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Walk-to-ladder Climb Transfer with Force Adjustment for a Multi-locomotion Robot

[1]Zhiguo Lu, [2]Tadayoshi Aoyama, [3]Kosuke Sekiyama, [4]Yasuhisa Hasegawa and [3]Toshio Fukuda
[1]Department of Mechanical Engineering and Automation, Northeastern University, Shenyang, 110819, China
[2]Department of System Cybernetics, Hiroshima University, Hiroshima, Japan
[3]Department of Micro-Nano Systems Engineering, Nagoya University, Nagoya, Japan
[4]Department of Systems and Information Engineering, University of Tsukuba, Tsukuba, Japan

Abstract: This study presents a walk-to-ladder climb transfer for a Multi-locomotion Robot (MLR) with force adjustment using a key joint method which has been developed originally for releasing the additional internal stress by changing a redundant position control joint to force control. Walk-to-ladder climb transfer is a multi-contact complicate robot motion with robot hands and feet cooperation. Three sub-motions were designed in this motion transfer: (1) Raise hands to catch the ladder's rung, (2) Walk close to the ladder, (3) Climb on the ladder with legs. In order to compensate the position errors which always happened with position control, the key joint method has been studied in this study to improve the contact situations between the robot hand and the supporting rung. Experimental results show that this control method is effective for compensating the distance errors between hands and feet, thus the sliding of robot foot and the tumble problems has been prevented successfully. As a result, the MLR performs the walk-to-ladder climb transfer stably and smoothly.

Key words: MLR, walk-to-ladder climb, force adjustment, key joint method

INTRODUCTION

In recent years, there are many kinds of researches about moving motion in order to make robot move like animals but most of the robots can only do one type of locomotion and cannot change it from one to another. As is known to all, the environment in the world is various. It is not enough to adapt to different situations for only one type of moving motion. In order to solve this problem Fukuda *et al.* (2012) has developed an anthropoid-like "Multi-locomotion Robot (MLR)" which has several locomotion modes such as biped and quadruped walking, Climbing and brachiation as shown in Fig. 1. In past years, we have designed some types of motions, such as biped walking on flat terrain (Aoyama *et al.*, 2009a, b, 2012), quadruped walking on a slope, brachiation on a horizontal ladder (Kajima *et al.*, 2004) and climbing on a vertical ladder (Lu *et al.*, 2011).

However, these types of locomotion are realized and developed separately at present. But the environment around the robot will not be all the same. If the environment changed from one type to another such as from flat terrain to vertical ladder, in that case, the locomotion also needs to change automatically. So, the transition motion from biped walking to ladder climbing is needed. Walk-to-ladder climb transfer is a complete, multi-contact motion with changed environmental boundaries.

There have been some researches on the corporation of arms and legs for arm manipulation. The "Generalized Zero Moment Point (GZMP)" was defined for arm/leg coordination in humanoid robot whose hands touch an environment (Harada *et al.*, 2003). Harada *et al.* (2004) generated whole body motion for a pushing task through

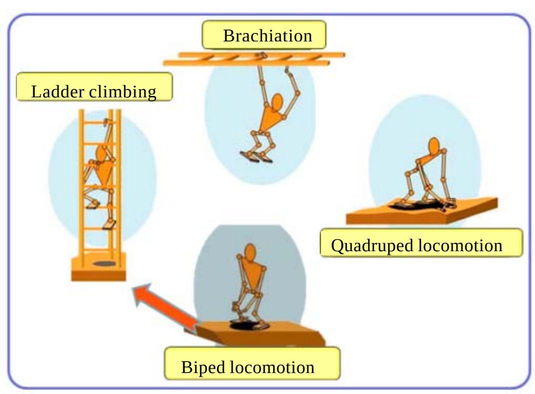

Fig. 1: Concept of multi-locomotion robot

Corresponding Author: Zhiguo Lu, Department of Mechanical Engineering and Automation, Northeastern University, Shenyang, 110819, China

cooperating arms and legs moment. There are some studys introduce the generating of body motion and steps to increase arm manipulability and robot stability (Inoue *et al*., 2005). In addition, a robot (HRP-2) walking on a rough terrain is realized assisted by a handrail (Koyanagi *et al*., 2008).

