Design and Implementation of Transformable Tracked Robots

Yong-cing Cheng, Pin-jui Chen, Tzu-hao Lin, and Lian-wang Lee*

***Abstract*—This study aims to create a transformable tracked robot with remote autonomous navigation control to overcome the limitations of traditional robot locomotion structures. Most robot locomotion structures available today are of a single type, which affects their mobility efficiency in complex environments. To address this problem, we aim to design a transformable tracked robot that combines the advantages of wheeled and tracked structures. We will also develop the robot's design specifications and propose a transformation structure design scheme that allows it to change its movement mode according to different terrain changes in complex operating environments. We have planned three preliminary transformable modes: full track mode for crossing road obstacles and climbing environments with high and low elevation differences, quasi-four-wheel mode for fast movement on flat roads, and elevated mode for passing through water puddles and obstacles in certain depths in the form of an elevated track. This research project also aims to propose a design scheme for remote autonomous navigation control. We will develop a LabVIEW graphical control software that uses embedded systems as the core and combines various environment information from the robot's built-in ultrasonic sensors, lidar, encoders, webcam, thermal camera, and wireless IP routers to write signal acquisition, remote control, and autonomous navigation control programs. To solve the problem of autonomous navigation return when remote control signals are lost, we will propose a design scheme that allows the tracked robot to automatically return to a location where it can receive remote control signals.**

INDEX TERMS—TRANSFORMABLE MOBILE ROBOT, REMOTE AUTONOMOUS NAVIGATION, WHEELED STRUCTURE, TRACKED STRUCTURE

I. INTRODUCTION

IN recent years, many mobile robots have been developed worldwide to make life more convenient, including home service robots, military robots for bomb disposal, and tracked robots for environmental research. Currently, the mobility of these robots can be broadly classified into three categories: wheeled, legged, and tracked. However, the terrain and environmental conditions on Earth are diverse and constantly changing, such as deserts, wetlands, stairs, steep slopes, mud, and water puddles, making it challenging for these robots to navigate and maneuver in complex environments.

Legged robots are becoming increasingly popular due to their superior obstacle-crossing abilities, and researchers are analyzing animal gaits to develop advanced legged robots that can adapt to any environment. Reference [1] focuses on the development of a new type of crawling robot that mimics the movements of quadrupeds. Parasuraman *et al.* designed a crawler capable of executing fifteen different gaits. The robot closely imitates the movement patterns of quadrupeds. Thanks to its legged design, the robot is more nimble than wheeled robots when it comes to traversing obstacles. However, its speed on flat surfaces is slower than that of wheeled robots, and each leg generates minor errors with every step, which can accumulate over time and cause problems for the robot. To overcome the inadequate obstacle-crossing ability of wheeled mechanisms, Victor Klemm *et al.* successfully combined a jumping mechanism with a wheeled robot [2] The robot is equipped with a torsion spring mechanism that can be compressed and released to make the robot jump. The center of mass of the robot is located on the same vertical line as the center of rotation of the wheels, preventing the robot from rotating during jumps and avoiding impacts on the floor outside of the wheels. To prevent damage from falls, the robot is made of a sufficiently elastic plastic material and is manufactured using 3D printing. This robot significantly improves the obstacle-crossing ability of wheeled robots due to the addition of the jumping mechanism, whereas retaining the flexibility and speed of wheeled robots. However, the lifespan of the robot components after impact from landing jumps still needs to be explored. Additionally, because the robot is driven by wheels, there is still the possibility of wheel slippage or sinking in sandy or muddy environments. To address the problem of inadequate obstacle-crossing ability and poor terrain adaptability of wheeled mechanisms, tracked mechanisms have been successfully applied to robots and deployed on the battlefield. One such robot is the Dragon Runner from QinetiQ [3]. It is a portable remote-controlled robot capable of operating in complex terrain. Weighing only 7 kilograms, it can be easily carried in a combat backpack, making it very convenient for combat operations. Equipped with four cameras, it provides continuous image transmission and receives image signals via a wireless remote control, allowing operators to monitor the situation in real-time. Additionally, the Dragon Runner has a robotic arm that can grab objects or perform bomb disposal tasks. However, since it is operated remotely, there are limitations on the distance it can be used, and the use of a tracked structure results in high energy consumption and low Mobility. Pendulum-arm tracked robots have been successfully applied in military applications, and the American company iRobot has developed a pendulum-arm robot called PackBot [4]. The pendulum-arm design increases the obstacle-crossing ability and adaptability to terrain. The robot has performed

