Mobile Robot Navigation Based on Pedestrian Flow Model Considering Human Unsteady Dynamic Behavior

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Abstract: Achieving robot navigation that satisfies the requirements of safety and efficiency in a dynamic environment crowded with people is a challenging task because of the need to implement social aspects of robot behavior. In this study, a robot navigation method based on an unsteady dynamic pedestrian flow model is proposed, taking into account the unsteady dynamic nature of pedestrian flow, which has not been taken into account in conventional algorithms. We propose a method that enables continuous following of unsteady pedestrian flow, which allow the robot to approach the destination safely and efficiently. The social compatibility of the proposed navigation system, consisting of safety and efficiency, is evaluated through several simulations and actual experiments.

1 INTRODUCTION

Navigation in densely populated environments is the most important research topic from the viewpoint of satisfying all the requirements of safety and efficiency during movement since robots interact closely with people. Trautman et al. stated that it is important to consider human-robot interaction in order to engage closely with people (Trautman et al., 2013). One strategy for close interaction between humans and robots is a navigation strategy that takes social interaction into account (Rios-Martinez et al., 2015). Pedestrian flow observed in crowded environment is often formulated depending on human social interaction and connection as shown in Figure 1 (Helbing et al., 2001; Hoogendoorn et al., 2004). Robotic movement along the pedestrian flow reduces pedestrian deceleration, avoidance, and crossing behavior. Respecting the crowd flow therefore enables safe and efficient crowd navigation.

The following three studies have been conducted on navigation methods using pedestrian flows. Du et al. developed a group surfing method that generates actions that mimic pedestrian flow behavior (Du et al., 2019). Yao et al. proposed a method for incorporating a population-aware Social Force Model into GAN (Yao et al., 2019). Kumahara et al. proposed a potential method that integrates the Lennard-Jones potential and wrapped normal distribution (Kumahara et al., 2014). Pedestrian flow following and merging control using the above methods enable crowd navigation in congested environments. However, the navigation systems proposed in previous studies are not considerd unsteady pedestrian flows, which may lead to failure of robot navigation. A method for following unsteady pedestrian flows to increase the success rate of navigation is thus proposed in this study. The safety and efficiency of the proposed navigation system are then evaluated and demonstrated through several simulations and experiments on actual equipment.

2 ROBOT NAVIGATION SYSTEM

The system configuration of experimental robot navigation is shown in Figure 2. In this study, Terapio (Tasaki et al. 2015), an omni-directional mobile medical examination support robot with advanced mobility capabilities in a dynamic crowded environment, is used because there are no restrictions on the direction of movement. The robot is controlled by speed commands generated by a control PC based on dynamic pedestrian flow information and robot

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Figure 1: Pedestrian flows in dense human crowds.

information. At this time, the robot is controlled in the x-axis direction of the world coordinate system and the x_r-axis direction of the robot coordinate system.

The dynamic pedestrian flow information is consisted of pedestrian flow and pedestrian size information. Since the use of surveillance cameras has rapidly increased in recent years in the city, pedestrian flow is measured using an RGB camera (LOGICOOL STREAMCAM, Logitech CO., Ltd.) with an overhead viewpoint similar to a surveillance camera. Pedestrian size information is measured using two LiDAR (UTM-30LX, Hokuyo Automatic CO., Ltd.) mounted on the front and rear of the robot. Thus, the pedestrian flow information is obtained by detecting and tracking the pedestrian's head from various color information, and pedestrian size information is obtained by measuring the pedestrian's stride length. The details of the algorithms for obtaining each piece of information will be described in another paper in the future.

3 UNSTEADY PEDESTRIAN FLOW

A method for following unsteady pedestrian flows is described in this section. Unsteady pedestrian flow is defined as a flow whose velocity changes over time. Moreover, pedestrian flow is defined as social group of neighboring pedestrians sharing similar motion patterns in this study. Since the pedestrian flows observed in real-world dynamic congested environments are unsteady, a potential function combining the LJ potential (LJ potential) and Wrapped Normal Distribution (WND) for steady flows generates unnecessary following behavior. Therefore, a potential function considered unsteady pedestrian flow is developed as follows.

$$U_{unsteady}(r) = \gamma \varepsilon_{LJ}\left[\beta\left(\frac{\sigma_{LJ}}{r-(r_{ro}+r_{pd})}\right)^{p} - \alpha\left(\frac{\sigma_{LJ}}{r-(r_{ro}+r_{pd})}\right)^{q}\right] \quad (1)$$

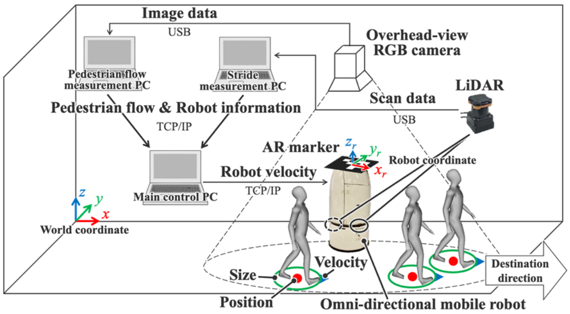


Figure 2: Schematic of a system construction.

