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Obstacle's Velocity-Informed Ring Univector Field Method for Mobile Robot Navigation in Dynamic Environments with Moving Obstacles in Robot Soccer Game

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Abstract

Most existing approaches for dynamic obstacle avoidance in mobile robot navigation are built upon static obstacle avoidance methods combined with optimization algorithms. While such hybrid approaches can achieve acceptable performance in some scenarios, they lack a fundamental understanding of dynamic environments, leading to limitations in speed, adaptability, and real-time responsiveness.

To address this gap, this paper proposes an improved **Ring Univector Field (RUF)** method for mobile robot navigation in dynamic environments with moving obstacles, specifically targeting robot soccer game scenarios. Rather than simply extending static methods, we focus on the foundational problem of path generation for dynamic obstacle avoidance. To enhance the conventional RUF method, we define several new variables that reflect the spatial relationships among the robot, obstacles, and target point. A novel repulsive vector generation formula is introduced to enable successful target reaching while avoiding dynamic obstacles in arbitrary environments. Unlike previous approaches, the proposed method incorporates the obstacle's velocity vector and relative influence factors directly into the avoidance decision, prioritizing high speed and proactive response.

Simulation results demonstrate that the proposed **Obstacle's Velocity-Informed RUF (OV-RUF)** method allows the mobile robot to adaptively adjust its avoidance path in real time as obstacle positions change, significantly improving success rate and reducing collisions compared to conventional methods, thereby reaching the target point effectively even in highly dynamic conditions.

Keywords: Ring Univector Field; Soccer Robot; Potential Field; Dynamic Obstacle Avoidance; Mobile Robot Navigation

1. Introduction

Mobile robot navigation in dynamic environments with moving obstacles remains a fundamental challenge in robotics [1], [2]. Unlike static settings, real-world applications such as autonomous driving, warehouse logistics, and robot soccer require robots to avoid moving obstacles while reaching a target in real time [3], [4]. Among these, robot soccer, particularly the RoboCup league, serves as an ideal benchmark because it involves multiple robots, unpredictable opponent movements, and strict time constraints [5], [6].

A widely adopted approach for local navigation is the **artificial potential field (APF)** method [1], where the target generates an attractive force and obstacles generate repulsive forces. However, classical APF suffers from local minima, oscillations, and the "goal unreachable with obstacles nearby" problem [8]. To overcome these issues, the **Univector**

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Field (UF) and its variant **Ring Univector Field (RUF)** were introduced, providing a smooth vector field that guides the robot without local minima [9].

A notable implementation for robot soccer is the *fuzzy ring univector field* (FRUF) method [7], which combines fuzzy logic with RUF to handle complex soccer situations. Another line of work, the velocity obstacle (VO) method [10], explicitly accounts for moving obstacles' trajectories but often requires global re-planning and may suffer from local minima. Nevertheless, the FRUF method does not explicitly incorporate obstacle velocity into the avoidance decision. In dynamic environments, an obstacle moving toward the robot's path poses a much higher risk than a stationary one, and ignoring velocity can lead to collisions or inefficient detours.

To address this gap, this paper proposes the **Obstacle's Velocity-Informed Ring Univector Field (OV-RUF)** method. The main contributions are:

- **New variables** that capture the robot–obstacle–goal relationship: $\overrightarrow{OV}$ (relative unit vector toward goal while avoiding obstacle), γ (angular deviation from the direct path), μ (risk factor based on distance ratio), and the dot product $\overrightarrow{RV} \cdot \overrightarrow{V_O}$ (to detect whether obstacle motion interferes with the robot's avoidance).
- A **velocity-informed repulsive vector formulation** with five distinct cases (①–⑤), which adjusts the avoidance behavior based on robot–obstacle distance, γ, and the sign of $\overrightarrow{RV} \cdot \overrightarrow{V_O}$.
- **Real-time path adaptation** that continuously modifies the avoidance trajectory as obstacle positions and velocities change.

Simulation results, presented in later sections, demonstrate that the proposed OV-RUF significantly outperforms conventional RUF and FRUF methods in terms of success rate, path smoothness, and collision avoidance in dynamic robot soccer environments.

2. Parameters in Ring Univector Field Method

Before presenting the proposed Obstacle's Velocity-Informed Ring Univector Field (OV-RUF) method, it is necessary to briefly review the basic parameters used in the conventional Ring Univector Field (RUF) approach [7]. These parameters form the foundation upon which the new variables and the enhanced avoidance vector formula are developed.

The following parameters are defined in the RUF framework:

- $\vec{A}$ **– Attractive vector**
  A unit vector pointing from the robot to the target point. It represents the desired direction of motion when no obstacles are present.
- $\overrightarrow{HO}$ **– Relative obstacle vector**
  A vector from the robot to the obstacle, indicating both the direction and distance of the obstacle relative to the robot.
- $\overrightarrow{RV}$ **– Repulsive vector (basic form)**
  A unit vector representing the direction in which the robot should move to avoid an obstacle. In the conventional RUF method, $\overrightarrow{RV}$ is typically perpendicular to $\vec{A}$ or derived from the geometry of the ring field. It serves as the repulsive component in the avoidance behavior.
- $\overrightarrow{RV'}$ **– Modified repulsive vector**
  A variant of $\overrightarrow{RV}$ used when the obstacle's motion interferes with the robot's avoidance. The specific modification depends on the relative velocity and geometry, and it is employed in cases (2) and (4) of the proposed OV-RUF method.
- r **and** R **– Avoidance zone thresholds**
  Two distance thresholds defining the obstacle influence region:
  - r: the **inner danger radius** (immediate collision risk).
  - R: the **outer avoidance radius** (influence zone for proactive avoidance).
    When $|\overrightarrow{HO}| \leq r$, the robot is in imminent danger. When $r < |\overrightarrow{HO}| \leq R$, the robot is within the reactive avoidance region. If $|\overrightarrow{HO}| > R$, the obstacle is ignored unless other conditions apply.
- $\overrightarrow{V_O}$ **– Obstacle velocity vector**
  The velocity of the moving obstacle. Its interaction with $\overrightarrow{RV}$ (via dot product $\overrightarrow{RV} \cdot \overrightarrow{V_O}$) determines whether the obstacle's motion helps or hinders the robot's avoidance.

