Tripod gait using buffer area around leg workspace for flexible direction change

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Tripod gait using buffer area around leg workspace for flexible direction change

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Abstract— **The tripod gait using a buffer area around leg workspace is proposed to improve the mobility of the hexapod robot. The proposed method provides the buffer area for the support leg located near the border of the workspace to make a continuous walking motion when the walking direction is suddenly changed from the current walking direction. The change of direction is frequently occurred in the teleoperation by the operator to adapt to the remote environment and the required tasks. In the case of a fixed workspace, the group of the support leg when it located on the border of the workspace has to stop the motion until the group of the swing leg will reach to a new landing position corresponding to the commanded direction. Since the buffer area is given to the support leg, it can move until the swing leg will land to the new target position for the direction change. In this paper, the buffer area is defined around the workspace so that the trajectory generation method of the direction change of the support leg and the swing leg using the buffer area are implemented. The smooth direction change using the proposed method is shown based on the actual robot parameters.**

Index Terms— **multi-legged robot, tripod gait, teleoperation**

I. INTRODUCTION

Multi-legged robots are expected to operate in various environments which the wheeled robot cannot move over. However, since the structure of the multi-legged robot is complicated, the walking motion generation is still major topic. To ease the control of the multi-legs, a fixed stride length and a cyclic walking pattern are employed for a regular motion. For example, a tripod gait for a hexapod robot employs the trajectory of the outer periphery of cylindrical workspace[6]. The fixed trajectory can be used by assuming the semi-static walking motion, and it is easy to implement with low calculation cost. Assuming an intermittent gait, when the supporting legs reach the outer periphery of the workspace, walking is continued by exchanging the group of supporting legs and the group of swing legs. If the direction of next step is known in advance, the position of the next support leg is set to a position that optimizes movement in the indicated direction. On the other hand, as a general real-time operation, it is assumed the walking direction is frequently changed. For example, when a robot avoids obstacles that suddenly appear in the direction of travel, or a robot loses its stability due to a disturbance, it has to change the moving direction. When the position of the support leg is located near the boundary of the workspace, there is an inaccessible direction in which the foot cannot be moved sufficiently corresponding to the new indicated direction, and the next landing foot position optimized for the expected movement direction cannot be used. In these cases, the group of the swing leg and the support leg must be changed again to react to the new indicated direction. Such a situation also occurs when the robot is controlled remotely in an environment where the route is not determined. In many cases, the operating environment for remote operation only shows the captured image by the camera on the robot, and the operator has to control the robot by using a joystick indicating a target walking direction and velocity (Fig.1). In this control interface, the operator doesn't need to consider the state of the leg. In other words, it is difficult to control the robot in consideration of the workspace of the legs. In the conventional method, the step change timing is decided by the timing of reaching the border of the work space. When the operator wants to change the direction of movement frequently near the boundary of the work area, the gait efficiency is reduced because of frequent support leg changes. Thus, it is necessary to consider the effective step change method that do not interfere the continuous movement

In the related works, several multi-legged robot walking motion control were proposed. Suzuki[1], [2] et.al proposed the adaptive walking control on uneven terrain. They proposed a method that the rear leg follows the foot stamp where the front leg grounds on to achieve stable walking. In recent years, many studies have been proposed to realize dynamic walking motion, adaptation to unknown environment, and robust walking motion for disturbance by walking control using neural network[3], [4], [5]. In our laboratory, the hexapod robot walking motions were studied but the issues mentioned above were not addressed[7], [8], [6].

