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Multi-task Control for a Quadruped Robot with Changeable Leg Configuration

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Abstract—**This paper proposes a multi-task control strategy for a quadruped robot named THU-QUAD II. The mechanical design of the robot ensures a wide range of motion for all joints, which allows it to stand and walk like a mammal as well as sprawl to the ground and crawl like a reptile. Five basic leg configurations are defined for the robot, including four mammal-type configurations with bidirectional knees and one sprawling-type configuration. A multi-task control framework is developed by combining configuration selection and gait planning. According to the locomotion environments, the robot can nimbly switch between different configurations, which gives it more flexibility when facing different tasks. For the mammal-type configuration, a parametric climbing gait is designed to traverse structural terrain. For the sprawling-type configuration, a crawling gait is designed to achieve robust locomotion on uneven terrain. Simulations and experiments show that the robot is capable to move on multiple challenging terrains, including doorsills, stairs, slopes, sand and stones. This paper demonstrates that even some challenging locomotion tasks can be achieved in a rather simple way without using complicated control algorithms, which suggests us to rethink about the leg configurations in designing quadruped robots.**

I. Introduction

Quadruped robots are biologically inspired from four-legged animals, which are considered to be more capable of traversing rough terrains than wheeled or tracked robots. The major groups of four-legged animals include mammals (dogs, horses), reptiles (lizards, turtles) and amphibians (frogs, toads). Similarly, quadruped robots can be classified into two groups according to their leg configurations, including a mammal-type which mimics mammals and a sprawling-type which mimics reptiles or amphibians [1].

The majority of reported quadruped robots belongs to a mammal-type, which walks with its body relatively high from the ground and locates its foot downward from the body. This allows the robot to walk fast and step over large obstacles. For mammal-type quadruped robots, they can further be divided into several subtypes according to the bending direction of their legs. For example, a forward/backward configuration [2] means the hind legs bending forward while the front legs bending backward. This type includes HyQ [2], BigDog [3], LittleDog [4], StarlETH [5], Anymal [6], etc. Another popular type is the backward/backward configuration, with the typical examples like Spot, Vision 60, Laikago, MIT Cheetah [7], etc. The features of different leg configurations have been investigated in [8, 9]. In general, each configuration may have some advantages on a particular environment. It seems that no one configuration can win out in all environments. For example, from the perspective of collision avoidance, the backward/backward configuration may be most suitable for going upstairs while the forward/forward configuration might be best for going downstairs. Therefore, we realize that a changeable-configuration design could be very helpful to handle multi tasks. Technically speaking, the capability to change configuration mainly depends on the range of motion for the joints. To our knowledge, most of the existing quadruped robots are unable to change configuration due to the joint angle limitations. However, MIT Cheetah and Anymal are two exceptions. MIT Cheetah uses a belt drive and has shown the capability of changing configuration in their test video [10], while the leg links of ANYmal [6] are built with an offset such that all joints can be fully rotated and thus allows for various configurations.

Unlike the mammal-type robots, a sprawling-type quadruped robot keeps their body close to or even against the ground while walking. This makes the robot highly stable and robust to disturbances from uneven ground. Additionally, even if the robot falls, the damage to the robot is relatively small. Typical robots belong to this type are the TITAN series robots built in Tokyo Institute of Technology [11], with the latest version to be TITAN-XIII [12]. Through decades of evolution, TITAN has gained the capability to walk on steep slopes, stairs, and surmount substantial obstacles.

Considering the advantages of both mammal-type and sprawling-type quadruped robots, it is naturally to think about integrating them into one robot with changeable leg configuration. After all, more configurations mean more possibilities. To this end, a prototype quadruped robot named THU-QUAD II was built in Tsinghua University for demonstration. A special emphasis was put on its configuration-changing capability to help it achieve a wide range of locomotion tasks. Till now, the most relevant work might be ANYmal [13], which can use various configurations to operate in harsh environments. Besides, the LittleDog robot can use some unusual gaits to climb over obstacles nearly as tall as the robot's legs [14]. However, the topic on configuration transformation and the relationship between different configurations and environments have not been investigated systematically yet. Therefore, this paper intends to elaborate more on this topic. Firstly, it is comprehensively illustrated how to conduct configuration switch between the mammal-type and sprawling-type configurations, or within

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the four kinds of mammal-type configurations. Secondly, a multi-task control framework is developed by combining configuration selection and gait planning, which gives more flexibility to the locomotion control of quadruped robots. Thirdly, based on the multi-task control framework, locomotion strategies are proposed for several typical environments, including doorsills, stairs, slopes, and uneven terrains, which are demonstrated through several simulations and experiments.

