Kylin: a transformable track-wheel hybrid robot

Shaozun Hong, Meiping Wu, Junhao Xiao, Xiaohong Xu, Huimin Lu
College of Mechatronics and Automation
National University of Defense Technology
Changsha, China

272097637@qq.com, meipingwu@263.net, junhao.xiao@ieee.org, xxhac311@126.com, lhmnew@nudt.edu.cn

***Abstract*—This paper presents a track-wheel hybrid robot, named Kylin, which is designed to integrate the advantages of both wheeled locomotion and tracked locomotion. To save the research and development time, the robot is built upon our tracked robot named NuBot, by integrating modular components for wheeled locomotion without changing the main body of NuBot. Kylin can run 3.7 m/s on the ground, climb up 45 degree slops and 0.5 m steps. It has been employed in UGVC 2016, and won the vice-champion.**

Keywords—Wheel-track robot; Mobile robot; Control system; Multiple locomotion modality

I. INTRODUCTION

The Unmanned Ground Vehicles Competition (UGVC) is an international competition held by the Military Technical College of Egypt. Aiming to develop high performance unmanned ground vehicles, the field of the competition is laid out on the grass over an area of 100m×60m. As shown in Fig. 1, there are six gates in the field, and each has white lines showing the right direction to enter it. Behind the gates, there are slopes from 15° to 45°, vertical drops up to 1m and steps up to 0.5m. Red boxes are obstacles to avoid. The competition requires the vehicles to pass through all the gates in the appointed direction, at the same time cannot crash on against any obstacle, within 20 minutes. In order to win this competition, each team should design a robot which possesses both high speed and enough climbing capability.

In general, traditionally, robots can be divided into three categories i.e., wheeled robots, tracked robots and legged robots. Among them, wheeled robots have been studied the most comprehensively against others, as they have advantages such as simple, long working life and high efficiency [1]. Along with the mature research of wheeled robots, they have been widely used in the agriculture, industry, domestic service, monitoring, etc. However, it is weaker than the tracked robot with respect to the climbing capability and environmental adaptability [2]. Due to the strong climbing capability, tracked robots have played an important role in complex environments, e.g. disaster rescue, space exploration, military UGVs [3-6]. Legged robots have been one hot and challenging research topic in the past decades, which integrate bionics, bioscience, mechanics, sensing and other related technologies [7]. Most of legged robots are bionic robots that have strong environmental adaptability. However, compared to wheeled and tracked robots, they are not good in the efficiency and speed.

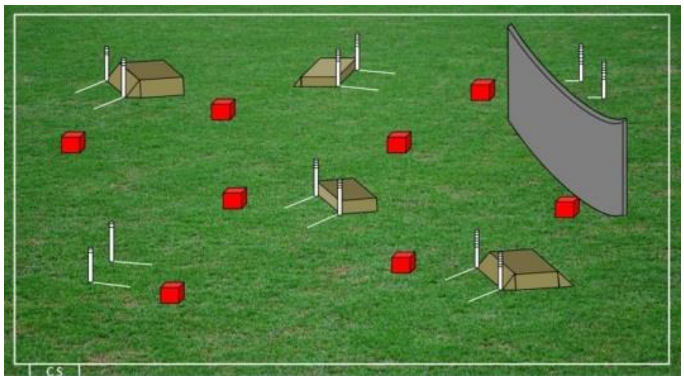


Fig. 1 The over view of UGVC field, which is approximately 100m×60m. It has six gates through the course each has white lines showing the correct direction to enter. The randomly displaced red squares are obstacles to avoid. A grey barrier is set to block the communication at one of the gates.

As mentioned above, wheeled robots have difficulties when climbing steps, while the moving speed of tracked robots and legged robots are a little slow. In other words, single locomotion modality cannot fit requirements of the UGVC well. As a result, we propose to build a multiple locomotion modality robot platform, i.e., a track-wheel hybrid robot, as shown in Fig.2. There have been some studies focusing on track-wheel hybrid robots. For example, Li, et al, designed a transformable wheel-track hybrid robot, NEZA-I, which can surmount the obstacle of 120 mm that is twice as high as its wheel [8]. Zhang, et al, designed the WALS-robot which can transform among five locomotion modes to fulfill locomotion requirements in indoor unstructured environments [9]. And Kim, et al, developed a track-wheel hybrid robot that can change the shape of track to move fast on flat terrain [10]. Peng, et al, designed a track-wheel hybrid robot that can climb the step up to 130 mm [11]. However, these robots cannot win the UGVC because they are unable to meet the requirements of speed and climbing capability at the same time. To save the research and development time, it is actually constructed based on our NuBot tracked robot [12]. The track-wheel hybrid robot is named Kylin, and compared against its predecessor, it not only improves the step climbing capability, but also significantly increases the speed on the smooth ground.

