Foundations and Trends® in
Robotics
5:2

Design of Dynamic Legged Robots

Sangbae Kim and Patrick M. Wensing

now
the essence of knowledge

Design of Dynamic Legged Robots

Sangbae Kim
Massachusetts Institute of Technology
United States
sangbae@mit.edu

Patrick M. Wensing
Massachusetts Institute of Technology
United States
pwensing@mit.edu

now
the essence of knowledge
Boston — Delft

Foundations and Trends® in Robotics

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

S. Kim and P. M. Wensing. *Design of Dynamic Legged Robots* . Foundations and Trends® in Robotics, vol. 5, no. 2, pp. 117–190, 2014.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-256-3

Design of Dynamic Legged Robots

Foundations and Trends® in Robotics
Volume 5, Issue 2, 2014
Editorial Board

Editorial Scope

Topics

Foundations and Trends® in Robotics publishes survey and tutorial articles in the following topics:

- Mathematical modelling
- Kinematics
- Dynamics
- Estimation methods
- Artificial intelligence in robotics
- Software systems and architectures
- Sensors and estimation
- Planning and control
- Human-robot interaction
- Industrial robotics
- Service robotics

Information for Librarians

Foundations and Trends® in Robotics, 2014, Volume 5, 4 issues. ISSN paper version 1935-8253. ISSN online version 1935-8261. Also available as a combined paper and online subscription.

Foundations and Trends® in Robotics
Vol. 5, No. 2 (2014) 117–190

DOI: 10.1561/2300000044

now
the essence of knowledge

Design of Dynamic Legged Robots

Sangbae Kim
Massachusetts Institute of Technology
United States
sangbae@mit.edu

Patrick M. Wensing
Massachusetts Institute of Technology
United States
pwensing@mit.edu

Contents

Abstract

Animals exhibit remarkable locomotion capabilities across land, sea, and air in every corner of the world. On land, legged morphologies have evolved to manifest magnificent mobility over a wide range of surfaces. From the ability to use footholds for navigating a challenging mountain pass, to the capacity for running on a sandy beach, the adaptability afforded through legs motivates their prominence as the biologically preferred method of ground transportation. Inspired by these achievements in nature, robotics engineers have strived for decades to achieve similar dynamic locomotion capabilities in legged machines. Learning from animals' compliant structures and ways of utilizing them, engineers developed numerous novel mechanisms that allow for more dynamic, more efficient legged systems. These newly emerging robotic systems possess distinguishing mechanical characteristics in contrast to manufacturing robots in factories and pave the way for a new era of mobile robots to serve our society. Realizing the full capabilities of these new legged robots is a multi-factorial research problem, requiring coordinated advances in design, control, perception, state estimation, navigation and other areas. This review article concentrates particularly on the mechanical design of legged robots, with the aim to inform both future advances in novel mechanisms as well as the coupled problems described above. Essential technological components considered in mechanical design are discussed through historical review. Emerging design paradigms are then presented, followed by perspectives on their future applications.

S. Kim and P. M. Wensing. *Design of Dynamic Legged Robots* . Foundations and Trends® in Robotics, vol. 5, no. 2, pp. 117–190, 2014.
DOI: 10.1561/2300000044.

Abstract

Animals exhibit remarkable locomotion capabilities across land, sea, and air in every corner of the world. On land, legged morphologies have evolved to manifest magnificent mobility over a wide range of surfaces. From the ability to use footholds for navigating a challenging mountain pass, to the capacity for running on a sandy beach, the adaptability afforded through legs motivates their prominence as the biologically preferred method of ground transportation. Inspired by these achievements in nature, robotics engineers have strived for decades to achieve similar dynamic locomotion capabilities in legged machines. Learning from animals' compliant structures and ways of utilizing them, engineers developed numerous novel mechanisms that allow for more dynamic, more efficient legged systems. These newly emerging robotic systems possess distinguishing mechanical characteristics in contrast to manufacturing robots in factories and pave the way for a new era of mobile robots to serve our society. Realizing the full capabilities of these new legged robots is a multi-factorial research problem, requiring coordinated advances in design, control, perception, state estimation, navigation and other areas. This review article concentrates particularly on the mechanical design of legged robots, with the aim to inform both future advances in novel mechanisms as well as the coupled problems described above. Essential technological components considered in mechanical design are discussed through historical review. Emerging design paradigms are then presented, followed by perspectives on their future applications.

S. Kim and P. M. Wensing. *Design of Dynamic Legged Robots*. Foundations and Trends® in Robotics, vol. 5, no. 2, pp. 117–190, 2014.
DOI: 10.1561/2300000044.

1

Introduction

Developing legged machines that walk and run like humans and animals has long been a grand challenge in robotics. Mobility is one of the most critical, yet immature, technological components for future mobile robotics applications. Many engineers aim to develop robots capable of navigating in human environments, and legs are considered the biologically-preferred mode of ground locomotion. Current modes of ground transportation are primarily dominated by wheeled systems or variations such as tracks. Wheeled systems offer great simplicity and robustness in relatively well-structured environments and have impact in a variety of applications, whereas man-made legged machines have started demonstrating basic capabilities only recently. Although legged systems are designed to navigate rough terrains that wheeled vehicles cannot access, the performance of the legged robots to date has yet to unlock these benefits.

