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Towards the Design and Evaluation of Robotic Legs of Quadruped Robots

YIFU GAO

Università degli Studi di Genova
and
Istituto Italiano di Tecnologia

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Yifu Gao:
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TUTORS:

Dr. Claudio Semini
Dynamic Legged Systems Lab - Head
Istituto Italiano di Tecnologia (IIT)

Prof. Darwin G. Caldwell
Advanced Robotics Department - Director
Istituto Italiano di Tecnologia (IIT)

CO-TUTOR:

Dr. Victor Barasuol
Dynamic Legged Systems Lab - Postdoctoral researcher
Istituto Italiano di Tecnologia (IIT)

REVIEWERS:

Prof. Giorgio Figliolini
Associate Professor
Dept. of Civil and Mechanical Engineering
University of Cassino and Southern Lazio

Dr. Guowu Wei
Lecturer in Mechanical Engineering Design
School of Computing, Science and Engineering
University of Salford

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

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Yifu Gao
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Abstract

Legged systems have potentials of better mobility than traditional wheeled and tracked vehicles on rough terrain. The reason for the superior mobility of legged systems has been studied for a long period and plenty of robots using legs for locomotion have been developed during recent few decades. However the built legged robots still exhibit insufficiency of expected locomotive ability comparing with their counterparts in nature with similar size. The reason may be complicated and systematic associated with several aspects of the development such as the design, key components, control & planning and/or test and evaluation. The goal of this thesis is to close the gap between legged robots research & development and practical application and deployment. The research presented in this thesis focuses on three aspects including morphological parameters of quadruped robots, optimal design for knee joint mechanism and the development of a novel test bench— Terrain Simulator Platform.

The primary motivation and target for legged robots developing is to overcome the challenging terrain. However few legged robots take the feature of terrain into consideration when determining the morphological parameters, such as limb length and knee orientation for robots. In this thesis, the relationship between morphological parameters of quadruped robots and terrain features are studied by taking a ditch/gap as an example. The influence of diverse types of morphological parameters including limb length, limb mass, the center-of-mass position in limbs and knee configuration on the ditch crossing capability are presented.

In order to realize extended motion range and desired torque profile, the knee joint of HyQ2max adopts a six-bar linkage mechanism as transmission. Owing to the complexity of closed-loop kinematic chain, the transmission ratio is difficult to design. In this thesis, I used a static equilibrium based approach to derive the transmission relationship and study the singularity conditions. Further desired torque profile of knee joint are realized by a multi-variable geometric parameters optimization.

For the test and performance evaluation of robotic leg, I designed and constructed a novel test bench— **T**errain **S**imulator **P**latform (TSP). The main function of the TSP is to provide sufficient test conditions for robotic leg by simulating various terrain features. Thus working status of robotic leg can be known before the construction of the whole robot. The core of the TSP is a 3-$\underline{P}$RR planar parallel mechanism. In this thesis, the structure design and implementation, the kinematics including singularity, workspace etc, and dynamics of this 3-$\underline{P}$RR mechanism are presented.

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Publications

Journal

- C. Semini, V. Barasuol, J. Goldsmith, M. Frigerio, M. Focchi, **Y. Gao** and D. G. Caldwell. Design of the Hydraulically Actuated, Torque-Controlled Quadruped Robot HyQ2Max. *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 2, pp. 635–646, April 2017.

Conferences

- **Y. Gao**, V. Barasuol, D. G. Caldwell and C. Semini (2016). Study on the Morphological Parameters of Quadruped Robot Designs Considering Ditch Traversability. *IEEE International Conference on Robotics and Biomimetics (ROBIO)*.
- **Y. Gao**, V. Barasuol, D. G. Caldwell and C. Semini (2017). Kinematic Design of a Configurable Terrain Simulator Platform for Robotic Legs. *IEEE International Conference on Advanced Robotics and Mechatronics (ICARM)*.

