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A Design for Proprioceptive Force in 3D Agility Robot Through Use of AI

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Abstract

For robots to be considered effective, they should be able to maneuver through 3D environments. To achieve such mobility, robots needs to be designed in such a way that would span various topographies. So, artificial intelligence algorithms have been developed to ensure agility of the robots when walking on murky topographies. In the current state of the art legged robots, there is still much progress need to be made in research to turn them into automobiles with great agility to be used in the real world utility and provide mobility in rough. GOAT leg as a means of artificial intelligence is still a new phenomenon. There still exists a number of preliminary tests that need to be done in accessing and in the characterization of the leg's current performance and its implications in the future. This study seeks to develop and agility model which would be useful in ensuring that the robots remain agile in such complex environments. To do this, a simulation has been through Matlab analysis. Results of the current study showed that, 3-RSR was designed to ensure that a high fidelity proprioceptive force control would enable legs with the mechanically spring stiffness. Implications and future recommendations also discussed.

Keywords: 3D environment; foot sensing; artificial intelligence; GOAT leg.

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1. Introduction

The advent of modern machinery has benefited the transport system in society. Machines like boats, cars, and trains have been invented to ease the transportation process, overcome the limitations in terms of speed and distance in human beings, and create convenience [1]. While technology has eased communication for human beings, conventional automobiles still need some high level of infrastructure to access most of the earth that is often inaccessible. These are isolated places where sure-footed animals always roam freely. While human beings are pushing the barriers of communication to extra-terrestrial lands where the terrain is hardy, and the atmosphere is drastically dense, conventional automobiles that have much agility on earth would often have trouble landing on such spaces. Thus, an exploration into such terrains would require an alternative approach to be used- an approach that looks at biology for inspiration. For instance, the mountain goat is a notorious animal for its awkward mobility in environments that are naturally untraversable. These legged animals often exhibit an unmatched multimodal ability to transverse areas that are stiff and mountain-like, often in most cases, using their dexterous limbs to maintain static balance on cliffs. Such static ability exhibited by the mountain goats in changing elevation and reach statically unreachable stable motions is impressive. In addition to maintaining agility and stability, the mountain goats can jump to heights of 12 feet in one single leap and running up to speeds of 15mph, and swim in bodies of water. Such a level of agility is often unmatched and unsurpassed by modern automobiles [2]. Thus, for many decades, scientists have turned into biology to develop creations that would provide convenience and competence as exhibited by the animals. In the current state of the art legged robots, there is still much progress to be made in research to be able to turn them into automobiles with great agility to be used in the real world utility and provide mobility in rough terrains [3]. The most notable progress that has been made in legged robot agility is demonstrated by recent videos by Boston Dynamics, which features robots such as Atlas, BigDog, Spot, and SpotMini [4]. These videos feature biped and quadruped hydraulically and electrically actuated robots that seemingly navigate through rough terrains in the forests to confined spaces such as staircases and parks. However, despite the progress made on autonomous balancing and in the legged technology algorithms, the largest barriers towards makings such technology reaching the real world continue to be the multimodal mobility used in force control and interactions between humans and the real world and secondly, power efficiency needed to control such machines without the need to recharge them manually constantly. It is estimated that only 50% of the total earth landmass is accessible through wheeled or tracked machines. Human beings and animals are, however, readily available to access most of this landmass, and it is often desirable that robots and machines be able to maintain and achieve such levels of agility [5]. Biologically inspired robots offer enhanced mobility to access the often impassable environments in situations that are unsafe and not feasible for human beings to travel. Despite the fact that it is an immense promising legged robot, most of this is often limited dynamically and thus, and they make the little trade-off between achieving efficiency, dexterity, and mobility. To achieve effectiveness in the real world, these legged robots have to be capable of navigating through complex 3D environments and achieving multiple modes of agility and mobility at the same time. Achieving mobility in such complex environments such as rough terrains is a challenging task, and robots would have to be highly static and have stable emotions and have high dynamic maneuvers such as having the ability to leap, do compliant landing and running, and to be able to optimally traverse a rough terrain [6]. Thus, the capability to transverse in such rough terrains should be both dexterous, in a bid to achieve precise footstep placement and dynamic, to achieve running and jumping simulations when they are reached or faced with obstacles. For instance, an extra-terrestrial landscape or a collapsed ruble, disaster zones,, or even when required or called to action in ubiquitous warfare will often contain terrains that are highly rugged and have a relatively level ground [7]). In such environments, using high bandwidth virtual compliance tools made possible with low impedance actuators have sensors to allow the legged robots to conform and perform with gait and agility in such environments. Alternatively, when terrains are both sloped and rugged, it would be ideal for robots to crawl or climb them slowly with precise footholds that are only made possible through the use of dexterous limbs in a large workspace [8]. Likewise, war zones and disaster areas provide local discontinuities in the robot's path that would have otherwise impaired movement for the robots. To be able to move is such a range of mobility, conventional pure position based control method will, in essence, not is adequate to ensure movement. In a bid to accomplish this range of mobility, robotic machines should be designed to provide an accurate position and force control that works in a parallel manner.

