Smooth Motion Control of Mobile Robot in Human-robot Coexisting Environment

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Abstract: In order to operate service robots in a human-robot coexisting environment, smooth motion control that does not give discomfort to the human is important. In this paper, we propose a smooth motion control method that considers human's behavior. The proposed motion control method is based on the DWA (Dynamic Window Approach) which is a widely used obstacle avoidance scheme using the optimization of several objective functions. Considering human's behavior, an additional objective function for DWA is defined to realize the smooth motion control of the mobile robot.

Keywords: Mobile robot, Autonomous Navigation, Motion control, Dynamic windows approach.

1. INTRODUCTION

Recently, autonomous mobile robots are expected to be used in service for daily human life (i.e., human-robot coexistence environments, such as offices and living spaces). Considerable studies to solve obstacle avoidance problem have been intensively conducted (Zhu et al. (1991), Sakahara et al. (2007), Missura et al. (2019)). However, in the human-robot coexistence environment, robots need to avoid humans by considering that a human is a special obstacle, which changes their movement according to the surrounding environment. Therefore, one of the functions required for these robots is smooth motion control that takes human's behavior into consideration. Tamura et al. proposed a method to estimate the intention of a person trying to avoid a collision with a robot and generate an appropriate avoidance trajectory accordingly by using SFM (Social Force Model) (Helbing et al. (1995)) as a human's motion model (Tamura et al. (2010)). However, the avoidance behavior is limited to only simple movements such as left and right movement, and more general trajectory generation considering the structural information of the surrounding environment has not been realized.

Based on the above problems, in this paper, avoidance behavior considering human's motion model is applied to Dynamic Window Approach (DWA) (Fox et al. (1997)), which is one of the popular motion control and obstacle avoidance methods for mobile robots. In this way, we propose an autonomous navigation scheme that can perform smooth motion control without giving people discomfort even in the human-robot coexisting environment.

The remainder of this paper is organized as follows. Section 2 and Section 3 briefly summarize the DWA to control the motion of the robot and the SFM to predict the motion of the human, respectively. Section 4 presents the proposed DWA expansion to realize smooth motion control of mobile robots. Then, in Section 5, the effectiveness of the proposed smooth motion controller is evaluated by the experimental results. Finally, Section 6 concludes this paper and discusses future work.

2. DWA

DWA (Fox et al. (1997)) is one of motion control methods widely used as obstacle avoidance method for mobile robots. In this paper, differential wheeled mobile robot with nonholonomic characteristics is assumed and the output velocity at time t is defined as $\boldsymbol{V}_t = [v_{\mathrm{left}}\ \ v_{\mathrm{right}}]^{\mathrm{T}}$ where v_{left} is the left wheel speed and v_{right} is the right wheel speed. In DWA, an evaluation function is calculated for each candidate $\boldsymbol{V}_t$, and optimal $\boldsymbol{V}_t$ is output by maximizing the value of the evaluation function. By defining a DW (Dynamic Window) that can take into consideration the robot's kinematic constraints when performing the search for optimal $\boldsymbol{V}_t$, the amount of computational cost is reduced because the search area in the v_{left}-v_{right} plane can be narrowed.

2.1 Evaluation Function "Heading"

In the evaluation function "Heading", evaluation values are calculated taking into consideration the angle from the robot to the destination, and it makes it possible for the robot to turn smoothly toward the destination. In "Heading", the evaluation value term $g_{\mathrm{H}}(\boldsymbol{V}_t)$ is defined as follows:

$$g_{\mathrm{H}}(\boldsymbol{V}_t) = 1 - \frac{\theta(\boldsymbol{V}_t)}{\pi} \tag{1}$$

where $\theta(\boldsymbol{V}_t)$ is the angle from the robot to the destination when $\boldsymbol{V}_t$ is output.

