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Collision Avoidance of Multi Modal Moving Objects for Mobile Robot Using Hybrid Velocity Obstacles

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Abstract: Mobile robotic systems must have the ability to guarantee safety for operating in close proximity with other moving objects. This paper aims to develop collision avoidance method based on velocity control with respect to several modal of moving objects in the vicinity of wheeled mobile robot. We propose a method that is called Hybrid Velocity Obstacles to avoid multi modal moving objects. This is different from Hybrid Reciprocal Velocity Obstacles approaches in the assumption that objects in the robot's surrounding move with arbitrary speed and directions. The main advantage of the method is in the ability to avoid unknown nonlinear trajectories of moving objects. Collision avoidance is achieved by considering static objects, other mobile robots, and moving objects with nonlinear trajectories. These different characteristics of robot's surrounding objects are calculated to produce avoidance velocity. Our approach is implemented in simulations for a two-wheeled differential-steering mobile robot in the environment contains moving objects. The results show that our approach is capable to avoid collision with multi modal moving objects by maintaining safety with average value 0.17 of Proximity Index. It is envisaged that the proposed method can be very useful for developing transport robot that operate in human environment.

Keywords: Velocity control-based collision avoidance, Multi modal moving objects, Differential-steering wheeled mobile robot, Hybrid velocity obstacles, Nonlinear trajectories.

1. Introduction

The market demand of service robots is projected to grow substantively in the future [1]. Demand on service robots annually has increased greater than 30% [2]. Asia-pacific region represents the biggest and the fastest growth of market zona in service robot selling. Among several type of service robots, logistic and transport robot gains 53% of all demand in service robot. Mobile robot has achieved the highest selling among some categories in service robot. This data establishes the fact that demand on mobile robot research for logistic and transport service still high.

Transport robot system as a part of logistic and transport robot requires improvement in navigation technology, perception and cognition with the highest complexity depends on the working environment. There are five challenges that need to be solved in the next generation of transport robot systems: autonomous navigation, mapping, localization, adaptation in environment with changing structured, and operating in the near-distance with other moving objects. This research focus on the last problem.

Robot shares and collaborates with moving objects in its mobility so that safety of objects in the vicinity must be considered with the highest priority [3]. These requirements need to be fullfilled with respect to the main task of transport robot on delivering goods to target position [4].

There are at least three approaches in collision avoidance research. Artificial Potential Field (APF) [5] has been adopted nature law in physics into collision avoidance strategy. While Vector Field Histogram (VFH) [6] results direction of movement for controlling avoidance motion. In other way, Velocity Obstacles (VO) [7] make use velocity as a means to control safe motion.

A collision avoidance approach should take into account kinematics of robot in order to implement it in real-time robotic system. VFH does not consider kinematics.

Guarantee of safety in general can not be provided by all collision avoidance algorithms except by VO [7]. Hybrid Reciprocal VO (HRVO) [8] that combined VO, and Reciprocal VO (RVO) was proposed by Snape, van den Berg, Guy, and Manocha in 2011 to maintain safety for robot navigation system. This method was adopted in Proactive Social Motion Model (PSMM) [9] was proposed by Truong and Ngo in 2017 to provide human safety. HRVO in both researches assumed that objects move linearly with constant velocity.

In reality, robot workspace may contain of several type of objects that move with nonlinear trajectories between their initial position and target. In this research, these objects are called multi modal moving objects. Hence, previous approaches do not consider nonlinearity in the trajectory of multi modal moving objects.

This paper aims to develop collision avoidance system for handling multi modal moving objects with respect to kinematics of mobile robot by presenting Hybrid Velocity Obstacles. This research contributes in changing HRVO with HVO to avoid multi modal moving obstacles with unknown non-linear trajectories.

Our proposed collision avoidance system uses velocity command selection of linear and angular velocity reference. This approach is the first new feature compare to previous research which based on orientation reference. The second new feature of our approach that different from previous work is avoidance velocity generation with no need to tune the collision avoidance parameter. Unlike previous study, our approach considers more complete moving obstacles that comprise of individual pedestrian, group of pedestrians, and another mobile robot. In this paper, these obstacles are called multi modal moving objects. This new environment configuration is the third new feature of our proposed system. Based on these new features, the advantages of our approach compare to previous approaches are simpler, faster, and more complete in obstacle modality. It is simpler because linear and angular velocities as the output of our proposed method can be directly applied to robot. It is faster because no process for parameter tuning is needed to define avoidance velocity. It is more complete because our system is tested with various real problems. Comparison data about previous works on collision avoidance are summarized in Table 1.

Table 1. Comparison data of previous works on collision avoidance

Method	Modality of Obstacles	Kinematics	Control
APF [5]	Static and moving objects	No	θ
VFH [6]	Static objects	No	θ
VO [7]	Linear path	No	v
HRVO [8]	Constant velocity	Yes	v
PSMM [9]	Constant velocity	Yes	v
Set-based switch guidance [10]	Static objects	Yes	θ
APF/VFH-based [11]	Static and moving objects	Yes	v
VO-based [12]	Static lane edges, and single crossing pedestrian, or another vehicle	Yes	v
HVO, our proposed method	Static objects, moving objects with circular path and cloverleaf path, single walking human, group of walking humans, and another mobile robot with unknown trajectories	Yes	v, ω

The remainder of the paper is organized as follows. The state of the arts in collision avoidance are presented in Section 2. Section 3 reviews multi modal moving objects. Section 4 defines our proposed collision avoidance system used in this research. Section 5 presents our Hybrid Velocity Obstacles for multi modal moving objects. Section 6 evaluates our approach in simulations with two scenarios. Section 7 concludes this paper.

2. Related works

There are several works on collision avoidance in robotics and intelligent vehicles. In the following section, some research achievements of collision avoidance will be described.

An interesting combination of path following, and obstacle avoidance was proposed in [10]. Encircle movement was used to avoid obstacles. Switch control systems was applied to choose orientation reference for path following and obstacle avoidance. Our approach does not consider on orientation reference. In this paper, our proposed collision avoidance system is based on switching between linear and angular velocity reference.

A unique integrated approach for following the desired path and avoiding obstacle that were consists of persons and robots was discussed in [11]. Sigmoid and Gaussian function were introduced to define reference and avoidance curve. Several scenarios were tested with circular path, sine wave, straight line, and by considering static and moving obstacles. Their proposed obstacle avoidance method’s performance had similarities with APF and VFH with properly and opportunely tuned on some parameters of their approach. On the contrary, the collision avoidance technique proposed in our paper does not need to be tuned to define avoidance velocities. Furthermore, in this article the proposed method is tested against static and multi modal moving objects. These moving objects that act as obstacles comprise of circle path, cloverleaf path, and unknown path. Details of multi modal moving objects will be described in the following section.

An obstacle avoidance method based on VO algorithm of outdoor vehicle to avoid collision with crossing pedestrian in [12]. They only considered single crossing pedestrian and other vehicle and was not yet taken account of group of pedestrians. In contrast, in this article moving obstacles are represented by single pedestrian, group of pedestrians, and another wheeled mobile robot.

