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Development of Track-changeable Quadruped Walking Robot TITAN X -Design of Leg Driving Mechanism and Basic Experiment-

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Abstract— We propose track-changeable quadruped walking robot, named "TITAN X". TITAN X is a new leg-track hybrid mobile robot with a special leg driving system on each leg. A belt on each leg changes to a timing-belt in leg form and a track-belt in track form. TITAN X walks in leg form on rough terrain and makes tracked locomotion using track-belt on level or comparatively low-rough terrain. The characteristics of TITAN X are: 1) it has a hybrid function but is lightweight, 2) it has potential capabilities to demonstrate high-performance on highly-rough terrain. In this paper, details of leg design using a special belt are reported. Also form changing mechanisms are integrated into the system. We have constructed prototype of TITAN X to demonstrate basic performance. Experiments were conducted to verify the validity of the concept of track-changeable walking robot.

I. INTRODUCTION

Since walking machines can contact the ground with discrete points and the contact points can be arbitrary selected according to the terrain condition, walking machines have such special characteristics:

1) Walking machines can move stably over a rugged terrain, and can pass over fragile objects on the ground without touching them.
2) Walking machines can change the direction of motion without slipping even if the sole contacts the ground with a large area.
3) The legs can be utilized not only for motion, but also rest. At standstill posture, the legs become outriggers to hold the upper body stable even on an uneven ground. The upper body can be actively driven while the feet are fixed to the ground.

However, wheeled or tracked vehicles can move more smoothly and have superiority in mobile speed and efficiency when mobile environment is flat at some level. Therefore, a lot of study on hybrid mobile machines are reported [1]–[5]. But, conventional hybrid mobile machines are restricted because they are equipped with leg driving system and wheeled or tracked driving system separately and the addition of multiple driving systems causes the robot to gain weight and grow in size. In many cases, wheeled or tracked mechanism do not contribute to walking because these mechanisms are used while the leg mechanisms are being driven.

To solve these problems, we proposed hybrid mobile robot, named "Roller-Walker" [6], [7]. Roller-Walker is a walking machine with a special foot mechanism on each leg which changes to a sole in leg form and a passive wheel in skating form. We showed the effectiveness of constructing hybrid mobile robot with minimum mechanism and switching its style of locomotion.

On the basis of design method of hybrid mobile robots that was established in the study on Roller-Walker, we propose a hybrid mobile robot named "TITAN X", which is a quadruped walking machine that combines the properties of leg and track.

II. TRACK-CHANGEABLE QUADRUPED WALKING ROBOT, TITAN X

A. Concept of track-changeable walking robot

Fig.1 shows the concept of track-changeable quadruped walking robot, TITAN X. TITAN X is a walking machine with a special belt driving system on each leg which changes to a timing-belt in leg form and a track-belt in track form. The mechanism that combines the properties of leg and track is named "Track-changeable Leg Mechanism" and the walking robot that uses track-changeable leg mechanism is named "Track-changeable Walking Robot".

The style of locomotion is selected by mobile environment. On rugged terrain the robot walks in leg form, and on level or little rugged terrain the robot makes tracked locomotion by track-belt.

B. Characteristics of track-changeable walking robot

The features of track-changeable walking robot are considered as follows:

1) There is no need to add extra driving system for constructing hybrid mobile robot, because the driving system for tracked locomotion is integrated in the driving system for walking. Therefore, the only extra mechanism is the mechanism for switch the style of locomotion. This avoids the biggest problem for conventional hybrid mobile robot that its driving system gets heavy.
2) The legs of walking machine have large work space and output force for walking motion. The proposed track-changeable walking robot can realize not only the switching of its locomotion style with mobile