2.2 Evaluation Function "Clearance"

In the evaluation function "Clearance", evaluation values are calculated taking into consideration the position of the surrounding obstacles, and it makes it possible for the robot to generate a trajectory that can avoid the obstacles. In "Clearance", the evaluation value term $g_C(\boldsymbol{V}_t)$ is defined as follows:

$$g_C(\boldsymbol{V}_t) = \frac{T_{\text{collision}}(\boldsymbol{V}_t) - T_{\text{stop}}(\boldsymbol{V}_t)}{T_{\text{maxstop}} - T_{\text{stop}}(\boldsymbol{V}_t)} \tag{2}$$

where $T_{\text{stop}}(\boldsymbol{V}_t)$ represents the fastest time required for the robot to stop from $\boldsymbol{V}_t$. T_{maxstop} represents the time required for the robot to stop from the maximum speed. $T_{\text{collision}}(\boldsymbol{V}_t)$ is the time take to collide with the closest obstacle when the robot keeps navigating with $\boldsymbol{V}_t$.

2.3 Evaluation Function "Velocity"

In the evaluation function "Velocity", the evaluation value calculation taking into consideration the translational speed is performed, and it allows the robot to navigate at an optimal speed. In "Velocity", the evaluation value term $g_V(\boldsymbol{V}_t)$ is defined as follows:

$$g_V(\boldsymbol{V}_t) = \frac{V_{\text{max}} + |v_{\text{trans}}(\boldsymbol{V}_t)|}{2V_{\text{max}}} \tag{3}$$

where V_{max} is the maximum value of the wheel speed and $v_{\text{trans}}(\boldsymbol{V}_t)$ is the translational speed at $\boldsymbol{V}_t$.

2.4 Composition of Evaluation Functions

By combining all the evaluation functions, we can obtain an evaluation function $g(\boldsymbol{V}_t)$ that reflects the features of each element. The integrated evaluation function $g(\boldsymbol{V}_t)$ is given:

$$g(\boldsymbol{V}_t) = \alpha g_H(\boldsymbol{V}_t) + \beta g_C(\boldsymbol{V}_t) + \gamma g_V(\boldsymbol{V}_t) \tag{4}$$

where α, β, and γ are the weights for the composition of the "Heading", "Clearance", and "Velocity" evaluation functions, respectively.

3. SFM

SFM (Helbing et al. (1995)) expresses the motion model of a walking person by virtual forces as shown in Fig.1. While walking to the destination, humans avoid surrounding obstacles and people. In SFM, these factors are reflected by attractive forces and repulsive forces. The virtual force $\boldsymbol{F}_A(t)$ that a human A receives at time t is given:

$$\boldsymbol{F}_A(t) = \boldsymbol{F}_A^0(t) + \sum_B \boldsymbol{F}_{AB}(t) + \sum_W \boldsymbol{F}_{AW}(t) \tag{5}$$

where $\boldsymbol{F}_A^0(t)$ is the attractive force received from the direction of the destination. $\boldsymbol{F}_{AB}(t)$ and $\boldsymbol{F}_{AW}(t)$ denote the repulsive force received from the human B and the obstacle W, respectively. SFM can predict the future trajectory of a person by using $\boldsymbol{F}_A(t)$ represented in (5) as a prediction value of acceleration, and this term is reflected in the new evaluation function in DWA described in Section 4.

3.1 Attractive Forces Received from The Destination

The attractive force $\boldsymbol{F}_A^0(t)$ is defined as follows:

$$\boldsymbol{F}_A^0(t) = \frac{1}{\tau_A}\left(v_A^0 \boldsymbol{e}_A(t) - \boldsymbol{v}_A(t)\right) \tag{6}$$

where τ_A is the time required for acceleration by a person, v_A^0 is the speed of walking desired, $\boldsymbol{e}_A(t)$ is the direction vector of the desired movement, and $\boldsymbol{v}_A(t)$ is the actual velocity of the person.

