Design of Dynamic Legged Robots

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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: 978-1-68083-25ď¿č

Foundations and Trends® in Robotics

Volume 5, Issue 2, 2014

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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

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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.

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.

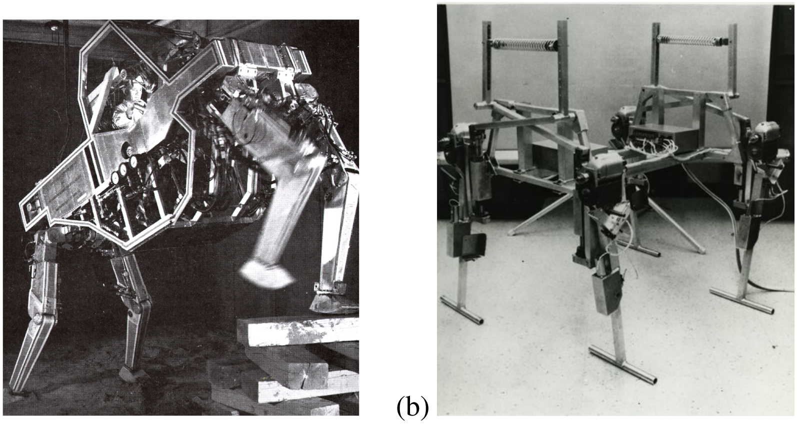
1.2 A Brief History of Legged Robots

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-

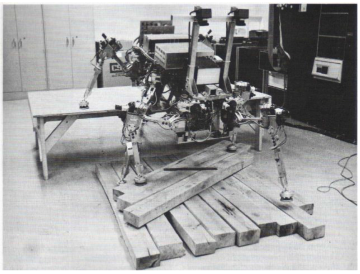
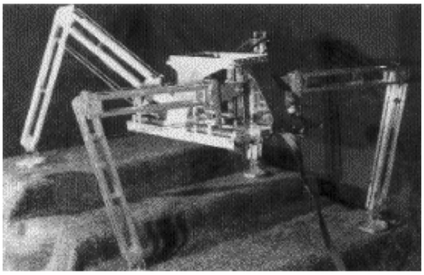
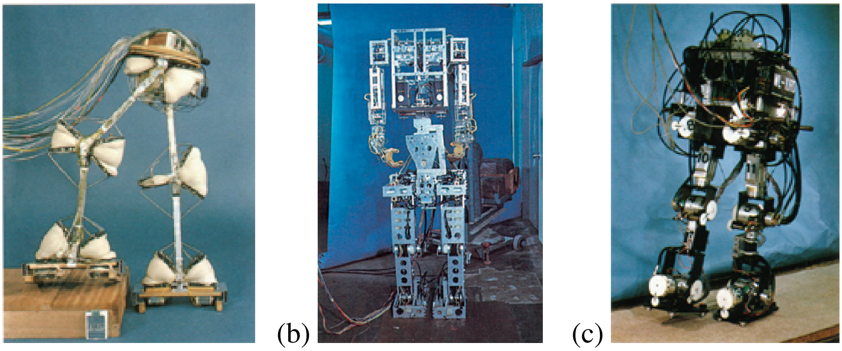
(a)  (b) 

Figure 1.2: (a) The OSU Hexapod (b) Hirose's PV-II quadruped featuring a PANTOMECH leg.

chine. The hexapod was able to perform a variety of basic gaits and showed the ability to turn, walk sideways, and negotiate locomotion over piles of lumber. The nascency of computer control and available balance control theories dictated a great deal of the design in these systems. Gaits were designed to be statically stable, that is, their center of mass (CoM) was design to remain over their base of support at all times. To simplify application of this strategy, these early computer controlled machines were designed with a wide support base, not unlike their wheeled counterparts.

Despite the power of this early computer control approach, significant computational resources were required for basic kinematic computations. Drawing inspiration from the early days of legged machines, Shigeo Hirose, at the Tokyo Institute of Technology, showed how clever mechanical design could be revived to reduce the computational needs of adaptive machines. Roughly, he could embed portions of the kinematic computations into the design of his mechanisms. Hirose developed a three-DoF pantograph leg mechanism the PANTOMECH (Figure 1.2), where each actuator produced approximately linear motion of the foot in the primary Cartesian directions. Freeing up the control from kinematic computations, Hirose's quadrupeds (Hirose, 1984) could focus control on higher-level goals, enabling his machines to climb up and down stairs and handle obstacles. Hirose's machines are a representative early example of how strategic changes in mechanical design can alleviate the burdens on control towards unlocking new levels of performance.

During this period of active research on quadrupedal and multi-legged machines, great strides were being made in the bipedal realm with research



(a) (b) (c)

Figure 1.3: (a) WAP-3 (b) WABOT-1 (c) WL-10RD. Courtesy of the Humanoid Robotics Institute, Waseda University, Tokyo.

on quasi-static walking. Professor Ichiro Kato, a pioneer of robotics in Japan, began creating his famous bipedal machines in 1967 (Lim and Takanishi, 2007). The pneumatically actuated 2D biped WAP-1 and 3D biped WAP-3 (Figure 1.3) were capable of statically stable bipedal locomotion, with WAP-3 representing the first time this was accomplished in 3D.

