Sensor subsystem design for small unmanned surface vehicle

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Abstract. The construction of unmanned vehicles is a major trend in a modern robotics and automation. One of the promising branches is the development of unmanned boats and surface vehicles (USV). They possess the great variety of possible applications, including environmental studies, military and security issues. In this paper, we consider the design and rapid prototyping of sensory subsystem for small-sized USV. The proposed sensor system incorporates the lidar, Doppler radar rangefinder and video camera in a waterproof housing. The housing is made with additive technology and provides the efficient and rigid placement of chosen set of sensors. The circuitry and design of the sensory subsystem are given and discussed in comparison with existing solution. The prototype of the system is described and the results of its experimental testing are provided.

Introduction

Nowadays robotics is one of the most dynamic and relevant branches of technical knowledge. It is believed that the development of unmanned surface vehicles (USV) will enter a new phase in the near future, as they could soon be applied widely in both military and civilian service [1]. During the design of the floating robot, the developer decides how to organize the interaction between the robotic system and the environment; he also decides how to obtain information about robot location and the parameters of the surrounding space. In order to adjust the trajectory of motion, avoid the obstacles and accurate positioning of the manipulators, the robot must have a kind of “sense organs” [2]. Thus, the sensory subsystem is a block of a robot, which converts the physical parameters of the environment into information. For the efficiency and reliability of the sensory system of an unmanned boat, it is necessary to fulfill such requirements as moisture protection, clear visibility in rough and choppy water, low weight. The subsystem and its elements must be placed in the way to lower the center of gravity for maximum stability of the boat and have streamlined structural elements to reduce air resistance and minimize the risk of structural failure in case of large waves. All these issues became extremely important in a case of small USV, where they are accompanied by the low energy consumption and weight economy. Nevertheless, the overall requirements for sensor systems of small USVs are not significantly lower, than for full-size unmanned ships. We still need to solve positioning and obstacle avoiding problems, but are limited with resources. This makes the development of new design techniques relevant for small USV construction.

Sensory system design

In our design, we chose the following set of sensors: a Doppler radar, a lidar and a camera. For the subsystem of early detection, the lidar and the radar are chosen. The lidar performs accurate
measurements at a sufficient distance, but some properties of the obstacles may confuse its readings. In order to avoid this, the radar (Fig. 3) is placed coaxially, allowing to detect the objects with complex reflective properties. These sensors are installed on a radially movable platform driven by a stepper motor.

![Figure 1. Map of distances to the nearest objects](image1)

For accurate sensor readings and a stable camera image, the stabilization device is necessary. It is supposed to use an active stabilizer on which the lidar and camera will be placed. For high performance, they both require to be relatively precise positioned. Since these sensors have a high acquisition speed, they allow us to construct a precise circular (360 degrees) map of distances to the nearest objects (Fig. 1). The minimal step of the selected stepper motor is 0.9 degrees. The lidar has the longest response time in the rotary sensory head of 0.02 seconds. Therefore, it is necessary to perform 400 motor steps to complete a full 360-degree rotation. On each step the sensory system measures the distance during 0.02 sec. Taking this into account, the system will require 8 seconds for a full scan. This time can be reduced by dropping the number of motor steps and, subsequently, the scanning resolution.

Despite the variety of possible sensors available on market, in our project we chose non-expensive and available sensors that meet minimal accuracy criteria and can be easily purchased for mass-production of USV.

The first sensor to choose was the Lidar-Lite v3 (Fig. 2) because of its sufficient measurement accuracy and the required range.

![Figure 2. Lidar-Lite v3](image2)

The radar is the HB100, a compact, powerful sensor with low power consumption (Fig. 3).
Figure 3. Microwave Motion Sensor Module [4]. Characteristics: frequency setting: 10.520–10.530 GHz; settling time: 3–6 µSec (0.000006) sec; received signal strength: 200 µVp-p; noise: 5 µVrms; antenna beam-width (3 dB) – azimuth: 80°; antenna beam-width (3 dB) – elevation: 40°; supply voltage: 4.75–5.25 VDC.

The PI Cam. V2.1 was chosen as a main camera because it has small dimensions, low cost and relatively high performance (Fig. 4).

Figure 4. PI Camera V2.1 [5]. Characteristics: maximum resolution: 8 MP (3280×2464); supported video formats: 1080p (30fps), 720p (60fps), 640×480p (90fps); lens aperture: f/2; size: 2592×1944

To move the sensor system we chose the bipolar two-phase stepper motor 36HT20-0504MA (Fig. 5). This motor allows making turns at an arbitrary angles that are the multiples of 0.9°. The motor has four inputs: two for each winding of the available two phases.

Figure 5. Stepper motor [6]. Characteristics: step: 0.9 ° ± 5% (400 per turn); rated supply voltage: 6.5 V; holding torque: not less than 0.95 kg × cm; maximum starting speed: 1500 steps / sec; shaft diameter: 5 mm; weight: 0.16 kg.

