Development of KAIST Grey-Duck USV for 2014 Maritime RobotX Challenge

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Abstract

This paper is a development report of the Grey-duck unmanned surface vehicle (USV) system for the 2014 RobotX Challenge competition, developed by the Angry Nerds team from KAIST. Using a commercial WAM-V vehicle platform, the USV system was developed to perform five competition mission tasks autonomously. The system configurations for the vehicle's propulsion and electronics systems were designed, implemented and installed considering the system requirements to accomplish the given mission tasks. Commercial-off-the-shelf (COTS) parts were used for most of the components, and the hydrophone array system for the underwater search mission task was developed in collaboration with small high-tech companies. The software algorithms for vehicle autonomy were developed and tested in simulations, and then executable computer codes were implemented and integrated to the developed USV system. Field experiments using the integrated USV system were carried out to check the performance and validity of the developed USV system. All the system development and the field experiments were performed through team planning and close collaboration between the team members.

1. Introduction

Over the last several decades, unmanned vehicle systems technology has been greatly improved with the advance of computer capabilities and artificial intelligence. Among various types of unmanned vehicle systems, unmanned surface vehicles (USVs), also known as unmanned surface vessels, have attracted much interest for their ability to perform dangerous and/or time-consuming missions in marine environments.

Recognizing the importance of USV research, we have been conducting related studies over the past few years. In line with this, we decided to participate in the 2014 RobotX Challenge competition as a team, Angry Nerds, representing KAIST. The RobotX competition, organized by AUVSI and sponsored by ONR, is composed five mission tasks: 1) Task 1 - navigation and control, 2) Task 2 - underwater search and Report, 3) Task 3 - identify symbol and dock, 4) Task 4 - observe and report, and 5) Task 5 - detect and avoid obstacles. Intelligence is a key factor of each mission task in the competition, and all the mission tasks are required to be performed autonomously with no human intervention.

For the competition, we were provided a 16 foot-long catamaran boat platform (i.e., WAM-V by Marine Advanced Research Inc.) but with no propulsion system. The system configurations and specifications for the vehicle's propulsion were determined and the electronics systems were configured considering the system requirements to accomplish the mission tasks. Commercial-off-the-shelf (COTS) parts were used for most of the equipment and components except for the hydrophone system for the underwater search mission which was developed in collaboration with small high-tech companies who are sponsoring our competition effort. All the software algorithms for perception, path planning and control were developed and tested in simulations. Then, the computer codes were implemented in C/C++ for real-time applications and hardware interface towards the final hardware/software integrated USV system.

Experimental tests to validate the performance and tune various system parameters of the developed USV system were performed in an outdoor water environment (i.e., Gap-River near the KAIST campus in Daejeon, Korea). Considering the difference of the environmental conditions, we expect that additional tests and parameter tuning at the competition site (i.e., Marina Bay in Singapore) are an essential and important part to prepare for the competition.

The details of the USV system development procedures, system configurations and developed algorithms are described in the following sections.

2. System and mission requirements

The basic system requirements to achieve the mission tasks of the competition are identified and the strategies for the mission tasks are described in this section.

2.1 Navigation and control systems

Navigation (or localization) is a crucial capability for USV operations. An integrated navigation system that combines an inertial measurement unit (IMU) and global positioning system (GPS) is employed in the USV system. IMU provides vehicle motion information in the high-frequency range and GPS provides low-frequency position fixes. Therefore, the integration of these two sensors leads to an ideal complementary combination for high-precision vehicle navigation which is essential for performing all the mission tasks of the competition.

In addition, optical sensors (e.g., cameras, lidars) are necessary and the associated sensor data processing are required to perform relative navigation with respect to surrounding structures (e.g., gate buoys, obstacle buoys, docking structures) in the competition environment.

Control capability is also an important part for USV development and operations. Considering the catamaran hull form and underactuated motion properties of the USV vehicle, appropriate propulsion/actuation systems and control algorithms need to be designed. In particular, it can be quite challenging to control the vehicle under wind and waves in real ocean environment. The propulsion system is required to provide sufficient power and the control algorithm has be robust enough to overcome environmental disturbances.

2.2. Mission requirements

The objective of Task 1 is to traverse a linear course bounded by two sets of gates (i.e., start and end gates). To navigate between the gates autonomously, waypoints need to be automatically generated using the relative distance and heading to the gates, and a waypoint tracking control algorithm can be employed for keeping the course. The entry and end gate buoys can be detected using a lidar and/or a camera by combining the sensor measurements and prior information regarding the approximate position of the start and end points of the mission task.