The real test in measuring agility for legged robots is traveling to locations that are hard to reach or those that are not safe to be reached through the foot. Such areas of interest are often characterized by the following;

1. Terrains that are largely unstructured and impassible by wheeled vehicles
2. Pits, holes, and ditches
3. Long-distance missions in terrains that needs different gaits and modes of locomotion
4. Tight spaces
5. Obstacles of large and steep variation

The legged robots utilize a variety of leg topologies and actuation strategies that makes agility easily attained. However, currently, existing robotic technologies have fundamental shortcomings in attaining such levels of agility. In tight spaces with discontinuous walking paths, the current robots would have to turn in place when faced with the desired heading, then walk or even jump forward when faced with such an obstacle. This is ideally different from simply moving or jumping in the same direction of the desired movement and going forward. Thus, there is a need to address these shortcomings [4]. One way to do so is through the use of sensors. The sensors should be proximal to the body, not in direct contact with the environment, and high bandwidth sensing.   A solution that would address all these three criteria is to measure motor torque in the motor current and use the leg Jacobian method to force a ground rotation force. Such a solution doesn't require actual distance sensors, nor does it put the sensors directly into contact with the load path.

A. Research objectives

This article is aimed at

1. To develop a new leg topology and accentuation paradigm that would enable the legged machines to use proprietory force and enable the machines to exhibit agility through the use of both static and highly dynamic motions.
2. To explore the design concepts, implementation details, and the controls strategies that can be used to realize

a new crop of 3D agility that would one day see the light and be used in the exploration of the extra-terrestrial world and rough terrains.

B. Research Questions

1. Does the task-optimized 3-DoF leg topology allow for a robotic leg to be dynamic in 3D model agility?
2. Does accurate proprioceptive sensing achieve virtual compliance while at the same time ensuring mechanical robustness?

2. Literature Review

This chapter seeks to explore the current research on dynamic legged machinery and evaluated the advantages, disadvantages, and existing trade-offs and limitations on the current leg designs and their actuation. Thus, this chapter documents and builds on the current body of knowledge on the GOAT leg.

C. Dynamic Legged Robots

Extreme multimodal mobility is still undeveloped. Robots that exhibit such a high level of multimodal agility include RHex, LittleDog, and MIT Cheetah robots. The RHex robot has been able to demonstrate capable locomotion through the use of simple mechanically compliant legs that is compliant to the existing rough terrains. Rhex has been developed to exhibit dynamic jumping maneuvers despite the fact it is developed on a 1-DoF sagitally constrained leg limit in the out of plane 3D jumping. On the other hand, LittleDog uses an alternative approach in transversing rugged terrain by planning the mass trajectories exclusively. It largely relies on the dexterous limbs to interact with the perceived rough terrain environment [4]. While LittleDog has in the past demonstrated high dynamic jumping and running abilities, it has been criticized for its slow leg swing speed and the leg topology that limits the magnitude of its jumping spree. On the other hand, although the Boston Dynamics uses wheels in place of legs, it does exhibit highly dynamic multimodal agility based on its ability to drive over flat grounds and through the use of compressed gas to launch. MIT Cheetah uses low-impendence actuators to launch and generate high speed and high force sensors [2]. However, the dynamic mobility of this is constrained by the limited leg workspace. From the above, it is evident that there exists a challenge in designing a legged robot with immense multimodal ability. A crucial challenge in designing legged robots lies with the selection or in the synthesis of an appropriate leg topology that would be able to realize the desired motion outcome.

