Water Surface Cleaning using a Multi-Sensor Surface Vehicle

YU Mengling[1,2], YANG Long[1,2]*, ZHU Jiannan[1,3], YANG Yixin[1,2], *Member, IEEE*, YANG Huizhen[1]
1. School of Marine Science and Technology, Northwestern Polytechnical University
Xi'an, China
2. Shaanxi Key Laboratory of Underwater Information Technology
Xi'an, China
3. ORCA-Uboat
Xi'an, China

OCEANS 2023 - Limerick | 979-8-3503-3226-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/OCEANSLimerick52467.2023.10244503

***Abstract*—Autonomous robots have seen dramatic advances in recent years; however, it still lacks application in water surface cleaning, which mainly relies on manual operation. This paper presents a fully autonomous robot, SMURF, for water surface cleaning including mechanical, hardware design, and the core part-autonomy system. Through investigating the needs of water surface waste cleaning in different water scenarios, we proposed a multi-sensor fusion scheme, which has been applied to the SMURF to achieve better water surface cleaning effects. In addition, we conducted experiments in two different water scenarios to verify the accurate self-localization and independent path planning ability of the SMURF. The experimental results indicate the SMURF has the above capabilities, which can guarantee the smooth implementation of the water surface cleaning tasks. This can to some extent prevent waste from being transported to the ocean.**

Keywords—autonomous surface vehicle, multi-sensor fusion, obstacle avoidance, water surface cleaning

I. INTRODUCTION

The presence of marine debris has sustained effects on the whole ecosystem. A major source of marine debris is the waste generated on land and entering the ocean through the inland waterways. Therefore, limiting the flux of waste pollution from river freshwater systems into marine ecosystems is a key factor in reducing the accumulation of global waste in the marine environment [1]. Meantime, the lack of maintenance of the river freshwater systems will lead to eutrophication of water bodies and seriously affect civilization and health [2], as shown in Fig. 1.

Fig.1. The floating waste in river freshwater systems

To avoid waste to flow into the ocean, it is necessary to clean up the waste in river freshwater systems. Currently, the relatively common method of water surfaces waste collection still relies on human operations, and there are two major problems in this manual means. On the one hand, due to the large and irregular of the water area, it is difficult and low-efficiency to clean completely relying solely on manual cleaning. On the other hand, since personnel is prone to accidentally drowning when working in water, there is a high risk of this work.

In recent years, the introduction of autonomous equipment has brought new possibilities to reduce the risk of water surface cleaning and improve cleaning efficiency. Autonomous robots have been considered with surface-cleaning devices to clean water surfaces by researchers, which can reach places that are dangerous to humans for thorough cleaning. The Ro-Boat is an autonomous river-cleaning intelligent robot incorporating mechanical design and computer vision algorithm [3]. The Floating Waste Scooper Robot, proposed by Niramon Ruangpayoongsak et al., collects floating garbage on the surface through a floating waste scooper device with the front and side scoopers [4]. The WasteShark, created by the Ranmarine Technology, uses a suction mechanism to suck garbage while it uses way-point tracking to navigate itself [5]. However, previous researchers have focused mainly on cleaning devices' mechanical design, instead of improving autonomous performance. Hence, we focus on robots with a higher intelligence level to combine with the cleaning devices to reduce manual operations, which can increase the cleaning efficiency a lot.

But to the best of the authors' knowledge, there are fewer robots can be directly applied to water surface cleaning. Some autonomous surface cleaning mechanisms proposed by scholars are basically prototype principles, commonly used for waste cleaning in laboratories or some small water areas like the swimming pool which makes it hard to be used for conventional waste cleaning tasks [6-9]. So, how to safely clean waste in urban waterways? The robots should have a complete waste-collection system, can localize itself accurately, and should be equipped with an efficient program on path planning to calculate an obstacle-free path.

To realize autonomous water surface cleaning, we propose a multi-sensor fusion scheme, which is carried on a robot, SMURF. To safely clean up surface waste in urban waters, the robot we designed can achieve effective path planning and

* Corresponding author, lyang@nwpu.edu.cn. This work was supported by the National Natural Science Foundation of China under Grant No. 11974286.

obstacle avoidance with decimeter localization accuracy while having a complete waste collection system.

