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ORIGINAL RESEARCH

Design and control of a robotic system with legs, wheels, and a reconfigurable arm

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Abstract

Unmanned robotic systems are expected to liberate people from heavy, monotonous, and dangerous work. However, it is still difficult for robots to work in complicated environments and handle diverse tasks. To this end, a robotic system with four legs, four wheels, and a reconfigurable arm is designed. Special attention has been given to making the robot compact, agile, and versatile. Firstly, by using separate wheels and legs, it removes the coupling in the traditional wheeled–legged system and guarantees highly efficient locomotion in both the wheeled and legged modes. Secondly, a leg–arm reconfiguration design is adopted to extend the manipulation capability of the system, which not only reduces the total weight but also allows for dexterous manipulation and multi-limb cooperation. Thirdly, a multi-task control strategy based on variable configurations is proposed for the system, which greatly enhances the adaptability of the robot to complicated environments. Experimental results are given, which validate the effectiveness of the system in mobility and operation capability.

KEYWORDS

legged robots, mobile manipulation robot, reconfigurable systems, wheeled robots

1 | INTRODUCTION

Unmanned systems have attracted great attention in recent years due to their potential applications in inspection, exploration, search, and rescue, which can liberate people from heavy, monotonous, and dangerous work. A typical example is the Fukushima nuclear incident that occured in 2011, which highlighted the necessity of developing unmanned robotic systems to replace humans to enter hazardous environments. Mobility and manipulability are two fundamental skills for unmanned systems. A successful unmanned system needs to deal with complicated environments and handle diverse tasks, which requires the robot to have strong locomotion capabilities to overcome obstacles and rough terrains, as well as dexterous manipulation skills to accomplish a variety of operation tasks.

One of the challenges for unmanned systems is locomotion in complicated environments. Mobile robots typically employ a wheeled, tracked, or legged base to achieve mobility. The NASA Centaur [1] and the KUKA youBot [2] are examples of wheeled robots, that can move fast but are restricted to relatively flat ground. In contrast, tracked robots have good adaptability to irregular terrains, and have been deployed in many rescue-oriented projects, such as the ARGOS challenge [3, 4]. However, tracked robots are usually cumbersome, which may limit their use in some narrow environments. Compared to wheeled or tracked robots, legged robots [5, 6] have more degrees of freedom (DOF) and have isolated contacts with the ground, giving them great flexibility to overcome complex terrains. In 2005, the Defense Advanced Research Projects Agency (DARPA) launched the 'Learning Locomotion' programme to promote quadrupedal locomotion over rough terrain. During the programme, research teams such as the University of Southern California [7], Stanford University [8], and Institute for Human and Machine Cognition [9] have achieved amazing locomotion performance for the LitttleDog robot [10] on extremely challenging terrains, which demonstrates the feasibility and unique capability of legged robots.

Considering the respective advantages of legged robots and wheeled robots, many attempts have been made to combine them to make a wheeled–legged hybrid robot. As seen from the DARPA Robotics Challenge (DRC), which focused on semi-autonomous robots for disaster response scenarios, many teams have adopted the wheeled–legged design. Among them, NimbRo [11] has four legs that end in steerable wheels, while RoboSimian [12] utilises four general purpose limbs with active and passive wheels that can be used in a sitting posture. The final winner, DRC-Hubo [13], which is a humanoid robot, has also employed active and passive wheels in both knees and ankles. By utilisation of the wheeled–legged design, the robot is able to leverage fast motion over flat ground by wheels as well as transverse rough terrains by legs. Motivated by this idea, the biped robot Handle [14] from Boston Dynamics and the quadruped robot Anymal [15] from ETH Zurich have added active wheels to their legs, which greatly improves their moving speed over flat ground and even on slopes and stairs. Besides, a centaur-like robot, CENTAURO, [16] which has four legs and a humanoid upper body, and a wheel-track-leg hybrid robot [17] are also equipped with wheels at the end of each leg. These robots have presented us with a new possibility to achieve highly agile and versatile locomotion, which is very important for real-world applications that require rapid and long-distance movement on challenging terrain.

Despite the advantages of wheeled–legged robots, most of them tend to place the wheels at the end of each leg, which may have a negative impact on their locomotion capability. On the one hand, the wheels add weight to the leg, which is unfavourable for the motion control of the centre of mass (CoM) since a heavy leg has a non-negligible influence on the CoM motion during a leg swing. On the other hand, those robots have a relatively high CoM position when running on wheels, which more likely makes the robot fall due to disturbances.

