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Obstacle avoidance approaches of autonomous mobile robots in harsh environment

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Abstract. Obstacle avoidance has been a hotspot in the field of robotics. Good performance of obstacle avoidance is key to the success of robots, especially in harsh environment where the external environmental factors pose challenges to the robots. Currently, numerous obstacle avoidance methods are being developed in an attempt to optimize the decision of the autonomous mobile robots in harsh environment. To enhance the reliability of obstacle avoidance methods, it is essential to have a clear picture of the advances and breakthroughs in this field and see which research area needs to be improved. This paper focuses on the current obstacle avoidance methods or path-planning algorithms in the underwater environment and the space environment, with description of their works and discussion of their advantages and weakness. Current problems of these methods include lack of reliable field tests, inadequate assumption of obstacles when designing the algorithm and limited capability in handling special cases that no possible path is feasible. This paper intends to provide researchers with a generalized review of obstacle avoidance methods in harsh environment and a proposal of the potential research directions in this field in the future. It is recommended that researchers to design more complex scenarios, improve the performance of robots to avoid being trapped in special situations, and consider the adaptability of robots in different environment.

Keywords: Obstacle avoidance, path-planning algorithms, harsh environment

1. Introduction

Obstacle avoidance is a hotspot in the field of robotics. Mobile robots need to detect the obstacles and avoid collision with them. Good performance in avoiding obstacles is a key characteristic of robots to complete certain tasks, especially in harsh environment. For example, robots are being developed to work in deep sea or space, and they face the challenge of path planning [1]. This situation calls for a summary of the existing obstacle avoidance methods to show the future directions of this field.

Currently, two types of obstacle avoidance methods are being currently developed: one is the global obstacle avoidance based on known environmental data, while the other one is local obstacle avoidance based on real-time environmental data from sensors. In real world applications, however, the robot faces the biggest challenge that unexpected changes may happen in the working environment, even though the working environment is well-structured [2]. Therefore, the obstacle avoidance methods in a dynamic environment are another focus of the research in path planning of robots.

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In addition, obstacle avoidance is always accompanied with path planning, which can also be divided into two categories: classical approaches and heuristic ones. Classical approaches include roadmap, cell decomposition, artificial potential field and so on, but they have the problems of poor path-planning efficiency and tendency to get trapped in local minima [3]. On the other hand, genetic algorithm, ant colony optimization and particle swarm optimization are typical heuristic approaches, which prove to be successful in problems with multidimensionality [3]. Both of these types will be discussed in the paper.

Due to the wide application of robot in the coming future, it is essential to integrate information of recent technological advances and breakthroughs and foresee the future trends of obstacle avoidance methods. The purpose of this review is to summarize the current research trend of obstacle avoidance and path planning in harsh environments, discuss some existing questions and envision the developing directions of the obstacle avoidance methods in the future.

2. Obstacle avoidance in harsh environment

Obstacle avoidance methods are often more challenged in situations of "harsh environment". As Fahrner and Werner mentioned, the "harsh environment" for sensor system is always accompanied with the following characteristics of high pressure, high temperature, high toxicity, electromagnetic pulses and so on [4]. From another perspective, the environment which is hard for agent to operate in can also be defined as a "harsh" one. In this paper, the latter one is preferred since the obstacle avoidance methods are designed for autonomous mobile robots that doesn't rely on human manipulation. In this sense, it is expected that the robot can work in environments unsuitable for human to work in, such as underwater environment or space environment.

Currently, the major challenges of obstacle avoidance methods applied in harsh environment can be categorized into external factors and internal ones. For the external factors, the dynamic obstacles and other unique environmental conditions cannot be neglected. For example, for robots operating in an underwater environment, they face the challenge of dynamic ocean currents or unknown seafloor terrain [5]. For the internal factors, the position and structure of the robot may increase the difficulty of obstacle avoidance methods. For instance, since some manipulators in space are mounted on the International Space Station (ISS), which has a complex geometry, large safe zones are unlikely to be designated for them and the obstacles in their workspace are complicated [6]. Both of the external factors and internal ones all pose potential challenges and difficulty to the development of the obstacle avoidance methods. This paper will introduce the current progress of obstacle avoidance methods in underwater environment and space environment as a reference to researchers in this field.