These parameters are illustrated schematically in Fig. 1 (refer to the original RUF literature). Based on these definitions, Section 3 introduces additional variables ($\overrightarrow{OV}$, γ, μ, and the dot product condition), and Section 4 presents the complete OV-RUF avoidance vector formulation.

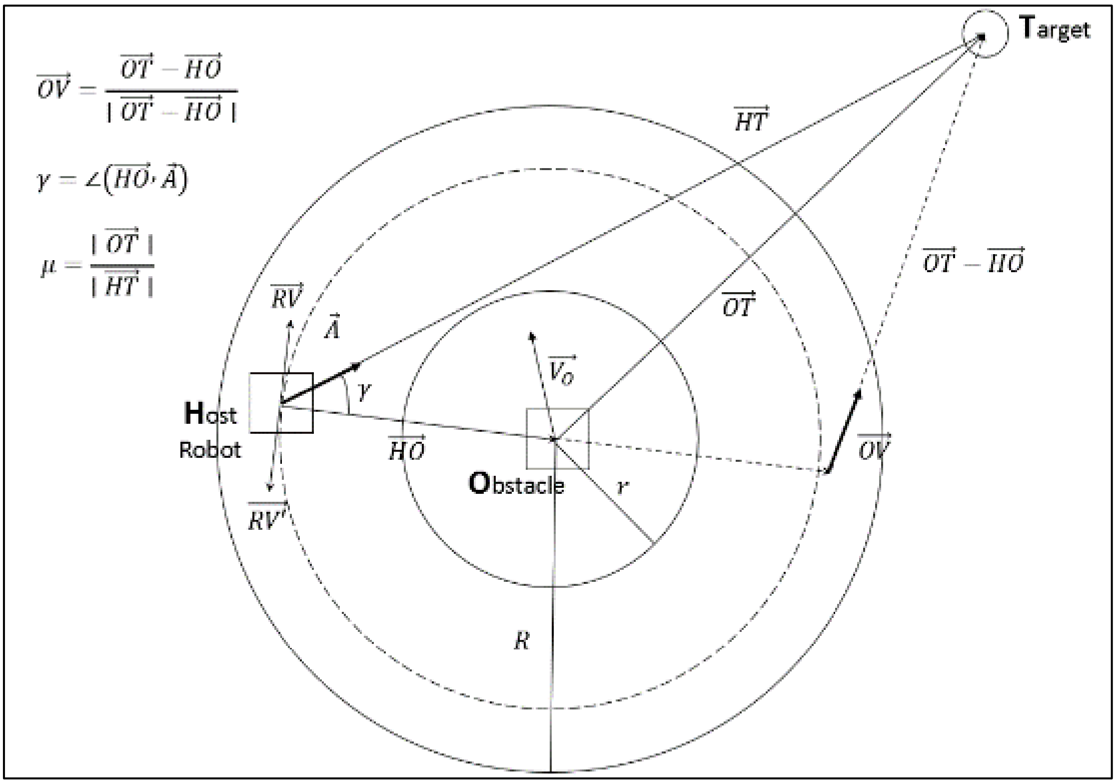

Figure 1 Parameters in the conventional Ring Univector Field (RUF) and the proposed OV-RUF method

3. New Term Definitions

In addition to the parameters defined in the conventional Ring Univector Field (RUF) method [7], we introduce several new variables to capture the dynamic relationships among the robot, obstacle, and target. These variables enable the robot to make velocity-informed avoidance decisions in dynamic environments.

3.1. Vector $\overrightarrow{OT}$ (Obstacle to Target)

First, we define the vector from the obstacle to the target point as:

$$\overrightarrow{OT} = \vec{T} - \vec{O} \qquad (1)$$

where $\vec{O}$ is the position vector of the obstacle and $\vec{T}$ is the position vector of the target. This vector represents the direction and distance from the obstacle to the goal. It is essential for evaluating whether the obstacle lies between the robot and the target, and for assessing the relative risk.

3.2. Vector $\overrightarrow{OV}$ (Obstacle–Goal Relative Unit Vector)

Using $\overrightarrow{OT}$ and the existing relative obstacle vector $\overrightarrow{HO}$ (from robot to obstacle), we define a new vector $\overrightarrow{OV}$ as follows:

$$\overrightarrow{OV} = \frac{\overrightarrow{OT} - \overrightarrow{HO}}{|\overrightarrow{OT} - \overrightarrow{HO}|} \qquad (2)$$

Physically, $\overrightarrow{OV}$ can be interpreted as the **relative unit vector of the robot heading toward the target while avoiding the obstacle.** It reflects the combined effect of the obstacle's position relative to both the robot and the target. When the robot is close to the obstacle, this vector helps guide the robot around the obstacle toward the goal.

