Design of Kinematic Mechanism of Wheel-legged Robot

Lei Ying
Beijing University of Chemical Technology, Beijing, 100029, China
2017100052@mail.buct.edu.cn

Abstract. Mobile robots can be roughly categorized in wheeled type, tracked-skidded type, legged type, trunked type, etc. Among them, the wheeled mobile robot can move on the flat road, but with poor performance when crossing an obstacle; the legged type mobile robot has a slow motion speed and poor bearing capacity; the tracked-skidded mobile robot has a large weight; while the trunked mobile robot has limited use occasions. In order to overcome these shortcomings, this paper studies the wheel-legged structure and distributes the performance of various commonly used structures. On the other hand, by analyzing the newly emerged structure, the impact of the organization's own shortcomings on performance is hoped to be reduced. By comparing the structure and distribution of different leg configurations, the advantages of the locomotion performance of each type of wheel-legged mobile robot and the development trend of the wheel-legged mobile robot in the future are analyzed.

1. Introduction
With the development of science and technology, mobile robots play an important role in human life and production, which can be used for many heavy or dangerous work. The wheel-legged mobile robot combines the rapid movement of the wheeled robot and the obstacle crossing ability of the legged robot, which effectively improves the mobile ability of the mobile robot in complex environments and improves the efficiency of the mobile robot. In this paper, through a comprehensive analysis and comparison of several different leg structures and distribution ways of wheel-legged mobile robots, the locomotion efficiency of the wheeled leg part is analyzed. At the same time, the advantages and disadvantages of various control methods of the current mainstream wheel-legged mobile robots are analyzed through comparisons between different control methods. The analysis in this paper provide more thinking about the structure design theory of wheel-legged mobile robots.

2. Overview of leg structure of legged mobile robot
As most of the leg structures are complex and highly integrated, reducing the number of legs can effectively reduce the production cost of mobile robots. However, the more legs there are, the more landing points the feet will get, which brings better stability to the mobile robot [1]. Three is the minimum number of legs for the mobile robot to maintain static stability. At present, most legged robots are bipedal, quadruped and hexapod [2-4], and most of them are distributed symmetrically on both sides of the body. The hexapod robot uses three legs alternately in its mobile mode, and the center of gravity is projected in the triangle of the three supporting legs. Compared with hexapod, the stability of quadruped is decreased and the control complexity is increased.

There could be different forms of the mechanical structure of wheeled mobile robot in different applications. According to the structure, it can be roughly categorized in wheel-leg connected type, wheel-leg separated type and wheel-leg variant type [5].
• Wheel-leg connected type can be further divided into foot-end-connected and joint-connected types according to the position of where the wheels and legs are connected. In the foot-end-connected type, the wheel is installed on the foot, and the wheel is used as the contact point between the foot end and the ground under the condition of the legged locomotion, while the joint-connected type combines the middle joint of the wheel fish mechanical leg, and switches the wheel leg through the structural deformation of the mechanical leg.
• The wheel-leg separated type connects the wheel mechanism and leg mechanism directly with the body.
• The wheel-leg variant type is the one that switches the mechanical structure between that of the wheel and of the leg to realize the switch between wheeled type mode and legged type mode.

3. Locomotion mode of wheel-legged robot
At present, the most common wheel-legged robots are bipedal, quadruped and hexapod ones. They have been fully developed because of their stability and practicability, especially in the aspect of gait planning and control.

3.1. Movement mode of biped robot
The walking motion of biped robot is divided into static walking and dynamic walking. Static walking has the characteristics of slow walking speed and slight movement in its center of gravity. In the process, one foot must contact the ground, and the projection of the robot's center of gravity on the ground is always within the range of the supporting polygon. On the contrary, dynamic walking can achieve faster walking speed, in which two feet may leave the ground at the same time. At present, most walking robots apply the static walking motion[6].

The bipedal wheel-legged robot combines the advantages of the biped robot and the wheeled robot and better adapts to the environment. The robot can quickly pass through the flat ground and can deal with various complex road conditions such as stairs through bipedal motion [7]. However, most of the current biped wheel-legged robots can only cross the stairs and other regular terrain but cannot deal with the more complex terrain in the wild field.

Osamu Matsumoto and a few other scientists in Japan developed a five-degree rotatable biped wheel-legged robot in 1998 [8]. The legs of the robot can swing alternately. The upper legs of the robot were equipped with ball screws controlled by servo motors to extend and shorten the legs and there was a group of rollers at the end of each foot. The robot could demonstrate high-speed motion on flat ground and also complex motion such as going up the stairs to cross obstacles.
The DRC Hubo bipedal robot designed by the Korean Academy of Science and Technology (KAIST) accomplished the wheel-legged mechanism by adding driving wheels at the knee joint and adding universal wheel at the front end of the sole. The robot could switch between leg and wheel by the switch of kneeling and standing posture. When the robot was in its kneeling position, it could realize four-wheel motion and hence quickly pass through flat road. When in its standing position, it could complete the movement of a legged robot, and could pass through complex obstacles such as steps through the movement of the legs, so as to expand its motion performance [9-11].