Only 6 years after the start of his work, in 1973, Kato created the first full-scale anthropomorphic robot WABOT-1 (Kato et al., 1973). This hydraulically actuated machine (Figure 1.3) was capable of static walking and was equipped with artificial ears and eyes to detect distances to objects. In 1980, Kato developed the 10 DoF biped WL-9DR which could execute quasi-dynamic walking (during weight transfer between feet), taking an important step away from the current practice of focus on static stability for the first time to date.

Collectively, these advances across the globe provided the cornerstone for adaptive walking robots. It wasn't long, however, until new designs for dynamic legged machines disrupted much of this previous thinking.

1.2.2 Dynamic Balance and Raibert's Machines

Prior to the 1980s, adaptive legged machines relied largely on their static stability to maintain balance. Whether through large feet or multiple limbs in contact, these early machines took great effort to place their center of mass (CoM) over their base of support. Although this strategy did not rigorously guarantee that the systems would not tip over during motion, when confined to their slow conservative movements, balance was effectively ensured.

Ultimately, however, this strategy limited early machines. Indeed, humans and animals often purposefully "tip" over their support to reach far away footholds or to let gravity do work to propel the system forward. Even the most moderate of human walking gaits are marked by periods of static instability where we roll over our foot naturally, knowingly placing ourselves in a state where we require the next step to prevent a fall. This notion of a type of balance that requires continuous motion, coined dynamic balance by Marc Raibert, was a new idea that fueled a series of groundbreaking machines in his lab during the early 1980s. Machines that remain on the ground do posses the opportunity to study this type of balance. Raibert, however, set forth to design machines that would enable him to study dynamic balance in the extreme setting – the case where legged machines also experience flight. Creating machines which could fly through the air and regain stable contacts however, required as much redesign mechanically as it did in control.

In 1981, Marc Raibert founded the leg lab at Carnegie Mellon University and began work on a new class of hopping machines. Although the first hopping robot was actually built in Japan by Matsuoka (1980), Matsuoka's 2D machine simplified control, operating in low effective gravity by laying on shallow inclined table. Raibert's machines thus were the first to regulate balance during ballistic flight. The first machine he constructed at CMU was a single-legged 2D hopper (Raibert and H. B. Brown, 1984), shown in Figure 1.4, weighing 8.5 kg with height around 50 cm. The machine featured point feet and springy prismatic limbs, providing natural dynamics with a paradigm shift away from the higher-impedance designs of previous quasi-static locomotors. Raibert's machines again illustrate the degree to which paradigm changes in control and design have been historically intertwined.

As he explains in his book (Raibert, 1986), this machine was designed in order to focus on the general mechanisms of legged balance, without the need to focus on combinatorial issues of leg sequencing that had consumed much academic work in the preceding decades. It was Raibert's idea that general mechanisms to control a single leg should be immediately applicable to the control of so-called one-foot gaits such as human running, where a single foot was in stance at any given time. He further reasoned that these principles

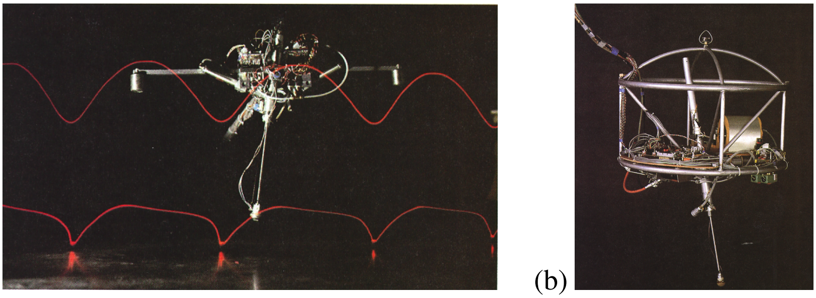
(a)  (b)

Figure 1.4: (a) Raibert's 2D hopper and (b) 3D hopper.

of balance could be used in gaits with multiple feet in stance at a time, such as a trot, provided that these legs work together to simulate the operation of a single leg. These ideas ultimately came to fruition through a series of impressive machines.

Raibert's original single-leg 2D hopper was effectively an actuated spring-loaded inverted pendulum (SLIP) model. The design consisted of an actuated pneumatic leg spring that could store and release energy passively during stance through compression and decompression of an air chamber. Another pneumatic actuator controlled the angle of this virtual leg. Two counter weighting masses were attached at a distance on the body of this machine, increasing its angular inertia, and placing the net CoM roughly along the axis of the leg spring. A floor-attached boom was used to approximate planar motion by constraining the machine to move in a sphere. This breakthrough machine was able to maintain dynamic balance by decomposing its control law into three roughly decoupled parts: hopping control, forward speed control, and body attitude control. With this three-part approach, the machine could travel up to 2.6 mph and was able to jump over small obstacles.

Following the success of this platform, Raibert built a 3D version of the machine (Figure 1.4) and employed a 3D generalization of his three-part control decomposition (Raibert et al., 1984). This one legged machine again utilized a pneumatic leg actuator for its stroke. The hopper was robust to push disturbances and was able to move fully unconstrained in 3D at speeds of up to 4.5 mph.

