ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

LOCOMOTION ANALYSIS OF QUADRUPED ROBOTS

M.Sc. THESIS

Esra ÇELİK

Department of Mechatronic Engineering

Mechatronic Engineering Programme

SEPTEMBER 2011

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

LOCOMOTION ANALYSIS OF QUADRUPED ROBOTS

M.Sc. THESIS

Esra ÇELİK

Department of Mechatronic Engineering

Mechatronic Engineering Programme

Thesis Advisor: Prof. Dr. Hakan TEMELTAŞ

SEPTEMBER 2011

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DÖRT AYAKLI ROBOTLARIN HAREKET ANALİZİ

YÜKSEK LİSANS TEZİ

Esra ÇELİK
(518081011)

Mekatronik Mühendisliği Anabilim Dalı

Mekatronik Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Hakan TEMELTAŞ

SEPTEMBER 2011

Esra ÇELİK, a **M.Sc.** student of ITU **Institute of / Graduate School of Science and Engineering and Technology** student ID **518081011**, successfully defended the **thesis** entitled "**LOCOMOTION ANALYSIS OF QUADRUPED ROBOTS"** which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Hakan TEMELTAŞ** İstanbul Technical University	....
Jury Members :	**Prof. Dr. Hakan TEMELTAŞ** İstanbul Technical University	....
	Yrd. Doç. Dr. S. Murat YEŞİLOĞLU İstanbul Technical University	....
	Yrd. Doç. Dr. Berk ÜSTÜNDAĞ İstanbul Technical University	....

Date of Submission : 22 November 2013
Date of Defense : 11 September 2011

Dedicated to my brother

FOREWORD

First of all, I want to express my sincere gratitude to Professor Hakan Temeltaş for giving me oppurtinity to work with him and informed guidances and advices through out my study.

I gratefully acknowledge Prof. Bernd TIBCKEN for valuable suggestions and interesting questions which made me think deeper into this research topic. It has been a great honour for me to work with him.

I am also so thankful to Dr.Ömür Öcal for his support during my research in Bergische Universitat Wuppertal.

I am really indebted to Abdullah Ali Çim for assisting me during design processes of my research.

Most of all, I am indebted to family and friends, especially to my cousin Abdurrahman GÜL and also Dr. Yasemin ÖNER and Fatma Nihan Doğan for being always there giving me not only their love and friendship in good and bad moments, but also their support while doing this thesis. To all of them my sincere warmest thanks.

September 2011

Esra ÇELİK
Electrical Engineer

TABLE OF CONTENTS

Page

ABBREVIATIONS

CLSM	:Crab Longitudinal Stability margin
COG	:Center of Gravity
COM	:Centre of Margin
COP	:Center of Pressure
CGI	:Common Gateway Interface
DOF	:Degree of Freedom
DSM	:Dynamic Stability Margin
EMC	:Effective Mass Center
ESM	:Energy Stability Measure
FASM	:Force-angle Stability Measure
GCOM	:Gravitiy Center of Margin
GIS	:Geographic Information Systems
NDESM	:Normalized Dynamic Energy Stability Margin
NE	:Normalized Energy
NESM	:Normalized Energy Stability Margin
TSM	:Tumble Stability Margin
ZMP/CoP	:Zero Moment Point/ Center of Pressure
SSM	:Static Stability Margin

LIST OF TABLES

Page

LIST OF FIGURES

Page

LOCOMOTION ANALYSIS OF QUADRUPED ROBOT

SUMMARY

In recent years, studies on walking robots is increasing. This is because legged walking has some advantages from the conventional wheeled and tracked movement such as good potential to be an effective and efficient transportation device on rough and/or soft terrain which has been well demonstrated in biological systems and, in principle, in a few walking machine prototypes. And also the complex and challenging nature of the problem has been very attractive to many pioneering researchers. In legged robot field, especially bipedal and quadruped robots have become popular and the other multi-leggeds follow them.

In this study quadruped locomotion is investigated theoretically in past studies with basic concepts. For this purpose, began with stability term which is one of basic concepts of legged locomotion, especially quadruped, necessary definitions is given such as stability margins type static and dynamic separately for sake of be well understand. Another basic term of locomotion, gait, is examined into two main title as static and dynamic walking evidently relation between stability.

Also kinematic equations, of quadruped robot model are derived accepting three degree of freedom for each leg. For forward kinematics Denavit-Hartenberg methods is used and for inverse kinematics only algebraic solution method is mentioned.

In the last phase of study, a primarily 3D drawing of a quadruped robot designed in CATIA and transferred to another modeling platform ADAMS. Theoretically investigated Static (crawl) and one type of dynamic walking (trot gait) is simulated in ADAMS. Angles and position changing in joints is observed. Simulation results is given.

In conclusion, the study is aimed to provide the basis for further study walking and control algorithms can be developed in MATLAB. Therefore ADAMS-MATLAB Co-Simulation infrastructure has been established with ADAMS/View plug-in ADAMS/Control and MATLAB- Simulink and described how to set this co-simulation structure detailed.

DÖRT AYAKLI ROBOTLARIN HAREKET ANALİZİ

ÖZET

Robotik bilimi her geçen gün popülerliğini artırmaktadır. Günümüzde ise yürüyen robotlar üzerine yapılan çalışmalar artış göstermektedir. Bunda yürüyen mekanizmaların, klasik tekerlek ve paletli robotlara göre bazı konularda avantaj göstermesi etkili olmaktadır. Mobil robotlar günümüz teknolojisinin bir gereği olarak laboratuar dışında, gerçek dünyada özellikle engebeli arazilerde kullanılmaya başlanmıştır. Bu durum dolayısıyla geleneksel tekerlekli, paletli ve raylı sistemlerin tasarımlarının zayıf yönleri ortaya çıkmış ve araştırmacıları farklı alanlara itmiştir. Dolayısıyla klasik tekerlek ve palet tasarımına sahip araçların tasarım sınırlarının aşılması için yapılan çalışmalar gün geçtikçe artan bir eğilim göstermektedir. Bu sınırları aşmak için, mobil robotların bir dalı olan bacaklı robotlar, biyolojik esinlenmelerden yararlanarak yeni tasarımlar gerçekleşmesine neden olmaktadır. Bu yeni tasarımlar daha çok bacaklı sistemleri içermekte ve farklı bacak sayılarında farklı kinematik yapılarda tasarımları ortaya çıkarmaktadır. Bacaklı sistemler bilinen geleneksel tasarımlardan çok daha fazla hareket kapasitesine ve çok yönlülüğe sahiptirler.

Bu çalışmada dört ayaklı yürüyen robotlarının hareket analizi konu edilmiştir. Bu amaçla öncelikle yürüyen mekanizmalar ve ayaklı robotların klasik yöntemli tekerlek veya paletli tasarımlarla kıyaslanmasına yer verilmiştir. Daha sonra yürüyen mekanizmalar içerisinde biyolojik yaklaşımlı olarak geliştirilen iki, dört ve çok bacaklı robotlar ve yürüyüşlerine değinilmiştir. Biyolojik yaklaşımlı bir robot için bacak tasarımı örneklenerek ve ayaklı robotlar alanında gerçeklenen önemli iki çalışmaya yer verilmiştir.

Dört ayaklı robotların hareket analizi çalışmasında robot yürüme hareketini tanımlamakta esas olan temel kavramlar teorik olarak irdelenmiş ve alt başlıklarıyla birlikte tezde ifade edilmiştir. Bunların içerisinde, robotun hareketinin gerçeklenmesinde en önemli parametre olan stabilite unsuru, statik ve dinamik altbaşlıkları altında konu edilmiştir. Stabilite kavramıyla ilgili yapılan teorik araştırmaların neticesinde statik ve dinamik dengenin ifadesinde kullanılan statik denge marjı, boylamsal denge marjı,enerji dengesi marjı, normalize enerji marjı, dinamik stabilite marjı kavramları tanımlamaları yapılmış ve formülleri ile ifade edilerek robotun hareketiyle ilişkileri açıklanmıştır.

Tez çalışmasında, dört ayaklı robotların hareketinde diğer bir temel kavram olan yürüyüş biçimlerine değinilmiştir. Başlangıç olarak yürümenin tanımı yapılmış ve stabilite konusunda olduğu gibi burda da yürüyüş biçimleri statik ve dinamik olarak iki ana başlık altında toplanmıştır. Ayrıca yürüyüşün tanımlanmasında kullanılan temel ifadelere yer verilmiştir. Yürüyüş biçimleri statik ve dinamik olmak üzere iki ana biçimde irdelenmiştir.

Biyolojik yaklaşımlı robotlarda, robot hareketinin doğadan esinlenerek gerçeklenmesi esas alındığı için bu bölümde doğada hayvanlar üzerinde görülebilen yürüme biçimleri kategorize edilerek yürüyen mekanizmalara göre ifade edilmiştir. Statik yürüme biçiminde, dört ayaklı robotların bir avantajı olan yönsüz yürümeyi gösterecek şekilde robotun ileri, yana ve rotasyon hareketi gerçekleştirebilecek şekilde adım sıraları çıkarılmıştır. Dört ayaklı robotlarda dinamik yürüme için yapılan çalışmalarda özellikle atların hareketinin referans alındığı görülmüştür bu sebeple dinamik yürüme biçimi atların gerçekleştirdiği yürüyüş türleri üzerinden tanımlanmıştır. Yürüyüş biçimleri başlığı altında ayrıca stabilite ve yürüyüş arasındaki ilişkiye kısaca değinilmiştir.

Dört ayaklı yürüyen robotun hareketi aynı zamanda bir kinematik problemi olarak ele alınmış kinematik denklemleri çıkarılmıştır. Kinematik bilindiği gibi, bir robot kola ilişkin yörünge planlaması dinamik ve kontrol problemleri ele alındığında ilk gereksinim duyulan konulardan biridir. Çalışmada kinematik modeli oluşturulurken bir ayak üç serbest dereceli RRR robot kolu şeklinde kabul edilerek, Denavit-Hartenber yöntemi uygulanmış D-H değişken tablosu çıkarılmış aynı şekilde bütün robot modeline eksen takımları yerleştirilerek robot bütününde kinematik yapı elde edilmiştir. Düz kinematik problemi, klasik robot kolunun uç noktasının konum ve yönelimini eklem değişkenleri cinsinden ifade ederken, burada robotun ayak uçlarının konum ve yönelimini temsil etmektedir. Ters kinematik de aynı şekilde, robot uç noktasının verilen konum ve yönelimi sağlayacak eklem değişkenlerini ifade etmekteyken dört ayaklı robotlarda robot ayak ucunun verilen nokta ve yönelime göre sağlaması gereken eklem değişkenlerini temsil eder. Ters kinematik problemi her durum için komplex denklemler türetmektedir ve pek çok farklı methodla çözüme ulaşılabilmektedir. Bu nedenle tez çalışmasında robot ayak modelinin ters kinematik denklemlerin elde edilmesinde sadece cebrik yaklaşım metoduna yer verilmiştir. Bu denklemlerin çıkarılması konunun teorik olarak daha iyi anlaşılmasına katkı sağlamıştır.

Son olarak, teorik olarak incelenen yürüyüş biçimlerinin simulasyonu için robot modeli tasarlanmıştır. Mekanik tasarım ilk olarak CATIA ortamında geliştirilmiştir, çizim yerine üç eklemi temsil edecek şekilde servo motor örnekleri kullanılarak gerçeklenmiştir. Bu aşamada robotun uygulanabilir bir yapıda olması göz ardı edilmemiştir. Tüm ana parçalar ve bağlantı parçaları oluşturularak bir bütün haline getirilmiştir. CATIA ortamında oluşturulan dört ayaklı robot tasarımı, başka bir 3D modelleme programı olan Unigraphics ile parasolid forma dönüştürülerek ADAMS ortamına aktarılmıştır. MSC. ADAMS ortamında çalıştırılmasında amaç robot hareketinin simulasyonun kolayca gerçeklenebilir olmasıdır. Ancak MSC.ADAMS platformunda modelin hareketlendirilebilmesi için, mekanik tasarımda kullanılan her bir parçanın şekil, kütle, yoğunluk ve atalet momenti gibi parametreler ile yer girilerek gerçek simulasyon ortamı sağlanmıştır. Bunların dışında, üç serbestlik derecesini sağlayacak şekilde eklemlerin tipleri, eklemlerin dönüş yönleri, yer çekimi, sürtünmeler gibi diğer parametreler modelde tanımlanmıştır.

