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Object Carrying Motion with Handover and Wide Gap Traversing by Hexapod Tracked Robot

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***Abstract*—A hexapod tracked mobile robot, which is equipped with tracks and six legs, is able to not only move over rough terrain, but also perform a variety of tasks by using its legs as manipulation arms. In this study, we consider an object carrying with wide gap traversing by the support of the legs as a typical task representing the abilities of this type of robot. We specifically analyzed the motion of picking up an object with handover between legs basically required in the task. Experiments by the developed hexapod tracked robot were conducted for the task. The results showed an ability to achieve hybrid tasks by this type of robot.**

***Index Terms*—hexapod tracked mobile robot, wide gap traversing, object carrying, handover motion**

I. Introduction

It is highly expected that robots are able to perform a variety of tasks in a disaster area or construction site with rough terrain. Some literature has reviewed hybrid locomotion systems with legs and wheels/tracks for ground-traversing mobile robots [1][2]. Bruzzone et al. noted that both leg-wheel and leg-track hybrid systems offer a high degree of mobility over uneven terrain [2]. The authors, however, consider that the robots should have the ability to not only travel over the ground but also perform tasks with handling because required tasks for the robots in such area will be involved in some work with handling operation such as transportation. To complete such handling tasks, it is necessary for a robot to have multiple manipulation arms as well as track driving mechanisms.

Based on this consideration, the authors have developed a hexapod tracked mobile robot, which consists of two tracks attached to the main body and six 4-DOF legs which can be used as manipulation arms, as shown in Fig. 1 [3]. This robot is able to walk by six legs, drive by tracks, and carry an object using two or more legs as manipulation arms. Moreover, this mechanism enables the robot to traverse wide gap such that the legs support the robot to avoid falling down with holding the object by middle two legs in a transportation, as shown in Fig. 2.

This study focuses on this type of hybrid motion in an object carrying task. In this task, the robot needs to initially pick the object up by the front legs then hand it over the middle legs. We consider the motion consisting of pick-up and handover. Kobayashi et al. described an object handover between human and robot [4]. Deng et al. described an object carrying by hexapod robots [5]. The type of motion to be considered here is different from them. Thus, we analyze the handover motion for the hexapod tracked robot based on a kinematics model, and confirm the validity of the motion

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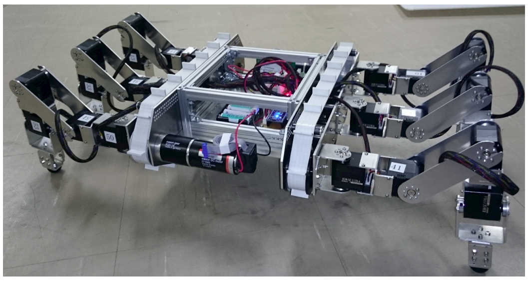

Fig. 1. Developed hexapod tracked mobile robot

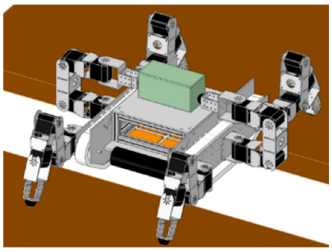

Fig. 2. Traversing a wide gap with object carrying by hexapod tracked mobile robot

for the hybrid object carrying in simulations and experiments by the developed robot.

In the following, Section II will explain overview of the object carrying motion with wide gap traversing by the hexapod tracked robot, Section III will analyze handover motion, and Section IV will demonstrate experimental result for the motions.

II. Object Carrying with Wide Gap Traversing

Fig. 3 shows a sequence of object carrying motion by the hexapod tracked robot. We assume that the target object is a homogeneous box-shaped object for simplicity. The number with circle in each panel indicates the order of the motion. The small red point on the object shows the center of gravity of the object. The panels from ① to ⑥ in Fig. 3 show a motion in which the robot picks the object up using the front legs and hands it over to the middle legs. The panels from ⑦ to ⑯ show a hybrid motion traversing a wide gap by track driving and leg-supporting with object carrying.