D. Leg Design Principles

A legged robot does require a variety of actuation schemes to achieve dynamic ability. While it is evident that the design of the dynamic legged robots varies, there exist some common design requirements to improve agility, such as

1. High force, high-speed legs
2. Passive or active compliance

3. Robust leg mechanism
4. And energy efficiency

Such design specifications lead to implementing a system that makes it possible to have trade-offs based on what the designers prioritized under each of these specifications. Many of these designs are often coupled; thus, selecting and achieving actuation in the leg topologies and the performance is often a non-trivial matter. For instance, selecting a high force and high-speed legs would lead to a trade-off with achieving strong structure and high speed in a given system [6]. High-speed legs for a set of actuators often minimize leg mass and its inertia. Thus, reducing leg mass through the reduction of the structure in the cross-section often yield stress. Further, an increase in the proprioceptive force-sensing fidelity would often impede the leg actuators torque; thus, leading to a reduction in the total force production. Thus, such trade-offs in the robot may impair the achievement of total agility by the robots today There exist certain design trade-offs and competing design goals when designing an actuator design for the leg topologies. It is always important to choose a given leg topology that complements another to achieve design specifications and allow maximum legged mobility. Thus, the design methodology starts with an unmodified electric brushless DC motor in which the torque is the limiting resource. Hydraulic, electro-hydraulics, and pneumatics would be ruled out of this analysis due to the fact that it utilizes a large overhead fracture such as the heat exchangers, the pumps, the internal combustion engines, and the hydraulic pressure units.

3. Methodology

This study seeks to utilize the Gearless Omni-directional Acceleration Vectoring Topology in its methodology as the novel leg to bypass all the current leg designs and 3d agility. The GOAT leg is a modular topology used to design robots with greater mobility [9]. Further, GOAT is often used with various legged robot morphologies such as monopod, biped, and quadruped. For this study, the focus of the researcher would be the monopod. The first-ever truly dynamic legged robots to be put in place through direct-drive and quasi-direct-approach were done by previous scholars and in the MIT Cheetah project [7]. Thus, much of the work in this thesis would be inspired by the two works on dynamic legged robots. To do this, a simulation has been through Matlab analysis.

E. A Novel 3-RSR Leg Topology

The current dynamic legged robots utilize variations that are exhibited through the prismatic and series articulated linkages. While each of these has its fair share of challenges and advantages, all of them do share a commonality through the leg Jacobian system. Such a constraint extends to the physical realization and in the structure of the leg mechanism, which in most cases is prone to failure. Thus, to overcome these challenges, this study proposes the utilization of the Omni-directional leg Jacobian model that would use large forces with high speed and moves in any given direction in the frontal plane. Further, it is well known that the forward kinematics in the parallel spatial linkages is often difficult to solve through analytical means. Thus, this study proposes to use 3-RSR"s forward, and inverse kinematics using MATLAB function and further would be mixed through the use of C++ in the real-time constraining optimization.

Risk Analysis

This research study would seek to reduce the risks involved with the project failing at all times. A significant theme in the 3-RSR leg design is the use of a simple, high fidelity virtual model that would control the virtual compliance. Thus, to achieve such compliance, the criteria that would be used is;

1. Rapidly change the actuator torques in a bid to emulate the bandwidth of a mechanical spring-damper
2. To sense the sense accurately and be able to deliver foot forces through the use of the Jacobian model

Thus, the forced transparency in the leg system must be maximized in a bid to ensure that there is accuracy in the forces that are being sensed and those that are being delivered in a bid to mimic the mechanical compliance through the use of the kHz time scales [10]. Secondly, the proprioceptive sensing accuracy through measuring motor current is always hindered by the mechanical impedance in the overall load path. Thus, to be able to minimize this risk, this study would be able to minimize the total leg impedance. Mechanically, this would be addressed through the elimination or the minimization of all the sources that cause friction, stiction, and backlash.