3.2. Movement mode of quadruped wheel-legged robot
Compared with quadruped legged mobile robot, quadruped wheel-legged mobile robot could be added with the function of fast movement on the flat ground, and can realize various gaits such as crawling, jumping, fast running, etc., which wheeled robot cannot achieve, thus greatly increasing the flexibility of the robot’s movement. Compared with bipedal wheel-legged robot, the quadruped one better deals with complex terrains, including not only relatively regular terrain like stairs, slopes and so on, but also the complex terrains in the wild field in most cases.
In 2018, the robot laboratory of the Federal University of Technology in Zurich, Switzerland, developed the "ANyMal" quadruped wheel-legged robot, which was a kind of wheel-leg-connected robot [12-13]. The robot could achieve a variety of complex gaits, cross or clear obstacles, and even get up and move on its own after being pushed down. It could choose the appropriate movement mode for different terrains.

University Pierre and Marie Curie (UPMC) in France developed a quadruped wheeled robot “Hylos” [14]. The robot was designed to deal with the complex outer space surface. It adopted the mechanical structure of wheel-leg connection and possessed the function of locking the part of the wheeled type at the same time, so that the locked wheels could be used as feet to contact the ground stably. The robot had a strong ability of climbing up slopes and crossing obstacles.

3.3. Movement mode of hexapod wheel-legged mobile robot
CPG is the most commonly seen as the control method for hexapod wheel-legged mobile robots. Such control method was proposed by Shik et al. in 1966 based on the research of animals’ control mechanism [15]. In 1995, Matsuoka of Kyushu Institute of Technology proposed that the oscillation behavior of CPG could be coupled with external signals, and established the mathematical model of neural oscillator, which initiated the application of CPG in the engineering field [16].

At present, the research results of hexapod robot have been mainly based on bionics. Researchers plan and study the gait of hexapods in nature, such as cockroaches, bamboo insects and crabs, etc. Therefore, in most cases the legs are distributed symmetrically on both sides of the body. Hexapod wheel-legged robot possesses excellent stability, while the too many legs also make the robot itself more cumbersome, and the gait planning methods more diverse. The gait of the robot can be divided into three-legged, four-legged and five-legged one according to the number of the legs in contact with the ground at each moment [17].
3.4. Other new leg structures

Wang Yandong of Tianjin University designed a new type of wheel-legged mobile robot with articulated links [18]. The leg mechanism on one side of the robot is shown in the figure below.

![Figure 5. Single link articulated wheel-leg (Driving wheel-leg A & Driven wheel-leg B)](image)

The two connecting rods are always parallel, and the angular velocity and angular acceleration are also equal. Thus, only one motor is sufficient to drive two legs. The robot increases the number of legs while reducing the number of motors, which makes it more stable.

![Figure 6. Exploded view of the 3D model of the twin whegs](image)

Zhang Lihua et al. in China have designed a wheel-legged robot with the design of the motion characteristics of parallel quadrilateral suspension mechanism. The robot can cross obstacles by combining its swing arm and planetary gear mechanism, demonstrating fair motion performance [19].
Figure 7. Wheel-legged robot with parallel quadrilateral suspension mechanism crossing an obstacle

Zhang Na et al. in China have designed a mobile robot that can automatically adapt and switch between the wheeled type and the legged type [20]. Such mechanism can demonstrate the state of extension without having the wheel-leg contacting the ground, but instead, such state can be triggered by the interaction between the compressed spring and mechanical limit. While the wheel-legs that contact the ground will contract, caused by the robot's own gravity. At the same time, due to the mechanical limit, the wheel can move in the form of circular wheel. When encountering obstacles, the robot turns around in the manner of differential steering. The self-adaptive switching mechanism realizes the switch between the wheel and the leg skillfully and improves the flexibility of the movement.

Figure 8. Self-adaptive arc-shaped wheel-legged robot crossing an obstacle

4. Conclusion
This paper focuses on the analysis of different wheel-legged mechanical structures. In view of the difficulties in the control of biped wheel-legged mobile robots, at present, the application of the wheeled type of robots in some specific areas is generally extended by the legged-type ones.
Quadruped wheel-legged type has a relatively average ability of moving on flat ground and crossing obstacles, while possessing fair stability and moderate control difficulty. Hexapod wheel-legged type has good stability, but at the same time its gait becomes more complex. Currently, researches on the more novel arc-shaped legged or link articulated types have mainly focused on passively crossing obstacles or the methods of switching between the wheeled type and the legged type. So far, the research idea of the leg structure of wheel-legged robots has been rather simple, and it is still aimed towards bionic goals. Most of the research results have been based on the studies of the animals existing in nature. It is expected that the mechanical wheel-leg structures which do not exist in nature could be developed and studies on subjects of, for example, odd-numbered foot (feet) could be conducted. The follow-up research will focus on the asymmetric wheel-legged mechanical structure, as well as the analysis of its motion performance and control principle.

