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Mechanical System and Stable Gait Transformation of a Leg-Wheel Hybrid Transformable Robot

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Abstract— **This paper proposes a novel and mechanically decoupled leg and wheel hybrid transformable robot called HyTRo-I that combines the fast speed of wheeled vehicles on a flat ground and the high degree of flexibility of legged robots over irregular terrains. According to different terrain conditions, HyTRo-I can choose from three motion modes: wheeled rolling, quadrupedal walking mode and leg-wheel hybrid mode. By shifting among these moving patterns, the mobility of HyTRo-I over various surface conditions can be fully realized. While the control technology of actuating the wheeled vehicles is mature and simple, the control of quadruped walking is an area of active research. Therefore, we develop a statically stable gait controller for our robot. In addition, we study the locomotion mechanism of transformation that concerns the feasibility of three moving methods of HyTRo-I. By the mutual transformation gaits illustrated in details, HyTRo-I can be smoothly and reciprocally transformed between wheeled rolling mode and quadrupedal walking mode. Finally, we experimentally test the mode transformations of HyTRo-I.**

I. INTRODUCTION

Over the years, numerous mobile systems have been designed and developed. There include wheeled, tracked, legged, serpentine, wriggling systems etc. These ground mobile platforms provide different mobility performance under different operational conditions. However, there are various performance limitations on each of these mobile systems such as speed, obstacles traversing, slope climbing, energy efficiency and control complexity. With the ever-growing requirements of ground mobile systems with high mobility performance, attention should be paid to expanding new movement platforms. To enhance the holistic locomotion performance of robots in environments, such as grasslands, marshes and mountains, researchers integrate various ground mobility mechanisms into a hybrid mechanical system. In particular, hybrid systems including both legs and wheels have received extensive attention in the field of robotics. In comparison of three locomotion systems, wheeled, tracked and legged systems, each system has both merits and demerits. For example, legged robots, such as Bigdog [1], Littledog [2] and HyQ [3], are generally more capable of crossing complicated obstacles than the other two. On the other hand, wheeled robots are able to move faster than tracked and legged robots on flat terrain with lower power requirements and less control complexity. A combination of leg and wheel may inherit the advantages of both legged and wheeled vehicles. Several hybrid systems exist with different dimensions and configurations. We classify existing leg-wheel robots into two categories based on their mechanical configuration: traditional, and innovative.

A conventional leg-wheel hybrid robot is characterized by passive or active rolling wheels installed on the legs or body of the robot. A typical example, Roller Walker [4], based on the principle of roller-skating, is a vehicle with a special foot mechanism which can be switched from a four-legged walking mode into a passive rolling mode. The jumping robot Air-Hopper [5] consists of pneumatically driven four-bar linkage legs with active wheels on its feet driven by electric motors. Hylos I [6] and II [7] robots are highly mobile, redundantly actuated vehicles, which have four legs each combining a two degrees of freedom (2-DOFs) suspension mechanism with a driven wheel. The Wheeleg robot [8] is similar to two wheels cargo carriage of ancient times, and consists of two independently driven rear wheels that bear most of the load on the systems and two pneumatically actuated 3-DOF front legs that enhance the ability to grip the ground and climb over obstacles.

Several innovative hybrid mobile platforms have been designed. Some are characteristic of rimless wheels with actuated spokes that provide the functionality of legs. For example, IMPASS [9] has two rimless spoke wheels and one tail, using its unique ability to intelligently extend and retract its spokes to improve its mobility over irregular terrain. The compliant leg hexapod robot RHex [10] is also based on the concept of the rimless wheels. In addition, the Quattroped [11] robot can transform the morphology of full-circle wheels into 2-DOF half-circle legs.

The leg-wheel hybrid robots mentioned above share some advantages of the two locomotion concepts. The mobility performance of these systems over rough terrain improved over a simple wheeled vehicle. However, we believe that they still a compromise on some of the benefits of wheeled robots. For example, wheel vehicles can move faster and with better stability at high speeds than these hybrid robots on flat ground. Meanwhile, the legged robots can be better to adapt to the unfriendly surface than these hybrid systems over uneven terrains.