MSC.ADAMS/View ortamında eklemlere programda tanımlı step gibi verilen komutlarla robotun yürüyüşü sağlanmıştır ve bu aşamada teorik olarak irdelenen yürüme modelleri simule edilmiştir. Statik yürüyüş biçiminde ileri yönlü statik yürüyüş için tespit edilen adım sırasını takip edecek şekilde diz ve bilek eklemleri motive edilmiştir. Yürüme hareketini sağlayacak giriş komutları eklemlere uygulanmıştır. Teorik olarak incelenen statik yürüme biçimi robot simulasyonu üzerinde gerçeklenerek robotun stabilitesini koruyarak yürüyüşünü gerçekleştirdiği gözlemlenmiştir. Statik yürüyüş simulasyonun yanı sıra dinamik yürüyüş biçimi de uygulanmıştır. Bunun için, robotun iki ayağının havada iki ayağının da destek fazında kaldığı trot yürüme biçimi çalışılmıştır. Dinamik yürüme biçimlerinde en rahat gerçeklenebilir olması tercih sebebi olmuştur. Trot yürüyüş simulasyonunda robotun dört ayağında bilek ve diz eklemlerine girişler uygulanarak bir adımlık yürüyüş sonuçları elde edilmiş ve robotun hareketi izlenmiştir. Statik yürüme simulasyonunda stabilite unsuruyla ilgili bir sorun fark edilmezken trot yürüyüşte robot gövdesinden alınan pozisyon sonuçlarına göre kısmen dengesinin bozulduğu görülmüştür. Buna sebep olarak dinamik yürüyüşte dengenin esas kriterinin hareket olması ve dengenin sağlanabilmesi içni gerekli girişlerin çok iyi şekilde tespit edilmesinin gerektiği görülmüştür. Çalışmanın ilerleyen aşamalarında bu konu üzerine ağırlık verilerek dinamik yürüyüş modelinin geliştirilmesi hedeflenmektedir.

Sonuç olarak bu tez çalışması, elde edilen robot modelinin MSC.ADAMS/View ortamında komute edilebildiği gibi MATLAB ortamında komplex yürüme ve kontrol algoritmaları geliştirilebilecek ileri bir çalışmanın temeli olarak yürütülmüştür. Bu amaçla MSC.ADAMS ve MATLAB arasında gerçeklenecek eş simulasyon yapısı da kurulmuştur. MSC.ADAMS/View ‘ın eklentisi olan ADAMS/Control üzerinde modelin daha önce ADAMS/View üzerinde komute edilerek hareketlendirilen eklem hareketleri giriş olarak, hareket esnasında gözlemlenecek eklem açıları ve diğer parametreler çıkış olacak şekilde değişken olarak tanımlanmıştır. ADAMS/Control ile robot modeli MATLAB ortamında işlenebilir hale getirilmiştir bu durum modele yürüme ve kontrol algoritmalarının eklenebilmesine ve bu bağlamda geliştirilebilmesine fayda sağlayacaktır.

İlerleyen çalışmalarda öncelikle statik ve dinamik yürüyüş için her bir yürüme modeli oluşturularak bu yürüme biçimleri arasında geçiş yapabilen, verilen bir güzergahı takip edecek bir robot modeli için gerekli kontrol algoritmalarının kurulması hedeflenmektedir.

Tez çalışması kapsamında dört ayaklı robotların hareket analizi incelenirken yapılan diğer çalışmalar incelenerek hareket analizinde gerekli teorik altyapı kurulmuştur. Bunun için stabilite, yürüme biçimleri, kinematik model konularının ele alınması uygulama aşamasında dikkate alınarak konunun efektif şekilde anlaşılmasına katkı sağlamıştır. Ayrıca mekanik çizim ve tasarım alanında da uygulama yapılmasına fırsat verilmiştir. Konuya sahip olunan mesleki vizyonun -elektrik- haricinde mekanik bir yaklaşım gösterilmesine olanak sağlamıştır. Aynı şekilde dinamik simulasyon programlarının öğrenilip kullanılmasına yönelik iyi bir fırsat olmuştur.

1. INTRODUCTION

Walking mechanisms are very popular in robotic field at recently. Bipedal and quadruped robots are the best known of them. In this study, a four-legged walking robot's , quadruped movement and the different forms of relatedconcepts were examined and analyzed.

In this part, mentioned comparison of wheeled and legged locomotion. Also biologocicallay inspired robot in different number of legs and leg design for these types robots. Lastly, state of the art and content of thesis are explanied.

1.1. Comparison of Wheeled and Legged Locomotion

Legged robots are omni-directional so their mobility much than the wheeled robots and tracks. When a leg robot can change direction independently of the direction of the main body axis with changing its footholds. On the other hand, wheeled robot would have to do some manoeuvring to be able to change direction. A legged robot can overcome obstacles with stepping on them but wheeled robots must heights up to half of the wheel radius. The tracks can surmount higher obstacles than a wheeled one but they using large body motions when overcome obstacles. Active suspension providing is also important when adapting to irregular terrain in robot locomotion and legged robots can cover highly irregular terrain with body levelled by adapting the leg lengths to terrain irregularities. Also it is proved legged systems under very irregular terrain conditions are more efficient than wheeled or tracked systems. Legged systems do not require piori-knowledge terrain, like wheeled do, and they can move on sandy, muddy, stiff, and soft with similar efficency. In soft terrain, wheeled vehicles move difficult since of wheels can sink but if one leg is placed vertically on the ground it only compacts soft ground in the same direction. Leg lifting is performed vertically, withoutinterfering the ground. When the body is propelled, feet rotate around theirjoints; therefore, legs do not interact with the ground and do not cause anyjamming problems [1]. Comprosion of legged and wheelled mechanism is shown figure 1.1.

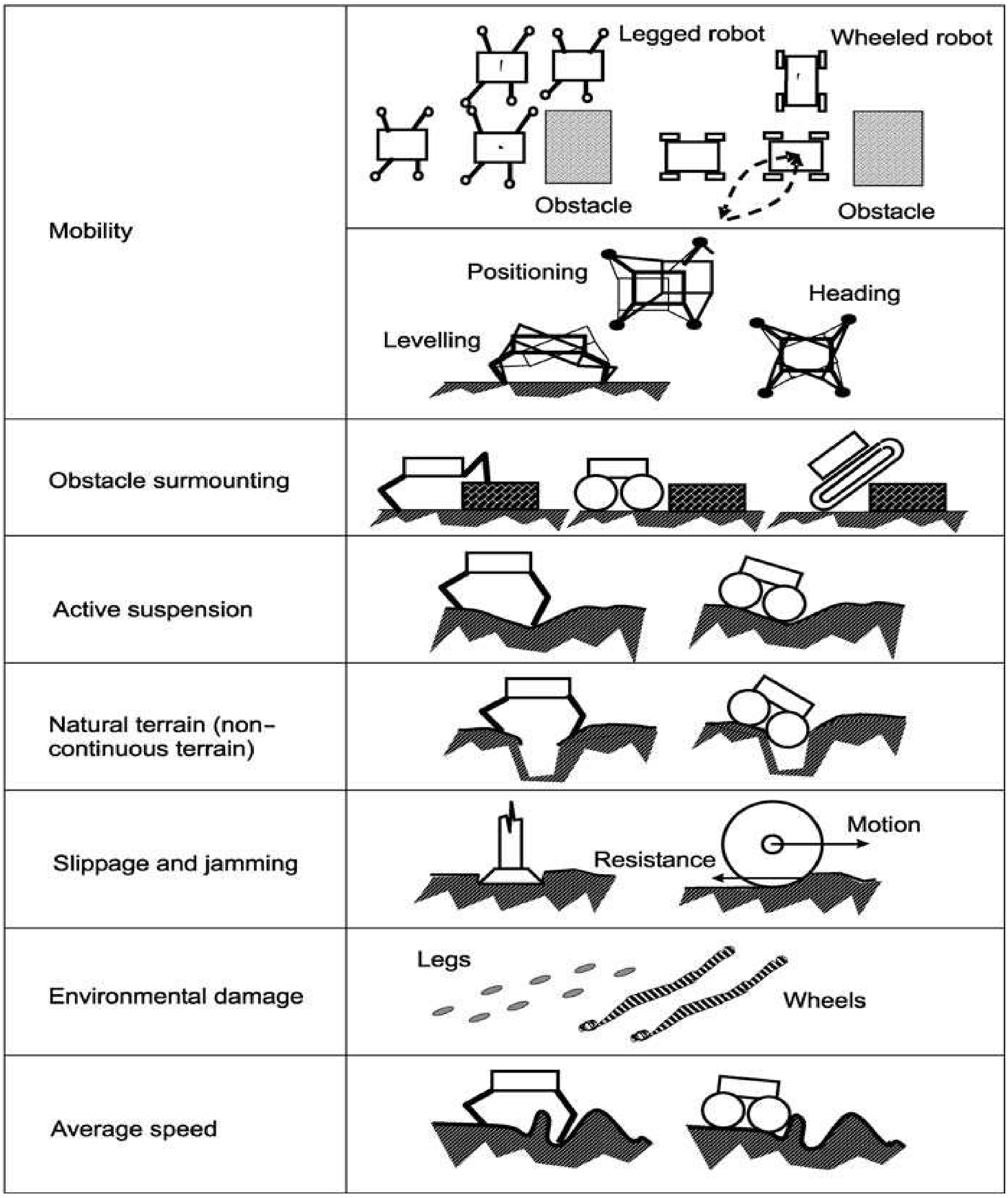


Figure 1.1:Comparison of Legged and Wheeled Mechanism [1].

1.2. Biological Inspired of Robot

Many of the animals have legs that differ according to the conditions of life. They have different number of legs and different types of walking. Crocodiles, Spiders, crocodiles, dogs, horses and humans are instance to them. The walking types in nature, is categorized by number of legs; bipedal, quadrupedal, hexapedal and octopedal.

It is understandable that people turned their attention to those walking animals, after it was recognized that the human invented wheeled and tracked systems did not satisfy all the needs. In this sense, legged systems have a peculiarity of imitating the nature. This imitation is obvious in structural similarity between legged robots and imitated animals, however, for today the imitation is not limited to structural design. Today researchers are trying to understand the underlying biological principles of walking in animals, namely the operational and control structures [2]. Bipedal walking is shown figure 1.2.

Bipedal walking and humanoid robots are investigated by mobile robotic researchers. Bipedal walking is much complicated than quadrupedal and the others.

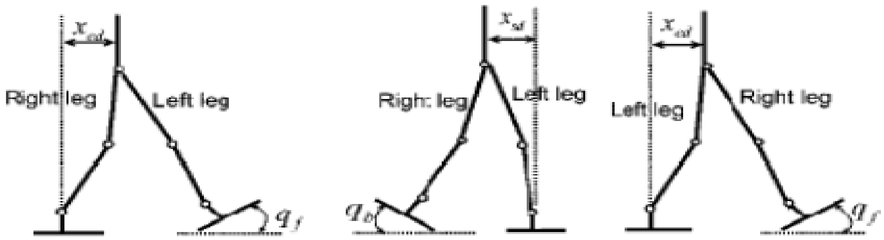


Figure 1.2: Bipedal Walking [2].

Bipedal walking consists of two parts, two legged support phase and single leg support phase. Two legged support phase starts with contact of stepped foot to ground and finishes with lifting up tip toe of the back leg. In single leg support phase, while one leg supporting the body, other leg lift up and goes on. Honda P3 humonoid robot is shown figure 1.3 and legged structure is shown figure 1.4.

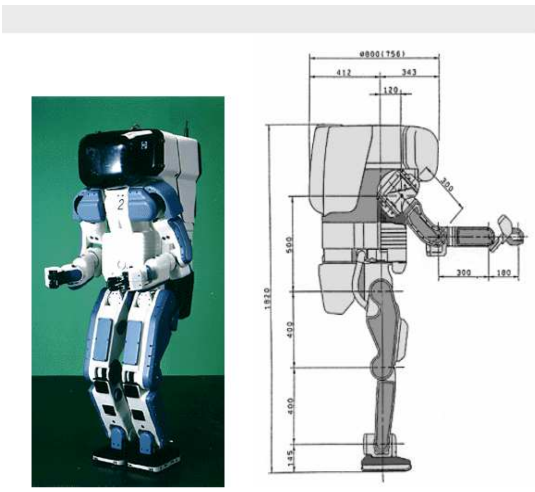


Figure 1.3: Honda P3 Humonoid Robot.

Four-legged animals, have different kinematic structured legged and different kind of walking which depend on whether vertebrate and invertebrate or reptile and mammals.