A video showing the robot capacities can be found at https://www.trustie.net/attachments/download/202142/Kylin_robot.wmv.

This work is supported by National Key R&D Program of China (No. 2017YFC0803300)，National Science Foundation of China (No. 61503401，No. 61403409), China Postdoctoral Science Foundation (No. 2014M562648).

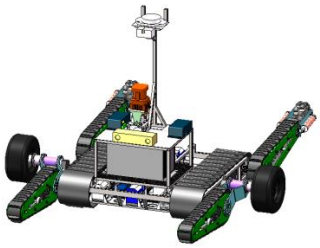


Fig. 1. The mechanical model of our designed wheel-track robot-Kylin

This paper is organized as follows: Section II introduces our rescue robot, NuBot, and proposes why we need Kylin. Section III discusses the realization of wheel-track integration in detail and describes our design. And the design of driving system and control system of Kylin are described respectively in Section IV and Section V. Afterwards, we provide the performance indexes of Kylin and discuss the aspects needed to be improved in the future work. Finally, Section VI concludes the paper.

II. THE NUBOT TRACKED ROBOT

As shown in Fig.3, our NuBot tracked robot is a three-section six-tracks robot platform. Compared against the traditional double-section four-tracks robot platform, its climbing ability is improved because the added fins will make the robot platform more adaptive in the face of more dangerous terrains with oversize obstacles. NuBot has successfully participated in RoboCup for a long period and won several champions in RoboCup ChinaOpen.

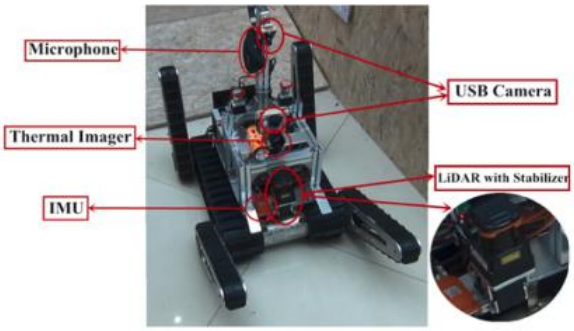


Fig. 2. The overview of our NuBot rescue robot

Although the stability and climbing capability have been tested by many competitions, NuBot is not suitable to participate in UGVC which is held in a relative large outdoor environment, because its maximum speed is only 0.2m/s. Furthermore, there are several obstacles that have exceeded its climbing capability in the UGVC such as the step up to 0.5m and the drop up to 1m. As a result, it is necessary to improve NuBot's overall performance in an effective way.

III. THE DESIGN OF WHEEL – TRACK INTEGRATION

The integration of the wheel and track is the most significant character of our newly designed robot, as well as the key to ensure the multiple locomotion modality. Theoretically, there are several integration methods among which we attempt to find one that has the lowest cost at changing the mechanical structure of NuBot itself. In other words, by analyzing the characteristics of multi-track robots, we design a modular mechanism that can be easily used to transform a track robot to a wheel-track one without any disruptive changes on it. The overall design idea is trying to place wheels at the end of the front fins and the fear fins. Thus, using the existing mechanisms' action, the rotation movement of the fins, the wheels can reach the ground and then hold up the robot. As a result, the robot can conduct the transformation between the track mode and the wheel-track mode.

While one fin has two ends, there are three configurations to place the wheels ignoring which side of wheels are driving wheels. To make it clearer, we place all the possible wheels at the robot, and the side view of the robot is shown in Fig.2. We define the end near the rotation center of a fin as the rear end of the fin. Similarly, another end of the fin is called front end of the fin. As shown in Fig.4, we can get three configurations, two rear ends on the ground, one front end and one rear end on the ground, two front ends on the ground. Each configuration's advantages and disadvantages are illustrated in TABLE I.