In this study we focused on the transition motion from biped walking to ladder climbing by MLR. The related information is given beforehand. After that we can make it possible for the robot to move on the ladder by planning the motion and designing the trajectories of hands and hip.

There are some problems should be solved in the transition motion. For one thing, it is important for the MLR to grasp the rung exactly. However, there are same errors from the environmental information, internal model, or the initial angle errors from the robot joint; For another thing, we need to control the reaction forces or compensate the position error with robot hand and foot constrained condition in the robot walking close to the ladder; In addition, the balance of MLR should be considered when the MLR extends hands to grasp the target rung of ladder by standing with two legs.

In this study, we introduce the control system to solve these problems. The experiment results prove that the MLR can realize the transition motion from biped walking to climbing stably and smoothly.

MULTI-LOCOMOTION ROBOT

We have developed the MLR (Gorilla III) which is modeled based on the structure of actual gorilla (Fig. 2a). The spec of Gorilla III is as following: The height is 1.0 m, weight is about 22 kg and DOFs of the whole body is 24. Each link length is shown in Fig. 2b. The hand is ape hand and it can grip a rung. The rubber plate is attached to the foot sole to prevent from slipping (Fig. 2c). This MLR is operated by real-time OS (VX Works). Each joint has a built-in servo motor and reduction gear. The servo motor can perform force control and position control and the control type of each joint can be easily switched by changing the configuration the servo package.

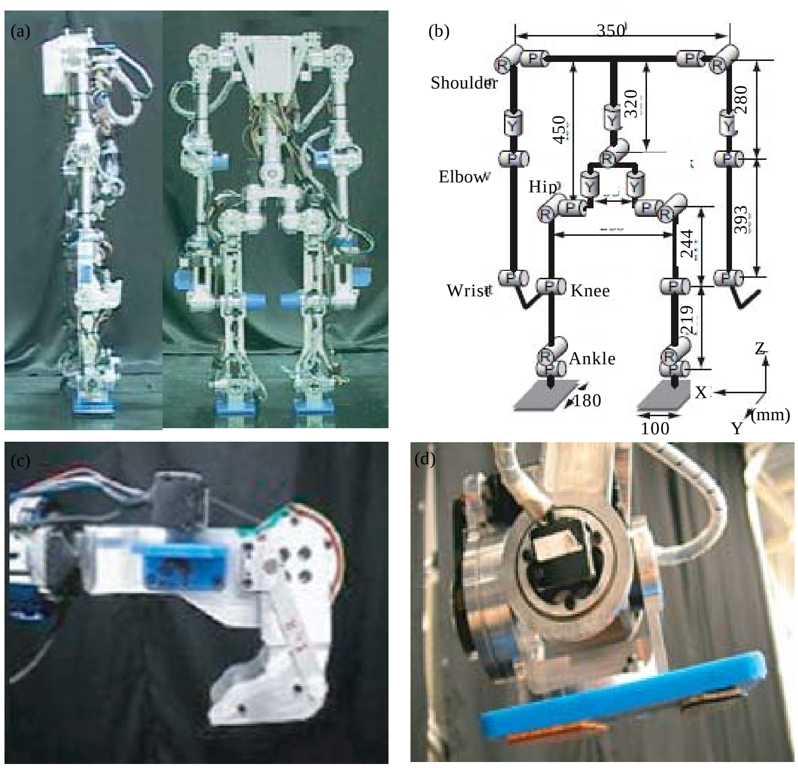

Fig. 2(a-d): Proto type of multi-locomotion robot, (a) Gorilla III, (b) Link and joint structure of Gorilla III, (c) Hand structure and (d) Foot structure

WALK-TO-LADDER CLIMB TRANSFER

Motion planning

Connected posture: Standing on the floor using two legs is the end posture of biped walking and the robot getting on the ladder using two hands and two legs is the start posture of ladder climbing. In the beginning, the MLR stands in front of the ladder at a biped posture and the environmental information about the ladder is given beforehand.

