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Design and Development of a Leg-Wheel Hybrid Robot "HyTRo-I"

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Abstract—**This paper proposes a novel and mechanically decoupled leg and wheel hybrid transformable robot called HyTRo-I that combines two mobility concepts. For example, while wheeled vehicles shares higher speed than legged and tracked machines on a flat ground, they have relatively lower degree of flexibility than the other two on irregular terrain. The HyTRo-I robot evolves three motion modes: wheeled rolling, quadrupedal walking and leg-wheel hybrid mode. Despite the over-whelming complexity of obstacles, only several typical obstacles are selected for the study, which are stairs, large protrusions and ditches. Firstly, the transition locomotion mechanism between wheeled rolling mode and quadrupedal walking mode should be studied in detail. In the course of reciprocal transition locomotion, the static and reversible transformation gait not only guarantees the shifting stability and a small number of transition steps, but also the relatively balanced torque of joints. Secondly, after HyTRo-I converting to effective locomotion mode, the adaptive gait control strategies are proposed to traverse three types of obstacles. Finally, a serial of experiments were performed to verify the validity of the proposed transformation gait and adaptive step-up gaits.**

I. Introduction

Over the years, to improve the mobility of robot under complicated terrain condition is a fundamental subject that has caught many researchers' attention. Various mobile systems have been developed. There include wheeled, tracked, legged, serpentine, wriggling systems etc. These ground mobile platforms provide different mobility performance under different operational conditions. Recently, In terms of the capability of locomotion systems, three characterized systems which are wheeled, tracked and legged system were chosen. The wheeled robots were able to move at higher speed and move with lower energy requirement than tracked and legged robots on flat terrain. However, they had difficulty in climbing slopes over 15 degrees because of the low slip ratio. Both the tracked robots and the legged robot not only had better slope climbing and obstacle traversing capabilities, but also had the disadvantage of high power consumption. Particularly, the legged robots, such as Bigdog[1], Littledog [2] and HyQ[3], were more stable while crossing over obstacles and possessed better stability than the other two. As we can image that if the wheeled robot integrates one of the tracked vehicle and the legged mechanism or both types into one locomotion system, the mobility performance of the hybrid system over rough terrain would be significantly enhanced, which inherits both advantages of two mobile concepts.

Based on that combination method, the hybrid system consists of the leg-wheel system, the track-wheel system and the leg-track-wheel system. A wide variety of hybrid systems with different geometries, sizes, and configurations were developed to improve the mobility performance. The leg-wheel systems, such as AirHopper[4], Hylos[5]and ATHLETE[6], got the passive or active wheels to install on the plantar of legged machines. The Chariot[7, 8] series had two very large wheels installed on each side of the body. The leg-track-wheel system AZIMUT[9] had four independent articulated parts that combines a leg, a track and a wheel attached to the comers of the square frame.

In the paper, the leg-wheel hybrid concept has been realized in our deigned robot called HyTRo-I, of which the legs and wheels mechanically associate with each other in a decoupled manner. For the HyTRo-I robot, four wheels suspension system were used to roll fast over smooth terrain, while four legs walk system were used to traverse over irregular terrain. The two basic locomotion modes were defined as wheeled rolling mode and quadrupedal walking mode. In additional, they can be converted to each other optionally. Also, HyTRo-I had a third locomotion mode named leg-wheel hybrid mode, in which it can cooperatively move by using both legs and wheels over extreme terrain.

The selection of locomotion mode for the HyTRo-I robot depend on different applications. By recognizing nature environment, such as slopes, vertical obstacles, pebbled road and muddy land, the HyTRo-I robot decided the optimal locomotion mode. For example, the surface condition varied from the relatively smooth ground to the gravel road, HyTRo-I should change moving pattern from the wheeled rolling mode to the quadrupedal walking mode to preferably adapt the uneven terrain. Similarly, HyTRo-I come across steps, stairs and steep slopes in the outdoor environment, which it cannot move over in wheeled rolling mode. It should either convert the moving method to quadrupedal walking mode or switch to the leg-wheel hybrid mode, in which HyTRo-I can traverse over complicated obstacles.