$$f_{ND}(v_{pd}) = \frac{1}{\sqrt{2\pi\sigma_{WD}}^{2}} \sum_{i=-\infty}^{\infty} \exp\left[\frac{-(v_{pd}-\mu_{flow})^{2}}{2\sigma_{ND}{}^{2}}\right] \quad (2)$$

$$\gamma = f_{ND}(v_{pd})/f_{ND}(\mu_{flow}) \quad (3)$$

$$f_{WND}(\theta) = \frac{1}{\sqrt{2\pi\sigma_{WND}}^{2}} \sum_{i=-\infty}^{\infty} \exp\left[\frac{-\left(\theta \times \frac{\pi}{180}\right)+2\pi i}{2\sigma_{WND}{}^{2}}\right] \quad (4)$$

$$\alpha = \frac{f_{WND}(\theta)}{f_{WND}(0)},\ \ \beta = (1-w_{WND})\alpha + w_{WND} \quad (5)$$

where r [m] is the distance between the robot and the pedestrian; ε_{LJ}, p, and q are parameters that adjust the magnitude of the proposed potential function, the repulsion term, and the attraction term; σ_{LJ} is a parameter that adjusts the approach distance to the pedestrian to be tracked; r_{ro} [m] is the robot radius; r_{pd} [m] is the pedestrian radius; σ_{ND} is the standard deviation of the normal distribution; μ_{flow} [m/s] is the pedestrian flow velocity to be tracked. v_{pd} [m/s] is the pedestrian velocity; θ [°] is the angular difference between the robot's destination direction and the pedestrian's direction of travel; σ_{WND} is a parameter that determines how far away from the robot destination direction and the pedestrian's direction of travel the robot will follow or not follow; w_{WND} is a parameter that adjusts the magnitude of the repulsion term in the proposed potential function.

(1) is a potential function that combines the LJ potential and WND, weighted by (3). The outline of the potential graph generated by (1) is shown in Figure 3. By weighting (1) with (5), the robot follows pedestrians moving in a direction similar to the destination direction and avoids others. Moreover, by weighting (1) with (3), it is possible to reduce the potential effect generated by unsteady pedestrians moving at a velocity different from that of the pedestrian flow. Therefore, the potential function that is considered unsteady pedestrian flows generates a continuous following motion for the unsteady pedestrian flow.

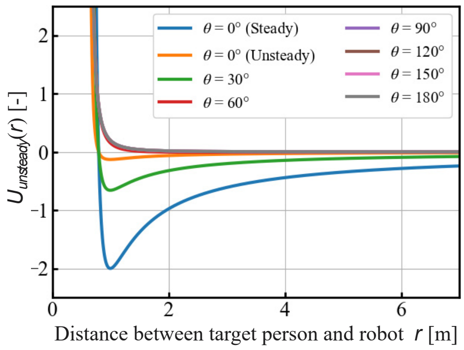


Figure 3: Potential graph.

4 CROWD ENVIRONMENT SIMULATION

The safety and efficiency of the proposed system were evaluated with several simulations in a congested environment with unsteady pedestrian flow. Simulations are performed in the environment shown in Figure 4. The robot moving velocity is 1.3 m/s, and the pedestrian velocity is 1.0 m/s. However, if the robot x-coordinate exceeds 6 m, the velocity of one pedestrian in front of the robot is set to 0.5 m/s.

Figure 5 shows the simulation results of the conventional system (Kumahara et al., 2014) and the proposed system. It is important to note that the proposed system is implemented with a pedestrian flow merging algorithm to increase the navigation success rate, but the details of the algorithm will be discussed in a future paper. The conventional system is not implemented with the merging algorithm and is not considered unsteady pedestrian flows. Therefore, the robot fails to merge with the pedestrian flow heading in the direction of the destination and is pushed back as shown Figure 5(a). Furthermore, it does not overtake and follows pedestrians moving slower than the pedestrian flow velocity. These movements were unnecessary movements. The proposed system is implemented with a merging algorithm and considered unsteady pedestrian flows. Therefore, it is confirmed that the robot is heading toward the confluence point where it can safely and efficiently travel to the most destinations as shown Figure 5(b). It also overtook pedestrians moving slower than the pedestrian flow velocity and continuously followed the unsteady pedestrian flow. The above results show that the proposed system takes less time and travels shorter distances to the destination than the conventional system. Furthermore, the generated robot trajectory is smooth.