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Acronyms

HyQ	Hydraulically actuated Quadruped
TITAN	Tokyo Institute of Technology, Aruku Norimono (walking vehicle)
CoT	Cost of Transport
BLDC	Brushless Direct Current
PSI	Pound per Square Inch
ASTM	American Society for Testing and Materials
LF	Left-Front
RF	Right-Front
LH	Left-Hind
RH	Right-Hind
FF	Forward-Forward
FB	Forward-Backward
BF	Backward-Forward
BB	Backward-Backward
HAA	Hip Abduction/Adduction
HFE	Hip Flexion/Extension
KFE	Knee Flexion/Extension
DoF	Degree of Freedom
CoM	Center of Mass
GRF	Ground Reaction Force
SLIP	Spring Loaded Inverted Pendulum
DARPA	Defense Advanced Research Projects Agency
TSP	Terrain Simulator Platform
PPM	Planar Parallel Mechanism
ADAMS	Automated Dynamic Analysis of Mechanical Systems

DLS	Dynamic Legged System
RobCoGen	Robotics Code Generator
SL	Simulation Laboratory
MBD	Multi-Body Dynamics

1

Introduction

Legged systems have potentials of better mobility than traditional wheeled and tracked vehicles on rough terrain. For instance only about half the earth's landmass is accessible to existing wheeled and tracked vehicles, whereas a much larger fraction can be reached by animals on foot [Raibert, 1986]. The reason for the superior mobility of legged systems has been studied for a long period and plenty of robots using legs for locomotion have been developed during recent few decades. However the built legged robots still exhibit insufficiency of expected locomotive ability comparing with their counterparts in nature with similar size. The reason may be complicated and systematic associated with the design (scheme and morphological parameter selection), key components (actuator, transmission and sensing system), control and planning and/or test and evaluation.

In this thesis, three aspects of quadruped robots development are investigated: (a) the effect of morphological parameters on featured terrain; (b) the optimal design of the transmission mechanism and (c) the development of a novel test bench— terrain simulator platform TSP. These three research studies can be considered as important elements in the road map for the development of useful quadruped robots.

1.1 Motivation

The principal motivation inspiring the research in this thesis is to explore a systematic method for the development of legged robots especially hydraulically actuated quadruped robots. The primary advantage of legged robots is the employment on challenging terrain, thus the relationship between the morphological parameters such as leg length, leg mass, the CoM position of leg and the knee configuration, should be studied in the design stage of quadruped robots. However most of the work on quadruped robot design consider less about the feature of terrain. The example of a ditch (or gap) which is commonly found in nature and easy to model, is taken to research the influence of diverse morphological parameters including the knee configuration. The research result could be one of a guideline for quadruped robot design for rough terrain.

Legged robots have specific restriction on the dimension and weight of moving legs, and moreover the joint output of robot leg is highly correlated with desired characteristic motion. Thus the mechanical design and actuator selection for robotic leg will be a challenging task as well. In order to acquire desired output profile, e.g. joint torque vs. joint angle, a optimal design can be a solution. Considering multiple-link mechanisms are able to generate complex transmission relationship, so a linkage optimization based design approach will be an effective method of design complex mechanism in confined space and with less mass.

In a quadruped robot, usually most of the DoF of the system are distributed in the robotic legs. Robotic legs can be regarded as the most important subsystem of a quadruped robot. However, the development of robotic leg is usually conducted together with the whole robots. And when the prototype of robotic leg is built, due to the entire robot is incomplete, the test of leg will be limited. On one hand, the robotic leg lacking of fully test and validation may lead to a risk to the entire robot construction; on the other hand, the designed leg is difficult to be transplanted to other robotic platform, since the robotic leg is designed for and debugged within specific architecture, rather than an independent robotic system. Considering the issue above, a new test bench— Terrain Simulator Platform (TSP) is proposed, designed and constructed for the test and evaluation of robotic legs. The TSP is able to generate desired terrain features, i. e. slope, stairs and uneven ground by the movement of its end-effector (a pedal or a mini-scale treadmill) to interact with the foot of robotic leg. Thus robotic leg under test is able to behave like that in real environments together with other components of an entire robot. The majority of key specifications such as force output, moving velocity of foot and energy consumption of a robotic leg can obtain on TSP. In addition TSP could also be used to test and evaluate different control algorithms. Consequently based on the results acquired from TSP, the design process of legged robot will be more efficient, further robotic leg can be used in diverse robot design with different size and number of legs.

1.2 Contributions

The main contributions of this thesis are the following:

- Study on the influence of morphological parameters of quadruped robots on their ditch crossing capability. The effect of all four types of knee configurations on ditch width crossed are researched and compared.
- Structural optimization for the transmission mechanism of the knee joint of HyQ2max. The mechanism and the size of actuator are optimized and selected conform to the targeted joint torque profile.
- Design and construction of the 3-$\underline{P}$RR planar parallel mechanism of the TSP. The mechanism, kinematics and the dynamics of TSP particularly the 3-$\underline{P}$RR mechanism are investigated. The approach utilizing TSP to simulate diverse terrains for robotic leg tests is proposed and implemented.