Around the same time as Raibert's hoppers, Kato's lab back in Japan was also making great strides on dynamic locomotion. Using the zero-moment

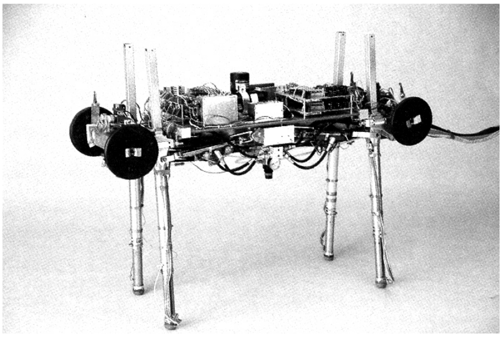
(a)  (b) 

Figure 1.5: (a) Raibert's quadruped and (b) 3D biped.

point (ZMP) criterion of Vukobratovic (Vukobratovic and Juricic, 1969; Vukobratović and Stepanenko, 1972), Kato and Takanishi realized fully-dynamic ZMP walking for the first time in the world on the WL-10RD in 1985 (Takanishi et al., 1985). This 3D biped (Figure 1.3) had 12 DoFs driven by hydraulic actuators, was 1.43m tall, and weighted 84.5 kg.

In 1986, Raibert moved the leg lab to MIT and began work on his multi-legged machines. Raibert and Hodgins demonstrated the applicability his previous design and control mechanisms on a 2D planar biped that was capable of top speeds of 9.5 mph (Hodgins et al., 1986). The planar biped had two telescoping legs driven by hydraulic actuators with passive series air springs. With the basic mechanisms of balance addressed through previous work, Hodgins concentrated on methods to modify the gait to hop over uneven terrain (Hodgins and Raibert, 1991) and to perform an open-loop flip (Hodgins and Raibert, 1990).

Following the success of the planar biped, Raibert constructed a 3D quadruped. The quadruped leg design mirrored that of its bipedal predecessor with hydraulically actuated prismatic legs positioned by a set of lower strength hydraulic cylinders. Even prior to construction, in Raibert's mind, quadruped trotting was already a solved problem. Raibert reasoned that trotting is like having a biped at each instant, and two-legged hopping can be treated as single virtual leg, so you should be able to run on four legs as if they are one. By coordinating multiple legs of the quadruped to act as a single virtual leg, the three-part decomposition was in fact able to stabilize Raibert's quadruped (Raibert et al., 1986).

In his last years at MIT, Raibert worked with Robert Playter and created one of his most impressive dynamic machines to date. The 3D biped, shown in Figure 1.5, was able to run outside on grass, pull its operator along in a wheeled cart, and even execute a running somersault on a treadmill (Playter and Raibert, 1992). Like many of Raibert's designs, control was facilitated by placing the hip joints nearly coincident with one another and the CoM, and by designing a high inertia torso in comparison to the legs. These strategic design decisions reduced influences of the leg motions on the body and prevented impulses along the leg from creating unwanted moments on the torso. This design, in part, enabled Raibert's biped to execute a range of dynamic behaviors that still, in many ways, remain the gold standard to which other dynamic bipeds are compared.

1.2.3 Iterating Towards the State of the Art - Dynamic Legged Machines in the Wake of Raibert

Passive Dynamic Walking

Just as Raibert's machines were demonstrating the capability to actively control dynamic balance, a provocative new idea was introduced by Tad McGeer from Simon Fraser University. Similar to how clever kinematic mechanisms were sought to simplify static locomotion in the early days of the field, McGeer carefully designed a completely passive planar walking machine (Figure 1.6) that led to a naturally stable dynamic gait down a gentle slope (McGeer, 1990). While relying simply on the energetic interplay between gravity and inertia, this passive machine seemed arguably the most lifelike when compared with any robot to date.

Passive dynamic walkers, by nature, are not able to walk on level terrains where inevitable dissipations prevent continuous steady state locomotion. More recently, a number of minimally actuated walkers have been constructed to glean the energetic benefits of passive dynamic designs while retaining the capability to locomote on flat or moderately included surfaces (Collins et al., 2005). Collins and Ruina (2005) designed the Cornell biped (Figure 1.6) which has an energetic efficiency on par with human walking. This system has five internal degrees of freedom and is powered by electric motors and springs that are primarily responsible for ankle push off to restore energy in each stride.

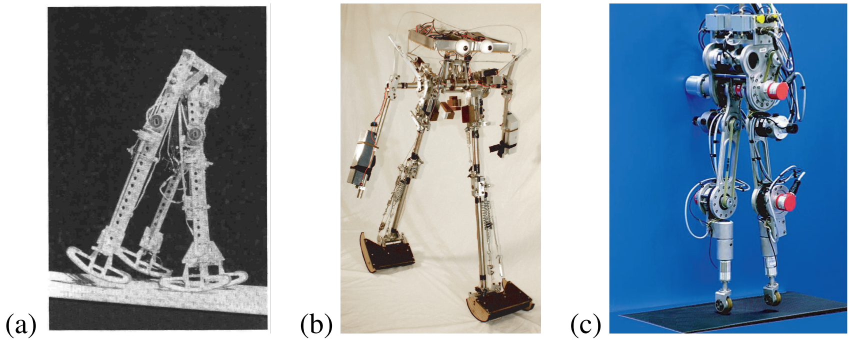


Figure 1.6: Bipeds on the spectrum of passive design. (a) Tad McGeer's passive 2D walker (b) A 3D, minimally actuated walker designed by Collins and Ruina and (c) RABBIT, an underactuated point-foot biped.