In this paper, the tripod gait using a buffer area around leg workspace is proposed to improve the mobility of the hexapod robot. The proposed method provides the buffer area for the support leg located near the border of the workspace to make a continuous walking motion when the walking direction is suddenly changed from the current walking direction. Since the buffer area is given to the support leg, it can move until the swing leg will land to the new target position for the direction change. The leg trajectory and the buffer area in the cylindrical work area are defined, and

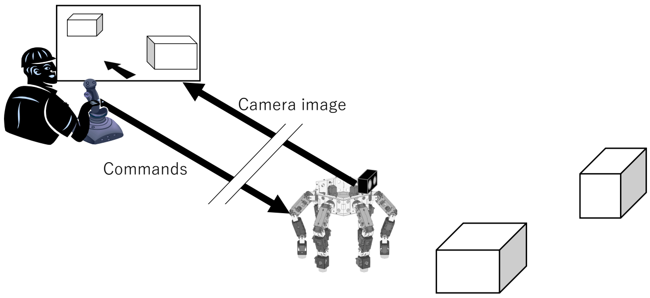


Fig. 1: Teleoperation mobile robot

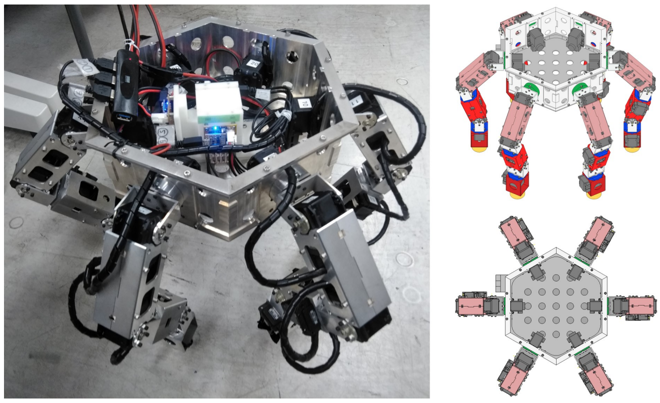


Fig. 2: Appearance of ASTERISK

it is shown by the numerical calculation that the proposed method is effective for the turning motion near the boundary of the work space. The smooth direction change using the proposed method is shown by dynamic simulator using an actual hexapod robot parameters.

II. MULTI-LEGGED MOBILE ROBOT

A. Integrated limb mechanism robot ASTERISK

As a model of multi-legged walking robot, the integrated limb mechanism robot ASTERISK[9] is used in this study. ASTERISK has six limbs which can behave as both arms and legs. These limbs are arranged symmetrically at 60° intervals radially from body, and ASTERISK can walk in any directions by tripod gait using them. Each limb has 6 degrees of freedom (DOF) and it can control the position and orientation of each tip of limb. When the ASTERISK walks by alternative tripod gait, a workspace is set for each leg as shown in Fig.3. The tip of the leg can move inside the workspaces. These workspaces are cylindrical in order to move legs equally in all directions.

Workspaces are defined as follows. First, leg tips must be able to reach anywhere in their workspace. Next, it is necessary to leave at least leg tip diameter between adjacent two workspaces so that these legs will not collide each other when two adjacent leg tips place workspace edges nearest to another.

The latter rule can be expressed as follows equation (1) using R_{max} as maximum workspace radius, r as leg tip radius and D as the distance between centers of each adjacent workspace.

$$R_{max} = \frac{D - 2r}{2} \tag{1}$$

Once the value of R_{max} is calculated, workspace radius R and height H meeting former rule can be determined by R_{max} and inverse kinematics (IK) analysis. For the actual robot, $D = 0.18$[m] and $r = 0.0335$[m] are determined by robot size, and R and H are calculated as following equation (2).

$$\begin{aligned} R &= R_{max} = 0.0565[\mathrm{m}] \\ H &= 0.035[\mathrm{m}] \end{aligned} \tag{2}$$

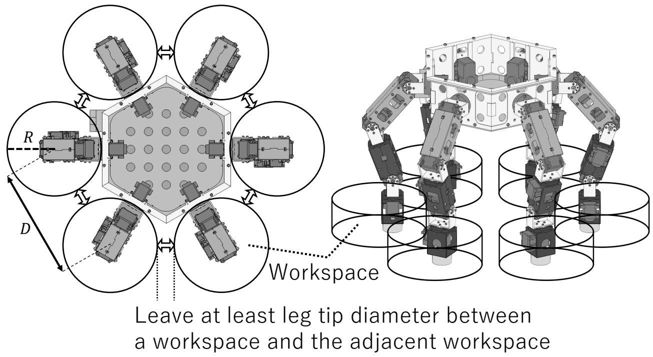


Fig. 3: Workspaces for ASTERISK leg tips

B. Tripod gait

The ASTERISK walks using tripod gait[6]. As shown in Fig.4, the legs are divided into two groups and each group of legs works as support legs alternately.