2.1. Underwater environment

Underwater environment is a "harsh environment" to robots. The underwater obstacles are unique compared with air or space ones. The underwater robot will face the problem of rapid attenuation of acoustic and electromagnetic signals and high ambient pressure, which poses challenges on the communication between operators and robots and the design of the underwater robots [7]. Therefore, to operate well in such an environment, the autonomous underwater robots are expected to have high reactivity to ambient changes, high robustness to handle unexpected problems, and good reliability to work for a certain period of time [8]. Based on these basic requirements of underwater robots, the obstacle avoidance methods need special alteration to adapt the unique environmental factors, which will be discussed in the following paragraphs.

An and Guo studied an uncertain moving obstacle avoiding method for the spherical underwater robot, which shortened both the distance and the time of obstacle avoidance method, based on the improved velocity obstacle method [9]. They first proposed a stability system with PID controller to ensure that the spherical underwater robot has stable movement. Then they optimized the ant colony algorithm by referring to the particle swarm optimization algorithm. The result of their experiments showed that the obstacle avoidance time and travel distance of the spherical underwater robot have been shortened, which indicated an improvement in 3D path planning of the robot. However, the altitude control of the robot and the timeliness of the reply are still under development. Besides, the method is evaluated by simulation tests, so its effectiveness in real experiments is doubtful. The optimization based on real circumstances is needed for the further development of the algorithm.

Another 3D obstacle avoidance algorithm is developed by Cai and Wu, which focused on the application of Dubins curve in complex underwater environment [10]. The algorithm utilizes the rotation of coordinate system to optimize the Dubins curves designed for the robot to move repeatedly. The results from the simulation in MATLAB proves success in deriving a smooth trajectory of movement and avoiding the obstacle among multiple targets, but its application in a real underwater environment hasn't been evaluated. The future goal of the paper is to optimize the performance of the algorithm under more general scenarios with more obstacles.

Both of the two researches mentioned above lack the essential underwater test, so other ones will be introduced for the combination of theory and practice. Brafinsky and Guterman put forward the idea of avoiding underwater obstacles with the assistance of two forward-looking sonars (FLSs) to make real-time orientation both horizontally and vertically [11]. They applied the two-layer obstacle avoidance algorithm (OAA) that combines a fuzzy logic algorithm and a reactive one, with the vertical approach developed to avoid failure to find path. In addition, they focused on the seabed gradient method and solved the problem of low-range detection range of the vehicle. Results from simulation of the methods showed the flexibility of path-planning for the underwater vehicle. In a real experiment, the vehicle succeeded in changing its altitude while returning to its pre-planned path. For the seabed gradient method, a comparison between the Doppler velocity log (DVL) and forward-looking sonars (FLS) was made, yielding the result of relatively small error between these two methods. Different from the previous algorithms, the obstacle avoidance methods developed in the essay are technically testified in a real underwater environment, with enough advances in altitude change and path-planning flexibility. For the seabed gradient method, it succeeds in enlarging the detection range of the vehicle and providing information on the seabed curvature. The research on the obstacle avoidance methods is a good example of the combination of theory and experiment, which gives other researchers a clear instruction of developing algorithms based on real underwater environment.

2.2. *Space environment*

Space robotics is a promising approach to complete missions for on-orbit servicing missions, such as refueling, repairing and removing orbital debris, but nowadays it is accompanied by various challenges [12]. For instance, since space robots are designed to capture the target before starting their missions, there exist problems in predicting the location of the target and minimizing kinematic errors. Therefore, the path-planning methods need to be optimized to achieve higher efficiency in the basic tasks of space robots.