3. Multi modal moving objects

There are several types of objects that exist in the surrounding of robot. These objects act as obstacles with respect to robot route from initial to target position. The first type of obstacles is static object. The wall, door, table and other non-moveable office things are included in this type. The second type can be found on situation when human interacted with static objects. A person who looked at a painting or read announcements at a wall magazine are two examples of this type of obstacle. The third type are another mobile robot that operate in the same environment as the robot does. The last type is moving obstacles in the form of individual or group of humans. This research uses a group of human consisting of two to five people.

Multi modal moving objects that have been a focus of this research are obstacles that move with nonlinear trajectories. Obstacles in indoor environment such as office, hospital or campus can include some modality of moving humans such as walking, running and also people with disabilities that move by cane, crutches or wheelchair. It is possible that there is another mobile robot operates in the same workspace environment.

Fig. 1 illustrates scenario of collision avoidance of a two wheeled mobile robot in an indoor environment with multi modal moving objects. This mobile robot has to transport goods to certain target position by maintaining safety of each objects exist in its surrounding. The dashed circle at the boundary of each grey objects show the area of a safety standard that must be avoided by robot. Robot-human interaction in this research is designed based on safety standards that are defined in [13].

A walking individual human, a group of walking human, and another mobile robot are three examples of multi modal moving objects used in this scenario illustration. These objects represented by dashed circle that filled with grey colour. Each of multi modal moving objects has centre and radius. The centre of individual object positioned at its centre of gravity. While the centre of group objects was defined at its centre of group interest. Nonlinear trajectories that resulted from the motion of these objects can be categorized into motion with loop and motion without loop. Motion with loop consists of object which moves with a circular path or other path model such as cloverleaf.
Circular path is expressed by:

$$x_o(k) = x_c + r_{path}\cos(k\omega_o T),$$
$$y_o(k) = y_c + r_{path}\sin(k\omega_o T) \tag{1}$$

The centre of circular path is represented by x_c and y_c with radius r_{path}, k = 0, 1, 2, ..., while ω_o

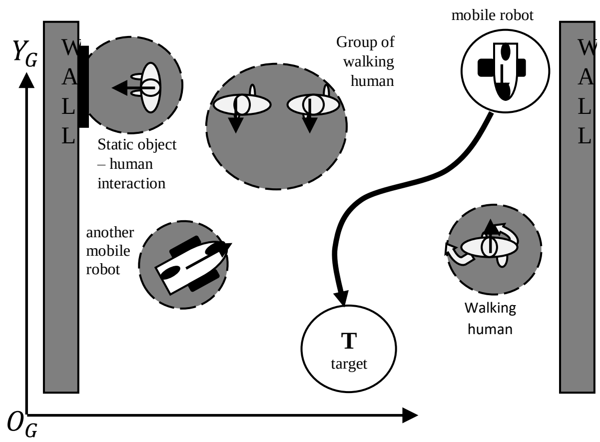

Figure. 1 Interaction space between mobile robot and multi modal moving objects

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expresses object angular velocity and T symbolizes sampling time. Fig. 2 illustrates an object moves with circular path.

Another type of motion with loop can be found on moving object with cloverleaf path such as depicted in Fig. 3. Cloverleaf path is expressed by:

$$x_o(k) = x_c + a\sin(k\omega_o T)\sin(2k\omega_o T),$$
$$y_o(k) = y_c + a\cos(k\omega_o T)\sin(2k\omega_o T) \quad (2)$$

The centre of cloverleaf path is represented by x_c and y_c with amplitude a.

Motion without loop comprises of some nonlinear paths. These paths can be generated by Probabilistic Road Map (PRM) planner [14]. For generating nonlinear path of motion without loop, there are some data that need to be prepared as illustrated in Fig. 4. Environment map of robot workspace is the first input for PRM. Based on this map, some nodes are randomly generated.

These nodes represent important points in real environment that can be interconnected each other to form network. Number of nodes and distance between interconnected nodes can be adjusted to arrange this network. Nonlinear path as a collection of interrelated nodes $[x_o(k), y_o(k)]$ from start to goal point of this network can be generated by supplying initial position and target position.

Fig. 5 demonstrates the ability of PRM planner to generate random nonlinear path of motion without loop. For the same pairs of initial and target positions, there are some different paths can be resulted when this process run in separated time.

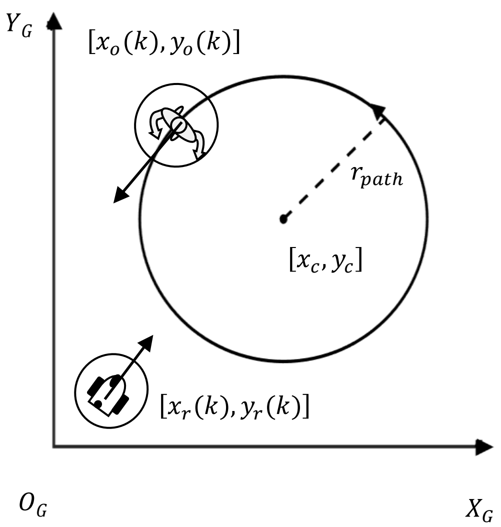

Figure. 2 Moving object with circular path

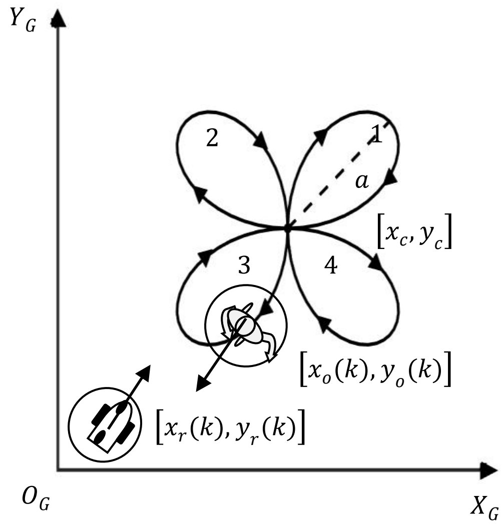

Figure. 3 Moving object with cloverleaf path

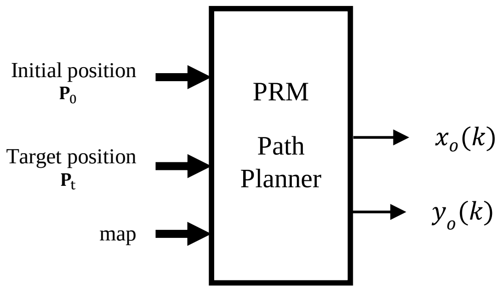

Figure. 4 PRM is used to generate nonlinear path of motion without loop

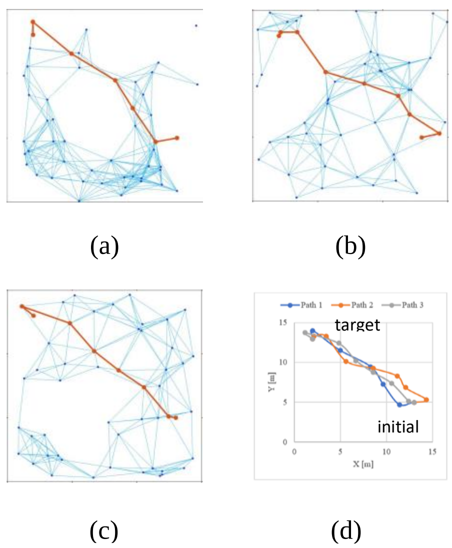

Figure. 5 Three different nonlinear paths of motion without loop that are generated by PRM path planner in separated time with the same initial and target position: (a) trial 1, (b) trial 2, (c) trial 3, and (d) all trial

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The first trial to generate nonlinear path is illustrated in Fig. 5 (a) with given initial and target position. By using the same initial and target position, a different path of the second trial is resulted as depicted in Fig. 5 (b). The third trial with the same pair positions to produce diverse path is shown in Fig. 5 (c). For comparing results of three trials, these unique nonlinear paths are presented in Fig. 5 (d).

