

Obstacle-aware Autonomous Flipper Control Method Based on Terrain Geometry

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Abstract

Rescue robots play crucial roles in search and rescue missions at disaster sites. Crawler mechanisms, which are valued for their high traversability on unstructured terrain, can be equipped with flipper arms featuring four single-rotation joints to enhance their performance. However, operating these flippers is challenging. Although various control methods have been developed recently, difficulties persist in adapting to three-dimensional uneven terrains and in avoiding interference between flippers and the environment. In this study, we propose an obstacle-aware autonomous flipper control method that actively adjusts the flippers based on the progress of the robot and terrain geometry.

Keywords: Autonomous Flipper Control, Rescue Robotics, Crawler-type Robot

1. Introduction

Recently, there has been a growing demand for remote controlled rescue robots that can gather information at disaster sites. At disaster sites, where there is rubble and uneven ground, many rescue robots use a crawler mechanism called a flipper (sub-crawler), which is a mobile mechanism with four joints, to adapt to uneven ground [1]. Crawler robots equipped with flippers can climb high steps, this allows them to expand the range of their activities. Flippers can also be used to change the posture of the vehicle body to ensure stability on uneven ground [2], and can also be used to cushion the impact on the robot when it descends steps. However, when operating a remotely controlled robot, it is extremely difficult to operate the four flippers independently. Particularly, when remotely controlling a robot in an unstructured environment, such as rubble, there is a risk of the robot falling over. Thus, research has been conducted on the autonomous control of flippers. As a strategy for traversing rough terrain for crawler-type robots, the contact area with rough terrain is maximized and the robot posture is appropriately transitioned using flippers. As a method of semi-autonomous control that utilizes the interaction between the robot and the environment, a method using passive flippers that move in response to gravity and the reaction force of obstacles [3] and a method of changing the joint torque in response to the robot posture based on rules [4] have been proposed. These methods are useful because they do not require high-load computational processing. However, the robot may unintentionally get stuck in the environment and immobilize itself because of the lack of terrain information. Recently, 3D LiDAR sensors have been used in crawler-type robots for environmental

information gathering [1], [5], [6], [7], [8]. In these studies, it is possible to plan the movement of the flippers according to the terrain from the sensor information [5], [6]. Additionally, it is possible to maintain a stable posture even on uneven terrain by estimating the contact points between the robot and the terrain [7]. Furthermore, the path following on uneven terrains can be achieved using an environmental map [8]. However, many studies only consider obstacles in the forward direction and often drive the left and right flippers in sync [5], [6], [7]. As a result, they might struggle with 3D uneven terrains, such as entering a slope from the side. Even in methods where each flipper adapts to the terrain, side collisions during turns are not considered [1], [8]. Yuan et al. proposed a control method that predicts the contact between the flipper and the ground [9]. They demonstrated that overcoming a step diagonally or approaching a slope from the side by driving the four flippers independently is possible. However, because the goal is to maximize the contact area with the terrain, the pitch angle may increase if the step is large. In this study, we developed a flipper control method that considers contact with the environment from the flipper's side, utilizing environmental information on 3D uneven terrain. Furthermore, by using a grid map, which is a smooth representation of a 3D map, we ensured the continuity of the robot's posture. We evaluated the proposed method through physical simulations on 3D uneven terrain to determine its traversability.

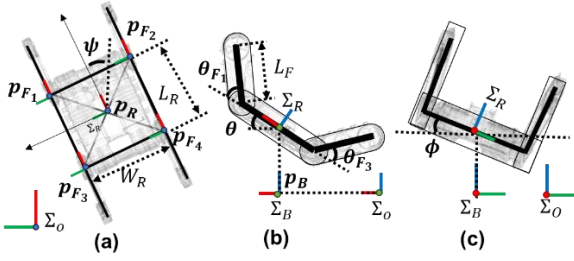


Fig. 1 Coordinate system of the crawler robot: (a) top view, (b) side view from the left, and (c) front view.