Wang, Luo and Walter designed a non-linear model predictive control (NMPC) strategy for the obstacle avoidance of free-floating space robots to complete the task of removing space debris [13]. They intend to relieve the given task from the constrains of input, output and anti-collision by connecting the control strategy with the path-planning problem. For the anti-collision constrains, strictly convex objects were assumed to reduce the computational requirement and weight matrices were determined for input and output to indicate the tracking error and control effort respectively. In an attempt to prove the effectiveness of NMPC strategy, the researchers did two simulation case to make a comparison between NMPC and the traditional resolved motion acceleration control (RMAC) strategy, which showed that NMPC has a smaller residue error than RMAC in the joint position and velocity. Besides, NMPC is more capable of handling the designed constrains. The remaining problem of the paper centers on its assumption of strictly convex obstacles and pre-determined weight matrices. In real cases, the assumption of strictly convex obstacles may no longer be reliable. Meanwhile, the weight matrices need to be adjusted for different space scenarios.

Besides the single manipulator, Ni and Chen proposed a coordinated trajectory planning method for a dual-arm space robot to avoid obstacles and developed a method to adjust the penalty factor of the optimizing problem based on the particle swarm optimization (PSO) [14]. For the dual-arm space robot, one arm is designed to complete tasks and the other one is utilized to move the base. In the research, the researchers tested two numerical simulation cases to verify the effectiveness of PSO in finding the optimal solutions with less reliance on the iteration steps. The results showed that PSO succeeded in balancing the penalty factor with the search ability while satisfying the constrains of the robot and adapting well to the different situations. However, the research assumed that the obstacle is standard circular to simplify the simulation, which failed to imitate the real obstacles. Further study is needed to enlarge the working range of the robot.

Huang et al. has combined the null-space motion with reinforcement learning (RL) to develop a new obstacle avoidance method for redundant space robots, which enhanced the flexibility of the robot to stick to its predetermined trajectory while reacting to the obstacles [15]. In their simulation tests, they generated random obstacles in the environment, trained the RL agent with hyperparameters and compared its performance with that of the curriculum learning strategy and the random initial configuration strategy. The results illustrates that the success rate of their RL method is higher than the other ones. They drew the conclusion that their training method proves to be effective in enhancing the adaptability to avoid obstacles in a dynamic environment and the extensibility to handle complex tasks by applying different trajectory generators for the end-effector, with less computational time compared with the common gradient projection method (GPM). Despite its excellence in avoiding obstacles, it cannot be neglected that the success rate of the simulated robot is not 100 percent, because its strong restriction to follow the pre-planned trajectory may make it fail to find feasible paths in some special situations. Further study should focus on when and how to loosen the null-space constrains to enhance the flexibility of the robot in handling situations that obstacle movement exceeds the ability of the RL method.

3. Discussion

Six articles on obstacle avoidance methods have been reviewed in details in this study, with its publication date ranging from 2016 to 2023. These articles show a clear direction of the development of obstacle avoidance in harsh environment that either has unfavorable environmental factors or is inaccessible for human to operate in. The underwater environment and the space environment are selected as examples of the harsh environment, which will be discussed below.

A summary of the underwater robot is shown below in Table 1. From the review of obstacle avoidance methods for underwater robots, a challenge to these methods is summarized. A majority of underwater obstacle avoidance methods are only verified in simulation and lacks reliability in real field tests. Even if field tests are conducted, they are often done in a pool, which only simulates a simple environment, since the chance to test the robot in real underwater environment is limited to only a few researchers. This is why the current research focuses more on simulation of algorithm. In the future of developing underwater vehicle, how to define more general scenarios for field tests or simulate the underwater environment with lower cost and relatively higher difficulty will be the key to more advanced obstacle avoidance methods in the future.

Table 1. Summary of underwater obstacle avoidance methods

Authors	Methods	Advantages	Weakness
An and Guo [9]	Ant colony algorithm Particle swarm optimization algorithm	Reduced obstacle avoidance time and travel path	Lack of underwater tests
Cai and Wu [10]	Optimization of the traditional Dubins curve	Continuous and smooth obstacle avoidance path	Lack of underwater tasks; Poor ability to handle general scenarios with more obstacles
Brafinsky and Guterman [11]	Two-layer obstacle avoidance algorithm Seabed gradient method	Flexibility of path-planning by changing altitude of robots; Larger range of detection for robot moving on the seabed	Not mentioned