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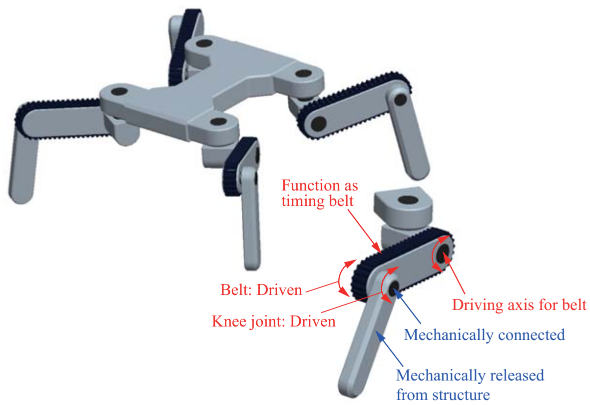
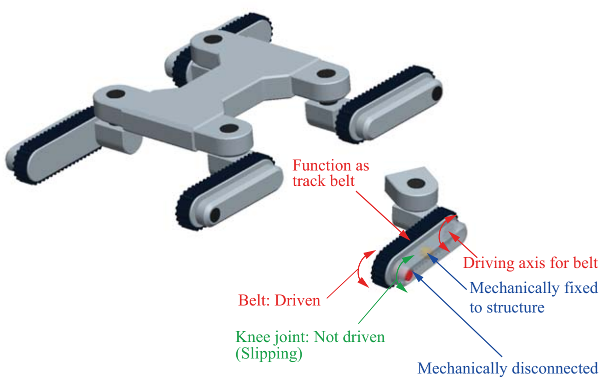


(a) Leg form



(b) Track form

Fig. 1. Concept of track-changeable walking robot, TITAN X


(a) Terrain-adaptive locomotion System

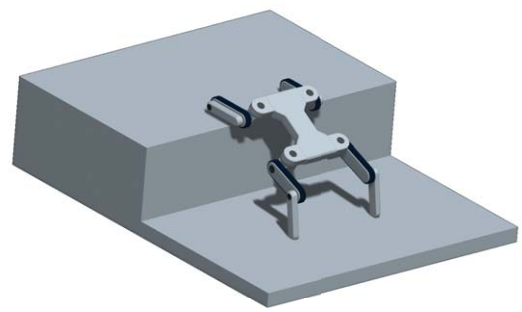

(b) High-performance vehicle on rough terrain

Fig. 2. Main features of TITAN X

environment as shown in Fig.2(a), but also high-performance motion such as hybrid motion that combines the properties of leg and track as shown in Fig.2(b).

Thus, the proposed track-changeable walking robot is a mobile one with great potential. To realize this track-changeable walking robot, we considered some mechanisms as follows:

(A) Special driving system that combines the functions of tracked locomotion with those of drive transmission for driving the knee joint.

(B) Small and lightweight mechanism for changing the locomotion style, named "Form Changing Mechanism".

(C) Two-stage transmission that changes speed and torque of belt depending on the locomotion style.

(A) is belt driving system that has not only the functions of drive transmission to trim weight of the end of the leg, but also those of tracked locomotion for moving. Many conventional walking machines have belt driving system using timing-belts, wires and chains which transmit power that is generated by actuators mounted around the body to the joint around the end of leg. Focusing on this design of a driving system, we devised a method of converting a track-belt to a timing-belt. (B) is a small and lightweight mechanism based on design principle of variable constraint mechanism [8]. It is composed of a driving force transmission mechanism that transmits driving force from the belt to the knee joint in leg form and a fixation mechanism which fixes the end link of leg in track form. (C) is needed because speed and torque of the actuator for driving belt are different by the locomotion style.

However, (C), the two-stage transmission, is expected to be difficult to developing. In this paper, design of two mechanisms, (A) and (B), are considered because the track-changeable walking robot can be realized with these two mechanisms. Focusing on these mechanisms, the design of track-changeable leg mechanism are discussed in detail below.

III. DESIGN OF TRACK-CHANGEABLE LEG MECHANISM

A. Design of driving system

Track-changeable leg mechanism has three DOFs. It is composed of serial link mechanism with two DOFs and swing mechanism that turns this link mechanism.

