Evading of Pedestrian Pursuer and Avoiding Obstacles Using Path-Velocity Planner

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ABSTRACT The ability to navigate mobile robot from initial to target position while maintaining the safety and comfort of pedestrian have to be supported by a collision avoidance system. In the case of pursuit-evasion when a pedestrian pursues a robot, navigation must be able to evade capture from the pursuer. This paper aims to improve the collision avoidance method based on Hybrid Velocity Obstacles (HVO) concerning the pursuer. This paper proposes a path-velocity planner that consists of a global path planner, and two velocity planners. These velocity planners combine pure pursuit path following and proposed collision avoidance method. This research presents a modified version of the Headed Social Force Model (MHSFM) based on modified HVO (MHVO). The linear velocity of MHVO is employed to generate the MHSFM target force. The interaction force of MHSFM is influenced by static and moving objects, and pursuers. The angular velocity of MHVO is used to steer the robot away from the pursuer. This proposed method was evaluated with two simulation scenarios. MHVO-based MHSFM was implemented into a two-wheeled differential-steering mobile robot that navigated in an indoor human environment. The results show that the proposed method is capable to evade a pedestrian pursuer by maintaining the safety and comfort of other pedestrians with an average value of 0.25 on the Threat Level Index (TLI).

INDEX TERMS Collision avoidance, differential-steering mobile robot, modified headed social force model, modified hybrid velocity obstacles, path-velocity planner, pedestrian pursuer.

I. INTRODUCTION COVID-19 pandemic has changed the world’s regular living. This condition is influencing the way to deliver services and impacting the approach to obtain needs. These daily activities must be accompanied by the enforcement of safety protocols with a priority on public health. A safe human work environment can be accomplished by utilizing robotics technology. Several work areas that can utilize robots in this global health crisis include robotic applications in the field of cleaning, manufacturing, logistic, health care, and telepresence [1]. Robots can play an important role in daily activities by taking part as a reliable logistics fleet to respond to potential supply chain disruption. As a reliable logistics fleet, mobile robots are used to deliver packages to target locations [2]. To be able to carry out this task, the robot must have the ability to navigate in the human environment by maintaining the safety and comfort of humans around it [3]. Navigation can maintain both of these factors with the support of collision avoidance.

There are several approaches in collision avoidance that have been proposed in the literature. A modified Artificial Potential Field (APF) was implemented in a mobile robot in [4]. This modified APF solved the local minimum and oscillation problem but still could not cope with dynamic moving obstacles. Vector Field Histogram (VFH) was applied to laser scanner-based mobile robots [5]. This version of VFH was able to avoid static and moving obstacles though it could not handle non-linear motion. A technique integrating the LIDAR and Velocity Obstacles (VO) sensors was explored in [6] for an Autonomous Indoor Vehicle (AIV). An application of VO to track planning for avoiding curbs, crossings, and other vehicles was investigated in [7]. Reciprocal Velocity Obstacles (RVO) was used to avoid collisions between agents in crowd navigation in research [8]. To help mobile
robots that navigate close to humans by avoiding multi-modality moving objects, Hybrid Velocity Obstacles (HVO) was proposed in [9]. Although this algorithm can maintain human safety around the robot, additional capabilities are still needed to maintain human comfort so that the robot can operate in the human environment properly. Some approaches that take into account the comfort side of human psychology were studied in [10] and [11]. Research [12] examined collision avoidance on an Unmanned Aerial Vehicle (UAV) in a condition known as Suicidal Pedestrian Game (SPG). The pursuer and the evader have a constant velocity of different values. The pursuer is agile whereas the evader has limited maneuverability. In general, these previous studies assume that the obstacle object moves at a constant speed and has a specific target goal. When the transport robot brings the package to the target location, there can be a pedestrian who makes the robot a target. Research that explores a pedestrian as an uncooperative moving obstacle that chases a robot at non-constant speeds while the robot has to maintain the safety and comfort of humans around is still rare and interesting to be investigated.