4. Proposed collision avoidance system

Collision avoidance system is designed by considering kinematics of mobile robot with respect to safety distance of objects in the vicinity of robot.

4.1 Structure of HVO-based collision avoidance system

Structure of collision-free trajectory tracking with respect to kinematics of two wheeled differential-steering mobile robot is displayed in Fig. 6. Definition of the mathematical symbols are described in Table 2.

Desired mobile robot pose that is used as reference or set point can be presented as $\mathbf{P}_d = [x_d \quad y_d \quad \psi_d]^T$. The collection of desired robot poses that form waypoints from its initial to target pose has to be tracked by mobile robot.

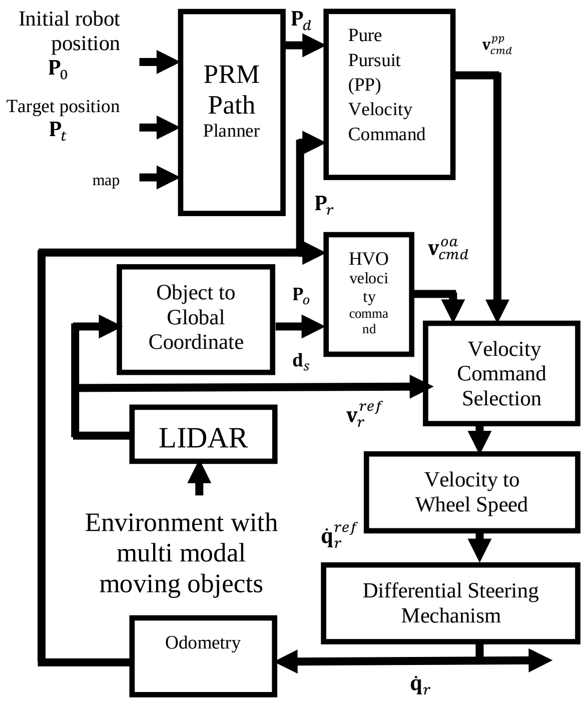

Figure. 6 Structure of HVO-based collision avoidance system in trajectory tracking of two-wheeled differential-steering mobile robot

Table 2. Notation list of HVO-based collision avoidance

Symbol	Description
$\mathbf{P}_d$	Desired mobile robot pose
$\mathbf{P}_0$	Initial robot pose
$\mathbf{P}_t$	Target pose
$\mathbf{P}_r$	Actual robot pose
$[x_r \quad y_r]^T$	Robot position
ψ_r	Robot orientation
$\dot{\mathbf{P}}_r$	Configuration transition of mobile robot pose
$\dot{\mathbf{q}}_r$	Wheel speed
$\dot{\theta}^R{}_r$	Wheel speed of right motor
$\dot{\theta}^L{}_r$	Wheel speed of left motor
d	Diameter of robot
$2r$	Diameter of wheel
$\mathbf{v}_r$	Linear and angular velocity of mobile robot
v_r	Linear velocity
ω_r	Angular velocity
$\mathbf{P}_o$	Multi model moving Object pose
$\mathbf{d}_s$	Distances that are sensed by LIDAR
$\mathbf{v}_{cmd}^{pp}$	Velocity command for path tracking purposes
$\mathbf{v}_{cmd}^{oa}$	Velocity command for obstacle avoidance purposes
$\mathbf{v}_r^{ref}$	Velocity reference
$\dot{\mathbf{q}}_r^{ref}$	Wheel speed reference
PI	Proximity index to evaluate safety distance between robot and object
σ	The closest distance to object
d_{r-o}	Actual distance to object
VO	The set of velocity that will result collision with static object and moving object with constant velocity
RVO	The set of velocity that will result collision with another mobile robot
NLVO	The set of velocity that will result collision with moving object with nonlinear trajectory
HVO	The set of velocity that will result collision with multi modal moving objects
$V_{safe_\Omega} = \overline{HVO_\Omega}$	The set of velocity that will avoid collision with multi modal moving objects

Probabilistic Roadmap (PRM) path planner is used to generate desired pose $\mathbf{P}_d$. Actual mobile robot pose is expressed as $\mathbf{P}_r = [x_r \quad y_r \quad \psi_r]^T$. Obstacle's pose $\mathbf{P}_o$ and robot pose $\mathbf{P}_r$ act as input for HVO.

Obstacles comprise of multi modal moving objects as described in the previous section. These objects consist of human or another mobile robot. Standard of safety distance and kinematics model of mobile robot are presented in the next sub sections.

4.2 Standard of safety distance

Multi modal moving objects that exist in the vicinity of mobile robot represent obstacles which their states are defined as $\mathbf{P}_o = [x_o \quad y_o \quad \psi_o]^T$ with respect to the outer border of each objects. Violation in certain distance will threaten their safety.

This research proposes Proximity Index (*PI*) to evaluate the safety distance for each object existing in the environment as follows:

$$PI = \frac{\sigma}{d_{r-o}} \tag{3}$$

This evaluation index comparing between the closest safe distance to objects σ and actual distance of each object to mobile robot d_{r-o}.
The closest distance σ is defined at 0.35 m. This parameter is chosen to have value according to the size of robot. While actual distance between mobile robot and objects d_{r-o} is calculated using Euclidean distance. A standard safety line is defined at 0.5 m or equal with 0.7 of *PI*. This value is selected based on safety standards as reviewed in [13]. The smaller *PI* value means the safer condition is. Object safety is threatened when *PI* value greater than 0.7.

4.3 Kinematics model

In this research, mobile robot is defined as a two wheeled differential-steering robot that has to deliver a task from its initial to target position. The posture of robot is illustrated in Fig. 7 in the Cartesian coordinate system.

With d represents width of robot, C as the centre of left-right wheel axis, G states centre of mass and point representation of robot in the X-Y coordinate. Diameter of wheels are represented by $2r$. Both wheels are connected to left and right motors. There are two castor free wheels set to give stability at the front and the rear part of robot body.

Mobile robot state and configuration transition are represented as follows:

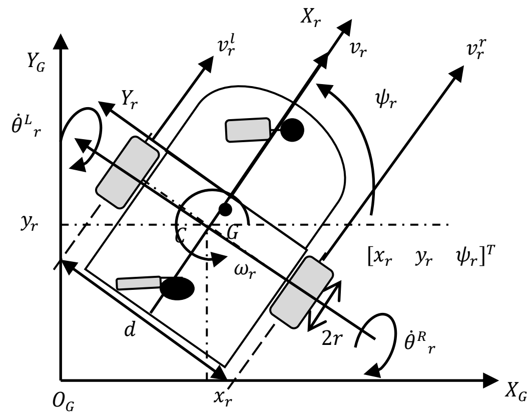

Figure. 7 Configuration of a two wheeled differential-steering mobile robot

$$\mathbf{P}_r = [x_r, \quad y_r, \quad \psi_r]^T, \tag{4}$$

$$\dot{\mathbf{P}}_r = [\dot{x}_r, \quad \dot{y}_r, \quad \dot{\psi}_r]^T \tag{5}$$

where robot position is represented by x_r and y_r and orientation is denoted by ψ_r.