In this paper, we proposed a hybrid robot, HyTRo-I, which incorporates mechanically decoupled legs and wheels and which fully benefits from the advantages of both wheeled and legged systems. The HyTRo-I robot combines the mobility of a wheeled vehicle on flat ground and the high degree of flexibility of a legged robot over irregular terrains, and the ability

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to traverse complicated terrain by coordinating locomotion of the wheels and legs simultaneously. We also propose transitions between the wheeled and legged modes which respect joint range limitations using simple statically stabile motions.

The remainder of this paper tests the viability of our hybrid locomotion concept. We first develop a conceptual model of our decoupled leg-wheel design. We then design a statically stable walking gait for our conceptual model. To facilitate transitioning between locomotion modes, we then develop a reversible trajectory that maintains static stability throughout the transformation between walking and rolling configurations. We then introduce our experimental prototype, proposed controller, and experimental results.

II. The Leg-Wheel Hybrid Robot

A. Hybrid Design Concept

A prototype of a hybrid robot incorporating mechanically decoupled legs and wheels is shown in Fig 1. It is primarily composed of a torso, a wheeled platform and four modular leg mechanisms. The wheel mobile vehicle is suspended from the abdomen of a quadrupedal robot's body while the four modular leg mechanisms were attached to the 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.

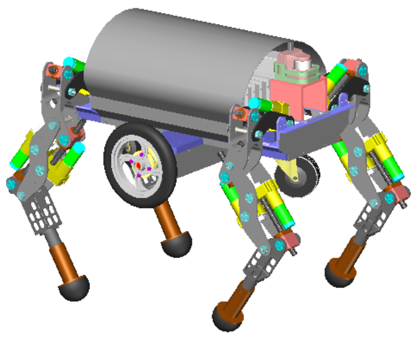


Fig 1. Design concept of the HyTRo-I robot.

The HyTRo-I robot can implemented three locomotion modes, including two basic movement types and a hybrid movement type. The two basic motion modes are rolling on wheels on flat ground, with two active driving wheels and two passive wheels, and a quadrupedal walking mode that walks on unstructured terrain with four legs. The hybrid movement type uses both legs and wheels simultaneously to traverse very complex terrain. If the surrounding and topographic features are known from high level of sensors, HyTRo-I could move through a desired path by using a combination of these moving patterns. Therefore, the mobility performance of HyTRo-I over a wide variety of terrains can be realized.

B. Leg and Wheel Mechanisms of Hybrid Robot

As shown in Fig 2, two passive omni-directional wheels and two active driving wheels were installed on the bottom of a rhombic-shaped body. The two actuated wheels were mounted on the right and left side of the body and two non-driven wheels on the front and back side. The four legs were designed to be modular and reconfigurable. Each leg has three actuated revolute joints $\{\alpha, \beta, \gamma\}$ and a passive compliant translational joint. The revolute joints actuators were driven by ball-screws. The spring stiffness of the translational joint was tuned to allow energy storing and protection against ground impact forces. A primary overview of major components and mechanical characteristics of HyTRo-I are illustrated in Fig 2.

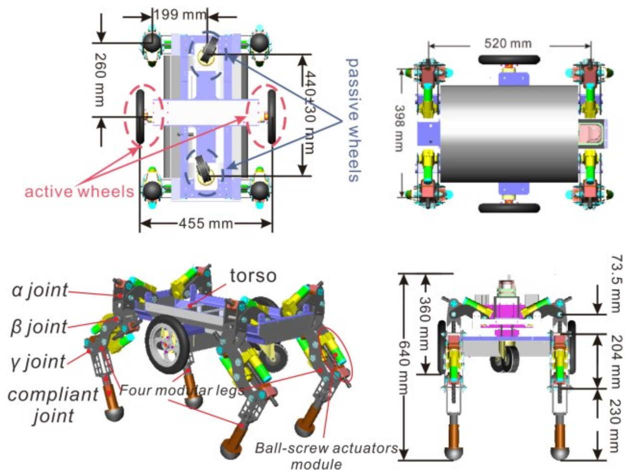


Fig 2. Model of the HyTRo-I robot with no payload.

The HyTRo-I robot can transform between the quadrupedal walking mode and the wheeled rolling mode using a stable transition. The model in wheeled rolling mode and the robot dimensions are depicted in Fig 3.