4. Results

The 3-RSR in this study was designed to ensure that a high fidelity proprioceptive force control would enable legs with the mechanically spring stiffness. Those that ensured dampening were to be emulated by means of ensuring virtual compliance with the electronic, magnetic actuators. We shall first begin with an apt description of both the SLIP Model and the Raibert controller system for the sake of this study. The SLIP Models utilizes a 3-RSR leg topology that is quasi-direct and uses a drive scheme intending to enable a high fidelity to the virtual model control and in ensuring that the otherwise mechanically stiff leg would be able to act like a spring when landing in high fidelity and virtual model control and thus in the process, would be prevent hoping from occurring. On the other hand, the Riabert Hopping Controler is a developed control algorithm, monopod, biped, and quadruped, hoping that all of these are working essentially under the same control scheme. The control scheme contains three panels that aid in the modulation process.

Table 1: Event triggers as elaborated

State	***Trigger Event***	***Action***
1) Loading	Touchdown	zero hip torque
2) Compression	leg shortens	servo body attitude with hip
3) Thrust	leg lengthens	pressurize leg, servo body with hip
4) Unloading	leg near full length	stop thrust, zero hip torque
5) Flight	Ballistic	position leg for landing

These panels include the hopping height, the forward speed and the body based attitude. All of these is based on event triggers as elaborated on the following table.

Virtual Model Control Model used in Compliant Dynamic Motions

Jerry Pratt (2010) created the concept of the virtual model control model as a force-based controlled framework that works through virtual components in the creation of virtual forces that interact between the environment and the robots. Such a control algorithm does require no dynamic model to be developed for the robot, no existent knowledge on the terrain or even environment, and thus it enables the development of a machine with minimum sensory systems and one that only requires low computational power. While virtual model control systems do not attempt to cancel the natural dynamics with the environment, it emulates its mechanical components such as springs, dampers, masses, latches, and the non-linear potential fields. In testing the virtual model control leg, this utilized a simulation model.

Simulation Model

A simulation model was created through MATLAB's SimMechanics physic engine. A model for the 3-RS leg was then created through this. Consequently, the simulated virtual model control involved with the 1- DoF hopping monopod was also created. The simulation model dropped its leg from an initial height of 0.5m, and virtual spring and the damper coefficients involved in the study was also tested in a bid to determine its virtual compliance by means of parameter landing while at the same time ensuring energy absorption and minimization of oscillations in the whole process. Decreasing oscillation was done by the process of dampening coefficient. Further, to increase the landing impact, decreasing the spring stiffness was done until a point when the desired performance in the study was arrived at.

Study Validation

The control architecture in which these models are emulated is shown in the figure below. The control architect allows for leg compliance by absorption of the touchdown impact and providing for leg thrusts through the exertion of large amounts of energy required for the high jumping to be done successfully. In this control system, the comptroller has both a stance and a flight. To ensure high fidelity compliance, a modified impedance controller was modified to emulate the module position rather than the joint position. The aim of this was to generate the desired torque trajectory.

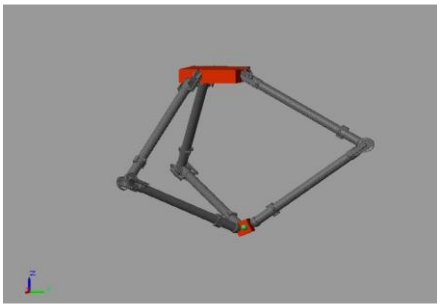

Figure 1: Model of Architecture

Virtual Compliance

Continuous gain scheduling impedance controller was used to determine and arrive at a precise torque at the hip joint, which would enable the creation of a high fidelity virtual model control to be implemented. For this study, numerous tests were conducted through virtual springs and dampers. The virtual compliance was also tested through emulation of the physical torsion and the robots' full leg compliance. The experimental results from this are given in the graphs below. As illustrated, the two rows correspond to the torsional joint springs with an initially estimated stiffness being between 18 and 36 Nm/rad while the bottom of the plot shows a total full leg stiffness of about 250 N/m with a dampening rate of 10 N-s/m. further the full leg compliance was also rectified through the use of virtual linear damper given that the spring can course or exert a force in a negative z-direction. This enables for achievement of shorter settling times and also in achieving a lower perceny overshoot.