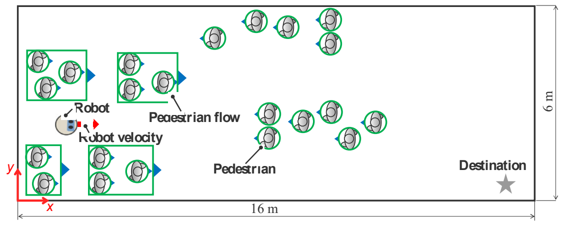
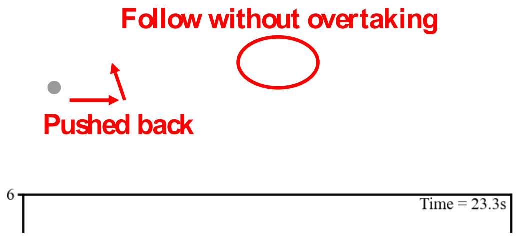
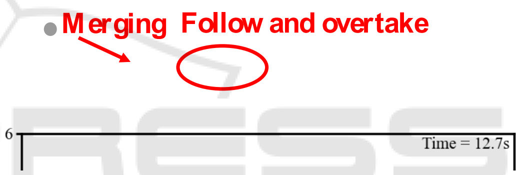


Figure 4: A simulation environment.



(a) Conventional system.



(b) Proposed system.

Figure 5: Results of simulation experiments with the proposed system and comparison system.

Such robot behavior is considered safe and efficient. Therefore, it can be evaluated that the proposed navigation system is safer and more efficient than the conventional navigation system by implementing sociality that continuously follows unsteady pedestrian flows.

5 NAVIGATION EXPERIMENT IN UNSTEADY PEDESTRIAN FLOW

An experiment based on dynamic pedestrian flow information is conducted using an omnidirectional mobile robot in an environment with dynamic pedestrian flow. In the experimental environment, there are four pedestrians moving at 0.5 m/s in the direction of the destination and one pedestrian moving at 0.5 m/s in the opposite direction.

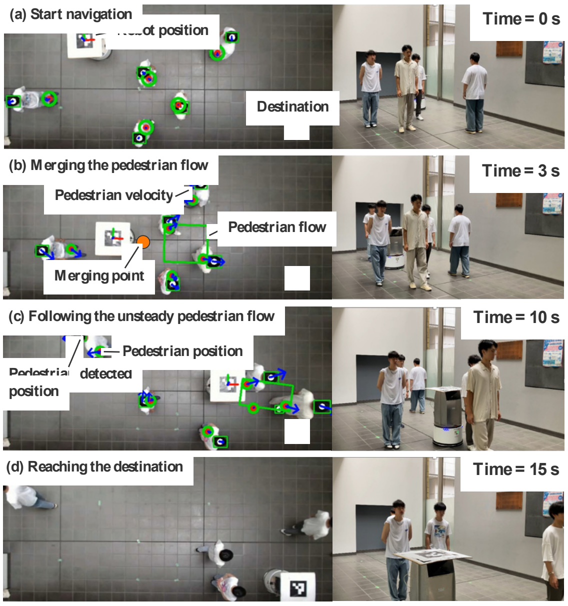


Figure 6: Results of experimental navigation using dynamic pedestrian flows.

The actual navigation results are shown in Figure 6. The left side is a rendered image of the pedestrian flow information, and the right side is a robot motion image viewed from the side. In the rendered image, the robot position is drawn as a coordinate system, the pedestrian head detected by the overhead view camera is depicted as a white circle, the detection area is shown as a green rectangle, the pedestrian position as a red circle, the pedestrian velocity is indicated as a blue arrow, the pedestrian size is marked as a green circle, the pedestrian flow is illustrated as a large green rectangle, the merge point is indicated as an orange circle, and the destination point is marked as a white star. The robot successfully merges into the optimal pedestrian flow using the proposed system as shown in Figure 7(b). It also overtakes pedestrians moving slower than the pedestrian flow velocity and continuously follows the unsteady pedestrian flow as shown Figure 7(c). Similar to the simulation, it can be verified that the robot action satisfies safety and efficiency without interfering with the pedestrian action and without taking unnecessary actions, even when the pedestrian flow is unsteady. The safety and efficiency of the proposed system have been evaluated in terms of pedestrian and robot trajectories in the current stage. In the future, we will evaluate the proposed system from a psychological point of view by asking subjects to complete questionnaires on evaluation items such as safety and naturalness of the robot navigation.

6 CONCLUSIONS

A navigation system based on an unsteady dynamic pedestrian flow model is proposed to achieve crowd navigation that satisfies the requirements of safety and efficiency in a densely populated environment. Continuous following behavior for unsteady pedestrian flow is achieved by using a normal distribution to reduce the potential effect generated by pedestrians moving at a velocity different from the pedestrian flow velocity. Social robot navigation in congested environments with multiple unsteady pedestrian flows can be realized by considering pedestrian flow is dynamic and unsteady.

At this stage, experiments in specific scenes have only been able to conduct. In the future, we will conduct experiments assuming various scenes, such as people staying in the flow and merging into the flow. The usefulness of the proposed system in a complex environment will then be verified.

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