Legs in each group move in their workspaces as shown in Fig.5. Support legs move straight backward to push the robot body forward, and other legs, the swing legs, are moved forward to prepare the next movement as support legs.

The movements of the support legs and swing legs during the tripod gait walking are modeled as follows. The radius of the cylindrical workspaces R and height H are defined in section II-A. First, during the robot walking straight, as shown in Fig.6a, support legs move $2R$ and swing legs move $2R$+$2H$ in a step. Here, v_{su} and v_{sw} are velocities of support leg tips and swing leg tips in the robot body coordinate, T_{su} and T_{sw} are the time required for the support leg motion and the swing leg motion in a step. They are derived as follows.

$$T_{su} = \frac{2R}{v_{su}} \tag{3}$$

$$T_{sw} = \frac{2R + 2H}{v_{sw}} \tag{4}$$

In this step motion, if the swing leg moves in advance of the support leg, and then the swing leg switches to support leg at the same time as the support leg movement ends, the robot can move forward at a continuous velocity without stopping. When the robot walks continuous as such, the swing leg and the support leg must complete their motion simultaneously.

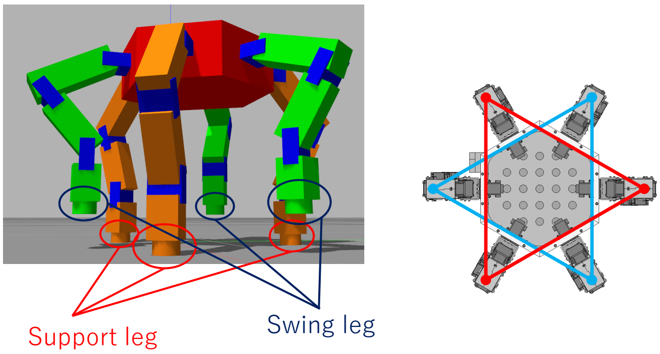


Fig. 4: Tripod gait

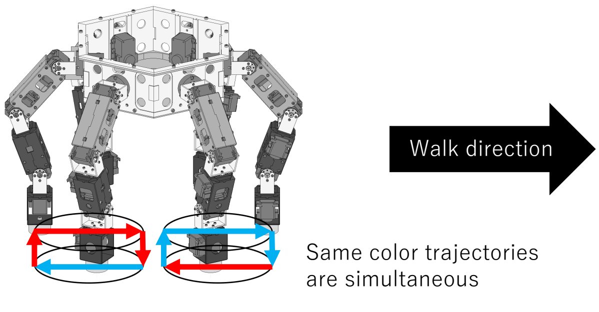
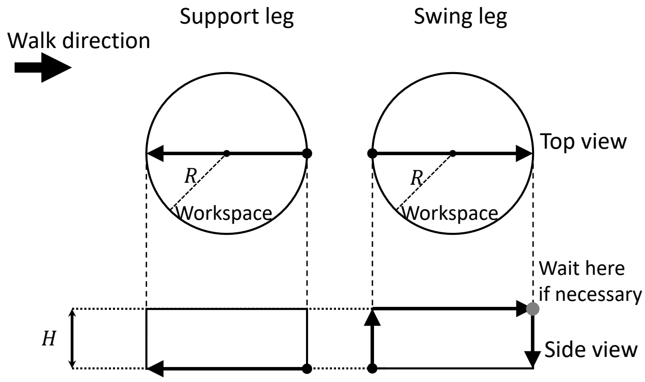
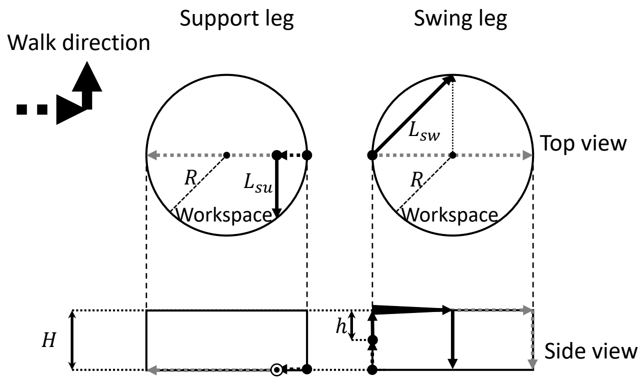