2. Methodology

2.1 Terrain Processing

We used the contact conditions of a crawler robot with the flipper skeleton model and the terrain expansion used by Yuan et al. [9]. A simplified model that connected each link with a straight line and expanded the terrain with the radius of the pulley. In this method, the diameter of the flipper pulley must be unique for the crawler and flipper. The flipper angle is constrained within a range of -90° and 90° . When the robot exists in the world coordinate system Σ_0 , its position and posture are represented as $p_0^R = [x, y, z]^T$ and $\Phi_0^R = [\psi, \theta, \phi]^T$, respectively (Fig. 1). The base coordinate system Σ_R , which is defined as $z = 0$ in the vertical direction below the center of the robot, is defined as follows:

$$p_B^o = [x, y, 0]^T, \quad R_B^o = R(\psi, \theta, 0), \quad (1)$$

where $R(\psi, \theta, 0)$ is a rotation matrix with yaw angle ψ .

Target posture of the robot was generated by smoothing the terrain. In this study, we assumed that the terrain was accurately represented as a point-cloud map and that two layers were generated using a grid map (Fig. 2). h_F is the terrain expanded by the wheel radius. If the skeleton model is in contact with h_F , it is inferred that the actual robot is in contact with the ground or wall. This layer was used for angle estimation based on the estimation of the flipper in contact with the ground, which is described later. h_R is a terrain that gently connects to uneven ground. This method is based on the method of obtaining the body-referenced posture of a four-legged robot by Fabian et al. [10]. In this study, we adjusted the parameters of each filter to apply the proposed method to crawler robots. The following inequality must hold:

$$(k_2 + k_{3x}) * \alpha_x \geq 2L_F + L_R \quad (2)$$

$$(k_2 + k_{3y}) * \alpha_y \leq 2W_R \quad (3)$$

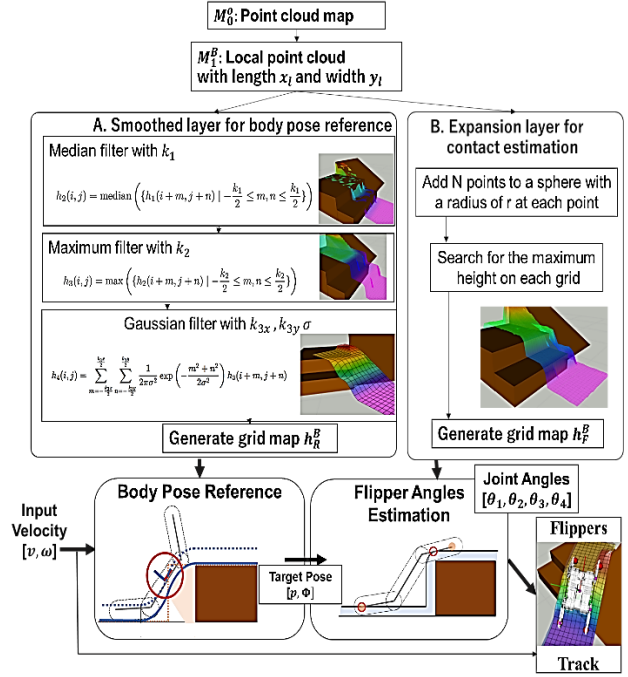


Fig. 2 By processing the point cloud around the robot, two grid map layers were obtained. Each layer is used for pose reference and flipper angle estimation.

here, alpha represents the resolution for each respective variable.

2.2 Autonomous Flipper Control Method

The aim of the control system is to avoid collisions between the flippers and the environment and to overcome obstacles when the robot is given a speed input. The body posture is obtained based on the terrain information, and the four flipper angles were calculated. The target posture of the robot is calculated using gradient information in the grid map $= h_R^B$. When the speed input $v_R = [v_x, 0, 0]^T$ and $\omega = [0, 0, \omega_z]^T$ is given to the crawler, the next position is calculated. First, the velocity input was converted from the robot coordinate system to the base coordinate system V_B and ω_B . Subsequently, the next robot position from the current base coordinate system was calculated. The next position $p_R^{B'}$ is updated as follows:

$$p_R^{B'} = (V_x^B / \omega_z) \cdot [\sin(\omega_z \Delta t), 1 - \cos(\omega_z \Delta t), 0]^T \quad (4)$$