The SMURF can realize fully autonomous water surface cleaning based on multi-sensor fusion. It can work normally in GPS-attenuated chaotic urban waters by using Inertial Measurement Units (IMUs), millimeter wave radars, and cameras for robust high-precision state estimation and water surface cleaning. We conducted experiments in two different water scenes to verify that the design of the robot can be adapted to multiple water scenes.

In the following sections, we first exhibit the prototype, hardware, and the novel autonomous system of the SMURF in Section II. Section III describes the multi-sensor fusion scheme with an improved path planning and obstacle avoidance algorithm of the SMURF. The autonomous path planning and obstacle avoidance experiments will be presented in Section IV and brief conclusions are given in Section V.

II. DESIGN OF SMURF

The SMURF is designed for water surface cleaning with greater autonomy and can achieve fully autonomous operation. A catamaran-based body is selected for the SMURF, which can bring better stability. An aluminum alloy mix is selected to improve the lifespan of the SMURF, which is corrosion-resistant and environmentally friendly. The core of the SMURF can be divided into two parts: the electronic module and the cleaning module. Fig. 2 shows the details of the SMURF.

Fig.2. The SMURF

The cleaning module is designed with central components, including two extension devices, a unilateral device, and a trash can. These two extension devices are situated forward of the SMURF, like two "arms", which can help the SMURF to store more garbage at one time. The unilateral device will open at a cleaning state and close at other states, like a "door". The trash can will contain the collected waste and send a signal when it is fully loaded.

The electronic module encapsulates a central shell, and the shell is housed by an actuation, a power, some sensors, and a microcontroller unit. To ensure autonomy, a distributed processor architecture, with NVIDIA Jetson AGX Xavier as the main processor, and STM32 microcontroller as the co-processor.

For sensors, there have IMUs, GPS, millimeter-wave radars, and cameras. It is crucial for the SMURF to obtain its localization and attitude information, which will influence autonomous navigation. Therefore, a 6-axis IMU is used to provide 3-axis acceleration and 3-axis angular velocity information. The Real-time kinematic (RTK) method is used to process GPS data to realize a positioning accuracy of cm-level in an open space. Besides, the GPS antenna is placed on the roof of the robot for avoiding signal occlusion. For localization and obstacle detection, millimeter-wave radar and binocular camera are installed on the top center of the robot, and two millimeter-wave radars are equipped on both sides. There is also a camera on the top for environmental monitoring to achieve a full-range vision. Furthermore, considering wireless remote control and real-time video transmission, the 2.4G and 4G antennas are placed on the top of the robot.

III. MULTI-SENSOR FUSION SCHEME

Since most of the floating waste on the water's surface accumulate on the shore, and some of them are scattered randomly in the water. Therefore, to be able to clean up waste more efficiently, the SMURF needs to have the ability to simultaneously plan the path of the entire water area and walk along the shore. For inland waters, to achieve the above effects, two necessary issues need to be addressed. One problem is that the waters to be cleaned often have irregular boundaries. We need to consider how to divide irregular areas and achieve global cleaning. The author has provided a detailed introduction on how to solve this problem in another paper [10]. Another problem is that during walking along the shore, GPS signals are affected by things such as trees and buildings, and the localization accuracy of the robot decreases. We need to consider how to achieve planning path with accurate obstacle avoidance even when the localization accuracy is not accurate. To solve this problem, we propose a multi-sensor fusion scheme that can still update the SMURF's location in real-time and follow the prescribed path even when GPS signals are missing. The autonomy framework of SMURF proposed by us is shown in Fig 3, which uses a multi-sensor fusion scheme for environmental perception and corrects the global location results brought about by GPS.