A strategy to split a path planner into global and local path planners was investigated in [6]. A Probabilistic Road Map (PRM) planner was exploited to generate the global path. Whereas Pure Pursuit (PP) and Modified Steering Velocity Obstacles (MSVO) were utilized as local path planners by depending on sensor reading for planner activation. An interesting indoor navigation system was introduced in [9] by substituting MSVO with HVO to deal with multi-modal moving obstacles. This research adopts the navigation structure as presented in [6] and [9] by adding a modification in PRM pre-processing phase and introducing modified HVO-based modified HSFM in velocity planner for collision avoidance.

PRM defines the reference path by providing the initial and target location of the robot navigation task. The border of environment, static, and moving objects are some elements needed to calculate this global path. By executing global path generation only once at the beginning of the task, the computation time of the total process can be reduced. Both velocity planners, path following and collision avoidance, result linear and angular velocities by concerning kinematics and dynamics of a mobile robot to achieve simplicity in the real robot implementation.

Waypoints with fixed values were used in [7] to guide pedestrian to reach destination location. Other research orders the robot to cross between two points [4]. A random set of desired paths were explored in [6] and [9] by applying PRM. This method was applied to moving objects in the environment to represent reality. This approach is taken in this study to make the simulation more realistic because humans move with their random trajectory [15].

Some studies in collision avoidance, such as in [4] and [6], are concerned about maintaining a safe distance with static objects. Researches in [5] and [7] investigated methods to avoid static and moving objects such as in [5] and [7]. Several studies considered keeping the comfort of individual pedestrian [7] and [9]. Other studies included the comfort of a group of pedestrians as their objectives, such as examined in [10] and [11]. In general, these studies had the assumption that the velocity of pedestrians is always constant except in [11].

HVO as a velocity-based collision avoidance method is proposed to overcome the obstacle that moves with non-constant velocity. This study offers to modify the HVO to prioritize velocity towards the target to compensate for avoidance motion. To maintain the comfort of other pedestrians around the robot, the HSFM is chosen because it supports the characteristics of a non-holonomic mobile robot and is suitable for use in human environments. This study explores the integration between modified HVO and modified HSFM to overcome the problem of evading a pedestrian pursuer and avoiding collision with other humans around the robot. This paper aims to develop a path-velocity planner for pursuer evasion and collision avoidance while following reference path from initial to target position to maintain physical safety and psychological comfort of humans by presenting modified HVO-based modified HSFM.

The main contributions of this paper are:

- Global path planner of proposed indoor robot navigation system exploits Probabilistic Road Map (PRM) planner to generate a random desired path from initial to the target location for mobile robot and each pedestrian in simulation. This method application is unique and more realistic compare to previous research which is based on a fixed set of waypoints. This paper proposes a new way to generate random nodes that differ from previous research with a constant number of nodes.
- Structure of path-velocity planner adopts switching strategy between path following and collision avoidance to generate linear and angular velocity command. By separating global path planner and local velocity planner, navigation structure becomes more detailed and computation is faster because the system does not have to do replanning when the environment changes. It also differs from other investigations based solely on velocity or orientation for controlling mobile robot movement. The output of this strategy, linear and angular velocities references, can be simply applied to a real robot.
- Local velocity planner combines Pure Pursuit (PP) and Modified HVO-based modified HSFM (MHVO-based MHSFM) to handle path following and collision avoidance. This research contributes to utilizing modified HVO for providing steering command and desired velocity of modified HSFM for guiding the robot to reach the target without colliding with obstacles. Unlike previous studies, this research considers maintaining safety and comfort while it evades from a pedestrian pursuer.

The rest of this paper is organized as follows. Section II describes the kinematics and dynamics of the mobile robot. Section III exposes about pedestrian pursuers as a special...
obstacle in this study. Section IV introduces the proposed path-velocity planner that consists of the proposed path planner, the switch-based velocity planner, and the proposed collision avoidance method. Simulation results are explained in Section V. Section VI concludes this paper.