1.3 Thesis Outline

This thesis is organized as follows: Chapter 2 reports the background and related work on legged robots and legged locomotion. The conventional approaches, dynamic models and test rig for experiments and evaluation are presented as well.

Moreover representative legged robots developed in recent years and their characteristics in the leg design are also analyzed. Chapter 3 presents the effect of morphological parameters of quadruped robots on the ditch crossing capability in simulation. The impact of all four kinds of knee configurations are researched and compared. Chapter 4 describes the optimization process of the transmission mechanism used in the knee joint of HyQ2max. By optimization, a six-bar mechanism that is able to generate desired torque profile is identified. Chapter 5 describes the design and implementation of the mechanical system of the TSP. A 3-$\underline{\text{P}}$RR planar parallel mechanism is designed and implement. The details on the design specification, key components selection and structure design are introduced. Chapter 6 presents kinematics of the 3-$\underline{\text{P}}$RR mechanism including forward and inverse kinematic, workspace, singularity and the prototype experiments. Further dynamic model of the 3-$\underline{\text{P}}$RR mechanism based on Lagrange method is derived and verified through numerical simulation. Chapter 7 draws the conclusions and presents ideas for future work regarding the research presented in this thesis.

2

Background and Related Work

In this chapter, works related to legged locomotion and legged robots are reviewed. Owing to the complexity of legged systems which include animals and legged machines, many correlative researches have been conducted ranging from animals' locomotion, dynamic models to test/evaluation facilities. In addition, several representative legged robots are presented and the structure of legs are analyzed.

2.1 Legged Locomotion and Related Research

Many researchers have studied the locomotion of animals including human beings and the bio-mechanical properties of legs. These results form a fundamental basis for design, control, and evaluation of legged machines. This section will focus on works correlated with the legged locomotion, the structure and configuration of legs and the evaluation facility of a legged machine.

2.1.1 *Muybridge Picture Sequences*

Eadweard Muybridge, an English photographer, was original to use the stop-motion photograph technique to study and document the running motion of animals in the 1870s. Eadweard Muybridge used several cameras to rapidly capture the successive phases during running and proved for the first time that a horse can become airborne during a gallop. Fig. 2.1 shows a picture sequence of a galloping horse. Muybridge also had a large collection of photograph sequences of fast motions of diverse animals including a bird, leopard, elephant and human. Even one century later, researchers still make use of the photograph sequences of Muybridge to develop bio-inspired legged robots, e.g., the study in [Raibert, 1986].

2.1.2 *Models for Legged Locomotion*

To describe the behaviors of legs in walking and running, several models are proposed and introduced [Alexander, 1990]. The SLIP (spring loaded inverted pendulum) model is an extensively used dynamic model to describe the springy behavior of a leg in fast motions like running and hopping, the concept of the SLIP model is shown in Fig. 2.2a. The SLIP model is comprised of a point mass indicating the Center of Mass (CoM) of the system and a mass-less springy leg connected with the point mass through a rotary joint usually representing the hip joint. The entire system moves in the plane of leg swings with three DoFs, two translational and one rotational. The main feature of the SLIP model is that the motion of the system