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many reconnaissance missions in the Iraq and Afghanistan wars and is equipped with cameras, allowing soldiers to remotely control it. Depending on the mission requirements, the PackBot can be equipped with different tools, such as a robotic arm for bomb disposal tasks, or sensors such as acoustic location sensors, laser rangefinders, and infrared cameras to detect enemy positions. It has performed well in military operations, but like other tracked robots, it is also limited using tracks for movement.

There are advantages and disadvantages to various types of mobile mechanisms. Wheeled robots offer mobility, structural simplicity, speed, and high mechanical efficiency, but they have limited obstacle-crossing ability. Legged robots are highly mobile and have strong obstacle-crossing ability, but this type of robot is still in an immature state. Tracked robots have the best terrain adaptation ability, but they suffer from greater friction and slower speeds compared to wheeled and legged robots. Most existing mobile robots adopt a single structure design that can only adapt to a single type of environment, making it impossible to cope with various complex terrain changes. After discussing the above types of robots, we believe that to create a mobile robot that can operate on a wider range of terrains, we need a robot with transformable capabilities that can combine the advantages of different types of mobile structures. This is the only way to ensure that the robot maintains high efficiency across diverse terrains. Additionally, we are attempting to improve the problem of signal loss in mobile robot remote control by using autonomous navigation control.

II. Design

To enhance a robot's adaptability to varying operational environments and address the limitations of single-action structure robots, this study will focus on the robot's structure and aim to amalgamate the benefits of wheeled and tracked structures. We utilized the model concept of the parallelogram transformation structure. Next, we will design and develop the driving program for the transformable tracked robot, enabling it to smoothly transform into three modes: quasi-four-wheel mode, all-tracked mode, and elevated mode, As shown in Fig. 1. This will improve the robot's mobility, environmental adaptability, and obstacle-crossing ability. Additionally, we will incorporate autonomous navigation control technology to allow the robot to autonomously return to a location where it can receive remote control signals when signals are lost, addressing the problem of navigating autonomously when signals are lost.

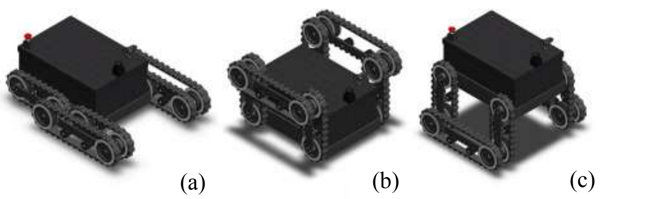

Fig. 1. Three movement mode of the robot. (a) Full track mode for crossing road obstacles and climbing environments with high and low elevation differences. (b) Quasi-four-wheel mode for fast movement on flat roads. (c) Elevated mode for passing through water puddles and obstacles in certain depths in the form of an elevated track.

A. *Tracked Robot Mechanism and Structural Design*

The robot body will have a front and rear short track arm, which will be connected by a long-tracked arm. The short, tracked arm at the front and rear will allow for the adjustment of the contact area between the tracked and the ground, achieving a quasi-four-wheel movement. The use of tracks will also allow the robot to cross water or obstacles smoothly and with less chance of overturning. The joints at the intersection of the tracks use free 360-degree rotation, and the joint connection between the tracks and the body uses a motor to control the elevation angle of the track arm. One motor can control the tracked arms on both sides, saving space and avoiding synchronization problems. DC motors will be used as the driving device for the transformation tracked robot, and a cycloidal gear reducer will be used as the transmission device to increase the output torque and save space.