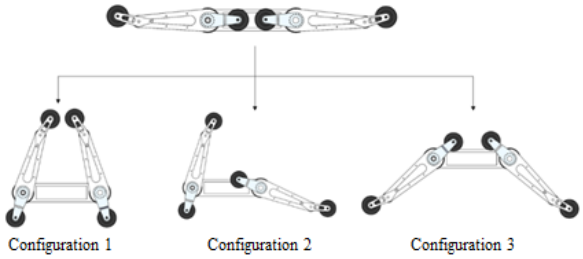


Fig. 3. Three configurations to place wheels

TABLE I. THE COMPARISON OF DIFFERENT CONFIGURATIONS

Transformation configuration	Advantages	Disadvantages
Configuration 1	A. The radius of in-situ turning is small B. The torque needed for the transformation is small	A. The transformation time is long B. The robot will quake a lot when it starts or stops due to the backlash of related mechanism
Configuration 2	A. Wheels at the front of fins can be used for adding fins' length, which can improve the robot's obstacle climbing capability. B. The radius of in-situ turning is medium C. The moving process of the robot is stable	It is hard to keep the body of the robot horizontal when it transforms to the wheel mode if there is no attitude information
Configuration 3	A. The radius of in-situ turning is adjustable B. The time needed for the transformation is short	A. The motor is difficult to install B. The torque needed for the transformation is large

It can be seen, both of configuration 1 and configuration 3 have unexpected disadvantages. As a result, we choose configuration 2 as the way to realize the wheel-track combination.

Since the robot has four wheels, the next step is to determine whether to use two-wheel driving mode or four-wheel driving mode. Generally speaking, four-wheel driving is more powerful than two-wheel driving. However, we choose two-wheel driving mode and install the driving wheels at the rear ends of fins for the following reasons. Firstly, it is easy to install. Secondly, when the robot is conducting an in-situ turning in the wheel mode, the side friction can be very large which requires more driving force, at the same time, which poses challenges for the related mechanisms. To deal with this situation, two omni-directional wheels are employed as its passive wheels. Thus, the large side friction when doing the in-situ turning in the wheel mode can be slashed, where the robot can possess more flexible steering characteristics without consuming much unnecessary power. Furthermore, the using of omni-directional wheels will make the robot's transformation between the wheel mode and the track mode easier. As shown in Fig.5, when transforming, the fins should perform rotating movement and one side of the robot will touch the ground as a fulcrum [11].

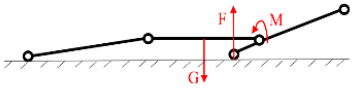


Fig. 4. The force analysis when the robot is transforming

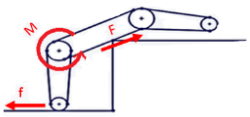


Fig. 5. The force analysis when the robot is climbing a step obstacle

If this fulcrum is fixed, there will be an opposite movement trend introduced by the fins' rotation movement. In this case, the fixed fulcrum will produce a large friction that blocks the fins' movement. In other words, the action requires a large torque and the related mechanisms should be strong enough. To deal with this problem, passive wheels are employed to make the fulcrum movable, where the large sliding friction with ground becomes a small rolling friction. As a result, the transformation is much easier.

Similarly, as shown in Fig.6, the fins' rotation attempts to rise the robot up to cross the step obstacle. Unfortunately, the contacting point between the fins and the ground will bring a reverse friction which pulls the robot back. If passive wheels are used, there will be a relative little rolling friction at the supporting point, which makes it easier to climb the step obstacle, as shown in Fig.7.

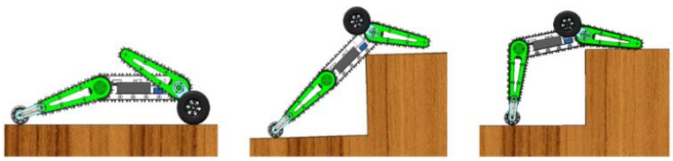


Fig. 6. The process of the wheel-track transformation and climbing step using passive wheels

Furthermore, when climbing the step, the height of the step obstacle that the robot can climb only depends on the effective length of the robot's main body and rear fins, if the motive force is enough. For further clarity, the effective length of the robot's body is the distance between the rotation point of front fins and the rotation point of rear fins; the fear fins are the two below the step; the effective length of fear fins is the distance between the rotation point of fear fins and the farthermost of the fear fins. The key action of climbing step obstacle can be simplified as shown in Fig.8.

