COLREGS-COMPLIANT PATH PLANNING FOR RIVERINE AUTONOMOUS SURFACE VESSLE

Jian Hong Mei[1, 2], M. R. Rizal[2] and Jing Rui Tang[3]
[1] College of Electronic and Information Engineering, Hebei University, Baoding, China
[2]Underwater, Control and Robotics Research Group, School of Electrical and Electronic Engineering
Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Penang, Malaysia
[3]Imaging and Intelligent Systems Research Team, School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia
Email: meijianhong@gmail.com

ABSTRACT

International Regulations for Preventing Collisions at Sea (COLREGs) are marine traffic rules for all vessels working in water environment. It is not only essential for human navigated ships but also for Autonomous Surface Vessel, since it should behave same way to other ships when encounters other ships for collision avoidance. This paper presents an artificial potential field method to guide the ASV cruise in the river and be able to avoid obstacles. The repulsive potential is modified to ensure that the evasive manoeuvre complies with COLREGs. The recover manoeuvre is also achieved to make the ASV fast return back to its original path. The simulation results illustrate that the proposed approach is effective for obstacles avoidance and path planning for ASV navigation in riverine environment.

Keywords: COLREGs, autonomous surface vessel, artificial potential field, obstacles avoidance, path planning.

INTRODUCTION

Travelling in an unstructured or unknown environment is still a challenging task for Autonomous Surface Vessels (ASVs) since it needs a high level of autonomy to make reasonable decisions and safe behaviours. Obstacles detection and avoidance (ODA) is fundamental capability for fully autonomous navigation of ASV. The ASV Navigation, Guidance and Control (NGC) system plays a central role to increase the autonomy of ASV for various missions in commercial, research and military applications.

Navigation of ships mainly depends on the mariners' experience and judgment. However, a lot of the accidents at sea are attributed to human error. Thus the International Marine Organisation (IMO) defined The International Regulations for Preventing Collisions at Sea (COLREGs) [1]. COLREGs are marine traffic rules for navigators to make evasive manoeuvres to avoid collision when encounters other ships in open sea and confined water area. Since navigation of ASV is expected to imitate mariners' behaviors, COLREGs are supposed to be included in the guidance system for case that the ASV encounters other ships, and so as to other static and dynamic objects.

Obstacles avoidance and path planning is an essential performance for ASV NGC system. Improvement of ODA capability is not only significant for autonomy level of ASV, but also can work as an aided system or warning and advising system for ships. It is required to make decisions that independent on human interactions and subject to human error [2].

A number of methods have been applied to obstacles avoidance and path planning of ASV to comply with COLREGs. Naeem *et al.* designed guidance system by line of sight coupled with manual biasing scheme to generate COLREGs compliant routes [3]. This method is applied to dynamic model of ASV and the simulation results are compared with DPSS algorithm in environment with both static and dynamic obstacles. Benjamin *et al.* developed an interval programming based multiobjective optimization approach in a behaviour-based control framework to represent the COLREGs rules, and this method is implemented and verified with multiple ASVs [4].

Artificial intelligence is also popular to realize ASV navigation for various tasks and scenarios [5, 6]. Lee developed a modified virtual force field method that incorporated two behaviour parameters which were determined by fuzzy logic rules under COLREGs guidelines [5]. It indicated that this method is able to both obstacles avoidance and track keeping. Kao *et al.* proposed a fuzzy logic method to integrate Vessel Traffic Service (VTS) and Automatic Identification System (AIS) data to predict location and time of all potential collisions and avoid them [6].

The aim of this paper is to design a COLREGs compliant path planner using Artificial Potential Field (APF) for ASV riverine surveillance. The ASV is required to travelling along in the river and able to avoid obstacles. Previous work has been achieved to realize the ASV tracking along the river by keeping its position in the centre of river [7-9]. This is performed by detecting the distance from the left and right sides of the riverbanks with vision system [7, 8]. Distance from both the left and right sides to the riverbanks are compared and integrated to a balance control scheme to keep the ASV in the center of river [9]. We proposed a modified APF method to make the ASV capable of avoiding obstacles on the waterway and comply with COLREGs.

The organization of the paper is as follows. Section 2 presents the problem statement and section 3 presents the proposed approach. Simulation results and discussion are addressed in section 4. The conclusion and future work is presented in section 5.