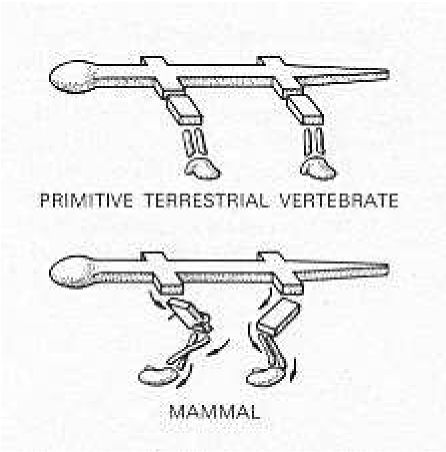


Figure 1.4: Leg Structure of mammals and reptile.

Reptiles such as crocodiles are moving with static creep gait, the other mammals animal can make dynamical walking.

The walk gait that is adopted by almost four legged animals, the trot gait of horses, the rack gait of camels, the canter and gallop gaits of horses, and the bound gait of dogs are some of the dynamically stable gaits of four legged animals in nature [3]. Three example of four legged animal gaits is shown figure 1.5.

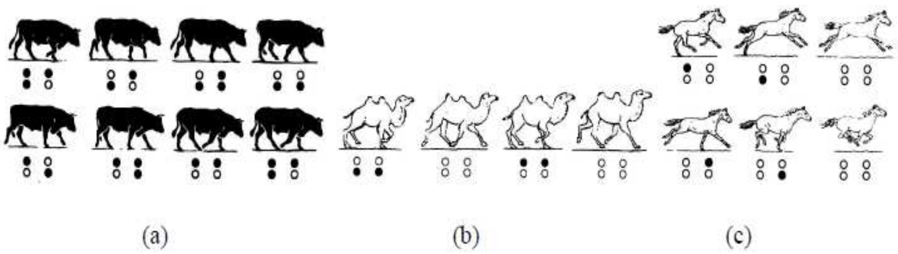


Figure 1.5: Three examples of four legged animal gaits; a) Ox in walk gait, b) camel in rack gait c)horse in transverse gallop [3].

Almost all insects are six-legged. Six-legged walking walking is the most common form of invertebrates. Tripod, legs in groups of three six-legged walking is the most common form of nature, gait type. As the same way, tetrapot; the legs take a step in groups of four and the actual form of walking. The example of six-legged gait is shown figure 1.6.

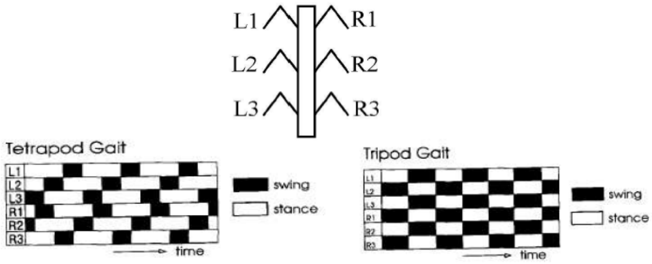


Figure 1.6: Hexapedal Gait.

1.3. Leg Design for Multi-Legged Robots

A simple mechanical leg might have as few as 2 joints, shoulder and knee (or elbow), where both can rotate through much larger angles than in animals, as well as some means to absorb impact shocks in lieu of complicated bending movements in the joints. This might be a linear shock absorber of some kind, or maybe just a rubber ball. The complexity of the shock absorbing mechanism will be directly related to the types of stride the mechanical being engages in. If it isn't going to run and jump, then the requirements are not as stringent. In addition, having a knee that can bend like both knee and elbow, ie a "knelbow", would allow the robot to raise and lower itself by scissoring its legs inboard, and also walk and run like animals. The major requirements are that the leg be fully extendable to front and back at close to a 45 degree angle, shorten to about 70% of that length during the impact phase of the step (based upon simple geometry), and lastly shorten to less than 70% of its maximum length during the movement which takes the leg forward to initiate the following step.

On the other hand, the horse above steps through a much smaller angle, about +/-30 degrees, so the shortening amount is only about 86% there (ie, cosine of the angle). The swing angle will obviously depend upon whether the animal is doing a simple walk, a trot, or a run. +/-45 degrees from vertical will accommodate both walking and trotting; more would be necessary for running. The shortening amount will directly relate to the swing angle used for each specific stride [4].

1.4. State of Art

In this section, briefly introduced in some quadruped robot which are well known such as Tekken, Warp, BigDog.

Tekken is developed by Kimura and Cohen from University of Electro-Communication in Tokyo. In Tekken I and II central pattern generators (CPGs) plat an important role .The implemantation of the robot includes a nerbous system model qith a neural oscillator that provides the robot with some ability to adapt to irregular terrain, both in walking and in running. Tekken IX, was developed for a drilling task on a sloping construction site . The length of the legs is 3.7 m,and the weight of the robot is 7,000 kg .

To the best of ourknowledge, TITAN XI is the largest quadruped in the world.The legs are driven by hydraulic cylinders, and a drill ismounted in the middle of the body. Two winches are installedon the back to reel tethers to assist in climbing a slope [5] .TITAN XI is shown figure 1.7.

Figure 1.7: TITAN XI climbing up a test slope.

BigDog is the alpha male of the Boston Dynamics robots. It is a rough-terrain robot that walks, runs, climbs and carries heavy loads. BigDog is powered by an engine that drives a hydraulic actuation system. BigDog has four legs that are articulated like an animal's, with compliant elements to absorb shock and recycle energy from one step to the next. BigDog is the size of a large dog or small mule; about 3 feet long, 2.5 feet tall and weighs 240 lbs. Bigdog is shown figure 1.8.

Figure 1.8: BigDog.

1.5. Content of Thesis

In the introduction part, differences between legged mechanism and conventional wheeled mechanisms, biologically inspired robots types were described, leg design for multi-legged walking mechanism and also two examples of quadruped robots were given.

Chapter 2,3 contains important subjects of quadruped locomotion; Stability and Gaits. In chapter 2, static and dynamic stability criterias are defined with in chapter 3 Gaits types and relation between stability and gaits were investigated.

Chapter 5, simple model of quadruped robot was obtained in MSC.Adams/View and Matlab. At last, conclusion part was included in the model for the development of goals and recommendations.

2. STABILITY

In the past, much work has been done to investigate four-legged walking. Two of the earliest works are the G.E. Quadruped and Phoney. With the introduction of more powerful computers, more and more bionic robots have been invented in recent years. WARP1I21 in 2002, TITAN from 1989, BISAME in 1998 and SCOUT II in 1999 are examples for these developments. Based on bionic technology, Legged robot has priority than wheeled robot in bumpy environments as dene, marish, massif and so on. However one of most challenge that many researcher must well treat is stability question. So how to exactly evaluate stability and stability margin has the vital significance in legged robot research such as gait plan, motion and structure parameters selection, control method and so on [6].

McGhee, and Frank proposed to use the shortest distance from the vertical projection of the center of gravity onto a horizontal plane, to an edge of the convex polygon formed by the vertical projection of the feet contact points onto the same horizontal plane, that they call the stability margin [6].

Walking and running machines are classified into two categories based on the stability of their motion: stability stable and dynamically stable. For a passively stable system, the vertical projection of the center of mass always remains within the closed region formed by the contact points of the feet on the ground. This region is called the support polygon. They typically have four or six legs but may be bipeds with large feet surface area. In contrast, dynamically stable systems utilize dynamic forces and feedback to maintain balance. Dynamically stable machines have been built with one, two, and four legs. Because dynamically stable systems are more difficult to design, control and analyze, the early legged robots were mostly statically stable machines [7].

The first generation of walking machines emulated this principle of locomotion. Early walking robots were huge mechanismsfeaturing heavy limbs too difficult to control. Theadoption of statically stable gaits could simplify their control. However, duringthe motion of the heavy limbs and body some inertial effects and otherdynamic components (friction, elasticity, *etc*.) were found to arise, restrictingthe robot’s movements to low, constant velocities. Thus, the adoption of staticstability facilitated motion control at the price of speed.

The only way to increase walking-robot speed is to consider the robotdynamics in the control of robot stability. The intrinsic complexity of considering the whole robot’s dynamics led some researchers to look for solutions by designing very mechanically simplified machines having onlya few degrees of freedom, which adopt the stability criteria designed for bipeds (*i.e.* humanoidrobots), extended to a couple of additional legs. The motion of thesequadrupeds is limited to even terrain, because the stability criterion used –based on the Zero Moment Point is only valid. Also, the mechanical simplicity of these designs makes the robotuseless for real applications, where manipulation and payload transportationare required.

Little effort has been made to cope with the dynamic effects thatlimit statically stable machines’ performance. However, one of thegoals of research on legged locomotion is the use of walking robots in industrial,field and service applications, and such robots are not meant always totrot or gallop but also to walk under static stability on uneven terrain [1].

The few dynamic stability criteria defined for quadrupedal walking seemto give different forms and names to a single idea: the sign of the momentaround the edges of the support polygon caused by dynamic effects acting onthe vehicle’s center of mass. The suitability of each criterion for each particularapplication (*i.e.* manipulation forces and moment present, uneven terrain,*etc*.) is not clear at all. Nevertheless, the use of a stability criterion not suitablefor the current application may prevent the task from succeeding. Therefore, in this chapter, static and dynamic stability criteria are briefly surveyed [1].

2.1. Static Stability

Static stability is defined as the following: An ideal legged locomotion machine is statically stable at time t if all legs in contact with the support plane at the given time remain in contact with that plane when all legs of the machine are fixed at their locations at time t and the translational and rotational velocities of the resulting rigid body are simultaneously reduced to zero. Where an ideal legged locomotion machine is defined as a machine where "the trunk [the robot's main body] is modelled as a rigid body, the legs massless and able to supply an unlimited force (but no torque) into the contact surface at the feet's contact points" which is a good approximation of a legged robot.

The above definition means that the robot is statically stable when its center of mass is within of the support area, which is the area created by drawing lines between outermost parts of the surfaces currently in contact with the ground (feet or wheels). When a foot is lifted up from the ground, support area becomes much smaller which makes the robot much less stable. If the center of mass comes outside the support area, the robot will fall over if it does not adjust its balance (i.e. use dynamic stability). Some margin must be kept between the center of mass and the edges of the support area in order to handle external forces, such as the inertial forces subjected to the robot if it is moving and then suddenly stops or when it turns. In order to remain statically stable the robot must therefore only lift its feet in such a way it this does not "shrink" the support area too much. It can only move its center of mass (relatively to its support area) a small distance before it needs to modify the support area (which usually means taking a step). The advantage of static stability is that since the robot can stop its motion at any time, this means that the demands on the control of the robot in terms of responsiveness and precision are much smaller than if dynamic stability is used [8].

Walking systems being particularly suited to locomotion on irregular grounds, restricting their analysis to the only case of a flat level ground can be a severe shortcoming. Still, these two criteria have been widely used to check the static or dynamic balance of walking systems. And besides checking their balance, it haseven been usual to consider that walking systems are dynamically (resp. statically) stable if their ZMP/CoP (resp. the pro- jection of their CoM) lies strictly inside the convex hull of the contact points, unstable if it lies on the edge of the convex hull. This led to measure in many different ways the distance from these points to the edge of this convex hull, deducing a Static Stability Margin, an Energy Stability Margin, a Dynamic Stability Margin, a Tumble Stability Margin and other equivalent propositions. But all of these stability margins agree to conclude that tipping over an edge of contact points is an unstable situation for a walking system, even though this happens tobe not an unusual situation in stable walking [9]. Support polygon and different margin is shown in figure 2.1.

Statically stability subject is needed to define center of gravity projection. The system is statically stable if the horizontal projection of the center of gravity is within or on the edge of the support polygon. This stability margin was introduced by McGhee, R. B. and Frank gives a statement for the stability of a system on even terrain. This margin defines the base stability of a system, but does not give any degree, which can be used [10].

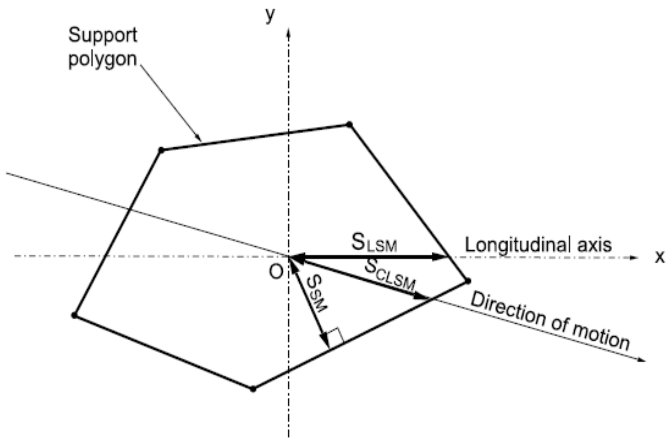


Figure 2.1: Support polygon and different static stability margins.