In the motion for picking up and handing over, as shown in ① to ⑥ of Fig. 3, the robot firstly approaches the target object (①), grips it at an upper position (②), and lifts it up (③). Th robot then moves the object backward horizontally by the fore legs as long as it can move on the horizontal trajectory at a height in the space of upper body (④). When the object reaches the position where the middle legs can grip it at the center of the object with horizontal posture of the tip, the robot grips the object by middle legs (⑤) and

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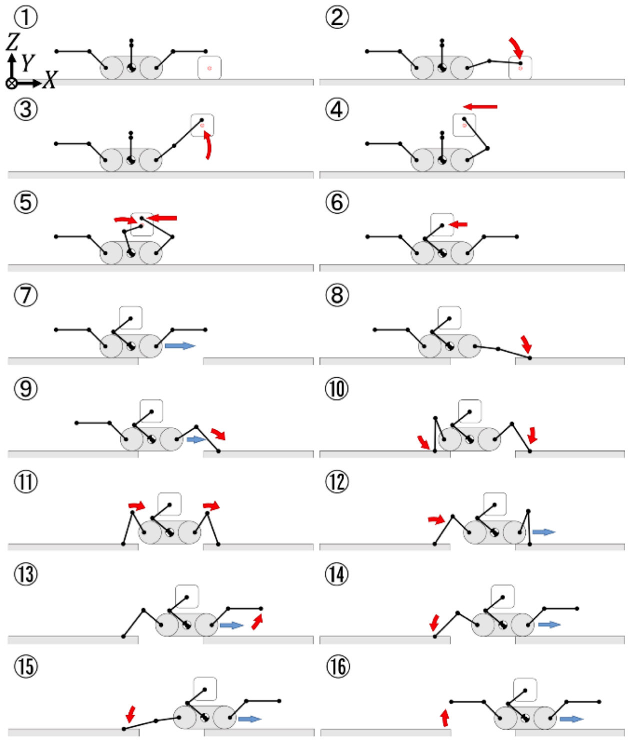

Fig. 3. Sequence of object carrying with traversing a wide gap

releases the fore legs from the object. The robot continues to move the object horizontally to the top of the body center (⑥), then it starts moving with keeping the position and orientation of the object by the two middle legs.

When the robot reaches a wide gap, the robot performs its leg-track hybrid motion to traverse it, as shown in ⑦ to ⑯ of Fig. 3. The robot moves by tracks until the center of gravity of the robot comes the edge of the gap (⑦), then puts the tips of fore legs on the opposite ground (⑧). The robot moves forward by tracks with supporting by the fore legs (⑨) then puts the tips of rear legs on the ground just before the body releases from the ground (⑩). The robot moves the body by fore and rear legs supporting without track driving (⑪) until the body touches the opposite ground. When the front part of the body touches the ground (⑫), the robot restarts its track driving and releases the fore legs from ground (⑬), then moves by track driving with supporting by the rear legs (⑭). When the center of gravity of the robot reaches on the edge of the opposite ground (⑮), the robot releases the tips of rear legs from the ground and finishes traversing (⑯).

III. Handover Motion

A. Motion Analysis

We analyze the handover motion described above using kinematics. Let us consider in the coordinate system shown in Fig. 3. We suppose that a target object is in front of the robot at the right angle and right and left legs move symmetrically. Let $\boldsymbol{q} = (q_x, q_y, q_z, q_\theta, q_\phi, q_\psi)^{\mathrm{T}}$ be a generalized state vector of tip for a leg, where q_x, q_y, and q_z are positions for X, Y, and Z axes, and q_θ, q_ϕ, and q_ψ are rotational angles around these axes. In this case, a joint angles vector of four joints, $\boldsymbol{\theta} = (\theta_1, \theta_2, \theta_3, \theta_4)^{\mathrm{T}}$, for $\boldsymbol{q}$ for a leg is obtained as follows.

Based on the conditions described above, q_y must be constant at all time in the motion, and q_z becomes constant when moving the object horizontally. According to these constraints, small change of $\boldsymbol{q}$, $\Delta\boldsymbol{q}$, is given so that the tip moves to the target position. In picking the object (from ② to ③ in Fig. 3), we can consider the fore legs only, and set $\Delta q_y = 0$ because q_y must be constant, and suppose $\Delta q_\theta = 0$ for stable gripping. When moving the object horizontally (from ④ to ⑥ in Fig. 3), both fore and middle legs need to be considered, and $\Delta q_y = 0$ and $\Delta q_z = 0$ are set by the conditions described above.