The core of Task 2 is to search and report the location of an acoustic sound source (i.e., acoustic pinger) that is hidden underwater and periodically emits acoustic signals. Multiple hydrophones are needed to locate the pinger. Either the first arrival or cross-correlation method can be used to determine the time difference between the hydrophone receptions, which enables finding the direction to the pinger. Finally, bearing-only tracking can be performed to estimate the location of the pinger.

The purpose of Task 3 is to enter the designated docking bay by recognizing symbols on a placard using computer vision. Various image filtering techniques can be used to improve the performance of the vision system considering varying lighting conditions in a marine environment such as light reflection and glint from the water surface. For symbol recognition and identification, the adaptive template matching algorithm can be applied using a monocular camera for capturing a sequence of images along with lidar measurements for detecting the distance to the placard.

In Task 4, the USV is required to find a light buoy and then detect and report the color sequence of the buoy. A lidar can be used to detect the supporting pier structure of the LED tower and find the relative distance and bearing for approach and station-keeping maneuvers. Image processing algorithms including color detection can be applied in the region of interest (ROI) area extracted based on the estimated LED panel location. In order to guarantee the robustness of color detection, a voting algorithm is considered.

In Task 5, the vehicle needs to detect and avoid randomly distributed obstacle buoys while it travels through the obstacle region until it reaches the goal point. A lidar will be the main sensor to detect obstacles in this task. A point distance-based clustering algorithm can be applied for clustering the obstacles [1]. An important issue in this task is how to remove noisy or false lidar measurements in the obtained point cloud data. To minimize the noise effects, the prior information on the obstacle's size and statistical characteristics of the lidar measurements can be considered.