In section II, the concept of hybrid scheme of HyTRo-I was presented in Figure 1. To fully retain the structure feature of quadrupedal animals, the mechanical structure of modular legs and wheel suspension system were independently designed and integrated. Also, the control strategy of HyTRo-I was mentioned.

In section III, according to the stability margin of ZMP[10], we developed a statically stable gait controller for our robot. HyTRo-I regulated the posture from the initial standing position to cyclic walking state by intermittent gait and then walked in a continuous type. The hip motion assisted to

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improve stability margin. Based on the periodic walking gait, the stable transformation principle between two basic locomotion modes was analyzed in detail and a statically, reversibly transformation gait sequence was illustrated. The specific gait transformation motion was a common interface while HyTRo-I want to transform between the wheeled rolling mode and the quadrupedal walking mode randomly.

In section IV, the motion ability and motion control strategies of HyTRo-I in nature environment were introduced. The wheeled rolling mode was mainly used to navigation and pass through smooth surface quickly. However, when come across rubble road, large vertical obstacles, stairs and steps, HyTRo-I need to traverse over the unfriendly conditions with adaptive and optional locomotion mode. These cases concerned the automatic switchover of movement patterns. In terms of typical examples of step and stair, two adaptive gait motion sequences by simulation figures were proposed in the section.

In Section V, the experimental behaviors of HyTRo-I were performed to prove the potential mobility advantages. Finally, our conclusions and future works are provided in Section VI.

II. SYSTEM OF THE HYTRO-I ROBOT

A. Mechanical Structure

As shown in Figure 1, the prototype of HyTRo-I is composed of a suspension torso, a wheel mobile vehicle and four modular leg mechanisms. The suspension torso was duty for payloads and equipment. The wheel mobile vehicle that suspended from the abdomen of a quadrupedal robot’s body had two passive omni-directional wheels and two active driving wheels. The two independently actuated wheels mounted on the right and left side of the body respectively and two non-driven wheels on the front and back side. In addition, four modular leg mechanisms were attached to the suspension torso. After considering four possible leg configurations, we found the configuration, with the front leg knee joints pointing forward and the hind leg knee joints pointing backward with respect to the direction of motion, to be suitable (Fig.1). This configuration avoids range of motion interference between the leg and wheel mechanisms, but results in a more compact structure.

The Figure 1 also presents a simplified model of HyTRo- I and major mechanical components and specifications. Each of four modular leg mechanisms was a 3 degrees-of-freedom serial link, which was interconnected by three actuated revolute joints and a passive compliant translational joint. The revolute joint actuators were driven by ball-screws modules that can turn shaft rotation of motors into translational motion of end-effectors of ball-screws modules. The revolute joints provide a wide motion range to ensure the flexibility of HyTRo-I. The spring stiffness of the translational joint was tuned to allow energy storing and protection against ground impact forces. Also, the feet were wrapped with rubber to enhance the surface friction.

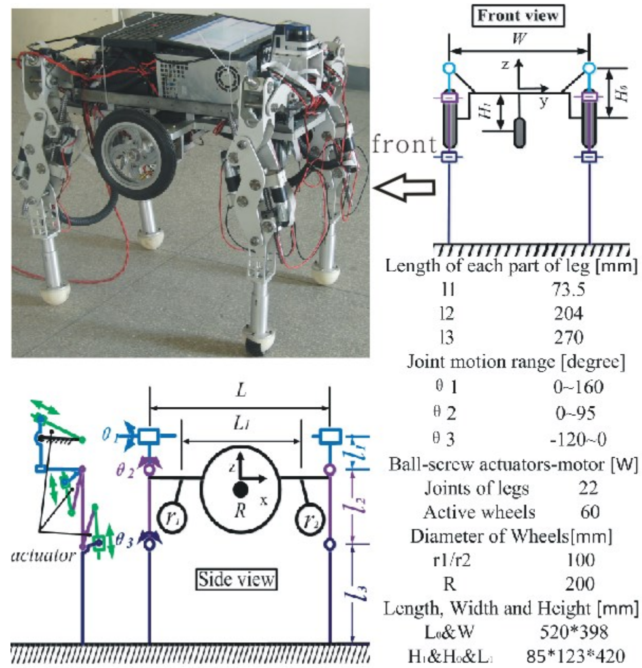

Figure 1. The prototype and a simplified model of key mechanical components and specifications of HyTRo-I.