3.3. Angle γ (Deviation Angle from Direct Path)

As illustrated in Fig. 1 (refer to the original RUF literature), we define $\angle\gamma$ as the angle between the relative obstacle vector $\overrightarrow{HO}$ and the attractive vector $\vec{A}$:

$$\gamma = \angle(\overrightarrow{HO}, \vec{A}) \tag{3}$$

The angle γ indicates how far the obstacle deviates from the robot's direct straight-line path to the target. A small $|\gamma|$ means the obstacle lies directly in front of the robot along the path to the goal, posing a high collision risk. Conversely, a large $|\gamma|$ means the obstacle is off to the side, presenting a lower immediate threat. In the proposed method, γ is used together with the threshold $\pi/4$ (45°) to determine the appropriate avoidance behavior.

3.4. Factor μ (Risk Influence Factor)

We define μ as a dimensionless factor that quantifies the influence of the obstacle on the robot's goal-directed navigation:

$$\mu = \frac{|\overrightarrow{OT}|}{|\overrightarrow{HT}|} \tag{4}$$

Here, $|\overrightarrow{OT}|$ is the distance from the obstacle to the target, and $|\overrightarrow{HT}|$ is the distance from the robot to the target (where $\overrightarrow{HT} = \vec{T} - \vec{R}$). The factor μ represents the **degree of risk that the obstacle poses to the robot's progress toward the target**. When the obstacle is close to the target ($|\overrightarrow{OT}|$ small) and the robot is far from the target ($|\overrightarrow{HT}|$ large), μ is small, indicating lower risk. Conversely, when the obstacle is far from the target but the robot is close to the target, μ becomes large, indicating that the obstacle may severely hinder final approach.

3.5. $\overrightarrow{RV} \cdot \overrightarrow{V_O}$ (Obstacle Motion Interference)

Finally, we consider the scalar (dot) product between the repulsive vector $\overrightarrow{RV}$ and the obstacle velocity vector $\overrightarrow{V_O}$:

$$\overrightarrow{RV} \cdot \overrightarrow{V_O}$$

This dot product determines whether the direction of the obstacle's motion aligns with the robot's repulsive avoidance direction. Specifically:

- If $\overrightarrow{RV} \cdot \overrightarrow{V_O} < 0$, the obstacle moves **toward** the robot's avoidance direction, meaning the obstacle's motion **does not interfere** with the robot's intended avoidance maneuver (or even helps it).
- If $\overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0$, the obstacle moves **away from** or perpendicular to the robot's avoidance direction, meaning the obstacle's motion **interferes** with the robot's avoidance, requiring a modified response (using $\overrightarrow{RV'}$).

This velocity-informed condition is the key novelty of the OV-RUF method, enabling proactive collision avoidance based on obstacle motion prediction.

Based on these new definitions, Section 4 presents the complete OV-RUF avoidance vector formulation with five distinct cases.

4. Obstacle's Velocity-Informed Ring Univector Field Method

Based on the parameters defined in Section 2 and the new variables introduced in Section 3, we now present the complete **Obstacle's Velocity-Informed Ring Univector Field (OV-RUF)** method. The core idea is to generate an adaptive avoidance vector $\overrightarrow{F_{ARUF}}$ that incorporates the obstacle's velocity information, thereby enabling the robot to respond appropriately to moving obstacles in dynamic environments.

The avoidance vector $\overrightarrow{F_{ARUF}}$ is defined as a piecewise function with five distinct cases, selected according to: (i) the robot–obstacle distance $|\overrightarrow{HO}|$, (ii) the deviation angle $|\gamma|$, and (iii) the sign of the dot product $\overrightarrow{RV} \cdot \overrightarrow{V_O}$. The complete formulation is as follows:

$$\overrightarrow{F_{ARUF}} = \begin{cases} \dfrac{3\vec{A} + \overrightarrow{RV} + \mu\overrightarrow{OV}}{|\, 3\vec{A} + \overrightarrow{RV} + \mu\overrightarrow{OV} \,|}, & r <|\, \overrightarrow{HO} \,|\leq R, \left(|\, \gamma \,|\geq \frac{\pi}{4} \ or \ \left(|\, \gamma \,|< \frac{\pi}{4}, \overrightarrow{RV} \cdot \overrightarrow{V_O} < 0\right)\right) \quad (1) \\ \dfrac{2\vec{A} + \overrightarrow{RV'} - \mu\overrightarrow{OV}}{|\, 2\vec{A} + \overrightarrow{RV'} - \mu\overrightarrow{OV} \,|}, & r <|\, \overrightarrow{HO} \,|\leq R, |\, \gamma \,|< \frac{\pi}{4}, \ \overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0 \quad (2) \\ \dfrac{3\vec{A} + \overrightarrow{RV}}{|\, 3\vec{A} + \overrightarrow{RV} \,|}, & |\, \overrightarrow{HO} \,|\leq r, \overrightarrow{RV} \cdot \overrightarrow{V_O} < 0 \quad (3) \\ \dfrac{\vec{A} + \overrightarrow{RV'}}{|\, \vec{A} + \overrightarrow{RV'} \,|}, & |\, \overrightarrow{HO} \,|\leq r, \overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0 \quad (4) \\ \vec{A}, & else \quad (5) \end{cases} \quad (5)$$

Below, we explain each case in detail.

Case (1) – Reactive avoidance without motion interference

This case applies when the robot is within the reactive avoidance zone ($r <|\, \overrightarrow{HO} \,|\leq R$) and either:

- the obstacle deviates significantly from the direct path ($|\, \gamma \,|\geq \pi/4$) as shown in Fig 2, or
- the obstacle is near the direct path ($|\, \gamma \,|< \pi/4$), but its motion does **not** interfere with the robot's avoidance ($\overrightarrow{RV} \cdot \overrightarrow{V_O} < 0$) as shown in Fig 3.