II. KINEMATICS AND DYNAMICS OF MOBILE ROBOT

This research uses a two-wheeled differential-steering mobile robot to deliver a package from its initial to target position in an indoor environment. The robot posture in the Cartesian coordinate system is depicted in Fig. 1. The width of the wheel axis is expressed as \( d \). The center of the left-right wheel axis \( C \) coincides with the center of mass \( G \). This point represents the robot in the global X-Y coordinate. Left and right motors rotate wheels with diameter \( 2r \). Mobile robot pose and its velocities are denoted as follows:

\[
\mathbf{P}_r = \begin{bmatrix} x_r, y_r, \psi_r \end{bmatrix}^T, \quad \dot{\mathbf{P}}_r = \begin{bmatrix} \dot{x}_r, \dot{y}_r, \dot{\psi}_r \end{bmatrix}^T
\]  

Robot location is denoted as \( \mathbf{L}_r = [x_r, y_r]^T \) and its orientation is symbolized as \( \psi_r \). Velocity command \( v_r^{cmd} \) and \( \omega_r^{cmd} \) of velocity planner for path following and collision avoidance to drive both motors of a differential-steering mobile robot using wheel velocities \( \dot{\theta}_r \) by utilizing inverse kinematics:

\[
\begin{bmatrix} \dot{\theta}_r^R \\ \dot{\theta}_r^L \end{bmatrix} = \begin{bmatrix} \frac{1}{r} & \frac{d}{2r} \\ \frac{1}{r} & -\frac{d}{2r} \end{bmatrix} \begin{bmatrix} v_r^{cmd} \\ \omega_r^{cmd} \end{bmatrix}
\]  

Actual wheel velocities \( \dot{\theta}_r = [\dot{\theta}_r^R, \dot{\theta}_r^L]^T \) from mobile robot movement are changed into linear velocity \( v_r \) and angular velocity \( \omega_r \) by using forward kinematics:

\[
\begin{bmatrix} v_r \\ \omega_r \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{d} & -\frac{r}{d} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r^R \\ \dot{\theta}_r^L \end{bmatrix}
\]  

Actual robot pose are defined by exploiting linear and angular velocities:

\[
\begin{bmatrix} x_r(k+1) \\ y_r(k+1) \\ \psi_r(k+1) \end{bmatrix} = \begin{bmatrix} x_r(k) \\ y_r(k) \\ \psi_r(k) \end{bmatrix} + kT \begin{bmatrix} v_r(k)\cos\psi_r \\ v_r(k)\sin\psi_r \\ \omega_r(k) \end{bmatrix}
\]  

where wheel speeds \( \dot{\theta}_r = [\dot{\theta}_r^R, \dot{\theta}_r^L]^T \) are employed to drive the mobile robot based on its wheel radius \( r \) and width of robot \( d \) by affecting its linear \( v_r \) and angular velocity \( \omega_r \). The dynamic model of the mobile robot can be expressed as follows:

\[
\dot{v}_r = \frac{1}{m_r} (\tau_R + \tau_L)
\]  

\[
\dot{\omega}_r = \frac{d}{I_r} (\tau_R - \tau_L)
\]  

The linear acceleration \( \dot{v}_r \) is determined by the sum of right \( \tau_R \) and left \( \tau_L \) torques divided by its mass \( m_r \) and wheel radius \( r \). The angular acceleration is affected by the width of wheel axis \( d \), the difference between torques, inertia \( I \), and wheel radius.

III. PEDESTRIAN PURSUER

This scenario is illustrated in Fig. 2. This mobile robot has to transport some packages to a certain target location by providing safety and comfort to humans in the vicinity of the robot. The dashed boundary
of each grey object shows the area of a safety and comfort standard that must be avoided by the robot. An indoor human environment, such as a hall, may contain static humans and pedestrians. Static humans comprise human-object interaction (HOI) and a group of static humans in standing still formation. Among pedestrians, there may be people chasing the robot to grab its packages. This kind of pedestrian acts as an uncooperative moving obstacle that moves with non-constant speeds to chase the robot.