To control the motor using a microcontroller, one needs an intermediary stepping motor driver. We choose Troyka-Stepper Motor Driver for our project since it is ready-to-go and easy-to-use solution based on the L293D driver chip (Fig. 6).

Figure 6. Motor Driver [7]. Characteristics: motor power supply: 4.5–25 V; peak voltage on Vin contacts: 35 V; voltage of the logical part: 3.3–5 V; continuous current: up to 600 mA; peak current: 1200 mA.
Figure 7. Sensor subsystem ranges of detection.

Figure 7 shows the sectors and ranges for the selected sensors. Due to the fact that the sensors are fixed on the rotary mechanism, the whole area within a radius of 35-40 meters can be covered. Of the three sensors available, the lidar has the narrowest viewing angle, the camera is the largest.

Housing design

The microwave radar module, camera and lidar are placed on the rotary head (Fig. 8) that can only turn 170 degrees in each direction. The real angle is limited because of the restrictions determined by wire flexibility. Such construction allows to scan the wide operational area and to create a distance map.

In our design we implemented model-based principles, creating a set of digital twins before real construction. One can see from Fig. 8, that the camera is located on top, while the radar is located beyond lidar position. The casing does not affect measurements since it does not create a difference between the output and the input radar signals. Since microwaves overcome an obstacle in the form of a casing, it is not necessary to design special holes for it.

Figure 8. Rotary head: a – PI camera, b – lidar, c – microwave sensor module.

The overall height of the construction is 112 mm, the width is 100 mm. This construction is covered with the protective casing (Fig. 9), which provides the necessary dust and moisture protection. The casing is secured with four M3 screws. The head is fastened to the shaft by clamping details. The clamp is attached to the head with two M5 screws.

Figure 9. The cutaway of sensory head in protective casing.
Thus, the total height of the rotary head with the protective casing is 130 mm and width is 105 mm. The inner part of the base is equipped with two bearings with an internal diameter of 8 mm. They make the shaft more resistant to various vibrations and increase the overall rigidity of the construction. The agility of the sensor head is provided by the radial ball bearing, which serves as an interlayer between the support base and the sensor head (Fig. 10), the outer diameter of the bearing is 63.5 mm, the internal diameter is 50.8 mm.

![Figure 10. Base.](image)

To prevent the ingress of water and dust into the structure through the head and base joint assembly, it is protected by a stuffing box with an inner diameter of 85 mm, an outer diameter of 100 mm, and a width of 10 mm. The place of contact of the stuffing box with the movable part has a gasket in the form of a copper ring, which ensures the best fit of the stuffing box to the overall construction and increases its efficiency and service life. The smooth copper ring with the application of a lubricant oil will wear out the stuffing box much less in a case when the base body will be made of PLA plastic.

The shaft is attached to the motor through a flexible coupling that is able to damp some vibrations. Fig. 11 illustrates the whole assembly.

![Figure 11. Overall construction (cutaway): a – radial bearing, b – copper ring, c – ring gasket, d – radial bearing, e – stepper motor, f – clamping of motor shaft, g – motor shaft, h – clutch.](image)

The cables from the sensors and the motor are connected directly to the Raspberry Pi placed into the sealed container inside the boat’s hull.
Figure 12. The prototype of USV with the sensor subsystem.

To demonstrate the whole structure, a model of the boat was developed with the sensor subsystem installed (Fig.12).

Conclusion

In this paper, the requirements imposed on the sensory system of the small unmanned surface vehicle were formulated. These requirements include accuracy, protection against atmospheric influences, scanning surface and stabilization. The concept of sensoric subsystem was developed and 3D models were done in order to estimate the overall applicability of given approach. The product is now on prototyping stage, and we plan to publish a larger follow-up paper about our USV in peer-reviewed journal after the development of the prototype.

The described sensors and other elements of this design are selected in accordance with the permissible weight, dimensions and power consumption, and the general configuration of sensor system has been synthesized. Other types of sensors such as thermal camera, stereoscopic vision systems are energy consumptive types of sensors. In our design we were restricted by funding limitations as well. We plan to consider other types of sensors in a further development of our project.

The use of different sensors in this system makes it possible to avoid the problems inherent in using a single sensor of any type. Installing sensors on a rotating stabilized platform allows to scan a broad sector of the environment and acquire more information about USV operational area. To rotate the platform with installed sensors the stepper motor was chosen.

As an improvement of this system, we plan to implement the signal processing system. Real data obtained from the sensors must be processed to clear the resulting signal from interference. We can also add permanently installed ultrasonic sensors to the system (for example, 4 sensors located at a 90-degree angle to each other) to increase system reliability in close-range contacts. It is also possible to place promising types of sensors, such as chaotic sonar, resistant to crosstalk and environmental noise [8].

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