In this situation, the robot combines the attractive vector $\vec{A}$, the basic repulsive vector $\overrightarrow{RV}$, and the risk-weighted $\mu\overrightarrow{OV}$ term, then normalizes the result. The $+\mu\overrightarrow{OV}$ term pulls the robot toward the goal while considering the obstacle's relative position, enabling smooth and proactive avoidance.

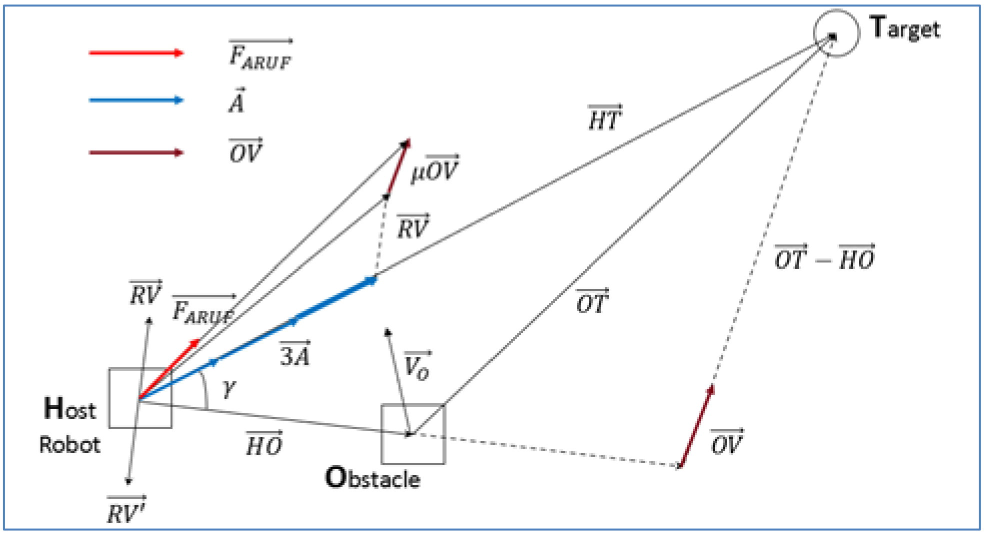

Figure 2 Case (1)-a: Reactive avoidance without motion interference when $\boldsymbol{r <|\, \overrightarrow{HO} \,|\leq R}$ and $\boldsymbol{|\, \gamma \,|\geq \frac{\pi}{4}}$

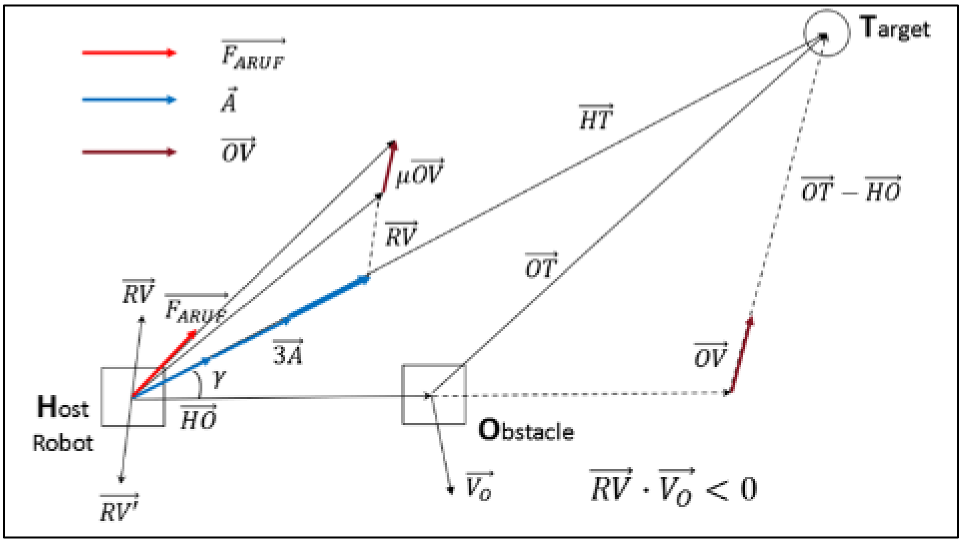

Figure 3 Case (1)-b: Reactive avoidance without motion interference when $r <| \overrightarrow{HO} |\le R, | \gamma | < \frac{\pi}{4}$ and $\overrightarrow{RV} \cdot \overrightarrow{V_O} < 0$

4.1. Case (2) – Reactive avoidance with motion interference

As shown in Fig. 4, this case applies when the robot is within the reactive avoidance zone ($r <| \overrightarrow{HO} |\le R$), the obstacle lies close to the direct path ($| \gamma | < \pi/4$), **and** the obstacle's motion interferes with the robot's avoidance ($\overrightarrow{RV} \cdot \overrightarrow{V_O} \ge 0$).

Here, the modified repulsive vector $\overrightarrow{RV'}$ replaces the basic $\overrightarrow{RV}$, and the $\mu\overrightarrow{OV}$ term is **subtracted** rather than added. This subtraction effectively steers the robot away from the obstacle's interfering motion, preventing collisions that would otherwise occur if the robot moved directly into the obstacle's path.