Motion design: Since the environmental boundary conditions change from a flat terrain to a vertical ladder and there are always some irregulars near the connection area, the cooperation of robot hands and feet is considered for helping the robot to keep balance. Then, the transition motion is designed as follows (Fig. 3):

- Raise hands with balance as shown in Fig. 3a-b
- Walk close to the ladder as shown in Fig. 3b-e
- Climb up on the ladder as shown in Fig. 3e-h

Controller design

Balance control: This control is used before the MLR grips the ladder's rung. The arms' center of masses will move when the MLR extends its arms. In order to keep balance on gripping motion, other joints need to cooperate with this motion. Considering the static balance, the robot keeps balance by planning the projection of the Center of Gravity (COG) in the range of two feet. The robot motion is designed symmetrically in lateral plane and the posture is decided by the angles of pitch joints which are illustrated by small circles as showed in Fig. 3.

Ladder detection: It is important for the MLR to grasp the rung exactly. A shock is likely to occur when the moving hand comes in connect with the rung which is fixed on the vertical ladder. We can observe this phenomenon according to the change of the force loaded on arms. The robot start gripping the hand after it is recognized that the hand of the robot comes in connect with the ladder. The force sensor installed on each arm played an important

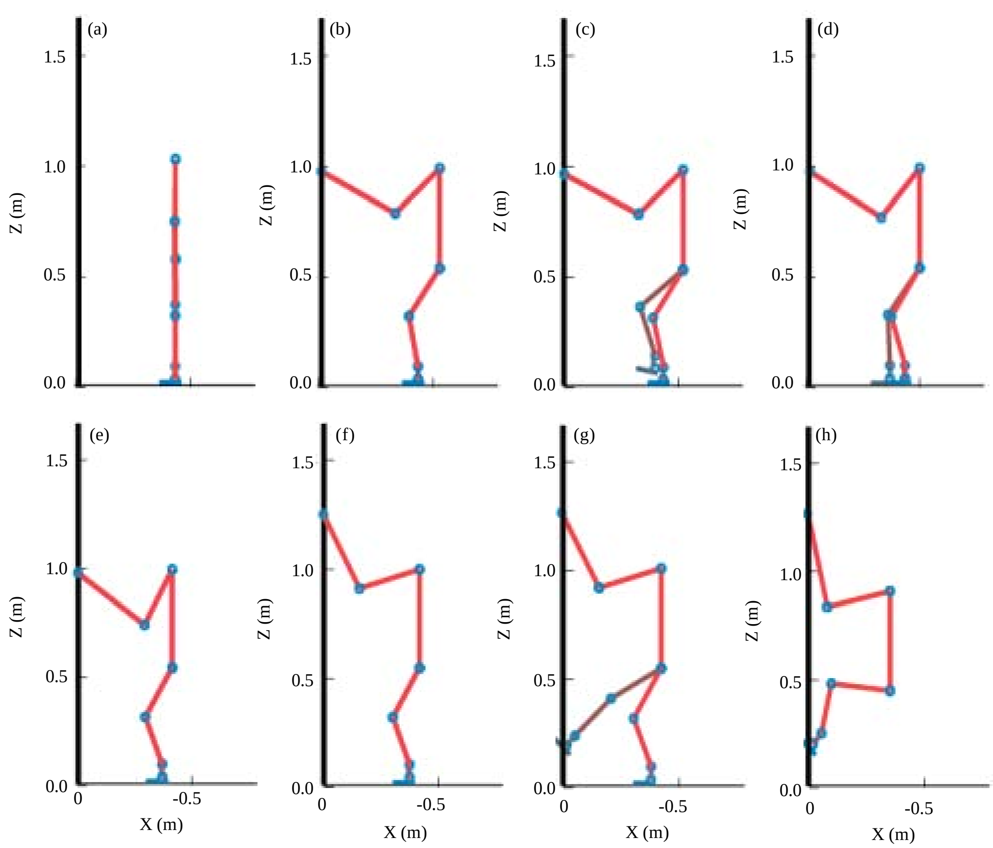

Fig. 3(a-h): Transition motion from biped walking to ladder climbing

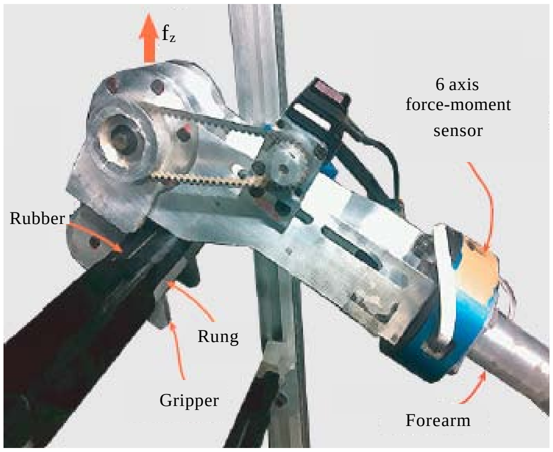

Fig. 4: Force sensor on forearm, where f_z is the reaction force acting on the robot hand in the Z direction