where Δt denotes a time step. The height z' and posture $p_{ref}^{B'}$ of the robot in the next step are obtained from the smoothed surface $h_R^B(x, y)$, where x and y are the positions of the robot of $p_R^{B'}$, and h_R^B returns the height corresponding to that position. Also, the pitch and roll angles were calculated based on the slope of the height information in the grid map. The flipper angle is the maximum angle at which each flipper contacts the ground

when the body is at its target position. Based on the flipper angle and length, we determined whether the position of the endpoint of each flipper in the base coordinate system, $p_{Fie}^B = (x^B, y^B, z^B)$, contacted the grid map h_F^B . In the robot coordinate system, the endpoint position of the flipper was calculated as follows:

$$\begin{aligned} x^R &= x_i + (-1)^{\lfloor \frac{i-1}{2} \rfloor} \cdot L_F \cdot \cos(\theta), \\ y^R &= y_i, \\ z^R &= L_F \cdot \sin(\theta). \end{aligned} \quad (5)$$

where x_i, y_i are the joint positions of the flipper, L_F is the flipper's length, and L_F to r are the values of the range of contact. θ is the flipper's angle, and $(-1)^{\lfloor \frac{i-1}{2} \rfloor}$ is a symbol indicating whether the flipper is in front or not.

3. Experimental Results

To evaluate the performance of traversing an uneven terrain in three dimensions, we conducted a simulation of the movement of the crawler robot using Gazebo, an ROS standard physics simulator as shown Fig.3. In the experiment, we verified (a) the ability to follow the target posture in random steps, and (b) the ability of the flipper to avoid obstacles when turning. We also investigated the limits of the ability of the robot to traverse slopes and steps without falling over by changing the angle of incidence in (c) traversing slopes from the side and (d) traversing steps from the side. The robot moves straight ahead at a constant speed in (a), (c), and (d), and turns in (b). In the simulation of the crawler belt in the Gazebo, we used the method of Okada et al.[11]. We use the following parameters for the experiment: $L_B = 0.45$, $W_B = 0.46$, $L_F = 0.29$, $r = 0.082$, $k_1 = 7$, $k_2 = 4$, $k_{3x} = 11$, $k_{3y} = 7$, $\sigma = 5.0$, $\alpha = 0.04$.

Fig. 4 illustrates the robot's movements during the task. As shown in (a), even when the robot approached the step at a 45° angle, it was able to climb over the 30 cm high step. Fig. 5 presents the time series data of the target and actual values in Task (a). When the robot approached the step, the right front flipper rotated according to the step height following the Expansion Layer. Afterward, according to the Smoothed Layer, target values for roll and pitch angles were provided, and by moving the four flippers separately, the target posture was followed. However, when the robot proceeded at a 50° angle, the roll angle increased significantly before the left front flipper contacted the step, causing the robot to fall. Thus, it was found that traversability differed depending on the direction of movement. When using the robot in practice, this issue could be addressed by imposing movement direction restrictions based on the Smoothed Layer during motion. In (b), even when the robot turned close to an obstacle, the flippers did not collide with the wall surface, following the Expansion Layer. In (c), the robot was able to climb a 30° slope from the side. When

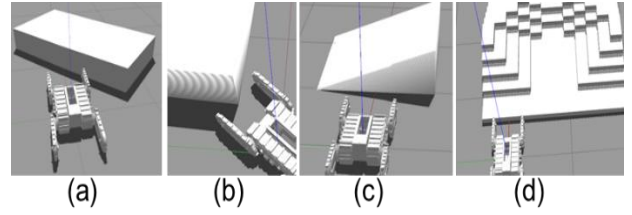


Fig.3 Test environment in Gazebo.