B. Control Architecture

The Figure 2 depicts the control architecture of HyTRo-I for the experimental behaviors. The hardware architecture is composed of a low level, with motors with microprocessors, and a high level with sensors and a centralized host-PC. The motors were controlled using a cubic spline interpolation of PVT (position, velocity and time) reference points. Communication with the controllers was complemented with a CAN serial bus. The sensors included a gyroscope, laser radar and GPS, were mounted on the torso to detect obstacles and regulate body posture.

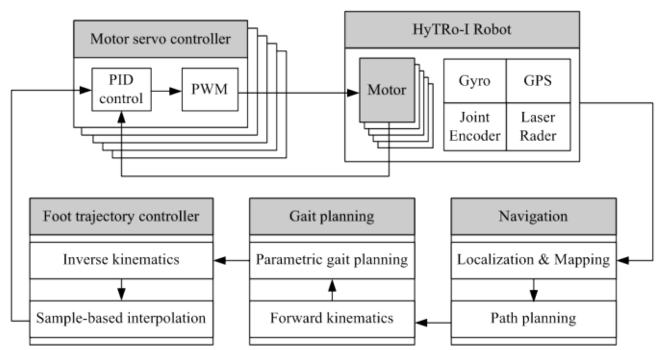

Figure 2. The control architecture of HyTRo-I

III. STUDY OF STATIC WALK AND TRANSFORMATION MOTION

A. Independent Control of Basic Locomotion Modes

For the wheeled rolling mode of HyTRo-I, the real-time obstacles avoidance control approach of operating wheeled vehicles from start position to target location based on laser radar has been omitted because of the limitation in literature. For the quadrupedal walking mode of HyTRo-I, a control method to determine a statically stable walk gait based on ZMP, a stability criterion, was chiefly developed. The Figure 3 shows the supporting and swaying phases of four legs in a cycle period of static walking. Before it, HyTRo-I was in a standing posture. To transit to the first step of periodic walk gait, HyTRo-I adjusted the initial body position by a discontinuous gait. The gait used a double supporting triangle with the help of hip motion. The diagrammatic drawing was shown in the Figure 3 (a). The center of gravity (COG) of HyTRo-I was always within the two triangles generated by dashed lines and solid lines. After the initial body position regulation, HyTRo-I adopted a motion sequence of 1-4-2-3 in quadrupedal walking mode as Figure 3 (b) described. While a leg was in the swing phase, HyTRo-I maintained the static stability by other three legs. During the periodic walk gait, the movement of HyTRo-I was at least triangle supporting state and the hip motion contributed to enhancing the static stability margin.