The main contributions of this paper are twofold. Firstly, a modular quadruped robot "THU QUAD II" is designed using integrated joint modules. Unlike most existing quadruped robots, the robot is able to exhibit multiple configurations thanks to its wide range of motion for all joints. Secondly, some heuristic rules are proposed to choose the leg configuration and corresponding gait to achieve movement over certain terrains. It is shown that even some challenging locomotion tasks can be achieved in a simple way without using complicated control algorithms, which demonstrates the advantages of the variable-configuration design for quadruped robots.

The remainder of this paper is organized as follows: Section II introduces the prototype quadruped robot THU-QUAD II. Section III presents the multi-task control strategy. Section IV presents three types of gaits for the robot. Section V gives the simulation and experimental results. Conclusions are given in Section VI.

II. PROTOTYPE QUADRUPED ROBOT WITH CHANGEABLE LEG CONFIGURATION

The aim of the quadruped robot project in Center for Artificial Intelligence and Robotics, Tsinghua University is mainly for rescue, thus it requires the robot to have strong locomotion capability and can endure a high payload. For this purpose, the first generation quadruped robot, THU-QUAD I [15] was built in 2019 as shown in Fig. 1(a). The robot uses 12 Kollmorgen's RGM robotic joint modules, which makes the robot modular and easy to assemble. Due to the linking mechanism, the range of motion for the knee joint is limited to about 180°, preventing the robot from some configurations such as sitting down. To solve this problem, the new version "THU-QUAD II" was built in late 2019 as shown in Fig. 1(b).

(a) THU-QUAD I (b) THU-QUAD II

Fig. 1. Quadruped robots in Center for Artificial Intelligence and Robotics, Tsinghua University.

As can be seen from Fig. 2, THU-QUAD I adopts a "L"-shaped link mechanism, which prevents the joint from large rotations due to the mechanical interference. Instead, THU-QUAD II uses a new linking mechanism with offset, making the knee joint to gain a wider range of motion up to 330°.

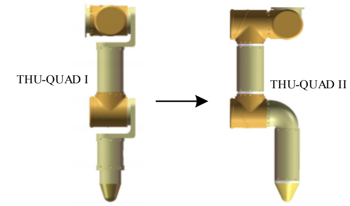

Fig. 2. Leg evolution from THU-QUAD I to THU-QUAD II. The linking mechanism with offset enlarges the range of motion for the joint, which contributes to the configuration-changing capability of THU-QUAD II.

Thanks to the new linking mechanism, THU-QUAD II gains the capability to have multiple configurations as shown in Fig. 3. Addtionally, THU-QUAD II is equipped with 4 wheels under the body, including two active wheels and two passive wheels, which can be used to drive the robot at a high speed on level ground and can also support the robot's body during sprawling-type locomotion. It should be noted that the location of the wheels is rearranged in Fig. 3 to avoid interference with the legs, which has not been applied to the physical robot yet. The specifications of THU-QUAD II are given in Table I.

Fig. 3. THU-QUAD II in different configurations.

TABLE I

SPECIFICATIONS OF THU-QUAD II

Size (L × W × H, fully stretched legs)	0.72m×0.4m×0.6m
Weight	45kg (about 8 kg for each leg)
Number of joints	12 (3 per leg, including HAA, HFE, and KFE)
Range of Motion	HAA: 360° , HFE: 330°, KFE: 330°
Joint Speed at Continuous Torque	15rpm
Joint Continuous Torque	61Nm
Payload	20kg

We define five basic configurations for THU-QUAD II, including four kinds of mammal-type configurations and one sprawling-type configuration as shown in Table II.