Fig. 5: How to move legs to walk



(a) Walking straight



(b) Just after changing direction

Fig. 6: Model of walking legs

Therefore, continuous walking is possible when equation (5) is satisfied.

$$T_{sw} \leq T_{su} \tag{5}$$

In this equation, when $T_{sw} < T_{su}$ is satisfied, in other words when the swing leg movement can end first, the swing legs can wait on their trajectories to end each leg movement simultaneously.

For actual robot, v_{su} and v_{sw} are determined as follows:

$$\begin{aligned} v_{su} &= 0.03[\mathrm{m/s}] \\ v_{sw} &= 0.06[\mathrm{m/s}] \end{aligned} \tag{6}$$

Then, substituting parameters (2) and (6) for equation (3) and (4), $T_{su} = 3.77$ and $T_{sw} = 3.05$ are calculated and equation (5) is satisfied.

Next, there are situations that the robot change walk direction while walking straight. Fig.6b shows the motions of the legs in the time from just after changing direction to end of the step. Then, the time from changing direction to end of motions of the support legs and swing legs T'_{su} and T'_{sw} are expressed by the equation (7) and (8) using L_{su}, L_{sw} and h in the figure: L_{su} and L_{sw} are lengths of leg tip trajectories in the horizontal plane and h is height to top of the workspace from the initial position of the swing leg tip.

$$T'_{su} = \frac{L_{su}}{v_{su}} \tag{7}$$

$$T'_{sw} = \frac{h + L_{sw} + H}{v_{sw}} \tag{8}$$

In this case, even if equation (5) is satisfied while walking straight, if following equation (9) is not satisfied when changing direction, the robot will stop and not be able to continue continuous walking.

$$T'_{sw} \leq T'_{su} \tag{9}$$

III. WORKSPACE BUFFER AREA

In order to improve robot motion when the walking direction is changed suddenly, a method using the workspace buffer area is proposed. As shown in Fig.7, the workspace radius is reduced, and a buffer area of width B is set in outside of the workspaces. When the support leg trajectory length is not enough to satisfy the equation (9), the trajectory length is extended by using the buffer area temporarily as shown in Fig.8.

Reduced workspace size and buffer area size are determined as follows. First, from section II-B, minimum workspace radius R_{min} to continue straight continuous walking can be calculated. Substituting in equation (3)(4) for

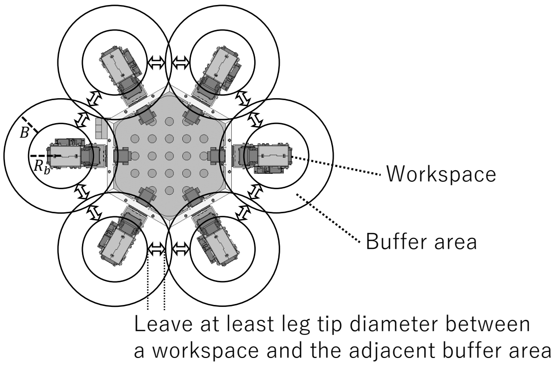


Fig. 7: Workspace buffer area

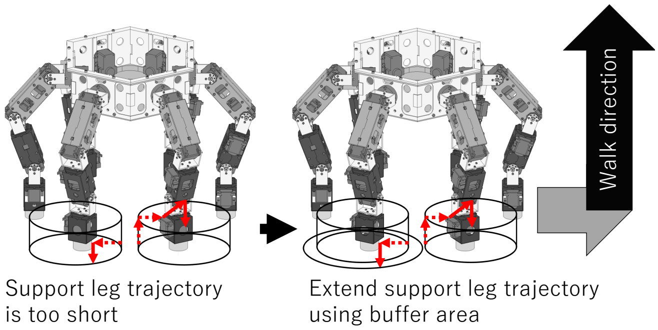


Fig. 8: Using buffer area

equation (5) gives following equation (10).

$$R \geq \frac{v_{su}}{v_{sw} - v_{su}} H = R_{min} \tag{10}$$

Then let reduced workspace radius R_b be $R_b = R_{min}$.