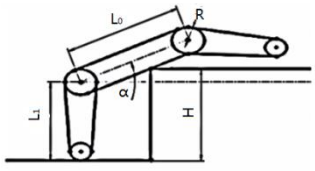


Fig. 7. The key action of climbing step

We define the effective length of the rear fins asL_1; the effective length of the robot's body asL_0, the inclination of the robot's body compared to the level asα, the height of the step obstacle as H. Then we can obtain the relationship as follows:

$$H = L_1 + \frac{L_0}{2} \cdot sin\alpha \tag{1}$$

The inclination α can be regarded as a parameter that determines the stability of the process of climbing step obstacle which is bound up withL_0, L_1 and the center of gravity of the robot. Without considering that the motive forces are enough or not, by increasing the value of L_1 while keeping other parameters unchanged, the height of the obstacle that the robot can climb, i.e.H, will be increased linearly.

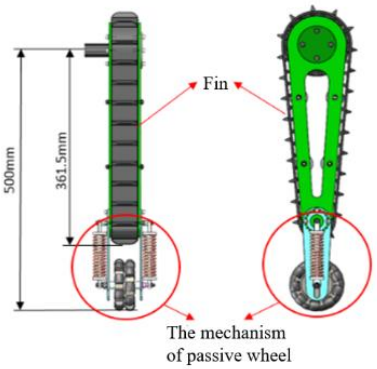


Fig. 8. The mechanism model of the fin after installing the passive wheel

Thus, by installing the passive wheels at the front ends of rear fins, the effective length of rear fins will increase. Meanwhile, the robot's overall performance is improved such as the maximum height of obstacle that the robot can climb which is shown in Fig.9.

IV. THE DESIGN OF THE DRIVING SYSTEM

The design of driving system of Kylin is the key to make it compact and efficient. Kylin's driving system can be divided as three parts: the driving system of tracks, the driving system of fins and the driving system of wheels.

A. *The Driving System of Tracks*

All the Kylin's tracks, including two main tracks and four fin tracks, are driven by two separated driving systems. Each driving system controls one side of tracks. The track driving system plays a critical role on driving the robot to overcome various obstacles. The design of this part will not pursuit the speed performance, but will focus more on the dynamics and stability. With this prerequisite, we use a worm gear reducer as a secondary decelerator on the base of the motor's own reducer. Then, theoretically, the final output torque will be magnified the same as the reduction ratio of the worm gear reducer without considering transmission efficiency. Using worm gear reducer, we can change the final direction of the motor's output shaft, which can make the inside body of the robot more compact and neat. The worm gear reducer can be easily replaced according to different total weight of the robot to ensure enough final output torque. The detailed form of transmission structure of this part is shown in Fig.10.

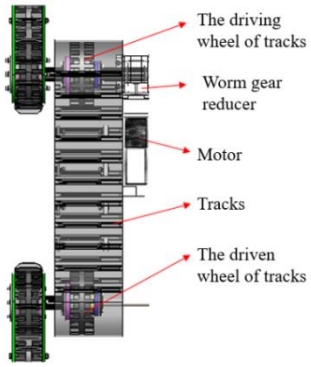


Fig. 9. The drive system of tracks

The working flow is as follows: the motor provides the initial torque, and then the torque is amplified by the motor's own reducer and the worm gear reducer as the first amplification and secondary amplification; through the spline shaft, the toque will motivate the rotation of the driving wheel; one side of the driving wheels makes the main track on its side move and drives the driven wheel through the main track; the two fin tracks are respectively driven by the driving wheel and driven wheel through another two spline shafts; finally, all the tracks of the robot obtain the driving force.