TABLE II

CONFIGURATIONS OF THU-QUAD II

Configuration		**Definition**
Mammal-type	Outward-standing	Standing with front legs bending forward and hind legs bending backward
	Inward-standing	Standing with front legs bending backward and hind legs bending forward
	Forward-standing	Standing with all legs bending forward
	Backward-standing	Standing with all legs bending backward
Sprawling-type	Sprawling	Sprawling with knees above body

Fig. 4 shows the four kinds of mammal-type configurations, where the robot's body is relatively high and has advantages to cross large obstacles. From the perspective of collision avoidance, there are little difference between the four configurations when walking on level ground. While in some particular scenarios, one of the configurations can be much better than the others. For example, when going upstairs or uphill, the backward-standing configuration is the best since it can avoid the shank to collide with the staircase or the slope. On the contrary, the forward-standing configuration is the best when going downstairs or downhill for the same reason. Besides, in some special cases such as the two shown at the bottom of Fig. 3, outward-standing and inward-standing may become the best option, respectively.

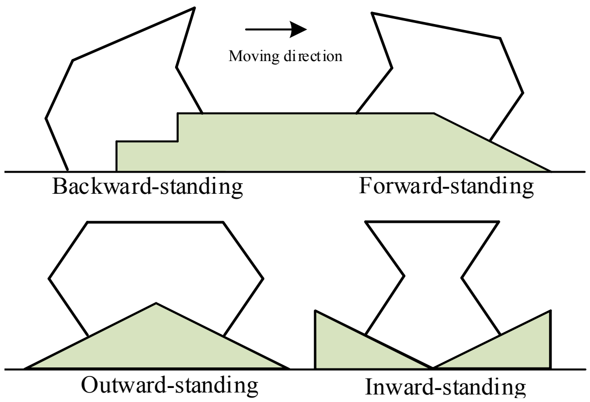

Fig. 4. Four kinds of mammal-type configurations.

Fig. 5 shows the sprawling-type configuration, where the robot can either support its body with legs or wheels. The main feature of this configuration is that the robot has low center of gravity which helps the robot gain more stability against disturbances from uneven terrain.

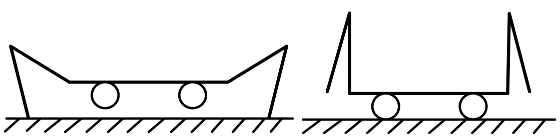

Fig. 5. The sprawling-type configuration.

III. THE MULTI-TASK CONTROL FRAMEWORK

The locomotion tasks considered in this paper include level ground, stairs, slope, doorsill, gap, and uneven terrain, which can cover most of the human environments. To accomplish all the tasks by our prototype quadruped robot, a multi-task control framework is developed as shown in Fig. 6.

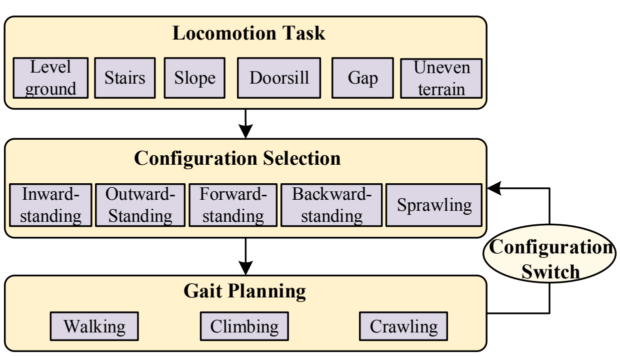

Fig. 6. The multi-task control framework.

In this framework, configuration selection and gait planning are two key elements which cooperate with each other to conquer multiple tasks. For a given task, the robot first selects the most appropriate configuration and then adopts the corresponding gaits. During a task or when transfer to another task, the best configuration may change and the robot needs to make decision to switch to another configuration.

To take full advantage of different configurations, the strategy we adopted for configuration selection obeys two basic principles as follows.