The MIT learning biped developed by Tedrake et al. (2005) utilized passive dynamic principles to achieve a nominally passive baseline gait. This design simplified an online stochastic gradient descent algorithm enabling it to automatically discover actuated walking control policies from a blank slate in a matter of minutes. Martin Wisse developed a set of robots (Wisse et al., 2007; Hobbelen et al., 2008) inspired by McGeer's designs with once-per-step active actuation that improved gait robustness in comparison to a purely passive approach.

More generally, a number of underactuated (Spong, 1998) walking machines have been constructed where the number of actuators are less than the number of degrees of freedom. Without the ability to manipulate the entirety of system dynamics at each instance, these systems must rely on mechanical couplings amongst the many degrees of freedom, much like in passive walkers. As one prominent approach, systems utilizing the framework of Hybrid Zero Dynamics (Westervelt et al., 2003) have demonstrated efficient, stable walking gaits in planar walkers controlled by DC motors. By optimizing gaits that are as close to passive as possible (as measured through actuated torque or work-based metrics), these methods are able to utilize natural dynamics to attain stability in spite of under actuation. Westervelt et al. (2004) showed the applicability of the framework on the position controlled 5-link planar biped RABBIT (Figure 1.6). Martin et al. (2014) have recently shown that the incorporation of curved feet, as employed in the original passive dynamic walkers, can further push these methods towards efficient gaits in experimental machines. In practice, however, the impedance of actuators employed in physical robots may limit the existence of any favorable natural dynamics for HZD-based control laws to leverage.

Compliantly Actuated Bipeds

In 1992, Marc Raibert left the leg lab to found Boston Dynamics, pursing the advancement of his legged machines to higher and higher levels of technological readiness. Following Raibert's departure, Gill Pratt inherited the MIT leg lab and began new lines of research to move away from inefficient hydraulic actuation technologies. Gill Pratt formalized a new actuation paradigm called series elastic actuation (Pratt and Williamson, 1995), in an attempt to provide a low-impedance high-power-density electric drive. Because of the low impedance of these actuators, they did not override the natural dynamics of the underlying mechanisms that they control, enabling those natural dynamics to potentially be exploited (Pratt, 2000b). Although Raibert's machines were able to accomplish this goal through the existence of series air springs, their reliance on messy, inefficient hydraulics in series was seen as an unnecessary downside.

Pratts SEAs (Pratt and Williamson, 1995) were capable of 300 lbs. of linear force and had a force-control bandwidth of 20 Hz. SEA designs were incorporated into his robots Spring Turkey and Spring Flamingo (Figure 1.7), enabling them to execute continuous planar walking while attached to a boom (Pratt et al., 2001). Taking advantage of the force control capabilities of the SEAs, Pratt was able to implement virtual impedance behavior through a closed-loop control approach named virtual model control.

Series elastic actuation principles continue to find their way into more recent machines. The University of Michigan's MABEL biped (Figure 1.7), designed by Jonathan Hurst (Park et al., 2011), incorporated large nonlinear leaf springs into its design. This design gave rise to natural SLIP-like dynamics that could be leveraged through HZD control (Poulakakis and Grizzle, 2009). These concepts were able to be applied to generate walking at 3.4 mph (Sreenath et al., 2011), robust walking over uneven terrain through reactive gait modification (Park et al., 2013), and running at 6.8 mph (at the time a speed record for a kneed bipedal machine) (Sreenath et al., 2013). In

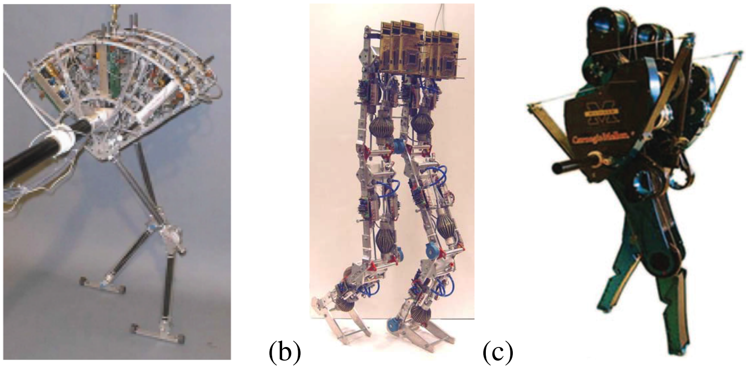

(a) (b) (c)

Figure 1.7: Compliant bipeds (a) Spring Flamingo with linear SEAs and (b) Lucy with variable compliance pneumatic artificial muscles and (c) MABEL actuated using a nonlinear leaf spring to provide compliance along the virtual leg.

comparison to DC motors alone, SEAs have also shown to enhance performance in hopping bipeds (Knox and Schmiedeler, 2009; Curran et al., 2009; Liu et al., 2011) and have been important in the design of modern passively compliant quadrupeds (Hutter et al., 2010, 2011) and humanoids (Tsagarakis et al., 2013).