In this motion, we use Jacobian $\boldsymbol{J}$, which is obtained by the joint angles at each time. We now remove the rows all elements of which are zero from $\boldsymbol{J}$ and $\boldsymbol{q}$. Let $\boldsymbol{J}_4$ and $\boldsymbol{q}_4$ be those 4×4 Jacobian matrix and 4×1 state vector respectively. Then we can obtain the change of joint angles by

$$\Delta\boldsymbol{\theta} = \boldsymbol{J}_4^{-1}\Delta\boldsymbol{q}_4. \tag{1}$$

We can obtain $\boldsymbol{\theta}$ by updating the position and orientation at each time by Eq. (1) and repeat it so that the position of tip traces the target trajectory. Basically, $\boldsymbol{J}_4$ is solved by setting Δq_ϕ and Δq_ψ to zero when picking and lifting up the object and setting Δq_θ, Δq_ϕ, and Δq_ψ to zero when moving it horizontally. If $\boldsymbol{J}_4$ becomes singular, specific small values are given to them and it is solved again. However, if $\boldsymbol{J}_4$ can not be solved in all case of combination for them, we give up and assume the trajectory is impossible.

Let q_{zf} and q_{zm} be Z positions of the tips for the fore and middle legs when moving the object horizontally. The height of the object that the robot is able to hand over, h_0, has to meet

$$2(q_{zf} - q_{zm} + l_m) \geq h_0, \tag{2}$$

where l_m is the minimum height between upper surface of the object and the position of fore tip. It is also necessary for the developed robot to meet $q_{zf} - q_{zm} \geq 65$ [mm] so that the fore and middle legs do not make physical contact each other. When meeting these conditions, the handover motion between the fore and middle legs is possible in a region where both q_x values of $\boldsymbol{q}$ overlap.

B. Simulation

Possible motions for the legs were computed based on the method described in the previous section. Fig. 4 shows the result for a box-shaped object which has 145 mm in height, 210 mm in width, and 115 mm in length. The initial position of the object is (386, 0, 73) mm in the robot coordinate system. Each number with circle corresponds to the number in Fig. 3. The value of N described in each panel shows the step number corresponding to execution time. At the time N=1, the fore tips approach the side surfaces of the target object (① in Fig. 3). At the time N=101, the object is gripped by the fore legs (②). The object is lifted from N=102 to N=301 (③) and moved horizontally from N=302 to N=434 (④). Then, at the time N=453, the robot performs handover of the object between the fore legs and middle legs by holding it by the middle tips and releasing the fore tips from it (⑤). After that, from N=454 to N=567, the object is moved horizontally to the top of the center of the body by the middle legs only (⑥).

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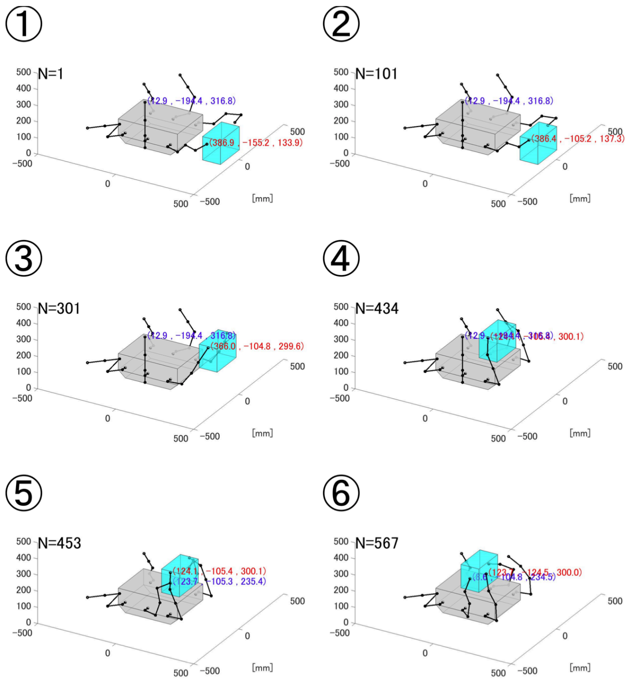