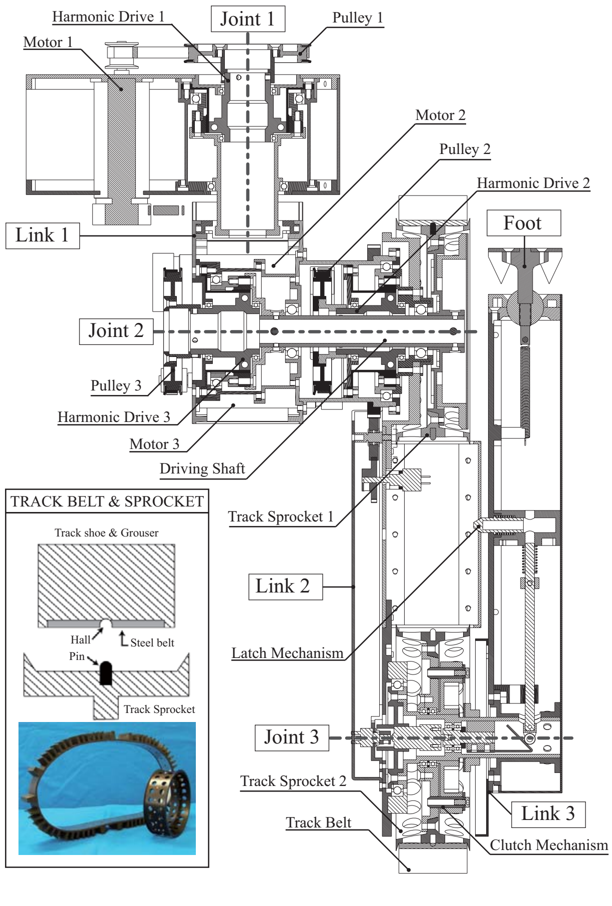
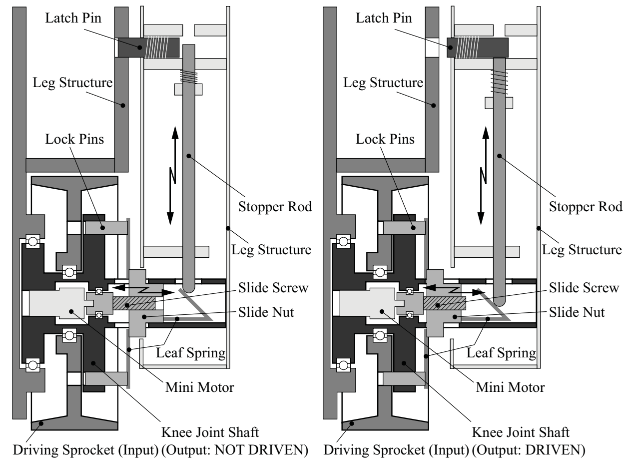


Fig. 3. Design of track-changeable leg mechanism

In leg form, the tip of the leg can be placed to the arbitrary three-dimensional position in its workspace. In track form, movable joints are two because the last link of the leg are fixated. But it has more DOFs than conventional track robot and can show high mobility on rough terrain. The design of track-changeable leg mechanism is indicated in Fig.3. The introduction of track-belt to driving system is quite characteristic of it.

A Rubber track covering a steel-belt is used as the driving belt for the proposed driving system, which is developed by TOPY Industries Ltd. in Japan [9]. It is made of a hard rubber attached to a steel-belt. Pins attached to the sprocket and holes in the steel-belt bite each other when driven. It has little retractility and the property of great allowable torque, so it is considered to be suited to a timing-belt for walking machines. Pulley and harmonic drive, which has high efficiency and zero backlash property, are used as reducers for each joint.

The driving system of Joint1 is composed of Motor1 and reducers of Pulley1 and Harmonic Drive1. Similarly, that of Joint2 is composed of Motor2 and reducers of Pulley2 and Harmonic Drive2. Track Sprocket1 is driven by Driving Shaft, which is arranged coaxially with the rotation axis of Joint2. Driving Shaft is driven by Motor3 and reducers of Pulley3 and Harmonic Drive3. If the robot is in leg form, Joint3 is driven by Track Sprocket2.



(a) Track form (Input and output are disconnected)

(b) Leg form (Input and output are connected)

Fig. 4. Cross-section of knee joint including form changing mechanism

B. Design of form changing mechanism

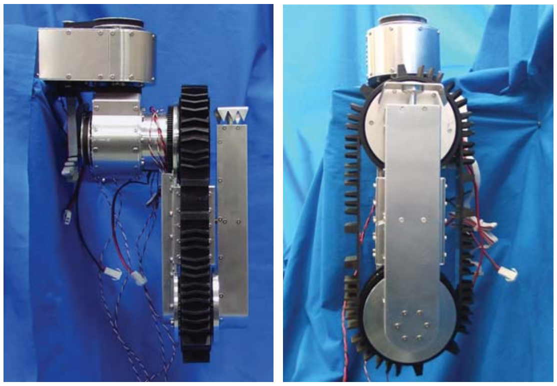
The following functions are needed to realize "Form Changing Mechanism":

1) Clutch function: mechanism for transmitting the rotation of track sprocket to the knee joint shaft, which can be engaged and disengaged.
2) Fixation function: mechanism that holds the position of the last link of the leg that is unconnected with the knee joint shaft in track form.