The other challenge for unmanned systems is to handle diverse operation tasks. While a wheeled or tracked robot can be easily attached with one or more manipulators, legged robots usually have limited space and payload capability for a manipulator. Although NimbRo [11] and CENTAURO [16] are equipped with two 7-DOF arms, the additional weight of the arms may degrade their locomotion efficiency. In contrast, RoboSimian [12] adopts four general purpose limbs with 7 DOFs, which can be used not only as arms but also as legs. However, when used as legs, the joints are redundant and may provide degraded performance. Other quadruped robots like Anymal [15] and MIT Cheetah [18], can use their 3-DOF leg to perform simple manipulation, such as pressing an elevator.

Motivated by the systems mentioned above, we intend to design a mobile manipulation system that is compact, agile, and versatile. On the one hand, to achieve good mobility, we make use of the wheeled–legged concept while separating the wheels and legs by mounting the wheels directly under the torso of the robot. In this way, the couplings between the wheels and legs are removed, which guarantees highly efficient locomotion in both wheeled and legged modes. On the other hand, to obtain good manipulability, we intend to take full advantage of the legs and simultaneously add some extendibility to the system, particularly for more delicate manipulation. Recently, reconfigurable modular robots [19] have attracted much attention. With specially designed connecting mechanisms, robots that provide a convenient way to extend the robot physically can be reconfigured [20, 21] or self-assembled [22, 23]. Inspired by the modular robot concept, we design a 3-DOF reconfigurable arm for the system, which can be connected with one of the legs and turned into a 6-DOF manipulator. In this way, it reduces the weight for the robot and allows the robot to perform dexterous operations. Besides, the other legs can also cooperate with the reconfigured manipulator to accomplish some coordination tasks. Based on the proposed system, a multi-task control strategy is particularly developed for this purpose considering its capability to have multiple configurations. The feasibility of the proposed system and the effectiveness of the proposed control strategy are demonstrated through several experimental trials.

The main contributions of this study are summarised as follows:

1. The design of the separated wheels and legs removes the coupling in the traditional wheeled-legged system and improves the efficiency in wheeled and legged locomotion.
2. The leg–arm reconfiguration design maximises the utilisation of the legs, which not only reduces the total weight but also allows for dexterous manipulation and multi-limb cooperation.
3. A multi-task control strategy based on variable configurations greatly enhances the adaptability of the robot to complicated environments.

The remainder of this study is organised as follows: Section 2 describes the main components of the system and Section 3 presents the multi-task control strategy with variable configurations. In the Section, three kinds of gaits are designed for quadrupedal locomotion. Section 4 gives the experimental and simulation results to verify the capabilities of the system. Conclusions are given in Section 5.

2 | HARDWARE DETAILS

2.1 | Design concept

The final goal of the proposed robotic system is mainly for rescue and we have achieved some preliminary results. The basic requirements for the system are as follows:

(1) The system is capable of moving in complicated environments, such as stairs, slopes, gaps, obstacles, and uneven ground.
(2) The system can achieve high-speed movement in flat ground.
(3) The system can handle basic operation tasks, such as door opening, key pressing, and grasping.

To fulfil the above requirements, we adopt a step-by-step design strategy and go through several design iterations, which is shown in Figure 1. In the first step, we design a quadruped robot ‘THU-QUAD I’ [24]. The leg links are made of aluminium alloy and are connected with no offset. It is found that the robot is too heavy, and the range of motion for the knee joint is limited to about 180°, preventing the robot from sitting down. After that, we design the second prototype robot ‘THU-QUAD II’ [25, 26]. This time, we use carbon fibre for the leg links, and a new linking mechanism with offset is used, making the knee joint gain a wider range of motion up to 330°, which allows the robot to have multiple configurations. We also add wheels under the torso to enable fast movement. However, it is found that the wheels interfere with the legs, and the torso is too long, which easily vibrates during walking. Therefore, in the third design, we shorten the length of the torso and reposition the wheels to the outside of the hip motors. Besides, a reconfigurable arm is added to the robot. This leads to the latest prototype robot ‘THU-QUAD III’.

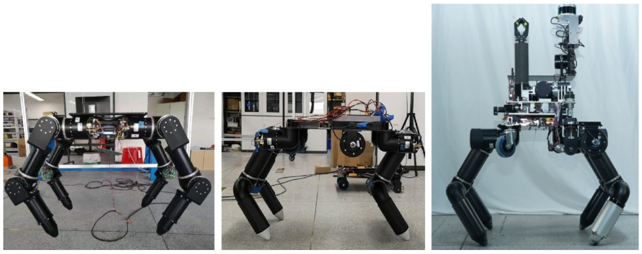

(a) (b) (c)

FIGURE 1 The design iterations. (a) THU-QUAD I. (b) THU-QUAD II. (c) THU-QUAD III.