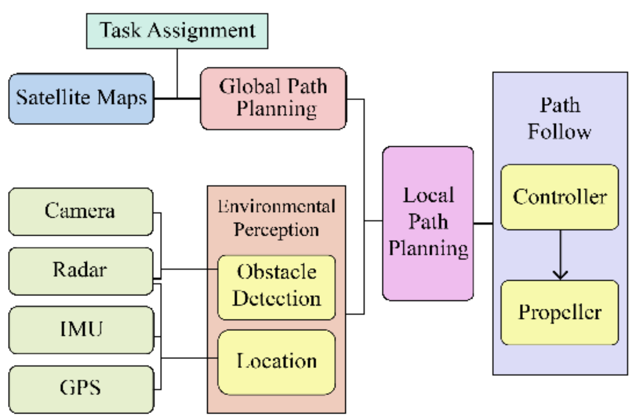

Fig.3. Autonomy framework of SMURF

As mentioned previously, localization for robots in the water surface cleaning scene is a challenge. The GPS can provide absolute localization for the SMURF. By using RTK, its localization accuracy can reach centimeter-level in open scenes with the GPS. Nevertheless, when the robot works in occlusion scenes such as shore vegetation and under bridges, the GPS signal quality will deteriorate. The localization error will increase to several meters, making SMURF unable to work autonomously. Through simultaneous localization and mapping (SLAM), the robot can obtain relative localization information through sensors (camera, lidar, etc.) to achieve localization without GPS signals, but it exists the problem of cumulative error [11]. Where GPS signals are occluded, the occluder often easy becomes a landmark in the SLAM algorithm, helping the application. Therefore, we combined GPS-based localization with the SLAM to design a fusion localization method shown in Fig.4. With the SMURF work scenarios' characteristics, we improve the classic LiDAR SLAM algorithm and adapt it to the RADAR point cloud characteristics.

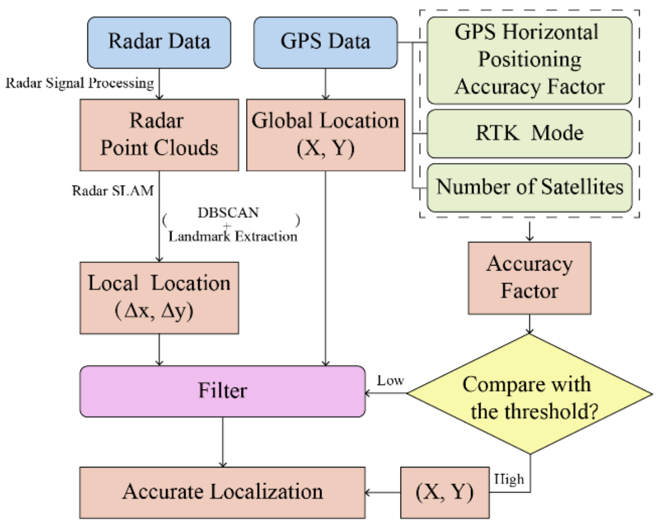

Fig.4 The proposed multi-sensor scheme

In this framework, the GPS accuracy is judged based on the GPS horizontal localization factor, RTK module, satellite quality, and other information. Due to the shelter of shore vegetation and buildings, this information is usually missing, reducing the localization accuracy. When the localization accuracy is lower than the threshold, the fusion localization module is started, and the previous cycle's GPS absolute position is taken as the initial position. The current GPS output position and the previous cycle output position are differentiated. The difference results and the relative position output by the SLAM algorithm are fused through a filter, such as the Kalman filter and the Extended Kalman filter. In the fusion, the GPS horizontal localization factor and the localization accuracy factor output by the SLAM algorithm are used as important weighting factors in the filter. In the fusion module, the position estimation is continued. When the GPS localization accuracy is higher than the threshold, the fusion localization module is exited.

In our scheme, a stable relative localization output is essential. As a low-cost sensor that replaces LiDAR, millimeter-wave radar has received more and more attention in autonomous driving in recent years. Meanwhile, it is not affected by weather and light, which has good environmental adaptability and robustness. However, compared to the dense point clouds of LiDAR, the point clouds of millimeter-wave radar are sparse. For the classic SLAM algorithm based on LiDAR, the point clouds of millimeter-wave radar are challenging to apply directly. Therefore, with the SMURF work scenarios' characteristics, we improve the classic LiDAR SLAM algorithm to adapt to the characteristics of RADAR point clouds, and implemented local obstacle avoidance path planning through multi-sensor data fusion to achieve efficient water surface cleaning operations. The method flow is as follows:

1) Capture Data: Control multiple radars to start asynchronously, acquire point cloud data from each radar, perform time calibration on the point cloud data, and perform data fusion with sensors data to obtain fusion data packets from each radar.

2) Handle Data: Perform time synchronization processing for each radar based on the fusion data packet. By setting the main radar, the fusion data packets of the sub-radars are time synchronized based on the timestamp of the fusion data packets of the main radar. Merge the point cloud data of the main radar and all sub-radars into the main coordinate system to obtain a fusion point cloud. The fusion point cloud is filtered using a clustering method to remove outliers in the fusion point cloud, and a point cloud cluster is obtained as the filtered radar fusion point cloud. The filtered fusion point cloud is projected onto the established grid map coordinate system to obtain a radar grid map, and the grid positions covered by the radar fusion point cloud projection in the grid map coordinate system are marked as obstacle points. Obtain the current GPS coordinates of the SMURF, extract a local grid image centered on it with a radial dimension greater than the radar detection distance, and then filter out discrete clutter.