B. *The Driving System of Fins*

Fins of the robot are not only vital when the robot climbing step obstacles, but also the basis for its transformation between the wheel mode and the track mode. To ensure that fins can prop up the robot in any posture and arbitrary environment, the driving system of this part should provide great torque and good structural stability. Therefore, we decide to use worm gear reducer again as the secondary decelerator. Due to the self-locking characteristics of the worm reducer, the torque will not act on the motor but on the reducer once the motor stops working and keeps the fins at a specific location. So the fins' movement can be more stable and reliable. The detailed form of transmission structure of this part is shown in Fig.11.

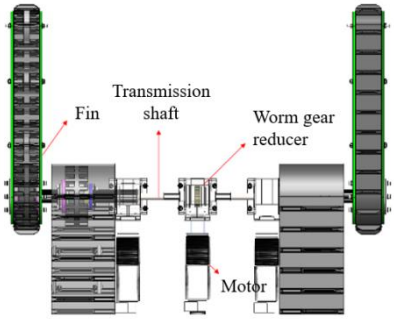


Fig. 10. The driving system of fins

Taking one side of fins as an example, the working flow is as follows: the motor provides the initial torque, and then the torque is amplified by the motor's own reducer and the worm gear reducer as the first amplification and secondary amplification; then the torque is transferred to the two fins through the fins' transmission shaft, and finally, the fins of the robot obtain the driving force.

C. *The Driving System of Wheels*

The wheels' driving system can be recognized as an important additional module to enhance the speed performance of the robot when running on the flat ground. When Kylin transfers to the wheel mode, the wheels bear the full support of it, which requires that the mechanism of this part should be very durable. Taking it into account that this driving system only needs to provide a large output speed and enough starting torque, we make the motor drive the wheel through the built-in reducer directly. For avoiding the impact from uneven pavement and the supporting force used to hold up the robot, we use two bearings and one coupling on each side of the wheels. The locations of bearings and coupling are shown in Fig.12.

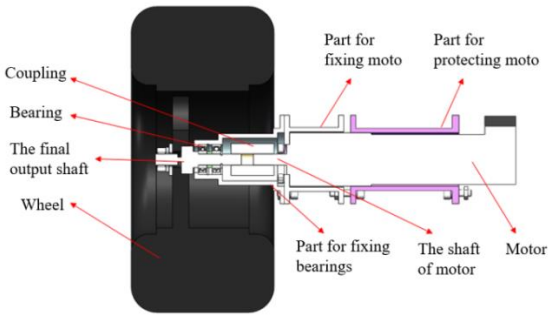


Fig. 11. The driving system of wheels

The working flow is as follows: the motor provides an output speed through its built-in reducer; since the shaft of the motor is coupled to the wheel's shaft by a coupling, the wheel will get the speed. Using two bearings with a certain span, the wheel's rotation can be smoother because the shaking of the wheel's shaft is reduced. The structure of two bearings can withstand greater force. The coupling will insulate the possible tangential force from the wheel's shaft to protect the motor.

V. THE DESIGN OF THE CONTROL SYSTEM

Remote control is required in order to drive the robot to the environment which is difficult for human beings to explore [12]. Furthermore, to increase the efficiency, an autonomous mode is added to the system. In this case, when Kylin runs on a long flat road, it will use the autonomous mode. In this mode, Kylin will transfer into the wheel locomotion modality and run quickly to the destination. When Kylin goes into a complex environment, it is switched into the remote control mode, so the operator can control it to fulfill the task. Kylin's control system can be divided into two parts: remote control side and robot side. The robot side can be further subdivided into high-level control part, hardware control part and the mechanisms body, as shown in Fig.13.

In the autonomous mode, the real-time control of the robot is mainly done by the on-board computer. The control process is as follows: the sensors of the vehicle control side (including the binocular vision system, the laser radar system, the integrated navigation, etc.), obtain the environmental information to it; by processing, judging and decision-making, the computer will output commands and send them to the executive end; then the executive end works so that the mechanisms of the robot can move to the predetermined position. Besides, in the autonomous mode, the on-board sensors will send the environmental information back to the remote control side through transmission broadcasting station, so the operator can monitor the movement of the robot in time and conduct necessary intervention. Fig.13 shows the signal flow of this process.