RIVER TRACKING AND OBSTACLES AVOIDANCE

As mentioned above, the ASV is developed to cruise in the river with constant speed and capable of avoiding obstacles, as shown in Figure-1. It could be decomposed into two distinct behaviors, river tracking and obstacles avoidance. Balance control scheme is proved to be effective in paper [9] to keep the ASV cruise in the center of river, while artificial potential field is utilized to realize obstacles avoidance in this paper. The basic idea of balance control scheme is to compare the distances from ASV to the left and right side of the riverbanks for heading control.

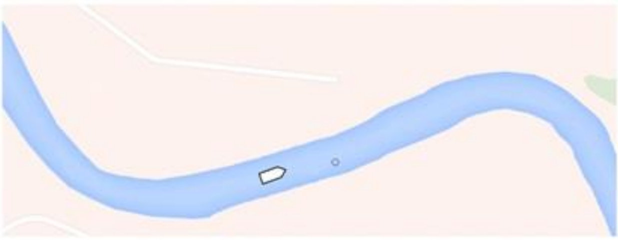

Figure-1. Sungai Kerian river map from Google map.

$$\delta = K_p \times K_{att} \times (D_L - D_R) + K_d \times r \qquad (1)$$

where D_L and D_R are the distances from ASV to left and right side riverbanks, and K_{att} is scale parameter. They are compared and integrated to a PD controller to control the heading angle to keep the ASV in the center of river, which is indicated in Equation. (1). K_p and K_d denote the proportional gain and differential gain respectively. δ is heading angle input to rudder for steering.

Artificial potential field is able to perform both target tracking and obstacles avoidance simultaneously by applying virtual attractive and repulsive force to the robot.

The attractive force is generated by the goal and it attracts the robot to track the goal, while the obstacles repulse the robot away to avoid collision. Thus the route of robot is determined by the resultant of attractive and repulsive forces. The ASV in this paper is to track along the river instead of a specific target, thus attractive force does not exist. Only the repulsive forces from obstacles are working on the ASV, which is indicated in Equation. (2).

$$F_{rep}(X_R) = \begin{cases} K_r \times \left(\frac{1}{(d(X_R, X_o) - d_0)^2} - \frac{1}{(d_m - d_0)^2}\right) & d \le d_m \\ 0 & d > d_m \end{cases} \qquad (2)$$

where F_{rep} denotes repulsive force, and $d(X_R, X_o)$ denotes the distance from ASV to obstacle, d_m is influence range of obstacle. d_0 is minimum safety distance to avoid collision, K_r is repulsive potential field constant.

In this paper since the ASV is travelling with a constant speed, only the heading angle is affected by repulsive force. The Equation. (1) and Equation. (2) are combined to guide the ASV in the river.

$$heading = \begin{cases} K_{att} \times (D_L - D_R) - angle(F_{rep}(X_R)) & d \le d_m \\ K_{att} \times (D_L - D_R) & d > d_m \end{cases} \qquad (3)$$

where $angle(F_{rep}(X_R))$ is the angle extracted from repulsive potential.

From Equation. (3) we can see that when ASV is out of the influence range of obstacles, it is navigated by balance control scheme; when ASV enters the influence range of obstacles, heading angle of ASV is the resultant of balance control and repulsive function.

The method in Equation. (3) is simple and efficient for ASV riverine cruise mission; however, it still has two problems. The first problem is that it does not comply with COLREGs, which means that it is not compulsory to pass by from the starboard side of the obstacle.

The COLREGs are designed for all types of marine crafts. Though there is no pilot on the ASV, it is still required to obey the marine traffic rules. Otherwise it may make incorrect actions and cause collision when encounters other vessels. Rule 13-Rule 15 regulates three situations when own ship encounters another vessel, overtaking, head-on and crossing situation respectively. The main idea of these three rules is that it requires the own ship to steer starboard side when keep out of the way, and so as to avoid other objects. However, the steering determined by original artificial potential field depends on the location when ASV enters the influence range of obstacles. Therefore it may steer port side.