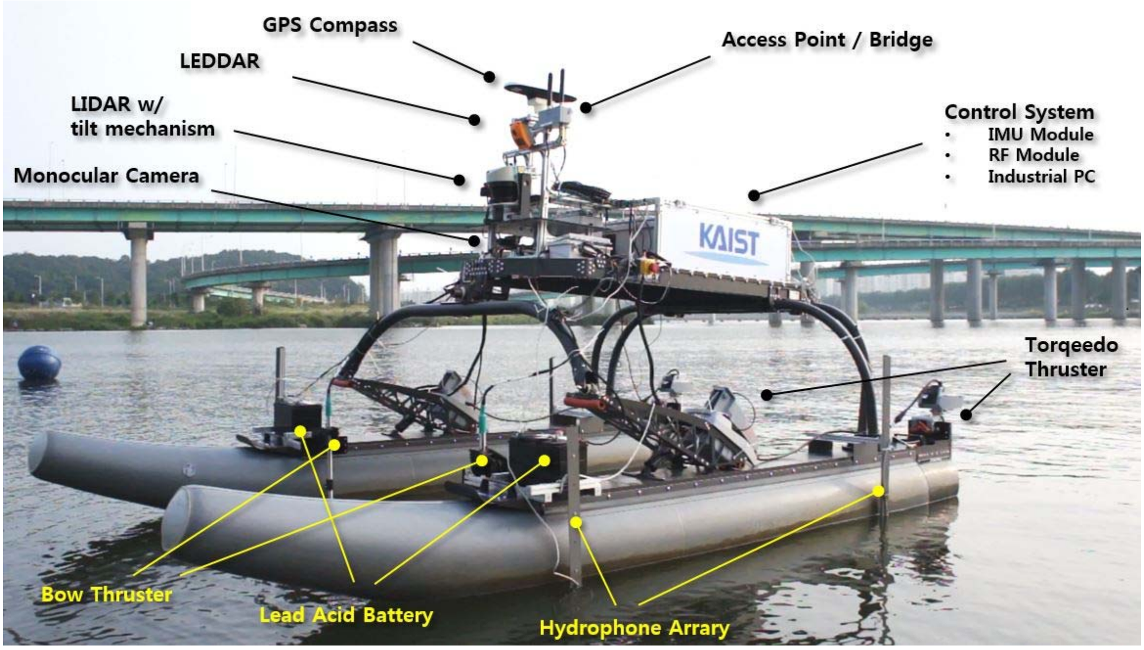

Figure 1. KAIST Grey-duck USV system

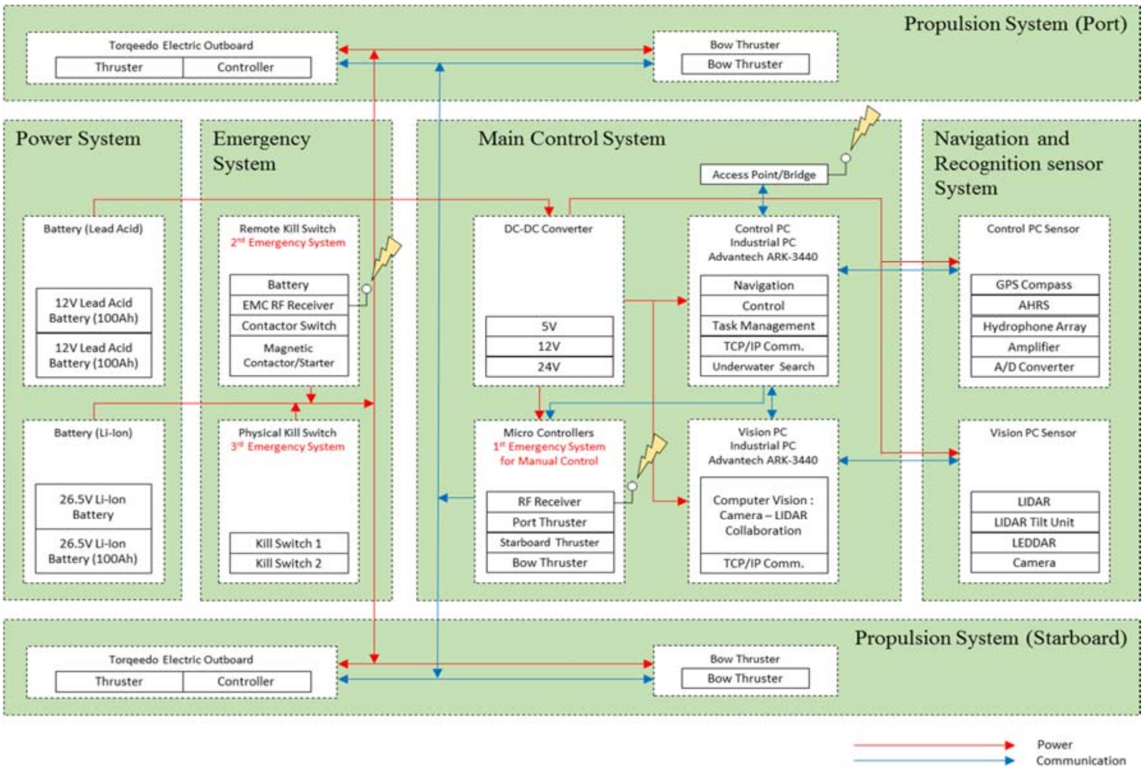

Figure 2. System architecture of Grey-duck USV

3. USV System design and development

The developed Grey-duck USV system (see Fig. 1) consists of five parts: 1) propulsion system, 2) sensor system, 3) computer system, 4) power system and 5) emergency system. The system architecture is shown in Fig. 2 and the details of each system is described in the following.

3.1. Propulsion system

The USV has a catamaran hull form, and thus two electric outboard thrusters are installed as a main propulsion system. The USV can be steered using differential thrust in nominal operating conditions (e.g., cruise mode). However, the resulting underactuated motion characteristics and the dynamic coupling between surge, sway and yaw induce control difficulties in performing Tasks 3 and 4 for which station-keeping (or hovering) capability can be useful. In order to resolve this control issue, two additional outboard thrusters are installed in the fore part of the twin hull.

Figure 3. Electric outboard thrusters for the main propulsion system (left) and the bow thruster system (right)

This bow thruster system allows for parallel maneuvers and easier docking. The thrusters for the main propulsion and bow thruster systems are shown in Fig. 3 and some key technical specifications of the thrusters are shown in Table 1.

Table 1. Specifications of thrusters

Item	Main thruster	Bow thruster
Model	T1003L (Torqeedo)	R3 30 (Motor guide)
Max. Propeller Submergence	71 cm	61 cm
Weight (in air)	14 kgf	10 kgf
Propulsive Power	3 HP	0.48 HP

For station-keeping control of the USV, thrust allocation is introduced to distribute thrust forces over two main thrusters and two bow thrusters.