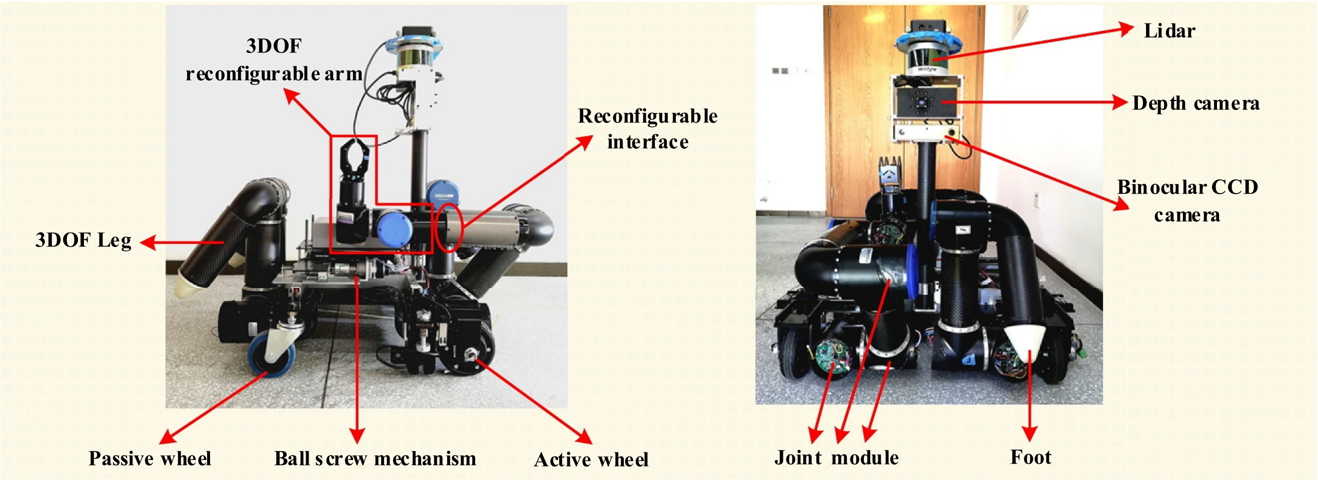
Although THU-QUAD III is not highly dynamic compared to other quadruped robots such as the MIT Cheetah [18], it is more versatile thanks to the multi-configuration design.

The main components of the THU-QUAD III are shown in Figure 2. The robot has four legs with 3-DOF, four wheels (2 active and 2 passive), and a reconfigurable arm with 3-DOF, which can be connected with one of the legs to form a 6-DOF manipulator.

2.2 | Leg

The CAD graph of the leg is shown in Figure 3. This robot adopts the classical roll-pitch-pitch structure for each leg. The upper and lower links of each leg have an equal length of 30 cm. To guarantee a wide range of motion for the knee joint, a linking mechanism with the offset is used. This allows the robot to have multiple configurations. To reduce the overall weight, carbon fibre tubes are adopted for all the straight links. The foot is designed in the shape of a cone with a spherical tip and is covered with a 3D-printed polyethylene shell to prevent slip.

To simplify the design process, we use Kollmorgen's RGM20 robotic joint modules (see Figure 4) for all the leg joints. The joint module is highly integrated, and combines a frameless torque motor, low voltage DC drive, brake, strain wave gear, dual feedback system, and thermal sensor in a single joint assembly, which can be conveniently used in a robot configuration.



(a) (b)

FIGURE 2 The THU-QUAD III robot. (a) Side view. (b) Front view.

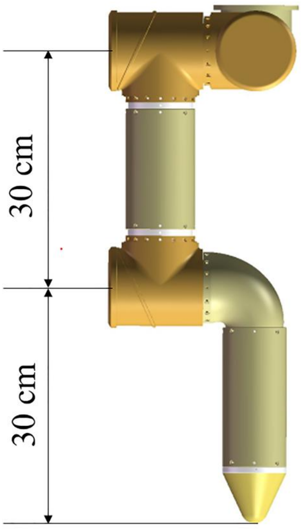


FIGURE 3 The CAD graph of the leg.