Recently, other methods of achieving compliance in bipedal machines have been proposed (Vanderborght et al., 2008a; Verrelst et al., 2005) using pleated pneumatic artificial muscles. These actuators, used in the Lucy biped (Figure 1.7), can actively change their compliance, providing opportunity to tune the passive dynamics of the system and reduce energetic costs (Vanderborght et al., 2008b). Lucy was capable of walking and executing a jump, although running was never demonstrated.

Quadrupeds and Multilegged Machines

Ideas to reduce actuation and rely partially on compliant passive dynamics for running permeated quadruped designs in this time as well. Scout II, designed by Papadopoulos and Buehler (2000), was potentially the most influential of the machines that followed. Scout II (Figure 1.8) weighed just under 21 kg and was 0.55 m long. The machine included very minimal actuation, with only a single hip actuator per leg along with passive leg springs. On-board power made Scout II the first self-contained quadruped capable of running,

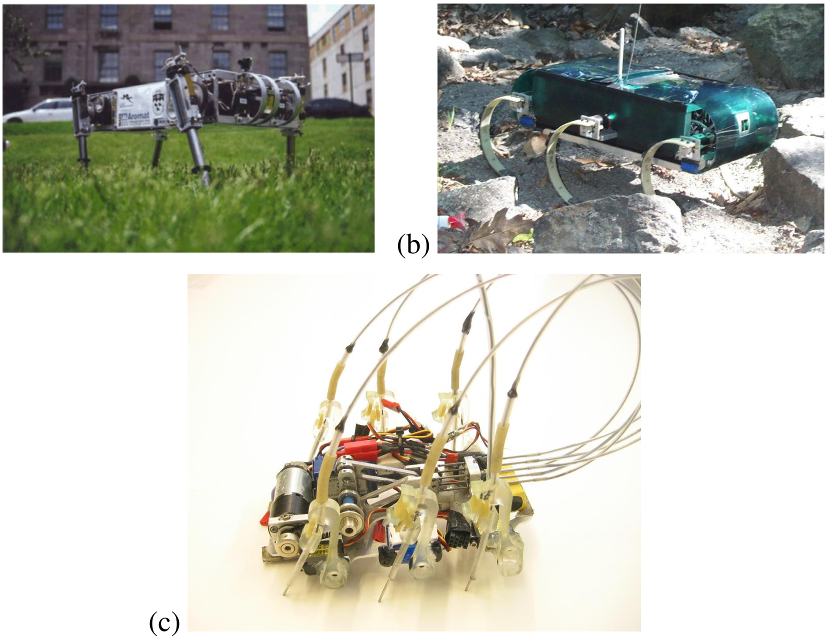


Figure 1.8: Minimally actuated multi-legged machines (a) Scout II (b) RHex and (c) iSprawl.

with a top speed of 1.3 m/s (Poulakakis et al., 2005, 2006). This system also claimed the notable mark of also being the first to demonstrate galloping in a quadruped robot (Smith and Poulakakis, 2004), although its minimal actuation provided little authority over heading.

Other multilegged machines have been created using minimal actuation as inspired by principles in nature. The hexapod RHex, originally designed by Saranli et al. (2001), consisted of a single rigid body with six compliant legs, each driven by a single actuator. The design (Figure 1.8) was motivated by clock-driven, mechanically self-stabilizing, compliant sprawled-posture mechanics proposed by (Full et al., 1998) as inspired by observations in the cockroach *Blaberus discoidalis*. With its recirculating compliant legs, RHex was capable to travel at one body length per second over height variations exceeding its body clearance (Saranli et al., 2001). Despite its apparent lack of similarities to Raibert's original hopping machines, the design of RHex similarly has been shown to anchor SLIP dynamics (Altendorfer et al., 2001).

Inspiration from experiments with the cockroach informed the design of the Sprawl series of robots around this same time as well. Using shape deposition manufacturing (SDM), these robots out of the lab of Mark Cutkosky were able to embed actuators and sensors into structures with locally-varying compliance and damping (Cham et al., 2002; Kim et al., 2006). Sprawlita was capable of running at 3.5 body lengths per second using off board pneumatic pumps, while iSprawl (Figure 1.8) was capable of running at 15 body lengths per second (2.3 m/s) with a completely autonomous design. More recent minimal designs using the Smart Composite Microstructures (SCM) process have produced the X2-VelociRoACH (Haldane and Fearing, 2015) which is capable of running at 4.9 m/s (approximately 45 body lengths per second, which represents a current record).

Humanoids in the ZMP domain

On the opposite end of the spectrum, the development of high DoF anthropomorphic humanoid systems has attracted a vast amount of research in the past 20 years. Bipedal systems without an upper body offer the opportunity to focus on the balance, but do not require difficult orchestration to coordinate the upper body with the legs. Despite this challenge, legged machines will ultimately need to be just as adept at manipulation as locomotion in order to interact meaningfully with the world. The upright posture of humanoids facilitates this interaction with a world designed to accommodate human forms, further driving the field forward.

