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Abstract

Ability to translate to a goal position under the constrains imposed by complex environmental conditions is a key capability for biological and artificial systems alike. Over billions of years evolutionary processes have developed a wide range of solutions to address mobility needs in air, in water and on land. The efficacy of such biological locomotors is beyond the capabilities of engineering solutions that has been produced to this date. Nature has been and will surely remain to be a source of inspiration for engineers in their quest to bring "real mobility" to their creations. In recent years a new class of dynamic legged terrestrial robotic systems \cite{Autumn-Buehler-Cutkosky.SPIE2005,Raibert.Book1986,Raibert-Blankesport-Nelson.IFAC2008,Saranli-Buehler-Koditschek.IJRR2001} have been developed inspired by, but without mimicking, the examples from the Nature. The experimental work with these platforms over the past decade has led to an improved appreciation of legged locomotion. This paper is an overview of fundamental advantages dynamic legged locomotion offers over the classical wheeled and tracked approaches.

Keywords

legged locomotion, robotics, dynamic, rhex

Disciplines

Biomechanics and Biotransport | Controls and Control Theory

Dynamic Legged Mobility — An Overview

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Abstract. Ability to translate to a goal position under the constrains imposed by complex environmental conditions is a key capability for biological and artificial systems alike. Over billions of years evolutionary processes have developed a wide range of solutions to address mobility needs in air, in water and on land. The efficacy of such biological locomotors is beyond the capabilities of engineering solutions that has been produced to this date. Nature has been and will surely remain to be a source of inspiration for engineers in their quest to bring "real mobility" to their creations. In recent years a new class of dynamic legged terrestrial robotic systems [1–4] have been developed inspired by, but without mimicking, the examples from the Nature. The experimental work with these platforms over the past decade has led to an improved appreciation of legged locomotion. This paper is an overview of fundamental advantages dynamic legged locomotion offers over the classical wheeled and tracked approaches.

1 Introduction

Natural environments present major challenges to locomotion. Wildly varying contact dynamics, chaotic obstacle topology, actuator power limitations and tight sensory constraints render the task of moving from one point to another extremely difficult.

At the first glance the apparent ease of commute in our daily lives suggests that the problem of mobility has been long mastered by mankind. On the contrary, our engineered vehicles can only offer a limited solution and requires very expensive infrastructures to be in place. In the specific case of *terrestrial* locomotion—the primary focus of this paper—the basic vehicle design [5] has not fundamentally changed since the invention of wheel [6] circa 4000 B.C. and heavily depends on the availability of a smooth driving surface—roads [7]. In fact less than half of the World's land mass is accessible to wheeled and tracked vehicles [3].

Nature's solution to terrestrial mobility takes a radically different approach in the form of *legs*. From very small insects to large mammals, legged morphologies offer agile and efficient locomotion [8] to animals facilitating their conquest to the farthest reaches of Earth.

This very dexterity of legged locomotion has been an inspiration for engineers and scientist since the ancient times [9, 10]. There has been many attempts to *copy* biological systems, both in the past [11,12] and more recently [13], in the hopes to capture capabilities of animals. However, all such mimicry have fallen short of their goal due unavoidable, and significant, differences between available engineering building blocks and their biological counterparts.

Recent system identification studies and comparative analyses on animals [8,14–17] led to the development of formal template models [18] for dynamic legged locomotion [19] and producing actionable principles to guide engineering design [2,4,20,21].

Experimental work over the past decade with a novel class of robotic mobility systems based on the seminal RHex design [4] (and in part with the RiSE platform [1]) has led to renewed appreciation of legged locomotion. This paper will review two fundamental lessons learned: 1) advantages of legged locomotion in rugged natural settings; and 2) role of dynamic behavioral capabilities in task accomplishment.

The outline of this paper is as follows. Section 2 will introduce the RHex-class robotic designs. Section 3 will outline various advantages of legged mobility over its counterparts, wheels and tracks. The dynamic behaviors and their utilization in task accomplishment is discussed in Section 4.