The second problem is local minima problem for artificial potential field. As shown in Figure-2, the ASV is attracted by target and repulsed by obstacle. The motion of ASV (heading and speed) is determined by the resultant of attractive force and repulsive force.

$$F_{total} = F_{att} + F_{rep} \qquad (4)$$

Assuming the case that $F_{att} = -F_{rep}$, the total force equals to zero, which means that the ASV will be trapped in the local minimum and cannot reach the target. In this paper there is no target for ASV to track, and the heading angle is determined by the resultant of balance control scheme and obstacle repulsive force. The direction of repulsive force is from obstacle to ASV, when it is exactly opposite to the heading angle determined by balance control scheme the collision will happen because the ASV is travelling with a constant speed and the heading angle is not changed. This problem is similar to original artificial potential field but leads collision rather than trap.

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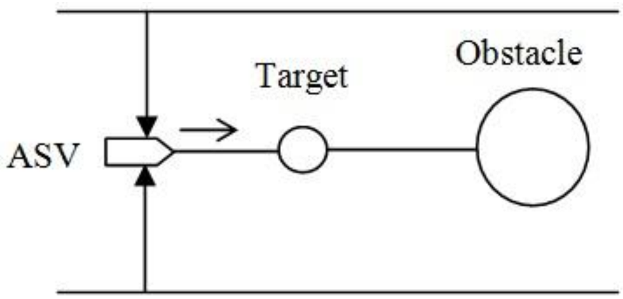

Figure-2. Local minimum problem.

MODIFICATION OF ARTIFICIAL POTENTIAL FIELD

a) COLREGs compliant navigation

The COLREGs compliant and local minima problems stated above will be solved in this section. The repulsive function in Equation. (2) determines the way that ASV passes by the obstacle. The direction angle extracted from Equation. (2) can be negative or positive that depends on the location of obstacle. When repulsive direction angle is positive, the ASV will pass by the obstacle from port side; when repulsive direction angle is negative, the ASV will passes by the obstacle from starboard side. Thus we can force the repulsive direction angle to be negative then the ASV will turn starboard side when enters influence range of obstacle, which is indicated in Equation. (5).

$$heading = \begin{cases} K_{att} \times (D_L - D_R) - abs(angle(F_{rep}(X_R))) & d \le d_m \\ K_{att} \times (D_L - D_R) & d > d_m \end{cases} \quad (5)$$

where abs is the absolute value of $angle(F_{rep}(X_R))$. In addition, Equation. (5) is an iterative process to generate an evasive maneuver action until satisfied COLREGs.

b) Local minima problem

For original artificial potential field, the robot will be trapped in the local minima and make no progress if the attractive and repulsive forces balance. Local minima problem happens for some different cases, such as narrow corridor and goals nonreachable with obstacles nearby (GNRON) [10]. Yun and Tan proposed method that switched the APF to a wall following mode when the robot fell into a local minimum [11]. Ge and Cui took the relative distance between the robot and the goal into account to guarantee that the goal position is the global minimum of the total potential, and solved the GNRON problem [12].

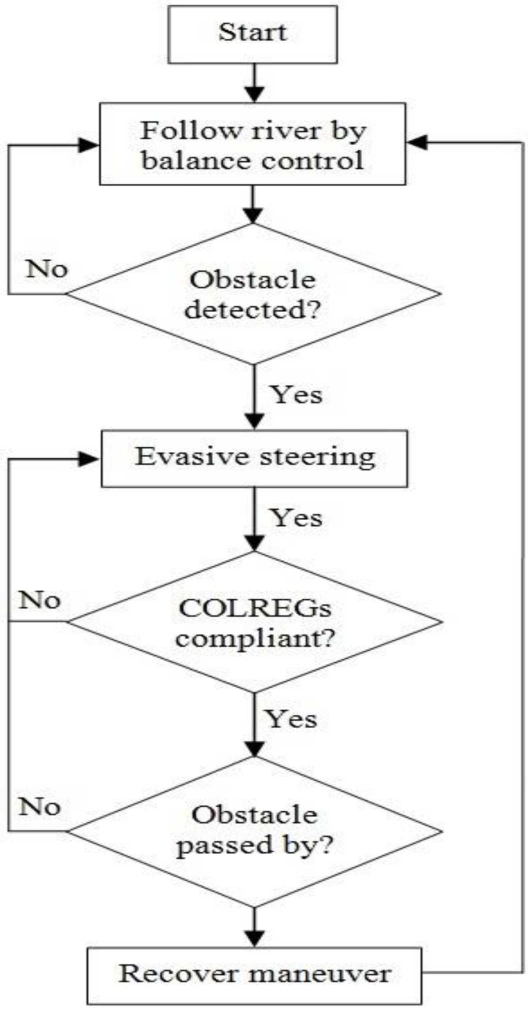

Figure-3. Flowchart of proposed method.