Configuration transition of robot from body to global coordinate is presented as follows:

$$\begin{bmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\psi}_r \end{bmatrix} = \begin{bmatrix} \cos\psi_r & 0 \\ \sin\psi_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} \tag{6}$$

where mobile robot velocity $\mathbf{v}_r = [v_r \quad \omega_r]^T$ triggers the change in its pose in global coordinate $\dot{\mathbf{P}}_r = [\dot{x}_r, \quad \dot{y}_r, \quad \dot{\psi}_r]^T$. Forward kinematics model of a two wheeled differential-steering mobile robot is represented as follows:

$$\begin{bmatrix} v_r \\ \omega_r \end{bmatrix} = r \begin{bmatrix} 1/2 & 1/2 \\ 1/d & -1/d \end{bmatrix} \begin{bmatrix} \dot{\theta}^R{}_r \\ \dot{\theta}^L{}_r \end{bmatrix} \tag{7}$$

where wheel speeds $\dot{\mathbf{q}}_r = [\dot{\theta}^R{}_r \quad \dot{\theta}^L{}_r]^T$ are used to steer mobile robot by affecting its linear and angular velocity $\mathbf{v}_r$.

In other way, inverse kinematics can be used to obtain wheel speeds $\dot{\mathbf{q}}_r$ from its linear and angular velocity $\mathbf{v}_r$ as defined as follows:

$$\begin{bmatrix} \dot{\theta}^R{}_r \\ \dot{\theta}^L{}_r \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & d/2 \\ 1 & -d/2 \end{bmatrix} \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} \tag{8}$$

Pose of robot can be updated by applying Eulerian integration to velocity as follows:

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$$\begin{bmatrix} x_r(k+1) \\ y_r(k+1) \\ \psi_r(k+1) \end{bmatrix} = \begin{bmatrix} x_r(k) \\ y_r(k) \\ \psi_r(k) \end{bmatrix} + kT \begin{bmatrix} \dot{x}_r(k) \\ \dot{y}_r(k) \\ \dot{\psi}_r(k) \end{bmatrix} \quad (9)$$

4.4 LIDAR sensor

Mobile robot was equipped with LIDAR (light detection and ranging) scan that has max sensing range of 20 m. This sensor's scan angles set to 8 points in the surrounding body of robot as depicted in Fig. 8. Each scan angle to other had distance of 45°. It produces ranges that measured from the sensor to obstacles in the environment at specific angles.

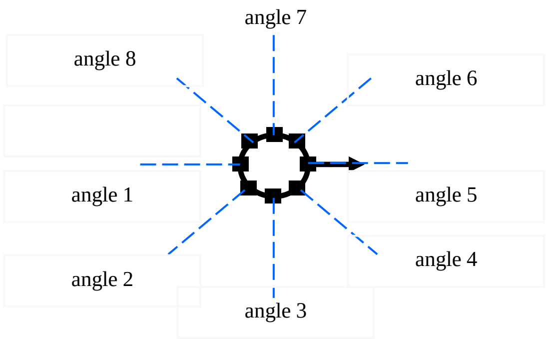

Fig. 8. Scan angles configuration of LIDAR sensor on mobile robot

4.5 Velocity command selection

Based on lidar scan at objects in the surrounding of robot, velocity command selection block decides to activate one of two methods for generating appropriate velocity by using Algorithm-1.

4.6 Pure pursuit velocity command

Pure Pursuit (PP) acts as a tracking method for path following purposes. It computes the linear and angular velocity commands that move the robot from its current position to reach some look-ahead point in front of the robot [15].

PP can be used by specifying waypoints, the desired linear and maximum angular velocities. Given the desired pose and actual pose of the robot as input, the linear and angular velocities commands of path tracking $\mathbf{v}_{cmd}^{pp} = [v_{cmd}^{pp} \quad \omega_{cmd}^{pp}]^T$ for mobile robot can be calculated.

4.7 HVO velocity command

HVO produces output in the form of velocity $\mathbf{v}_{cmd}^{oa} = [v_{cmd}^{oa} \quad \omega_{cmd}^{oa}]^T$ for obstacle avoidance purposes. This velocity command is resulted by implementing HVO method given some input that consist of obstacle's pose $\mathbf{P}_o$ and robot pose $\mathbf{P}_r$. Details of HVO is described in Section 4. Furthermore, $\dot{\mathbf{q}}_r$ is used for rotating both of robot wheels in order to make transition of configuration $\dot{\mathbf{P}}_r$. An integrator (9) is utilized for achieving robot position $\mathbf{P}_r$ from $\dot{\mathbf{P}}_r$.

5. Hybrid velocity obstacles

The desired velocity to reach target is the collision-free of robot velocity. Set of mobile robot velocity v_r in velocity space $\mathcal{V}$ that will cause collision between mobile robot MR and an obstacle O in each time point t in the future between initial time t_0 dan Time Horizon (TH) is as follows:

$$VO = \bigcup_{t=t_0}^{TH} \{v_r \in \mathcal{V} | \exists t \in [t_0, TH], MR(t) \cap O(t) \neq \emptyset\} \quad (10)$$

Set of robot velocity relative to obstacles is defined in Collision Cone (CC) as $MR(t) \cap O(t) \neq \emptyset$. VO consists of some steps as written in Table 3.

Algorithm-1 Velocity Command Selection
1: if lidar scan ranges < alert distance
2: activate HVO
3: else
4: activate Pure Pursuit

Table 3. Procedure to achieve VO

1.	Define robot as a point and enlarge obstacle circle with respect to robot radius.
2.	Define Relative Collision Cone (RCC) with apex in robot position with both tangent line perpendicular to obstacle circle.
3.	Shifting RCC with respect to obstacle velocity resulting Absolute Collision Cone (ACC).
4.	Define limitation of dynamics of robot acceleration as $\mathcal{V}$.
5.	Determine intersection area between $\mathcal{V}$ and ACC as VO.
6.	Produce V_{safe} by performing subtractions between $\mathcal{V}$ and VO.

Velocity space $\mathcal{V}$ consists of velocities that can be reached by maximum and minimum acceleration of robot MR.

In the case of avoiding obstacle O has similar avoidance characteristics with mobile robot MR, RVO is formulated as follows:

$$RVO_O^r(v_O, v_r, \alpha_O^r) = \bigcup_{t=t_0}^{TH} \left\{ v'_r \middle| \tfrac{1}{\alpha_O^r} v'_r + \left(1 - \tfrac{1}{\alpha_O^r}\right) v_r \in VO_O^r(v_O) \right\} \quad (11)$$

Moving human as individual or group is obstacle that has nonlinear characteristics with uncertain direction and speed.