We have initially planned three transformation modes for the tracked robot, including: full track mode - for crossing surface obstacles and climbing environments with high and low variations; quasi-four-wheel mode - for fast movement on flat surfaces in a wheel-like manner; elevated mode - for passing through water or obstacles in a raised track form within a certain depth.

B. *Kinematic Analysis*

The transformable tracked robot in this study is broadly divided into walking motion and transforming motion. Because there are different walking conditions in different modes, mechanical analysis and data need to be obtained. For ensuring the robot can transform smoothly without getting stuck, we need to calculate the required torque to lift the tracked arm to different elevation angles. The size and weight specifications are shown in the TABLE I. The location of the symbols which were in the TABLE I is shown in Fig. 2.

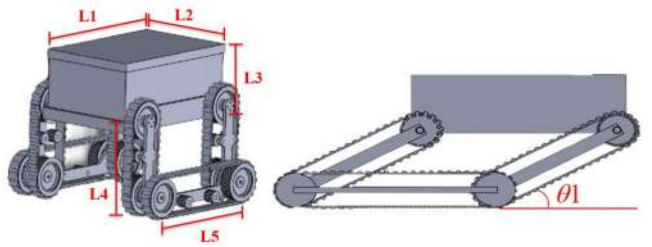

Fig. 2. Location of the symbols on the robot

TABLE I
Specification of The Robot

Symbol	meaning	value
L1	Length of the robot	600 mm
L2	Width of the robot,	400 mm
L3	Height of the robot	250 mm
L4	Length of the short track arm	300 mm
L5	Length of the long track arm	500 mm
$\theta 1$	Angle between the short arm and ground	0~180 degree
m	Weight of the robot	40 kg
m_t	Weight of the robot and payload	140 kg

The total weight of the body and four driving wheels, denoted as m, is 40 kilograms. With a short-tracked arm length of 30 centimeters, the weight of 40 kilograms is distributed evenly among the four tracked arms, meaning that each tracked arm must bear 10 kilograms. Therefore, the required torque for one tracked arm can be written as (1)

$$9.8\times 10\times 0.3\times \cos(\theta 1) \tag{1}$$

When the tracked robot tries to transform from full track mode to elevated mode, θ1 will continuous increase from 0 degree to 90 degree. We use MATLAB to analyze the required torque during the deforming phase. Fig. 3 shows the required torque for each angle of the track arm, indicating that the maximum required torque is 29.4 Nm. Based on a safety factor of 30%, the required torque for the motor is 38.2Nm.

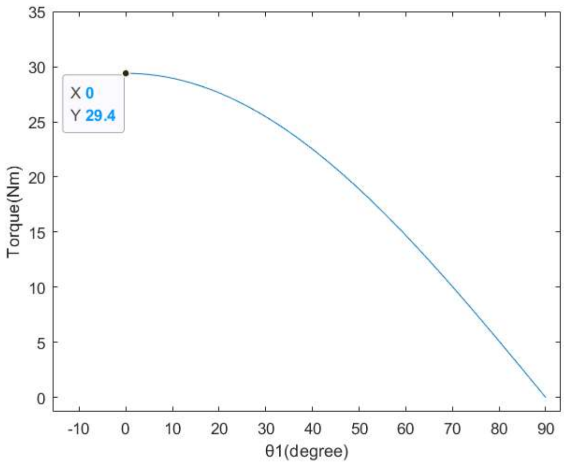

Fig. 3. The required torque of the track arm during transforming.