Pedestrian pursuer that has been a concern of this study is a type of pedestrian that moves with varying velocities and targeting the robot. It has the same character as a single pedestrian in that it moves with changeable velocities and nonlinear trajectories. But it differs in that its target always changing position. Single pedestrian properties are illustrated in Fig. 3. An individual pedestrian can be described by a pedestrian pose in X-Y coordinate $[x_{pi}, y_{pi}, \psi_{pi}]^T$, velocity $v_{pi}$, acceleration $a_{pi}$ and radius of the $i$th individual pedestrian body $r_{pi}$ that can be affected by arms reached or helping devices as formulated as follows:

$$S_{pi} = [x_{pi}, y_{pi}, \psi_{pi}, v_{pi}, a_{pi}, r_{pi}]^T$$  (8)

IV. PROPOSED PATH-VELOCITY PLANNER

The collision avoidance system is designed by considering kinematics and dynamics of a mobile robot concerning the safety and comfort distance of static humans, a single pedestrian, and a group of pedestrians in the indoor human environment. This study proposes an indoor navigation system based on a path-velocity planner. This planner consists of a global path planner, path following equipped with collision avoidance velocity planner concerning kinematics and dynamics of a two-wheeled differential-steering mobile robot such as described in Fig. 4.

 Desired mobile robot position that acts as a reference, $L_d = [x_d, y_d]^T$, is generated by the PRM path planner. This sequential reference position connects the initial location to the target by a set of randomly generated waypoints. The waypoints have to be tracked by the mobile robot. The actual mobile robot location is denoted by $L_r = [x_r, y_r]^T$ and its orientation is symbolized by $\psi_r$. Obstacle location is expressed by $L_o = [x_o, y_o]^T$. Desired robot position, obstacle and pursuer locations, and actual robot location are used to define velocity command either for path reference following or collision avoidance and pursuer evasion purposes.

Humans that exist in the environment include a static human, single pedestrian, group of pedestrians, and pedestrian pursuer are acted as obstacles. Although the robot has to evade the pursuer and avoid human obstacles, it must maintain the safety and comfort of humans while it navigates from initial to target position. This research uses TLI [11] as a standard of safety and comfort distance.

A. PROPOSED PATH PLANNER USING MODIFIED PRM

Pedestrian moves with a nonlinear path. This path is resulted by using Probabilistic Road Map (PRM) [13]. This method was utilized in [6] and [9]. PRM results in the shortest path connecting some randomized nodes from initial to target location that are not covered by obstacles based on the
environment map. The path is constructed by using objective function as follows:

$$J(L) = \sum_{j=1}^{n-1} E_j$$  

(9)

where Euclidean distance $E$ is used to measure the total path length of each pair of consecutive locations from initial $L_i$ to target $L_t$ of n randomized nodes such as illustrated in Fig. 5.

A sharp turn sometimes is formed to attain the shortest path of the interconnected randomized nodes. To improve the smoothness of the reference path, this research proposes a new approach by using the virtual mobile robot path following such as illustrated in Fig. 6. PRM path with sharp turn $[v_{ymr}(k), \omega_{ymr}(k)]$ is delivered to Pure Pursuit to follow the reference path by using linear and angular path following velocity of virtual mobile robot $[v_{ymr}(k), \omega_{ymr}(k)]$. These velocities are commanded to move a virtual non-holonomic mobile robot by applying $[\dot{\theta}^{R}_{ymr}(k), \dot{\theta}^{L}_{ymr}(k)]$. The movement of the virtual mobile robot from initial to target location results in a smooth tracked path that is used as reference $[x^d(k), y^d(k)]$.

B. SWITCH-BASED VELOCITY PLANNER

The mobile robot was equipped with a simulated LIDAR scan with a max sensing range of 20 m. The horizontal field of view is 360° with a resolution of 12°. It generates ranges reading $d_i$ that are measured from the sensor to obstacles in the environment concerning its specification. Velocity command selects to activate one of the two velocity planners according to LIDAR data. It decides whether velocity planner for path following or collision avoidance for generating appropriate velocity by using Algorithm-1.