This research replaces HRVO with NLVO that more suitable for nonlinear moving obstacles. NLVO is generalization of VO in that direction and magnitude of obstacle velocity, v_O , not always the same in each future time as stated as follows:

$$NLVO = VO \;\Leftrightarrow \exists (t_1, t_2) \in [t_0, TH]^2 | t_1 \neq t_2 \; and \; v_O(t_1) \neq v_O(t_2) \quad (12)$$

This research proposes contribution in the form of merging NLVO (12), RVO (11) dan VO (10) to become HVO to overcome several modes of obstacle objects around the robot stated as follows:

$$HVO = \bigcup_{o \in O} VO_{r|o} \cup \bigcup_{ro \in R} RVO_{r|ro} \cup \bigcup_{h \in P} NLVO_{r|h} \quad (13)$$

Collision-free mobile robot velocity v_r represents velocity that is outside HVO set. This velocity must be chosen from velocity space $\mathcal{V}$ with respect to limitation of robot dynamics for single obstacle and for multiple obstacles as follows:

$$V_{safe} = \overline{HVO} = \{v_r \in \mathcal{V} | v_r \notin HVO\} \quad (14)$$

$$V_{safe_\Omega} = \overline{HVO_\Omega} = \{v_r \in \mathcal{V} | v_r \notin HVO_\Omega\} \quad (15)$$

Set of collision-free of robot velocity V_{safe_Ω} can be calculated by using HVO (13). Desired velocity $v_r^{des} \in V_{safe_\Omega}$ is selected from collision-free robot velocity set. This velocity is defined as obstacle avoidance velocity command $v_{cmd}^{oa} = v_r^{des}$. Fig. 9 shows block diagram of our proposed HVO-based collision avoidance.

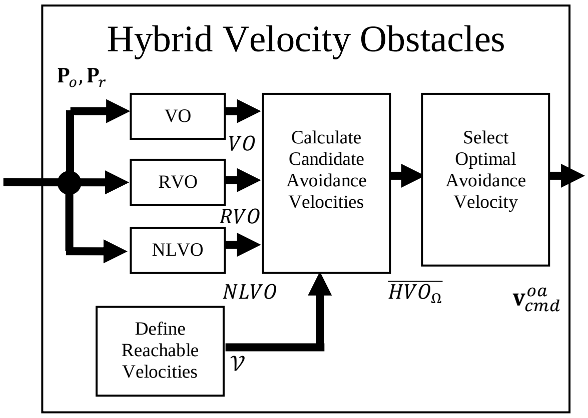

Figure. 9 Hybrid velocity obstacles-based collision avoidance

6. Simulations and results

For testing the ability of proposed method to handle several types of objects, the following two scenarios are used. In general, mobile robot is commanded to move from initial pose to target pose. This simulation uses a target that occupies a fixed location. Mobile robot must arrive at target location safely by avoiding some objects that move in between mobile robot initial and target pose. These simulations used multi modal moving objects as explained in Section 2.

The diameter of mobile robot body was set to 0.6 m. While the radii of mobile robot wheels set to 0.15 m. The desired linear velocity of the robot was 1.0 m/s. The single person agent had diameter of 0.6 m. The speed of single walking person was set to 0.5 m/s. The group of human consists of two peoples set to have diameter of 1.8 m. This group had speed of 0.3 m/s. Another wheeled differential-steering mobile robot that acts as obstacle had diameter of 0.6 m. The radii of obstacle-robot wheels set to 0.15m. The desired linear velocity of obstacle-robot was 0.5 m/s.

The first scenario is aimed to examine the ability of mobile robot to avoid multi modal moving objects with loop motion. Two circular paths with different radius and one clover leaf path are chosen to represent loop motion scenario. These loop motion paths are generated based on Eqs. (1) and (2). Mobile robot and target were arranged in opposite direction. The second scenario was implemented to evaluate the performance of mobile robot to avoid multi-modal moving objects with unknown trajectories. These trajectories of motion without loop are generated by using PRM. All agents were arranged in configuration such as illustrated in Fig. 1. For testing the effectiveness of our proposed collision avoidance, HVO is compared to HRVO, APF, VFH, and VO from previous works.

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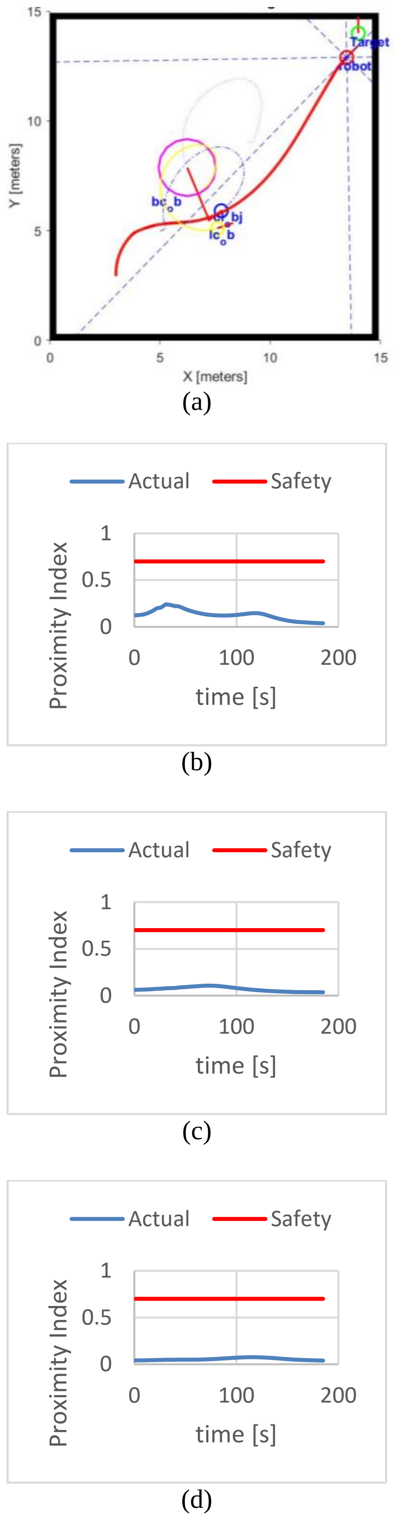

Figure. 10 Mobile robot avoids multi modal moving objects with loop motion by using HVO in Scenario 1: (a) trajectory of mobile robot from initial to target position, (b) *PI* of HVO while avoiding moving object with cloverleaf path (obstacle 1), (c) *PI* of HVO while avoiding moving object with little circle path (obstacle 2), and (d) *PI* of HVO while avoiding moving object with big circle path (obstacle 3)