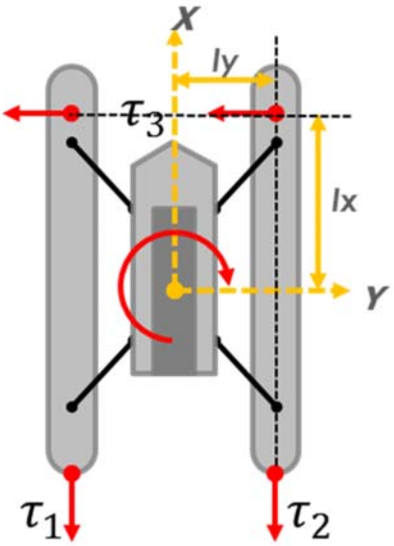

Figure 4. USV thrust allocation

In Fig. 4, the port and starboard thrusters generates τ_1 and τ_2, respectively. τ_3 is from two bow thrusters. τ_1, τ_2 and τ_3 are applied as control inputs. Once the required force vector is computed by the feedback controller, the thrust vector can be determined using Eq. (2).

$$\begin{bmatrix} X \\ Y \\ N \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ l_y & -l_y & l_x \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \tag{2}$$

3.2. Sensor system

In order to perform the given mission tasks, the USV has to be capable of perceiving the surrounding surface-water and underwater environments.

For navigation, the USV is equipped with an integrated GPS/IMU system to estimate the pose of the USV. Specifically, a GPS compass (V102) by Hemispher GNSS and a MEMS IMU (3DM series) by MicroStrain Sensing Systems are used.

In addition to navigation sensors, the USV system is equipped with a monocular camera, two lidars (SICK and LEDDAR) and hydrophone arrays for exteroceptive sensing. The monocular camera and the lidars are mounted to the front of the main deck plate and used to detect and identify various features and structures on the water surface. The camera with a wide lens has a field of view angle of 110°, and the frame rate is 10 fps. The SICK lidar has a planar sweep of 190° and its sampling rate to acquire measurements is 10Hz. A nodding mechanism was implemented using a step motor that tilts the lidar up and down at approximately 0.8 Hz from 20° to -20°, making it possible to scan the surrounding environment in 3D. The LEDDAR sensor which uses infrared light (IR) to measure distances combined with 16 independent active segments whose FOV is 45 degree width and 7.5 degree height is also used to detect the floating dock and obstacles.

To find the location of a sound source, four hydrophones are installed on the lower hull of the USV, two on the starboard side and two on the port. When the hydrophone array gets signals emitted from an acoustic pinger, the signals are amplified and filtered through a band-pass filter before finding the phase difference between each pair of hydrophone signals. This phase difference information is delivered to the PC for estimating the relative bearing and position of the pinger.

3.3. Computer system

In the ocean environment, higher standards for system reliability and robustness are required. Specially, the computer system (i.e., main processing unit) which handles all the measurement and command signals for sensing, navigation and control has to be reliably working under various disturbance effects due to vibration, impact, temperature, humidity, and many uncertain sources of risks.

A computational load is also an important issue to guarantee the system’s reliability. In particular, a large computational capacity is required for processing computer vision and lidar measurement data. Thus, the onboard computer system is physically separated into two parts to distribute the potentially excessive computational load, and two industrial PC's (Advantech ARK series) are used. The primary PC deals with control, navigation and task management, and the secondary PC takes charge of processing camera and lidar measurement. These two PC's are connected via a TCP/IP communication link.

3.4. Power system

All the onboard systems of the USV including the propulsion system are electrically powered by batteries. Two standard car batteries in series are used to provide the 24V DC power. In order to reduce the any noise issue, the power system for the propulsion is separated from the sensor and computer systems. The capacity of the USV power system is approximately 1920 kWh. The duration is expected to be over 4 hours, but it may vary with operating conditions.

3.5. Emergency system

In addition to a software switch by the computer program, the USV is equipped with two emergency switches which consist of a remote circuit breaker and four manual switches on the USV to release the power of the thrusters, as shown in Figure 5.

The emergency system can be activated by a remote controller if necessary, which disables all the thrusters (both the main and bow thrusters) immediately by physically disconnecting the power.