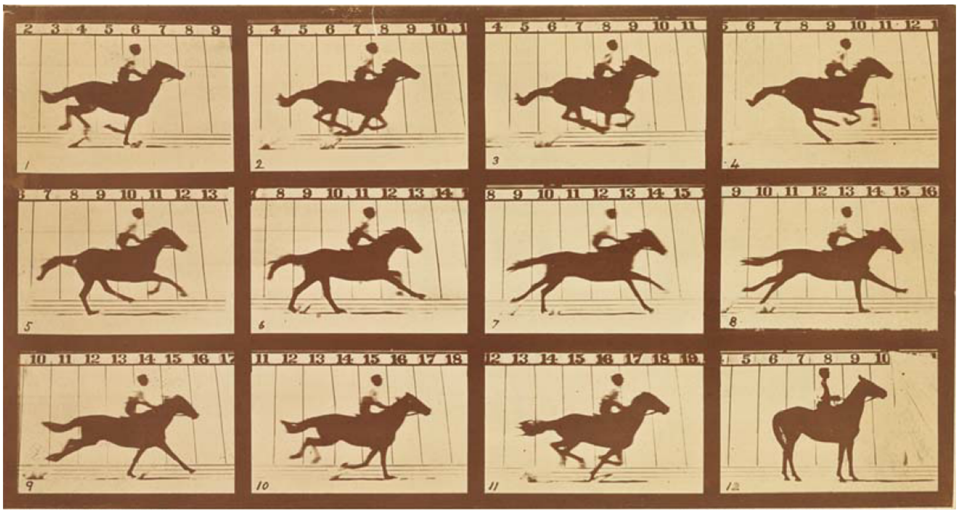


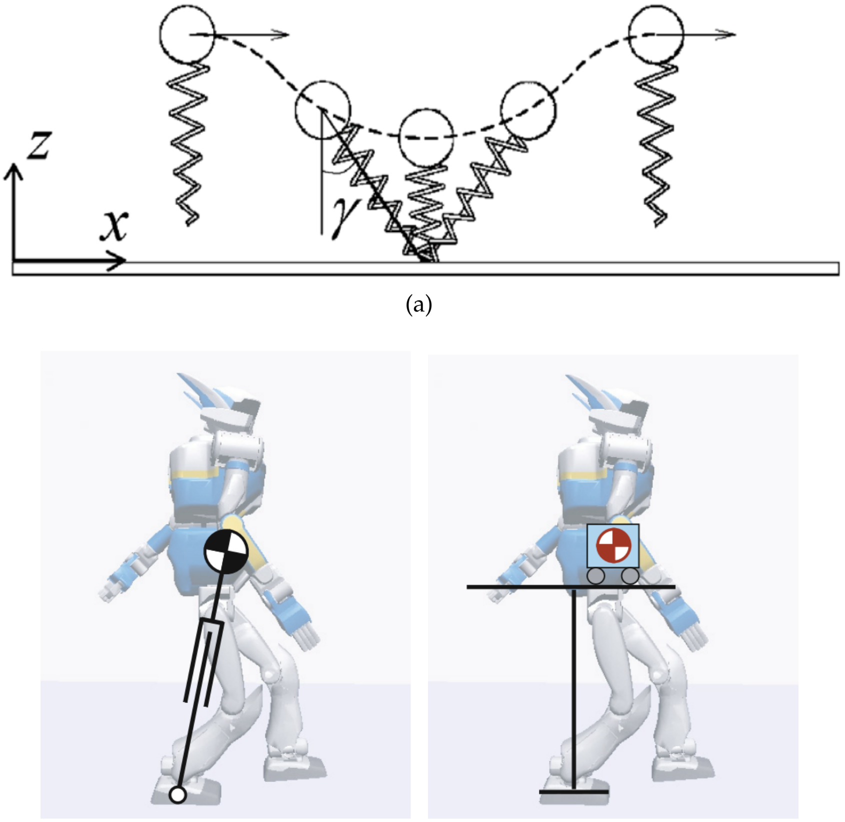
Figure 2.1: Muybridge's picture sequences of a running horse. In these photographs, it is clearly notable that the four feet of a horse are able to leave the ground at the same time and the legs mainly move planarly parallel to the horse's sagittal plane.

can be divided into two phases: stance and flight phase. In the stance phase, the mass is supported by a compressed leg and moves forward; in the flight phase, the system moves following a ballistic trajectory governed by gravity, only if ignoring the air drag. Owing to the existence of the flight phase and springy leg, the displacement of the CoM and hip joint in vertical direction oscillate obviously. The equation of motion of the SLIP model is also different for the stance and flight phase; see Eq. (1):

$$\begin{aligned}\text{Flight}: \ddot{x} &= 0;\\ \ddot{z} &= -g;\\ \text{Stance}: \ddot{x} &= k(x-x_0)(r_0-r)/(mr);\\ \ddot{z} &= k(z-z_0)(r_0-r)/(mr)-g;\\ r &= \sqrt{(x-x_0)^2+(z-z_0)^2},\end{aligned} \tag{1}$$

where r_0 and k are the free length and stiffness of the leg and (x, z) and (x_0, z_0) are the positions of CoM and landing foothold, respectively.

Besides the Spring Loaded Inverted Pendulum (SLIP) model, there are also other models used to abstract the leg motion in slower motions like walking. Cart-table and the linear inverted pendulum (LIP) model are also used in humanoid robots [Kajita et al., 2014]. Schematic drawings of LIP and the Cart-Table model are shown in Fig. 2.2b and Fig. 2.2c. Comparing to the SLIP model, the displacement of the hip joint and CoM in the vertical direction can be minimized; thus, the energy requirement could be lower and a smooth motion can be obtained.



(a)

(b)

(c)

Figure 2.2: Models for legged locomotion: (a) SLIP model; (b) linear inverted pendulum model and (c) the cart-table model. Figures (b) and (c) are adopted from [Kajita et al., 2014].