2 A New Class of Robots

Among biologically inspired robotic platforms *RHex-class* robots [4] stand out with their computational and power autonomous design that can negotiate a large spectrum of natural scenes [22]. Since its inception RHex morphology has been employed in various projects in educational programs [23] and robotic mobility studies [24,25].

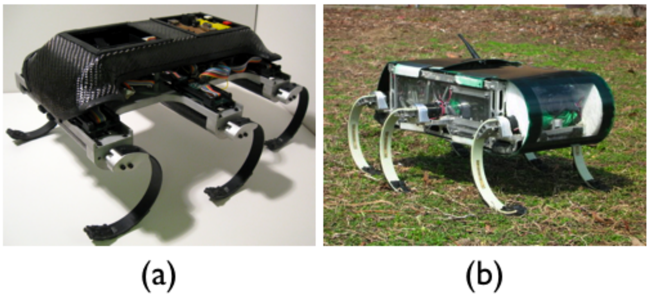

Fig. 1. (a) EduBot (b) RHex platforms.

Inspired by the studies on cockroaches the morphology of RHex-class robots is a hexapod organization of one (active) degree of freedom compliant legs. All the actuators, computational resources and power storage elements are embedded with in the body. Legs constitute a very small portion of the overall weight. This construction offers an impressive endurance in the face of sever natural condition.

Task level open-loop behavioral controllers have been shown to produce dynamic locomotive behaviors in RHex-class robots [26]. Discussions in the following sections are heavily informed by the experimental work that has been conducted on these platforms over the past decade.

3 Role of Legs

Legged locomotion is fundamentally different from the classic mobility technologies based on wheels and/or tracks[1]. This section will compare legs and wheels in three basic areas: 1) sensitivity to surface irregularities in Section 3.1; 2) controllability of ground reaction force in Section 3.2; and 3) functionality in Section 3.3.

3.1 Sensitivity to Surface Conditions

A wheel [6] is a convex device that is capable of rotating on its axis facilitating transportation by rolling on the ground surface whilst supporting the body mass. In the ideal case—infinitely rigid perfect circle wheel rolling on infinitely rigid flat surface—the wheel offers lossless mobility [7]. Unfortunately, practical situations (Figure 2(b)) are far from this ideal scenario (Figure 2(a)). Efficacy of wheeled mobility drops sharply as the wheel-ground contact becomes rough [22]. As a direct consequence outside the carefully constructed road infrastructure wheels are quickly rendered inoperable [3].

The reduction in mobility efficacy of wheels is a direct consequence of its design which constraints the wheel to maintain contact with the ground surface at *all times*. When the surface is flat this operating principle does not pose any problem. However, as the surface becomes rough the irregularities that are of comparable size to the wheel's radius present friction that must be actively compensated for. For this very reason in an off-road setting vehicles with larger wheels perform better than those with smaller wheels.

One of the primary advantages of legged locomotion is that ground contact is not maintained at all times. By design a leg is a hybrid dynamical system that makes and breaks contact with the surface. At the point of contact the *foot*[2] creates a temporary joint that permits the leg to support and propel the body forward without needing to roll over the irregularities on the surface. In between consecutive foot holds a leg would simply avoid the surface irregularities by in a sense *jumping* over them. As a result, legs offer a certain level of immunity from the surface irregularities which permits them to operate in on-road and off-road scenarios at very close energetic efficiencies [22].

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[1] In the rest of this discussion we will refer to wheels for the sake of text simplicity. However, the reader can extend the arguments to tracks as well

[2] Foot is loosely defined as the extremity of the leg that makes contact with the surface. A more generic discussion of what constitutes a foot can be found in [27].