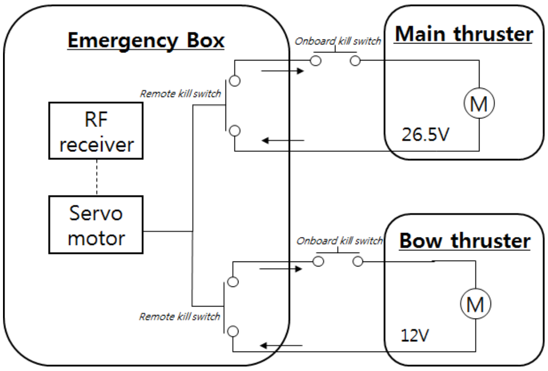

Figure 5. The schematic of remote emergency system

4. Mission strategies and algorithms

The strategies and algorithms of our team for performing the prescribed five mission tasks are briefly described in this section.

4.1. Task 1: Navigation and control

Our strategy is to maneuver the course between the gates by generating four waypoints and performing waypoint tracking control. The USV starts moving from a start point using the given GPS position information and performs heading control toward the predefined goal point. The nodding lidar system collects point cloud data and a point distance-based clustering algorithm is applied to detect the gate buoys at the start point. To achieve reliable clustering and robust perception under the effects of uncertain environmental factors, we utilize the known distances between the start and end gate buoys as prior information. A set of buoys satisfying the constraint are confirmed to be the start gate (see Figure 6) and the relative bearing and distance between the USV and the buoys are computed for waypoint design and tracking control.

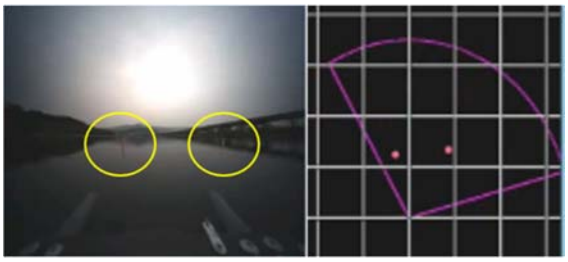

Figure 6. Camera (left) and lidar (right) images of the detected gate buoys

To represent the position of the detected gate buoys in the global frame, the position is transformed using the USV's pose information. The center of the gate buoys is set to be the first waypoint. Then, the mid-point between the first waypoint and the given (approximate) goal point is defined as the second waypoint. When the USV arrives within the acceptance region of the second waypoint, the USV starts searching the end gate buoys using the lidar. If the end gate buoys are found, it center is set to be the third waypoint in a similar manner to the start gate. Finally, the predefined goal point is set to be the forth waypoint. Task 1 is completed when the USV reaches this fourth waypoint.

3.2. Task 2: Underwater search and report

In order to determine the position and depth of the underwater acoustic pinger, the USV is equipped with a hydrophone array system. The hydrophone array system was desgined and developed by SonarTech Inc. which consists of four hydrophones and an amplifier (see Fig. 7).

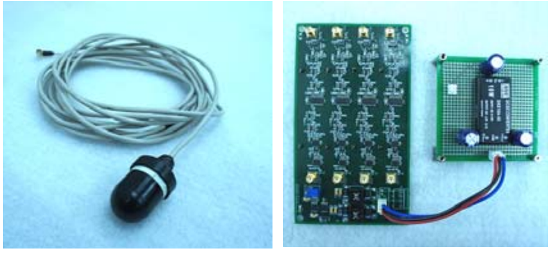

Figure 7. Hydrophone system components: hydrophone (left), amplifier (right)

Acoustic sound measurements are obtained using four hydrophones, and the time difference of arrival (TDOA) for each pair of hydrophones are computed by applying a cross-correlation and/or a first arrival picking method. The direction to the pinger from the USV's position is computed using the TDOA estimates, and the multilateralization technique is used to determine the location of the pinger. The computation procedure for this underwater search task is illustrated in Fig. 8.