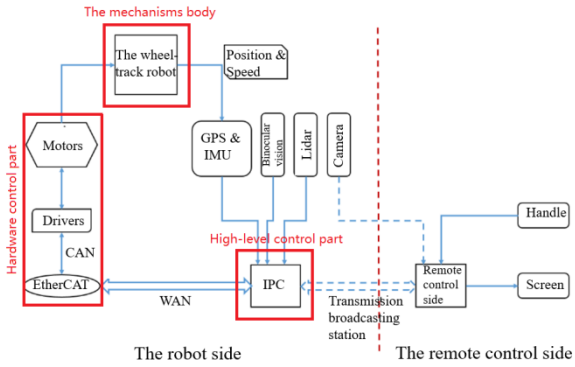


Fig. 12. The signal transmission process in the autonomous mode

In the remote-control mode, all control commands to the robot are generated by the operator. The control process is as follows: the operator acquires the surrounding environmental information of the robot through the real-time feedback information of the on-board sensors and makes a reasonable judgment; then, the operator generates control commands using the handle and transmits them to the on-board computer through transmission broadcasting station, and the commands are analyzed by the on-board computer and sent to the executive end; finally, the executive end works, so the mechanisms of the robot can move to the predetermined position. Meanwhile, the surrounding environmental information will be updated by the sensors and sent back to the remote control side, so the operator can perceive the robot's real-time state. The signal flow of this process is shown in Fig.14.

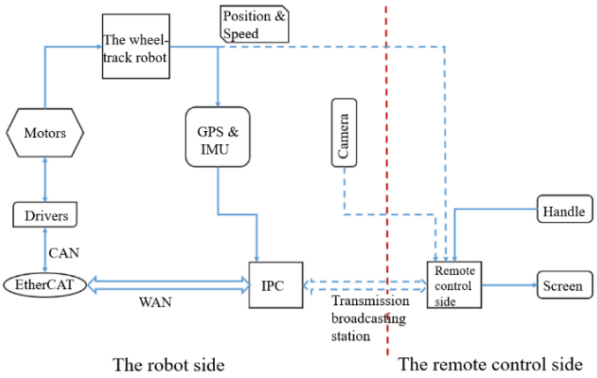


Fig. 13. The signal transmission process in the remote control mode

VI. RESULTS AND DISCUSSION

The final performance indexes of the robot are shown in TABLE II:

TABLE II. THE FINAL INDEXES OF KYLIN

Item	Index	Item	Index
Maximum speed in the track mode	0.2 m/s	Maximum speed in the wheel mode	3.7 m/s
No-load weight	33 kg	Maximum load weight	37 kg
Maximum climbing angle	45°	Maximum climbing height	52 cm

In comparison with the NuBot rescue robot, Kylin's maximum climbing height has increased from 32cm to 52cm. Due to the combination of wheels, its maximum speed is up to 3.7m/s, and the speed performance is improved greatly when running on the flat ground. What is more, for the purpose of improving Kylin's ability of going down step obstacle, we design another modular mechanism that is installed in the front fins to increase their length. As shown in Fig.15, this mechanism is somewhat like the passive wheel mechanism mounted in rear fins. To prevent unexpected sideslip of the wheels when the front fins touching the ground, we replace the omni-directional wheels by directional wheels with a large damping. As a result, after increasing the front fins' length to 87cm using this mechanism, Kylin can easily go down a step obstacle up to 1m.



Fig. 14. The wheel-track robot, Kylin, after adding increasing-length mechanism

Kylin has been tested not only in the experimental environment but also in the Unmanned Ground Vehicles Competition (UGVC 2016). There are various difficult

obstacles in the competition including the step up to 50cm shown in Fig.16, the slope up to 45° shown in Fig.17, and the cliff up to 1m shown in Fig.18, etc. In a time limit of 20 minutes, Kylin fulfilled all the tasks with the shortest time, 11minutes and 26 seconds, which verified the feasibility of Kylin's design.



Fig. 15. The wheel-track robot, Kylin, climbing the 50cm step in UGVC 2016



Fig. 16. The wheel-track robot, Kylin, going through the 45° slop in UGVC 2016



Fig. 17. The wheel-track robot, Kylin, going down the 1m cliff in UGVC 2016

However, there are still some problems that need to be solved. For Kylin itself, there are three aspects needing to be improved.

1) Kylin's body is a frame structure which is welded by hollow and square stainless-steel tubes, which largely reduces the weight and increases the seismic performance. However, when the robot passes through the sand and gravel road, there may be sand and gravel entering its body.