2.1.3 *Test Rigs for Legged Robot Experiments and Evaluation*

Experiment and evaluation facilities are important to the R&D (research and development) of mobile vehicles including legged robots. For example, automobiles the most typical mobile vehicle, use *road simulator* to generate desired road surface to evaluate and test the performance of suspension, steering and breaking system of automobiles. Fig. 2.3 shows the Model 329 road simulator from the MTS company [MTS Systems Corporation, 2014].

According to the survey of the author, three types of experiment and evaluation test rigs/facilities are often adopted in the development process of legged robots. The *tether mechanism*, originally introduced by Marc Raibert in [Raibert, 1986] as shown in Fig. 2.4a, is a device used in experiments with single-leg planar hopper. The *tether mechanism* provides proper constraints for the robot or robotic leg that is not good at self-balancing and allows the robot to move in a desired direction meanwhile measuring the status of motion such as forward velocity, vertical position, attitude etc. Typical *tether mechanism* consists of a long boom connecting with robot at one end and a pivot or sliding rail fixed on floor at the other

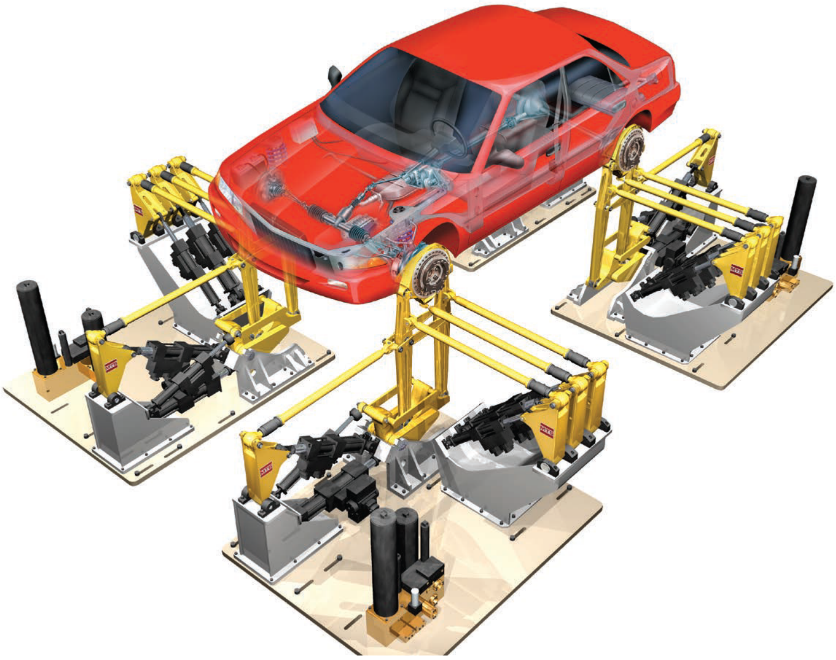


Figure 2.3: Model 329 road simulator from the MTS company used in automotive industry.

end. When robot or robotic leg moves forward, the boom will constrain the robot sideways, and then the robot can only move in a plane normal to the boom. Actually the allowable working space is a sphere surface with its center at the fixed pivot. The advantage of the *tether mechanism* is simplicity and low cost, thus it is able to be constructed by researchers themselves. But the *tether mechanism* requires more space for experiments, and another limitation is that *tether mechanism* can not provide complex terrain like stairs for robot. The *tether mechanism* are utilized in the development of many robots including ATRIAS (see Fig. 2.4b) [Hubicki et al., 2016], Kenken (see Fig. 2.4c) [Hyon and Mita, 2002] and SPEAR (see Fig. 2.4d) [Liu et al., 2015]. In order to reduce the space occupation, the *tether mechanism* can also be used with a treadmill i.e., the experiments of StarlETH leg (see Fig. 2.4b) [Marco, 2013] and Raptor (see Fig. 2.4f) [Park et al., 2014]. In the jump experiments of HyQ leg, due to the leg only moving in vertical direction, a simplified *tether mechanism* consisting a vertical linear guide is used, (see Fig. 2.4g) [Semini, 2010].

The second type of facilities for mobile robots, including legged robot tests and evaluation are test fields. One example of a test field is shown in Fig. 2.5b which was used in the experiment of hexa-leg robot RHex [Saranli et al., 2001]. Test field is constructed based on standard terrain features, and the size of robot, shown in Fig. 2.5a [Nie et al., 2013]. Nowadays American Society for Testing and Materials (ASTM) has issued standard test procedure to evaluate the mobility of mobile robots with different sizes in diverse scenarios[ASTM, 2011a,b,c].