2.2. Stability Margin Types

This section contains defitinitons of stability margin types stability margin is types which are above mentioned 2.1.

Static Stability Margin; is defined with the magnitude as SSM at time t for an arbitrary support pattern is equal to the shortest distance from the vertical projection of the center of gravity to any point on the boundary of the support polygon. If the pattern is statically stable, the stability margin is positive [11].

Longitudinal Stability margin**;** The stability of the system is guaranteed if the horizontal projection of the center ofgravity is within the support polygon on the x-axis. A very similar stability margin, the crab lngitudinal stability margin defines the stability in the same way, exept,that the axis is defined by the walking direction of the robot. Figure 2.1 shows clearly that the distances of S_{LSM} and S_{CLSM} are bigger than S_{SM}. This leads to the conclusion that only the degree of the Static Stability Margin will give us an appropriate value over the stability. If the robot is on rough terrain, it is not necassarily the case that the closest edge of the support polygon is in the direction of motion. The system may fall even if the CLSM is positive [10].

Energy Stability Margin**;** A measure of stability called "Static Stability Margin" (SSM) has been defined by McGhee to be the minimum distance from the GCOM to an edge of the support polygon. These stability margins, however, do not account for slopes or other irregularities of terrain or the height of the center of mass of the robot. An improved and more practical measure called the "Energy Stability Measure" (ESM) was proposed by Messuri . The ESM measures how much potential energy needs to be overcome before the robot tips. Essentially, this measures how much the center of mass must rise during tipping before it exits the support polygon. Mathematically this is given by:

$$S_{ESM} = min(mg\boldsymbol{h}_i) \quad \textbf{(2.1)}$$

$$\boldsymbol{h}_i = R_i \times (1 - \cos(\theta))\cos(\chi \boldsymbol{h} i) \quad \textbf{(2.2)}$$

Where *m* is the mass of the robot, *g* is the gravitational constant and h_i is the height the center of mass can rise before the robot tips along the *ith* edge of the support polygon. R_i is the distance between the COM and the *ith* edge of the support polygon, and is θ the angle between *Ri* and the gravity vector. *"i* indicates inclination of the *ith* edge of the support polygon with respect to its projection onto the plane normal to the gravity vector [12].

Normalized Energy Stability Margin(NESM); This stability was mainly designed for static walking on rough terrain. It is an adaptation of the energy stability margin (ESM) which calculates the stability by comparing the initial potential energy of the system to the maximal one which is passed by the center of gravity during the process of tumbling [13].

The equation defining this stability criterion:

$$S_{NESM} = \boldsymbol{h}_{max} - \boldsymbol{h}_0 \quad \textbf{(2.3)}$$

Although "NE Stability Margin" doesn't change essentially from "Energy Stability Margin", it has a few advantages as follows. i)Stability can be evaluated in proper way when such a disturbance as mentioned before occurs. ii)As it is expressed by not the unit of [J] but the unit of [mm], it is convenient to derive a gain by means of the geometric way. iii)When walking vehicles are on the ground, "NE Stability Margin" corresponds to "Stability Margin" in the case where the center of gravity touches to the ground, which has the continuous relationship and is easier to understand intuitively. Furthermore, “NE Stability Margin” can be made dimensionless if it is normalized by the total size. But the height of the center of gravity is expected to affect stability greatly, therefore, the dimension of length shall be remained in the criterion [13].

2.3. Dynamic Stability

The first dynamic stability criterion for quadrupeds using crawl gaits was proposed as an extension of the Center of Gravity Projection Method. The Center of Pressure (*COP*) Method claims that a robot is dynamicallystable if the projection of the *COG* along the direction of the resultantforce acting on the *COG* lies inside the support polygon. The Dynamic StabilityMargin is thus defined as the smallest distance from the *COP* to theedges of the support polygon. The*COP* Method coincides with the Center of Gravity Projection Method understatic conditions and uneven terrain. It was renamed the *COP* the Effective Mass Center(*EMC*), and redefined it as the point on the support plane where the resultantmoment due to terrain-reaction forces and moments vanishes. Note thatthe definition of the *EMC* coincides with what in the literature of biped robotsis commonly known as the Zero Moment Point (*ZMP*), first defined byVukobratovic and Juricic (1969). However, the use of the *ZMP* in quadrupedshas been less extended than in bipeds because the *EMC* or *ZMP* stability criterion is not valid for uneven terrain (tocompute the *ZMP*, the support polygon has to be confined in a plane).Some momentum-based stability criteria have been defined as well. Hereonly the most meaningful ones are reviewed. The statement is as follows.Given a robot-and-manipulator system as shown in Figure 2.2 the forces andmoments acting on the *COG* may destabilize it, making the system tumble.Dynamic equilibrium at the *COG* requires,

$$FI = FS + FG + FM \quad \textbf{(2.4)}$$

$$MI = MS + MG + MM \quad \textbf{(2.5)}$$

where subscripts I, S, G and M denote inertia, support, gravitational andmanipulation effects, respectively.

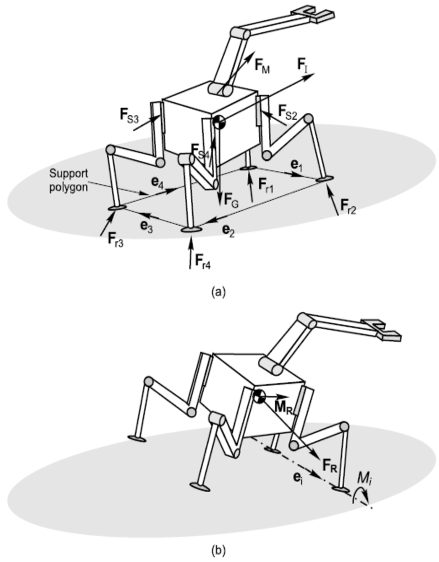


Figure 2.2: Forces acting on a robot + manipulator system; (b) Robot tumbling.

During the tumble the robot loses most of its support feet, leaving onlythose that conform a rotation axis. A resultant interaction force FR and moment MR between robot and terrain result to counteract theaddition of ground-reaction forces at every foot (Fri) and the momentum they generate around the *COG*, respectively. For the robot to maintain stability aresultant force and moment generate a moment *Mi* about the rotation axis*i* that must compensate for the destabilizing forces and moments to ensuresystem stability [1].

To solve the unusefulness of static stability margins when robot Dynamics are relevant some momentum-based stability criteria have been defined. Lin and Song defined the Dynamic Stability Margin, DSM, as the smallest of all moments M_i around the edges of the support polygon caused by robot/ground interaction forces, normalized by the weight of the system, that is:

$$S_{DSM} = min\left(\frac{M_i}{mg}\right) = min\left(\frac{e_i \times (F_R \times P_i + M_R)}{mg}\right) \qquad \textbf{(2.6)}$$

where Pi is the position vector from the CG to the i-th support foot, F_R and M_R are the resultant force and moment of robot/ground interaction, and ei is a unit vector that revolves around the support polygon in the clockwise sense. If all moments are positive (if they have the same direction and sense as e_i), then the system is stable [14].

Center of pressure method**;** The system is said to be stable if the center of pressure is within the support polygon. It was defined and takes the center of pressure as reference point to provide a reliable statement on the stabilityof the robot. If the COP remains within the support polygon, defined by the 3 supporting legs of the robot, the system remains stable. If the COP is located on the edge of the support polygon, the gravity of the robot is only supported by two legs and the robot is in critical stability. Any external force or moment will cause the robot to tip over. As result, the distance between the COP and the edge of the support polygon must be as large as possible. The bigger this distance is, the bigger the external forces and moments the system can cope with can be. This distance is defined as:

$$\overline{QC} = \overline{QG'} + \frac{\overline{n_3} \times \left(\overline{GG'} \times \overline{F_g}\right)}{\left(\overline{n_3}\left(\overline{F_g} + \overline{mg}\right)\right)} \qquad \textbf{(2.7)}$$

$$\overline{n}_3 = \frac{\overline{P_1P_2} \times \overline{P_1P_3}}{\left\|\overline{P_1P_2} \times \overline{P_1P_3}\right\|} \qquad \textbf{(2.8)}$$

W P_1 P_2 is the support polygon edge closest to the point C and Q is the nearest point on that edge. G’ represents the vertical projection of the center of mass and Q is the point that where the perpenicular to the porjection. COP is so to say an evolution of the center of mass. Again, this margin only defines if the system is dynamically stable or not, and doesnt give any values which could deliver a degree of stability [14]. Illustration of the COP is shown in figure 2.3.

The Dynamic Stability Margin(DSM); The SDSM is defined by Lin and Song as the minimum resultant moment about the boundaries of the supporting polygon normalized to the gravitational force of the system. A negative moment means that the system is unstable and will turn over. So the system is stable if all moments are positive and the smallest moment is the dynamic stability margin. The dynamic stability margin is given by the following equation:

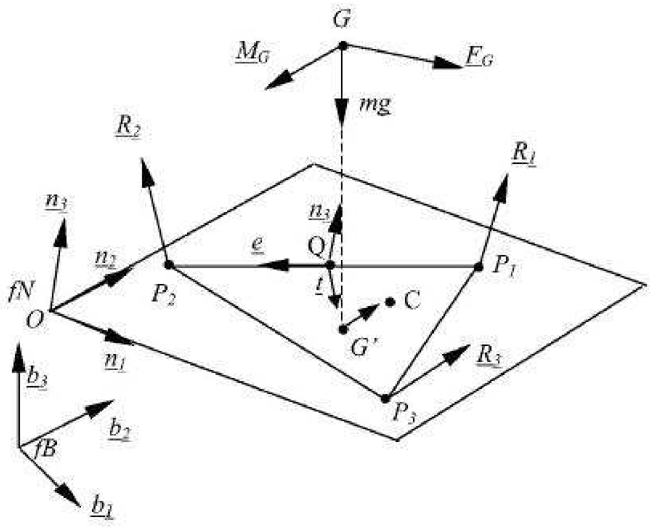


Figure 2.3: Illustration of the COP.

Where E_i is a unit vector along the boundary positive in clockwise direction. P_i is defined as the postion vector between the center of mass and any point at the boundary. R_f is the resultant force acting on the center of gravity and R_m is the resultant moment also acting on the center of gravity. So the requirements to compute this stability margin, are the knowledge of the exact position of its center of mass as well as which external forces and moments are acting on the system. A requirement for the dynamic stability margin says that dynamic equilibrium at the center of gravity is required because otherwise thesystem will tipp over.

$$F_I = F_S + F_G + F_M \quad \textbf{(2.9)}$$

the same for the moments:

$$M_I = M_S - M_G - M_M \quad \textbf{(2.10)}$$

where I stands for inertia; S for support, G is gravitational and M are the manipulation effects [10].

Tumble Stability Margin(TSM); The STSM introduced by Hirose and Yoneda in 1997 says, that if all moments relative to a unit vector are positive, the whole system will be stable. The special chacarcteristics in their calculation is, that they consider the legs of the robot as massless. By this way, the stability factor, that the leg masses bring to the system is not taken into consideration; Instability is reached faster. The leg-support and foot-reaction forces become the same with massless legs. This leads to a reaction force and moment defined as follows:

$F_R = F_I - F_G - F_M$ **(2.11)**

$M_R = M_I - M_G - M_M$ **(2.12)**

From these equations, the moment around each tumbling axis can be defined:

$$M_i = M_R \times e_i + F_R \times P_i \times e_i \quad \textbf{(2.13)}$$

Again, since the definition of the stability margin is the same as for the dynamic stability margin, the TSM becomes: STSM = min(Mimg) So except for the massless legs, these two stability margins coincide [10].

The Force-angle Stability Measure(FASM); A different criterion was proposed by Papadopoulos and Rey. The Force-Angle stability criterion finds the angle α_i between the resultant force acting from the CG on the ground (the opposite to the reaction force F_R) and the vector R_i, normal to the rotation axis from the CG. The system becomes unstable when this angle becomes zero. The stability magrin is the product of the angle times the resultant force F_R, that is:

$$S_{FSAM} = min(\alpha_i).\|F_R\| \quad \textbf{(2.14)}$$

These are the main stability criteria used for comparison with the herein proposed one. Recent research 20 has demonstrated that none of the static stability margins are suitable for measuring robot stability when robot dynamics are relevant. The FASM seems to be the best of the existing margins, because it accurately judges stability on flat terrain in the presence of inertial effects. However, it loses accuracy when manipulation effects arise or when the robot walks over uneven terrain. Furthermore, it shows that none of the dynamic stability margins accurately measure stability when there are manipulation forces and moments or dynamic effects during the transfer of the legs [14].