2) Kylin's upper loads can be replaced easily according to different requirements of different missions, because there are only eight screws used for the connection. However, due to the small size of the robot, the load space is limited.

3) Kylin's modular increasing-length mechanism in the font fins is very practical and easy to disassemble and assemble. However, since it is a cantilever structure, it cannot withstand too much force form the side.

This paper can only provide a design idea rather than a specific practice. The concrete modular mechanisms, such as the wheel-track combination mechanism and increasing-length mechanism, should be designed and simulated according to different applications.

VII. CONCLUTION

This paper presents a track-wheel hybrid robot named Kylin. Its mechanism design and control system design are introduced in details. Furthermore, this paper also attempted to convey a design idea of the modularization and combination. By the modularization and combination, there are two main advantages. One is that it can gather the advantages of different robots and form a new and more powerful robot. Another is that it can reasonably select the modules needed for the robot to complete the task according to different task requirements, and remove unnecessary modules so as to make the robot more convenient.

However, there are still some problems as we have discussed above. In the next step, we will attempt to solve these problems to realize a more powerful Kylin and obtain more useful and applicable design ideas.

REFERENCES

[1] Chung, Woojin, and Karl Iagnemma. "Wheeled Robots." *Springer Handbook of Robotics*. Springer International Publishing, 2016. 575-594.

[2] Schmidt, Daniel, and Karsten Berns. "Climbing robots for maintenance and inspections of vertical structures—A survey of design aspects and technologies." *Robotics and Autonomous Systems* 61.12 (2013): 1288-1305.

[3] Keiji Nagatani, Seiga Kiribayashi, Yoshito Okada, Kazuki Otake, and Kazuya Yoshida. "Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots." *Journal of Field Robotics* 30.1(2013):44-63..

[4] Ito, Kazuyuki, and Haruo Maruyama. "Semi-autonomous serially connected multi-crawler robot for search and rescue." *Advanced Robotics* 30.7 (2016): 489-503.

[5] Kleiner, Alexander, Fredrik Heintz, and Satoshi Tadokoro. "Special Issue on Safety, Security, and Rescue Robotics (SSRR), Part 1." *Journal of Field Robotics* 33.3 (2016): 263-264.

[6] Kleiner, Alexander, Fredrik Heintz, and Satoshi Tadokoro. "Special Issue on Safety, Security, and Rescue Robotics (SSRR), Part 2." *Journal of Field Robotics* 33.4 (2016): 409-410.

[7] Scott Kuindersma, Robin L.H. Deits, Maurice Fallon, and Russ Tedrake. "Optimization-based locomotion planning, estimation, and control design for the atlas humanoid robot." *Autonomous Robots* 40.3 (2016): 429-455.

[8] Zhiqing Li, Shugen Ma, Bin Li, Minghui Wang, and Yuechao Wang. "Design and basic experiments of a transformable wheel-track robot with self-adaptive mobile mechanism." *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010:1334-1339.

[9] Dandan Zhang, D. Wang. "WALS-robot: A compact and transformable Wheel-Arm-Leg-Sucker hybrid robot." *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2016:2584-2589.

[10] Yoon-Gu Kim, JeongHwan Kwak, Dae-Han Hong, and Jinung An. "Autonomous terrain adaptation and user-friendly tele-operation of wheel-track hybrid mobile robot." *International Journal of Precision Engineering & Manufacturing* 13.10(2012):1781-1788.

[11] Ansi Peng, Yimin Zhou, Jianbing Hu, and Yongsheng Qu. "Mechanical design for wheel/track transform mobile platform-search and rescue robot." *IEEE International Conference on Robotics and Biomimetics*, 2014:1787-1792.

[12] Yi Liu, Yuhua Zhong, Xieyuanli Chen, and Hui Zhang. "The design of a fully autonomous robot system for urban search and rescue." *IEEE International Conference on Information and Automation*, 2017.

[13] Dubbel, Heinrich, and B. J. Davies. Dubbel-Handbook of mechanical engineering. Springer Science & Business Media, 2013.

[14] Budiharto, Widodo. "Design of tracked robot with remote control for surveillance." *IEEE International Conference on Advanced Mechatronic Systems*, 2014:342-346.