The design of form changing mechanism is indicated in Fig.4. The clutch function that connects and disconnects Driving Sprocket to Knee Joint Shaft is realized by inserting and removing Lock Pins from holes in Track Sprocket. Lock Pins are supported by a leaf spring to avoid the force applied to them before they are inserted to the holes.

The fixation mechanism is realized by the simple mechanism that Latch Pin mounted in Link3 is inserted to the hole on Link2 by coil spring. Meanwhile, the release of Link3, removing Latch Pin, is done by the rotation of Joint3 (knee joint) after Track Sprocket is connected to Knee Joint Shaft. To ensure the fixation of the position of Link3, the motion of Lock Pins is used. When Lock Pins are removed from the holes, Stopper Rod is pushed by the motion of Lock Pins as shown in Fig.4(a) and after being fully pushed, Stopper Rod restricts the motion of Latch Pin not to be removed from the hole. On the other hand, when Lock Pins are inserted to the holes, the force applied to Stopper Rod is removed by the motion of Lock Pins and Stopper Rod returns by the coil spring to lift the restrictions on the motion of Latch Pin.

The weight of form changing mechanism that has two functions is 160 [g], which is 3 [%] of the total weight of the leg mechanism. This substantial reduction in weight became possible thanks to the introduction of



(a) Front view (b) Side view

Fig. 5. Prototype of track-changeable leg mechanism

TABLE I
Specifications of track-changeable leg mechanism

Length	485 [mm]
Mass	5.20 [kg]
Actuators	DC motor (60W) ×3
Reducers	Harmonic drive (SHG17)

the Form Changing Mechanism because the weight of the actuator to drive the joint (or track-belt) is about 1 [kg]. Therefore, the validity of track-changeable leg mechanism proposed in this paper is shown clearly.

The mechanical model of one leg is shown in Fig.5 and its specifications are indicated in TABLE.I.

IV. EXPERIMENTS

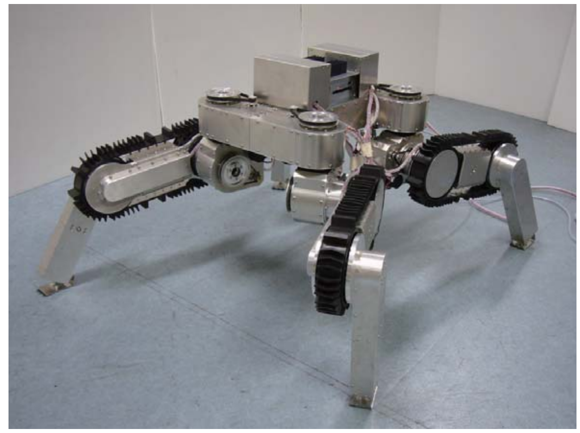
A. Configuration of TITAN X

Based on the foregoing discussions, we made a prototype of TITAN X as shown in Fig.6. The specifications of TITAN X are indicated in TABLE.II. Legs are mounted on the corners of the body, battery and computer are on the center of the body.

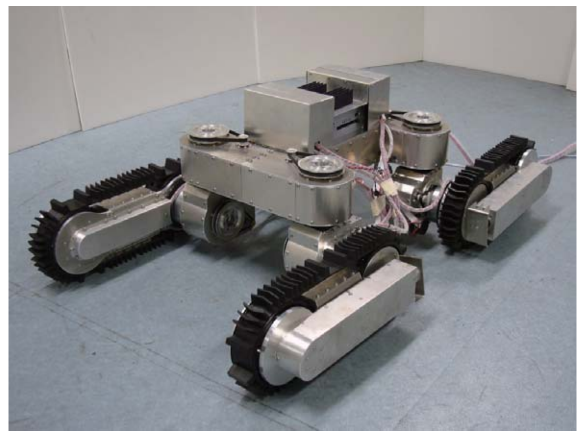
The control system of TITAN X is illustrated in Fig.7 and primarily consists of nine SH2 micro-controllers (two for each leg and one for the communication) and a embedded computer (Geode LX800). The micro-controllers are connected via CAN-bus and one of them and the embedded computer are connected via RS-232, the LAN device of the computer enables wireless communication with a second host for visualisation, user interface and test control. The embedded computer takes on the upper task such as motion planning and the micro-controllers takes on the lower task such as servo control of joints and data acquisition from sensors. Each micro-controller is connected with power amplifiers for each DC motor.The joint angles are measured by rotary encoders.