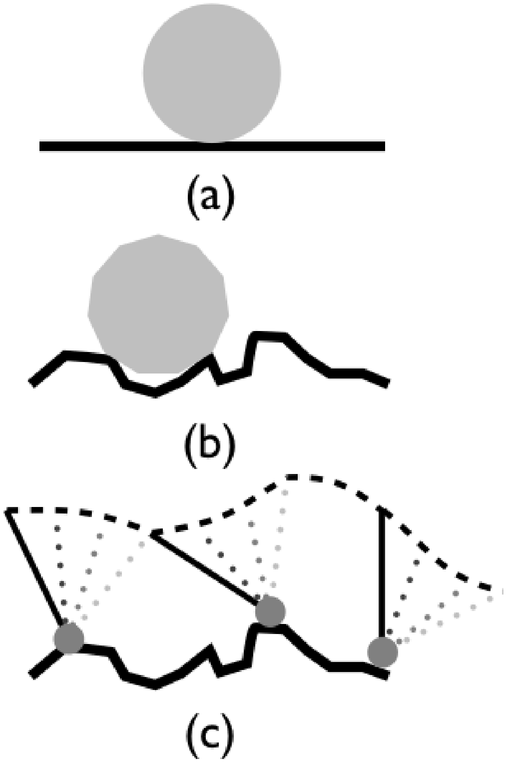

Fig. 2. (a) Wheel offers non-dissipative mobility in an ideal setting. (b) As the surface gets rugged or wheel is imperfect the effective friction increases. (c) In contrast, a leg makes ground contact intermittently avoiding majority of the surface irregularities which facilities more efficient locomotion on rugged settings.

3.2 Controllability of Ground Reaction Force

The ground reaction force (GRF), $\mathbf{F}_g$, is the force exerted by the ground on the body in contact with it. The GRF is responsible of the transportation of the body, and therefore, the level of its *controllability* has a strong impact over the behavioral repertoire of the vehicle. For the purposes of this discussion we choose to partition the GRF, $\mathbf{F}_g = \mathbf{F}_c + \mathbf{F}_u$, into two additive components: 1) its controllable component, $\mathbf{F}_c$; and its uncontrollable component, $\mathbf{F}_u$. We observe that for both wheeled and legged systems the uncontrollable component[3] of the GRF is of equal magnitude but opposite direction to the weight of the supported vehicle, $\mathbf{F}_u = -m\mathbf{g}$.

In the most generic sense the control input in a wheel system is the torque, τ, applied about the axis of its wheels. By design control torques can only produce

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[3] We are ignoring forces caused by non-holonomic constrains for the sake of simplicity

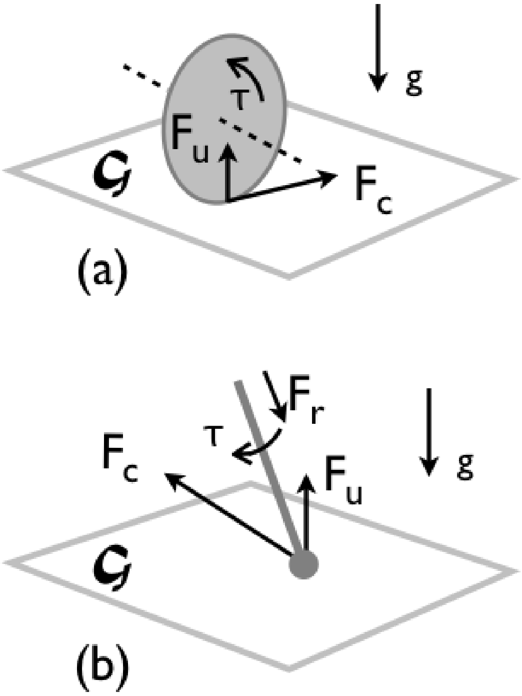

Fig. 3. (a) Active ground reaction forces (GRF) produced by wheel is constrained in the ground plane, $\mathcal{G}$. (b) In contrast, a leg offers a much more flexible control over the GRF. The ability to actively generate GRF normal to the ground surface opens up a wide range of behaviors, such as leaping, that are not feasible for wheeled and tracked vehicles.

ground reaction forces constrained within the tangent space of the ground plane at the point of contact, $\mathbf{F}_c \in T\mathcal{G}$, as depicted in Figure 3(a).