When the robot is in motion, the driving wheels generate a torque T to propel the robot and apply a force F on the floor. The floor then exerts a reaction force F on the track to drive the robot. It can be written as (2)

$$F=\frac{T}{r} \tag{2}$$

where F is the traction force on the track, T is the output torque of the motor, and r is the radius of the driving wheel. On flat ground, the robot needs to overcome rolling resistance. According to reference [5], the minimum resistance required for a tracked vehicle to overcome can be obtained using an empirical formula. This resistance is the minimum traction force required for a tracked vehicle, which can be written as (3)

$$P=\mathrm{R}_t+R_{in}+R_e \tag{3}$$

Where R_t is the interaction between tracks and terrain; R_{in} is the internal friction of the tracks; R_e is the external forces acting on the robot.

There are two components in R_t: tracks-ground interaction force and motion resistance. The tracks-ground interaction force can be written as:

$$R_c=b(\frac{K_c}{b}+K_\phi)\frac{z_0^{\;n+1}}{n+1} \tag{4}$$

Where R_c is tracks-ground interaction force; b is the width of the track; K_c, K_ϕ and n are characteristic parameters of the yielding terrain; Z_0 is the sinkage. The motion resistance can be written as:

$$R_b=b(0.67\cdot c\cdot z_0\cdot(N_c^{'}-\tan\phi^{'})\cos^2\phi^{'}+0.5\cdot z_0^{\;2}\cdot\gamma_s\cdot(\frac{2N_\gamma^{'}}{\tan\phi^{'}}+1)\cos^2\phi^{'}) \tag{5}$$

where c is the terrain cohesion; γ_s is the specific weight of the terrain; $N_c^{'}$ and $N_\gamma^{'}$ are the Terzaghi's modified bearing capacity factors. Finally, we can get the interaction between tracks and terrain of the n-tracks robot by combining the two components, which can be written as:

$$R_t=\sum_1^n(R_{c,i}+R_{b,i}) \tag{6}$$

The internal friction of the tracks can be estimate as:

$$R_{in}=m_t(0.222+0.0108\cdot v) \tag{7}$$

where R_{in} is internal friction of the tracks; $\mathrm{m_t}$ is the weight of the robot and the payload. and v is the speed of the robot. The external forces acting on the robot can be estimation as:

$$R_e=m_t(g+a) \tag{8}$$

where R_e is the external forces acting on the robot and a is the accelerate of the robot. We have set the payload capacity of this robot to be 100 kilograms to ensure that it can transport goods or personnel. Therefore, under the maximum payload condition, m_t would be 140 kilograms, considering the weight of the robot itself. After calculating by the (3) to (8) [5], we get the rolling resistance of the robot on dry sand is 463.7N. Once the traction force required by the robot is known, the required torque can be obtained by using (2). The radius of the robot wheel is 50 mm. From (2) can get the required torque is 23 Nm. As there are two motors to drive the robot motion, each motor requires an average torque of 11.5Nm. Based on a safety factor of 30%, the required torque for the motor is 15Nm.

C. Embedded System

The transformable tracked robot is controlled remotely and requires the transmission of environment information. To achieve this, the robot is equipped with lidar, encoders, network cameras, electronic compass, and thermal camera. The electronic component of the robot is list in TABLE II. Data is transmitted via a wireless IP router, and the operator can also send instructions to the embedded system for remote control through the same router. This robot will utilize LabVIEW to control the robot remotely with Human Machine Interface (HMI). The user can also get the information from the sensors of the robot with HMI. The human machine interface of the robot by LabVIEW is shown in Fig. 4. Besides the HMI, we also develop the control programs for remote/autonomous mode determination, environment sensing message processing, and path tracking to fulfill the control commands necessary for the transformable robot. In remote control mode, the robot will record its movement mode and track its direction and distance using an electronic compass and encoder respectively. In the event of a disconnection of the remote signal, the robot will utilize the records of movement mode, direction, and distance from the remote-control mode to navigate back along the path it originally traveled to a reconnection area, thus achieving the function of remote autonomous navigation. The flow chart for remote/autonomous navigation control of the robot is shown in Fig. 5.