Next, as shown in Fig.4, any adjacent legs belong to different groups in tripod gait, so the adjacent legs never role as support legs at the same time, and therefore never use the buffer areas at the same time. For that reason, it is only necessary to leave distance of the diameter of leg tips between a buffer area and the adjacent workspaces, without considering the distance between a buffer area and the adjacent buffer areas. This can be expressed as an equation (11) using R_b, the workspace centers distance D, the leg tip radius r and the buffer area width B. D and r in this equation are same as in equation (1).

$$B \leq D - 2R_b - 2r \tag{11}$$

For actual robot, substituting parameters (2) and (6) for equation (10) and (11), $R_b = R_{min}$ and B are calculated as follows:

$$\begin{aligned} R_b = R_{min} &= 0.035[\mathrm{m}] \\ B &= 0.029[\mathrm{m}] \end{aligned} \tag{12}$$

IV. SIMULATION

A. Numerical simulation

A numerical simulation using the model in section II-B and III shows the effectiveness of the proposed method.

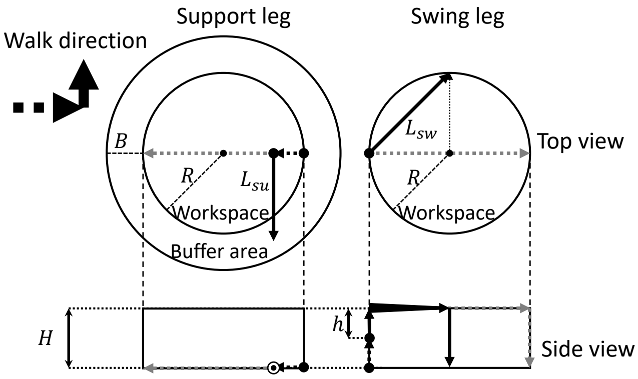


Fig. 9: Model about legs changing direction using buffer

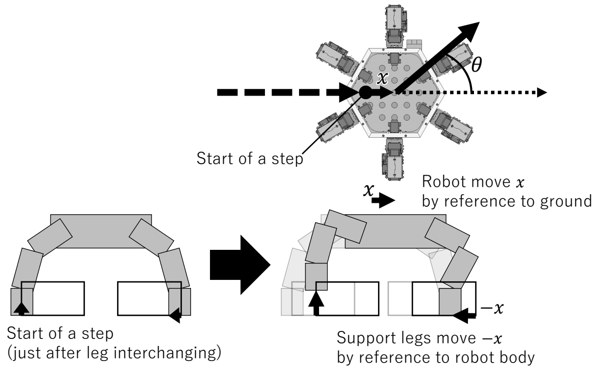


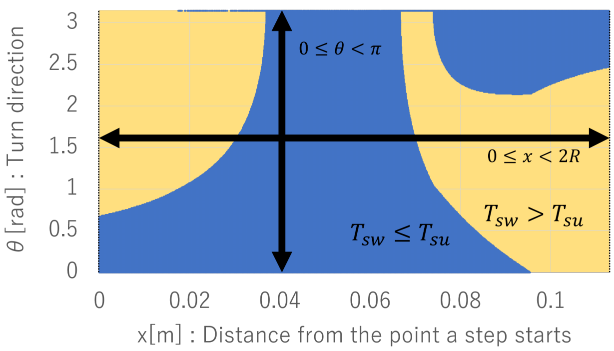
Fig. 10: Numerical simulation settings

While the robot walks straight, the swing legs land and the roles of the support legs and swing legs interchange. In this simulation, at the time the robot has walked a distance x from the position that the robot had located at the leg interchange time, walking direction changes to angle θ with respect to the initial walking direction (Fig.10). Then, varying x and θ in the range $0 \leq x \leq 2R$ (i.e. distance of a step) and $0 \leq \theta \leq \pi$, and plot values of x and θ that satisfy the equation (9): with such x and θ, the robot can walk into direction θ without stopping.