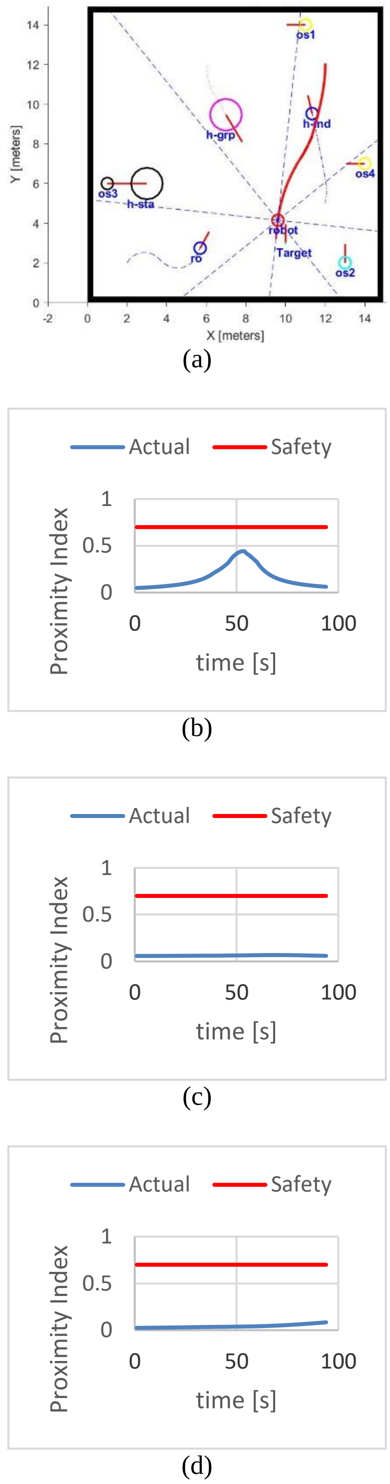

Figure. 11 Mobile robot avoids multi modal moving objects with unknown trajectories by using HVO in Scenario 2: (a) trajectory of mobile robot from initial to target position, (b) *PI* of HVO while avoiding obstacle 1 (moving object which represents single walking human), (c) *PI* of HVO while avoiding moving object which represents group of walking human (obstacle 2), and (d) *PI* of HVO while avoiding moving object which represents another mobile robot (obstacle 3)

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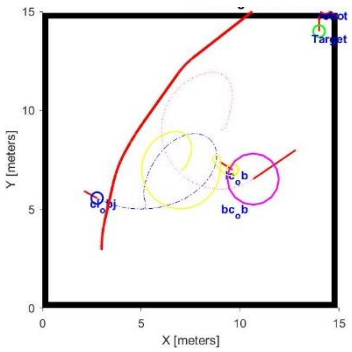

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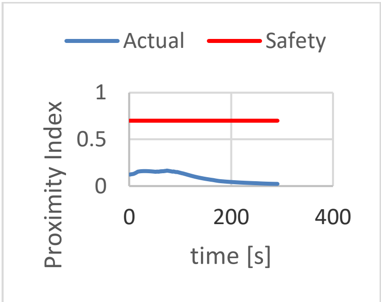

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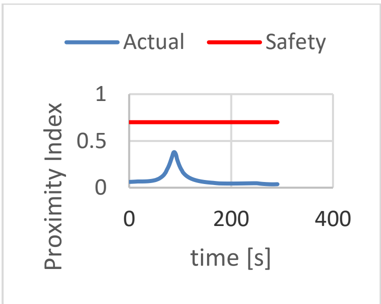

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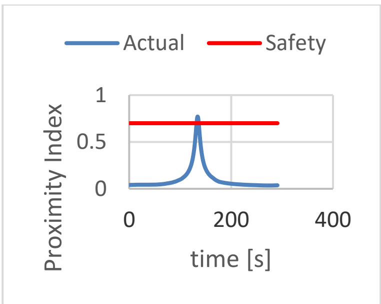
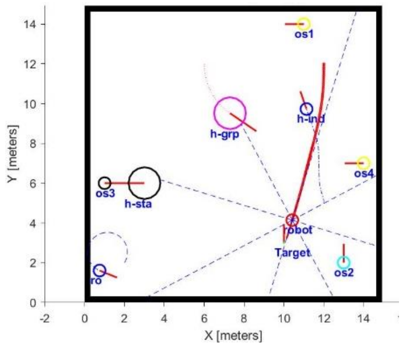


(d)

Figure. 12 Mobile robot avoids multi modal moving objects with loop motion by using HRVO in Scenario 1: (a) trajectory of mobile robot from initial to target position, (b) *PI* of HRVO while avoiding obstacle 1 (moving object with cloverleaf path), (c) *PI* of HRVO while avoiding obstacle 2 (moving object with little circle path), and (d) *PI* of HRVO while avoiding obstacle 3 (moving object with big circle path)



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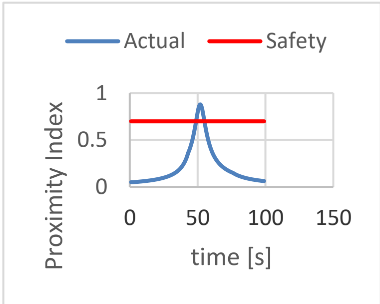

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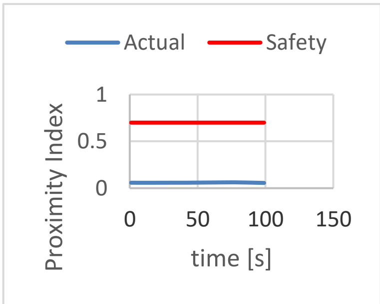

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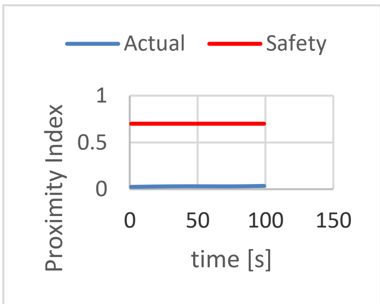

(d)

Figure. 13 Mobile robot avoids multi modal moving objects with unknown trajectories by using HRVO in Scenario 2: (a) trajectory of mobile robot from initial to target position, (b) *PI* of HRVO while avoiding obstacle 1 (moving object which represents single walking human), (c) *PI* of HRVO while avoiding obstacle 2 (moving object which represents group of walking human), and (d) *PI* of HRVO while avoiding obstacle 3 (moving object which represents another mobile robot)

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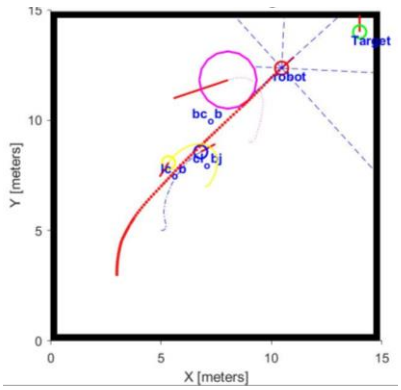

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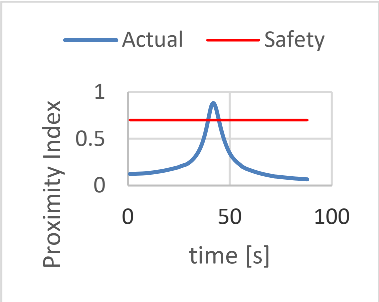

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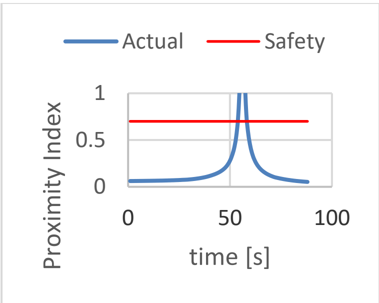

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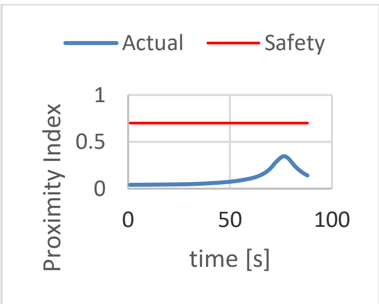
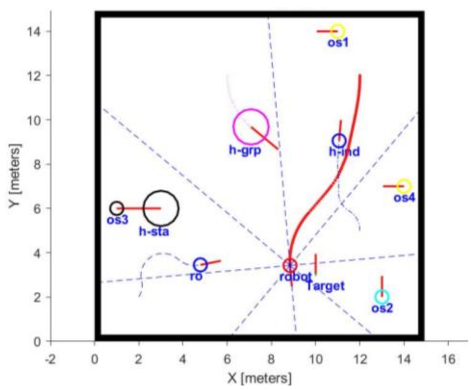