In terms of hardware configuration, we use two laptops as the control system. The first laptop serves as the master computer for remote control, equipped with a HMI program written in LabVIEW. The embedded system on the robot consists of Arduino and the second laptop, which work together. Arduino primarily functions as a receiver for sensor signals and transmits them to the server computer via USB for processing and control. Communication between the two laptops is established through Wi-Fi. The server computer, acting as the lower-level controller, exchanges commands and signals with the motor driver board through signal wires to control the motors. The sensors on the robot also transmit sensor signals to Arduino through signal wires. The hardware configuration is shown in Fig. 6.

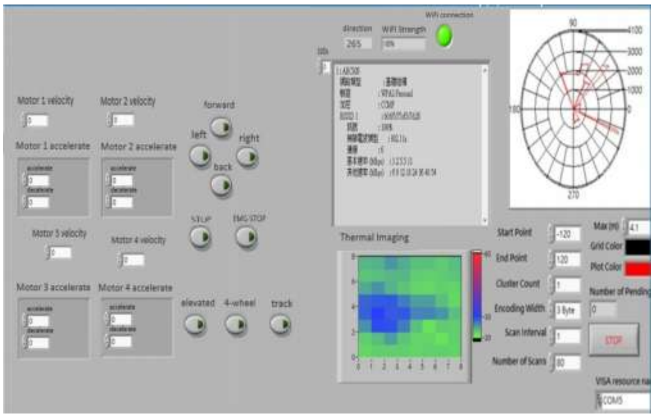

Fig. 4. The Human Machine Interface (HMI) of the robot.

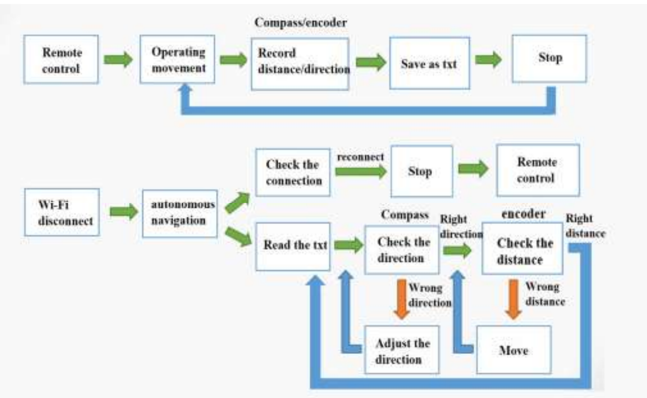

Fig. 5. The flow chart for remote/autonomous navigation control of the robot.

TABLE II
ELECTRONIC COMPONENT OF THE ROBOT

Name	Item model	Quantity
DC motor	Maxon DC motor 148867	4
motor controller	Maxon EPOS2 70/10 375711	4
encoder	Maxon encoder 110513	4
lidar	HOKUYO URG-04LX-UG01	1
webcam	Logitech c310	1
thermal camera	Adafruit AMG8833	1
electronic compass	HMC 5883L	1

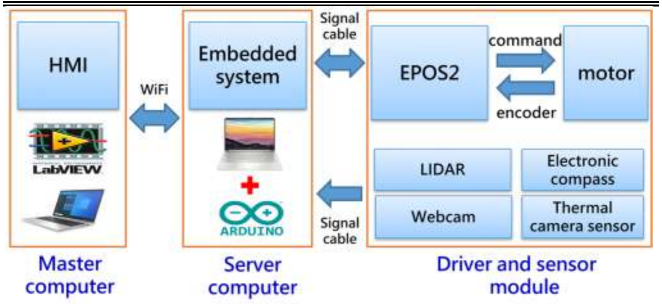

Fig. 6. The hardware configuration of the robot.

III. RESULTS OF THE TRANSFORMABLE TRACKED ROBOT

Based on the original design and specifications, the mechanism for the transformable tracked robot was manufactured, and the robot was ultimately completed as shown in Fig. 7 to Fig. 9. Fig. 7 to Fig. 9 demonstrate the three movement modes of the parallelogram design. In the full-track mode, the robot can walk on muddy or grassy terrain, and its superior mobility on such irregular terrain can avoid situations where it is limited by pits or mud. The powerful grip of the tracks allows the robot to avoid slipping. Additionally, the large contact area between the tracks and the ground allows the robot to walk more steadily on the road, making it safe to carry the weight of a person on the robot.

