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A Review of Legged Robots Based on Passive Dynamics

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Abstract. Legged robots have a huge advantage of walking on unstructured terrain, but the typical completely actuated robot exhibits high energy consumption, requires complex control, and lacks sufficient operational stability. Passive dynamics are used to achieve autonomous motion by virtue of intrinsic properties, such as inertia and gravity, which solve these problems. This paper comprehensively examines the related work on legged robot based passive dynamic system, the research about its evolution including from simple single-joint configurations, multi-joint couplings and further to adapting to the environment of various terrains, energy and environment efficiency improvement in terms of performance Passive designs can save energy, according to the study, but there are big issues like not coordinating closely enough between passive and active things, not being able to deal very well with really harsh places, being too expensive, and no set way to check how well they work, while smart planning and mixing different ideas is where it's going. In future research, it is important to pay attention to intelligent passive design, interdisciplinary cooperation, low-cost manufacture, and standardized performance evaluation so as to promote the extensive application of such methods in real-life situations.

Keywords: Passive Dynamics, Legged Robots, Terrain Adaptability, Hybrid Actuation

1. Introduction

Legged robots have recently drawn increasing attention due to their superior ability to traverse terrains that wheeled and tracked vehicles cannot access. By coordinating multiple joints, these systems can walk steadily and smoothly over rough, soft, or uneven surfaces. This capability enables legged robots to operate in a wide range of demanding scenarios, including emergency rescue, resource exploration, industrial inspection, and planetary missions. They can enter collapsed structures, hazardous or burning environments, and chemically contaminated areas to conduct search, observation, and material delivery, helping to protect human workers. In mining areas or offshore inspection sites, legged robots undertake equipment inspection, material transport, and geological sampling on steep, bumpy slopes or irregular platforms. In planetary exploration, legged robots equipped with passive-compliant joints have demonstrated stable locomotion on simulated Martian terrain, further verifying the feasibility of passive dynamics for extraterrestrial exploration [1].

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Despite these advantages, traditional fully actuated legged robots rely on electric or hydraulic actuators to control each joint independently, which demands complex algorithms for torque regulation and posture coordination. Such systems often exhibit high energy consumption, limited endurance, and reduced control bandwidth during dynamic locomotion. When navigating unstructured terrain, they require continuous state estimation and high-frequency control updates to adjust for varying contact conditions and body dynamics, increasing both computational effort and actuator load.

These limitations highlight the need for incorporating passive dynamics to enhance locomotion efficiency, stability, and robustness. Passive elements—such as compliant joints, springs, and gravity-assisted mechanisms—allow robots to store and release mechanical energy, react rapidly to disturbances, and reduce reliance on active control. By leveraging these intrinsic mechanical properties, robots can simplify control strategies while improving energy efficiency and adaptability.

This review focuses on legged robotic systems that integrate passive dynamics in various forms, including purely passive structures, passive–active hybrid mechanisms, and robots that employ elastic components for damping and energy exchange. It aims to examine the progression of passive configurations, analyze trends in efficiency and terrain adaptability, and discuss emerging opportunities for passive-dynamics-assisted legged robots.

2. Passive configurations of legged robots

2.1. Single-joint simplified passive configuration

Single joint was the first legged robot's PD model that sought out energy savings and simple locomotion stability. A traditional single joint passive design, using gravitational potential energy and elastic store, will save about 40% on energy than a robot fully actuated [2]. Then Cornell used the passive hip joint and spring-actuated leg with leg spring energy storage. When the robot hit the ground, the springs inside were storing up energy. When the robot swung forward, the energy from the springs would come out, so it only took the design process a 1/10-1/50 of how long it would normally take to do [3].

Hexapod robots with a passive ankle joint having a spring-spring-damper system, their gaits are smoother and more mechanically sound as they move [4]. Harbin Institute of Technology made the HITCR series, a passive contact switch, which used damping to prevent the system from relying too much on active control for it to keep moving [5]. First, some single-joint passive prototypes were tested in a lab, and they generated a huge amount of savings, but they also couldn't adapt to bad conditions [6].

The single joint passive configuration takes advantage of the inherent physical traits in order to make use of energy that's not spent all the time adjusting joint torque via tricky active control algorithms, and in lowering both computing and energy demands. But it is not free-moving and can only be used on level or slightly inclined grounds. There is no ability to actively coordinate between multiple joints; it cannot autonomously absorb shocks or remain balanced on hard terrains. The need to compensate with more direct control limits how passive it can stay, and makes it difficult to adapt to less-than-perfect conditions.