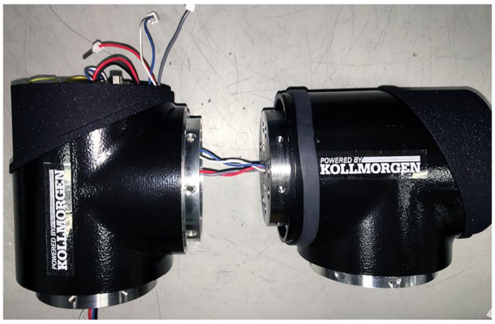


FIGURE 4 Kollmorgen's robotic joint module.

TABLE 1 RGM specifications

Specifications	RGM14	RGM17	RGM20	RGM25
Weight (kg)	1.48	1.97	2.56	4.20
Continuous torque (Nm)	13.5	49	61	118
Speed at continuous torque (RPM)	20	20	15	10

Kollmorgen offers the joint module in four different sizes, as listed in Table 1. Considering the weight and torque requirements, we finally select RGM20 for all the leg joints. Through simulation (see attached Video S1), it is found that the robot can sustain about 40 kg additional payload except its own weight (about 42 kg), which can fulfil our basic requirements. Similar to CENTAURO [16], our robot has a low-speed joint and is mostly position-controlled, which can transform between different configurations reliably and accurately. However, one drawback is that it cannot walk very dynamically.

2.3 | Arm

To enable the robot to perform delicate operations while maintaining a relatively low weight and compact layout at the same time, a reconfigurable arm is designed, and a leg-arm docking mechanism is adopted, as shown in Figure 5.

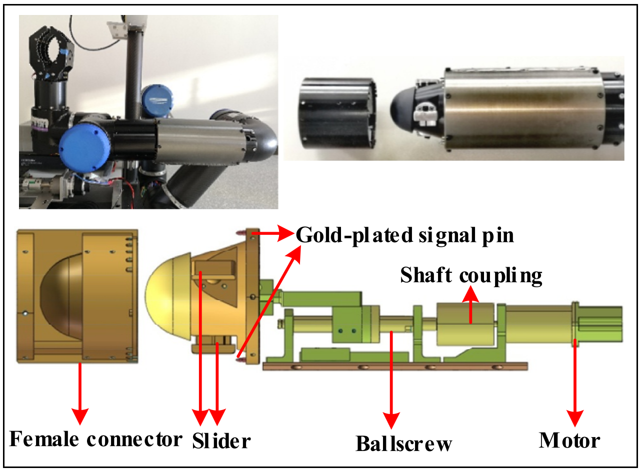


FIGURE 5 The docking mechanism of the leg-arm interface.

The 3-DOF arm is placed on a linear guideway on the torso, which is driven by a ball screw mechanism that allows the arm to shift forwards and backwards. One of the feet is particularly designed with three telescopic sliders around it, which are controlled by a motor inside the leg. Correspondingly, there is a female connector on the arm side, which has a circular groove inside. During docking, the foot is carefully positioned to remain aligned with the female connector, and then the sliders stretch out until they are locked with the female connector. The signal transmission and power supply of the arm are achieved through several gold-plated signal pins on the foot.

2.4 | Torso and wheels

To maintain a low weight without the loss of strength, the torso of the robot is made up of a carbon fibre board with a '#' shaped aluminium rib attached to the board. For the wheels, two active wheels are mounted in the front of the torso, and two passive wheels are mounted at the back. To avoid interference with the legs, the wheels are mounted outside of the hip joint of each leg. The active wheel is driven by a hub motor. The wheel has a diameter of 13 cm, a rated torque of 3.2 Nm, and a rated speed of 800 RPM. It allows the whole system to run at a maximum speed of 15 km/h.

2.5 | Head

The head of the robot is supported by a carbon fibre tube. It is currently equipped with a 3D LIDAR on the top, a depth camera in the middle, and a binocular CCD camera at the bottom, which can provide basic sensory feedback for location and guidance.

3 | CONTROL ARCHITECTURE

3.1 | Configuration switch

The design of THU-QUAD III has paid special attention to achieving a wide range of motion for all joints, which allows it to have multiple configurations.

The features of different leg configurations have been investigated in Ref. [27]. In general, each configuration may have an advantage in a particular environment. Therefore, the existing quadruped robots have adopted different configurations. The TITAN robot [28] uses a sprawling-type configuration, while the majority of reported quadruped robots belong to a mammal-type configuration. For example, LittleDog [10] and Anymal [15] adopt an inward-standing configuration, while the MIT Cheetah [18] uses a backward-standing configuration. Considering that our robot is able to perform all the configurations, it becomes possible to change configurations when in different environments. Therefore, a multi-task control strategy is proposed in the following.