In this paper, the heading angle for river tracking is computed by balance control scheme rather than attractive force from target, thus it is easily to be known by detection of distance from left and right side of riverbanks. For this case the ASV will not be trapped in the local minimum but cause collision because the speed of ASV is constant. From Figure-2 and Equation. (5) we can see that the local minima problem only happens when the direction angle of repulsive force is opposite to the heading angle of balance control. Therefore we give a manual bias angle to ensure that the ASV escapes from local minima state and avoids collision.

$$angle_{rep} = \max(abs(angle(F_{rep}(X_R))), \alpha) \quad (6)$$

where α is the manual bias angle, and it has to be positive to ensure that the evasive maneuver complies with COLREGs.

c) Recover maneuver

The ASV is expected to recover back to its original path as soon as possible after passing by the obstacle. However, the repulsive potential still works when the ASV passed by the obstacle but still in the influence range of obstacle. The obstacle will repulse the ASV away from its original path and will lead a longer route to return back. With assumption that the location of obstacle is known, we take the relative distance between ASV and obstacle into consideration. The relative distance is decreasing when ASV moves toward to the obstacle while it is increasing when ASV moves away.

$$angle_{rep} = \begin{cases} \max(abs(angle(F_{rep}(X_R))), \alpha) & dis(t) \le dis(t-1) \\ 0 & otherwise \end{cases} \quad (7)$$

where $dis(t)$ and $dis(t-1)$ are relative distance between ASV and obstacle at sample time t and (t-1) respectively. The repulsive potential is set to zero when ASV passes by the obstacle, even it is in the influence range of obstacle. Then the ASV will be only affected by balance control scheme and return back to the original path sooner with a shorter route.

The flowchart of proposed obstacle avoidance method is illustrated in Figure-3. It complies with COLREGs and is able to escape from the local minima problem. After passing by the obstacle, the ASV will recover to its original path as soon as possible.

SIMULATION RESULTS AND DISCUSSIONS

The proposed artificial potential field method is verified on an ASV platform with simulation results. The ASV platform is developed by Underwater Robotic Research Group Universiti Sains Malaysia for autonomous bathymetry survey at shallow water areas [13]. The simplified 3 degrees of freedom model is denoted in Equation. (8).

$$\begin{cases} \dot{\eta} = J(\eta)\nu \\ M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau \end{cases} \quad (8)$$

where matrices $J(\eta)$ is the transformation matrix for converting from body-fixed frame to earth-fixed frame; M is a mass matrix; $C(\nu)$ is a Coriolis matrix; and $D(\nu)$ is the summation of linear and nonlinear drag matrices, $D(\nu) = D + D_n$.

The specification of developed ASV is shown in Table-1. The dynamic model of ASV is generated in MATLAB, and the path planning simulation is implemented in Marine System Simulator GNC toolbox which is developed by Fossen and Perez [14].

Table-1. Specifications of URRG ASV.

Parameter	Value
Length	1.5m
Width	0.5m
Weight	50kg
Operating speed	2m/s

The river environment is obtained from Google map, which is shown in Figure-1. The river named Sungai Kerian locates in Nibong Tebal, Penang, Malaysia, near Universiti Sains Malaysia Engineering Campus. Firstly the riverbank lines in Figure-1 are extracted in MATLAB, and then the ASV is navigated in the simulated river environment.

Figure-4 shows a simulation result using original APF method. The black lines are the riverbank lines extracted from Figure-1, while the dash line is the centerline of river. The blue line is the trajectory of ASV travelling in the river. The obstacles are shown as red circles.

The ASV starts from initial location of (10, 0) with initial heading angle of 0°, then the ASV is navigated by balance control scheme. From Figure-4 we can see that the ASV is tracking along the river and keep on the center on river. When it enters the influence range of obstacle, the virtual repulsive force will compel the ASV to evasive from obstacles. After passing by the obstacles, the ASV returns back to the original path and is only guided by balance control scheme.

