Analysis of Mechanical Structure in Mobile Robots

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Abstract. Robotics is a rapidly growing field that combines knowledge and skills from various areas, such as computer science, mechanical engineering, electrical engineering, and mathematics. These skills are used to create robots in different sectors, such as healthcare, manufacturing, and agriculture. This article underscores the interdisciplinary nature of robotics and its far-reaching impact, emphasizing the significance of structural design in addition to software algorithms by exploring the fundamental principles of designing mobile robots and how their mechanical structures could affect movement capabilities. Rather than focusing solely on specific structures, such as bio-inspired legged robots, the article aims to address this gap by examining several common principles of mobile robot motion and make comparisons between them horizontally to analyze the pros and cons of legged, wheeled, and inflatable biomimetic robots, elaborating on their unique characteristics and uses. The potential for hybridization and fusion of mechanical structures, exemplified by wheel-legged robots, has also been highlighted and discussed to propose future research directions in robot design and applications. In summary, this article will provide a comprehensive overview of the principles of mechanical structure in mobile robots, aiming to promote a deeper understanding of robot motion and inspire further innovation in the field.

Keywords: Robotics, mechanical Structure, mobile robots, movement principles.

1. Introduction

Robotics, an interdisciplinary field integrating mechanical engineering, electronics, computer science, and artificial intelligence, has emerged as an essential part of technological advancement in the 21st century [1, 2]. Its pervasive influence extends across myriad sectors, from manufacturing and healthcare to space exploration and environmental monitoring. Robotics has indeed carved out a monumental significance in modern technology through the creation of intelligent machines capable of taking on sophisticated tasks, enhancing productivity, and solving problems once thought impossible.

While part of the essence of robotic innovation lies in the software algorithms that govern decision-making and sensory processing [3], the fundamental structural designs that dictate a robot's movement and interaction also play an essential role. This interplay between form and function is where the magic of robotics truly resides. As robotics sophistication continues to evolve at a marvelous speed, the quest for optimal movement principles and architectural configurations becomes ever more pressing.

One crucial problem encountered by the literature review is that introductions to the principles of mechanical structures are rarely done in moderate depth. Taking one paper, for example, inspired by the human leg's musculoskeletal system, the project simplifies it into a Snelson X-shaped tensegrity structure, leveraging the sliding motion and locking function of the human knee joint and using traditional mechanical structures to enhance the Snelson X mechanism, aiming to produce a novel bio-inspired design for a legged robot [4]. Although this approach yields valuable insights into the mechanics of the human leg and how they can be replicated in robotics, it represents just one piece of the broader landscape of legged robots' constructs. While this project offers a detailed exploration of a bio-inspired design for a legged robot, it exemplifies a common trend in robotics research: focusing on a single specific structure.

Besides, many studies focus on particular and individual projects, often providing only a cursory overview of the underlying principles [1, 4, 5]. To address this gap, this paper aims to classify and review several common principles of mobile robot motion. This will involve conducting a horizontal comparison and analyzing the advantages and disadvantages of each type.

In summary, the main goal of this paper is to explore suitable application scenarios for each type of mobile robot motion principle. By briefly analyzing the principles, the paper aims to facilitate a deeper understanding of mobile robot motion and its underlying principles, provide references for subsequent selection, and ensure that the chosen principle is appropriate for the given task. The following will describe the three locomotion systems' features: Legged, Wheeled, and Inflatable. These features will then be taken for some comparison to highlight their application fields and, eventually, discuss the possibilities of hybrids and give perspectives on future development.

2. Legged Robots

Legged robots move to designated locations through single or multiple legs. In their evolution, advancements have progressed from singular to dual and then multiple-legged designs, with leg structures evolving from rigid poles to increasingly intricate segmented and flexible structures.

Although single-legged robots have limitations in practical applications, their fundamental SLIP (Spring-Loaded Inverted Pendulum) dynamics model can provide valuable insights for studying the dynamic stability of legged robots, thus maintaining some research value. McGill University's ARL lab developed a second-generation single-leg robot that stood 0.7m tall and weighed 18kg. It featured a cylindrical-shaped, flexible leg. The system has 7 DOFs, but not all are simultaneously active—5 when in contact with the ground and six during jumps. It can run at 1.2m/s with an adaptive feedback controller that maintains a jump height within 1cm, consuming just 48W, significantly improving energy efficiency compared to its 125W predecessor [5].

One identical example of the bipedal robot field was the "Spring Turkey," created by MIT's leg lab in 1994. Weighing about 10kg, it featured one powered hip and knee per leg, with an unactuated boom preventing roll, pitch, and sideways motion, restricting movement to the vertical plane. Motors were housed in the upper body, transmitting power via cables to joints. Each joint used series elastic actuation (SEA) for precise torque application and shock absorption, implemented with springs at the hip and knee, offering maximum torques of about 12Nm and 18Nm, respectively. Potentiometers measured joint angles and body tilt. The aim was to maintain a constant hip-to-toe height of 0.6m. Notably, Spring Turkey utilized virtual model control, enabling it to walk continuously at about 0.5m/s, maintaining a steady height with a max deviation of 3cm, and keeping body inclination within ±5.2° [5].

With the booming of all-purposed quadruped robots finding a balance between the appropriate number of legs and stability, more and more attention has been paid to improving the former rigid and stiff leg structure. The new way of categorizing them has fallen on the kinematic chains those legs tend to carry and utilize—in other words, open-chain and close-chain legs.

2.1. Open-Chain Legs

Open-chain legs involve multi-DOF linkages and pose more significant challenges in control complexity. They often have fewer active joints to enhance control and maintain stability than other designs. One of the most popular constructs implemented the bio-inspired mechanisms resembling quadrupedal animals' joints, which feature unique knee and hock joints that can perform dorsiflexion and plantarflexion, using the entire structure itself to store propulsion and elastic energy, enabling the legged robot to shift the center of gravity and control its balance easily. Other advantages include maintaining or even enhancing the control, motion, and shock absorption capabilities. Many products have already moved out of the laboratories and have det out into the market, continuously maturing. One of the most famous examples of legged robots is Boston Dynamics's BigDog, which specializes in carrying capacities and complex urban terrain maneuvering [6]. On the other hand, just like the bipedal robot shown in Figure 1 came from Agility Robotics, some mainly focused on keeping the structure compact and straightforward to achieve lightweight.

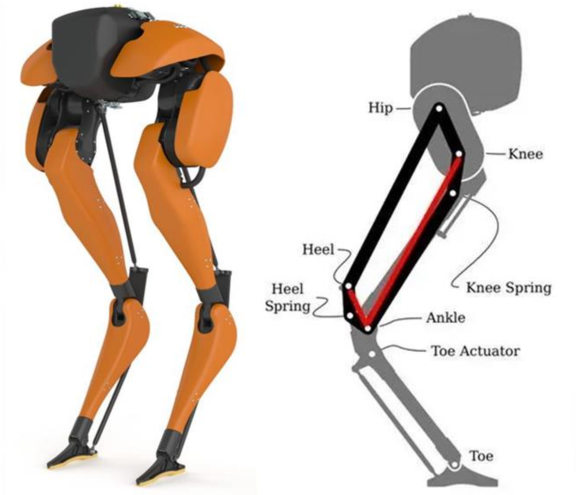

Fig. 1 Leg Structure of Agility Robotics' humanoid bipedal robot Cassie [7]

2.2. Close-Chain Legs

Open-chain platforms have many advantages, but they also have numerous issues. For instance, separate joint motors add weight, increase energy consumption, and put stress on upper-level drivers. They have low rigidity and have difficulty dealing with heavy loads. Generating smooth movements requires complex coordination between sensors and actuators. Conversely, closed-chain legs feature a single DOF linkage that cyclically generates gaits via crank rotations. This mechanism substitutes multiple motor synchronization with mechanical phase alignment, cutting down mass and control complexity. It also boasts greater load-bearing capacity and overall stiffness [8]. Some actual usage has been seen in art pieces. The Strandbeest, crafted by Dutch artist Theo Jansen, as shown in Figure 2, is a celebrated example of such a structure. Built from interconnected planar linkages arranged to create fixed phase disparities among neighboring cranks, it displays remarkable stability properties [7].

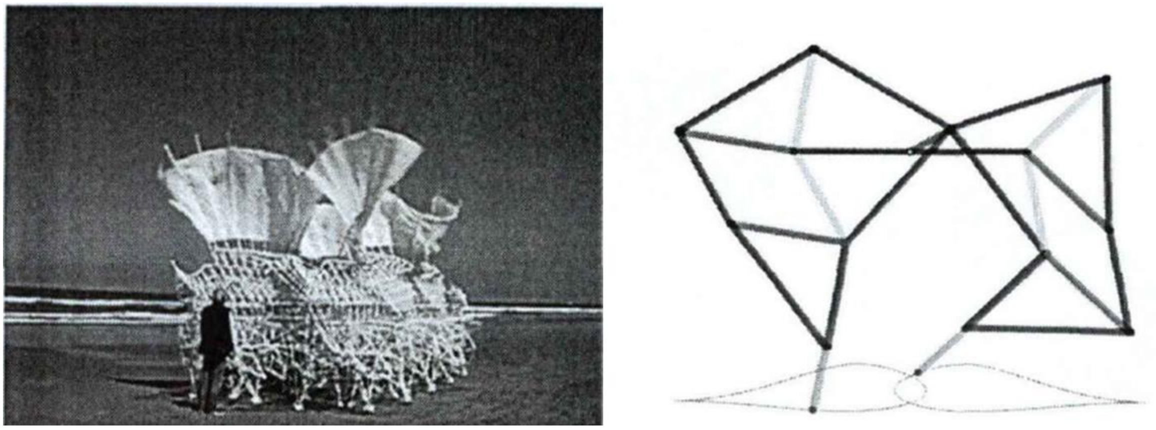

Fig 2. Theo Jansen’s Strandbeests and a concept of its leg structure [7]

2.3. Other Constructs

Currently, the mainstream trend for the legged robots is toward miniaturization, lightweight, and intelligence, which has started and is pretty much led by Boston Dynamics. However, a niche remains for other constructs, such as the six-legged ones. While maintaining the benefits of point-contact robots, such as inflicting significantly less environmental damage than other types of robots, such as wheeled and tracked ones, requires notably less stringent selection criteria for footholds upon contacting the ground [9]. One identical example is the ASV, shown in Figure 3, a hexapod robot with rigid legs that can achieve stable walking, climbing, and obstacle avoidance on complex terrain, climb slopes with angles up to 60 degrees, cross fences up to 1.35 meters high, traverse ditches up to

1.8 meters long, and reach a maximum speed of 2.3 meters per second [9]. These additional legs will grant this type of robot higher carrying capacity because the load is distributed across multiple limbs, which reduces stress on individual legs and enhances the overall load-bearing capability of the robot. Meanwhile, its stability and mobility as complex terrain traversal would also increase fault tolerance by bringing redundancies.

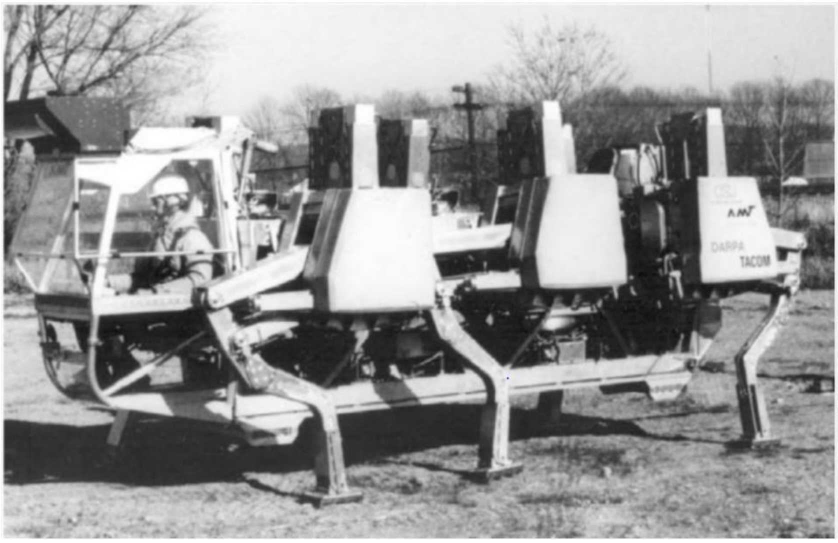

Fig 3. Ohio State University's Adaptive Suspension Vehicle (ASV) [9]

3. Wheeled Robots

In contrast to legged robots, wheel robots are less flexible and less durable when faced with leveled platforms and complex terrains. In compensation, this structure shares a straightforward mobile control algorithm and high execution efficiency. Wheels, as its main moving element, also ensure high speed and carrying capacity. The long development tradition also made this robot a well-matured and widely used product [7, 10].

Like the legged robots, wheel robots also have a tangible number of wheels, often ranging from one to six. In most cases, the wheels can then be further divided into two functions: Driven wheels, which are fixed and only have one axis of rotation, thus providing an easier connection to torque-providing equipment, making them the usual source of driving force, often come in pairs. On the other hand, steerable wheels usually go more freely on the rotating axis, sometimes even omnidirectional, but not necessarily powered, making them more passive. Its quantity rarely goes over 2. Combining those two types of wheels allows us to get wheeled robots' most common moving principles.

3.1. Differential Dirive

In a differential drive configuration, a robot typically has a set of independently driven wheels placed side by side, both fixed in their orientation. The speed and direction of these wheels can be controlled separately to produce a range of linear and rotational movements. By varying the speed ratio between the wheels, the robot can turn in place, move forward or backward, and execute curved paths. This structure is simple, cost-effective, and widely used in indoor robots and mobile platforms due to its simplicity and relatively small turning radius. It is also notable that this form of steering often requires more advanced speed control algorithms to make accurate turnings to a specific angle due to its differential nature.

3.2. Car-like Drive

If we replace the caster wheel, which moves freely on the differential drive model, and replace it with one or one set of steerable wheels, we get the tricycle or car-like drive. Similar to a tricycle or car, this arrangement includes two or more fixed wheels responsible for driving the robot forward and backward, while a third wheel (usually at the front or rear) functions as a steerable wheel. This configuration offers better stability and can handle rougher terrain than a differential drive robot. The steerable wheel controls the vehicle's direction, allowing it to turn while maintaining balance. The increased number of wheels also allows the load to be dispersed better, allowing for a higher carrying capacity. This design is commonly found in outdoor robots and larger-scale autonomous vehicles due to its enhanced stability and ability to mimic traditional automotive steering.

3.3. Omnidirectional Drive

In specialized scenarios where robots must be agile and maximize their turning and orienting abilities, omnidirectional robots precisely meet such requirements. They utilize specialized wheel designs or arrangements that allow them to move in any direction without changing the robot's orientation. A typical implementation is using three caster wheels placed at the vertices of an equilateral triangle. Each caster wheel can swivel freely, enabling the robot to move laterally or diagonally. Another popular variant uses plain steerable wheels. By independently controlling the speed and direction of these wheels, the robot can achieve true omnidirectionality, making it highly maneuverable in tight spaces and ideal for applications requiring quick and precise movements in all directions.

4. Inflatable Biomimetic Robot

In the context of advancing bionics and flexible materials, a series of endeavors have been undertaken in robotics to incorporate nature’s biological structures into the robots' locomotion mechanisms, often resulting in a more flexible and compact build.

Soft-bodied crawling robots represent a distinctive category within soft robotics, exhibiting unique advantages. One noteworthy prototype is the GoQBot soft robot created by researchers at Tufts University in the United States. It emulates a caterpillar's ability to roll and catapult itself [11].

Additionally, multi-chambered soft robots are pneumatically driven, where changes in internal air pressure within the chambers cause varying degrees of deformation in the robot's body, as shown in Figure 4. These robots incorporate differently textured friction pads at the front and back, periodically adjusting the friction between the soft robot and the ground surface. Researchers have investigated the non-linear relationship between the applied driving pressure and the forward displacement of the soft robot [12].

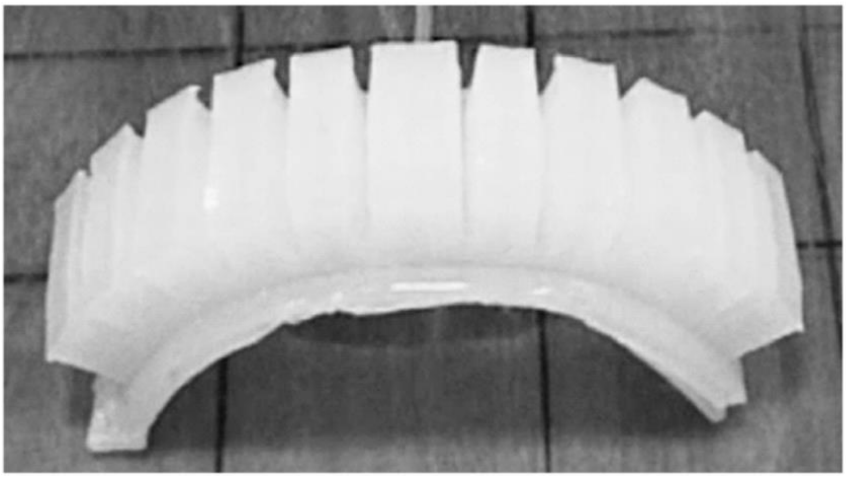

Fig 4. A model of the multi-chamber inflatable robot(inflated) [12]

Such novelty designs have allowed these robots to cover narrow and restrained terrains with unimaginable efficiency, such as piping systems and wreckage or ruins, for cleaning and rescue missions. However, such scenarios are still impossible for legged or wheeled robots to carry out without specialized modifications or sacrificing functionality.

5. Discussion

The previous analysis and introduction present the essential characteristics of three mechanical motor system types and some advantages or disadvantages. In this section, this paper will elaborate on the finer details of the several mechanical structure principles mentioned earlier and some variants and exceptions.

Legged robots achieve mobility by using multiple legs, which keep a relatively small contact area with the ground. This gives them excellent off-road capabilities in complex terrain, minimizes ground damage, and often results in lower weight-carrying capacity than wheeled robots. The more complex leg structure has the advantage of reducing and absorbing vibrations and impacts, improving energy efficiency. However, the increased complexity of control algorithms and mechanisms also somewhat reduces its stability and movement speed. Legged robots find applications in various scenarios, such as search and rescue missions in rugged terrain, exploration of disaster zones, and surveillance in urban environments where navigating obstacles and uneven surfaces is essential.

As mentioned in Table 1, wheeled robots have distinct advantages in terms of carrying capacity and speed, but their disadvantages are equally evident. Most wheeled robots can only operate on relatively smooth and flat surfaces, significantly reducing their performance when facing uneven terrain. Due to wheel spacing, both differential and car-like drive will produce a certain turning radius, making them less agile and requiring a larger workspace. Wheeled robots are commonly utilized in logistics and warehouse automation, indoor navigation tasks, and manufacturing processes where predictable and efficient movement on flat surfaces is required.

Table 1. Moving principles comparison

Type	Advantages	limitations	Preferred Environment
Legged	Rough terrain traversal capabilities. Agile and flexible.	Sophisticated structure and control algorithm. Parts wear out fast.	Complex terrains
Wheeled	High top speed with excellent cargo capacity. Simple structure	Performance highly relayed on the ground condition. Need extra space for turning.	Roads or floors
Inflatable	Requires little space to operate.	Low carrying ability and speed.	Small tunnels, pipelines, and slits

Another noteworthy point is that in almost every category, some unique variants either significantly improve overall appearance and performance without changing the fundamental driving principle or significantly improve the structure of the core functioning parts, granting them brand-new abilities and features.

One notable variant focuses on the agility of the robots. Mecanum wheels are a unique type of omnidirectional wheel designed to provide exceptional maneuverability and versatility to mobile robots. Unlike traditional wheels that roll along a single axis, Mecanum wheels feature a series of rollers mounted at a 45-degree angle to the wheel's rotation axis. This configuration allows Mecanum wheels to move in any direction without changing the orientation of the robot's chassis, making them ideal for applications requiring precise and agile movement in tight spaces. Due to its compact design and the above features, a wide field of applications lies in the warehouses. 1959, AGV was first used in warehouse automation and then rapidly developed. In 2015, Amazon in the United States introduced a robot named "Kiva" with an intelligent navigation function, which can lift and move shelves as a whole and is widely used in logistics warehousing goods handling. Fetch Robotics in the United States also launched two sets of robots, Fetch and Freight. Fetch is responsible for picking up goods, while Freight is responsible for transporting goods. In 2019, Fanuc introduced the mobile robot RocoMoV at the Tokyo Measurement Technology Exhibition, which can operate in all directions with a maximum carrying weight of 64kg. The robot is small in size and has spectacular performance, especially in narrow passages [13].

Indeed, while this study has previously discussed the classification of principles, it is worth emphasizing that they do not necessarily exist or function in strict isolation. There is considerable room for overlap and integration among them, an excellent example being wheel-legged robots. These robots combine the principles of wheeled motion, which is efficient and rapid on smooth surfaces, with legged locomotion, which allows for traversal over uneven terrain and adaptation to various environmental conditions. For example, the leg structure must balance motion performance, low weight, and agility in designing wheeled-legged mobile robots for terrain adaptability, speed, and endurance. Lightweight design in structure, size, and materials allows efficient switching between wheeled and legged modes based on terrain. A new quadruped leg structure design places wheels at the elbows for full-elbow walking. This design enables switching between wheeled and legged modes, distributing power between calf and thigh motors. The calf motor drives the wheels during wheeled movement while the thigh motor is inactive, enhancing endurance [1].

6. Conclusion

Mobile robots are crucial in various applications, from industrial automation to healthcare. The design of these robots' mechanical motor structures, which determine their movement capabilities, is a topic of significant interest and research within robotics. The fundamental principles of mechanical structure are paramount for attaining exceptional adaptability, stability, and efficiency in mobile robots, as well as explicitly elucidating their defining characteristics, notable achievements, and promising developments, hoping to provide readers with a panoramic view of the pros and cons of some everyday mobile robots from the perspective of their principles. Although this paper focuses on individual mechanical structures in mobile robots, there is potential for future hybridization and fusion of these structures. The wheel-legged robots have fully demonstrated how hybrids could gain benefits and features from both the original designs, thus surpassing them. With the advancement of robotics technology, researchers are exploring new ways to integrate and combine mechanical structures to create more efficient and effective robots. Another possible field of progression is to tap into the mechanical structure itself without changing the basic principle, just like the Mecanum wheels, which significantly improved agility within the framework of wheeled robots. Such innovations could lead to breakthroughs in mobile robot design and applications in various fields.

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