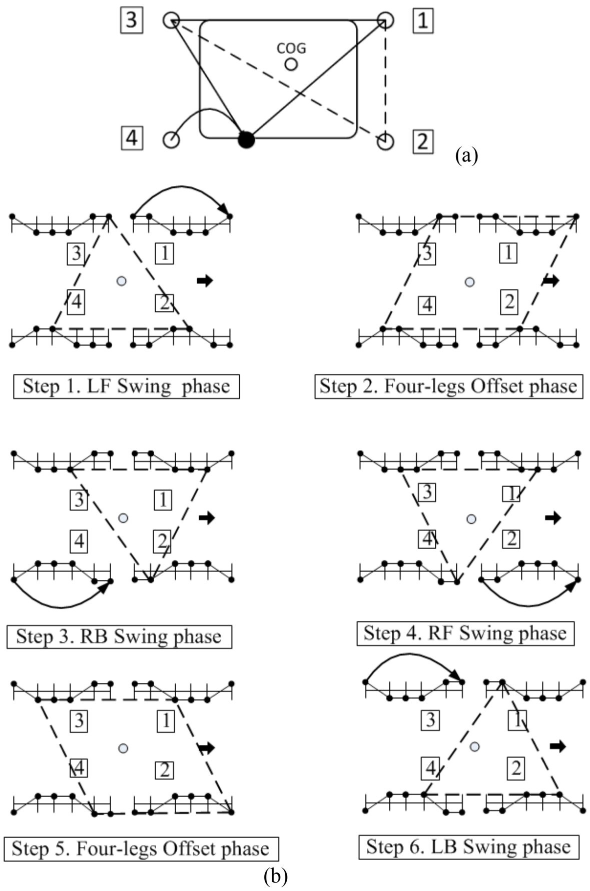

Figure 3. The static cycle walk gait sequence of HyTRo-I. The number signs of 1,2,3,4 respectively denote the left forward (LF) leg, the right forward (RF) leg, the left backward (LB) leg, the right backward (RB) leg.

B. *Transformation Gait Control Principle*

HyTRo-I can arbitrarily utilize three locomotion modes to move. But, how to automatically shift the move methods was a vital element for HyTRo-I to deal with diverse operational applications. In order to establish the relationship between two basic locomotion modes, transformation movement including dynamic and static transition for HyTRo-I should be probed. In this research, only the policy of static transition was studied.

To illustrate the principle of shifting motion, 3-D CAD model of HyTRo-I moving in the wheeled rolling mode and a front view of mode transformation from walking to rolling are elaborated in Figure 4.

This forward shifting motion from walking to rolling was primarily composed of three phases. First, the legs are repositioned laterally to provide a wider base of support. Second, the feet are raised to the level of the wheel bottoms, bringing the wheels in contact with the ground. Finally, to account for terrain irregularities, the feet are further raised to increase their clearance.

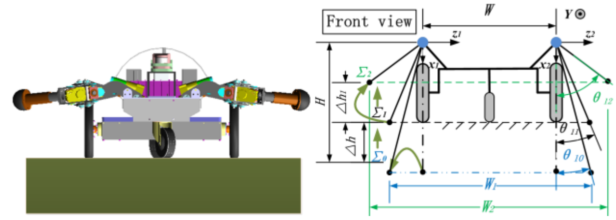

Figure 4. 3-D CAD model of wheels rolling mode and front view of transformation motion from walking to rolling.

Just as the Figure 4 expressed, if HyTRo-I decided to change the moving mode from the quadrupedal walking mode to the wheeled rolling mode, the principle of forward transformation was studied. The four modular leg mechanisms should be contracted above the plane of $\Sigma_1 - \theta_{11}$ at least. In order to not only ensure the retractable leg mechanisms of HyTRo-I to occupied the minimum space and also avoid the leg mechanisms to collide with obstacles during the wheels rolling mode, the angles of revolute joints $\{\theta_1, \theta_2, \theta_3\}$ should reach the extreme state. In the direction along the width of robot, θ_1 revolute joint attained to the value of -120° while θ_2 revolute joint was 95°. The θ_3 revolute joint got the value of 160° and enabled the maximum height of feet off ground to reach up to 180 mm.

$$\theta_{10} = \tan^{-1}\left(\frac{W_1 - W}{2H}\right) \tag{1}$$

$$\theta_{11} \geq \tan^{-1}\left[\frac{W_1 - W}{2(H - \Delta h)}\right] \tag{2}$$

$$\theta_{12} \leq \tan^{-1}\left[\frac{W_2 - W}{2(H - \Delta h - \Delta h_1)}\right] \tag{3}$$

Where H represented the perpendicular distance between feet and the revolute axis of θ_1 joint. The W, W_1, W_2 indicated the span of footholds in three action phases and the $\Delta h, \Delta h_1$ mean the height among three planes respectively.