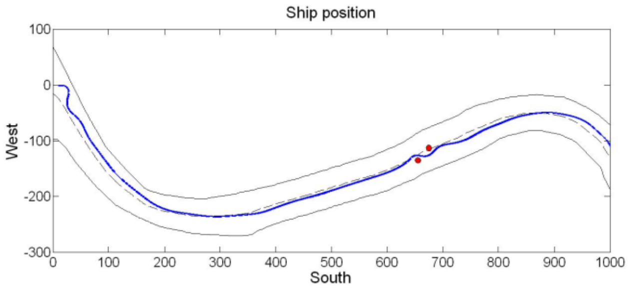

Figure-4. Obstacles avoidance with APF method.

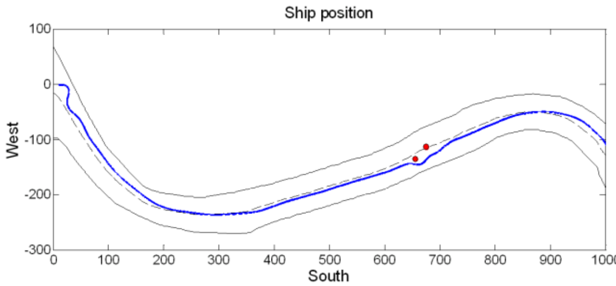

Figure-5. Obstacles avoidance complying with COLREGs.

However, the way that ASV avoids the two obstacles does not comply with the COLREGs, since the ASV passes by the first obstacles from port side. To ensure that the ASV obeys the marine traffic rules, Equation. (5) is applied to the navigation algorithm, and the result is illustrated in Figure-5. We can see that the ASV is forced to pass through the two obstacles from starboard side.

Figures-6 and 7 are compared to indicate the local minimum problem and the way to solve it. From Figure-6 we can see that the heading angle of ASV does not change so collision happens since that the speed of ASV does not change. Equation. (6) is applied to solve the local minimum problem using a manual bias angle. In addition, this method also complies with COLREGs.

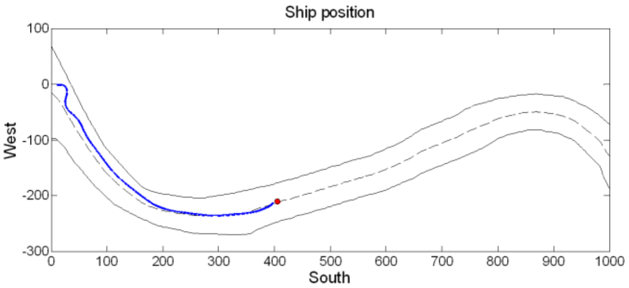

Figure-6. Local minimum problem of APF method.

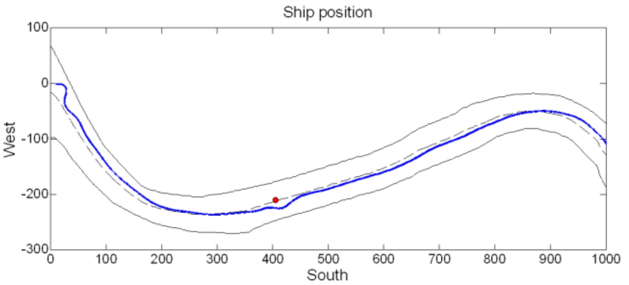

Figure-7. Manual bias angle to solve local minimum problem.

Table-2. Coordinates of obstacles.

x(m)	400	650	670
y(m)	-215	-140	-118

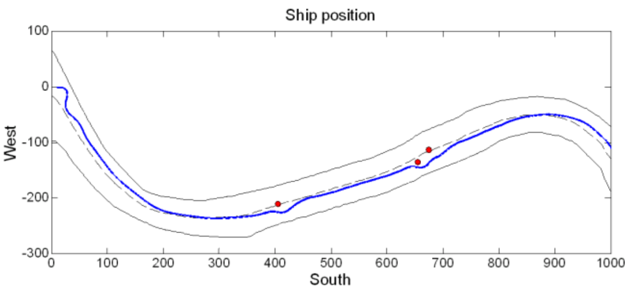

Figure-8. Full navigation of ASV.