Since the steerable component of the GRF, $\mathbf{F}_c$, is bound to be tangential to the ground, a wheeled system is not capable of dictating body movements that are normal to the ground. Therefore, behaviors such as leaping, bounding and so forth are not realizable for a wheeled platform.

In comparison to wheels, legs achieve more dexterous GRF control by proper application of radial force and rotational torque at the foot[4]. As a result a leg can actively produce reaction forces normal to the ground, $(T\mathcal{G})^{\perp}$ as well as within its tangent space, $T\mathcal{G}$. Figure 3(b) illustrates a cartoon representation of GRF production of a leg.

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[4] In this discussion we are ignoring all specifics of the leg morphology but instead focus on the resulting forces and torques at the leg's end-effector—the foot.

$$\exists \mathbf{F}_c = \mathbf{F}_{cn} + \mathbf{F}_{ch} \ s.t. \begin{cases} \mathbf{F}_{cn}, \mathbf{F}_{ch} \neq 0 \\ \mathbf{F}_{cn} \quad \in (T\mathcal{G})^{\perp} \\ \mathbf{F}_{ch} \quad \in T\mathcal{G} \end{cases} \tag{1}$$

The achievable domain of GRF in a legged system would strongly depend on the specific design of the leg. Yet, the ability to produce forces normal to the ground surface remains a common character of any legged implementation which opens up a wide range of new behaviors such as climbing [1], bounding [28, 29], leaping and so forth.

3.3 Functionality

Wheel—a device specialized for transportation—lacks the configuration freedom and actuation agility (discussed in Section 3.2). Its utilization as a (direct-able) sensor is fairly limited [30] and there is no meaningful manipulation service offer by the wheel. Therefore in wheeled platforms sensing and manipulation tasks are performed by additional (specialized) hardware [31] which increases the system complexity (and reduces overall robustness), body mass, energy consumption and the cost of production/maintanence.

The inherent dexterity of legged design permits implementation of highly integrated multi-functional appendages with (comparatively) low level of increase in the overall system complexity. Simply put, a leg can *simultaneously* serve: 1) as a transport device (its main role); 2) as a manipulator; and 3) as an exteroceptor sensor.

The multi-functional use of legs[5] can be clearly observed in the Nature. For instance, a cockroach employs its legs not only to run across the floor, but also to clean its antennae, to move food particles, and to sense its environment.

Multi-purpose utilization of legs have been successfully demonstrated in the RHex [4] project.

Without any morphological *specialization* RHex demonstrates a wide range of locomotive behaviors including tripod running/walking [32], bounding [28], pronking [33], bipedal running [34], stair climbing [35], and leaping [36] and even swimming [37]. In recent studies a smaller form-factor RHex platform, SandBot, has shown high locomotive performance on granular media [25].

Manipulation can be considered under two categories: self-manipulation; and external manipulation. The former is the process of changing the body configuration and orientation. The latter is the act of moving object around the body. The high centered movement control [38] and flipping [39] are two examples of self-manipulation behaviors in the RHex platform. The external manipulation is a relatively unexplored area but it has been demonstrated in various cursory studies[6].

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[5] Due to our mobility centric discussion this paper refers to legs—a specific form of appendages. However, the reader should note that the arguments can be extended to appendages in general.

[6] Our team demonstrated an automated "ball kicking behavior" at the RoboCup WorldCup 2006 in Bremen

Intimate and direct-able interaction of legs with their environment grants them a unique position to gather *tactile* information from the environment. In our past work such tactile information has been employed as a task level feedback for gait control [28, 40] as well as cues for gait transitions [41]. With proper consideration of the body dynamics tactile information from the legs of a platform can be utilized to calculate the body configuration (pose and translation) in a legged system [42].