B. Legged locomotion experiment

We conducted an experimental test on walking as shown in Fig.8. Fig.8(a) shows sequence motion of crawl



(a) Leg form



(b) Track form

Fig. 6. Prototype of TITAN X

TABLE II
Specifications of TITAN X

Size	890 [mm] ×581 [mm] ×303 [mm] (Track mode)
Mass	23.2 [kg] (including batteries)
DOFs	16 [DOFs] (including DOF for form change)

gait in one cycle and Fig.8(b) shows that of trot gait in two cycles. In this experiment, we changed duty factor β from 0.5 to 1.0 and repeated experimental test on static and dynamic walking. No tumbling and slipping are observed in walking experiments and we confirmed that TITAN X can walk using the developed driving system as conventional quadruped walking robots. It can walk at the speed of 110 [mm/s] in crawl gait and at the speed of 150 [mm/s] in trot gait.

C. Tracked locomotion experiment

In this section, the abilities of the tracked locomotion are tested. First, we conducted an experiment of negotiating stairs, using the stairs with 250-millimeter-wide treads and 150-millimeter-high rises, as shown in Fig.9(a). After the repeated experiments, we confirmed

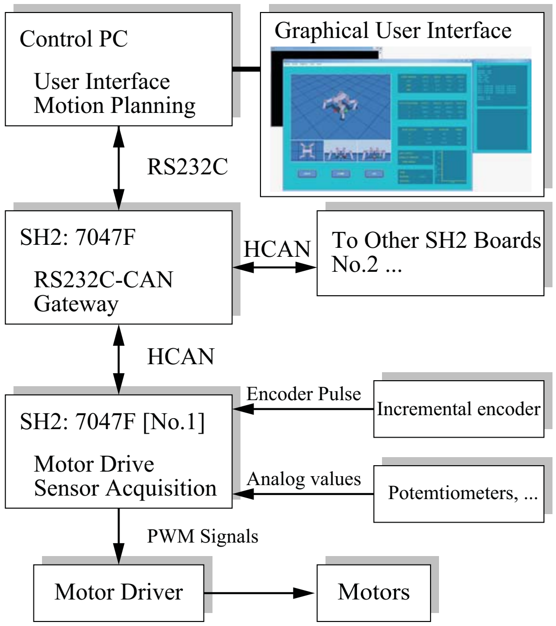


Fig. 7. Control system architecture

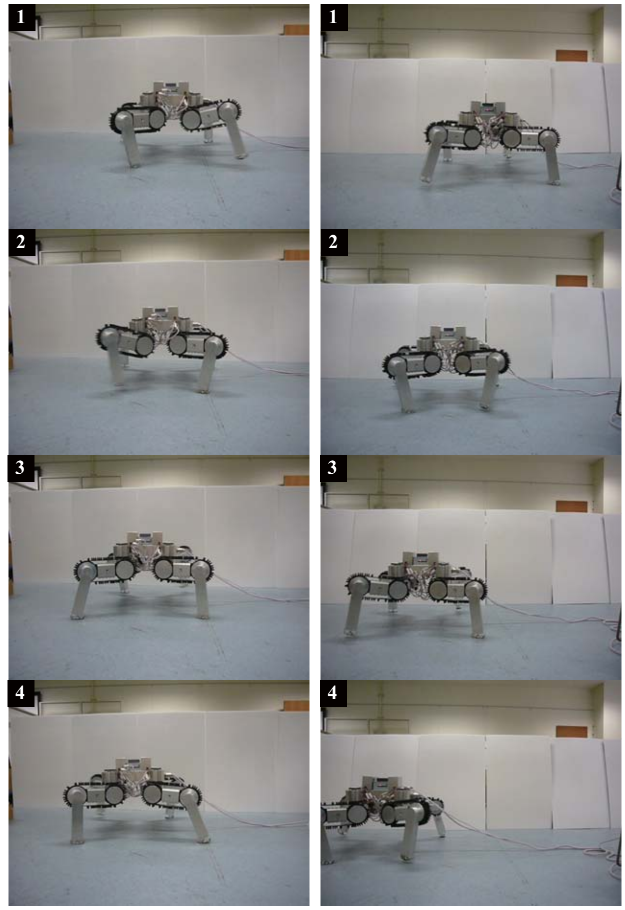
that TITAN X had the capability of going up and down the stairs stably without slipping. Second, we conducted an experiment of crossing a horizontal gap as shown in Fig.9(b). TITAN X succeeded in crossing a horizontal gap whose flute width was 400 millimeters. This is because TITAN X's tracks are connected to the front and back side of the body. Moreover, we confirmed the effectiveness of improving the apparent ground contact area of the tracks in its direction of motion by changing its posture. Then, an experiment for negotiating a large obstacle was performed. In this experiment, TITAN X could go over the obstacle with a height of 265 millimeters as shown in Fig.9(c). Finally, we performed an experiment which required TITAN X to go over an one-sided obstacle as shown in Fig.9(d). TITAN X succeeded in going over an one-side obstacle with a height of 200 millimeters. While going over the obstacle, swaying motion occurred on the roll axis, but TITAN X completed the task without a roll-over.