Locations of obstacles in Figures 4-7 are listed in Table-2. And the full obstacles avoidance is indicated in Figure-8. The navigation states, yaw rate, speed, yaw angle and rudder angle of ASV are indicated in Figure-9, 10, 11and 12 respectively. From the navigation states we can see that there are three dramatic changes in the riverine navigation. The first dramatic change occurs as the initial start of ASV. Since the initial location of the ASV (10, 0) is not on the centerline of river and the initial heading angle is 0°, the ASV starts to move horizontally, which causes that it moving close to the left riverbank. Then balance control scheme works to lead the ASV moves to the centerline of river.

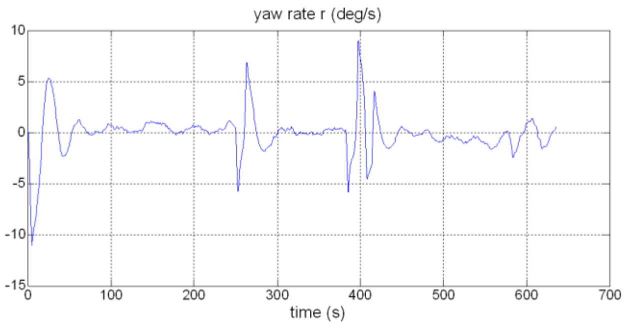

Figure-9. Yaw rate of ASV.

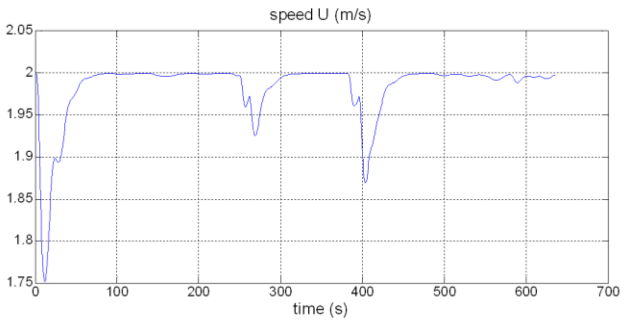

Figure-10. Speed of ASV.

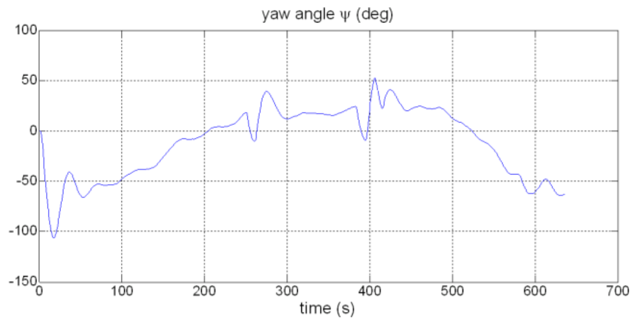

Figure-11. Yaw angle of ASV.

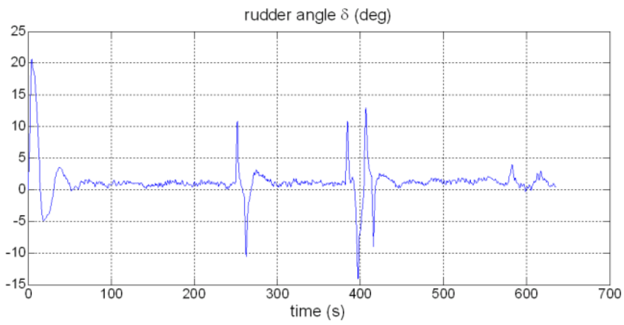

Figure-12. Rudder angle of ASV.

CONCLUSIONS

This paper presents a COLREGs compliant path planning method based on artificial potential field. The modified APF method is able to avoid obstacles from the starboard side, which obeys the marine traffic rules. In addition, the local minima problem and path fast return are solved. Simulation results prove that the proposed method is effective for the ASV riverine navigation.

Future work will be focused on the improvement of the proposed method to apply to the dynamic environment. It will be much more complicated since COLREGs regulates different actions with different encounter scenarios, such as head-on, overtaking and crossing. Artificial intelligence hybrid methods might be a better way to perform the mission.

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