Normalized Dynamic Energy Stability Margin; The normalized dynamic energy stability margin, shortly NDESM is referred to as the smallest of the stability levels required to tumble the robot around the support polygon, normalized to the robot mass. This stability criterion provides a precise measure of manipulation effects and inertial effects. The performance of this stability margin also takes external forces which act on the robot, into consideration. So even if the robot pulls weight for example, it will not tumble up to a certain degree. As for the implementation of this stability margin, the requirements are quite high.

Firstly you need to know the exact positions of the each foothold as well as the center of gravity positions in the fixed reference frame. Than you need to know all the forces which act on the robot to calculate the resultant force an moment. As special property you also need to know the maximum velocity the center of gravity can have just before it tumbles. This has to be tested experimentally before and takes time. The NDESM is supposed to be the most performant an most reliale on the one hand, but on the other hand this stability criterion also requires the most inputs to be calculated. A detailed description on how to implement the Normalized dynamic energy stability margin can be found in the appendix of the paper: "dealing with internal an external perturbations on walking robots"by E.Garcia,P.Gonzalez de Santos and F.Matia. This is the the most advanced and the newest of all the stabiliy margins and thatforeit is supposed to deliver the best results [10].

3. GAIT TYPES OF QUADRUPED

This chapter contains definitions about gait of quadrupeds and relation between gait and stability.

β,Duty Factor; The friction of the duration of the stride for which a foot is on the ground in the support phase. Stability and velocity of the gait are depend on duty factor.

T, *cycle time;* Time duration of one stride the time to complete one cycle of the leg movements.

Events of gait; the placing or lifting of any of the feet during locomotion. For n-legged machines, there are 2n events in one stride.

Relative phase φ; the tme elapsed from the setting down of a chosen refence foot until the foot of leg is set down given as the fraction of the cycle time.

Stability Margin; The startest distance from the vertical Projection of the center of gravity of the robot onto a horizontal plane, to the boundaryof the support area.

Stride; The complete cycle of leg movements for example from the setting down of a particular foot to the next setting down of the same foot. Where all the legs have beenn lifted and placed exactly once.

Stride Length; The distance travelled by the center of gravity of the walker in one stride stroke (λ) The distance that foot i, translates relative to the hip during the "support phase"

Swing phase; The phase when a foot is in the air and repositioned fort he next support phase [15].

Description of Gait**;** In legged locomotion ,the legs should be coordinated with respect to stability, propulsion and energy efficiency. In movement of a leg, the lifting and placing create a gait and these lifting and placing of the leg, are called as an event of the gait. Also the sequence in which the legs are lifted and placed is called a gait event sequence.

For n legged robot, the placement of foot *i* is denoted by event *i,* while the lifting of foot i is denoted by event i+n. Thus, a gait expressed as a sequence of events such as 2-4-5-7-3-1-8-6 , creating 2n different events. If two events occur at the same instant, the gait is termed singular gait, as opposed to totally ordered gaits, or non singular gaits. The number of possible non-singular quadruped gaits is the permutation of the 2n events; that is 2n!. Considering the number of event sequences starting from a given one, the result is N=(2n-1)! . For a quadruped, the total number of possible gait event sequences for a quadruped is N=5040 but only very small portion or them are suitable as gaits used by animals. Reason of this, during walking, leaving out of COG (center of gravity) from support area [1].

A complete cycle of leg movements, where all the legs have been lifted and placed exactly once, is defined as a stride and the time duration of stride is defined as cycle time. There are 8 events in one stride during the quadruped gait. These events lifting and placing of all legs.

3.1. Gaits and Stability

All gait types can be classified, in two types according to stability as statically and dynamically stable gait. Stability of gaits are related to speed of walking machines. Creeping gaits are called statically stable and faster gaits are called dynamically stable. While dynamically stable gaits remain balance by moving, statically stable gait remain balanced by relaying on the support area formed by the leg in ground contact.

In a statically stable gait, the vertical projection of the center of gravity (COG) onto a horizontal plane, is kept within the support area all the time. Statically stable and un stable is shown in figure 3.1.

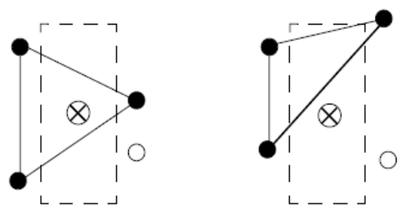


Figure 3.1: Statically Stable and Unstable.

For robots with point feet, a necessary condition for static stability is that the robot has at least three legs on the ground all times. This is necessary in order to form an area of support that can contain the projection of COG within its bord.

Distances from the center of gravity to the different edges of the support area for a quadruped with three legs in support area. The stability margin is defined as the shortest of these distances.

3.2. Gaits of Quadruped

The animals, which make quadrupedal locomotion, during their movements change the types of gait. Walking of a horse is the best example such that, the horse start to walking in a low speed but while increasing speed change the type of gait from walk to trot, canter and lastly gallop. Stability, speed, energy efficiency are effective while choosing gait type. Quadrupedal locomotion can be devided in two types as static and dynamic walking. In shortly it can be said for quadrupeds, statically stable or static walking gaits haveat least 3, and dynamically stable gaits at least 2 legs, incontact with the ground at all times.

3.2.1 Static walking

The static walking is the principal of most quadrupedal animals moving at low speeds as mentioned chapter 1. This causes a pattern of foot placements whereby support duringa stride occurs twice on the lateral legs, twice on the diagonals, twice on twofore-feet and one hind foot and twice on two back feet and one fore foot.Walking can also slow to a crawl, a gait that alternates between providingsupport on three and four feet.

Crawl gait is a type of creeping gait which has 0.75 duty factory that means the gait quite slow. They can be executed arbitrarily slow or even stop while being stable at all times. In a crawl gait, Stability Margin become maximum and is defined if the COG is within the support area and negative not.

As mentioned above, in 5040 different possible gaits for quadruped there are only 6 that allow the animal to have three legs in ground contact all time. Figure 3.2 shows a diagram for crawl gait, strike order as 1-4-2-3 and position of center of gravity while walking, always in support area.

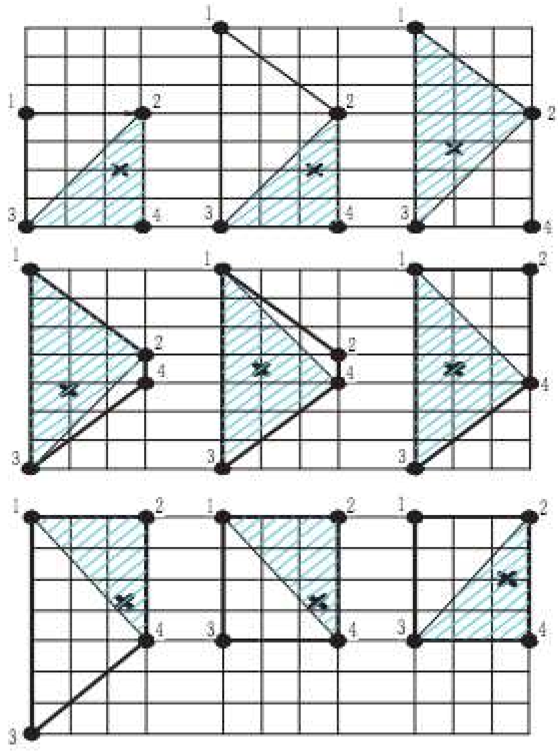


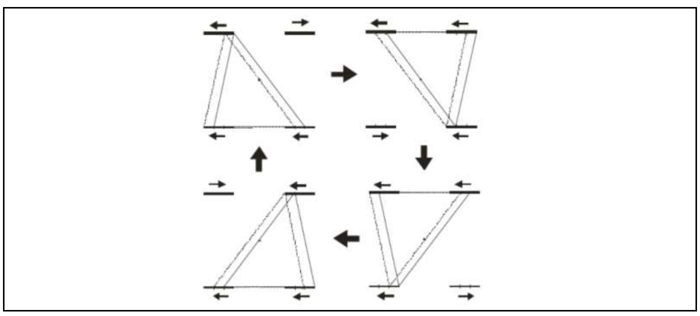
Figure 3.2: Diagram of Crawl Gait.

Figure 3.2 shows crawl gait while robot walking forward also quadruped can make side walk and rotation in crawl gait. In the study [16], with choosing of phasing that maximize stability margin bellowing strike orders.

Table 3.2.1: Strike orders for forward, side and rotation.

Leg	Front-left	Hind-left	Hind-right	Fron-right
Forward	1-2-3-4	2-3-4-1	4-1-2-3	3-4-1-2
Side Walk	1-2-3-4	3-4-1-2	2-3-4-1	4-1-2-3
Rotation	1-2-3-4	2-3-4-1	3-4-1-2	4-1-2-3

Walking diagram of side and rotation walking is given Figure 3.3.



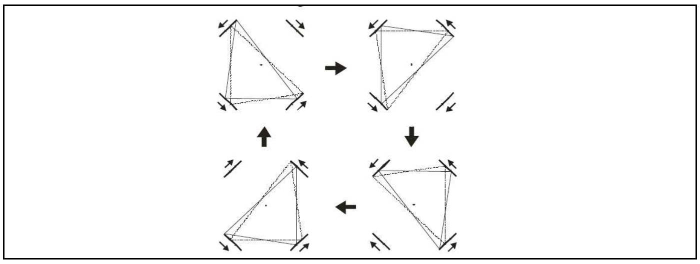


Figure 3.3: Side and rotation walking diagram.

3.2.2 Dynamic walking

The trot is the most common intermediate speed gait ofbiological quadrupeds, When animals transition from wakingto running to increase speed, trotting is typically he first gaitthey employ. The trot is generally a very stabledynamic gait because when each pair of legs is on theground, the line of support between the feet passesdiagonally underneath the body. For some reptiles andamphibians, the trot is actually the highest speed gait [16]. Figure 3.4 shows trot, pace and gallop.

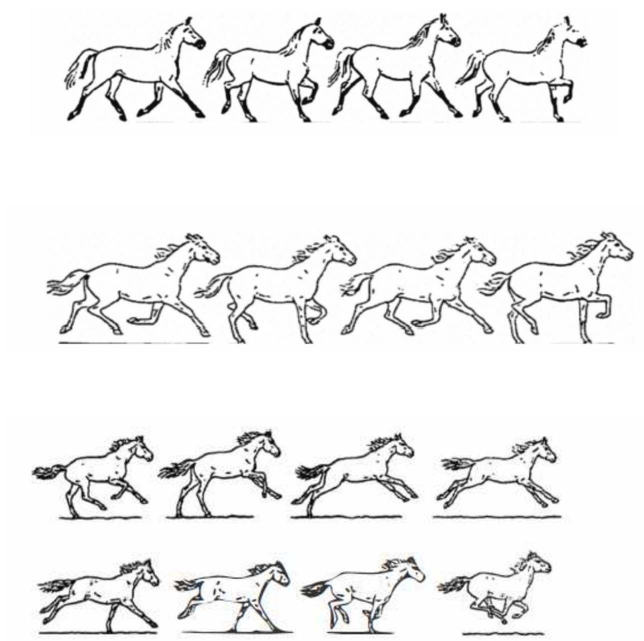


Figure 3.4: Trot, Pace and Gallop Gait of a horse.

The pace, sometimes called the rack, is also anintermediate speed gait, but it differs from the trot in that thelegs operate in lateral rather than diagonal pairs. The pace is lesscommon than the trot probably because it is less stable. Since the legs provide support in pairs on alternating sides of hebody, significant roll motion of the trunk is typical with this gait.

The gallop is the most common high-speed gait ofrelatively large biological quadrupeds. It is characterized bythe two front footfalls occurring sequentially, followed bythe two hind footfalls. In general, no two feet touch down atthe same time, and the phase difference between the twofront legs is typically larger than that between the two hindlegs. After the front feet lift off the ground, the flight phase isreferred to as "gathered" because the legs are gatheredtogether under the body. If a flight phase occurs after thehind feet lift off, it is referred to as "extended" because the legs are extended out from the body. The gathered flightphase is almost always present in the gallop and is generallylonger than the extended Right phase which appearsprimarily at high speeds. Both flight phases may also befound in the bound and half-bound [17].