3.2 Repulsive Forces Received from Other People

The repulsive force $\boldsymbol{F}_{AB}(t)$ is defined as follows:

$$\boldsymbol{F}_{AB}(t) = w(\boldsymbol{e}_A(t), -\boldsymbol{f}_{AB})\boldsymbol{f}_{AB} \tag{7}$$

where w is a weight in consideration of the visibility information of A and reflects that the interest in objects receiving attractive forces or repulsive forces. Therefore, it can be increases or decreases depending on the situation of human vision. w is described by

$$w = w(\boldsymbol{e}, \boldsymbol{f}) = \begin{cases} 1 & \text{if}(\boldsymbol{e}\cdot\boldsymbol{f} \geq \|\boldsymbol{f}\|\cos\phi) \\ c & \text{else} \end{cases} \tag{8}$$

where ϕ [rad] is a constant value which represents the half size of a person's field of vision. $\boldsymbol{e}$ and $\boldsymbol{f}$ are a direction vector toward the person's destination and a vector of a virtual force received, respectively. The function $\boldsymbol{f}_{AB}$ is defined as follows:

$$\boldsymbol{f}_{AB} = -\nabla_{\boldsymbol{r}_{AB}} V_{AB}[b(\boldsymbol{r}_{AB})] \tag{9}$$

where the repulsive potential $V_{AB}(b)$ is a function of b, which is a monotonically decreasing function. Here, $\boldsymbol{r}_{AB}$ denotes the relative position of A to B. The contour line of b is an ellipse, whose major axis is the moving direction of the B as shown in Fig. 2. b can be described by

$$b = \frac{1}{2}\sqrt{(\|\boldsymbol{r}_{AB}\| + \|\boldsymbol{r}_{AB} - v_B\Delta t\boldsymbol{e}_B\|)^2 - (v_B\Delta t)^2} \tag{10}$$

3.3 Repulsive Forces Received from Obstacle

The repulsive force $\boldsymbol{F}_{AW}(t)$ is defined as follows:

$$\boldsymbol{F}_{AW}(\boldsymbol{r}_{AW}) = -\nabla_{\boldsymbol{r}_{AW}} U_{\boldsymbol{r}_{AW}}(\|\boldsymbol{r}_{AW}\|) \tag{11}$$

where $U_{\boldsymbol{r}_{AW}}(\|\boldsymbol{r}_{AW}\|)$ is the potential for repulsive forces, which is a monotonically decreasing function. The vector $\boldsymbol{r}_{AW} = \boldsymbol{r}_A - \boldsymbol{r}_W^A$ represents the relative position of A to $\boldsymbol{r}_W^A$. Here, $\boldsymbol{r}_W^A$ is a position within W closest to A.

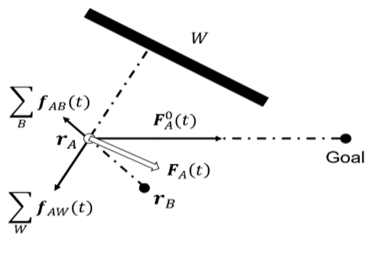

Fig. 1. Social force model acting on pedestrian A.

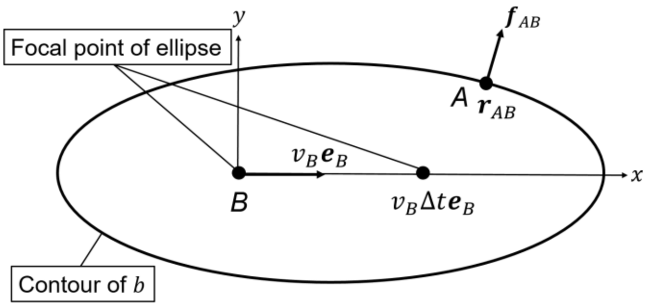

Fig. 2. Repulsive forces received from B.

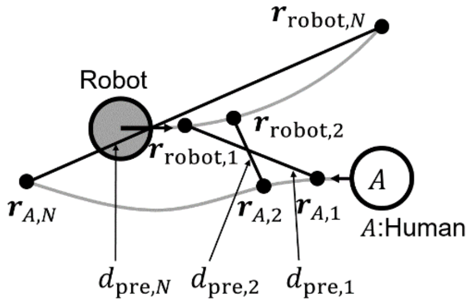

Fig. 3. Conceptual diagram of objective function "Person".