Based on the seven basic configurations, we study their relationships and draw the diagram of the configuration switch in Figure 6. It can be observed that the four kinds of mammal-type configurations can transform into each other conveniently, while the wheeled configuration can be exchanged with the mammal-type configurations through the outward-standing configuration.

3.2 | Legged locomotion

Three categories of gaits are designed. Two of them are mammal-type gaits that can be applied to all mammal-type configurations, including a walking gait for level ground and a climbing gait for stairs. The remaining gait is the sprawling-type gait, which is called the crawling gait here and is used for gap, slope, and uneven terrain. The match between different gaits and terrains is also shown in Figure 7.

To cover environments with different sizes, all the gaits are designed into standard parametric gaits where the gait parameters can be adjusted to adapt to different environments.

3.3 | Leg–arm reconfiguration

In the wheeled-type configuration, the robot can transfer into the manipulation mode by connecting the reconfigurable arm with the associated leg to construct a 6-DOF manipulator. The leg–arm reconfiguration process is depicted in Figure 8 and is described as follows (a Video S2 is also provided):

(1) From Figure 8a,b: The leg rotates such that the foot is aligned with the female connector in the arm.
(2) From Figure 8b,c: The motor under the arm drives the guide rail together with the arm to move towards the foot until the signal pins on the foot are firmly connected with the holes in the female connector.

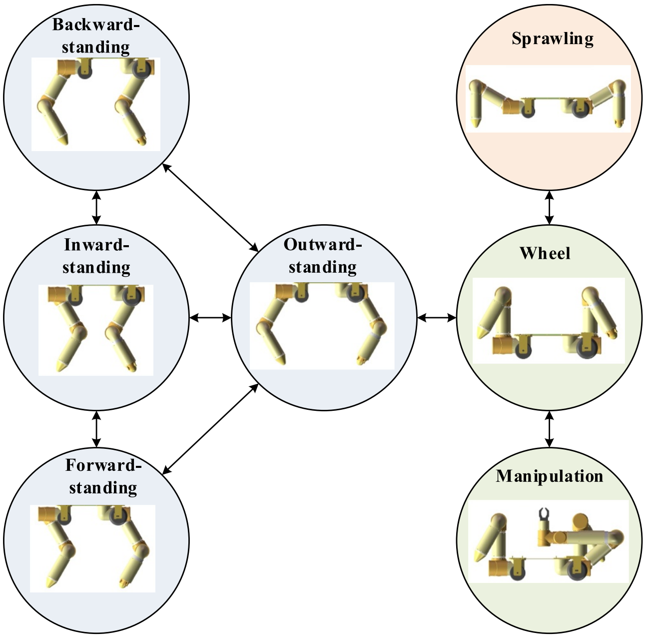


FIGURE 6 Diagram of configuration switch.

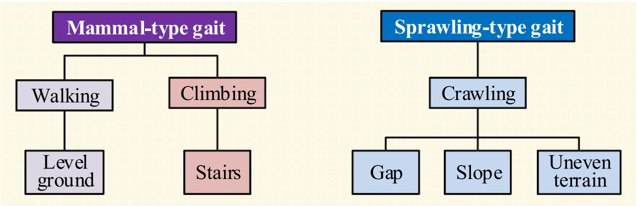


FIGURE 7 Match between different gaits and terrains.

(3) From Figure 8c,d: The sliders around the foot stretch out until locked with the female connector, then the guide rail moves 4 cm backward to leave some space between the annular base and the arm.
(4) From Figure 8d,e: The leg–arm docking completes and the reconfigured manipulator leaves the base for manipulation.
(5) From Figure 8e,f: The manipulator is placed on the base after manipulation, and the guide rail moves backwards to disconnect the arm from the leg.