2.2. Multi-joint coupled passive

In an attempt to solve the problem of a single passive joint limit, those researchers sought out many possible mechanical joint coupling coordination solutions. A combination of mechanical hip and

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knee joints can climb up a slope with an angle of 15degrees steadily and continuously, without active control [7]. Parallel linkages, energy-storing springs in the hip–knee–ankle system, make walking on grass and pebbles much better [8].

Hybrid Actuation: using motors to actuate hips and pneumatic-actuated legs to actuate knees to achieve a trade-off between passive(Actuation energy conservation) and active(control energy loss), the multi-joint coupling can better improve the ability to adapt to slopes and the performance of load distribution, but the fixed coupling parameters can make the performance of complex terrains poor, and the gait changes do not exist, the speed of running and jumping is too fast and it is hard to be agile [9,10].

Multi-joint coupled design, using the joint coupled design to improve the power that can be transmitted through the joints, and also using the coupled structure design to improve the stability and adaptability of the slope walk. And combined with an energy-storing spring, it would be much more improved to recover and use energy. But it means robots can use their fixed coupling parameter, but they can't change their gaits according to different surfaces, and cannot be flexible and agile. It gets even worse because the coupled system will get so many design troubles, so many mechanical troubles, and so many motion instabilities because everything is so mixed up on a very strong ground.

2.3. Terrain-adaptive passive configuration

The research that is going on right now is adapting to the land. It changes along with the change in the environment. V - Joints (Hybrid, Actuation, Biomechanics): Let it change its joint stiffer/ comply/damped based on terrain/gaits. Stanford did an electromagnetically controlled variable-stiffness knee joint that could rapidly change stiffness on level ground, ramp, and uneven ground in milliseconds [11]. A variable stiffness joint, a combination of a rigid parallel mechanism with a non-linear spring, can achieve the accurate movement of a bionic legged robot in 2 degrees of freedom [12]. Variable stiffness joints actuated by tendon-driven shape memory alloy can realize low-power operation even in low temperatures, and improve terrain adaptation [13].

Hybrid actuation uses passive joints and a reversible active joint to be able to have the exact postures. Use a passive support structure with active corrections for legged robots' positioning with an accuracy of up to 1mm in surgery inspections [14]; ETH Zurich made up the part at the bottom where things that look like animals are squishy so they would be able to move better on bumpy ground and also so their feet wouldn't get tired easily [15]. Biologically inspired knees, which can be in state-switchable Compliant -Rigid States, can give us a complete gait cycle with the least actuation.

With intelligent control would be even better. UC Berkeley: The passive impulse arms and model-predictive handle for movement on bumpy ground [16]; MIT's dribble bot: passive elastic joint and reinforcement learning for movement and handling the balls on sand and snowy ground [17]. And then using a bunch of robots together with these elastic joints, which are these passive compliant types of joints, can do 3D path moves all around this environment without having to explicitly tell it what the environment even is! Improvement can be made in these progressions to be used in multi-terrain, multi-gait, but the mechanical complexity and manufacturing cost are a problem.

Terrain adaptive configurations obtain adaptive tuning of joint stiffness, variable-stiffness joints, joint bionic design, intelligent control combination through dynamic tuning, highly improved multiple, terrain-applicable use, and extreme condition environment. Hybrid actuation combined with smart algorithms brings together passive energy savings and active, accurate control of one's

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posture. This means wider application. However, it's also a lot of mechanical complexity. Also, making parts, etc., Variable stiffness components' durability is lacking, smart materials don't have enough strength, interdisciplinary field integrations make it hard to be integrated with the system, which limits large-scale application and practical usage.