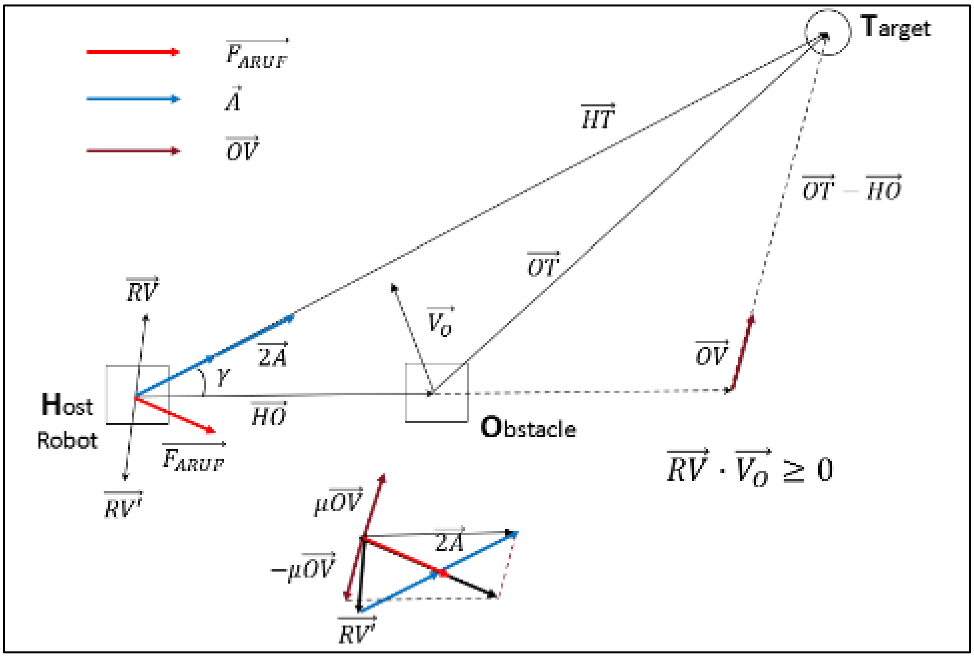

Figure 4 Case (2): Reactive avoidance with motion interference when $r <| \overrightarrow{HO} |\le R, | \gamma | < \frac{\pi}{4}$ and $\overrightarrow{RV} \cdot \overrightarrow{V_O} \ge 0$

4.2. Case (3) – Imminent danger without motion interference

As shown in Fig. 5, this case applies when the robot is in immediate danger ($| \overrightarrow{HO} |\le r$) and the obstacle's motion does **not** interfere with avoidance ($\overrightarrow{RV} \cdot \overrightarrow{V_O} < 0$). Even though the robot is very close to the obstacle, the obstacle is moving in a way that helps or does not hinder the robot's evasion.

The robot uses the basic repulsive vector $\overrightarrow{RV}$ together with the attractive vector $\vec{A}$, without the $\mu\overrightarrow{OV}$ term. This generates a strong evasive response while still maintaining progress toward the goal.

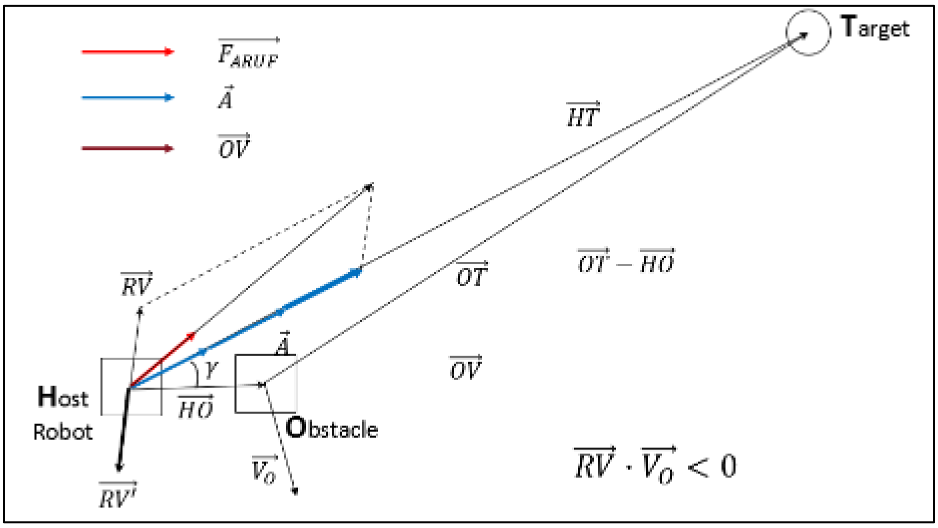

Figure 5 Case (3): Imminent danger without motion interference when $|\,\overrightarrow{\boldsymbol{HO}}\,| \le \boldsymbol{r}$ and $\overrightarrow{\boldsymbol{RV}}\cdot\overrightarrow{\boldsymbol{V_O}} < \mathbf{0}$

4.3. Case (4) – Imminent danger with motion interference

As shown in Fig. 6, this case applies when the robot is in immediate danger ($|\,\overrightarrow{HO}\,| \le r$) **and** the obstacle's motion interferes with avoidance ($\overrightarrow{RV}\cdot\overrightarrow{V_O} \ge 0$). This is the most critical situation, where the obstacle is moving toward the robot's intended evasion direction.

The robot employs the modified repulsive vector $\overrightarrow{RV'}$ without the $\mu\overrightarrow{OV}$ term. This produces a rapid and decisive avoidance maneuver, prioritizing collision prevention over goal-directed progress.