However, unnecessary high friction on flat roads can cause the robot to move slowly and consume a large amount of battery energy. To achieve higher speed and endurance, we have abandoned the high friction track mode and used a transformation mechanism to reduce the contact area between the robot and the ground to only four arc-shaped areas, achieving a similar effect to that of wheels. This greatly improves the robot's mobility, speed, and endurance.

Through the pictures, regardless of whether the robot is in full-track mode or quasi-four-wheel mode, its distance from the ground is very small. When encountering obstacles, the robot can only choose to detour, causing unnecessary delays. Additionally, if it encounters an impassable situation, the robot may become trapped. To address this problem, we can increase the distance between the robot and the ground through the elevated mode, allowing the robot to directly cross obstacles and avoid the problems.

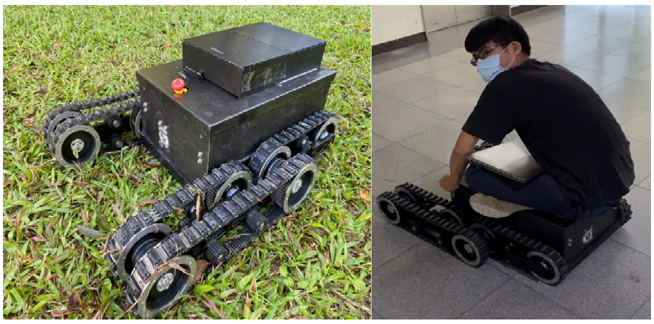

Fig. 7. In the full track mode, the transformable tracked robot can traverse terrains such as grass, sand, and mud, where wheeled robots are prone to getting stuck. The larger contact area with the ground in the full track mode provides increased stability, thereby enhancing the robot's load-carrying capacity.

Fig. 8. The four-wheel mode reduces the contact area, allowing the transformable tracked robot to increase speed and reduce energy consumption on flat surfaces.

Fig. 9. The elevated mode enables the robot to elevate its body, allowing it to directly overcome obstacles without the need for detours.

IV. Conclusion

After physical production and testing of the final product, the mobility of the variable transformable tracked robot structure has been confirmed. The video of the finished transformable tracked robot is shown in [6]. The parallelogram transformable structure used in this study can achieve the desired functionality by utilizing the different angles of the track swing arm to achieve different walking modes for the robot. Selecting the appropriate walking mode in different terrains can increase the efficiency of the robot. Through operating the robot to walk in various real terrains, the mobility of the transformable tracked robot proposed in this study has been verified. Finally, it was found that the robot can walk perfectly in various terrains when the appropriate walking mode is selected, whereas maintaining good efficiency. In addition, even when a person weighing 60 kilograms sits on the robot, it can still walk in full track mode, demonstrating its excellent load-carrying capacity. The transformable tracked robot also exhibits excellent obstacle-crossing performance in elevated mode, avoiding the problem of the robot being blocked by obstacles. The robot can also cross obstacles well in elevated mode, thanks to its transformable track design. Its sensors, including lidar, thermal camera, and electronic compass, provide users with environmental information, helping them avoid obstacles and navigate. Additionally, the electronic compass and encoder can record the robot's movement in remote control mode, facilitating autonomous return mode. The robot's remote-control mode and autonomous mode enable remote autonomous navigation. It can return along the original route to the controllable area in unstable signal areas, preventing it from getting lost. The robot can handle various terrains, and its electronic components can provide great assistance in complex environments. The function of autonomous return provides a guarantee in unstable signal areas. Overall, this robot is well-suited as a rescue robot in disaster relief scenarios and may be deployed in the field of disaster relief in the future.

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