and good acceleration properties with less energy cost [50].

3.2.1 Types of leg structures

During walking, a four-legged walking robot places its weight on three and four supporting legs alternately. Thus, it implies that in each locomotion cycle, there are instances when any leg has to carry a load that can section is presented a variety of leg geometries that can provide the motion required by a quadruped walker. Some of these mechanisms are:

- Straight Line Mechanism realizes body-propelling motion by one degree of freedom. With reduced degrees of freedom the control system becomes simpler. However, straight line linkage mechanisms have limitations like complex arrangement of links and restricted workspace. Also, adaptability to the terrain also becomes poor with such systems.
- Articulated legs have the advantage of a larger workspace. The arrangement of two coincident hip joints has the benefit of placing two of the leg actuators on so that their mass is not carried by the leg during foot transfer. Also, the perpendicular disposition of joint axes at the hip provides a larger leg bandwidth workspace and simplifies the leg kinematics. There are two variations of this leg: insect-type and mammal-type. In the insect-type leg, the knee joint is located laterally or at a position higher than the hip (Figure 3.4a), whereas, in mammal-type legs, the knee joint is placed under the hip (Figure 3.4b). Due to geometric work loss, articulated leg designs are often responsible for poor energy efficiency of the robot.

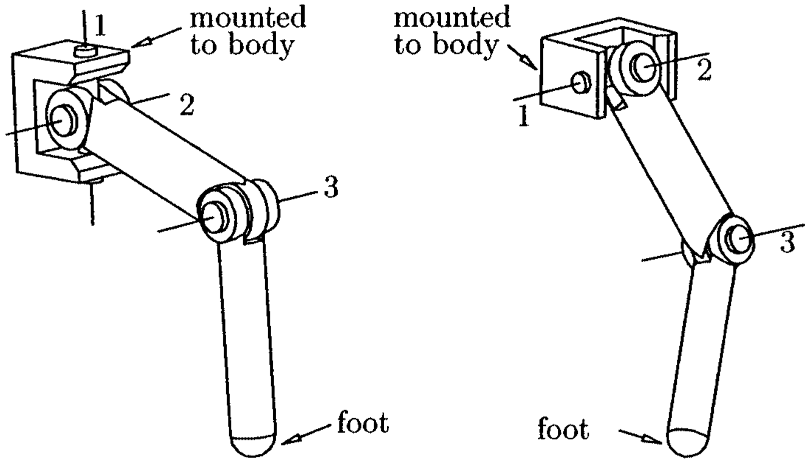


Figure 3.4 - a) insect-type and b) mammal-type articulated legs respectively [42].

- Gravitationally Decoupled method that dissociates the leg actuators that propel the body from the actuators supporting it during propulsion. Such mechanisms allow elimination of negative power by ensuring that the load-bearing actuators do not move and the actuators which move do not bear load. In the past, a number of leg mechanisms were used to perform such gravitationally decoupled actuation:

- *Orthogonal*: The legs are displayed in an orthogonal RPP (rotational-prismatic-prismatic) mechanism that decoupled horizontal and vertical motions. As shown in Figure 3.5, the configuration consists of a rotation link, an offset extension link, and a support link. There are three degrees of freedom per leg, with two rotational joints and one prismatic which held the foot.

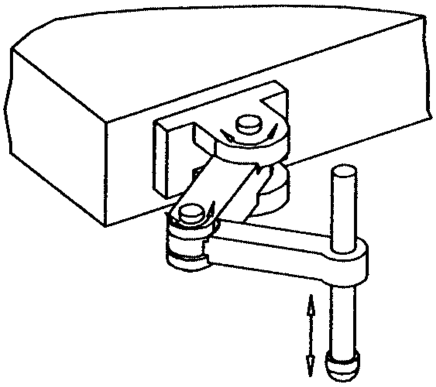


Figure 3.5 - Orthogonal configuration RPP [42].

- *Two-Dimensional Pantograph* - provides straight line foot motion along the forward and vertical directions. Foot motion in the lateral direction (if any) is due to rotation of the leg about an axis parallel to longitudinal body axis (Figure 3.6.a). In other case, the leg is designed for motion in the vertical plane which can rotate about the vertical hip axis (Figure 3.6.b).