(d)

Figure. 14 Mobile robot avoids multi modal moving objects with loop motion by using APF in Scenario 1: (a) trajectory of mobile robot from initial to target position, (b) *PI* of APF while avoiding moving object with cloverleaf path (obstacle 1), (c) *PI* of APF while avoiding moving object with little circle path (obstacle 2), and (d) *PI* of APF while avoiding moving object with big circle path (obstacle 3)



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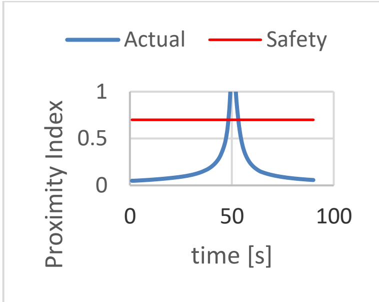

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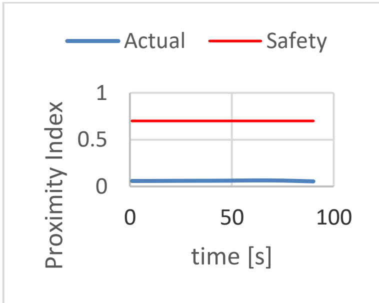

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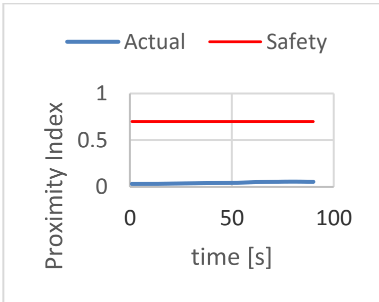

(d)

Figure. 15 Mobile robot avoids multi modal moving objects with unknown trajectories by using APF in Scenario 2: (a) trajectory of mobile robot from initial to target position, (b) *PI* of APF while avoiding obstacle 1 (moving object which represents single walking human), (c) *PI* of APF while avoiding obstacle 2 (moving object which represents group of walking human), and (d) *PI* of APF while avoiding obstacle 3 (moving object which represents another mobile robot)

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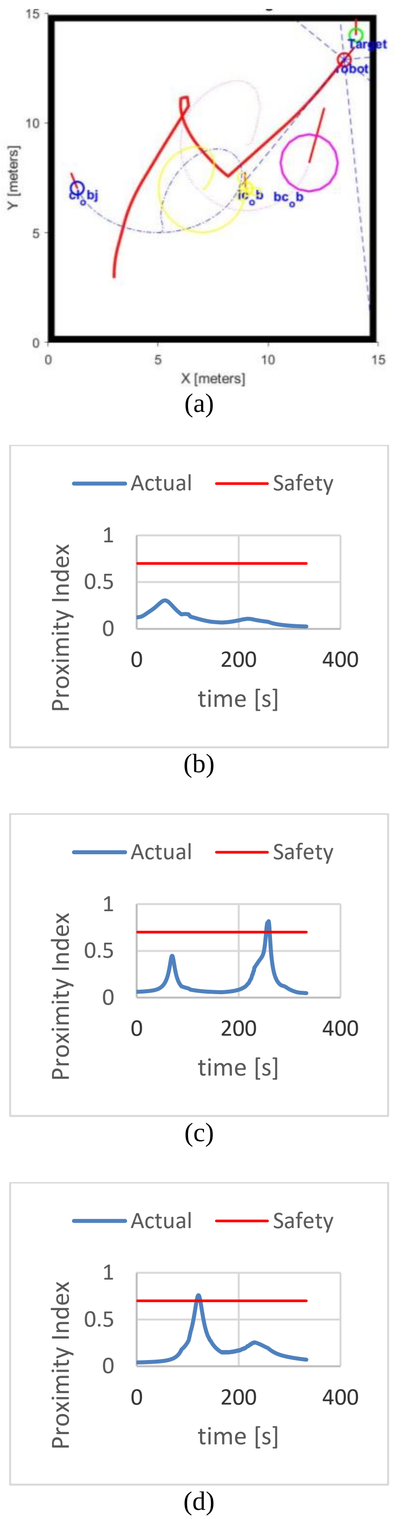

Figure. 16 Mobile robot avoids multi modal moving objects with loop motion by using VFH in Scenario 1: (a) trajectory of mobile robot from initial to target position, (b) *PI* of VFH while avoiding moving object with cloverleaf path (obstacle 1), (c) *PI* of VFH while avoiding moving object with little circle path (obstacle 2), and (d) *PI* of VFH while avoiding moving object with big circle path (obstacle 3)

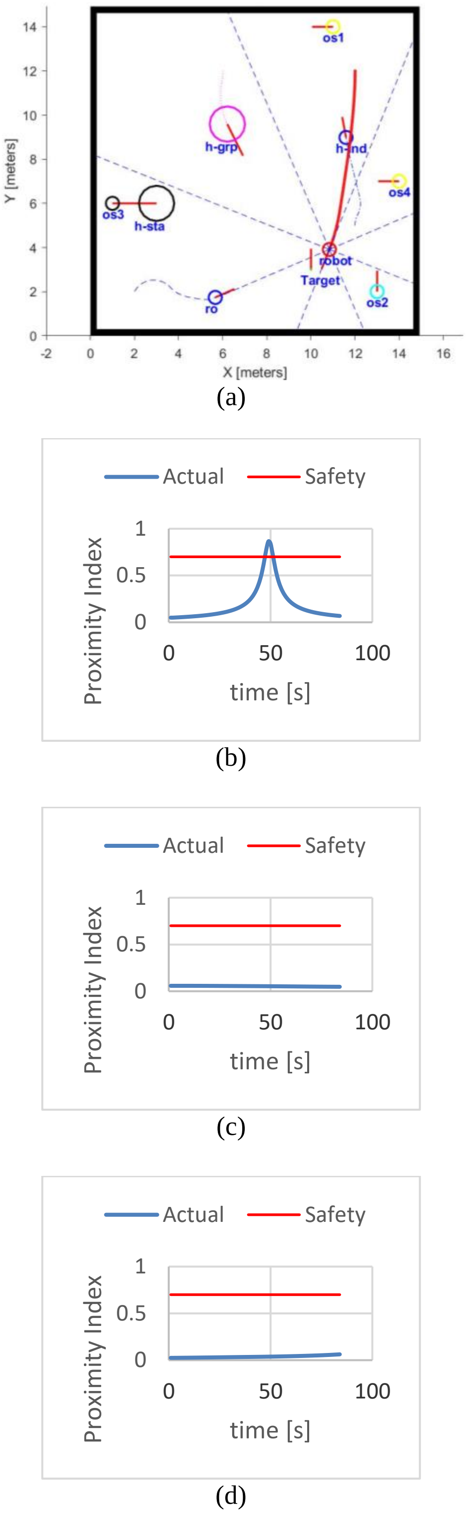

Figure. 17 Mobile robot avoids multi modal moving objects with unknown trajectories by using VFH in Scenario 2: (a) trajectory of mobile robot from initial to target position, (b) *PI* of VFH while avoiding moving object with cloverleaf path (obstacle 1), (c) *PI* of VFH while avoiding moving object with little circle path (obstacle 2), and (d) *PI* of VFH while avoiding moving object with big circle path (obstacle 3)