3.4 | Manipulation control

For manipulation control, a teleoperation framework is developed based on the V-REP software. The user can control the reconfigured robotic arm through a joystick. There are two basic operation modes for the robotic arm, including the task-space and joint-space modes. In the task-space mode, the end effector can move or rotate along each direction in the reference coordinate. To make it more convenient for the operator, two reference coordinates are provided, including the base coordinate and the end effector coordinate, which can switch

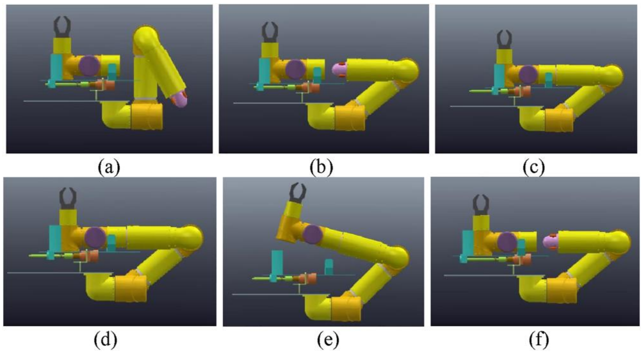


FIGURE 8 The leg–arm reconfiguration process. (a) Initial configuration. (b) Leg aligned with arm. (c) Leg connected with arm. (d) Holder leaves the arm. (e) Manipulator leaves the base. (f) Manipulator separates after manipulation.

through the button in the joystick. In the joint-space mode, we have provided several predefined configurations for the arm so it can switch to different configurations conveniently.

4 | EXPERIMENTAL RESULTS

To verify the capability of the robot, we apply the proposed control strategy to the robot through teleoperation as shown in Figures 9 and 10.

Firstly, a simulation model of the robot and the environment is built in the V-REP software. The simulation scenes for walking, stairs climbing, and manipulation are shown in Figure 11. The control strategy is applied through the Lua script within the V-REP software. Secondly, the joint angles are generated as the simulation runs, which are sent to the real robot through RF wireless modules. Then, the real robot tracks the received angle data to make movements. At the same time, the visual sensors on the robot detect the environment and send real-time sensing data to the operator. The operator then makes decisions and selects actions for the robot in real time. For example, the operator can select the approximate configuration or gait parameters such as the step length in each gait cycle. In this way, it forms a human-in-the-loop control, which facilitates the robot to accomplish different tasks.

In V-REP, we have adopted two ways for joint movement control, which includes task-space control and joint-space control. The task-space control is achieved by using the damped least squares inverse kinematics algorithm in V-REP. For the joint-space modes, the joint angle follows a desired trajectory $c_r = c_0 + (c_1 - c_0) \times t/T$ (t: $0 \to T$), where c_0 is the initial joint angle, c_1 is the target joint angle, and T is the time period to accomplish the configuration switch. We have predefined several configurations for the limbs so that the robot can switch between different configurations conveniently. The two control modes are applied alternately according to the tasks.

In the following, the experimental results are presented. Video S3 is also provided. It should be noted that all the experimental tasks are performed without any interruption.

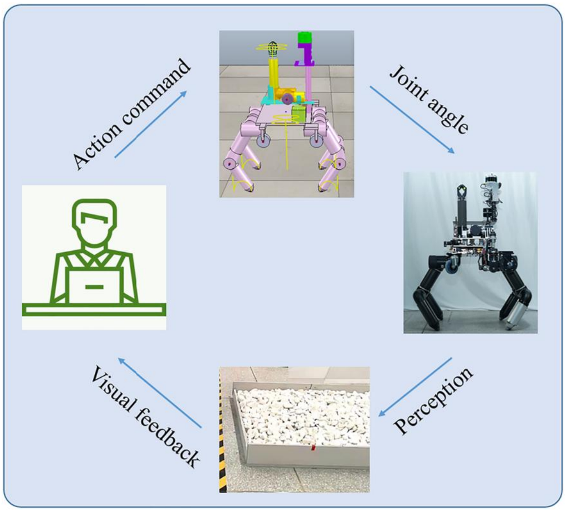
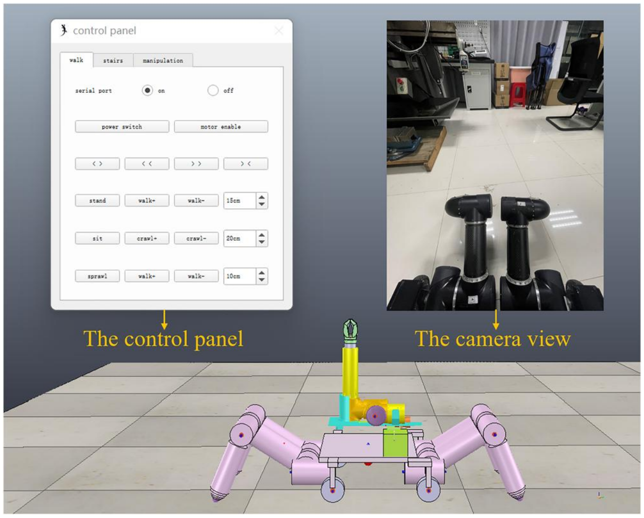


FIGURE 9 The teleoperation workflow.



serial port ● on ○ off

15cm
20cm
10cm

FIGURE 10 The operator's view during teleoperation.