role in the force detecting. The power to confirm the force in a vertical direction used data calculated in Eq. 1 for the arms of the robot by the force sensor which is fixed on the forearm as shown in Fig. 4. First, the robot raises its hands over the rung. Next, the robot lowers its hands to contact with the rung. The robot grasps its hand once it is judged to be in contact with the rung if the force gradient ε exceeds the threshold level ε_d. The force gradient is expressed as follows:

$$\varepsilon = f_z(t)-f_z(t-\Delta t) \quad (1)$$

where, $f_z(t)$ is the reaction force of the robot hand in the vertical direction at time t and Δt is the scanning period.

Problems statement: In the motion that the robot walks close to the ladder, the main supporting forces are from the robot foot. Since there are often some irregulars on the floor near to the vertical ladder, the assistant motion that two hands gripping the ladder is designed to help the robot keeping balance. However, there are always some distance errors between the robot end effectors and the supporting points on the environment. This errors may come from the information errors of the environment, the initial position error of the robot joint and the errors from inter model. These errors influence a lot to the contact situation especially for a multi-contact mobile robot. For the walk-to-ladder climb transfer introduced in this study, there are two unstable elements: One is robot foot slides on the floor when the distance between hand and foot shorter than expect, as shown in Fig. 5a; another is robot hand fails to catch the rung when the distance between hand and foot longer than expect, as shown in Fig. 5b.

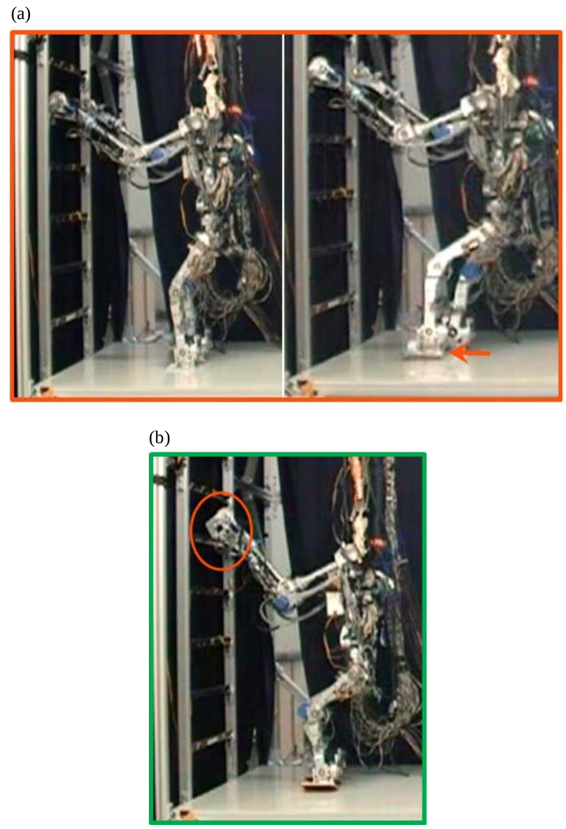

Fig. 5(a-b): Failures in motion transfer with position control (a) Robot foot slides on the floor and (b) Robot hands fails to catch the rung

Furthermore, the robot may fall down toward aside or rotates around the supporting axis in the line of jointing two contacts formed by a supporting hand and the supporting foot.