Because of the finite leg motion range, the HyTRo-I robot should contract it leg mechanisms above the level of the bottom of wheel vehicles with the side swaying motion of hips. The necessary minimum degree of lateral outside motion of θ_1 revolute joint can be calculated by the Eq.2. In the beginning of transition, the position of four legs located in the plane of $\Sigma_0 - \theta_{10}$ need to change from the phase represented by the black dashed dot line to the phase noted by black solid line described in Figure 4, the angle between which was θ_{10}. The θ_{10} can be obtained by the Eq.1. Figure 5 illustrates the stable forward shifting motion gait. With the special transformation gait sequence from step 1 to step 6, the footholds of four legs would successively located at the target positions in the plane of $\Sigma_0 - \theta_{10}$.

In addition, by lowering the center of robot body at a height of $\triangle$, the feet touchdown points can arrive on the plane of $\Sigma_1 - \theta_{11}$. Meanwhile, the four wheels were landing on the ground. Considering the actual motion environment of robot, the footholds of four leg mechanisms hold up to the plane of $\Sigma_2 - \theta_{12}$ at a height of $\triangle$ and it only required to sway outside the hip of legs at a degree of θ_{11}, which can be got by the Eq.3. Finally, HyTRo-I can move in the wheeled rolling mode on the level terrain.

Similarly, a backward gait transition should be studied when HyTRo-I made the decision of changing the movement pattern from the wheeled rolling mode to the quadrupedal walking mode. By reversing the movement phases of forward transformation motion, the backward shifting motion was simply achieved. In the process of backward transformation motion, the footsteps were firstly transferred from the plane of $\Sigma_2 - \theta_{12}$ to the plane of $\Sigma_1 - \theta_{11}$, and secondly from the plane of $\Sigma_1 - \theta_{11}$ to the plane of $\Sigma_0 - \theta_{10}$ and lastly from the position in the plane of $\Sigma_0 - \theta_{10}$ noted by black solid line to the original position of the periodic walking gait. During the second locomotion phase of backward transformation, the shifting gait sequence was from step 6 to step 1.

The gait control of forward shifting motion and backward shifting motion was reversible. The mode transformation procedures here only had a small number of transition steps. During the mode transformation procedures, the robot was supported by at least three legs. The legs are designed to support at least 1/3 of the total weight of the robot. So the transformation is statically stable and balances torques among the support legs. In addition, when transforming from the wheeled mode to the walking mode, HyTRo-I can smoothly transition to the periodic static walking gait without additional movements.

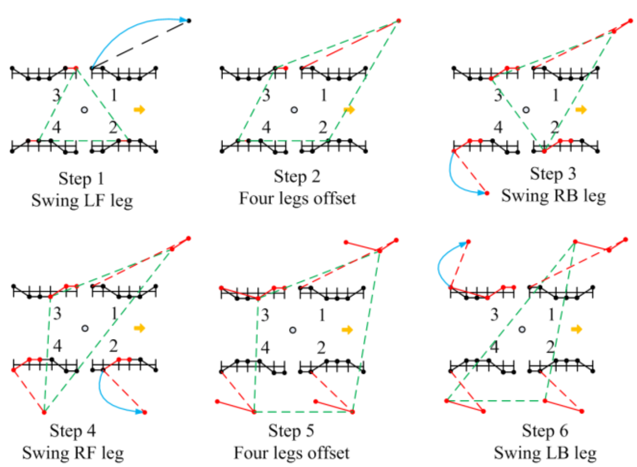

Figure 5. The stable transformation gait sequence of HyTRo-I.

IV. ADAPTIVE MOTION ABILITY AND CONTROL STRATEGY

Although the wheeled robot had the high mobile efficiency in relatively regular topographies, it would neither traverse over tough obstacles nor in an optional locomotion mode, including a certain height of step, rough terrain with unevenness, stair and the gradient of slope above 20 degree(Fig 6). When encountered obstacles higher than the robot or come across steep slope, it was beyond the ability for HyTRo-I in the wheeled rolling mode to climbing over them. Therefore, based on the information from the external and internal sensors, HyTRo-I was expected to cross over in the quadrupedal walking mode or leg-wheel mode. Particularly, the quadrupedal walking machine can not only move on rough terrain with unevenness by selecting stable footholds discretely, but also can climb over barriers that have vertical heights and gradients by regulating the posture to a suitable position. The leg-wheel mode was applicable to rugged road or other unfriendly terrain by supporting the stability of robot with legs and propelling with both legs and wheels.