It is switched based on lidar scan $d_i$ at objects in the surrounding of the robot. Modified HVO-based HSFM collision avoidance will be activated if LIDAR scan ranges reading $d_i$ less than alert distance $d_a$. Otherwise, Pure Pursuit will be invoked.

**Algorithm 1** Switch-Based Velocity Planner Using LIDAR

1. 
   if $d_i < d_a$
2. 
   ModHVO_modHSFM()
3. 
   else
4. 
   PurePursuit()
The repulsive force as a result of interaction with pedestrian pursuer is described as follows:

$$F_{r-p}^{rep} = K_{r}^{str} \exp \left( \frac{(r_{-p} - d_{-p})}{K_{r}^{ring}} \right) n_{r-p} + K_{r}^{cmp} g \left( r_{-p} - d_{-p} \right) n_{r-p} + K_{r}^{fri} g \left( r_{-p} - d_{-p} \right) \Delta v_{r-p}^{obs} t_{r-p} \quad (16)$$

Attractive force $F_{r-tar}^{att}$ that motivate robot to approach a target is defined as follows:

$$F_{r-tar}^{att} = K_{r}^{v} (v_{des} - v_{act}) \quad (17)$$

The robot will move to the target direction by using desired velocity $v_{des}$. Time-constant $K_{r}^{v}$ is needed for the mobile robot to move from the current actual velocity $v_{act}$ to desired velocity $v_{des}$. The desired velocity used to be defined by giving a certain value or by adjusting to a random number [10]. This research proposes to utilize HVO in [11] to generate the desired velocity based on LIDAR scan on robot surrounding as described as follows:

$$HVO = \bigcup_{o \in O} VO_{r-o} \cup \bigcup_{o \in R} RVO_{r-o} \cup \bigcup_{h \in p} NLVO_{r-h} \quad (18)$$

$$\overline{HVO} = \{ v_{r} \in V | v_{r} \notin HVO \} \quad (19)$$

$$v_{des} = \arg \min_{v_{max} \leq v_{act} \leq v_{max}} (v_{ca}) \quad (20)$$

By calculating the resultant of ModHVO-modHSFM forces, change on robot velocity can be determined as follows:

$$a_{r}(k) = \frac{1}{m_{r}} F_{r}^{ModHVO-modHSFM}(k) \quad (21)$$

where the acceleration of mobile robot $a_{r}(k)$ can be obtained by providing robot body mass $m_{r}$ and total force $F_{r}^{ModHVO-modHSFM}(k)$ that act on the robot. The actual velocity of the robot is denoted by $v_{r}(k)$. Discrete-time interval while acceleration $a_{r}(k)$ happen is symbolized by $T$. The new actual linear velocity of the robot is expressed by $v_{r}(k)$. This research proposes a new approach to result in angular velocity as described as follows:

$$\omega_{cmd}^{ca} \in \{ \arg \max_{d_{i}} (d_{i}) \} \quad (23)$$

Angular velocity $\omega_{cmd}^{ca}$ is chosen from the angle of steering avoidance that has the longest distance, the widest opening, and adding the third criteria that is the closest direction to the target location.

V. SIMULATION RESULTS

For demonstrating the effectiveness of the proposed method, Modified HVO-based modified HSFM has been implemented into a two-wheeled mobile robot to escape from a
pedestrian pursuer and to avoid collisions with pedestrians while navigating in an indoor human environment by using the following scenarios. Robot and pursuer set in a crossing situation. Mobile robot escaped from pursuer by applying the proposed method, modified HSFM based on modified HVO as illustrated in the left part of Fig. 8. After evading the pursuer, the robot followed the reference path until arrived at the target location such as shown in the right part of Fig. 8. The hall that was chosen as an indoor environment had dimensions 15 m × 15 m. The robot had a wheelbase 0.6 m, 0.15 m of the radius of the wheels, and moved with 1 m/s linear velocity when the pure pursuit was executed for path following purposes.