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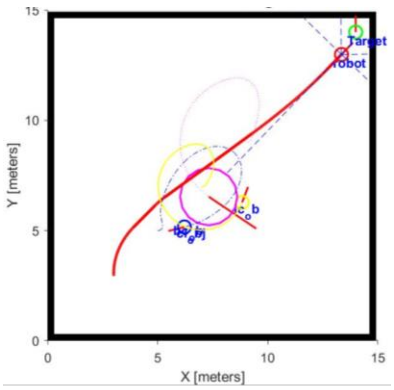

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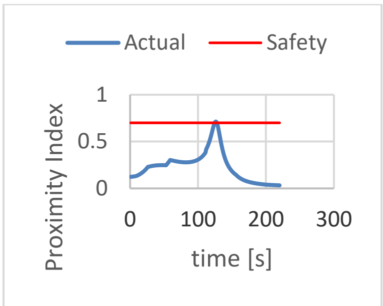

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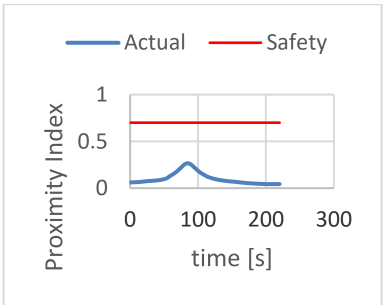

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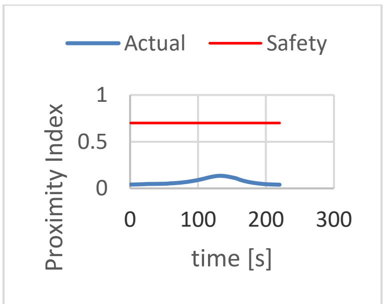
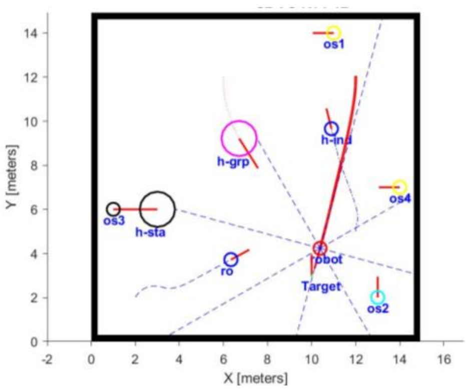


(d)

Figure. 18 Mobile robot avoids multi modal moving objects with loop motion by using VO in Scenario 1: (a) trajectory of mobile robot from initial to target position, (b) *PI* of VO while avoiding moving object with cloverleaf path (obstacle 1), (c) *PI* of VO while avoiding moving object with little circle path (obstacle 2), and (d) *PI* of VO while avoiding moving object with big circle path (obstacle 3)



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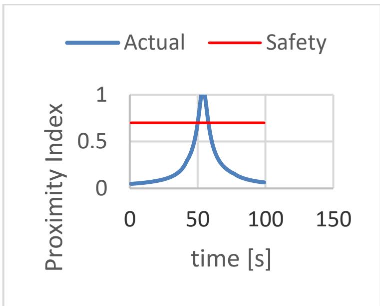

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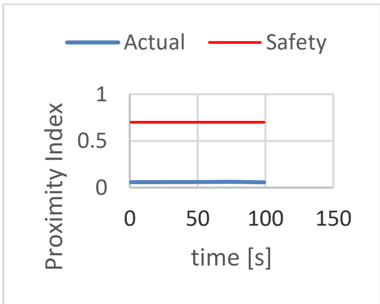

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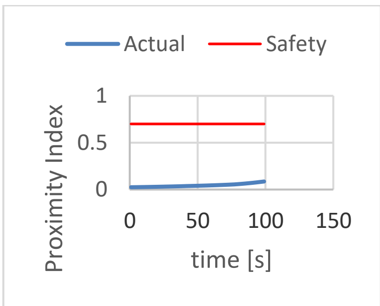

(d)

Figure. 19 Mobile robot avoids multi modal moving objects with unknown trajectories by using VO in Scenario 2: (a) trajectory of mobile robot from initial to target position, (b) *PI* of VO while avoiding obstacle 1 (moving object which represents single walking human), (c) *PI* of VO while avoiding obstacle 2 (moving object which represents group of walking human), and (d) *PI* of VO while avoiding obstacle 3 (moving object which represents another mobile robot)

Table 4. Performance evaluation of HVO-based collision avoidance compare to APF, VFH, VO, and HRVO

Simulation	**Number of Obstacles**	**Modality of Moving Objects**	**Proximity Index (*PI*)**				
			APF	**VFH**	**VO**	**HRVO**	**HVO**
Scenario 1	3	▪ 1st Moving object with cloverleaf path, ▪ 2nd Moving object with little circle path, ▪ 3rd Moving object with big circle path.	1.14	0.63	0.37	0.44	0.14
Scenario 2	3	▪ 1st Moving object represents single walking human, ▪ 2nd Moving object represents group of walking humans, ▪ 3rd Moving object represents another mobile robot.	0.51	0.33	0.4	0.33	0.2
		Average of *PI*	0.83	0.48	0.39	0.39	0.17

The snapshots of these simulations and performance evaluations of HVO are depicted in top part of Fig. 10 and Fig. 11. Safety assessment of HVO is reported in charts below snapshots. From these assessments, HVO is able to avoid all multi modal moving objects in both scenarios. From snapshots and performance evaluations that are showed in Fig. 12 and Fig. 13, HRVO collides with moving object with big circle path in scenario 1 and collides with single walking human in scenario 2. As depicted in Fig. 14 and Fig. 15, APF crashes with moving objects with cloverleaf, little circle path, and single walking human respectively. Snapshots and evaluation charts of VFH are displayed in Fig. 16 and Fig. 17. VFH hits both objects that move with little circle path, big circle path, and unknown path. While VO strikes moving objects with cloverleaf path and single walking human with unknown trajectory as reported in Fig. 18, and Fig. 19. Table 4 records performance evaluations of HVO compare to HRVO, APF, VFH, and VO in this research.

7. Conclusion

The aim of this study was to develop HVO for avoiding multi modal moving objects with respect to kinematics of mobile robot. The originality of this work is based on the combination of VO, RVO, and NLVO to avoid multi modal moving objects in the vicinity of robot. This work also proposes the use of *PI* index to measure safety of objects.

Our proposed HVO has been tested to avoid multi modal moving objects. There are two scenarios with different configuration of mobile robot, target and objects have been conducted in simulations.

From our simulations, HVO shows the ability to maintain safety of objects in mobile robot's surrounding. *PI* has been used as measurement to evaluate HVO performance. Based on simulation results, HVO can guarantee safety of all objects in these two scenarios with value below 0.7 of *PI* index. It means that multi modal moving objects are guaranteed to be safe. For future research, we will deploy HVO into our transport mobile robot navigation system in order to operate safely in human environment.

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