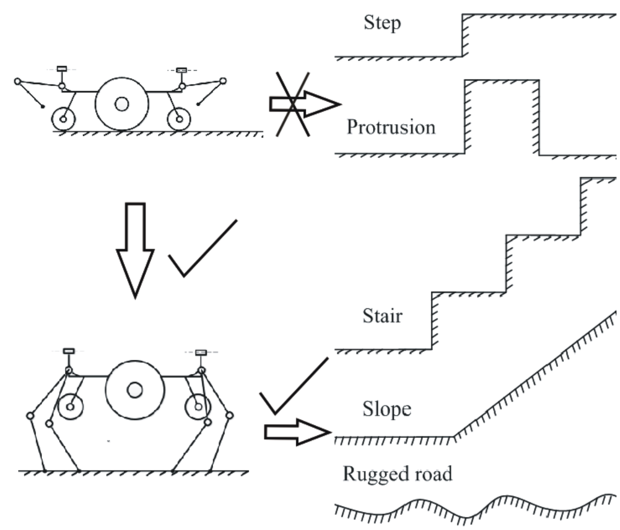

Figure 6. Intelligent locomotion motion choice according to barriers.

If three-dimensional laser radar explored the information of front road conditions, HyTRo-I intelligently switched the optional locomotion mode to adapt to terrain. In order to put HyTRo-I into practical use for the applications, HyTRo-I must manage to transform the locomotion from the wheeled rolling mode to the quadrupedal walking mode. Based on the description of Section III, the transformation gait control would be complemented in front of the obstacles.

With respect to the above barriers of step, stair and slope, we classified these obstacles as two types, vertical step and slope. Choi and Song[11] presented a study on fully automated gaits by a hexapod robot that used to traverse over these cases. Park and Chung [12] on the consumption that the dimensions of obstacles were acquired in advance, and the crossing gait by a four-legged walking machine was only designed by simulation figures. However, if we put the gait of obstacle crossing into practical use, it was a difficult thing to realize. Moreover, the height of vertical step that can be traverse over was limited by these gaits. Also the stability of robot was not easy to guarantee.

While stepping down the vertical wall and climbing the slope and stair, the robot would be easy to tumble over and the stance legs would be easy to float. To deal with the prevention of toppling over, Hirose and his coworkers [13, 14] has studied the energy stability margin to ensure the more stable position of robot based on ZMP. However, because of the finite motion range of leg, the energy stability margin was not assured by not regulating the body position.

A. Step

As depicted in Figure 7, for the wheeled rolling mode, HyTRo-I encountered the unavoidable vertical obstacles during navigation. If $H_{step} \geq R$, HyTRo-I cannot come cross the step and need to keep moving with the legs.

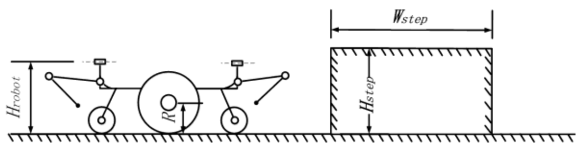

Figure 7. How to step up.

In terms of the quadrupedal walking mode of HyTRo-I, the pattern of step-up gait would be determined by the step height and the feet motion range. On the basis of the previous researches, we fully extended the forefoot vertical range and the height that can be traversed over by swaying outside the hip to increase the angle of body inclination and forefoot range. If $R \leq H_{step} \leq 180mm$, HyTRo-I can directly step on the surface of vertical step with static walk gait. If $H_{step} > 180mm$, HyTRo-I need to title the body angle and contracted the hind feet.