2.4. Comparative analysis and trends

According to some studies, there is also research on energy efficiency and terrain fit, as well as related technology. To systematically compare the performance differences of the three passive configurations (single-joint simplified, multi-joint coupled, and terrain-adaptive) discussed above, their key indicators are summarized in Table 1. Specifically, the single-joint will reduce energy consumption by about 40% less than multi-coupling, and the single-joint is better at flat terrain; the multi-coupling form is steady at mid-terrain. Terrain-adaptive designs pushed into even more extreme conditions than cold weather, steep slopes, soft ground- and there haven't been any that made it all the way to the system level [14], but prototypes have been built. Research on this topic indicates that there are actually more research directions: The energy one, the biomimetic one, and the coupling with the smart control. This results in a relatively challenging research path for legged robots based on passive dynamics. As shown in Table I, the single-joint simplified configuration excels in low mechanical complexity and cost with high energy efficiency, but its terrain adaptability is limited to flat or slightly inclined grounds. The multi-joint coupled configuration achieves a balance between energy efficiency and terrain adaptability, but its fixed parameters restrict flexibility. In contrast, the terrain-adaptive configuration demonstrates the highest terrain adaptability for extreme environments, yet it faces challenges of high mechanical complexity and manufacturing cost. Single-joint to a configuration suited to the ground is carried out to make the mechanical part more adaptive and more suited to the environment, so that it can be used to lower the energy cost and make it more adaptive. Single joint config serves as the foundation for passive energy saving, multi joint coupling frees itself from constraints of terrain complex, adaptative is for extreme adaptation to the environment, however universal thing remains intact, coordination between passive parts and active parts is not absolutely perfect, the more the configuration progresses, the more complicated the mechanical part would get and rising cost goes along with that, lack of unified assessment standard makes it hard to measure performances from different design schemes on equal footing for improvement. Future should be adaptive and flexible, and passive energy saving, and also controllable in terms of cost and technological feasibility should be possible.

Table 1. Comparison of different passive configurations of legged robots

Evaluation Indicator	Configuration Type	Performance
Energy Efficiency	Single-joint Simplified Configuration	High (Energy-saving via passive properties)
	Multi-joint Coupled Configuration	Higher (Optimized by energy storage + coupling)
	Terrain-Adaptive Configuration	Moderate-High (Balanced by hybrid actuation)

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Table 1. (continued)

Terrain Adaptability	Single-joint Simplified Configuration	Low (Only flat/slight slopes)
	Multi-joint Coupled Configuration	Moderate (General complex terrain; limited by fixed parameters)
	Terrain-Adaptive Configuration	High (Adapts to extreme environments)
Mechanical Complexity	Single-joint Simplified Configuration	Low
	Multi-joint Coupled Configuration	Moderate (Complex linkage & coupling structure)
	Terrain-Adaptive Configuration	High (Variable-stiffness components + interdisciplinary integration)
Technical Maturity	Single-joint Simplified Configuration	High (Mature lab verification; easy manufacturing)
	Multi-joint Coupled Configuration	Moderate (Partial practical validation; restricted by coupling parameters)
	Terrain-Adaptive Configuration	Low-Moderate (Prototype-level; pending large-scale application)
Cost Level	Single-joint Simplified Configuration	Low (Low manufacturing requirements)
	Multi-joint Coupled Configuration	Moderate (Increased by coupled components)
	Terrain-Adaptive Configuration	High (High cost of smart materials + precision manufacturing)

3. Current problem and next move

3.1. Key challenges

The active problems arising from the creation of passive-dynamics-based legged robots are problems not just about how things look but also about science and systems hidden inside. The bottleneck is directly correlated to the 3 passive configurations from the initial studies: The single joint has no terrain adaptability, the multi-joint coupled design has no parameter changes, and the terrain adaptability requires too much complexity and cost. Firstly, it is a fact that whether passive and active parts are connected in a coordinated relationship or not is a kind of energy and responsibility distribution issue, not a control issue. Passive components are physical features that generate their own energy, and then the active part needs to do the correct treatment and correct the posture. There is no dynamic match between them; either one participates too much and negates the benefits of passive, or the one underparticipates, leading to unstable movement of the object. Mismatches limit overall system performance improvement for the hybrid. The second reason is that there is no unified evaluation criterion due to the lack of a target evaluation system for passive dynamics. Traditional legged robot evaluation indicators, such as travel speed, carrying load, carrying capacity, etc., cannot reflect some important factors, such as recovery efficiency, mechanical adaptation, and fast dynamic response speed related to passive dynamics. Lack of systematic evaluation metrics makes horizontal comparison and iterative optimization of different active configurations impossible currently [16]. High manufacturing costs and short component lifespans result from the use of high-precision manufactured passive elements and smart elements.