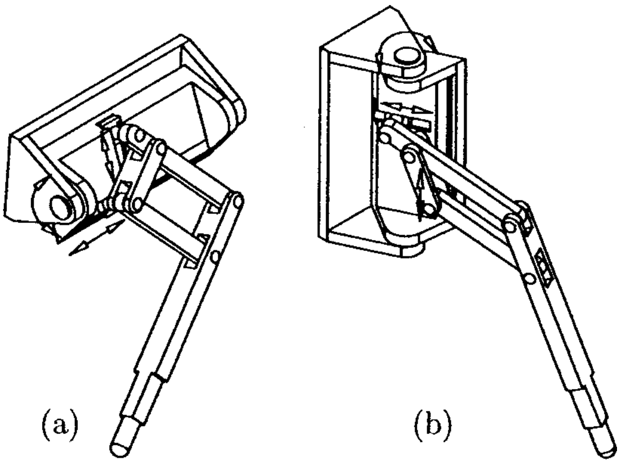


Figure 3.6 - Two-dimensional pantograph mechanism legs [42].

- *Three-Dimensional Pantograph*: In the three-dimensional pantograph, all the three motions are linear (Figure 3.7). The most important advantage of the pantograph mechanism is that geometric work loss can be completely eliminated. However such benefit can only be achieved if there are none tangential ground reaction forces. An important feature of three-dimensional pantograph is the particularity complexity of the mechanical design.

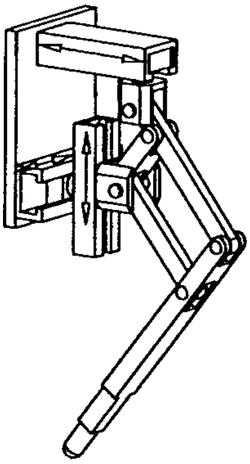


Figure 3.7 - Three-dimensional pantograph leg [42].

3.3 Cheetah robot

Over the years several legged robots applications were developed using the pantographic configuration. Due to the rising improvements and the successful simulations accomplished, the Cheetah pantographic mechanism, proved to be an interesting object of study, development and ultimatly an application to follow.

Oncilla robot, inherited like the Cheetah robot, fea segmented pantographic legs (see Figure 3.8) of a domestic cat (*Felis catus*). The first version of Cheetah was built by Simon Rutishauser [11] applying several principals in the design of a bioinspired quadruped robot. Since then, the robot has been upgraded several times, although the main features remain unchanged. For the work developed in this dissertation, some of the Cheetah's main design concepts and work principles were introduced in the new mechanism.

3.3.1 Three-segment leg

In Figure 3.8 is represented one of the most modern Cheetah robot design. As it shows, in both limbs a distinct three segmented construction is featured (plus one toe segment). For the hind limb is presented a hip joint and thigh (φ_1), a knee joint and shank (φ_2), and an ankle joint and foot (φ_3). The joint in each pair describes the proximal assembling point of the corresponding leg segment. The extra joint is connecting the toes as the fourth, most distal hind limb joint. For the robot the same relative segmentation is done [12] [14] [53].

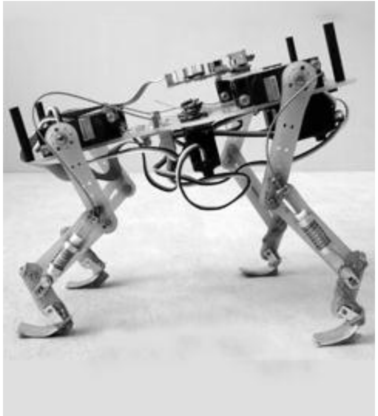


Figure 3.8 - Cheetah robot prototype and side view of the architecture schematics respectively [11].

In this robot is implemented a pantograph mechanism, constantly ensuring parallelism between two leg segments. More precisely, the pantograph holds the connection between proximal and distal limb segment, maintaining the first and third leg segment parallel during motion (φ_1 and φ_3, e.g. thigh and foot). This mechanism assembly resembles animal leg segment behavior for most of a step cycle. Hence, only one DOF influences the leg length and there is no need to deepen the study of the leg configuration stability [50] [53]. Also, the leg relative dimensions are designed based on biological data from small mammal, distance and ratio between the leg segments of the pantograph mechanism is a compromise to guarantee mechanical strength and energy efficiency [14] [50] [54].