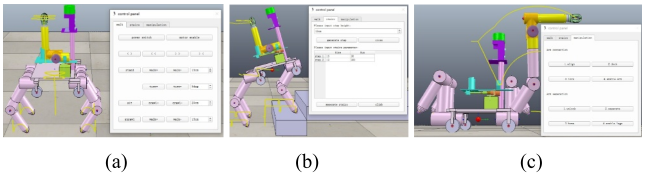

(a) (b) (c)

FIGURE 11 The simulation scenes. (a) Walking. (b) Stairs climbing. (c) Manipulation.

4.1 | Basic motion test

An experiment is carried out to test different configurations of the robot and the basic motions. The snapshots of different configurations are shown in Figure 12.

The robot is initially in the wheeled-type configuration. Then it stands up and relocates each foot to transfer into the

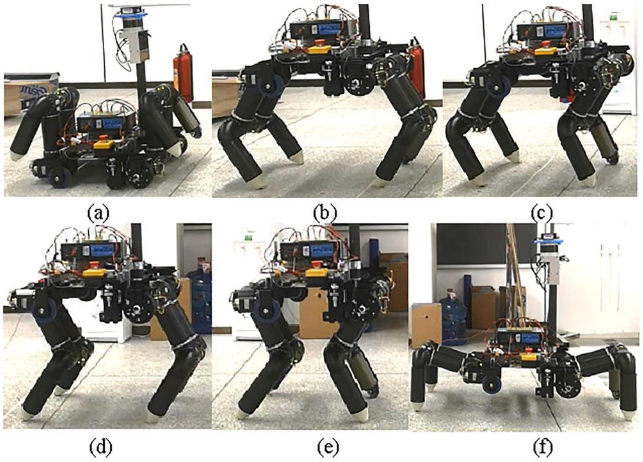


FIGURE 12 Snapshots of different configurations. (a) Wheeled. (b) Outward-standing. (c) Backward-standing. (d) Forward-standing. (e) Inward-standing. (f) Sprawling.

outward-standing configuration. Next it successively converts to the backward-standing, forward-standing, and inward-standing configurations by reversing the leg directions. It walks two steps in each configuration. After that, it recovers the wheeled-type configuration and crawls on the ground for a certain distance. Finally, it moves back and forth using wheels. This experiment verifies that the robot can nimbly switch between different configurations and can do locomotion under each configuration. In a gait cycle, the robot can walk 20 cm in 8 s, which indicates a walking speed of 0.025 m/s.

4.2 | Locomotion tasks

Several experiments in different scenarios are carried out to verify the locomotion capability of the robot. The first scenario contains two steps with a height of 15 cm and width of 30 cm, followed by a slope of 15°. The robot successfully passes the stairs and slope with the climbing gait through the tele-operation of the swing leg height and the step length. Figure 13 shows snapshots in this scenario. It can be seen that the robot first transfers to the backward-standing configuration to climb the stairs and then transfers to the sprawling configuration on the top platform to crawl down the slope. The time for climbing stairs shown here is 64 s. This experiment verifies the effectiveness of the climbing and crawling gaits.

The second scenario is a doorsill-type obstacle with a height of 21 cm and a width of 28 cm. The climbing gait is used here, and it takes full advantage of the configuration switch strategy. Figure 14 shows the snapshots in this scenario. It can be seen that the robot changes its configuration twice. One is when the front feet step on the doorsill, where the robot switches from backward-standing to outward-standing. The other is when the hind feet step on the doorsill, where the robot switches from outward-standing to forward-standing. In this way, the robot prevents its legs from colliding with the doorsill, which contributes greatly to its success in surmounting such challenging obstacles.

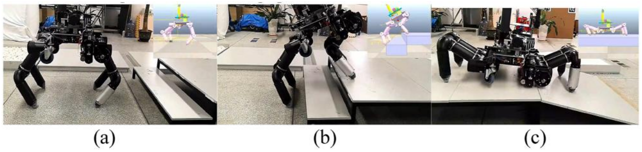


FIGURE 13 Snapshots of the stairs and slope task. (a) Robot arrives at the stairs. (b) Robot climbs stairs. (c) Robot crawls down slope.