3) Obstacle Avoidance Path Planning: The obstacle avoidance program starts when an obstacle point is detected by the SMURF. Among the subsequent path points after the obstacle point, an obstacle avoidance target point is selected, which is the first non-obstacle point satisfying the preset distance condition of the obstacle point. Based on the obstacle avoidance target point and the current position of the SMURF in the local grid map, the obstacle avoidance route is obtained by a heuristic search to bypass the obstacle point for the SMURF.

IV. Performance And Experiment

This section first presents a river scenario to validate the developed autonomy system abilities. In this experiment, we will demonstrate how the SMURF achieves path planning and obstacle avoidance with decimeter localization accuracy. It is conducted in a channel area of 160 m×80 m. This area is a typical scene where the water surface is large and irregular, as shown in Fig. 5. Since the area to be cleaned is not completely regular, the SMURF first divides the area into six regular small areas. Then, connect the working paths of these six small areas through path planning. As shown in the red box on the right side of Fig. 5, there is a large obstacle in the area. To avoid this obstacle, the SMURF continuously conducts local obstacle avoidance path planning during the work process. According to different area divisions, the SMURF accurately plans to avoid obstacle and clean. Through a week, ten independent tests were carried out under the scenario, recording the maximum error between the planning path and the actual path in each test. The accuracy of localization is calculated with the averaged errors. The results show that in the natural river, the path error of GPS signal loss caused by shore vegetation occlusion is the largest, and the average error is controlled below 0.4m. Through this experiment, we verify the ability of the SMURF's avoid obstacle in the natural environment with poor GPS signal quality.

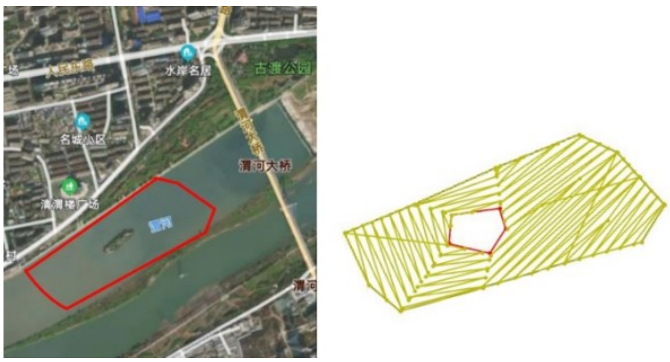

Fig.5 Result of autonomy in an irregular area

The second experiment is carried out to verify the waste cleaning ability of the SMURF. The cleaning area for the SMURF is set up of 200m×180m in a lake. The cleaning area is divided into four regular small areas, in each of which the SMURF designs the coverage planning path and conduct the cleaning task along this path. When the water surface waste is detected, the SMURF plans a local path and deviates from the predefined planning path to collect the water surface waste. After that, the SMURF returns the original planning path. Fig.6 shows the global coverage planning path generated by the SMURF and the practical cleaning path of the SMURF during cleaning procedure, respectively. To show the superior effectiveness of the SMURF, the comparison before and after using the SMURF is presented in the Fig. 7. It can be seen that the water surface waste is thoroughly cleaned by the SMURF. In terms of the working time, the SMURF takes 20 minutes to accomplish the cleaning task at the average speed of 1.2 m/s. Regarding the traditional manual operation, it will take about 2 hours for the same cleaning task. Compared with the traditional manual operation, the SMURF has significantly improved cleaning efficiency.

Fig.6 The global coverage cleaning path (blue line) and the real trajectory (orange line) during cleaning

Fig.7 Water surface before and after the cleaning task by the SMURF

V. Conclusion

Compared with the robots in traditional application scenarios, the robots in the water cleaning application scenario face unique challenges. This paper introduces a water surface cleaning robot with an improved multi-sensor fusion scheme, and introduces the design of its mechanical structure in detail. In addition, a new obstacle avoidance path planning method is applied to the SMURF. It has good water surface waste cleaning ability and can autonomously accomplish the cleaning task in a complex natural water environment.

Acknowledgements

The work is partially funded by ORCA-Uboat.

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