Space robot is summarized below in Table 2. Similar to underwater robots, the current researches on space robots still put emphasis on the algorithms for the manipulator to avoid obstacles because of the fact that real space tests are even harder to complete than underwater ones. However, the obstacle avoidance methods of space robots focus more on the motion of the manipulator and the joints instead of the whole robot, since in most cases the space tasks include the capture of objects by using the arms of the robots. As a result, several problems arise in the simulation of these arms. First of all, the objects defined in the simulation tests are always assumed to be perfectly round or convex to simplify the simulation process, which neglect the fact that space debris has various shapes. Secondly, since most studies try to achieve the target of reaching the designed destination while avoiding obstacles for the manipulators, the robot may fail to find its optimal path if all the possibilities are eliminated. Finally, the problem on how to adjust the method under different circumstances remains to be unsolved. Therefore, for the future development of space robots, it is expected that researchers can increase the complexity of simulated obstacles to enhance the extensibility of obstacle avoidance methods to avoid real obstacles. In addition, future researches can also focus on how and when to change the constrains set to the robots to prevent them from being trapped in finding local optimal.

Table 2. Summary of space obstacle avoidance methods

Authors	Methods	Advantages	Weakness
Wang, Luo and Walter [13]	Non-linear model predictive control	Higher capability in handling the constrains; Less error in joint position and velocity	Inadequate assumption of obstacles; Lack of change for weight matrices under different circumstances
Ni and Chen [14]	Particle swarm optimization	Balance between the penalty factor and the search ability; Great adaptability to different situations	Limited working range; Inadequate assumption of obstacles
Huang et al. [15]	Reinforcement learning	Enhanced adaptability to avoid obstacles in dynamic environment; Higher extensibility to handle different tasks	Limited flexibility in special situations

Based on the analysis of the current problems on avoiding obstacles, the development of these methods can accelerate by digging into the directions as follows: 1) Diversified scenarios need to be designed for robots to complete more complex tasks in harsh environment. To further test the developed algorithm, researchers should make the test environment more relevant to the real harsh environment experienced by robots in their tasks. In the future, although chances for robots to test in real environment may increase as the robots develop, it is still essential for researchers to design more complicated obstacles in the path of the robot to verify its effectiveness and reduce unnecessary costs. 2) Enhanced flexibility of robots in handling special situations is promising in the future. The obstacle avoidance methods being developed nowadays have already been quite capable of handling most of the normal cases. However, since the robot follows the pre-determined constrains strictly, special cases that no possible path is available will cause the robot to get trapped. Therefore, further studies should focus on how to change the constrains to relieve the robots from failure of calculating the path while achieving the primary goals. 3) Extensibility and adaptability to different scenarios is the future trend in obstacle avoidance methods. For robots to be more capable of handling tasks, they must be able to adapt different environment without colliding with unexpected obstacles. With the development of robots, the environmental adaptability of robot will become an increasingly important factor to consider the capability of the robots. Future researches should improve the algorithms to make robots more flexible, such as designing various modes for robots to cope with different tasks.

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4. Conclusion

Obstacle avoidance methods are essential for autonomous mobile robots to complete their tasks, especially in harsh environment. In this paper, two harsh environment cases are selected: one is the underwater environment and the other is the space one. For the underwater environment, the paper discussed the existing problems faced by robots and summarized some of the current methods, including ant colony algorithm, particle swarm optimization algorithm, optimization of the traditional Dubins curve, two-layer obstacle avoidance algorithm and seabed gradient method. These methods can enhance the flexibility and efficiency of robots in avoiding obstacles. For the space environment, the methods include non-linear model predictive control strategy, particle swarm optimization and reinforcement learning, which centers on controlling the manipulator to achieve higher adaptability of the robots for different scenarios. In both cases, the disadvantages are analyzed and the future directions are suggested. By following the predicted trends in this paper, the researchers can obtain inspiration to design more diversified scenarios, put emphasis on the solutions to avoid inaccessible local optimal in special cases or design various modes for different tasks. It is expected that in the future, the researchers can contribute to the development of the obstacle avoidance methods to achieve more efficiency, extensibility, adaptability and flexibility of robots in harsh environment by referring to suggestions in this paper.

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