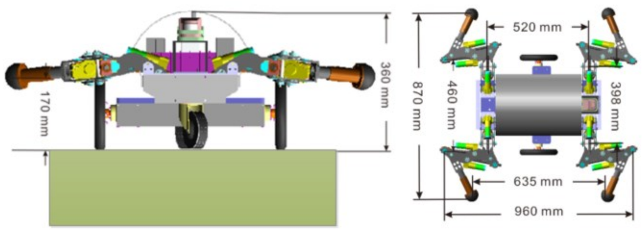


Fig 3. Model and dimensions of HyTRo-I in wheeled rolling mode.

III. Statically Stable Gait Design

While the control technology of operating wheeled vehicles is simple and mature, the control of quadruped walking is relatively complex. By building the kinematic model of one leg, we develop the kinematic and inverse kinematic equations, as well as the mathematical relation between working strokes of ball-screws and foot point trajectory. As the rigid round foot would roll over the ground during the leg in supporting phase, which results in position change in the hip from the planned hip position, we provide a simple method to simplify the round foot as a length of link in the kinematics model to solve the problem of vertical misplacement in the hip. Before designing the statically stable walking gait controller of HyTRo-I, we develop the desired foot swing trajectory.

A. Foot Trajectory Generation

- Kinematics Model

Appendix presents the kinematics model of one leg of HyTRo-I, and the inverse kinematics equation on the variations of joints and foot point trajectory. When the desired leg trajectory in swing phase has been determined, the drive output of joints is given by those equations. However, we do not define the control value of motor driver. The further model of one leg must be worked up to reveal the mathematical relationship between joint angles and driving motors.

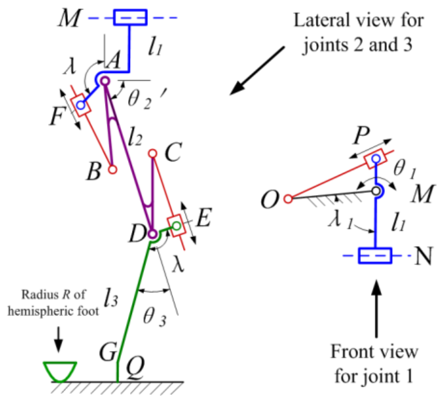


Fig 4. Model of one leg

Fig 4 describes the model of the mapping relation of working strokes of driving mechanisms and rotatory joint angles. HyTRo-I employs a fixed-ankle, hemispherical feet of radius R. However, this kind of foot is easy to roll over the ground during the leg in supporting phase. In Fig 4, the angle between the line connecting foot landing point Q to point D in the knee joint and the line in horizontal plane varied with the change of contact foot point during the support phase, as well as the length of the line QD. Therefore, the hemispheric end part of foot was simplified as a length of link R in the kinematics model of one leg and the value of R was not accounted for l_3. This solution avoids the vertical position change in the hip of leg from the hip desired and real position, which was planned by the kinematic equations. Due to limitation of content, the problem of body misplacement with round rigid foot [12] was not analyzed.

In the triangles of $\{\Delta OPM, \Delta AFB, \Delta CDE\}$ presented in Fig 4, the concrete relationships between axial-direction working strokes $\{l_{\overline{OP}}, l_{\overline{CE}}, l_{\overline{BF}}\}$ of ball-screw actuators and joint angles of one leg can be worked out as follows:

$$l_{\overline{OP}} = \sqrt{l_{MO}^2 + l_{MP}^2 - 2l_{MO}l_{MP}\cos\left(\pi - \lambda_1 + |\theta_1|\right)} \tag{1}$$

$$l_{\overline{BF}} = \sqrt{l_{AF}^2 + l_{AB}^2 - 2l_{AF}l_{AB}\cos\left(\pi - \lambda + \theta_2 - \cos^{-1}\left(\frac{l_{AB}^2 + l_{AD}^2 - l_{BD}^2}{2l_{AB}l_{AD}}\right)\right)} \tag{2}$$

$$l_{\overline{CE}} = \sqrt{l_{CD}^2 + l_{DE}^2 - 2l_{CD}l_{DE}\cos\left(\pi - \lambda + |\theta_3| - \cos^{-1}\left(\frac{l_{DE}^2 + l_{CD}^2 - l_{CE}^2}{2l_{DE}l_{CD}}\right)\right)} \tag{3}$$

where, $\theta_2' = \frac{\pi}{2} - \theta_2$, the value of λ and λ_1 are constant.