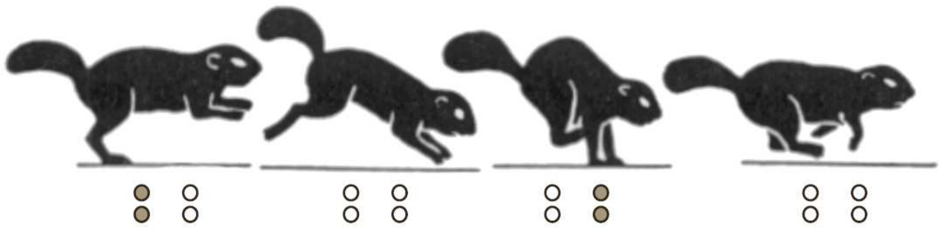


Figure 3.5: Bound gait.

The bound is a running gait used by a few small quadrupeds such as squirrels, rodents, and dogs. The bound gait is shown figure 3.5. In the bound, support alternates between pairs of legs, with the fore and hind limbs acting in unison to thrust the body forward. This gait is of particular interest since, of all gaits discussed so far, the bound has the shortest gait period, allowing for frequent interactions of the legs with the ground [18].

4. KINEMATIC OF QUADRUPED

Kinematics is the study of the geometry of a mechanical system, where the motionof the system can be described in terms of the velocity and acceleration of all itscomponents. The components can be connected through different types of joints,which limit how the components can move relative to each other. The interconnectionof the components implies that the motion of the components relative to eachother is constrained. Newtonian mechanics state that the forces acting on a systemchange the motion of the system. The forces can be divided into constraint forces,that limit (or constrain) the motion, and generalized forces, that cause the motion.

Kinematics describe the interconnection of the components and the constraintswithout regard to the constraining forces and defines the motion of the interconnectedbodies through space without regard to the generalized forces that cause amotion [15].

It is assumed here that each component of the mechanical system can be treated asa rigid body. A rigid body can be defined as a component for which the distancebetween any two points in the component is fixed, i.e. the points can not move relativeeach other. The generalized coordinates (or configuration coordinates) determinethe geometric configuration of the mechanical system. This means that anypoint in the mechanism can be specified by giving the values of the generalized coordinates.

The generalized coordinates can be chosen in different ways wherethe choice is dependent on, for example, which coordinates are of interest, forinstance due to placement of sensors, or simplification of the equations. The minimum number of generalized coordinates that specify the configuration of themechanism is called the geometric degree of freedom. A kinematic motion of themechanism is determined by specifying all the generalized coordinates as functionof one single variable, for example time, and thereby generating a curve for themotion of all points in the mechanism. The coordinates have to be given relative toa frame, usually a cartesian coordinate system, that is fixed relative to the earth [15].

In order to derive kinematic model a quadruped, each leg is modelled seperately and then whole body is considerd. Quadruped robot can be considered as invers RRR robot, which has a 3 DOF for each leg with 3 link, connected through joints and one effector. The end effector corresponds to the foot point of leg. According to this initial position and angles of joints are shown in below Figure.4.1.

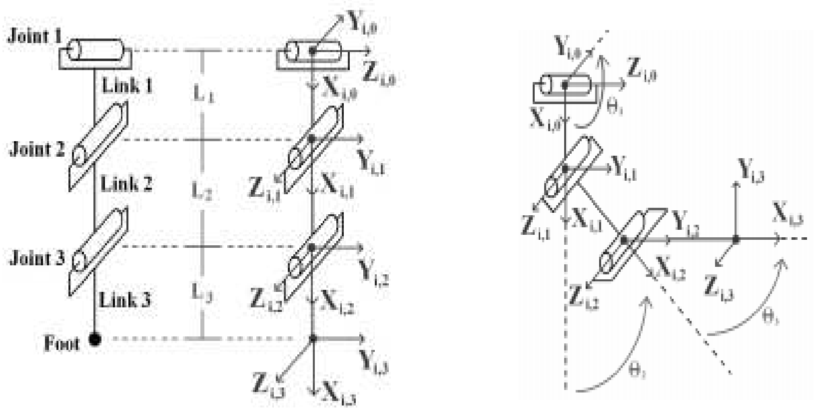


Figure 4.1: Danavit-Hartenberg convention for ith leg.

Danavit-Hartenberg table is obtained as follow Table 4.1

Table 4.1: DH Variable Table**.**

Link Nr. i	**Joint Variables θ_i**	**Twist α**	**Link length *l***	**d_i**
1	Θ_1	90	l_1	0
2	Θ_2	0	l_2	0
3	Θ_3	0	l_3	0

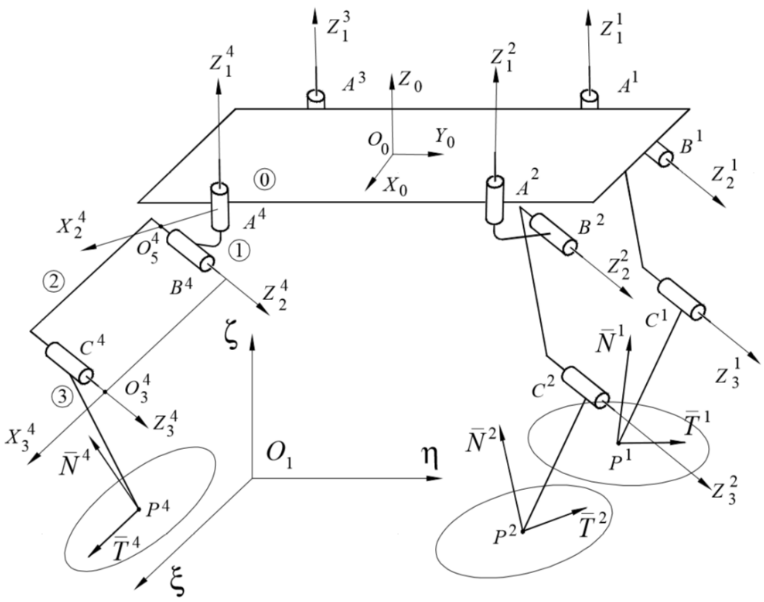


Figure 4.2: The Whole Body in The Denavit-Hartenberg coordinate systems.

Figure 4.2 shows illustration of D-H coordinate systems for whole robot body also shows normal component $\bar{N}$ and tangential component (or coulombian friction force) $\bar{T}$ parameters which terms is used to determine stable position of walking robots. Short definition of $\bar{N}$, perpendicular on the surface of terrain in the theoretical contact point, $\bar{T}$ situated in the tangent plane at terrain surface in the theoretical contact point.

The magnitude of *T* vector can not be greaterthan the product of the magnitude of normal component by the frictional coefficient between foot and terrain. If this magnitude is greater than the friction force, then the foot slips along the support surface down to the stable position, where the magnitudes of these component decrease under the above mentioned limit [21].

4.1 Forward Kinematics

Walking motion of the robot is a resultant of the interactions of the supporting legs. As mention in chapter 4 intro, four similar legs are motivated symmetrically to the robot body by revolute joints so each leg kinematic can be consider independently. During the robot motion the supporting leg accept as a robotic arm, the foot frame represents base frame and the robot bod is moving relative to it and frame. The Denavit-Hartenberg Coordinate parameters are given previous chapter, and the forward kinematic equations are below.

$$T_1^0 = \begin{bmatrix} cos\ (\theta_1) & 0 & sin(\theta_1) & L_1\ cos\ (\theta_1) \\ sin(\theta_1) & 0 & -cos\ (\theta_1) & L_1\ sin\ (\theta_1) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.1)$$

$$T_2^1 = \begin{bmatrix} cos\ (\theta_2) & sin(\theta_2) & 0 & L_2\ cos\ (\theta_2) \\ sin(\theta_2) & -cos\ (\theta_2) & 0 & L_2\ sin\ (\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.2)$$

$$T_3^2 = \begin{bmatrix} cos\ (\theta_3) & sin(3) & 0 & L_3\ cos\ (\theta_3) \\ sin(\theta_3) & -cos\ (\theta_3) & 0 & L_3\ sin\ (\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.3)$$

$$T_3^0 = T_1^0\ T_2^1\ T_3^2 = \begin{pmatrix} R_{3x3} & d_{1x3} \\ 0_{1x3} & 1 \end{pmatrix} \quad (4.4)$$

$$T_3^0 = \begin{bmatrix} c_1\, c_{23} & -s_{23} c_1 & s_1 & c_1(L_3 c_{23} + L_2 c_2 + L_1) \\ s_1 c_{23} & -s_{23} s_1 & -c_1 & s_1(L_3 c_{23} + L_2 c_2 + L_1) \\ s_{23} & c_{23} & 0 & (L_3 s_{23} + L_2 c_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.5)$$

$d=(x, y,z)^T$, therefore, the position of the foot is given by

$$x = c_1(L_3 c_{23} + L_2 c_2 + L_1) \quad (4.6)$$

$$y = s_1(L_3 c_{23} + L_2 c_2 + L_1) \quad (4.7)$$

$$z = (L_3 s_{23} + L_2 c_2) \quad (4.8)$$

4.2 Inverse Kinematics

The inverse kinematics consists in determining the joint variables $(q_1, . . . ,q_n)^T$ in terms of the foot position and orientation. For a 3-DOF leg the problems can be stated as

$$A_1(q_1)^1 A_2(q_2)^2 A_3(q_3)^3 \equiv \begin{bmatrix} a_{11} & a_{12} & a_{13} & x \\ a_{21} & a_{22} & a_{23} & y \\ a_{31} & a_{32} & a_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.9)$$

$(x,y,z)^T$ represents foot position and $(a_{11}, a_{21}, a_{31})^T$, $(a_{12}, a_{22}, a_{32})^T$, (a_{13}, a_{23}, a_{33}) are the orientation vectors of the foot. As can be seen systems is represented with 12 equations in 3 unknowns. This means solving all equations in closed form is quitely difficult, it is the difference of forward and inverse kinematics. Forward kinematic has one, unique solution but inverse kinematic may or not several. To solve inverse kinematic problem varied methods can be used. In this section an algebraic approach solution formulas is derived.

$$xS_1 - yC_1 = 0 \tag{4.10}$$

$$\tan\theta_1 = \frac{S_1}{C_1} = \frac{y}{x} \tag{4.11}$$

$\theta_1 = \arctan(y, x)$ $x \neq 0, y \neq 0$ if x=0 y=0 ,

an infinitive number of solutions exits for θ_1. In such a case we say the leg is in a singular configuration

$$S_j^2 + C_j^2 = 1 \tag{4.12}$$

$$C_{23} = \frac{xC_1 + yS_1 - L_2 C_2 + L_1}{L_3} \tag{4.13}$$

$$C_{23} + S_{23} = AS_2 + BC_2 = D \tag{4.14}$$

$$A=-z \tag{4.15}$$

$$B = L_1 - (xC_1 + yS_1) \tag{4.16}$$

$$D = \frac{2L_1(xC_1 + yS_1) + L_3^2 - L_2^2 - L_1^2 - z^2 - (xC_1 + yS_1)^2}{2L_2} \tag{4.17}$$

$$A = r\cos\emptyset, B = r\sin\emptyset \tag{4.18}$$

$$\emptyset = \arctan(B, A) \tag{4.19}$$

$$r = +\sqrt{A^2 + B^2} \tag{4.20}$$

$$\cos\theta_2 = \frac{D}{r} \tag{4.21}$$

$$\sin(\emptyset + \theta_2) = \frac{D}{r} \tag{4.22}$$

$$\cos(\emptyset + \theta_2) = \pm\sqrt{1 - \sin^2(\emptyset + \theta_2)} = \pm\frac{\sqrt{r^2 - D^2}}{r} \tag{4.23}$$

$$\tan(\emptyset + \theta_2) = \pm\frac{D}{\sqrt{r^2 - D^2}} \tag{4.24}$$

$$\theta_2 = -\emptyset + \arctan2\left(D, \pm\sqrt{r^2 - D^2}\right) \tag{4.25}$$

$$\theta_3 = \arctan2(B, A) - \arctan2\left(D, \pm\sqrt{A^2 + B^2 - D^2}\right) \tag{4.26}$$

5. DESIGN AND SIMULATION

This chapter includes designing and modeling stages of quadruped and also simulation results. The figure 5.1 shows that used programs.