With these among other consumer market motivations, HONDA launched a secret program to build a humanoid biped in 1986. Nearly a decade later, in 1998, Honda unveiled their humanoid robot P2 (Hirai et al., 1998). Using harmonic drives with a high-torque capacity and specially cast high-rigidity mechanical structures, P2 (Figure 1.9) was the first humanoid with on-board power and computing capable of stable walking. P2, much like its predecessors from Kato's lab, relied on the use of the ZMP for its walking control.

In the years following P2, Honda has continued to refine and improve its humanoid systems. Honda's ASIMO (Figure 1.9) is potentially the most well known humanoid to date (Sakagami et al., 2002) with current versions capable of walking, hopping, running amongst an impressive array of non locomotion-based intelligences (Takenaka et al., 2009d,a,b,c).

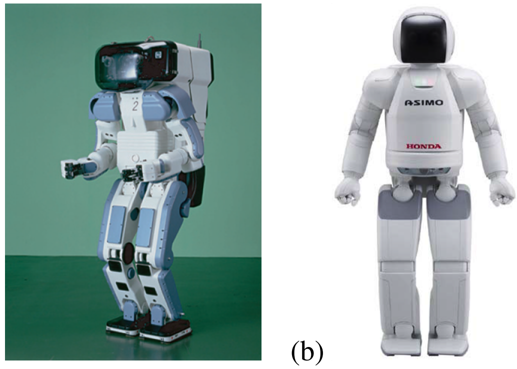
(a) (b)


Figure 1.9: Evolution to Honda's ASIMO (a) Original P2 (1998) to (b) Modern ASIMO (2009).

DC motors with harmonic drives have been a workhorse for many other humanoid designs. The HRP-2 (Kaneko et al., 2002b), SONY's QRIO (Nagasaka et al., 2004), and HUBO (Park et al., 2005) have all converged to a similar actuation paradigm. All of these designs are particularly amenable to position control and employ force sensors on the feet which are used to measure the ZMP. All of these systems have shown the capacity to execute a running gait (Kajita et al., 2007; Nagasaka et al., 2004; Cho et al., 2009; Takenaka et al., 2009d), where running is defined as a bipedal gait having one foot in contact at a time with a flight phase between footfalls. While these systems technically execute a run, their high impedance actuators cause large sensitivity to the impact velocity of the foot, and their flat-footed gaits resemble conservative ZMP-based walking more closely than graceful compliant running gaits observed in nature (Blickhan, 1989).

1.2.4 Today's Machines

Today, laboratories and research centers around the world have access to dynamic legged machines actuated by high-power DC motors and hydraulics. These robots continue to push the boundaries of speed and performance through advances in materials, design, and control.

Quadrupeds

Since creating Boston Dynamics (BDI), Raibert and colleagues have continued to innovate with their quadrupedal and bipedal machines. Using an on-board 15 HP internal combustion engine to power hydraulic pumps, Big Dog (Raibert et al., 2008) was created to be a rough-terrain robot capable of walking, running, climbing, and carrying heavy loads. The machine was about 3 feet long, 2.5 feet tall, and weighed 240 pounds. The machine could trot at 4 mph, walk across rubble, snow, and mud with slopes up to 35 degrees. Designed under DARPA funding, the machine was also able to carry a 340 pound load and had the capacity to autonomously follow a designated human leader.

BDI has introduced other groundbreaking descendants of Big Dog. The BDI cheetah, unveiled in 2012, was capable of running up to 28.3 mph with off-board power while constrained in 2D by a boom. The BDI cheetah had an articulated back that flexed back and forth on each step. In 2013, BDI released a self-contained version of the BDI cheetah, named WildCat, that was able to run untethered in 3D at speeds of up to 16 mph. WildCat could execute high-speed turns, although detailed specifications on their performance or the design have not been released.

Following acquisition by Google, BDI unveiled their smallest, most nimble quadruped, Spot, in early 2015. Very little is known about Spot other than a four sentence caption provided by BDI on their video release "Spot is a four-legged robot designed for indoor and outdoor operation. It is electrically powered and hydraulically actuated. Spot has a sensor head that helps it navigate and negotiate rough terrain. Spot weighs about 160 lbs.". This new robot is capable of walking up stairs and slopes, and has balance reflexes to respond to disturbances such as lateral kicks.

A variety of other dynamic quadrupeds have recently been developed in the academic realm, many outperforming BDIs machines in certain areas. Roland Siegwart's group at ETH recently designed the StarlETH quadruped (Hutter et al., 2014). StarlETH (Figure 1.10) is actuated by SEAs at its joints and is about 0.5 m long with a total weigh of 25 kg. The robot is capable to trot at speeds up to 0.7 m/s, with a cost of transport (COT) of 1.7. This dimensionless cost of transport measures how much energy it takes to move one kilogram one meter $\left(COT = \frac{E}{mgd}\right)$. StarlETH drastically outperforms BigDog, which has an estimated COT of 15. StarlETH was capable of a broad range of gaits (Gehring et al., 2013) and could trot over piles of lumber (Gehring et al., 2014). Marco Hutter, one of the original designers of StarlETH, recently introduced a more modular version of StarlETH, ANYmal (Hutter et al., 2016), which is able to climb steep stairs (50° inclination) and trot dynamically at 0.8 m/s.