(1) Firstly, the mammal-type configurations are preferred for structural environments where we can predict what will happen next, for example, stairs, slope, doorsill and gap. As for the leg bending direction, our main consideration is to reduce the collision risk of the legs with local environment on the robot's moving direction as far as possible. To achieve this, the principle can be briefly summarized as "bending legs to the downstairs or downhill direction". For example, we select the backward-standing configuration for going upstairs or uphill and the forward-standing configuration for going downstairs or downhill. In some special cases like surmounting a doorsill, the robot will experience both upstairs and downstairs twice, one for the front legs and one for the hind legs, respectively. In this case, the robot needs to change configurations twice: it firstly converts from backward-standing configuration to outward-standing configuration when its front feet step on the doorsill, and then convert from outward-standing configuration to forward-standing configuration when its hind feet step on the doorsill. By using this strategy, we find the robot can climb over large obstacles which can be hardly achieved by other quadruped robots with similar size.

(2) Secondly, the sprawling-type configuration is preferred for irregular terrain where uncertainties may exist and the foot contact is hard to predict. Typical examples are rocks and pebbles, where foot slippage often occurs due to unflat surface or pebble movement. Although a mammal-type configuration can also transverse rocky terrain such as the LittleDog [14], it relies heavily on footstep selection and complicated control algorithms, which requires intensive calculations. By using the sprawling-type gait which will be introduced later, locomotion on uneven terrain can be made safer and simpler.

With the principles above, the appropriate configuration can be determined for certain environment. In the next we will figure out how to switch between different configurations.

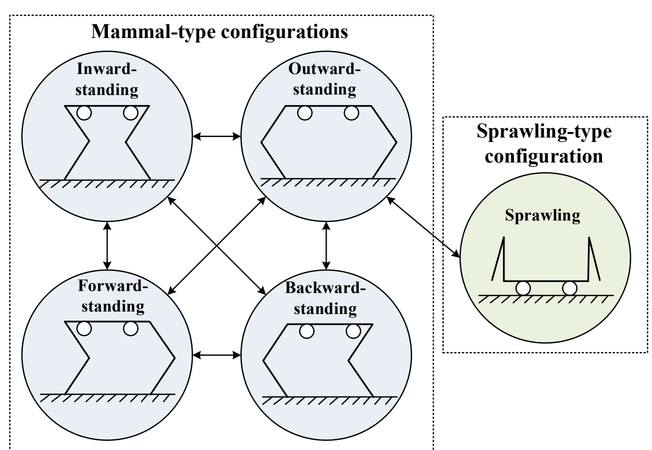

Fig. 7. Diagram of configuration switch.

Based on the five basic configurations defined previously, we study their relationships and draw the diagram of configuration switch in Fig. 7. It can be observed that the four kinds of mammal-type configurations can convert to each other directly, while the sprawling-type configuration can be reached or transfer into the mammal-type configurations through the outward-standing configuration.

Fig. 8 shows two examples of switching within the mammal-type configurations, where the left are standard configurations on level ground and the right are nonstandard configurations with the front legs on a doorsill. The feature of this transformation is that it does not change the foot position relative to the body, but only inverts the bending direction of the knee by changing the HFE and KFE angles. In other words, the joint angles before and after transformation are coupled solutions for the same inverse kinematics problem.

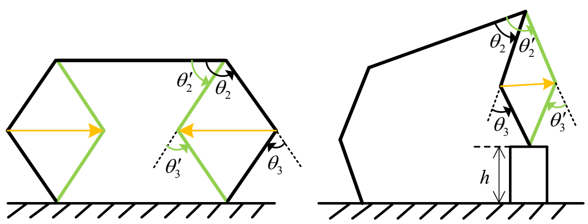

Fig. 8. Switch within the mammal-type configurations.

To realize the above transformation, the position control mode should be used for the involved joints. Because the prototype quadruped robot has adopted equal length for the thigh and shank (both 0.3m), the legs before and after transformation exactly form a rhombus in Fig. 8. Therefore, the relationship for the angles before and after transformation can be easily obtained as follows

$$\begin{aligned} \theta_2' &= \theta_2 + \theta_3 \\ \theta_3' &= -\theta_3 \end{aligned} \tag{1}$$

where θ_2, θ_3 denote the HFE and KFE angles before transformation and θ_2', θ_3' are the HFE and KFE angles after transformation (anticlockwise as positive). This applies to both standard and nonstandard mammal-type configurations.