- Foot Trajectory

When HyTRo-I walks on relatively even terrain, the foot trajectory must reach these conditions: cross over obstacles at a certain height, improve the vibration and instability of body that results from impact force generated by the foot contacting with the ground, and ensure the velocity and acceleration to continuous during the swing and stance phase. Fig 5 describes a periodic foot trajectory based on polynomial curve fitting without hip motion. The swing phase is a sixth order polynomial curve about time uniquely determined by 7 constraints while the stance is a fifth order polynomial curve about time uniquely determined by 6 constraints. These constraints include the information on the coordinate, the velocity and the acceleration of departure, landing, and maximal-foot-height point.

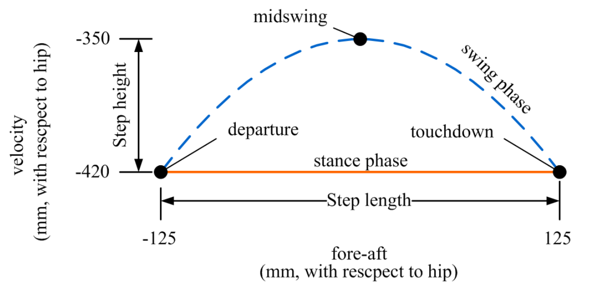
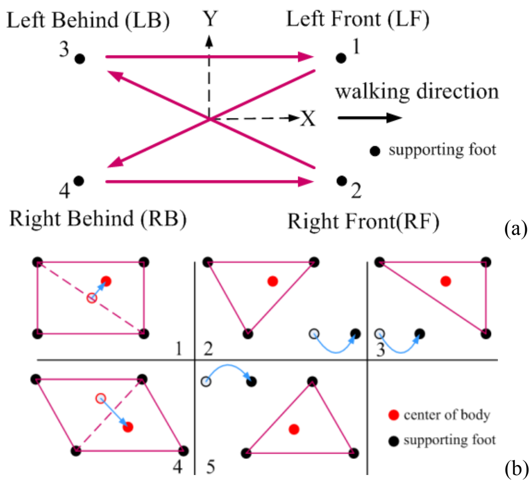


Fig 5. Foot trajectory with step height of 80 mm and step length of 250 mm. The velocity and acceleration are assumed as 0 to ensure the continuity at the departure and touchdown point.

B. Statically Stable Walking Gait Plan

Inspired by walking pattern of quadrupedal mammals, we chose a standard crawl gait walking sequence[13], which is depicted in Fig 6 (a). The bottom right corner part of Fig.2 shows the initial standing posture of the robot and Fig 6 (a) describes the vertical projection of four supporting feet of initial standing posture. Due to range of motion constraints, the body must be lowered at a proper height to allow forward movement. Before every two swing phases, the body is translated in the horizontal plane, by controlling the roll angles of the hip joints, to ensure static stability [13] over the next two steps (Fig 6 b, c). In addition, before HyTRo-I walking as the periodic walking gait illustrated in Fig 6 (c), the support pattern of HyTRo-I feet must regulate to the final state shown Fig 6 (b).