D. Form changing experiment

To demonstrate the concept of TITAN X, we conducted an experiment on form changing. Fig.10 shows the snapshot of sequence motion between leg form and track form:

1) TITAN X moves in track form.
2) It lifts up each Link2 of legs to spread each Link3.
3) It spreads each Link3 after form changing mechanism switched the locomotion style.
4) It lifts its body and walks.

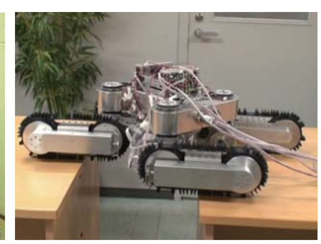
In this form changing motion, TITAN X places all four feet in contact with the ground at same time and smoothly switches motion from track form to leg form.



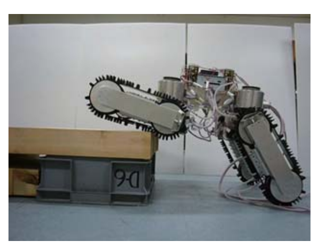
(a) Crawl gait (b) Trot gait

Fig. 8. Walking motions of crawl and trot gait

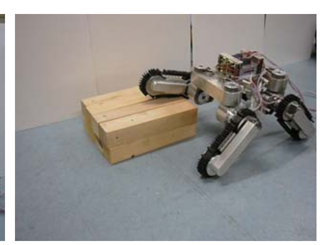
(a) Stair ascending and descending motion