Acknowledgements
I would like to appreciate Mr. Wang for his guidance in my learning process, and for his constant help whenever I have any questions. Also, I would like to thank my fellow classmates for their support during my study.

References
[1] Zhiying Miao. Research on Moving Performance of 3-PUU Wheel-legged Mobile Robot[D]. North University of China, 2018
[2] Yantao Tian, Zhongbo Sun, Hongyang Li, et al. A Review of Optimal and Control Strategies for Dynamic Walking Bipedal Robots.[J] Acta Automatica Sinica, 2016, 42(08): 1142-1157.
[3] Junjie Yang, Hao Sun, Changhong Wang, et al. An Overview of Quadruped Robots [J]. Navigation Positioning and Timing, 2019, 6(05): 61-73.
[4] Manhong Li, Minglu Zhang, Jianhua Zhang, et al. Review on key technology of the hexapod robot [J]. Journal of Machine Design, 2015, 32(10): 1-8.
[5] Ying Dong. Design and research of Six-Wheel-Leg Hybrid Mobile Robot[D]. Beijing: Beijing Jiaotong University, 2017.
[6] Chenxi Zhang. Gait Planning and Simulation Analysis of Small Humanoid Bipedal Robot[J]. Electric Engineering, 2020(02): 51-53+66.
[7] Shao Zhang. Research on System Design and Locomotion Control of a Bipedal Leg-Wheeled Robot[D]. Harbin Institute of Technology, 2020.
[8] Matsumoto O, Kajita S, Saigo M, et al. Dynamic Trajectory Control of Passing over Stairs by a Biped Type Leg-wheeled Robot with Nominal Reference of Static Gait[J]. Journal of the Robotics Society of Japan, 1998, 16(6): 868-875.
[9] Bae H, Lee I, Jung T, et al. Walking-wheeling Dual Mode Strategy for Humanoid Robot DRC-HUBO+[C]//Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2016: 1342-1348.
[10] Oh P, Sohn K, Jang G, et al. Technical Overview of Team DRC-Hubo@ UNLV's Approach to the 2015 DARPA Robotics Challenge Finals[J]. Journal of Field Robotics, 2017, 34(5): 874-896.
[11] Lim J, Lee I, Shim I, et al. Robot System of DRC-HUBO+ and Control Strategy of Team KAIST in DARPA Robotics Challenge finals[J]. Journal of Field Robotics, 2017, 34(4): 802-829.
[12] Bjelonic M, Sankar P K, Bellicoso C D, et al. Rolling in the Deep–Hybrid Locomotion for Wheeled-Legged Robots using Online Trajectory Optimization[J]. rXiv preprint arXiv: 1909.07193, 2019.
[13] Bjelonic M, Bellicoso C D, de Viragh Y, et al. Keep rollin’—whole-body motion control and planning for wheeled quadrupedal robots[J]. IEEE Robotics and Automation Letters, 2019, 4(2): 2116-2123.
[14] Grand C, Benamar F, Plumet F. Motion kinematics analysis of wheeled–legged rover over 3D surface with posture adaptation[J]. Mechanism and Machine Theory, 2010, 45(3): 477-495.

[15] Shik M L, Orlovskii G N, Severin F V. Organization of locomotor synergism[J]. Biofizika, 1966, 11(5):879-886.

[16] Matsugu M, Duffin J, Poon C S. Entrainment, Instability, Quasi-periodicity, and Chaos in a Compound Neural Oscillator[J]. Journal of Computational Neuroscience, 1998, 5(1):35-51.

[17] Tianran Sui. Research on Gait Analysis and Control of Hexapod Bionic Robot[D]. Changchun University of Science and Technology, 2020.

[18] Yandong Wang. Design and Analysis of a Novel Linkage-coupled Wheel-legged Mobile Robot[D]. Tianjin University, 2018.

[19] Lihua Zhang, Lanbing Fei, Fei Lou, et al. Structure Design and Analysis of Movement Characteristics for a New Type Wheel-Legged UGV[J]. China Mechanical Engineering, 2015, 26(21):2867-2872.

[20] Na Zhang, Lingbin Shen, Yezhuo Li, et al. Self-adaptive Deformable Wheel-legged Mobile Mechanism[J]. Mechanical Science and Technology for Aerospace Engineering, 2020, 39(11):1705-1712.