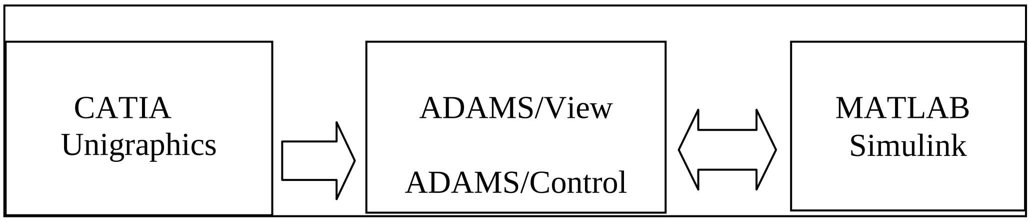


Figure 5.1: Design and simulation diagram

5.1. Robot Design

In this stuy, quadruped structure is designed as a dog with “Bioloid Kit” parts. Bioloid Kit is a composed of a collection of block-shaped parts and servos, a sensor modulue and a control unit that the user can assemble together to build a sophisticated robots. Example part of Bioloid Kit is shown in figure 5.2.

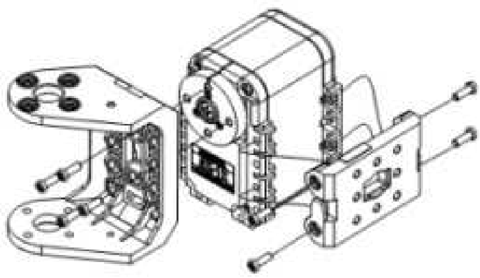


Figure 5.2: Example part of Bioloid Kit

The connection between the different parts can be easily achieved using a simple screw driver, frames made from injection molded plastic fit and connect perfectly [22]. But in this study, only mechanical parts were used, other parts such as control units and sensors were not used because the main aim is simulate to robot model so not need other parts.

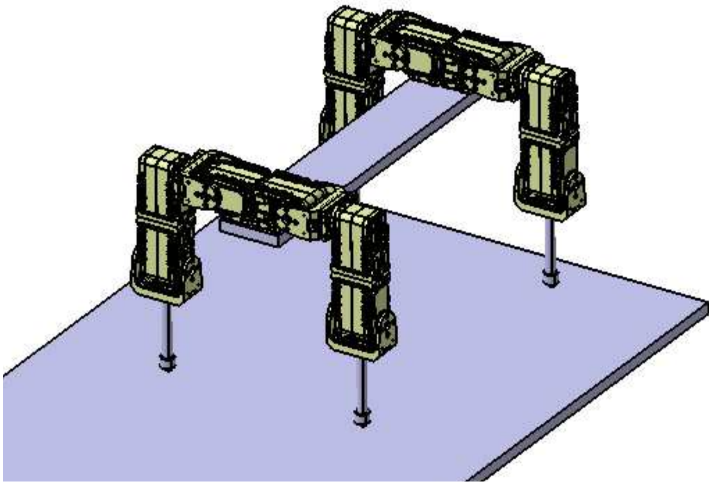


Figure 5.3: Catia model of quadruped

Figure 5.3 shows, CATIA model of quadruped which consisting of servos, brackets, frames, foots and body. Legs are designed by using 3 servos and requisite connection parts and foots. Three servos provides the intented kinematic structured.

Second step of the modeling is, motivate the model, performed in MSC.ADAMS program. Before acting model in Adams, Catia model is converted to parasolid form. Figure 5.4 shows ADAMS model of quadruped.

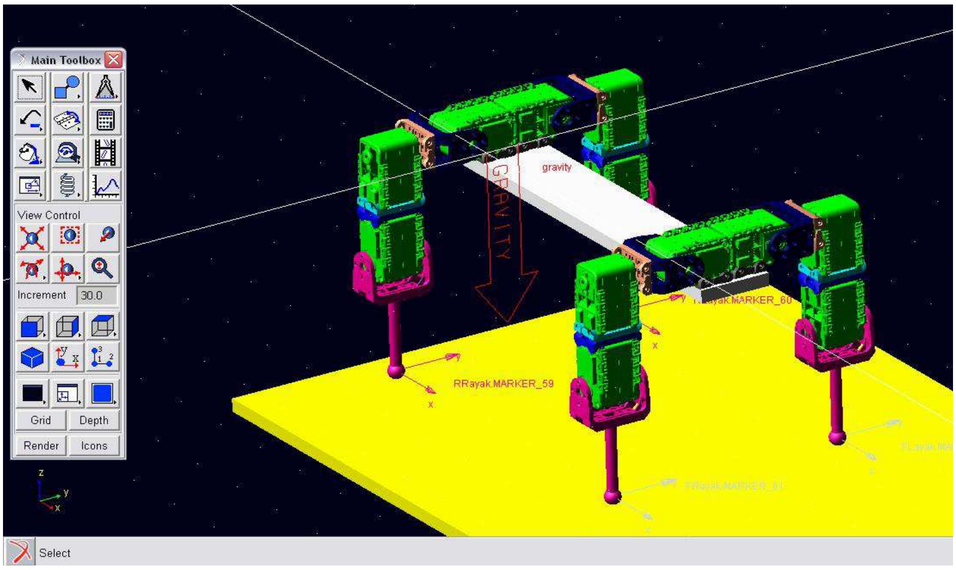


Figure 5.4: ADAMS model of quadruped

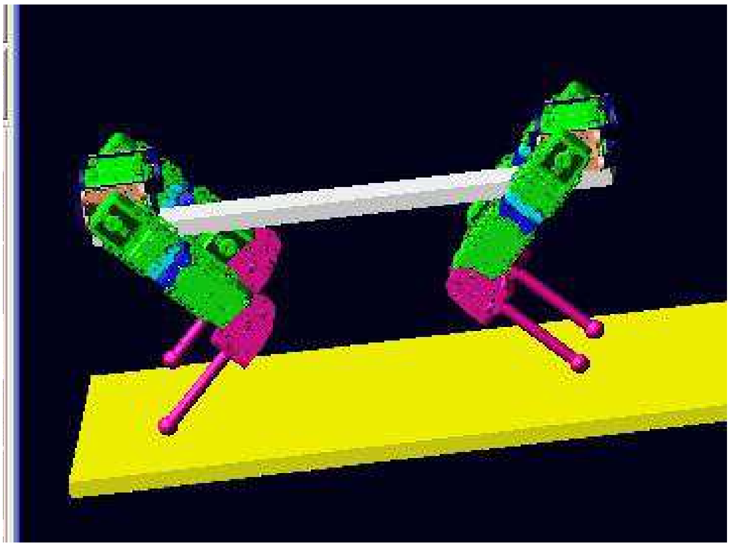


Figure 5.5: Modified joint configuration ADAMS model

Ahead of simulatig model some parameters are setup ADAMS/View, density, mass, inertia and geometrical shape of each part, initial position and orient conditions of each leg, individual rotational scope of each joint and also some characters of contact force between the robot and the terrains, such as stiffness, friction coefficient, and transition velocity of static friction. Modified joint configuration ADAMS model is shown in figure 5.5.

5.2 ADAMS-MATLAB Co-Simulation

There are four steps according the ADAMS/Controls specifications to model a co-simulation model by ADAMS/Controls and MATLAB/Simulink .

The first step in working with ADAMS/Controls is to import an ADAMS model, the model should be complete and include all necessary geometry, constraints, forces and measures; Definition of inputs and outputs through the information or startup file in ADAMS/View in the second step. The outputs describe the variables that go through the controls application.The outputs describe the variables that go through controls the application.

The inputs describe the variables that come back into ADAMS and, therefore, complete a closed loop between ADAMS and the controls application; in the third step the control system block diagram is built with MATLAB.

The ADAMS plant block is imported in the Simulink diagram model which contains the sfunctions.

And the last step is simulation of the combined mechanical model and control system. The following is the steps of co-simulation**.** First step. For importing the mechanical model created in ADAMS/View into ADAMS/Controls, a CMD file has to be exported by ADAMS/View.

Next point is to deactivate the motions in the control system. The motions will be replaced by torques and forces in a next step. It should be made sure that latest at this point that ADAMS and MATLAB are working in the same file directory.

Second step. In this step the state variables which are the inputs and outputs of ADAMS have to be defined.

For the ADAMS outputs simply state variables can be used by definition and the state variable can be simply set equal to a measure which was defined before.

A useful name for the state variable should be given so that it can be simply recognized in MATLAB. Another method is the full definition of a state variable, in whichthe state variable can be build by the function builder, but finally this corresponds to the measure definition. Adams controls plants inputs and outputs is shown figure 5.6

For the ADAMS inputs also state variables have to be created. In a first step these state variables must be set to zero in the. A useful model name has to be specified at first. Then using the variable browser the input and output state variables have to be inserted. Note, that the order of variables specified here is the same order as in the imported block diagram in MATLAB/Simulink.

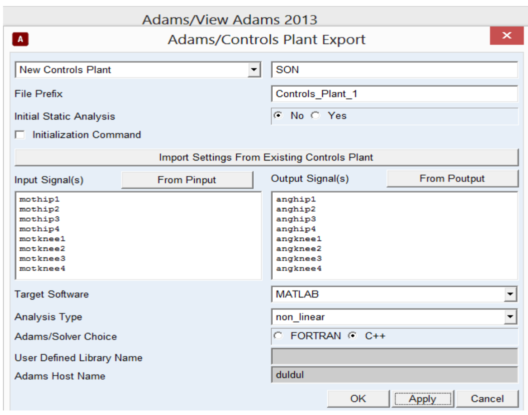


Figure 5.6: Adams controls plants inputs and outputs

Note also, that a unit conversion is necessary in MATLAB when there the model is being calculated using SI units. The export will create some files in the common ADAMS-MATLAB working directory.

Third step. The ADAMS/Control program can be closed and MATLAB/Simulink has to be started. When entering the MATLAB command prompt the m-file created by ADAMS has to be started first.

This m-file can be merged together with the mfile of the control system, so that before a simulation only onecommon m-file has to be executed. The ADAMS block can be integrated into theMATLAB/Simulink control system simply by copy and paste. Adams_sys file in Matlab/Sımulink is shown in figure 5.7.

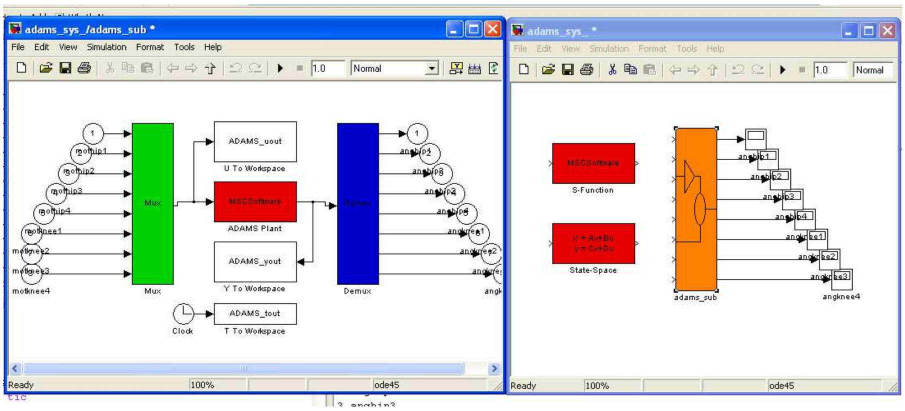


Figure 5.7: Adams_sys file in Matlab/Simulink

5.3 Simulation Results

At first, to observe the movement of the robot, Adams commands are used such as STEP, with this function joints actuate in given time and given angle. By following the steps equence to provide static balance one period of gait were obtained. While crawl gait, angle hip joints are showed figure 5.8. Strike sequence including as 1-4-3-2, required joints moved.

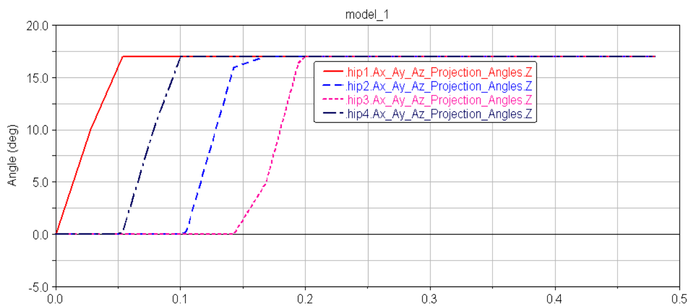


Figure 5.8: Angle hip joints while crawl gait

In one period of gait, hip joints angles are shown above. And the end of the period, center of gravitiy translational displacement about x axis are shown figure 5.9.