The third kind and the most widely-used of facilities are instrumented treadmills [Bertec Corporation, 2013], which have one or two tracks with adjustable velocity. Additionally instrumented treadmills are ofter equipped with force sensors or force plate under tracks to measure the ground reaction forces (GRFs) during locomotion. Some of instrumented treadmills even have the function of changing gradient to form a ramp to simulate the locomotion status on slope. Lots of research, e. g., [Wickler et al., 2000; Moro et al., 2013; Ugurlu et al., 2013] involving legged locomotion of animal and robot are performed on instrument treadmills.

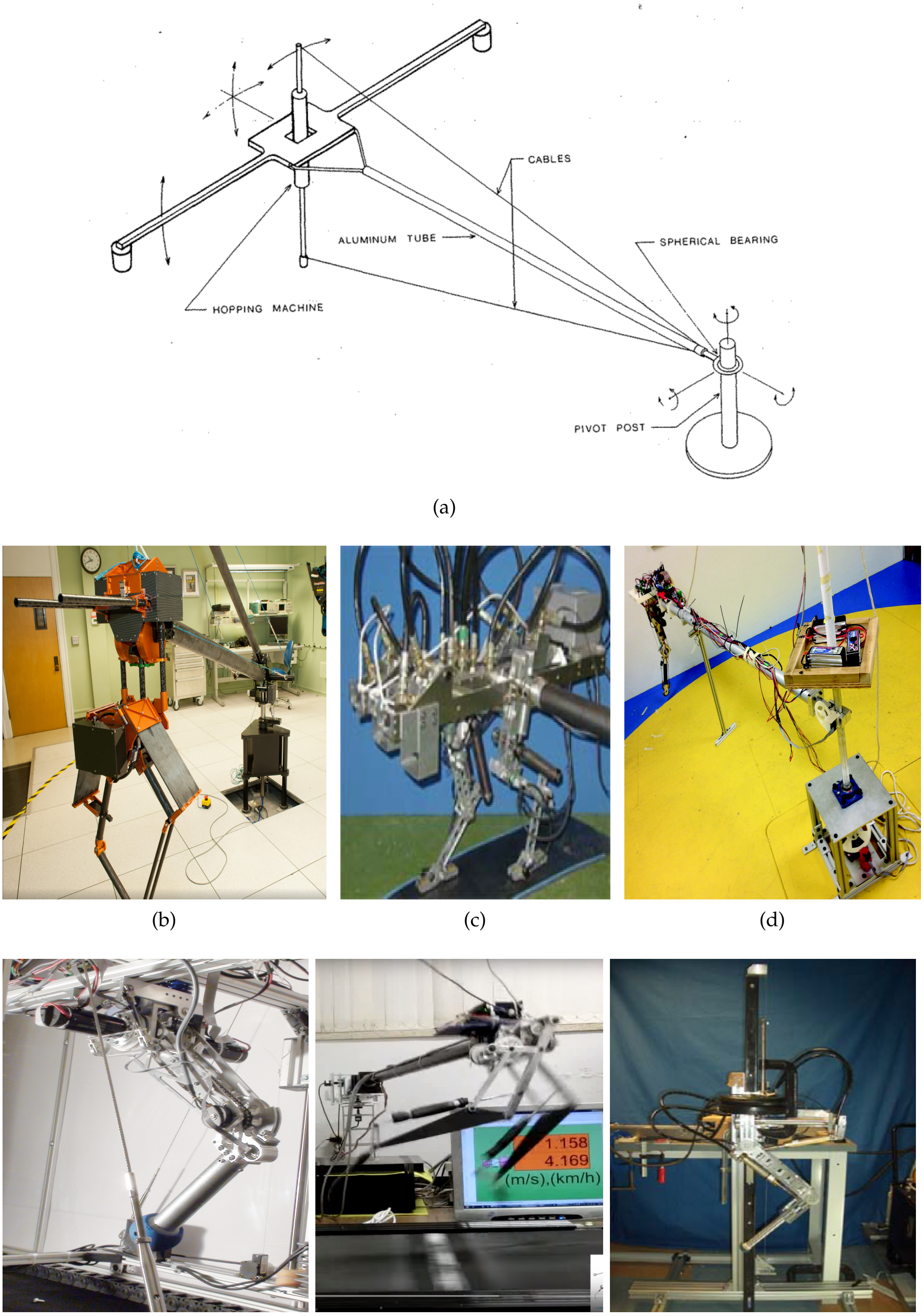
Every type of facility has its own advantages and limitations. For tether mechanism and instrumented treadmill, it is easy and convenient to measure and observe the locomotion status and movements details of subjects, e.g., forward velocity, oxygen consumption, GRFs, gaits. However the terrains provided by *tether mechanism* and instrumented treadmill are usually simple, such as flat ground or even slope. They are not to simulate the complex terrains in nature like rocky and sandy ground. By contrast test fields are able to be built into a rather complex terrain for robot test and evaluation. But once test field is made, the terrain is unchanged and is hard to modify for robots with different sizes and various terrain features for test, thus distinct test fields are needed.