In the following study, we only choose a step height $H_{step} = 310mm$, and step width $W_{step} = 306mm$ for purpose of automated step-up adaptive gaits by simulations figures. The motion sequence of walk-down can be acquired by reversing the motion sequence of walk-up. During the step-up and step-down motion, the criteria of stability was maintained by stability margin [15]and energy stability margin[16] .The Figure 8 shows the lateral motion sequences of walk-up and walk-down. Sequence 20 shows the complete sequence of the crossing. HyTRo-I would return to the wheeled rolling mode to move on the flat ground.

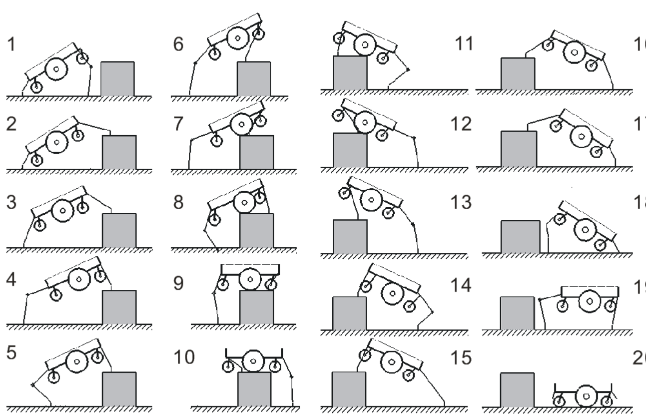

Figure 8. The lateral motion sequences of walk-up and walk-down.

B. Stair

The stair shown in Figure9 was composed of a serial of identical height and width of steps by adding layer upon layer. The gradient of stair was determined by the vertical height and the width. Generally, the scope of stairs was 125~160 mm height and 310~340 mm width. The inclination of stairs was 22~30 degree. There were three methods to enhance gait stability margin for the quadrupedal walking mode on the grade. The energy stability margin and stability margin were our analyzed factors.

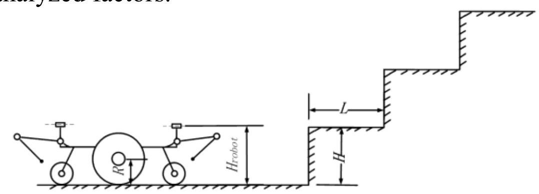

Figure 9. How to climb the stair.

Considering the finite motion range of forefoot, HyTRo-I should walk to a proper corner distance that was the location of the supporting feet and was measured from the first step corner of stair. In the following study, we choose a stair of $H = 157mm$ and $L = 285mm$ for purpose of automated climbing-stair adaptive gaits by simulations figures. In the Figure 10, hind legs cannot step on the stair with the fixed body height. Because the motion ranges of hind legs were limited and the energy margin could not ensure. Therefore, in order to guarantee the stability of HyTRo-I and improve the motion ranges of hind leg, we proposed the method of lowering the body height. Before the foreleg began to step on next stair, the body would be raised to the previous height.

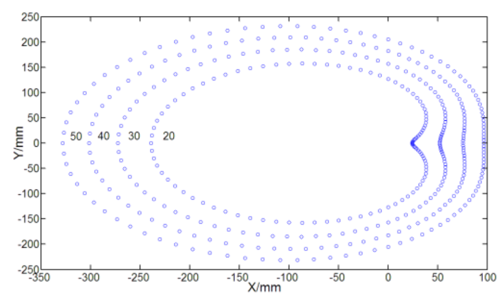

Figure 10. The energy stability margin contour

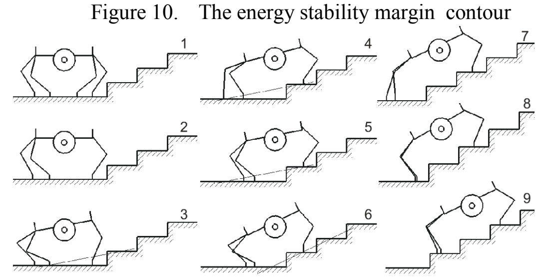

Figure 11. The motion sequences of climbing the stair.