The Cheetah-Cub robot at EPFL utilized a variety of parallel and series compliant mechanisms to provide self-stable locomotion over a range of speeds (up to 1.4 m/s) in a small quadruped (Sprowitz et al., 2013). Their design includes a spring-loaded pantograph mechanism inspired by the spring-loaded inverted pendulum template observed in biology (Full and Koditschek, 1999). The emergent self-stability provided by the leg mechanisms enabled central pattern generators (CPGs) to be used to generate kinematic targets for leg trajectories, without higher-level reflex mechanisms as used in previous CPG studies (Kimura et al., 2007). Despite the use of compliance in the design of Cheetah-Cub, the use of high-geared RC servos led to a minimum cost of transport of 6.9 in experiments, over 15 times that of simulation predictions. The use of compliant actuation strategies with lower-impedance servo drives represents an interesting area of future potential for designs in the spirit of Cheetah-Cub. Although smaller than many of other quadrupeds described in this section, this 1.1 kg robot is comparatively inexpensive and safe to handle, making it suitable to test prototype leg designs and bioinspired control strategies.

The MIT Cheetah robots have further pushed the boundaries of energetic efficiency with their unique high-force proprioceptive actuators (Seok et al., 2015). By incorporating large gap radius brushless DC motors into the leg design (Seok et al., 2012), the MIT Cheetah robots are able to obtain high torque density actuation without the traditional need for a large, lossy, staged gearbox. The MIT Cheetah 1 was constrained to operate in 2D and was capable to run up to 6 m/s with a COT of 0.5, on par with the energetic efficiency of actual cheetahs. Due to the unique actuator design, the Cheetah is able to emulate passive springs and dampers without the need to incorporate them physically into the design.

In a subsequent redesign, the MIT Cheetah 2 (Figure 1.10) has achieved a COT of 0.47 while running unconstrained in 3D with on-board power. Chee-

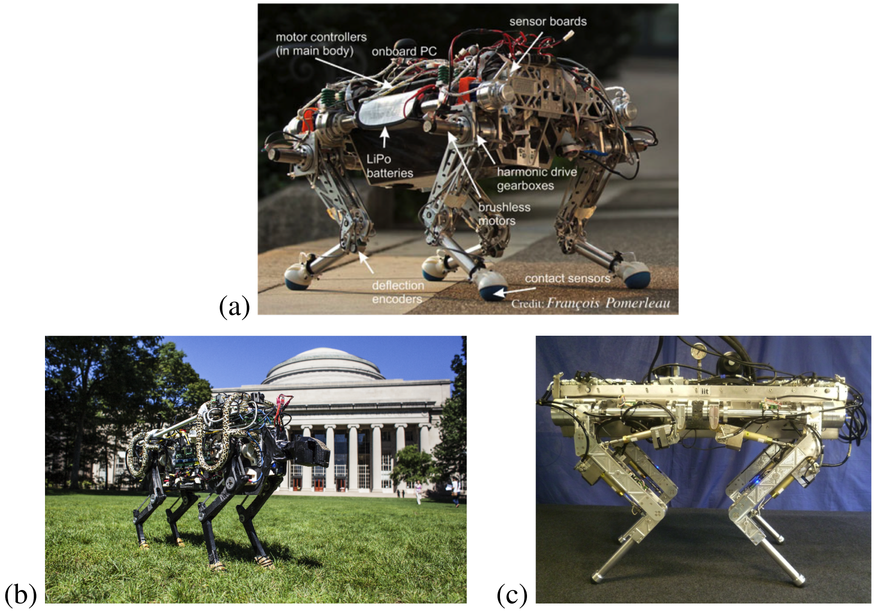


Figure 1.10: Modern Quadrupeds (a) StarlETH (b) MIT Cheetah 2 and (c) HyQ.

tah 2 is capable to run at speeds up to 6 m/s, and has shown the ability to autonomously jump over obstacles (Park et al., 2015a,b). The feat of landing an autonomous running jump had not previously been demonstrated in a experimental quadruped machine. While due in part to its control system, the ability to land the jump successfully is partially enabled by the backdrivability of the leg design which prevents otherwise prohibitively large impulses from causing structural damage.

Perhaps most similar in design to Big Dog and its predecessors, the hydraulic quadruped HyQ (Figure 1.10) was recently built in the advanced robotics department at IIT by Claudio Semini (Semini et al., 2011). HyQ is equipped with a combination of 12 torque-controlled hydraulic and electric actuators, is 1 m tall, and weighs around 90kg. While through a completely separate design paradigm from the MIT Cheetah robots, HyQ is also able to emulate passive springs and dampers with careful closed-loop force control on its hydraulic DoFs (Semini et al., 2015). Through the incorporation of vision, this platform has shown the capacity to navigate a variety of challenging terrains (Bazeille et al., 2014; Winkler et al., 2014).