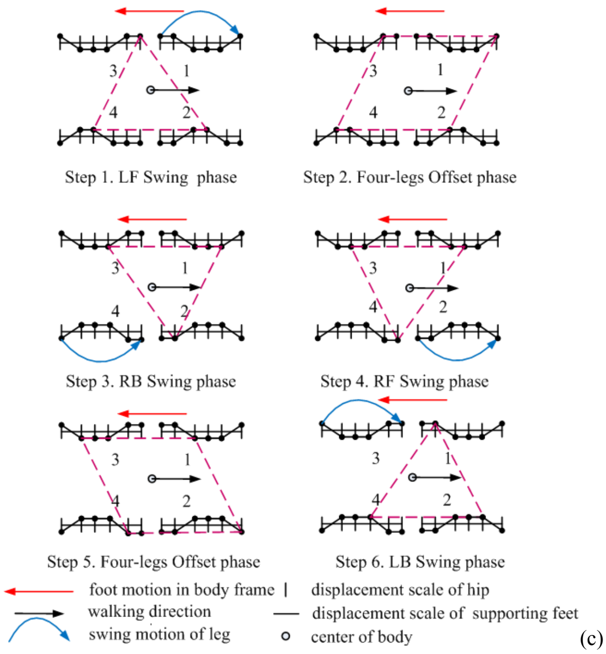


Fig 6. Static walking gait of HyTRo-I: (a) the walking partern of 1-4-2-3, (b) motion sequence of regulation, (c) motion sequence of a cycle walking gait with respect to body frame.

IV. STABLE MODE TRANSFORMATION DESIGN

By a stable transformation, the robot switches from a quadrupedal walking mode to wheeled rolling mode (forward mode transformation). Likewise, the robot can switch back from the wheeled rolling mode to the quadrupedal walking mode (backward mode transformation) by a reverse transformation. In order to realize reciprocally transformations between walking and rolling mode, a stable transformation is studied in this section.

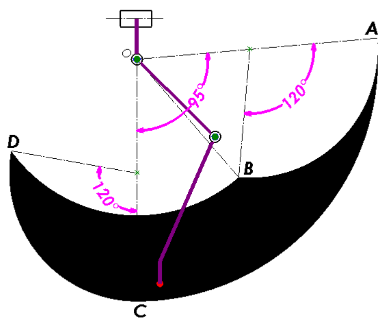


Fig 7. Simplified model of one leg of HyTRo-I in the lateral view and its reachable region without the hip link.

Fig 7 shows a simplified lateral view of one leg with the reachable region ignoring the hip link. The solid black region is composed of four kinds of arcs, which are arcs of AD, AC, BD, and BC in Fig 7. Considering the limited motion range, the contraction of leg mechanisms should be done with the side swaying motion of hips.

To illustrate the principle of mode transformation, a front view of the transformation from walking to rolling is shown in Fig 8. Transforming from walking to rolling has three primary phases. The footholds must be transferred from the initial position of periodic walking gait to a vertical plane above the level of the bottoms of the wheels, and due to joint limitations, this is accomplished in three phases (Fig 8a). 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. The second phase was complemented by the static stable transformation sequence shown in Fig 8 (b).

To transform from the rolling mode to the walking mode, we study a reverse transformation. We found that this could be achieved by simply reversing the motions of forward mode transformation. This consisted of two height changes, first bringing the feet back into contact with the ground, and then pushing down to raise the wheels off of the ground, followed by a repositioning of the feet on the ground to arrive at the initial position of the cyclic walking gait.

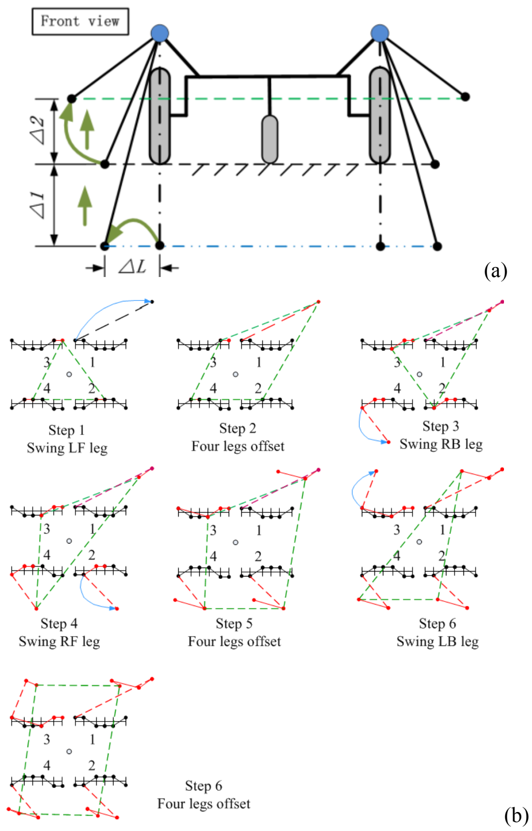


Fig 8. A front view of principle of shifting motion and motion transformation sequence of HyTRo-I. The red solid line indicates the supporting foot trajectory with respect to body frame.