4. DWA EXPANSION

DWA combines the multiple evaluation functions to output the optimal velocity $\boldsymbol{V}_t$ that satisfies all factors. Based on this structure, we define a new evaluation function that can take account of human dynamic information and synthesize it with the conventional evaluation function represented in (4).

4.1 Additional Evaluation Function "Person"

In this paper, a new evaluation function g_P for extended DWA is called "Person". In "Person", calculation of an evaluation value is performed considering the future motion of the person obtained by SFM. This allows the robot to navigate smoothly taking the behavior of the pedestrian into consideration. In "Person", the evaluation value term g_P is defined as follows:

$$g_P(\boldsymbol{V}_t) = min\left(\frac{\sum_{i=1}^{N} d_{\text{pre},i}}{N D_{\text{th}}}, 1\right) \tag{12}$$

where N is the number of frames at prediction, D_{th} is an experimentally obtained constant value. $d_{\text{pre},i}$ is the distance between the robot and a person after i frames which is calculated as shown in Fig. 3. Here, $\boldsymbol{r}_{A,i}$ is the predicted position of the person after i frame under the assumption that the person moves according to SFM. Similarly, $\boldsymbol{r}_{\text{robot},i}$ is the predicted position of the robot after i frame under the assumption that the robot moves while maintaining the velocity $\boldsymbol{V}_t$ of the current frame. Here, the value of $d_{\text{pre},i}$ is calculated from the Euclidean distance between $\boldsymbol{r}_{A,i}$, and $\boldsymbol{r}_{\text{robot},i}$.

4.2 Composition of Additional Evaluation Function

We combine "Person" with as the new evaluation function into DWA in order to enable the robot to navigate in consideration of the future behavior of the human. The extended evaluation function $g_{\text{new}}(\boldsymbol{V}_t)$ is given:

$$g_{\text{new}}(\boldsymbol{V}_t) = \alpha g_H(\boldsymbol{V}_t) + \beta g_C(\boldsymbol{V}_t) + \gamma g_C(\boldsymbol{V}_t) + \delta g_P(\boldsymbol{V}_t) \tag{4}$$

where δ is the weight for the composition of the evaluation function "Person". As a result, $\boldsymbol{V}_t$ that can be navigate more smoothly in the human-robot coexistence environment is output.

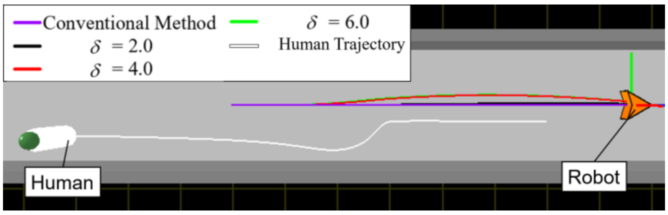

Fig. 4. Trajectories of robot and human (top view).

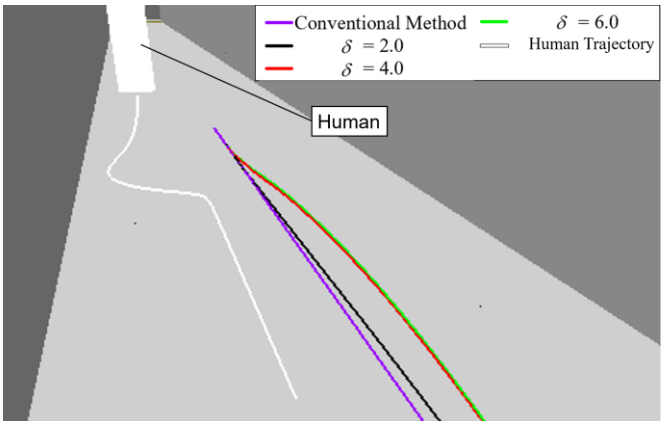

Fig. 5. Trajectories of robot and human (bird eye view).