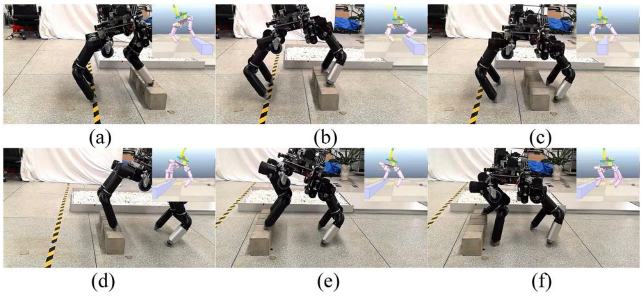


FIGURE 14 Snapshots of the obstacle crossing task. (a) Robot front feet step on the obstacle. (b) Robot transforms to outward-standing configuration. (c) Front feet step down. (d) Hind feet step on the obstacle. (e) Robot transforms to forward-standing configuration. (f) Hind feet step down.

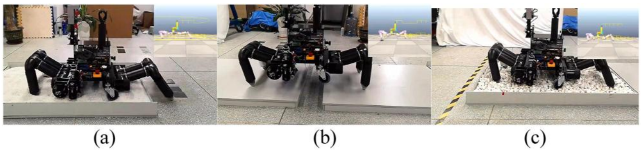


FIGURE 15 Snapshots of the sand, gap, and stones task. (a) Robot crawls on sand. (b) Robot transverse gap. (c) Robot crawls on stones.

The third scenario contains sand in a wooden case, a 20 cm gap, and stones in a wooden case. The robot transfers to the sprawling-type configuration and uses the crawling gait to transverse the obstacles, as shown in Figure 15. We find that the robot can move very well over uneven terrain in this way, which verifies the effectiveness of the crawling gait.

4.3 | Manipulation tasks

Several tasks are designed to test the manipulation capability of the robot. The robot needs to open a door to enter a room, then press keys on the safe box to open it and take out a target object. A cooperative manipulation strategy (using the leg to press keys and using the arm for door opening and grasping) is applied to accomplish this task. The snapshots are shown in Figure 16.

The details in Figure 16 are as follows: (a) the robot grasps the door handle using the manipulator and screws the handle to loosen the door; (b) The robot pushes the door; (c) The robot passes the door and approaches the safe box; (d) The robot uses the leg to press the numbers on the box to enter the password, which unlocks the safe box; (e) The robot pulls the door of the safe box using the manipulator; and (f) The

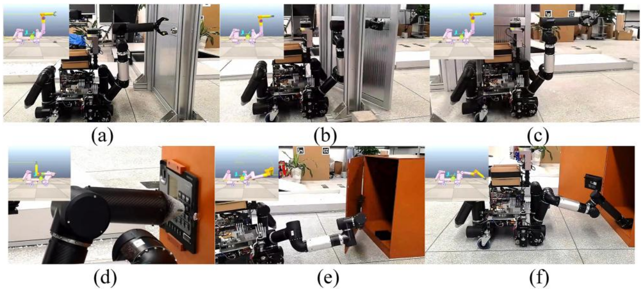


FIGURE 16 Snapshots of manipulation tasks. (a) Robot hand reaches door handle. (b) Robot pushes the door. (c) Robot goes to the safety cabinet. (d) Robot press keys with foot. (e) Robot opens cabinet door. (f) Robot grasps object in the cabinet.

robot grasps the object using the gripper and transfers it to the container on the torso. This experiment verifies the manipulation capability of the reconfigured robotic arm.

5 | CONCLUSIONS

This paper presents the design details and control strategy of a robotic system named THU-QUAD III. The robot is designed for rescue and we have paid special attention to making the robot compact, agile, and versatile. To achieve good mobility, the robot is equipped with four legs and four wheels, which are mounted separately to reduce coupling between legged and wheeled locomotion. The mechanical design ensures a wide range of motion for all the leg joints, which allows the robot to have multiple configurations. A multi-task control strategy based on variable configurations is proposed, which greatly enhances the adaptability of the robot to complicated environments. To achieve good manipulability, a reconfigurable arm is particularly designed for the robot, which can be connected with one of the legs and turned into a 6-DOF manipulator. Several experiments verify the capabilities of the system, which can transverse obstacles, stairs, slopes, gaps, and uneven ground as well as open doors, press keys, and grasp objects. However, the prototype shown in this study is still a preliminary result. In the future, we will focus on enhancing the IP (Ingress Protection) rating of the robot to IP66 and improving the robot's agility by using higher power density motors and force control.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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