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. The mode transformation procedures here require few steps and maintain stability. In addition, when transforming from the wheeled mode to the walking mode, the robot can smoothly transition to the periodic static walking gait without additional movements.

V. EXPERIMENTAL RESULTS

To experimentally test the procedures outlined above, we built a prototype HyTRo-I (Fig 9). 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 revolute leg joints were driven with 22W RE-max 29 motors, and the active wheels were driven with 29W RE30 motors (MAXON). All motors had encoders and were controlled with EPOS 50/5 controllers. The motors were controlled using a cubic spline interpolation of PVT (position, velocity, time) reference points. Communication with the controllers was implemented with a CAN serial bus. The sensors included a gyroscope, laser radar, and GPS, were mounted on the torso to detect the obstacles and regulate body movement. The control architecture of the hybrid robot system is depicted in Fig 10.

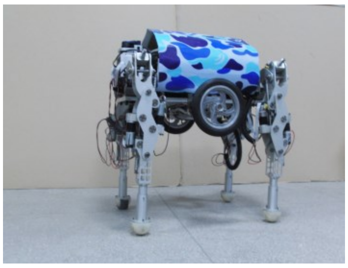


Fig 9. The prototype of the HyTRo-I robot.

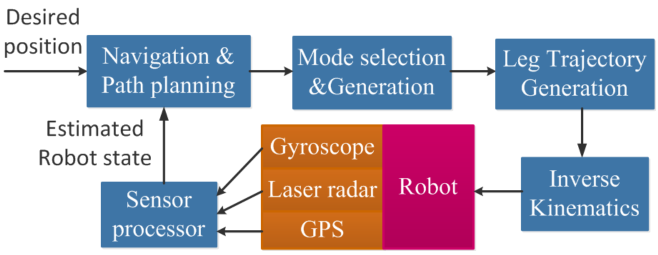


Fig 10. The control architecture of the robot system.

Based on the control method of robot system showed in Fig 10, experiments of statically stable walking and mutual transition of two basic moving modes were conducted in a consolidated control procedure to test the proposed statically stable walk gait and mode transformation.

We performed a basic static walking experiment at a velocity of 35 mm/s and a wheeled rolling experiment at 400 mm/s.

A. *Walking and Mutual Gaits Transition Experiments*

Fig 11 lists a series of snapshots of HyTRo-I walking and transforming between modes on flat ground.

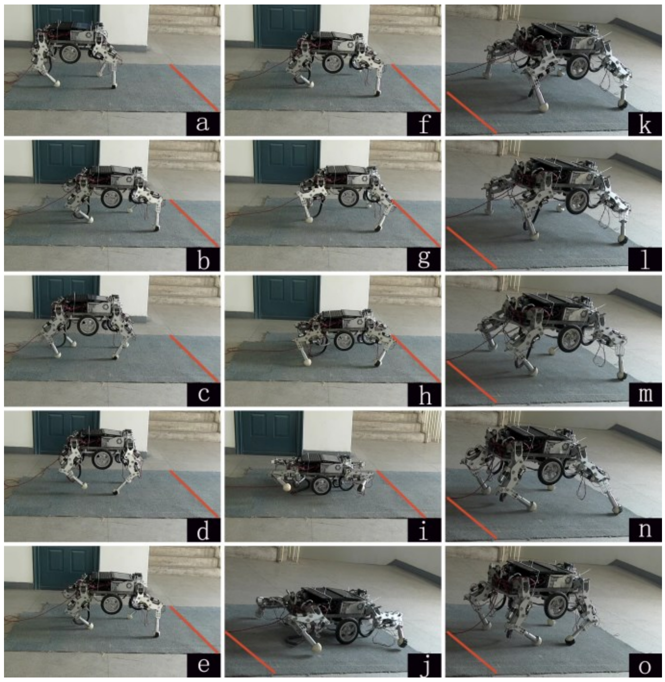


Fig 11. Sequence of snapshots of walking and mode transformation experiment. The first column shows the stage of static walking of HyTRo-I. The second column denotes the stage of transformation from the legged mode to wheeled mode, and the third column displays the stage of transformation from the wheeled mode to legged mode of HyTRo-I. Between the second and third stage, HyTRo-I rolls on wheels.