Force adjustment using a key joint method: The key joint method is a hybrid force/position control that realized by changing a redundant position control joint to force control inside a closed chain and the joint using force control is defined as a key joint which is identified based on its sensitivity to the internal stress inside the closed chain. The concept of key joint method and the principle of key joint identification have been fully introduced by Lu *et al.* (2012). As a new application, the key joint method is used for compensating the distance errors between robot hand and robot foot, furthermore the contact forces acting at robot hands are maintained.

For a multi-contact walk-to-ladder climb transfer, many closed chains are formed by the robot links and the environment, However, only the closed chain in lateral plane influence highly to the motion stability, thus the closed chains in lateral plane, as shown in Fig. 6, were considered. And then the internal stress (interaction force) between robot hands and supporting feet are easily to be maintained just by changing the shoulder pitch joint from position control to force control. Note that based on the key joint selection principle (Lu *et al*., 2012), the joint which has the maximum sensitivity to the internal stress should be selected as key joint.

In the walk closed motion, the internal stress (interaction force) between the robot hand and the supporting foot is in the line of jointing two contacts as shown in Fig. 6 and the shoulder pitch joint is identified as key joint in this motion process. Finally, the contact forces acting at robot hands are maintained

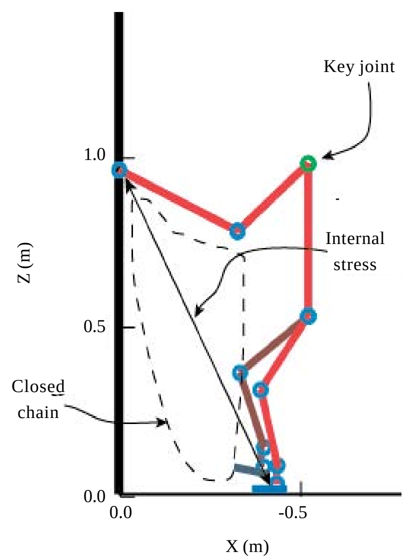

Fig. 6: Closed chain in lateral plane

using the key joint method and then the robot can perform the walk-to-ladder climb transfer successfully.

EXPERIMENTAL RESULTS

In this section, we show the experiments about stable transition motion from biped walking to ladder climbing by the MLR. The experimental conditions are listed as follows:

- A rigid ladder is set up vertically. The rungs are chosen as square aluminum tubes for convenience
- The MLR stands 0.45 m in front of the ladder
- The cross section of a rung on a vertical ladder is a square of 20×20 mm and covered with rubbers
- The intervals of rung on vertical ladder are is 200 mm

The snapshot of transition motion from biped walking to ladder climbing is shown in Fig. 7. The sliding angles shown in Fig. 9 illustrates that there exists some position errors between the actual model and designed model, these errors may come from the parameter error of the ladder's position or from the initial position error of the robot joint.

In the experimental result shown in Fig. 8 and 9, we find that the touching action happened Δt 's earlier than expect, it means the target rung is fixed a little higher or the initial position of robot hand is a little lower than the ideal motion model. Since a torque control was applied, the key joints were soft enough to sliding for compensating the unexpected position errors. The sliding angle of key joints which are related to the distance errors between robot hands and supporting foot are shown in Fig. 9. And the contact forces acting at robot hands were maintained by the torque control of key joints as shown