Fig. 9 shows the transition from standard outward-standing configuration to standard sprawling-type configuration. During this transition, the robot operates in inverse kinematics mode. The robot lowers its body until the feet leave the ground and reaches the given position. Since the feet are under the body in standard outward-standing configuration, it should be noted that the feet will slide a little bit on the ground to avoid collision with the body. Although the sliding is harmful, it offers a faster transition compared to moving out each leg successively under static balance. Similarly, the robot can also do the inverse transition to lift its body by stretching all the legs. However, in our experience, it is not recommended to take the horizontal sliding in the inverse operation. The robot can transfer into a nonstandard outward-standing configuration first, and then convert to other standard mammal-type configurations using joint position control to the predefined joint angles.

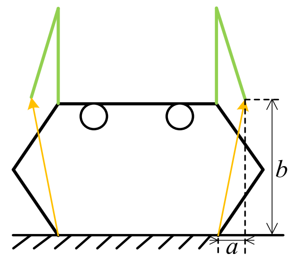

Fig. 9. Switch from mammal-type to sprawling-type configuration.

IV. Gaits Design

In this section, we will focus on gaits design. Since the joint speed of THU-QUAD II is relatively low, only static gait is considered here and the center of gravity of the robot is assumed to be located under the center of the body. Three categories of gaits are designed. Two of them are mammal-like gaits which can be applied to all the mammal-type configurations, including a walking gait for level ground/gap and a climbing gait for stairs/slope/doorsill. The remaining one is the sprawling-type gait, which is called crawling gait here and is used for uneven terrain. The match between different gaits and tasks is shown in Fig. 10.

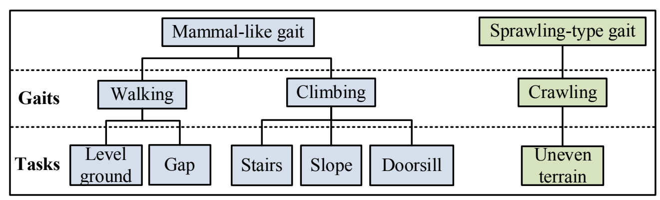

Fig. 10. Match between different gaits and tasks.

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.

A. Walking Gait

In our previous work [15], path following and gap crossing tasks have been solved using a straight walking gait and a turning gait. For simplicity, only straight walking is discussed here. The motion sequence in one gait cycle is shown in Fig. 11, where body shift and leg swing are executed alternately to keep static balance. This gait has only one parameter, that is, the walking distance d.

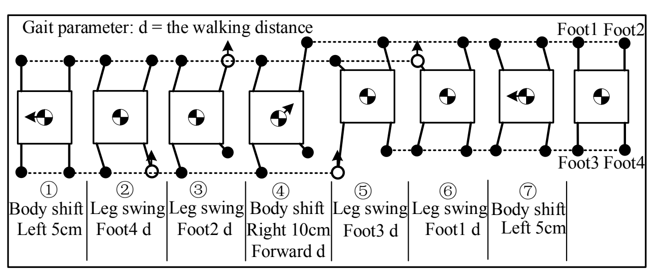

Fig. 11. Straight walking gait.

B. Climbing Gait

When walking on stairs or slope, the height of the foothold is changing, in this case a climbing gait is designed. Fig. 12 shows a general situation of the climbing gait cycle, while the front feet change the height of Δh_1 and the hind feet change Δh_2 after a gait cycle.

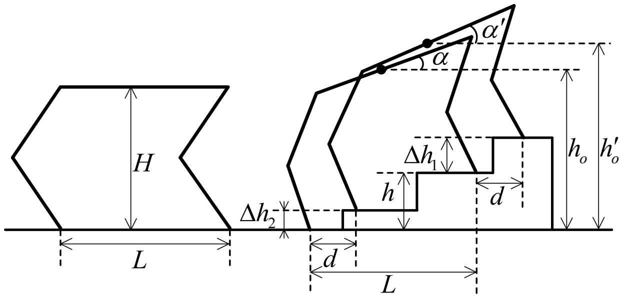

Fig. 12. Diagram of a climbing gait cycle.