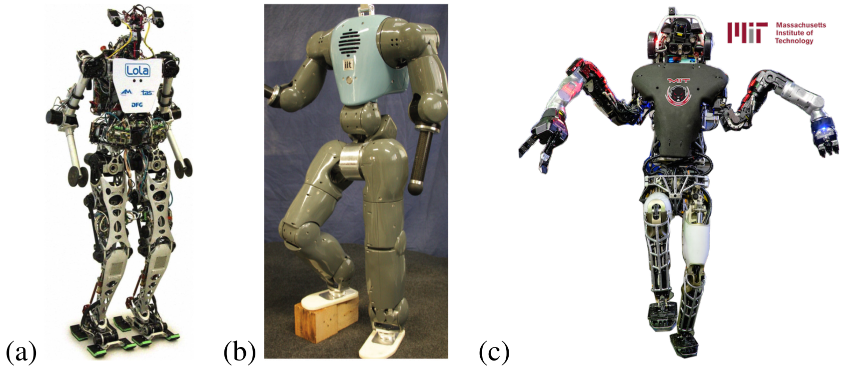


Figure 1.11: Modern Humanoids (a) LOLA, actuated by DC motors, (b) COMAN, actuated by DC Motor SEAs, and (c) ATLAS, actuated by high-power hydraulics.

Humanoids and Bipeds

Advances in DC motor, SEA, and hydraulic servo valve designs have also pushed the envelope in the performance capabilities of bipedal and humanoid machines. Taking insights from the design of JOHNNIE (Gienger et al., 2001), researchers at the Technical University of Munich designed the 25 DoF humanoid LOLA (Lohmeier et al., 2006) to study fast human-like walking. LOLA (Figure 1.11) is 180 cm tall and weights approximately 55 kg. The robot is driven by modular brushless motor modules and features lightweight 7 DoF legs to enable dynamic performance sufficient for fast walking (Lohmeier et al., 2009). LOLA has been able to walk at speeds of up to 3.34 km/h. Modular design strategies have also been employed in the construction of TORO (Englsberger et al., 2014), DLRs new torque-controlled humanoid, which uses similar integrated DC motor and torque sense hardware to the DLR lightweight robot (Hirzinger et al., 2002).

Series elastic actuation has begun to be incorporated into many modern humanoid designs. Both the Valkyrie (Radford et al., 2015), built at NASA Johnson space center, and COMAN (Tsagarakis et al., 2013), built at IIT, include joint SEAs that enable naturally compliant operation and joint-torque control. Valkyrie stands 1.87m tall and weighs 129 kg, while COMAN (Figure 1.11) stands 0.95m tall and weighs 31.2kg. The incorporation of SEAs into humanoid designs is still a very new trend, with the capabilities of these machines yet to reach their peak performance.

A number of other humanoids were designed to compete in the recent DAPRA robotics challenge (DRC), many within the traditional DC-servo motor design framework. As a notable exception, the ATLAS robot (Figure 1.11) used by multiple teams at the DRC was powered by on-board hydraulics for 28 actuated joints. ATLAS, designed by Boston Dynamics, is 1.88m tall and weighs 150kg (Boston Dynamics) with on board batteries and an integrated vision sensor suite.

With the focus on humanoid robotics in recent years, there have been comparatively less developments in bipedal machines. ATRIAS, however, is a recent 3D biped, built at Oregon State by Jonathan Hurst and colleagues, (Grimes and Hurst, 2012; Hereid et al., 2014) that has been designed to operate like a physical spring-loaded inverted pendulum model. ATRIAS strives towards this aim by employing large series springs in similar spirit to Hurst's previous designs. The robot has shown the ability to walk at speeds up to 1.2 m/s using a single set of optimization-inspired heuristics for control (Rezazadeh et al., 2015) and has shown empirical robustness to a wide variety of terrain disturbances in laboratory settings.

1.3 Challenges of Current Machines

Across the legged robots that dominate today's state of the art, designs have slowly converged towards supporting an ability to regulate force-based interactions with the environment. Whether through series elastic actuators, hydraulic actuators, or transparent DC electric motors, many of the most successful legged robots today manage balance through torque control at their joints. As future robots transition into less structured environments, this ability to be cognizant of interactions with the world will remain a priority in designs. Chapter 2 discusses some of the main challenges to actuator design in legged robots and discusses a recently developed technology called proprioceptive actuators in order to meet the needs of today's legged machines.

The rapid progress in locomotion technologies in recent years makes it clear that legged robots may soon roam beyond the lab. For legged robots to reach their full impact, they will need to extend their operational lifetime both in terms of reliability and energetic economy. Both of these aspects are incredibly complex due to the underlying interplay between so many contributing factors. Reliability will likely come with maturity of the field and technological components. Engergetics however, are a concern that require careful consideration in design. Energetics seems like something that should be able to be modeled. However, the factors that influence it rank among those that are most difficult to capture with accuracy. Chapter 3 further discusses philosophical perspectives on designing for energetic efficiency.

Grown out of both footstep placement in the spring-mass machines of Raibert to ZMP control in the humanoid walkers in 90's, current machines are able to take full advantage of both stepping and ground force shaping in their methods to maintain balance. These diverse modes of operation place unique demands on the more than simply the actuation systems. The design of legs themselves must be capable to handle high force and high-bandwidth loading patterns while minimizing weight to enable rapid replacement in flight. While this tradeoff has held true throughout the history of legged locomotion, the diverse functional requirements induced from more flexible control have only added to the challenge. Chapter 4 discusses trends in leg design and offers a case study using principles from observations in biology to design a leg for the MIT Cheetah.

Following these three Chapters on more detailed considerations in design, Chapter 5 concludes with a summary of future directions and applications.

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