From the experiment, we can see clearly that the gait mutual transformation motions were stable and required a small amount of transformation steps. In addition, HyTRo-I can be capable of reciprocally transforming between the legged model and the wheeled model in a stable manner with a payload of 30Kg. In our actual work, HyTRo-I in wheeled rolling mode can achieve the maximum moving velocity of 2m/s on a level terrain and real-time obstacle avoidance and navigation based on laser radar. Thanks to the additional propulsion mechanisms in the abdomen of quadruped robot, HyTRo-I also can surmount vertical obstacles at a height of 310mm and climb steep slope at a degree of 30.

VI. CONCLUSION

We designed a leg-wheel hybrid transformable robot named HyTRo-I which has both high mobility on flat ground and high adaptability over irregular terrains. We developed a static walking gait controller. To transform between the wheeled rolling mode and the qudrupedal walking mode, a gait transition control method was proposed in this paper. The statically stable gait controller demonstrated stable walking. In addition, we experimentally demonstrated changing between two basic locomotion modes.

Future work will primarily focus on the following aspects. First, we will explore the advantage of a hybrid locomotion mode, using both legs and wheels simultaneously, both in simulation and experimentally. We expect a combination of walking and rolling to allow traversing more difficult terrain that is possible with either mode alone. Secondly, in order to develop high level control algorithms and strategies for autonomous movement over uneven terrains, the control information from sensors, such as gyroscope, laser radar, foot force sensor and GPS, will be incorporated into the control algorithm.

APPENDIX

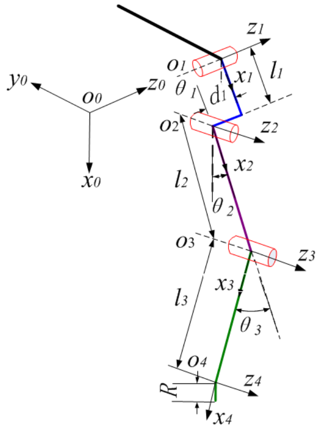


Fig 1. Kinematics model of one leg with coordinates and parameters.

To attain the mathematic relationship between joint angles and foot point trajectory, the kinematics model of a leg must be established. Fig 1 present the coordinate frames of 3-DOFs serial links of a leg according to the Denavit-Hartenberg (D-H) rules [14] and mechanical parameters of leg module. The foot movement was deal with the coordinate frame based on $\{o_0\}$, the origin of which fixed on the hip of robot body and coincided with the origin of coordinate frame $\{o_1\}$ .The z_0 pointed to the walking direction, x_0 pointed opposite to the gravity direction. The y axis of the coordinate frames $\{o_i\}$ (i =1, 2, 3) in revolute joints that obeyed right-hand screw rule were omitted.

In the Fig 1, the hemispheric end part of foot was simplified as a length of link R in the kinematics model of one leg and the value of R was not accounted for l_3. If given the coordinate of foothold G with $(X_p, Y_p, Z_p)^T$ in coordinate frame $\{o_0\}$, the corresponding joint variables θ_i (i =1, 2, 3) can be calculated as follows:

$$\theta_1 = \tan^{-1}\left(\frac{Y_p}{X_p}\right) \tag{1}$$

$$\theta_2 = \tan^{-1}\left(\frac{E + 2l_2^2}{\sqrt{4l_2^2 l_3^2 - E^2}}\right) - \tan^{-1}\left(\frac{a+b-l_1}{Z_p - d_1}\right) \tag{2}$$

$$\theta_3 = -\cos^{-1}\left(\frac{X_p^2 + Y_p^2 + (Z_p - d_1)^2 + l_1^2 - l_2^2 - l_3^2 - 2\sqrt{X_p^2 + Y_p^2}}{2l_2 l_3}\right) \tag{3}$$

where $E = (a+b-l_1)^2 + (Z_p - d_1)^2 - l_2^2 - l_3^2$, $a = \frac{X_p^2}{\sqrt{X_p^2 + Y_p^2}}$, $b = \frac{Y_p^2}{\sqrt{X_p^2 + Y_p^2}}$.

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