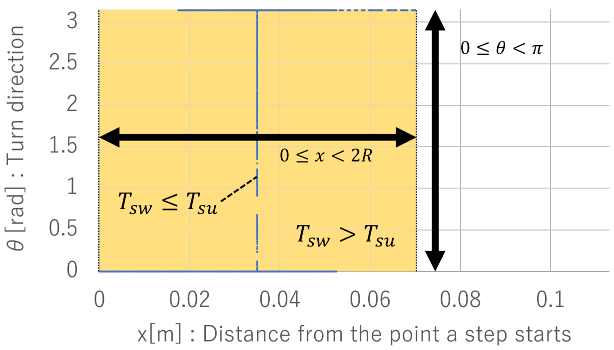
In this simulation, following 3 types of workspace based on parameter (2) and (12) are compared.

1) $R = 0.0565[\mathrm{m}],\ \ B = 0.0[\mathrm{m}]$
   Maximum R that adjacent workspaces doesn't interfere (equation (1)), not using buffer area.
2) $R = 0.035[\mathrm{m}],\ \ B = 0.0[\mathrm{m}]$
   Minimum R for continuous straight walking (equation (10)), not using buffer area.
3) $R = 0.035[\mathrm{m}],\ \ B = 0.029[\mathrm{m}]$
   Minimum R for continuous straight walking, B that adjacent workspaces doesn't interfere.

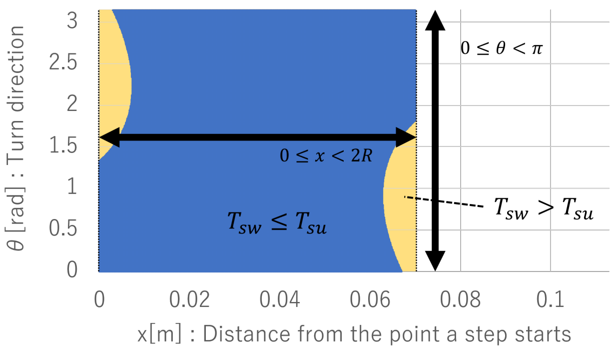
Fig.11 shows the simulation results. The blue area is the range of x and θ that the robot can change walking direction smoothly. In each case, there are areas that equation (9) is not satisfied with the range $0 \leq x \leq 2R$ and $0 \leq \theta \leq \pi$.



(a) $R = 0.0565$[m], $B = 0.0$[m] $(0.0 \leq x < 0.113$[m]$)$



(b) $R = 0.035$[m], $B = 0.0$[m] $(0.0 \leq x < 0.070$[m]$)$



(c) $R = 0.035$[m], $B = 0.029$[m] $(0.0 \leq x < 0.070$[m]$)$

Fig. 11: The numerically derived range that the robot can change walking direction

However, it can be seen from the figures that those areas can be narrowed by the proposed method using the buffer area.

B. Dynamic simulation

A dynamic simulation shows the effectiveness of the proposed method too. A simplified model imitating the structure of actual robot is constructed and the robot motion is simulated in the dynamic simulator Gazebo. Section IV-A shows that the robot is most inflexible for changing direction immediately before and after landing of the swing leg. Therefore, as an experiment, while the robot model is walking straight forward, a command to change walking direction for $\theta = \pi/2$[rad] from walking direction is sent just after the swing leg has landed, and we have observe the robot behavior before and after that.