It should be noted that $\Delta h_1, \Delta h_2$ can also be negative so the following derivation also applies for going downstairs or downhill. Assuming h is the initial height difference between the front feet and the hind feet in the gait cycle, L is the horizontal distance between the front feet and hind feet and is the same as that in the standard configuration, d is the walking distance. Then the climbing gait can be fully described by four parameters: $(h, \Delta h_1, \Delta h_2, d)$. We design the climbing gait by incorporating two additional movements into the aforementioned straight walking gait, that are, the adjustment of body height and pitch. Inspired by [16], the following two rules are used to determine the body height and pitch.

Rule 1: The body pitch keeps parallel with the "virtual slope" formed by the front feet and the hind feet.

Denote the pitch angles of the body at the beginning and the end of the gait cycle as α, α', respectively. It follows that

$$\begin{aligned} \alpha &= \arctan(h / L) \\ \alpha' &= \arctan\left[(h + \Delta h_1 - \Delta h_2) / L\right] \end{aligned} \tag{2}$$

according to Rule 1. This indicates the robot should pitch its body with the angle of $\Delta\alpha = \alpha' - \alpha$ during one gait cycle.

Rule 2: The body height equals a constant height plus the average height of the front feet and the hind feet.

Denote the heights of the body at the beginning and the end of the gait cycle as h_o, h_o', respectively. Then we have

$$\begin{aligned} h_o &= H + h / 2 \\ h_o' &= H + (h + \Delta h_1 - \Delta h_2) / 2 \end{aligned} \tag{3}$$

where H is the body height in the standard configuration. Therefore, the robot should raise its body for the height of $\Delta h_o = h_o' - h_o$ during one gait cycle.

By adopting the proposed climbing gait and adjusting the gait parameters $(h, \Delta h_1, \Delta h_2, d)$ in real time according to the position of the robot and the staircase size, the robot can easily cross stairs and doorsills with different sizes or slopes with different inclinations.

C. Crawling Gait

The crawling gait is designed for the sprawling-type configuration. Although a sprawling-type robot can move with a similar manner to the walking gait, it is not robust enough to walk on uneven ground in that way. Therefore, we design a special crawling gait as shown in Fig. 13, the gait cycle includes 4 phases: 1) The feet move down from overhead to lift the body from the ground; 2) The body move forward for distance d ; 3) The feet move up to lay the body on the ground; 4) The feet move forward for distance d and reset to the initial position.

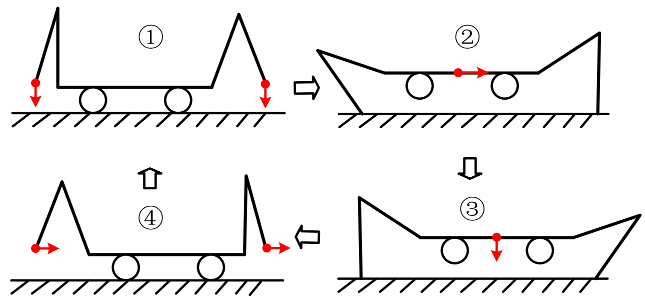

Fig. 13. Gait cycle of the crawling gait.

Though quite simple, the crawling gait is proved to be very effective in traversing uneven terrain. On one hand, because all the feet move simultaneously, the support polygon changes alternately between the rectangle of the four feet and the rectangle of the four wheels, where both areas are relatively large and can provide a relatively big stability margin. On the other hand, because the center of gravity of the robot is close to the ground, the risk of falling is very low. Even if the robot loses stability on uneven ground, it will not roll over and can recover balance soon. These two features make the crawling gait insensitive to small disturbances from the ground, which is a big advantage compared to the mammal-like gaits.

V. Simulations and Experiments

To test the effectiveness of the proposed multi-task control algorithms, three locomotion tasks are considered: 1) A doorsill followed by steep stairs; 2) Two steps connected with a slope; 3) A wooden case with sand and a wooden case with stones. First, simulations are performed in the V-REP software with the Newton physics engine. Then, the data of the joint angles obtained in the simulations are sent to and executed by the physical THU-QUAD II robot. A video is also provided in the attachment of this paper.