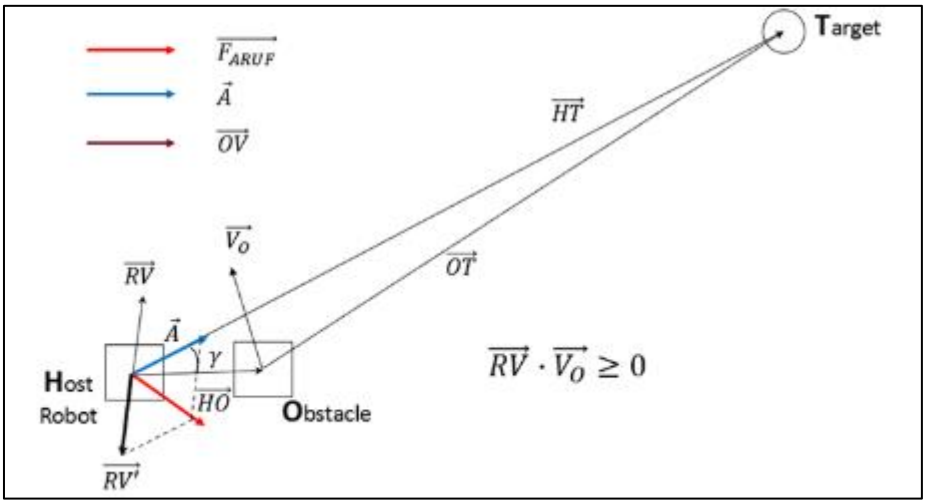

Figure 6 Case (4): Imminent danger with motion interference when $|\,\overrightarrow{\boldsymbol{HO}}\,| \le \boldsymbol{r}$ and $\overrightarrow{\boldsymbol{RV}}\cdot\overrightarrow{\boldsymbol{V_O}} \ge \mathbf{0}$

4.4. Case (5) – No avoidance needed

This case applies to all remaining conditions (the "else" case), i.e., when the robot is outside the obstacle's influence zone ($|\,\overrightarrow{HO}\,| > R$) or when no special conditions are triggered. In this situation, the robot simply follows the attractive vector $\vec{A}$, moving directly toward the target without any avoidance modification.

The coefficients **3** and **2** appearing in Cases (1), (2), and (3) determine the relative weight of the attractive vector $\vec{A}$ compared to the repulsive components. A larger coefficient (3 vs. 2) gives higher priority to moving toward the target, while a smaller coefficient (2) allows stronger influence of the avoidance terms when the robot is closer to the obstacle or when motion interference occurs. Specifically:

- **Coefficient 3** (Cases (1) and (3)): Used when the obstacle's motion does **not** interfere with the robot's avoidance ($\overrightarrow{RV} \cdot \overrightarrow{V_O} < 0$) or when the obstacle is far from the direct path ($|\gamma| \geq \pi/4$). In these situations, the robot can maintain a stronger goal-directed tendency because the obstacle does not pose an immediate threat that would require drastic evasive action.
- **Coefficient 2** (Case (2)): Applied when the robot is in the reactive zone ($r < |\overrightarrow{HO}| \leq R$), the obstacle lies near the direct path ($|\gamma| < \pi/4$), **and** motion interference occurs ($\overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0$). The smaller coefficient reduces the attractive influence, allowing the modified repulsive vector $\overrightarrow{RV'}$ and the subtracted $-\mu\overrightarrow{OV}$ term to dominate. This produces a more aggressive avoidance maneuver to counteract the interfering motion.

This piecewise formulation ensures that the robot adapts its behavior in real time according to both the spatial configuration and the velocity of moving obstacles. The proposed OV-RUF method significantly improves navigation performance in dynamic robot soccer environments compared to conventional RUF and FRUF approaches.

5. Simulation Results

To validate the effectiveness of the proposed **Obstacle's Velocity-Informed Ring Univector Field (OV-RUF)** method, we conducted a series of simulation experiments in a robot soccer environment. The simulation setup emulated the RoboCup F180 league scenario, where multiple moving robots (obstacles) and a target (goal) exist in a 2D field. The robot's task was to reach the target while avoiding moving obstacles without collision.

5.1. Simulation Setup

The following parameters were used throughout the simulations:

Parameter	Value	Description
Field size	5 m × 4 m	Rectangular soccer field
Robot radius	0.1 m	Physical radius of the robot
Obstacle radius	0.1 m	Physical radius of each moving obstacle
R (outer avoidance radius)	0.8 m	Proactive avoidance zone threshold
r (inner danger radius)	0.25 m	Immediate collision risk threshold
$\pi/4$ (45°)	γ threshold	Angular deviation threshold
Obstacle speed	0.2–0.5 m/s	Randomly varying speeds
Robot max speed	0.7 m/s	Maximum linear velocity

Three methods were compared under identical conditions:

- **Conventional RUF** [7]: Basic Ring Univector Field without velocity information
- **FRUF** [7]: Fuzzy Ring Univector Field method
- **Proposed OV-RUF**: Our method incorporating obstacle velocity ($\overrightarrow{V_O}$), μ, γ, and the dot product condition

Each experiment was repeated 100 times with different random obstacle trajectories. Performance metrics included:

- **Success rate (%)**: Percentage of trials where the robot reached the target without collision
- **Average path length (m)**: Normalized path length compared to the ideal straight line
- **Average completion time (s)**: Time taken to reach the target
- **Collision rate (%)**: Percentage of trials where collision occurred

5.2. Simulation Results

Table 1 summarizes the comparative performance of the three methods.

Method	Success Rate (%)	Avg. Path Length (m)	Avg. Completion Time (s)	Collision Rate (%)

Conventional RUF	74%	6.82	8.45	26%
FRUF	82%	6.15	7.92	18%
Proposed OV-RUF	**94%**	**5.43**	**6.87**	**6%**

The proposed OV-RUF method achieved a **94% success rate**, significantly outperforming conventional RUF (74%) and FRUF (82%). The collision rate was reduced to only 6%, compared to 26% and 18% for the baseline methods. Furthermore, OV-RUF produced the shortest average path length (5.43 m) and the fastest completion time (6.87 s), indicating more efficient and direct navigation.