V. BASIC EXPRIMENTS OF HYTRO-I

A. Basic Locomotion Modes and Mode Transformations

Fig.12 lists the serial of snapshots HyTRo-I walking and mutual mode transitions on a flat ground.

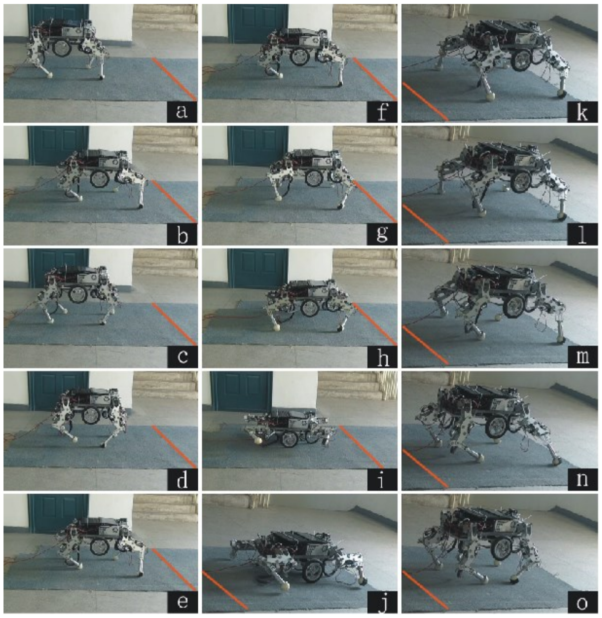

Figure 12. Sequence of snapshots of walking and mode transformation experiment. The first column shows the stage of static walking of HyTRo-I. The second column denotes the stage of transformation from the legged mode to wheeled mode, and the third column displays the stage of transformation from the wheeled mode to legged mode of HyTRo-I. Between the second and third stage, HyTRo-I rolls on wheels.

B. Climbing Up a Step

Fig.13 displays the serial of snapshots HyTRo-I climbing up the vertical step.

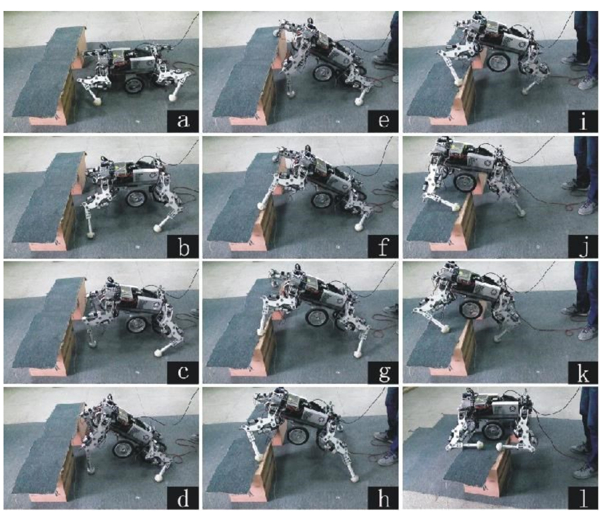

Figure 13. Successive sequence of snapshots of step-up [a-l].

VI. CONCLUSION AND FUTURE WORK

We had designed a leg-wheel hybrid transformable robot named HyTRo-I which has both the high mobility on the flat ground and the high adaptability over irregular terrains. In order to realize the reciprocal transformation of HyTRo-I between the legged model and the wheeled model, a mode transition control method was proposed in this paper. As the experiments showed, the statically stable gait completed the movement of robot for the quadrupedal walking mode. In addition, experiments for reciprocal mode transformation between two basic locomotion modes showed the validity of mutual mode transition and availability of shifting at random. Moreover, experiments for climbing up the vertical step were performed to show the advantage of the quadrupedal walking mode. The experiments of other cases were carried out later.

Future works will primarily focus on the following aspects. Firstly, by fully taking the merits of the hybrid advancing mode of harmonically using the legs and wheels, several gaits and simulations will be generated to reveal the powerful ability of traversing over different and complicated obstacles. Secondly, in order to develop high level of control algorithms and strategies for autonomous movement over uneven terrains.

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