2.2 Legged Robots and the Mechanical Structure of Robotic Legs

A large amount of of legged robots have been built during past decades all over the world. These robots are diverse in size, structure, and function; however, there is something fundamental in common among them because most legged robots, except a few single legged robots, are inspired by animals in nature. As this dissertation focuses on the mechanical structure of robotic legs, legged robots can be classified into types by the number of legs. Legged robots consisting of two and four legs are most popular and representative today. The other types, such as single-legged robot and multi-legged robots that have more than four legs exist, but these robots usually have defects in either the lack of functions or structural complexity.

2.2.1 *Honda Humanoid Robots*

A humanoid robot is a type of biped robot has a human-like shape. The outstanding characteristic of a humanoid robot is that it can move using two legs. Since the first modern humanoid robot WABOT-1 built in 1973 [Lim and Takanishi, 2007], plenty of humanoid robots have been built. Honda has developed many humanoid robots in past decades from E0 (1986), E1-E2-E3 (1987-1991), E4-E5-E6 (1991-1993), P1- P2-P3 (1993-1997), to the original ASIMO (2000) and the new ASIMO (2005), as shown in Fig. 2.6. Among them, ASIMO is the most successful and well-known [Hirose and Ogawa, 2007]. In revealed videos, ASIMO exhibits excellent biped mobility, including running, kicking a football, single leg hopping, etc. The specifications of ASIMO are listed in Table 2.1 [Sakagami et al., 2002]. By reviewing relevant works on leg structure and design, its notable that the robotic leg has similar joint configuration of human's. The leg of humanoid robots has a serial joint configuration, from torso to foot, three joints conventionally named hip, knee, and

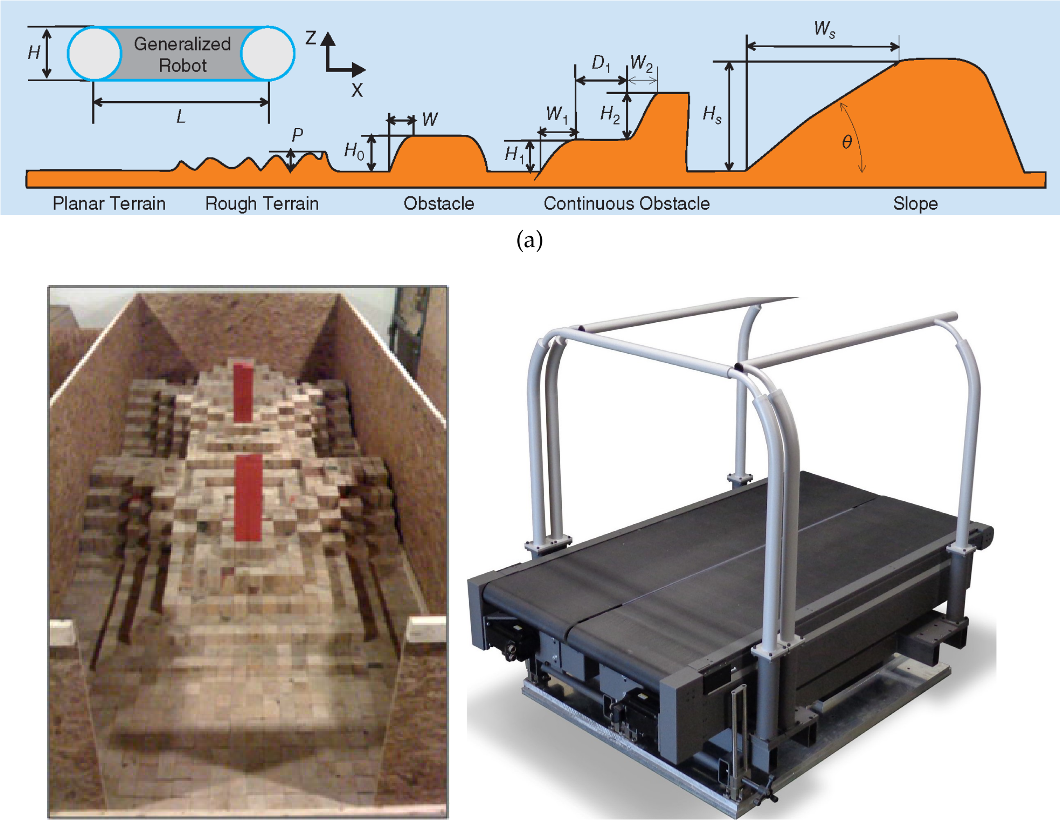


(a)