A. Simulations

The doorsill and steep stairs scenario is shown in Fig. 14 and the simulation screenshots are given in Fig. 15. The climbing gait is used here. It can be seen from Fig. 15 that the robot changes its configuration three times. One is when the front feet step on the doorsill, the robot switches from backward-standing configuration to outward-standing configuration. One is when the hind feet step on the doorsill, the robot switches from outward-standing configuration to forward-standing configuration. The rest is when the robot passes the doorsill and prepares to climb the stairs, it switches from forward-standing configuration to backward-standing configuration. In this way the robot prevents its legs from colliding with the doorsill and the stairs, which contributes a lot to its success in surmounting those challenging obstacles. As far as we know, such performance is hardly seen from other quadruped robots with similar size.

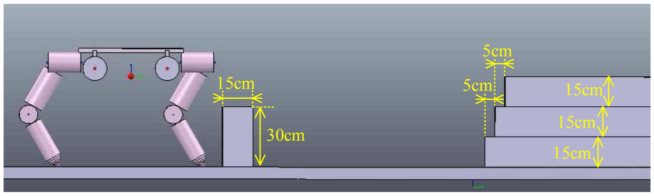

Fig. 14. Task scenario of a doorsill and steep stairs.

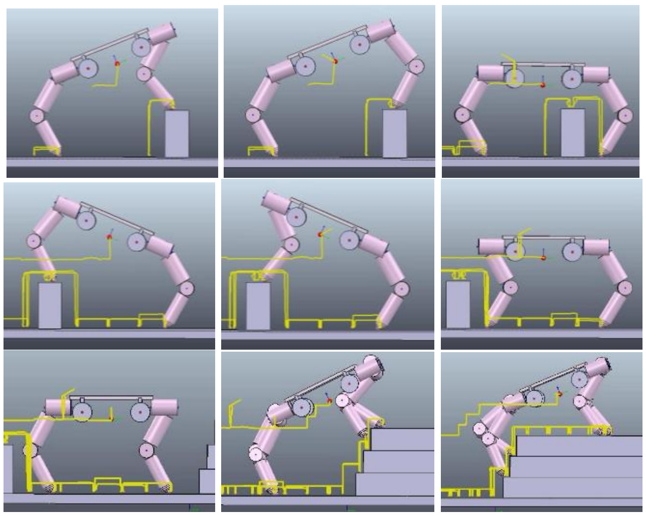

Fig. 15. Simulation screenshots for doorsill and steep stairs task.

The stairs and slope scenario is shown in Fig. 16 and the simulation screenshots are given in Fig. 17. The robot also adopts the climbing gait. It first goes upstairs with the backward-standing configuration, then transfers to the forward-standing configuration on the top platform to go down the slope. In this way, the robot does not need to make a u-turn on the top platform as can be seen in SpotMini's test video [17].

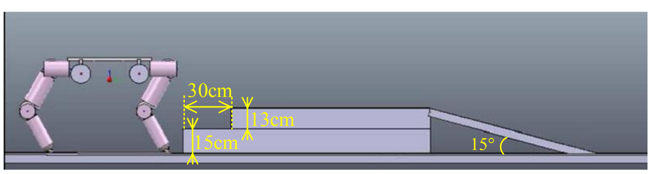

Fig. 16. Task scenario of stairs and a slope.

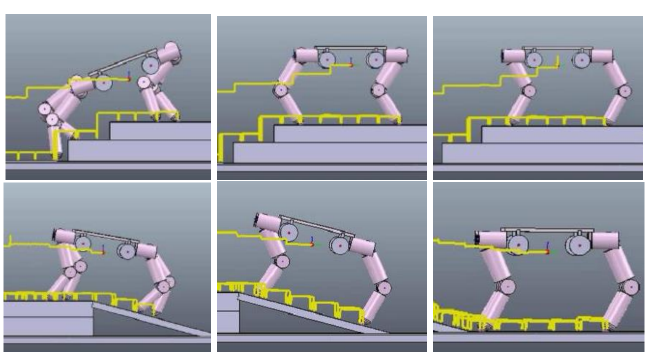

Fig. 17. Simulation screenshots for stairs and slope task.

For the sand and stones task, it is difficult to simulate the exact behavior, so only experimental results are presented.