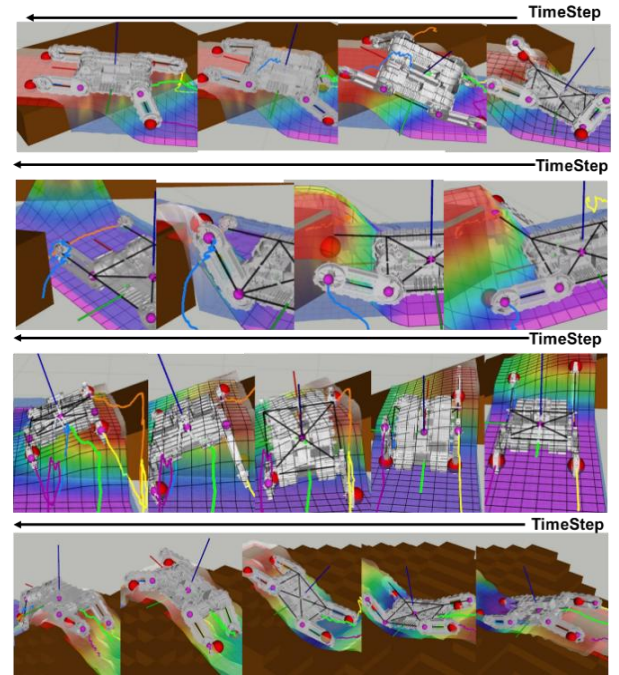


Fig. 4 Robot movement during the task. From top to bottom, (a), (b), (c), (d). All time steps are from the right image to the left image.

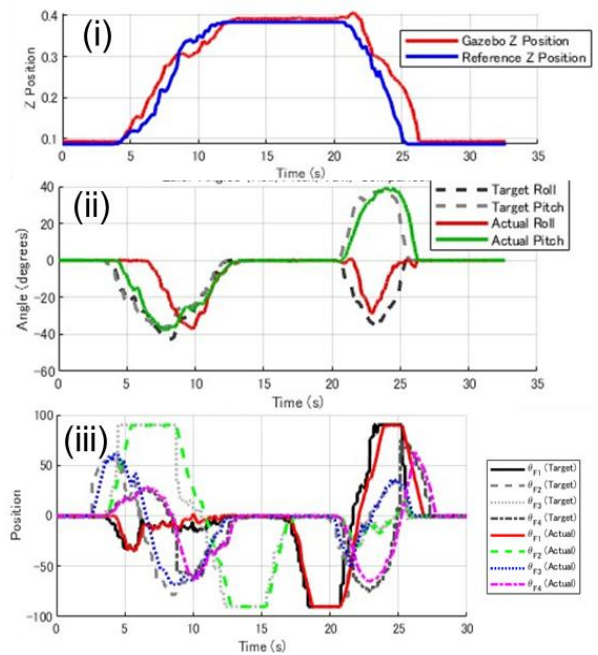


Fig. 5 Time series data of the target and actual values for (i) the robot's center of gravity (z-coordinate), (ii) the robot's posture, and (iii) each joint angle in Task (a).

approaching the obstacle, the angles of the left and right flippers changed according to the height difference. After climbing, roll angle commands were given according to the Smoothed Layer, and the robot proceeded by aligning its body to the slope of the ground. In (d), even on irregular terrain where the pitch angle fluctuated, the robot was able to adjust its posture according to the terrain shape and proceed. Additionally, the flippers did not get stuck during the execution of these steps.

4. Conclusion

In the proposed method, a flipper control strategy that considers contact with the environment during turning was developed, demonstrating the possibility of overcoming obstacles on uneven terrain in three dimensions. The target posture of the robot was continuously generated using smooth curved surfaces. This can be applied for navigation purposes, using a path-following algorithm. However, in the existing methodology, the target posture and joint angles are calculated at each time step. It should be noted that the continuity of the flipper angle values cannot be guaranteed. Furthermore, since the experiments in this study assume that the true values of the robot's posture in its environment and world coordinate system can be obtained, sensor noise and position errors must be addressed when applying the method to an actual robot. Additionally, as the objective was to ensure that the robot's posture followed smooth terrain, the stability of the robot was not considered. Future work includes generating target angles that match the flipper drive speed and developing a control method that accounts for stability.

Acknowledgements

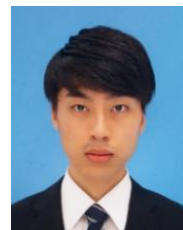
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