(b) Crossing a horizontal gap



(c) Posture to go over a large obstacle



(d) Motion to go over an one-side obstacle

Fig. 9. Experiment for test on tracked locomotion performance

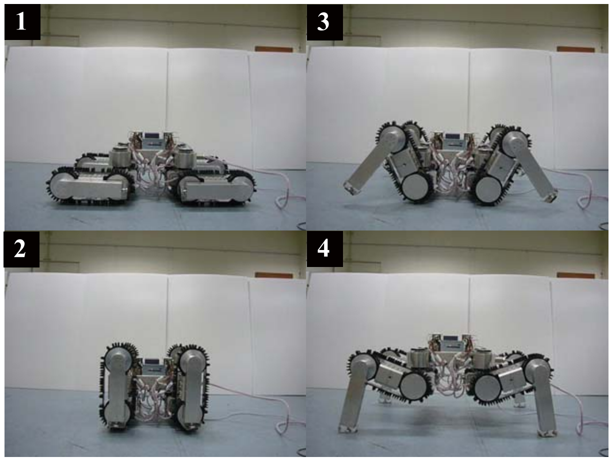


Fig. 10. Sequential motion of form changing from track to leg

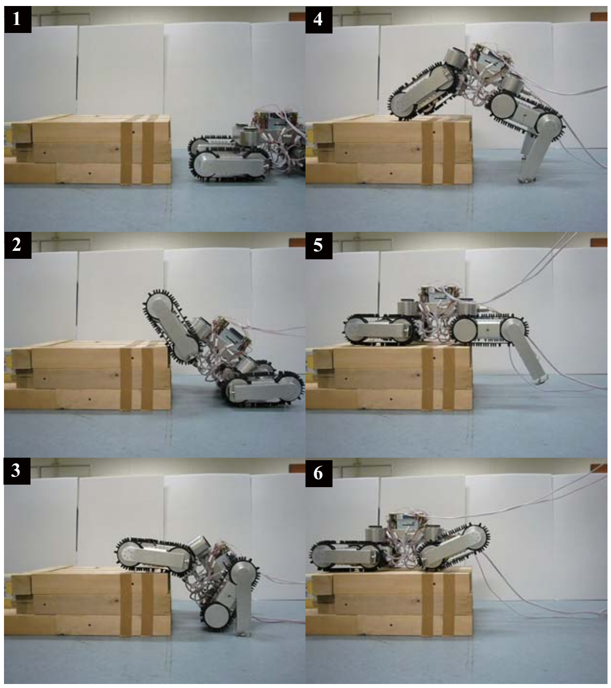


Fig. 11. Snapshots of hybrid motion to go over a large obstacles that TITAN X failed at track form

Switching motion from leg form to track form can be realized by performing the motion shown in Fig.10 in reverse.

E. Hybrid motion experiment

Fig.11 shows experimental result of hybrid motion that combines the properties of leg and track. By the support of rear legs, TITAN X could go over a large obstacle that it could not in track form. In this experiment, TITAN X succeeded in going over the obstacles with a height of 450 millimeters. This height is about 1.8 times higher than TITAN X can go over in track form. This hybrid motion in this experiment is replayed based on prior kinematic simulation. However, the experimental result shows that TITAN X can realize the hybrid motion actually and we have presented a strong argument for the validity of the developed driving system.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we presented the concept and characteristics of track-changeable walking robot, which has a novel belt-driving system that combines the functions of track locomotion with those of drive transmission for driving the knee joint. The proposed concept is quite different from that of conventional leg-track hybrid mobile robot. It is applicable to many walking robots and is a practical method for realizing hybrid mobile robots without restricting mobility.

We designed the proposed driving system using the rubber track covering the steel-belt and constructed mechanical model of TITAN X. In developing TITAN X, we confirmed the validity of the concept of track-changeable walking robot, which can solve the biggest problem for conventional hybrid mobile robot: the excessive weight of the driving systems.

Tracked locomotion, legged locomotion, form changing motion and hybrid motion were verified by experiments using TITAN X. We qualitatively confirmed that TITAN X had high mobility and great potential on rough terrain.

About future plans, we will consider the following:

- Development of small and light-weight two-stage transmission to change speed and torque of belt.
- Optimization of form changing motion from various perspectives such as time or consumption energy.
- Planning of hybrid motion that combines the properties of leg and track.

References

[1] H.Kimura, E.Nakano amd Y.Nonaka: “Development of Leg-Wheel Robot and Cooperational Motion of Legs and Wheels,” Journal of the Robotics Society of Japan, vol. 7, no. 2, pp. 520-525, 1992. (in Japanese)

[2] H.Adachi, T.Arai, K.Homma: “Study on Underground Space Excavating Machine,” 9th International Symposium on Automation and Robotics in Construction, pp. 751-758, 1992.

[3] H.Adachi, N.Koyachi, T.Arai, A.Shimizu and Y.Nogami: “Mechanism and control of a Leg-Wheel Hybrid Mobile Robot,” Proceedings of IEEE International Conference on Intelligent Robots and Systems, pp. 1792-1797, 1999.

[4] Ch.Grand, F.BenAmar, F.Plumet and Ph.Bidaud: “Decoupled control of posture and trajectory of the hybrid wheel-legged robot Hylos,” Proceedings of IEEE International Conference on Robotics and Automation, pp. 5111-5116, 2004.

[5] Francois Michaud, et al.: “Multi-Modal Locomotion Robotic Platform Using Leg-Track-Wheel Articulations,” Autonomous Robots, vol. 18, no. 2, pp. 137-156, 2005.

[6] G.Endo and S.Hirose: “Study on Roller-Walker: System Integration and Basic Experiments,” Proceedings of IEEE International Conference on Robotics and Automation, pp. 2032-2037, 1999.

[7] G.Endo and S.Hirose: “Study on Roller-Walker -Adaptation of Characteristics of the propulsion by a Leg Trajectory-,” Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1532-1537, 2008.

[8] S.Hirose: “Variable Constraint Mechanism and Its Application for Design of Mobile Robots”, Journal of Robotics Research, vol. 19, no. 11, pp. 1126-1138, 2000.

[9] http://www.topy.co.jp/english/dept/bdp/BG002_001.html