In order to envision critical applications for legged systems, it is important to understand the characteristics and unique advantages provided by legs at a broad scope. The next section discusses many benefits of legged systems and the special characteristics that distinguish them from more conventional means of transportation. Following this high-level motivation, Section 1.2 details a history of legged locomotion with focus on trends in design. In light of this historical background, Section 1.3 details important underlying challenges remaining in robot design. These reflections will serve to motivative the remaining chapters of the review.

1.1 Legs vs. Wheels

A legged architecture for locomotion machines has attractive promise for high versatility operation, providing mobility in challenging environments. However, the complexity of legs dwarfs that of wheels due to an articulated morphology that requires additional degrees of freedom (DoFs). Are there appropriate roles for legged machines when mankind has invented (and dramatically benefited) from wheeled vehicles[1] throughout its history? For transportation in air, we have taken inspiration from birds and sought to embody their operation without explicitly copying the complexity of wings. With this in mind, it should not be expected that legs are universally optimal for transportation on land. However, while airplanes drastically outperform animals in nearly every aspect of flight, there are still animals on land with ground transportation capabilities that well exceed our wheeled solutions.

1.1.1 A Case for Legs

Comparing legged and wheeled systems is hardly black and white – the utility of these two modes of transportation depends heavily on the application. However legs offer main advantages in applications that require the use of intermittent contacts and an ability to shift the center of mass relative to the contact locations. These advantages chiefly manifest in situations that require both an ability to transverse and manipulate geometrically complex environments.

In modern ground transportation, artificial modification of the terrain is essential. Conventional wheeled vehicles maintain continuous contact with the terrain, and their design assumes good conditions for the roads to accomplish this. The chassis of vehicles is connected to the wheels via a passive suspension mechanism, allowing toleration of variations in roadway materials (gravel, dirt paths, asphalt, etc.) as well as roadway geometry. Through

[1] Here, wheeled vehicles represent all vehicles that use wheels or tracks as a main means of transportation

this approach, wheeled systems can travel faster than most legged animals (ignoring scale differences) when the ground is fairly flat. Novel suspension designs, such as in the wheeled SHRIMP robot (Lamon et al., 2004), increase the ability to attenuate disturbances from contact irregularities but still maintain continuous contact with the terrain.

A practical middle ground between legs and wheels is the use of Whegs (Schroer et al., 2004), which combine the simplicity of wheels with discrete contact interactions provided by feet. Whegs designs were largely inspired by the RHex family of robots (Saranli, 2001), and can be described as discrete wheels. For instance, the rimless wheel represents the simplest embodiment of the Whegs concept. This morphology allows Whegs to change contacts from step to step and traverse varied terrain that is unable to be negotiated by wheels of the same radius. While Whegs can be seen as a middle ground between legs and wheels in terms of mechanical design, their maximum performance envelope represents a compromise between legs and wheels as well. Without articulation in the limbs, Whegs inevitably lack critical versatility for contact reconfigurability.

Legged machines provide improved mobility over wheeled vehicles chiefly through an ability to reconfigure and exploit discrete interactions in a large workspace. This ability to make and break contacts is important where the roughness of the ground varies, or continuous contact paths are unavailable. Whether for locomotion over bouldered grounds, stiff slopes, or even sheer cliffs, the ability to radically modify support structure from step to step can be critically necessary to negotiate the most extreme terrains. A large workspace amplifies these abilities, providing valuable additional options.

The ability to reconfigure contact geometries in legged machines further eliminates the need for a wide support polygon that stabilizes most wheeled systems solely based on their fixed geometry. Since the geometry and properties of contacts influence the ability to provide friction-limited forces, reconfigurable contacts allow for the generation of propulsive forces in a wider range of directions. This advantage allows legged systems to manage dynamic stability while subject to more narrow footprint requirements. Even in challenging passages found in disaster environments or a packed urban warehouse, legged systems can maintain balance despite their high center of mass and using only small footprints through the versatility of legs.

Articulation of the limbs also offers an ability to dynamically reconfigure the center of mass for high-power manipulation. In disaster response situations, for instance, being able to maintain balance with a high center of mass can be greatly advantageous. Simply opening a spring-loaded door requires high force generation at around 1.2 m above the ground where the door knobs are located. If the robot's center of mass is low, this task can be extremely difficult to achieve by solely relying on static stability. Using our dynamics, humans can generate much higher forces than in a static body posture. Throwing, kicking, and batting motions of humans well represent our ability to shift the center of mass of the body to generate momentum and thus generate greater power output. Although much less powerful, the mundane daily task of opening a spring-loaded door may require mastering the basics of such dynamic movements.

Until we mature the technologies for legged robots, it may be meaningless to argue which mode of transportation can be most useful for a given application. What is clear is that we need to advance legged locomotion technologies in order to develop mobile robots capable of operating in a wider range of environments. Across automation in agriculture and construction, assistance in the home, exploration of distant planets, search and rescue, or disaster response, mastering legged locomotion is a critical and logical step towards many future applications of mobile robots.