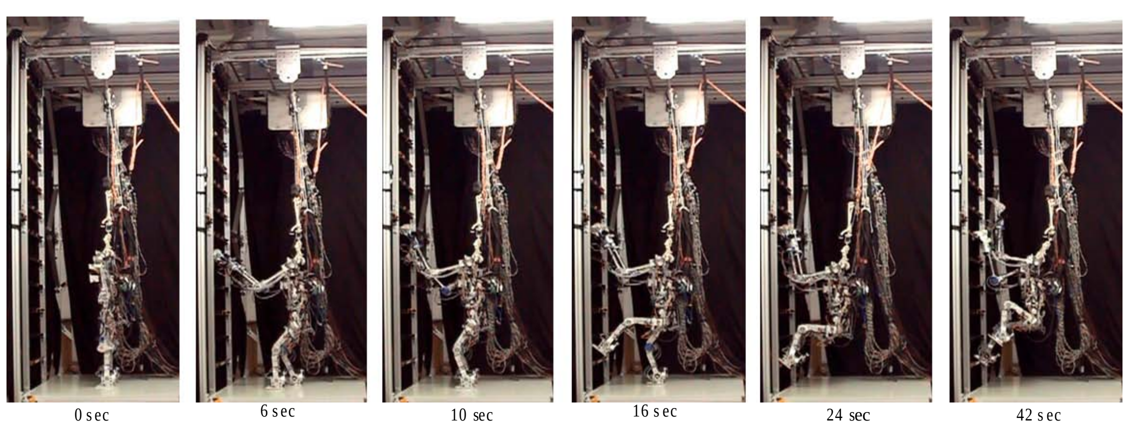

Fig. 7: Snapshots of walk-to-ladder climb transfer

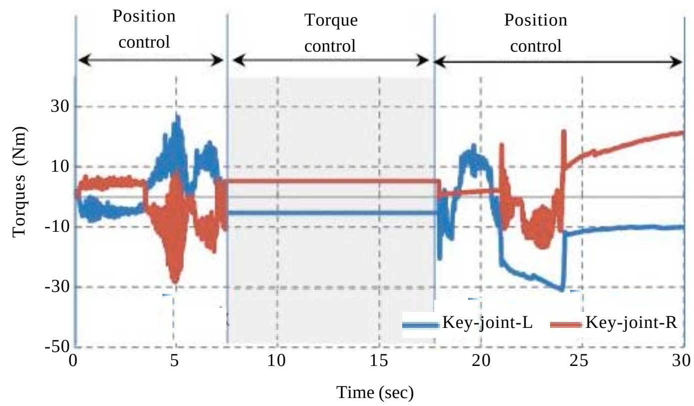

Fig. 8: Torque of key joints, where key-joint-L is the key joint in the left side corresponding to the left shoulder's pitch joint and key-joint-R is the joint of the right shoulder's pitch joint

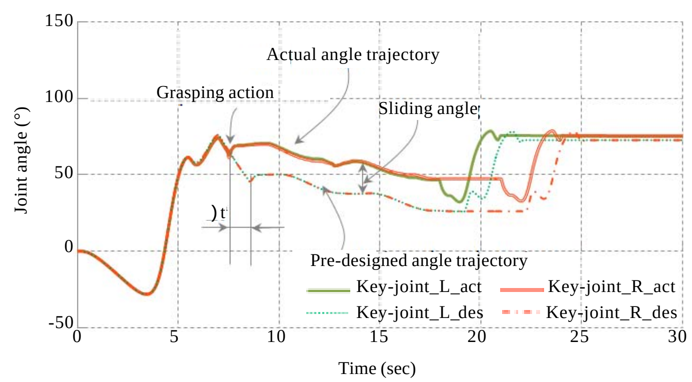

Fig. 9: Angle of key joints (shoulder joints in pitch direction)

in Fig. 8. In this experiment, force adjustment measure has been taken when the MLR moves after two hands gripping the ladder and the stability has been improved greatly.

CONCLUSION

In this study, the transition motion is designed for the real environment especially the vertical ladder. Using the balance controller and touch detection the robot can grip the rung of the ladder exactly. In the action of walking close to the ladder, the motion is performed well through the force adjustment measure based on the key joint method. Experimental results show that using these control theories the robot can do the transition motion from biped walking to ladder climbing stably and smoothly.

As a future work, we consider making the robot recognize the necessary information such as the distance from the robot to the ladder and the interval of each rung on the ladder those are helpful for the robot to transform the locomotion according to the real environment automatically.

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