4 Dynamic Behaviors

Energy takes many forms—kinetic, potential, thermal, gravitational, sound, light, elastic, chemical, nuclear and electromagnetic. Total energy of a system is (typically) distributed across multiple forms at any given moment. We recognize that for locomotive behaviors[7] the magnitude and manner in which energy is exchanged among these different forms of energy during behavioral progression has substantial impact on locomotive capabilities.

In accordance with the way total system energy is managed in the course of behavioral progression we categorize (locomotive) behaviors into three groups: 1) static; 2) quasi-static; and 3) dynamic behaviors. In the following discussions we will ignore the thermal energy produced by mechanical dissipation since it does not contribute to accomplishment of any mobility task.

We characterize a (locomotive) behavior *dynamic* if there exists *significant* (and repetitive if the behavior is cyclic) exchange between different forms of energy in the course of behavioral progression. An illustrative example for dynamic behaviors can be found in Figure 4 illustrating the running behavior for the SLIP model [19]. Consequently, if there is no change in the distribution of the total energy, the behavior is classified as static. Quasi-static behaviors are those where the exchange of energy is small in comparison to the total energy of the system.

It is important to note that speed does not necessarily imply realization of a dynamic behavior. For instance, a car driving on a straight path at a constant 100 miles/hr has a very high kinetic energy, however, there is no exchange between different forms of energy, and therefore, in accordance with our classification above, it is in fact a static behavior. Another potential misconception that should be addressed is that legged locomotive behaviors are not *all* dynamic. For example, biped walking is a quasi-static behavior since the small changes of the COM height in each stride results in small exchanges between kinetic energy and gravitational potential.

Natural environments present a wide range of difficulties (rock outcroppings, ditches, muddy patches, gravel and so forth [22]) rendering the task of translating the body to the goal position a complex *path planning* task within the *state space* (positions and speeds) that is punctured by various obstacles. Locomotion in such complex natural settings takes advantage of two tightly coupled aspects

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[7] The same argument can be extended to other types of tasks but it is outside the scope of this paper.

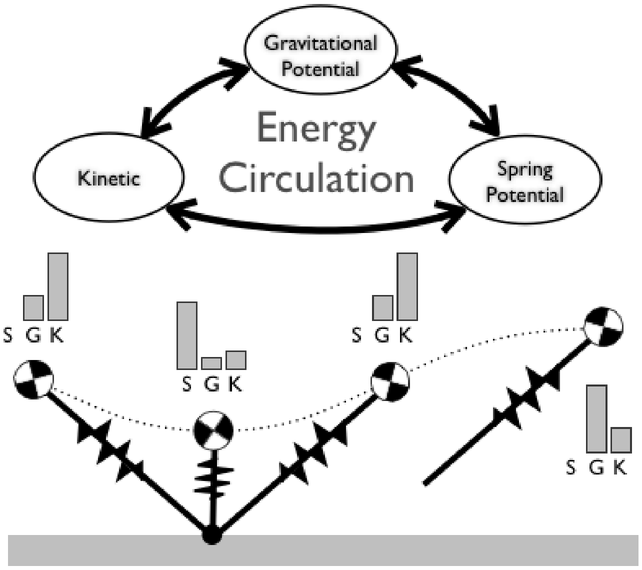

Fig. 4. Energy circulation in the spring loaded inverted pendulum (SLIP) model. The top illustration indicate the major forms of energy in the system and pathways for exchange. The bottom illustration captures four states of a SLIP stride and the distribution of total energy among the three forms of energy. SLIP system alternatingly uses the gravitational and elastic potential energy to store energy and redirect it to kinetic energy.

of dynamic behaviors: 1) improved obstacle negotiation; and 2) transportation efficiency.