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Due to the complexity in various working conditions under the influence of passive components, they suffer more than industrial servos, and the high cost of materials like shape-memory alloys and variable-stiffness springs cannot be widely applied. In mines, spring sparking and materials fail because of very large temperatures, as in planetary explorations, passive design is insufficient without the addition of scenario-related safety solutions.

3.2. Future directions

Future work has to look ahead and be realistic; it should also take into account the main scientific problems and systematic flaws pointed out above.

First of all, on the intelligent passive one, it works on stuff like trying to work out reinforcement learning-based online stiffness adjustments, and putting together passive deformation buildings or whatever with all sorts of new smart stuff like a kind of liquid crystal elastomer type of deal. A reinforcement learning strategy can achieve the real-time adaptive adjustment of joint stiffness and damping parameters based on environmental feedback, so as to improve the dynamic coordination between passive components and active components. Liquid crystal elastomers are new smart materials that can generate reverse deformation when influenced by the outer environment, such as temperature and light, so that they react passively without energy support.

The second is to strengthen interdisciplinary integration, form an interdisciplinary theory about the interaction relationship between passive structure, active control, and the environment. Mechanical engineering, control theory, materials science, and bionics—mechanical engineering provides the structure, and control theory enables better dynamic coordination. Materials science improves component performance, and bionics provides insights into efficient passive motion. Ultimately, manufacturing processes need to be optimized and scaled up, such as cost-effective manufacturing of variable-stiffness 3D-printed lattice passive joints and modular passive component technology. Such manufacturing technologies enable convenient and low-cost production of high-precision passive components, along with solutions for their storage, maintenance, and replacement.

Thirdly, establish a unified criterion for measuring the performance of PD-LRP, which mainly includes passive energy recovery rate, adaptability to the mechanical environment, and delay in dynamic response.

Fourthly, scene-specific safety designs for robots need to be developed, such as explosion-proof passive joints for robots used in mines, high-temperature resistance passive structures for robots in planetary space exploration, and make it possible to be applied in extremely dangerous environments.

4. Applications and case studies

Passive dynamics on legged robots are used in so many real-life situations. Disaster wastes were carried by a 4-legged robot whose joints are a hybrid of passive-active; it carried medicine and measured the structure. The robot with such joints, due to its energy efficiency, can operate in dangerous places for a long time without the need to constantly replace batteries. And it can also work on rough and unpredictable grounds with passive elements [15].

Industrial inspections use legged platforms with active damping, making them easier to control and use much less energy on simple repeated tasks of watching and guarding offshore oil rigs and looking under vehicles for the factory floor inspection. With passive elements that are compliant, the robot climbs the very steep slopes as well and goes up the rock to take the sensors up and move over the soft ground [18]. The Astronomy prototype Planar exploration tendon-driven variable stiffness

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joint developed by the research team based on MIT's idea can be used in low-gravity extra-terrestrial environments for adaptation purposes, which may provide support to future Mars and Lunar planning astronomy.

Passive dynamics do have some advantages for these practical applications. Passive dynamics can reduce dependency on computation and energy consumption, as well as improve mechanical dependability, but they also point out the need for higher-level hybrid control, standards for testing methods, and cutting costs for quick adoption [15].

5. Conclusion

Passive dynamics addresses issues such as high energy demand, slow response, and poor stability, particularly for legged robot limbs. Research went from simply using single joints, moving on to many linked joints, and then moving on to more advanced hybrid versions that can deal with a large, even extreme variety of different environments. Nowadays, robots have a lot more intelligence and a lot more control over themselves than in the past. They can run around everywhere now.

But it has some disadvantages, which are also reflected in Table I: The multi-joint coupled configuration lacks parameter adjustability, and the terrain-adaptive configuration suffers from high mechanical complexity and cost. Additionally, issues such as poor hybrid coordination, short component life, and the lack of unified evaluation standards further restrict practical application. In order to solve these problems, interdisciplinary collaboration, advanced manufacturing technologies, and improved system performance are required.

And then for future research & development, perhaps more towards smart passive design. In that way, and together with other disciplines, affordable to make, and standardized performance evaluation, beyond what has been previously mentioned - passive-dynamics legged robot as a standardized tool for situations such as in emergency recovery, factory inspection, planetary exploration, etc., which involve humans in danger.

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