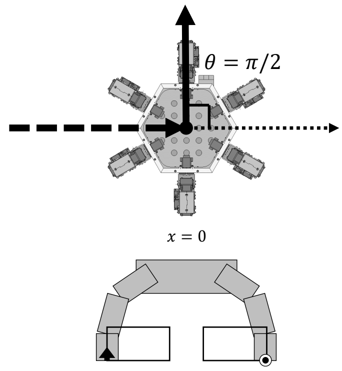


Fig. 12: Dynamic simulation settings

For dynamic simulation, parameters as shown in following (13) are set. These are same as (2) and (6), and additional parameter a as max acceleration of support legs (i.e. acceleration of robot body). Unless legs go out from their workspaces, the robot walks keeping absolute value of acceleration less than a.

$$\begin{aligned} H &= 0.035[\mathrm{m}] \\ v_{su} &= 0.03[\mathrm{m/s}] \\ v_{sw} &= 0.06[\mathrm{m/s}] \\ a &= 0.1[\mathrm{m/s^2}] \end{aligned} \tag{13}$$

Fig.13 shows the absolute value of the velocity of the robot model in horizontal plain, which is gotten from Gazebo simulator. The vertical axis shows velocity and the horizontal axis shows time. The time axis is originated in the time direction change command is sent. In Fig.13a, velocity drops suddenly. However, in Fig.13b, using buffer area, the robot doesn't stop.

V. Conclusion

In this paper, the tripod gait using the buffer area around the leg workspace for flexible direction change is proposed and the effectiveness is shown in the dynamic simulator. The result of the numerical analysis shows the ability of the direction change is improved, but the optimal parameter is not discussed. As a future task, we will propose the optimal parameter design method and show the operation performance improves by remote control experiments with multiple subjects.

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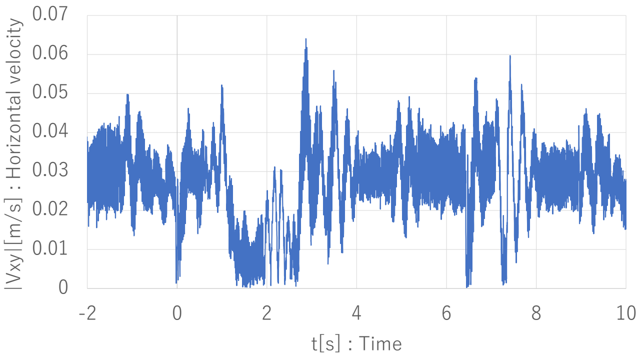
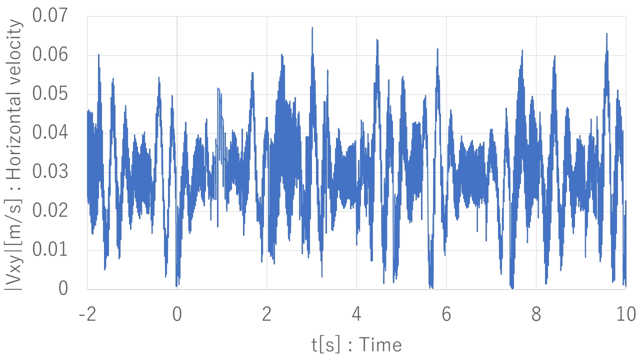
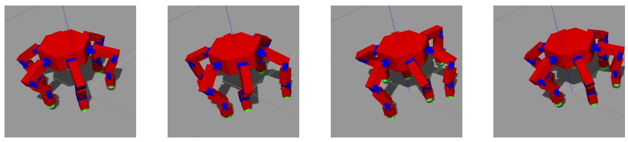


(a) Not using buffer ($R = 0.0565$[m], $B = 0.0$[m])



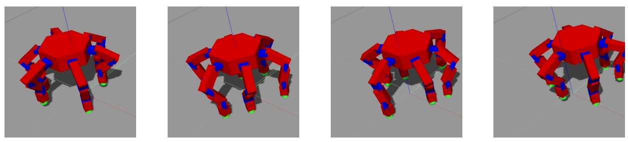
(b) Using buffer ($R = 0.035$[m], $B = 0.029$[m])

Fig. 13: Gazebo simulation result



$t = -2$[s] $t = 0$[s] $t = 2$[s] $t = 4$[s]

(a) Not using buffer ($R = 0.0565$[m], $B = 0.0$[m])



$t = -2$[s] $t = 0$[s] $t = 2$[s] $t = 4$[s]

(b) Using buffer ($R = 0.035$[m], $B = 0.029$[m])

Fig. 14: Capture images of Gazebo simulation

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