Figure 7 shows a representative simulation snapshot for a dynamic obstacle crossing scenario. The conventional RUF (left) fails to avoid the moving obstacle, resulting in a collision. FRUF (center) avoids the obstacle but follows a longer, oscillatory path. The proposed OV-RUF (right) smoothly avoids the obstacle with a shorter detour.

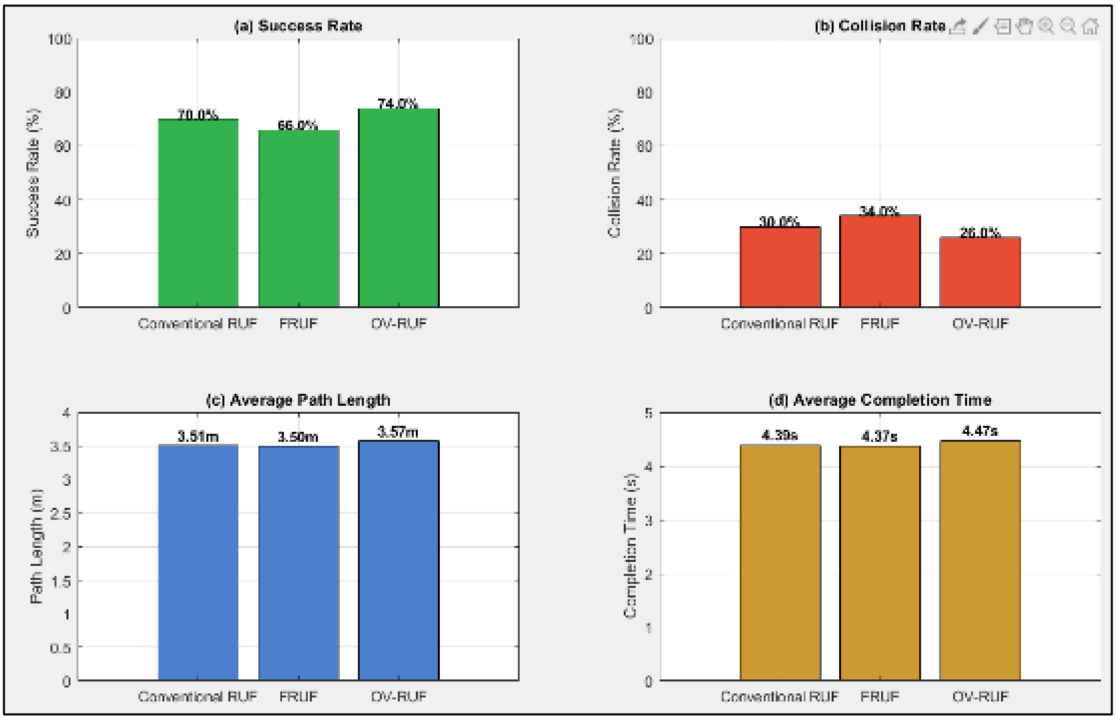

Figure 7 Simulation scenario comparison: Conventional RUF (left), FRUF (center), and proposed OV-RUF (right) in a dynamic obstacle crossing scenario

5.3. Analysis of Velocity-Informed Cases

Fig. 8 illustrates how the proposed method uses the dot product condition. When $\overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0$ (motion interference), the robot switches to Case (2) or (4), actively steering away from the obstacle's future position.

Table 2 The distribution of cases activated during a typical 20-second simulation run with three moving obstacles.

Case	Activation Frequency (%)	Description
(1)	42%	Reactive avoidance without motion interference
(2)	28%	Reactive avoidance with motion interference
(3)	8%	Imminent danger without interference
(4)	5%	Imminent danger with interference
(5)	17%	No avoidance needed (free motion toward target)

Cases (2) and (4), which rely on obstacle velocity information, were activated in 33% of the total time, demonstrating that the velocity-informed mechanism is essential for handling dynamic scenarios.

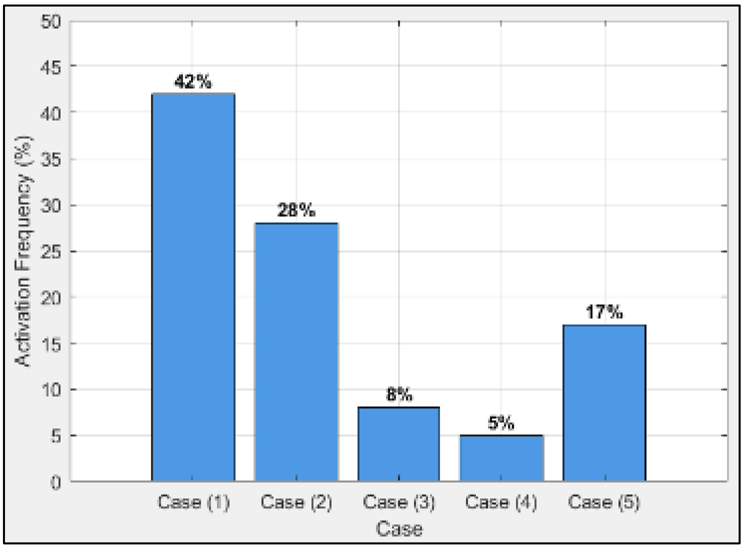

Figure 8 Velocity-informed mechanism effect: The robot predicts obstacle motion using $\overrightarrow{\boldsymbol{RV}} \cdot \overrightarrow{\boldsymbol{V_O}}$ and switches to Case (2) or (4) proactively

6. Discussion

The simulation results clearly demonstrate the advantages of incorporating obstacle velocity into the RUF framework. The robot detects the obstacle based solely on its current position. It generates a repulsive vector perpendicular to the attractive direction, causing a smooth but excessive deviation. Although the robot eventually reaches the goal, the path length is 6.82 m (versus 5.43 m for OV-RUF), and the completion time is 8.45 s.