5. SIMULATION EXPERIMENT

5.1 Simulation Conditions

In order to verify that the proposed method can perform smooth motion control in a human-robot coexisting environment, simulation experiments were conducted under a situation where a human and a robot are passing each other. The simulation environment is assumed to be a corridor which consists of sufficiently wide two walls. Note that destinations of the robot and the human are set at the opposite side of the corridor respectively. Here, we qualitatively evaluated how much smooth avoidance was realized by comparing the trajectories produced by the extended DWA depending on different weights of "Person" δ and the conventional DWA.

5.2 Results

Figures 4 and 5 show output trajectories of the robot produced by each of methods (i.e., conventional DWA and extended

DWA) with the human's trajectory generated by SFM. Figures 6 and 7 respectively depict the distance between the robot and human, and translation velocity at each frame. Note that we assumed that each estimated path of the robot and human has no error in the simulation environment. We conducted comparative experiments using various weights of "Person" (i.e., δ = 0.0, 2.0, 4.0, 6.0). Note that if the weight is zero (i.e., δ = 0.0), it is identical to the conventional DWA. Here, the robot's trajectories depending on different weights δ are represented by purple, black, red, green lines, respectively. The human's trajectory is represented by a white line.

In the case of the conventional DWA (i.e., δ = 0.0), the robot suddenly reduced the speed without changing the direction when it approached the human. This motion gives a sense of discomfort from a person's point of view. On the other hand, the smoother motions of the robot were generated as the weight value δ was increased. In case of the weight is 2.0, the generated robot's motion was not much different from the conventional DWA. However, in case of the weight is 4.0 or more, the robot navigates smoothly without reducing the speed even if it approaches the human since the robot had changed the running direction based on predicted human's behavior by SFM in advance. In case of the weight is larger than 4.0, the motion of robot was almost unchanged compared with the motion when the weight is set to 4.0.

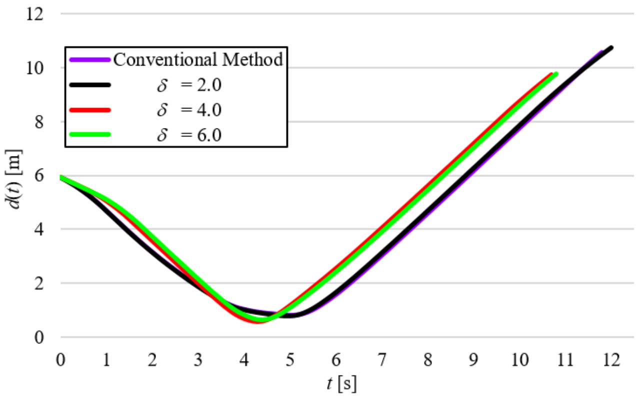

Fig. 6. Distance between human and robot.

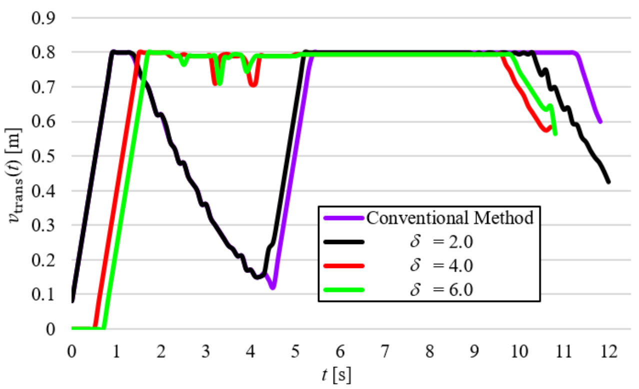

Fig. 7. Translational velocity of robot.

6. CONCLUSION

We realized smooth motion control in the human-robot coexisting environment by extending the DWA approach, which is one of the popular motion control methods for autonomous mobile robots. The validity of the proposed motion control method was investigated through experiments in a simulation environment.

Finally, the future work related to this study is as follows. In this study, the smooth motion control was implemented under the assumption that the position of the human is completely detected by the sensor mounted on the robot. However, it is difficult to accurately detect the human every frame. Therefore, we will develop a more robust scheme that could manage such uncertainty of human detection. Moreover, we plan to operate the proposed motion control method in real environment.

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