Fig. 4. Simulation result for handover motion

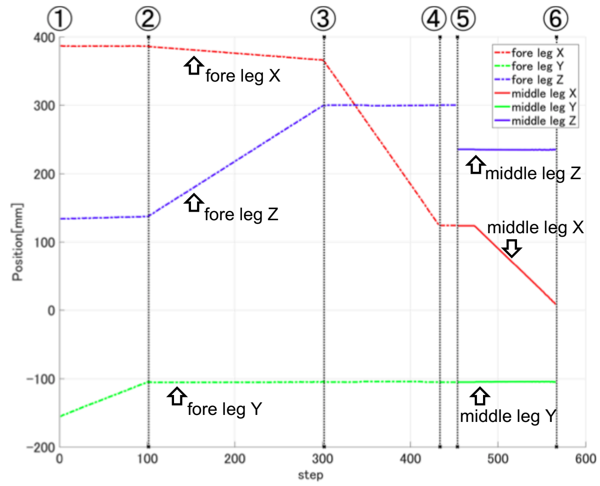

Fig. 5. Tip positions for the right-fore and right-middle legs in handover motion

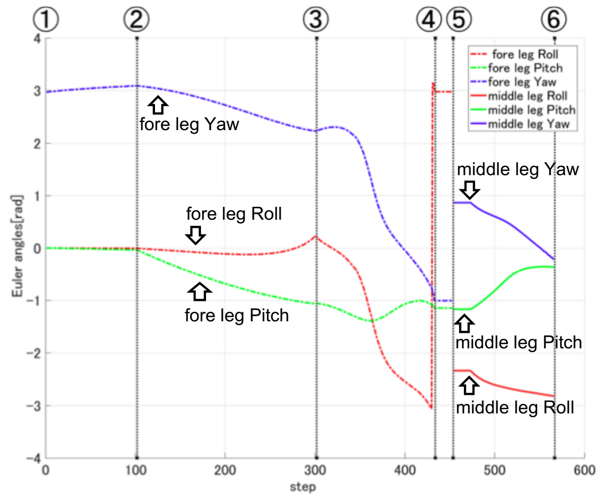

Fig. 6. Tip orientations for the right-fore and right-middle legs in handover motion

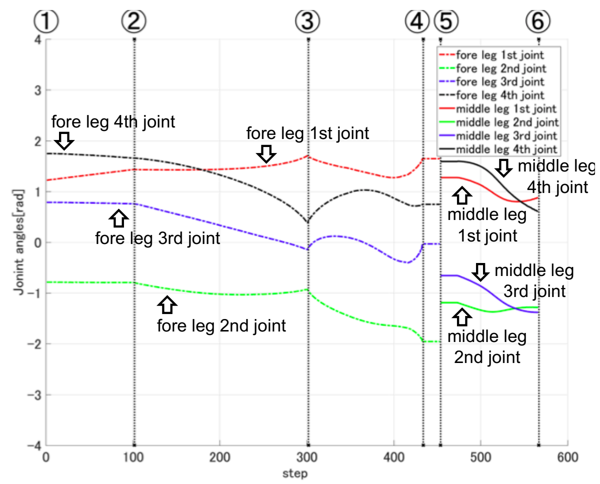

Fig. 7. Joint angles for the right-fore and right-middle legs in handover motion

Fig. 5 shows tip positions of X, Y, and Z directions for the right-fore and right-middle legs in this motion. Each number with circle indicates the state shown by the same number in Fig. 4. This result confirms that trajectories of tips satisfy required conditions mentioned above.

Fig. 6 shows tip orientations, rotation angles for roll, pitch, and yaw, for these legs in this motion; the roll, pitch and yaw rotations respectively correspond to the rotations around X, Y, and Z axes in the coordinate system described in Fig. 3, i.e. q_θ, q_ϕ, and q_ψ. The roll angles of the fore tip seem to change largely at the time of ④. However, it is because the angles are represented between $-\pi$ to π and actual difference was very small.

Fig. 7 shows joint angles for these legs in this motion. These results show that the tips of legs moved smoothly because of the small change of its orientation and joint angles.

Also, in this simulation, we set $l_m = 7.5$ mm. Because the result of Fig. 5 shows that the heights of fore and middle tips in horizontal movement of the object were $q_{zf} = 300$ mm and $q_{zm} = 235$ mm, we can see these meet the condition given by Eq. (2).

This simulation result showed that the robot is able to perform handover motion of a box-shaped object. However, Fig. 6 showed the roll angle of the fore tip was not constant in the status from ② to ③ even though we gave the condition $\Delta q_\theta = 0$. This may be caused by the errors of the value computed by forward kinematics in the use of the joint angles obtained in Fig. 7.