(b) (c) (d)

(e) (f) (g)

Figure 2.4: *Tether mechanism*. (a) Schematic drawing of the *tether mechanism* used by Marc Raibert. (b) ~(g) *Tether mechanism* used in different robot experiments.



(a)

(b)

(c)

Figure 2.5: (a) Terrain features for mobile robot field test, figure is adopted from [Nie et al., 2013]. (b) Test field (c) Instrumented treadmill.

ankle connected by links (thigh/tibia or upper leg/lower leg) in sequence. In general, there are three DoFs at hip joint, one degree-of-freedom at the knee, and two DoFs at the ankle joint. Typically each of the six degree-of-freedoms is designed as a modular actuator with independent actuation, sensing, and control system. Figure 2.7 presents the general kinematic configuration of humanoid robots [Kajita et al., 2014]. ASIMO is powered by battery and actuated by servo motors with harmonic drive reducer featured with zero backlash and high accuracy. This scheme is extensively used in the mechanical system of humanoid robots like [Park et al., 2005; Kaneko et al., 2004].

2.2.2 *TITAN Series Robots*

TITAN series robots are a family of legged robots developed by Shigeo Hirose's et al. at the Tokyo Institute of Technology since the 1980s . Researches on Tokyo Institute of Technology, Aruku Norimono (walking vehicle) (TITAN) series robots involve diverse fields of robotics including mechanical design, sensor development, motion planning, and control etc. [Hirose et al., 2009]. TITAN III weighs 80 kg and consists of four 1.2-meter long legs [Hirose and Kato, 2000]. The legs of the TITAN III

Figure 2.6: Humanoid robots developed by Honda.

employ a PANTOMEC mechanism, which is a spatial linkage mechanism enable to magnify the motion at one end to the distal end with a constant ratio. As a result, all three actuators in each leg are placed in the trunk of the robot to reduce the inertia of leg and motions from corresponding actuators are magnified and transmitted to the foot by the PANTOMEC leg. Another feature of PANTOMEC leg is GDA (gravitationally decoupled actuation) the effect which is helpful for improving energy efficiency during locomotion [Hirose and Umetani, 1981]. The feet of TITAN III are equipped with whisker-type sensors made of shape memory alloy wire to examine the status of contact with the ground. The improved version—TITAN IV with the same structure, has a bigger mass up to 160 kg. It was developed for a science exhibition held in Japan in 1985 . TITAN IV walked 40 km in total including climbing up and down stairs during the half-year exhibition [Hirose et al., 2009].

TITAN VII is a downscaled prototype developed for civil application on steep slopes [Hirose et al., 1997]. TITAN VII is designed based on the GDA principle and coupled-drive leg, which is allowable to drive one joint by several actuators in couple for large output force. In each lower leg of TITAN VII, there is a passively linear joint consisting of a spring and clutch to enhance terrain adaptability. In experiments, TITAN VII could climb and crawl on a slope up to 30 degrees. Based on the researches of TITAN VII, a huge quadruped robot TITAN XI with 6,000 kg weight and four 3.7 m-long legs was constructed for drilling tasks on steep slopes [Doi et al., 2005]. TITAN XI's legs are actuated by hydraulic cylinders and additionally two winches are equipped for assisting the robot in climbing steep slopes. In demonstration, TITAN XI can climb up a 70-degree slope with the aid of winches and fulfill drilling tasks.

From the point of view of mechanical systems, the leg and joint configuration of TITAN series robots are similar but actuation and transmission are diverse. Most TITAN series robots take insect-type or sprawling-type leg configuration in use, where the proximal joint connected with the truck rotates about the yaw axis and legs often stretch outside the trunk. Further, additional measures in mechanical design, for instance, PANTOMEC mechanism, GDA concept, and coupled drive, are often taken to improve the robot's performance. The actuation and transmission published already includes electrical linear actuators with PANTOMEC (TITAN III,