4.1 Obstacle Negotiation

A direct brute force approach can rarely accomplish negotiation of a complex obstacle within the physical constraints. Instead more feasible approaches often require a multi-step process steering around the above mentioned constrains and obstacles. For instance, crossing a sufficiently large ditch cannot be accomplished with a behavior that is geared towards flat surfaces and would unavoidably require *leaping* over it where a significant exchange of energy needs to be transfered to the gravitational potential. The source of the energy which is redirected to gravitational potential can be many forms of energy (kinetic, elastic, chemical, etc.) or combination there of.

It is important to note that in a behavior the magnitude of exchange between different forms of energy is not the task goal, but in fact, is the measure of how flexible the behavior (and the system that produces it) in navigating in the state space. At a very high level we argued that dynamic behaviors that can explore a larger portion of the state space has a higher performance in locomotive tasks in complex natural settings.

4.2 Transport Efficiency

The ability to transform system energy into different forms also offers improved energetic efficiency [43]. For various reasons certain desirable states (and the associated particular energy distributions) cannot be maintained for extended periods of time either due to physical constraints (a leg cannot extend forever) or environmental conditions (a ballistic body would eventually fall). One solution would be to actively inject energy into the system to maintain such states (having a jet engine to hover in the air). However, a more energetically efficient approach would be to transform the system energy into a different form for *storage* and to *restore* it towards the accomplishment of the task at a later time.

The Hamiltonian SLIP model (depicted in Figure 4) presents a good example of store/restore cycle in a locomotive task. The kinetic and potential energy of the body is transformed into elastic spring potential during ground contact and restored back to first kinetic and then gravitational potential to perform a ballistic hopping behavior. The power efficient jogging gait [32] of the RHex platform employs the same principle.

5 Conclusion

It is universally accepted that robots are better suited for *dirty, dangerous and dull (DDD)* jobs. Today, robots indeed satisfy this very expectation with increasing proficiency on factory floors all around the world. Yet, outside *structured* environments robots have not demonstrated any noticeable value added. A robot operating in a complex and unstable natural setting faces major technical problems. This paper focuses on one of these challenges—the *mobility.*

Today, the classical solution for mobility is the use of wheels and/or tracks [7]. Although these approaches are effective in structured environments their efficacy drops sharply as the environmental conditions deteriorate [22]. This very environmental dependency of wheels makes them inoperable in more than half of the World's land mass [3].

In contrast, billions of years of evolutionary process has led to a radically different biological solution for the mobility problem—*legs.* Although the products of the evolutionary process are not to be accepted optimal [44], the wide spread utilization of legs in extremely different environmental conditions [16] suggests that the legged locomotion offers a feasible solution for our locomotion needs.

The first part of this paper presents a high level discussion identifying three intrinsic capabilities of legs and contrasting them to that of wheel's. First, legs offer improved level of immunity against variations in the ground surface. By making and breaking contact with the ground legs eliminate the need to address all irregularities of the surface. Next, legs provide a better control authority over the ground reaction force production. Specifically, legs can generate GRF normal to surface which facilitates legged platforms to enjoy a wider range of behaviors (e.g. leaping) that are unattainable for their wheeled counterparts. Finally, leg appendages can serve mobility, sensing and manipulation tasks without any morphological specialization. This multi-functional use of legs can lead to designs that are compact and robust.

In the second part of the paper the author defines the *dynamic behavior* and discusses its role in mobility tasks in complex natural environment. Two tightly coupled aspects of dynamic behaviors are considered: 1) obstacle negotiation; and 2) transport efficiency. Their hybrid dynamics and flexible affordance on the GFR positions legged platforms to effectively produce dynamic behaviors.

Legged mobility technologies are in their infancy compared to the classical wheeled and tracked systems. Those aspects of legs that make them better suited for mobility in the natural settings are also the reasons why it is hard to design legged platforms and define effective controllers. Biologically inspired platforms such as RHex [4] and RiSE [1] presents the potential of legs which is just barely scratched. The basic RHex morphology has successfully served in many educational [23] and research activities [24, 25].

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