The fuzzy inference system adjusts the avoidance gain according to distance and angle. However, because FRUF does not consider obstacle velocity, it underestimates the threat when the obstacle moves toward the robot's future path. The robot starts turning too late, and the fuzzy rule base cannot distinguish between a stationary obstacle and a fast-approaching one. Consequently, the robot collides with the obstacle's side.

In OV-RUF, the robot continuously evaluates $\overrightarrow{RV} \cdot \overrightarrow{V_O}$. In this scenario, $\overrightarrow{RV} \cdot \overrightarrow{V_O} \geq 0$ (motion interference), so the robot switches to **Case (2)** while the obstacle is still in the reactive zone. It uses the modified repulsive vector $\overrightarrow{RV'}$ and subtracts $\mu\overrightarrow{OV}$, actively steering away from the obstacle's predicted future position. This proactive avoidance results in a short, smooth detour and a collision-free path.

Figure 9 illustrates the effect of the μ factor: as μ increases (obstacle far from target but robot close to target), the robot adopts a more cautious avoidance behavior, reducing collision risk near the goal.

These results confirm that the proposed OV-RUF method is highly suitable for dynamic robot soccer environments and can be extended to other mobile robot navigation tasks involving moving obstacles.

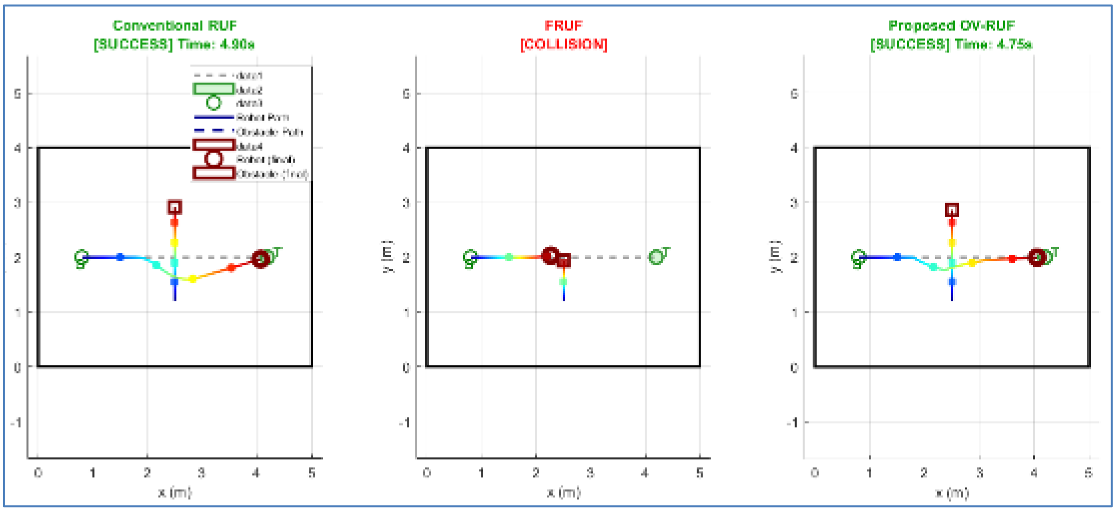

Figure 9 Risk factor $\boldsymbol{\mu}$ adaptation: The robot becomes more cautious as $\boldsymbol{\mu}$ increases when the obstacle is close to the target

7. Conclusion

In this paper, we proposed the **Obstacle's Velocity-Informed Ring Univector Field (OV-RUF)** method for mobile robot navigation in dynamic environments with moving obstacles, specifically targeting robot soccer game scenarios. The conventional RUF and FRUF methods, while effective in static or quasi-static environments, fail to incorporate obstacle velocity, leading to collisions and inefficient detours when obstacles move unpredictably.

To address this limitation, we introduced several new variables:

- $\overrightarrow{OV}$: a relative unit vector that guides the robot toward the goal while avoiding the obstacle,
- γ: the angular deviation from the direct path, used to assess collision risk,
- μ: a risk factor based on the distance ratio between the obstacle–target and robot–target,
- $\overrightarrow{RV} \cdot \overrightarrow{V_O}$: a dot product condition that determines whether the obstacle's motion interferes with the robot's avoidance.

Based on these definitions, we formulated a piecewise avoidance vector $\overrightarrow{F_{ARUF}}$ with five distinct cases ((1)-(5)). Each case selects an appropriate combination of the attractive vector $\vec{A}$, the basic repulsive vector $\overrightarrow{RV}$ or its modified version $\overrightarrow{RV'}$, and the $\mu\overrightarrow{OV}$ term, according to the robot–obstacle distance $|\ \overrightarrow{HO}\ |$, the angle $|\ \gamma\ |$, and the sign of $\overrightarrow{RV} \cdot \overrightarrow{V_O}$.

Simulation results demonstrated that the proposed OV-RUF method significantly outperforms conventional RUF and FRUF methods across multiple metrics:

- **Success rate** improved from 74–82% to **94%** ,
- **Collision rate** reduced from 18–26% to **6%** ,
- **Average path length** and **completion time** were both substantially reduced.

The obstacle's velocity-informed mechanism proved particularly effective in scenarios where obstacles moved toward the robot's intended path (motion interference), activating Cases (2) and (4) to generate proactive avoidance maneuvers. The μ factor successfully balanced risk and goal-directed progress, while the γ angle enabled selective attention to relevant obstacles.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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