1.1.2 Steps towards future applications: A need for design-centered thinking

Advancing these legged technologies will require addressing great complexity in design. A car needs two active degrees of freedom, propulsion and steering, which requires two actuators. In contrast, a legged system requires at least three degrees of freedom per leg to properly select and manage contact interactions in 3D. This complexity in structure drives up cost from many components. While this curse of complexity manifests in the mechanical design, a similar challenge accompanies the design of control algorithms, sensing systems, and other coupled components of these systems. To realize the full capabilities of legged machines, integrative challenges must be mastered across these intersecting domains. Ultimately, lagging capabilities in any of these domains may limit legged systems from achieving their full potentials.

It is a main hypothesis, however, that the treatment of mechanical design within locomotion robots is a limiting factor of their performance in current hardware. While better control algorithms will make current robots more capable, improvements in our design methodologies will yet simplify control and allow new levels of proficiency as mobile legged machines emerge from the laboratories and are let loose in real work. The past decades have provided a renaissance in the design of legged robots, and lend great credibility to this vision. The next section provides a review of this previous work. It is intended to provide a window into both how far the field has progressed as well as the challenges that remain to achieve biologically proven levels of legged performance.

1.2 A Brief History of Legged Robots

The design of machines with legged mobility has been a pursuit of engineers for over a century. Dating back to as early as the mid 1800's, efforts first concentrated on the use of clever linkage-based designs to mechanically produce fixed leg motions. The celebrated Russian mathematician Chebychev is credited with the earliest of these designs (Lucas, 1894), with similar ideas appearing in US patents by the late 19th century (Rygg, 1893) and making their way into machines constructed more recently (Morrison, 1968).

While many of these systems were capable of rudimentary locomotion on prepared surfaces, their fixed gait patterns prevented truly adaptive locomotion and limited the classes of terrain they could traverse. Starting in the early 1960s, however, a shift began to occur. Rather than focusing on linkage-based designs with fixed limb trajectories, researchers started to pursue methods for active control, and slowly, adaptive legged machines began to emerge.

1.2.1 The Beginnings of Adaptive Legged Machines

In 1962, the General Electric Corporation and R.S. Mosher began work on a quadruped that was unlike any of its predecessors. The GE Walking truck (Mosher and Liston, 1968) as shown in Figure 1.1 was a hydraulically powered, 12 degree of freedom quadruped weighing 1400 kg. Without complex linkages to coordinate the motion of its limbs, the Walking Truck was designed to be controlled by a skilled human operator.

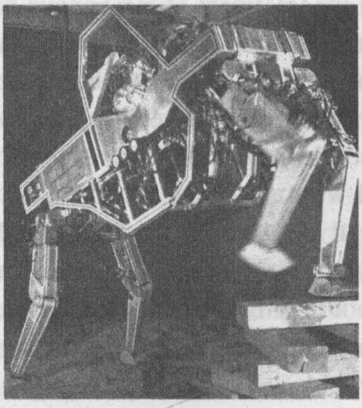
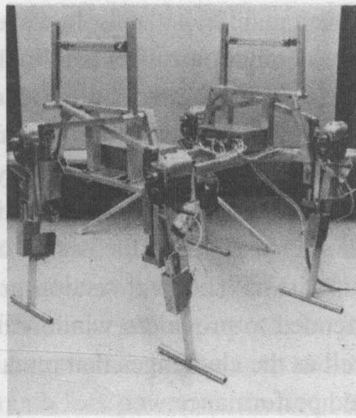
(a)  (b) 

Figure 1.1: (a) The GE Walking Truck and (b) Phony Pony, two of the first legged robots.

The teleoperation interface for this landmark system was truly ahead of its time. All 12 degrees of freedom were commanded by a human driver using a series of handles and pedals for their hands and feet. The system also provided the operator with force feedback which enabled response to obstacles or other terrain disturbances. After roughly 20 hours of operator training, the system was capable to climb railroad ties and walk along at 5 mph (Raibert, 1986).

Rather than rely on a skilled human operator, R. McGhee of the University of Southern California realized that an automated system could instead be used to coordinate the rhythmic motions of locomotion. Born out of his collaborative theoretical work with R. Tomovic (Tomovic and Mcghee, 1966), McGhee created the first legged machine to apply finite-state automata to robot walking (McGhee, 1968; McGhee and Frank, 1968). His robot, the Phony Pony (Figure 1.1), weighed 50 kg and consisted of 8 DoFs driven by electric drill motors. Using digital logic based on flip-flops, the system could perform a quadruped crawl and a diagonal walking trot.

It wasn't soon after until computer control of legged machines became a possibility. In 1977, following a move to the Ohio State University (OSU), McGhee built the OSU hexapod (Figure 1.2), the first computer-controlled walking robot (McGhee, 1985). His machine had 18 electrically actuated DoFs that were coordinated by the computer, which mainly used its processing power to solve kinematic equations and ensure static stability of the ma-