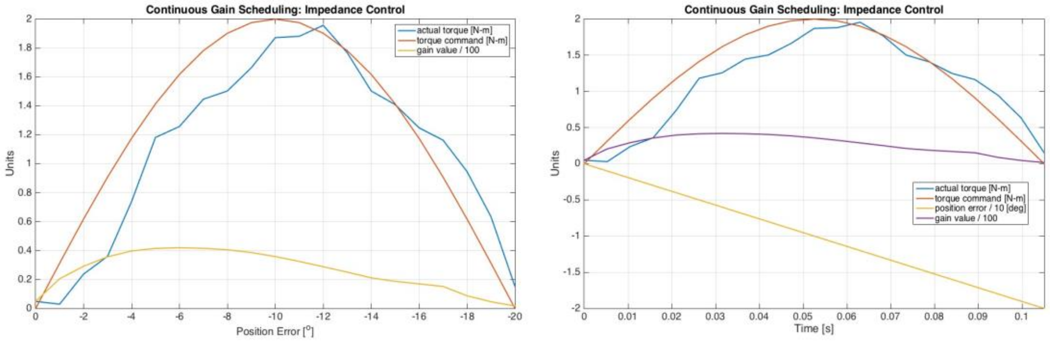

Figure 2: Times in achieving a lower perceny overshoot.

Table 4.2: Agile Performance Comparison in Dynamic Legged Robots.

Robot	**Legs**	**DoF**	**Leg**	**Mass**	**Motor**	**Gear**	**Max Vertical**	**Energy**
	#	*#*	*Length [m]*	*[kg]*	*Mass %*	*Ratio*	*Jump Height [m]*	*Delivered [J]*
GOAT	1	3	0.26	2.5	48	n/a	0.82	20.11
MIT Cheetah	4	3	0.275	33	24	5.8	0.5	161.9
Minitaur	4	2	0.2	5.0	40	n/a	0.48	23.5
XRL	6	1	0.2	8	11	23	0.425	33.3
Delta Hopper	1	3	0.2	2.0	38	n/a	0.35	6.9
StarlETH	4	3	0.2	23	16	100	0.32	72.2
HRP3La-JSK	2	6	0.6	54	9.2	??	0.27	143
ATRIAS	2	3	0.42	60	11	50	0.11	64.7

This data from this table has been tabulated and was presented originally from a study by Kenneally [11].

Vertical Agility

For this paper, various jump experiments were also done and conducted to determine and establish the maximum jumping height in each leg. In the preliminary tests, a minimum jumping height of 82 cm was attained and recorded. The experiments determined that the robot was able to land compliantly in all the jumping heights; thus, this indicated that the joint torque required in the landing was not a limiting factor for this study.

Foot force Sensing

In determining the accuracy of the proprioceptive foot force sensing, each of the legs was commanded to jump from a given height and then instructed to land, while in each case, the torque was calculated by use of directly calculating the current draw. The motor techniques were then further measures through the use of inverse leg jacobian transpose. The hopping tests were also done and included in the preliminary study experiments. Throughout, the leg was then commanded to have a virtual whole leg emulation that was rectified through spring stiffness and dampening.

5. Conclusion and Policy Implications

GOAT leg as a means of artificial intelligence is still a new phenomenon. There still exists a number of preliminary tests that need to be done in accessing and in the characterization of the leg's current performance and the implications that this has to the future. Thus in terms of policy implications, there exists a need for policymakers to ensure that custom electronics and the motor controllers have a developmental framework and that the development should be geared towards on-board robot mounting. Once this has been established, it would be easier for robots to achieve. With the energy tests measuring the costs of transports and efficiency of all the entire leg system used in the conversion of the electrical energy to be gravitation potential energy when there is a jump, it would be interesting and noteworthy to compare between direct-drive and also the quasi-direct drive during actuation. Future recommendations: While it is expected that the quasi-direct drive would use lesser energy due to the fact that the motors would not be in operation due to its high ineffiency, it would still be important to note the difference and how it relates. Another interesting paradigm for future works would be the augmentation of the GOAT leg with the physical spring connection at the hip of the foot. Such would allow for the recycling of energy by the each stride and also in the gait cycle through storage of kinetic energy.

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