A pedestrian had a body radius of 0.3 m and moved with 1.5 m/s linear velocities when it pursued the robot. The reference path that had to be followed by the robot was shown as the yellow line. The red line represented the robot’s actual path. While the pursuer’s actual path was illustrated by the green line. Based on Fig. 8, the robot was able to evade the pursuer. For comparison purposes, APF and VFH were implemented in the mobile robot. The results of these methods are displayed in Fig. 9. Mobile robot with APF, in the left part of Fig. 9, was caught by the pursuer. The pursuer captured the robot with VFH on the way to the target location as shown in the right part of Fig. 9. The proposed method and two previous methods were tested by the robot to evade the pursuer.

Linear and angular velocity profiles of MHVO-MHSFM, APF, and VFH are displayed respectively in Fig. 10. When the distance between robot and pursuer got closer, robot with MHVO-MHSFM decreased the linear velocity to 0.67 m/s and changed the angular velocity to evade capture from
pursuer. Quality of evading performance in TLI scale of pursuer of compared methods are described in Fig. 11.

Based on these charts, the maximum value of TLI of pursuer of the proposed method, APF, and VFH are 0.19, 1.86, and 2.17 respectively. The TLI of the proposed method has the lowest value compared to other methods. It means that the proposed method is able to guide the robot to escape from the pursuer.

In the second scenario, a pedestrian pursuer (SP), a group of pedestrians (GP), a human-object interaction (ST), and
a group of face-to-face formation (FF) were added to the environment. Mobile robot (MR) has succeeded in evading the pursuer and avoiding static and moving obstacles by using the proposed method such as illustrated in Fig. 12. MR moved with the linear velocity of 1 m/s. GP consisted of five pedestrians that moved with the linear velocity of 1 m/s. FF comprised of three standing persons. The pursuer moved by using higher linear velocity with the value of 1.5 m/s. The robot with APF was caught by the pursuer in the left part of Fig. 13. While the right part of Fig. 13 shows that the robot with VFH collided with a group of pedestrians.

The profile of linear and angular velocities while avoiding obstacles and evading pursuer by using MHVO-MHSFM, APF, and VFH respectively are described in Fig. 14. When the distance between robot and pursuer/obstacles got closer, the robot increased the linear velocity to 2.0 m/s and changed the angular velocity to evade from pursuer. The higher escape velocity in the second scenario was chosen to match the speed of the pursuer and obstacles. The quality of pursuer evasion and collision avoidance of the proposed method, APF, and VFH are presented in Fig. 15. Based on these graphs, the TLI of the proposed method scores 0.3 with respect to the pursuer. While APF scores 6.1 with respect to the pursuer. VFH scores 1.97 with respect to pedestrians.

Based on TLI values of the second scenario, the comfort of the obstacles can be maintained below 0.29 unless the TLI of pursuer. This fact represents that the proposed method is able to maintain the comfort of humans as obstacles. The comfort
of the pursuer can be neglected in order to maintain the safety of the robot.

VI. CONCLUSION
This research has an urgency for the realization of the need for a package delivery mobile robot during the pandemic. Robot that operates in a human environment must be equipped with the ability to maintain physical safety and psychological comfort for humans around the robot. This research investigates a method for a mobile robot to escape from a pedestrian pursuer with non-constant speeds while the robot has to maintain the safety and comfort of humans around.
This study proposes a path-velocity planner for an indoor robot navigation system. For network construction in PRM pre-process phase, a new approach is used by changing a constant distance between nodes with a function to produce varying distance values based on a number of nodes. This study contributes to a collision avoidance velocity planner by modifying HSFM and HVO. Repulsive forces of HSFM have been modified in this study by including pedestrian pursuer as an additional term. Angular velocity of HVO has been altered by selecting the avoidance direction that is closest to the target. From the results of the two scenarios in this research, the average TLI concerning pedestrians is 0.21. This value describes that the proposed method can escape from a pursuer and successfully avoid collisions with obstacles by maintaining the safety and comfort of all pedestrians.

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