B. Experiments

To test the proposed algorithm, several experiments are done with the robot THU-QUAD II. Since the robot is currently not attached with any localization sensors, we control the robot with the offline data of the joint angles exported from V-REP. Due to the limitation of experimental condition in our laboratory, the doorsill and steep stairs task is not tested experimentally yet.

The experimental snapshots for the stairs and slope (same size as in Fig. 16) task is shown in Fig. 18. With several times of careful tuning (mainly the swing leg height and the step length), the robot finally reproduces its simulation counterpart's behavior in real world. It successfully passes the stairs and slope with the climbing gait and also does well in configuration switch. A split-view comparison in the attached video shows that the experimental results coincide very well with the simulation results.

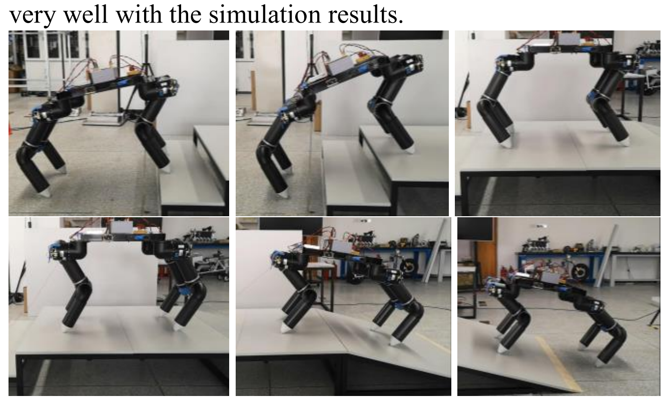

Fig. 18. Experimental snapshots for stairs and slope task.

The experimental snapshots for the sand and stones task is shown in Fig. 19. Both wooden cases are 1.5 m long and 7 cm high. It is found that the sand has little impact on the robot since the feet will sink into the sand. Therefore, we just use the walking gait with increased leg-swing height to cross the sand and it works well. After leaving the sand, the robot transfers to the sprawling-type configuration. Then it switches to the crawling gait to transverse the stones. We test several times to cross the stones and find the robot moves very well in this way. Although slippage happens sometimes, the robot can keep going without damage. Considering the high stability and strong robustness the crawling gait has exhibited, we believe it has great potential to cross much rougher terrain.

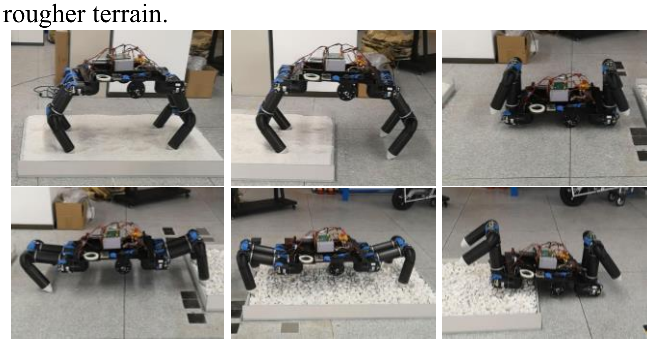

Fig. 19. Experimental snapshots for sand and stones task.

VI. CONCLUSION

To demonstrate the advantages of configuration-changing capability in facilitating quadrupedal locomotion, a quadruped robot named THU-QUAD II was designed. Special attentions have been paid on the mechanical design to ensure a wide range of motion for all the joints, which allows the robot to exhibit multiple configurations. Then a multi-task control strategy is proposed to choose the leg configuration and corresponding gait to achieve movement over various terrains. According to the environments, the robot can walk like mammals or crawl like reptiles and nimbly switch between them, which gives the robot more flexibility when facing different tasks. When walking like mammals, the robot can also change the bending direction of its knees to avoid collision with the environment. These features enable the robot to conquer some challenging terrains in a simple way without using complicated control algorithms. However, the robot is currently not attached with any visual sensors and is controlled with offline joint angle data to reproduce the simulation results. Future work will focus on detection of terrain features in real time and automatic adjustment of the leg configurations and gait parameters. Besides, we are also considering to equip the robot with reconfigurable joints so it can have more configurations and accomplish more tasks.

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