IV. Experiments

A. Handover motion

We conducted an experiment in which the robot picks an object up by the fore legs and hands it over the middle legs. As the simulation described in Fig. 4, a box-shaped object

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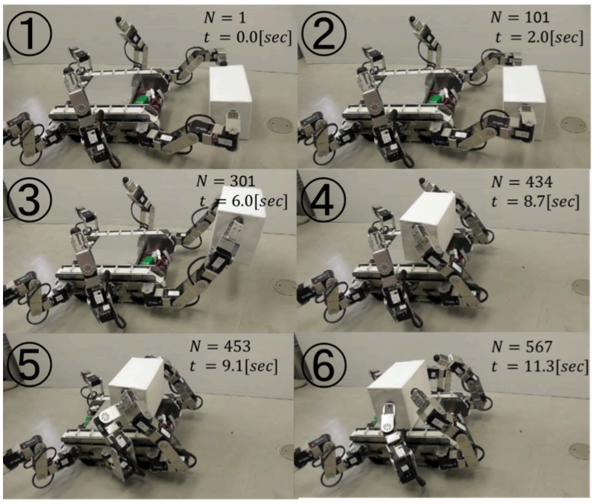

Fig. 8. Experiment of picking up and handover motion

which has 145 mm in height, 210 mm in width, and 115 mm in legnth, and 0.12 kg in weight, was used and placed at the position (386, 0, 72.5) mm in front of the robot. Fig. 8 shows an overview of the robot motion in the experiment. The numbers with circle shown in each panel correspond to those in Fig. 4. The robot moved the fore tips close to the grip position of the target object (Fig. 8①), gripped the object (②), and lifted it up (③). Then the robot moved the object horizontally to the position where the middle legs can grip (④), gripped the object by the middle tips (⑤) and finished handing over by releasing the fore tips (⑥). In this experiment, one step of the execution was set as 20 msec and the motion was finished in 11.3 sec. The result of this experiment confirmed the handover motion between fore and middle legs with keeping the posture of the object.

B. Wide gap traversing

We conducted another experiment in which the robot traverses a wide gap. The gap was set by placing two block board with specific interval on a flat floor. The robot traversed the gap by the leg-track hybrid motion with carrying a box-shaped object as shown in Fig. 3. The object used in this experiment is the same as that in the experiment described in Section IV-A.

The result when the gap width is 260 mm is shown in Fig. 9. The robot moved from right to left, and each number ①, ②, and ③ respectively corresponds to the state of ⑧, ⑪, and ⑭ in Fig. 3. Before the center of body reaches the gap edge, the robot started supporting track movement by grounding the fore tips in the state ①. Then, the robot grounded the rear tips just before the body was released from the ground and started moving forward by supporting using four legs in the state ②. When the robot body touched the opposite gap edge, the robot released the fore tips from the ground and started track driving again with the rear legs supporting in the state ③.

The result confirmed that the robot was able to traverse the gap the width of which was 260 mm, which was the 70% to the length of the robot body and 130% to the length that the track can ground, using leg-track hybrid motion with carrying an object.

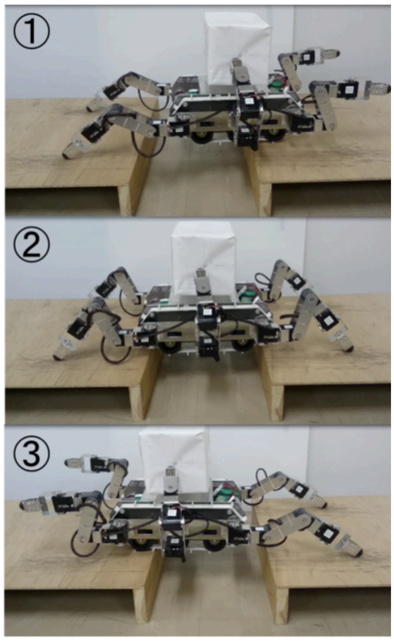

Fig. 9. Experiment of a wide gap traversing

V. Conclusions

This study presented leg-track hybrid motions for an object carrying task by the hexapod tracked mobile robot. The robot was able to traverse a wide gap with supporting track driving by the fore and rear legs and holding an object by the middle legs simultaneously. In particular, we mainly focused on the motions picking and lifting up the target object by the fore legs and handing it over to the middle legs as a component in the sequence of object carrying task. The motions were confirmed by simulation and experiments by the developed robot. We will consider the other types of hybrid motion such as step climbing with carrying an object as the future work.

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