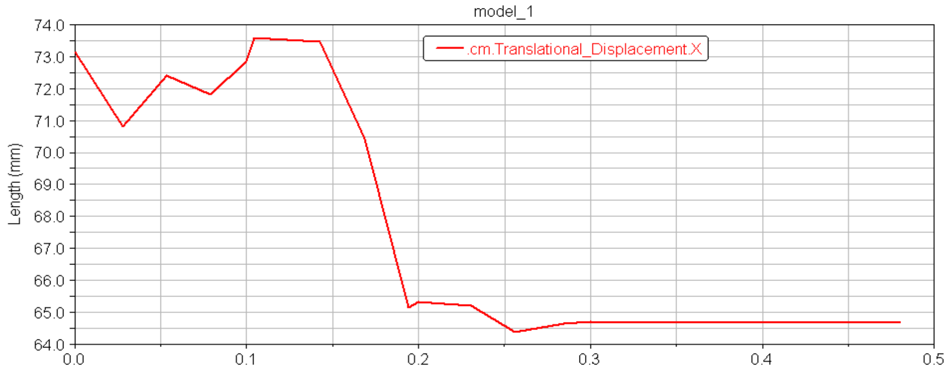


Figure 5.9: Center of Gravity translational displacement

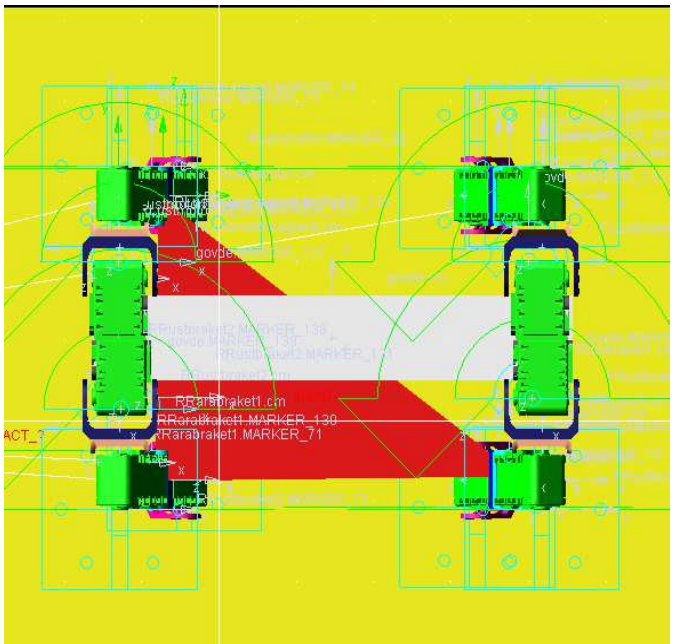


Figure 5.10: Support poligon.

Figure 5.10 shows support polygon of the quadruped while one leg in swing phase.

Trot gait walking type also simulated, as described in chapter 3 trot gait is a dynamic walking model. When a pair of legs in the air the others support the robot. F with actuating legs 1-3 and leg 2-4 pairs. In each leg only knee and hip joints activated. One cycle of trot gait results are given Figure 5.11 and 5.12.

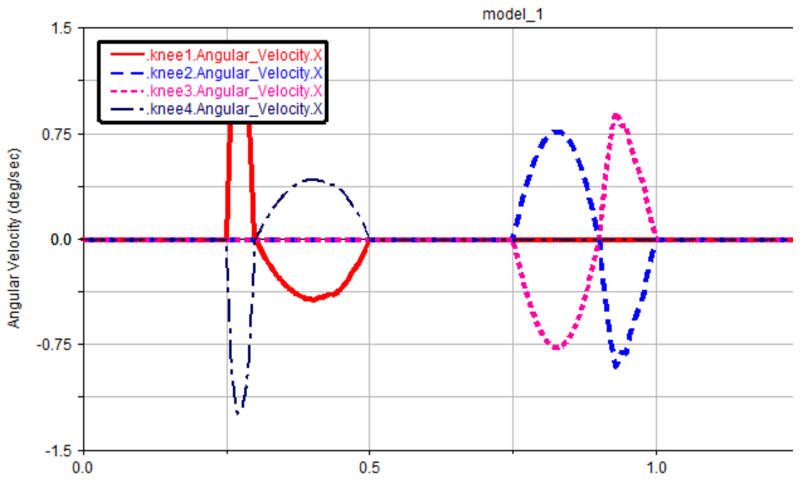


Figure 5.11: Angular velocity of knee joint changing in trot gait.

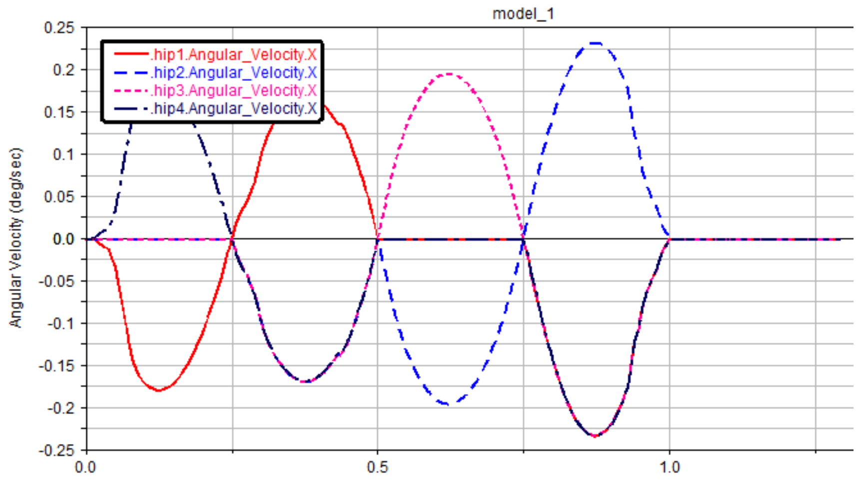


Figure 5.12: Angular velocity of hip joints in trot gait.

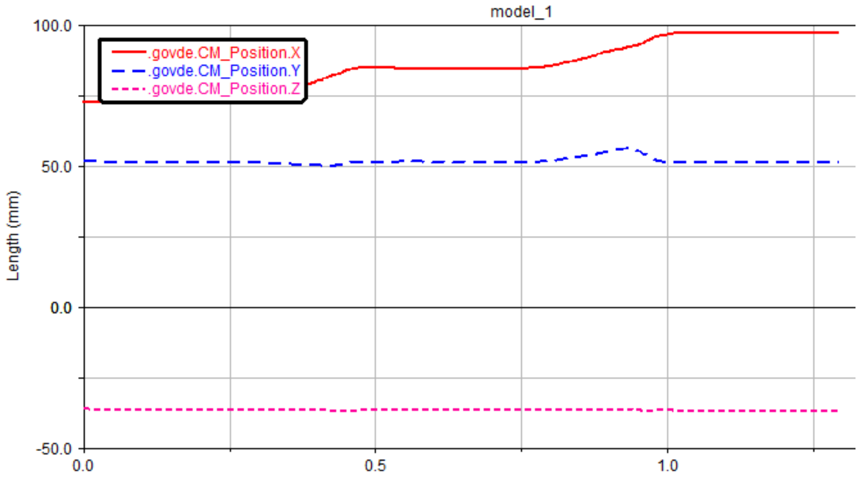


Figure 5.13: Position of center of gravity

Figure 5.13 shows position changing center of gravity of the quadruped. In figure, it can be seen y position is small changing it means, stability of the robot is partially corrupted.

6. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, quadrupedal locomotion is investigated theoretically in past studies. Mainly focused on stability, gait types, kinematics subjects are deeply reviewed in literature.

Stability is one of basic concepts of legged locomotion, especially quadrupedal, therefore plentiful academic journal and resource are reviewed and necesssary definitions was given such as stability margins type static and dynamic seperately for sake of be well understand.

The another fundamental concept gait terms with types and relation between stability are produced also static crawl gait and dynamic trot gait were simulated from examined walking models.

Quadruped kinematic model are obtained and kinematic equations derived.

In the last phase of study, primarily 3D drawing of a quadruped robot designed in CATIA and transferred to another modeling program ADAMS. Static(crawl) and one type of dynamic walking (trot gait) is simulated in ADAMS. Angles and position changing in joints were observed.

Finally, the study is improvable with using of data exchange between ADAMS and MATLAB, robot can be controlled with MATLAB feedback. Different gait and control algorithms can be developed.

REFERENCES

[1] **Gonzalez, P. Garcia E. and Estremera, J.** (2006). Quadrupal Locomotion: An Introduction to the Control of Four-Legged Robot, Springer, London

[2] **Erden, M. (**2006). Six-Legged Walking Mahine: The Robot EA208, PhD Thesis, Science and Technology Instute, Ankara

[3] **Lasa, M. de.** (2000), "Dynamic compliant walking of scout II quadruped." *Master Thesis*, submitted to Department of Electrical and Computer Engineering, McGill University, Montréal, Canada.

[4] Url-1 <**http://www.oricomtech.com/robotics**>, date retrieved 21.10.2011

[5] **Hirose, S. and Fukuda, Y.** (2009). Quadruped Walking Robots at Tokyo Instute of Technologoly, IEEE Robotics & Automation Magazine, vol.16, no.2, pp.104,114

[6] **Wieber, P.** (2002). On the stability of walking systems, International Workshop on Humanoid and Human Friendly Robotics,

[7] **Huberty L.** (2008). A comparison of different stability margins for quadruped walking machines, Autonomous Systems Lab report, Zurich.

[8] **Hemes B. and Papanikolopoulos N.** (2009). A New Modular Schema for the Control of Tumbling Robots, Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on , vol., no., pp.5659,5664, 10-15

[9] **Clark J. E.** (2004). Desıgn, Sımulatıon, And Stabılıty Of A Hexapedal Runnıng Robot, PhD Thesis, Standford University, Standford, MA.

[10] **Hirose, S.; Tsukagoshi, H.; Yoneda, K.,** (2001). Normalized energy stability margin and its contour of walking vehicles on rough terrain, *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on* , vol.1, no., pp.181,186 vol.1,

[11] **Garcia E. and Santos P.** (2005). An improved energy stability margin for walking machines subject to dynamic effects. Robotica, 23, pp 13-20.

[12] **Hardarson, F. (**2002).Stability Analysis and Aynthesis of Anatically Balanced Walking For Quadruped Robots, Doctoral Thesis,Royal Institute of Technology, Sweden

[13] **Brian S.,** (2006). Using Learning Algorithms to Develop Dynamic Gaits for Legged Robots, *PhD Thesis*, MIT, Cambridge, MA.

[14] **Wang, L. and Tao W**. (2010) Gait Analysis and Implementation of a Simple Quadruped Robot, *Industrial Mechatronics and Automation (ICIMA), 2010 2nd International Conference on* , vol.2, no., pp.431,434, 30-31 May 2010

[15] **de Lasa, M. and Buehler, M.** (2001). Dynamic compliant quadruped walking, *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on* , vol.3, no., pp.3153,3158 vol.3

[16] **Souto, R.F.; Araujo Borges, G.; Romariz, A. R S,** (2009) Gait generation for a quadruped robot using Kalman filter as optimizer, *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on* , vol., no., pp.1037,1042, 10-15 Oct.

[17] **Simionescu I., and Ungureanu M.** (n.d). Stability Analysis of Gaits of Quadruped Walking Robot MERO, *The 2nd National Workshop on Mobile Robots, WMRC*. Vol. 1.

[18] **Al-Zaydi, M.Y. and Amin, S. H M,** (1997). Simulation kinematics model of a multi-legged mobile robot," *Advanced Robotics, 1997. ICAR '97. Proceedings., 8th International Conference on* , vol., no., pp.89,94, 7-9 Jul 1997

[19] **Jean-Christophe Fillion-Robin, (**2007). Modelling of a Real Quadruped Robot Using Webots Simulation Platform,School of Computer and Communication Sciences Ecole Polytechnique Federale de Lausanne, Switzerland **R. J., and See, L.** (1998).Neural Network vs. ARMA Modelling: Constructing Benchmark Case Studies of River Flow Prediction.In GeoComputation ’98.*Proceedings of the Third International Conference on GeoComputation*, University of Bristol, United Kingdom, 17–19 September (CD-ROM).

[20] **Darıcı, O.** (2008). Dört Bacaklı Mobil Robotlarda Yürüme Analizi ve Yol İzleme, Yüksek Lisans Tez,, İTÜ Fen Bilimleri Enstitüsü

CURRICULUM VITAE

Name Surname: Esra Çelik

Place and Date of Birth: 08.01.1986/Bakırköy

Address: Osmaniye Mahallesi, Köyaltı Sok. No:4/6 Bakırköy/İstanbul

E-Mail: esrclk@yahoo.com

B.Sc.: Yıldız Technical University, 2008

M.Sc. (If exists):

Professional Experience and Rewards: