Overview of the Motion System of Ground Mobile Robots in Unstructured Environment

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Abstract: In the next 20 years, the global mobile robot market is expected to grow significantly, surpassing the industrial robot market in terms of sales and sales. Its important application areas are homeland security, surveillance, mine clearance, reconnaissance and agriculture in dangerous situations. The design of kinematic systems for mobile robots in a complex environment is extremely complicated, especially when they need to move on uneven or soft terrain, or climb obstacles. This article analyzes the current research status of ground mobile robot motion mechanisms, and focuses on the solution in an unstructured environment is analyzed to help the designer choose the optimal solution according to the specific operating requirements. From the highest speed, the ability to climb obstacles, the ability to climb stairs / stairs, the ability to climb, and on soft terrain the three types of mobile systems: wheeled w-type, tracked t-type, and leg-type three types of mobile systems are discussed in terms of walking ability, walking ability on uneven terrain, energy efficiency, mechanical complexity, control complexity, and technical readiness. Four main types of hybrid motion systems are composed of these main motion systems. Finally, this article outlines the current status and future of mobile robotics to develop trends.

1. Introduction

The predictions of most authoritative robot research institutions clearly show that in the next 20 years, the world market for service robots is expected to grow significantly, which will surpass the industrial robot market in terms of units and sales. Among them, ground mobile robots are the most extensive service robot Category. 75% of total unit sales of professional service robots in 2010 were defense or field robots. Most mobile robots are not only designed to operate in a structured environment, but also in an unstructured environment: important application areas It is homeland security, surveillance, intervention during terrorist attacks (Birk and, demining, reconnaissance in dangerous situations, agriculture. In addition, mobile robot technology is a typical dual technology because it has important military applications [1].

Researchers in academia and industry have proposed several mechanical structures for mobile robots. Of course, these structures have their own advantages and disadvantages. Therefore, when designing new mobile robots for specific application scenarios, designers must evaluate the breadth of their mobile systems and universal technical solutions that perform complex and time-consuming evaluations. In the early design stages of ground mobile robots, the expected operating environment must be analyzed, as these environments can belong to many different categories: flat, compact indoor structured environments (With or without stairs); rugged outdoor environments with different terrains; with or without obstacles, etc. Therefore, it is of great research significance to summarize various existing motion systems and comprehensively compare their advantages and disadvantages under different operating conditions.

In the main design goals of this work, both research prototypes and commercially available industrial products are considered. The current status analysis of ground mobile robot motion systems focuses on solutions for unstructured environments. In fact, many Mobile robots for structured environments are fairly simple from a mechanical point of view (in most cases, a differential steering with two active wheels and a passive caster layout is sufficient). In addition, when the When moving or climbing obstacles on soft terrain, the mechanical design of the motion system is much more complicated, and many different solutions have been proposed. Therefore, comprehensive comparison is more useful for designers.

Due to the variety of potential working conditions of ground mobile robots, it is difficult to make comprehensive and exhaustive comparisons of ground mobile robot motion systems. An overview of legged robots is presented in .In some existing studies, qualitative and the selection of quantitative parameters summarizes the concept of mobility for surface detection.

This article also made a similar comparison, but there are two main differences: the analysis not only focuses on the application area of space exploration, but also discusses four mixed categories (leg-wheel-lw, leg-rail-lt, wheel-rail- wt and leg-wheel-rail-lwt). The evaluation considered the following characteristics: maximum speed, obstacle surmounting ability, step / stair climbing ability, climbing ability, ability to walk on soft ground, ability to walk on uneven terrain, energy efficiency, Mechanical complexity, control complexity, and technical readiness.

It should be pointed out that there is a huge amount of scientific literature on mobile robots. Due to space reasons, it is not possible to list all of them in the references. This article selects the cited papers to comprehensively perform and compare all types of motion systems.

2. Classification and comparison methods of mobile robot motion systems

This paper considers the motion systems of robots that mainly move on the ground, some of which can even travel short distances over the water. In addition, dedicated motion principles will not be discussed (e.g., jumping robots, snake-shaped sliding robots, and sticking walls) Robots) because they are dedicated to very specific applications. In addition, some researchers have proposed advanced motion strategies that utilize two or more collaborative mobile robots. However, due to the need for complex surveillance systems and these collaborative methods are rarely used to solve Robot mobility issues will not be considered in this article. This article discusses the principle of motion of autonomous autonomous ground robots without interacting with other vehicles or fixed equipment.

In these spaces, ground mobile robots can be divided into three categories: wheeled robots (W), tracked robots (T), and legged robots (L). In addition, there are also robots characterized by a combination of these principles of motion, Called hybrid robots. In the fields of science and industry, there are four possible combinations that lead to examples of hybrid kinematic systems: leg-wheel (LW), leg-track (LT), wheel-frame (WT), and leg-wheel-rail (LWT). The three main categories and four mixed categories of ground mobile robots are shown in figure1.

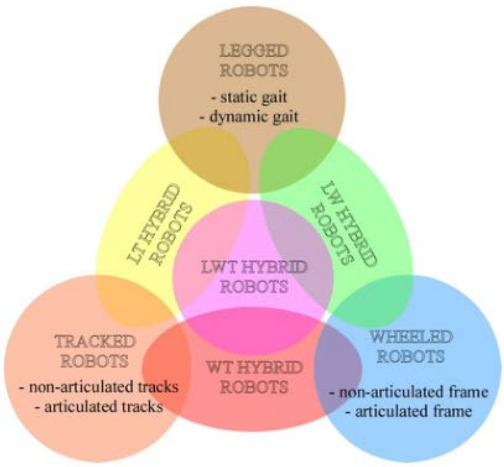

Figure 1 Ground mobile robot categories

In order to make a detailed comparison of mobile systems, a set of features that can be objectively evaluated must be defined; for this reason, a set of 10 features and their corresponding definitions are presented in Table 1. The first seven features (maximum speed, obstacle crossing ability) , Step / stair climb ability, slope climb ability, walking ability on soft ground, walking ability on uneven terrain and energy efficiency) are related to pure maneuverability and can be measured quantitatively; the remaining three functions (mechanical complexity (Complexity, control complexity, and technical readiness) describe the complexity of the system and affect other functions (such as reliability), which are not explicitly mentioned. Autonomy is not explicitly considered because it depends on energy efficiency.

Table 1 Description of the features considered in the comparison of locomotion systems.

Feature	Definition
maximum speed	maximum speed on flat and compact surfaces in the absence of obstacles
obstacle crossing capability	capability of crossing obstacles with random shapes in unstructured environments(e.g. rocks)
step/stair climbing capability	capability of climbing up single steps and stairs in environments structured for humans
slope climbing capability	capability of climbing compact slopes with a sufficient friction coefficient (> 0.5)
walking capability on soft terrains	capability of walking on soft and yielding terrains (e.g.sand)
walking capability on uneven terrains	capability of walking on uneven terrains (e.g. grassy ground, rocky ground)
energy efficiency	energy efficiency in normal operating conditions, on flat and compact terrains
mechanical complexity	level of complexity of the mechanical architecture
control complexity	level of complexity of the control system (hardware and software)
technology readiness	level of maturity of the necessary enabling technologies

3. Mobile robot motion system

In this section, the main features of the mobile robot motion system category are summarized and compared with the features defined in Table 1.

3.1 Wheeled Robot Motion System

Wheeled robots can reach high speeds with low power consumption and can be guided by controlling several active degrees of freedom, but their ability to overcome obstacles is usually limited. Wheeled robots can be classified based on the number and position of wheels. Achieve static stability The minimum number of wheels is three (the condition of static stability is that the vertical projection of the center of gravity of the robot on the ground must be within the polygon formed by the contact points between the wheels and the ground), and the stability is improved by using four or more wheels.

It should be noted that two-wheeled vehicles with an inverted pendulum layout have been developed for personal transportation, but in this case, balancing is achieved under dynamic conditions through a complex control system if the overall height of the vehicle and payload is not like humans so relevant in transport, then there is no substantial advantage for the three wheels.

Nowadays, there are also examples of two-wheeled robots (robot motorcycles) with a tandem structure, but the mechanical model and the corresponding balance stabilization and trajectory tracking control system are even more complicated than the system that controls the two-wheeled inverted pendulum scheme. In addition, at zero speed Assist legs or stabilizing rotors are required. For all these reasons, unlike passenger vehicles, this approach is rarely used by autonomous robots.

Three-wheeled mobile robots with two differential steering wheels and one idling caster are widely used in flat, structured environments, such as for drug delivery in hospitals, because they require simple control strategies and can be rotated around a vertical axis Rotating. Robotba (www.irobot.com) and other commercial vacuum cleaner robots also use the same three-wheeled structure. On the other hand, this mobile structure is not suitable for unstructured environments because it is on uneven and inclined surfaces Poor stability [2].

To improve stability, most wheeled robots used in unstructured environments usually have 4, 6, or 8 wheels. However, these layouts are ultra-static and require an articulated frame or suspension to ensure all wheels both are in contact with the ground. Regardless of the number of wheels, two types of wheeled robots can be distinguished: articulated frames and articulated ones.

It should be noted that the second type of robot includes only robots with passive articulated frames. If the wheel is carried by a component that moves relative to the robot body and this movement is driven, these components are considered legs, and the robot becomes a leg -Wheel hybrid.

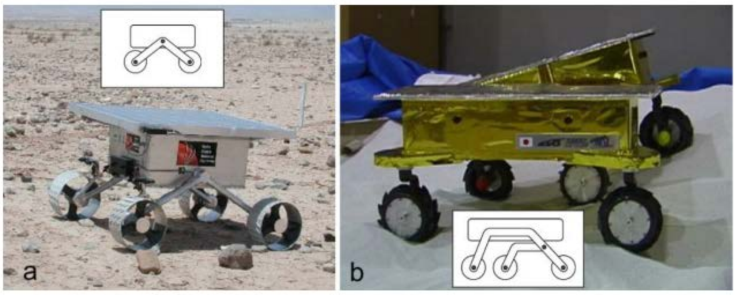

Figure 2 The four-wheeled SR2 rover and the five-wheeled Micro5 rover.

In a wheeled robot without an articulated frame, the relative positions of the wheels are fixed. When more than three wheels are used, the configuration is super static and rarely used. Due to the mobility of passive joints, The wheeled robot can adjust its configuration according to the terrain, which reduces resistance while overcoming obstacles and irregularities.

For a wheeled robot in an unstructured environment with four wheels, the simplest mechanical design is the 4 × 4 × 0 wheel formula (wheel formula: number of wheels × number of active wheels × number of active steering wheels); two on both sides Both wheels are driven by the same motor; steering is differential and is achieved by setting different speeds on the two actuators. An example of this plan is the SR2 Lunar Rover developed by the University of Oklahoma for the Marin Space Science System (Miller et al., 2003) .The rover chassis is articulated to provide uniform load distribution on the ground (Figure 2a); this scheme allows rotation, but the wheels slip on the ground when turning, reducing energy efficiency .

Where high speed is required, robotic motion systems can be derived from automotive technology, using automotive suspension and Ackerman steering geometry. Depending on the size of the mobile robot required, it can be achieved by installing a car or another with automatic Or remotely control a manned vehicle of the navigation system (usually four wheels) to make a self-driving car. This is the method used in the darpa challenge funded by the U.S. Department of Defense. Of course, this method has high robot speed, but Compared with other electric wheeled robots, the motion control accuracy and maneuverability in a small area are poor [3].

Five-wheeled mobile robots are rare; the Micro5 rover developed by the Japanese development agency Japan Aerospace Research and Development Agency (JAXA) uses a formula of 5 × 5 × 0 wheels (Figure 2b). The load is named Pentad class Suspension system distribution for auxiliary suspension (Pegasus) (Kubotam et al., 2005); its fifth wheel is connected to the main body through a passively rotated joint center. When climbing an obstacle, the traction of the fifth wheel generates momentum for the dive this increases the load on the front wheels and improves traction. This five-wheel architecture is designed to increase traction in extremely low speed (approximately 3 cm s−1) and low-energy applications, but it is not suitable for high-speed operation due to the absence of a suspension.

An example of a six-wheeled robot with an articulated frame is a rocker bogie type rover developed by nasa for Mars exploration, the Courage / Opportunity and the Sojourner (developed by scholars such as Lindeman and Wally in 2005). These rover vehicles use the formula of 6 × 6 × 4 wheels (front and rear wheels are independently controlled). Two rocker-bogie mechanisms on both sides of the vehicle (Figure 3a) keep all wheels in contact with the ground, even when not in use. This is also true in the presence of flat terrain and obstacles. The average pressure on the wheels is passively balanced, which improves the ability to move on soft terrain.

3.2 Tracked motion system

Tracked robots are great for moving on uneven and soft terrains and overcoming obstacles, thanks to their large ground contact surfaces, but they move more slowly and consume more energy than wheeled robots: the fact On the other hand, crawler robots are susceptible to vibration because the lateral trajectory contours are polygons with moving vertices and they rarely have a damping system installed. This limits the maximum speed and reduces the mechanical efficiency.

In order to further enhance the ability to adapt to uneven terrain and obstacles, other articulated crawler robots have more complex mechanical structures. For example, Gunryu (figure3) developed by Hirose-Fukushima Robotics Laboratory has four independent tracks; front and rear tracks It is connected to two independent bodies by a swivel joint. In addition, the two bodies are connected by passively connected arms (developed by Hirose et al. 1996). This configuration allows superior relative orbital manoeuvrability and therefore a high overcoming Obstacle ability.

Figure 3 Tracked robots: Nanokhod, Robhaz DT3 and Gunryu.

3.3 Leg movement system

Leg robots have a wide range of mobility, which makes them suitable for both structured environments and uneven terrain. However, they are relatively slow and consume a lot of energy. Generally speaking, the number of leg robot actuators is large, and the control system is complicated.

The development of leg mobile robots is clearly inspired by biology: robots with two legs (inspired by humans), robots with four legs (inspired by tetrapods), and robots with more than four legs (inspired by insects). Although the most obvious classification of leg robots is based on the number of legs, their most important feature is the type of gait, which can be static or dynamic [4].

3.4 Mixed Motion System

Hybrid mobile systems are probably the most interesting solution for mobile robots because they combine the advantages of various categories while trying to avoid disadvantages. In fact, in unstructured environments or environments built for humans (e.g., in stairs with (Case), leg movement is the most suitable solution. On the other hand, humans often use wheeled or tracked extensions to improve speed and energy efficiency. Unlike nature, in the design of mobile robots, legs, wheels and tracks can be freely integrated. Now discuss the four categories of hybrid mobile robots (lt, lw, wt and lwt).

3.5 Comparison of characteristics of several sports systems

Referring to the three main categories and four mixed categories of the motion system, Figure 4 The very comprehensive outline of the characteristics of the kinematic system is shown in Figure 4, where the relationship between mobility (Y) and speed and energy efficiency (X) in an unstructured environment is qualitatively plotted. (x, worst y); legged robots in the upper left zone (worst y, better x); tracked robots in the middle; hybrid combinations tend to the upper right zone (a combination of benefits).

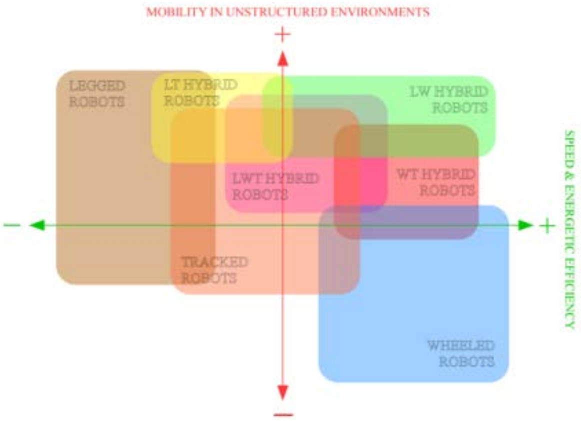

Figure 4 Comparison of locomotion systems.

In general, hybrid systems should combine the advantages of the different categories they derive from. Therefore, in Figure 4. In the chart in, each mixed category should be located in a region characterized by the maximum value of the original category along each axis. However, this did not happen completely (the chart was plotted accordingly) as the combination of alternative mobile devices decreased Overall performance: In fact, inactive mobile devices are non-negligible payloads. From this perspective, different motion systems share a hybrid solution with common members.

Because mobile robots can be of different sizes, some features (maximum speed, obstacle surmounting ability, step / stair climbing ability, walking ability on uneven terrain) have been standardized according to the size of the robot. Obstacle crossing ability is defined as Ability to pass obstacles of any shape in an unstructured environment (Table 1). However, semi-circles were selected for quantitative comparison.

As mentioned earlier, motion systems including wheels have high speed and energy efficiency. In particular, wheeled robots derived from automotive technology, with car-like suspension and Ackerman steering, make the most of these parameters If not only these functions are the most important, but also obstacle crossing and climbing ability, wheels and legs can be properly combined in a hybrid solution. On the other hand, if the task requires focusing on soft and yielding terrain On the other hand, it is more preferable to enhance the mobility of the robot by adding trajectories instead of legs, because the contact surface of the trajectories is larger, and the legs are more efficient for rigid obstacles with complex shapes.

From these general considerations, a combination of motion systems suitable for a hybrid solution can be selected based on specific task requirements.

4. Discussion on the future development trend of mobile robot technology

The global service robot market is expected to grow significantly in the next 20 years, both in sales volume and sales volume will exceed the industrial robot market. In this case, developing efficient and flexible ground mobile robot motion systems is a basic research topic.

Regarding the future trends of mobile robots, the most important enabling conditions may lead to the popularization of legged mobile robots, whose level of operational flexibility is comparable to that of humans and tetrapods. Regarding the future trends of mobile robots, the most important enabling conditions may lead to the popularity of leg mobile robots is comparable to that of humans and tetrapods in terms of operational flexibility, which is related to the development of model-based and adaptive dynamic gait. Control methods can faithfully reproduce animal behavior. Moreover, from a hardware perspective See, other important enabling conditions are the increasing computing power of the microprocessor and the increasing energy density of the battery, and the availability of actuators with high power ratings [5].

In the next 10-15 years, one of the most important technical challenges facing robots may be the transfer of high-performance legged robots from the research field to the industrial and commercial field through difficult but necessary cost reduction processes.

On the other hand, when certain specific feature sets are critical in the combination of operational requirements (for example, speed, energy efficiency, or mobility on prolific terrain), or when the robot's When it comes to cost and complexity, hybrid mobile systems are often the most appropriate solution.

For all these reasons, the strong diversification in the current mobile robot scene is likely to continue in the future, with a wide range of technical approaches and varying levels of mechanical and control complexity.

5. Conclusion

This article analyzes the current status of mobile robot motion systems from two aspects of research prototypes and industrial products, with a view to providing a useful reference for the early design stage of selecting a type of motion mechanism according to the requirements of use.

To this end, three main categories of mobile systems (wheeled, tracked, and legged) and four mixed categories (legged, wheeled, legged-tracked, wheeled-tracked, and legged-tracked) (Comparison), and 10 features were selected to evaluate not only the mobility performance under the most important conditions, but also the complexity and reliability of the entire system.

In addition, we briefly discuss the future development trends of mobile robotics. Arguably, the two most promising research directions are quadruped walking with dynamic gait for completely unstructured outdoor environments (such as Military and homeland security missions), as well as mixed motion, especially leg wheels and leg channels, for compact and low cost mobile robot platforms.

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