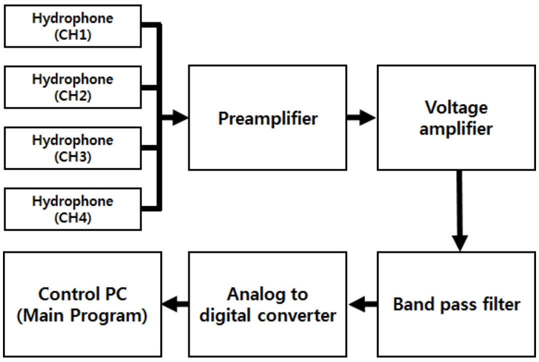

Figure 8. The computation procedure for the underwater search task

We employ the plane wave assumption for determining the relative bearing to the sound source, however this approach is not effective in finding the submergence depth of the pinger in a shallow water environment like Marina Bay. Thus, we decided to adopt a two-step approach. In the first step, acoustic waves are regarded to be unidirectional plane waves assuming that the distance from the USV to the sound source is much larger than the array aperture. This far-field approximation is effective when the USV is sufficiently distant from the pinger [2]. In order to reduce the position error induced by bearing error deviation, the USV is maneuvered to approach the sound source. However, the employed plane wave assumption is not valid in the vicinity of the sound source. Therefore, we use the second method based on the sphere wave assumption [3] to find the 3D position of the pinger when the USV is thought to be sufficiently close to the sound source.

After locating the sound source, we detect the color of the marker buoy in the quadrant where the pinger is located. In this procedure, the ROI for detecting the buoy is defined by using the information of the camera and lidar calibration parameters in pixel coordinates adaptively. With the ROI settings, we detect the circular object which has the shape of the marker buoy using the Hough transform technique.

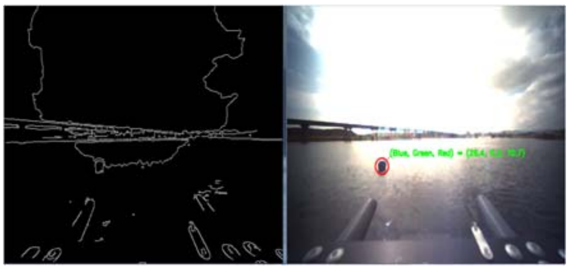

Figure 9. Application of Canny edge detection and Hough transform algorithms to detect the marker buoy

The values of the RGB colors inside the detected circle are averaged and the color is determined by comparing with the mean value of the RGB colors using the prior information of the buoy colors (see Figure 9). Finally, we report the determined color of the detected buoy and the 3D position of the sound source to the judge station.

3.3. Task 3: Identify symbol and dock

In this task, the USV is required to maneuver into the designated docking bay. In order to enter the correct bay, the USV is required to identify one of three symbols on a placard using computer vision, which is either a black cruciform or a black triangle or a black circle. The technical approach of ours combines point cloud segmentation and adaptive template matching techniques.

In order to find the relative bearing and range of the USV with respect to the three symbols, a line detection algorithm is applied using the reflected point cloud from the lidar. Among the obtained line measurements, the prior information on the width of each symbol placard and the separation between the placards is used to segment the lines associated with the actual symbols.

Figure 10 shows the result of the line segmentation and detection using the lidar measurements. The red lines represent the symbol placards and the circled line with white dots is the symbol representing the designated bay. Note that only two symbol placard were installed in the experiment shown in Fig. 10.

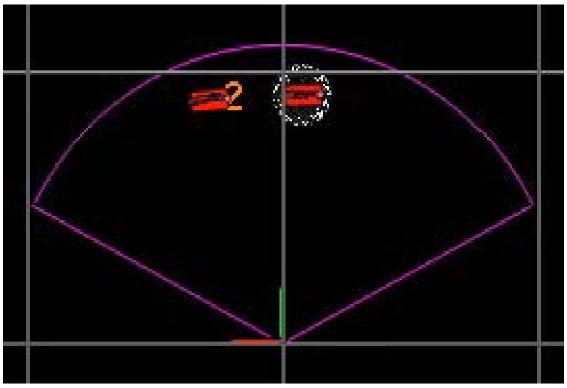

Figure 10. Segmentation and detection of the symbol placards using lidar measurements

Then, vision algorithms are applied, which were implemented using OpenCV library functions, to recognize the symbol and track the relative bearing to the symbol using the adaptive template matching and Extended Kalman Filter (EKF) techniques.

In this approach, we use the down-sampled image and the ROI to improve computational efficiency. Also, we use image filtering techniques to reduce the effect of luminance and glint effects from the water surface. The size of the predefined template image and the ROI are altered by considering the lidar's range information from the USV to the detected symbol placard. Lastly, the template matching algorithm is used to recognize the designated symbol in consideration of the changed template image.

For reliable tracking, an online tracking filter is designed and applied, which estimates the relative position between the USV and the selected docking bay by fusing the measured range and bearing information provided by the camera and the lidar [4]. The results of this algorithm is shown in Fig. 11. The green box represents the symbol region estimated by EKF and the cyan dot represents the center of the selected symbol computed through template matching.

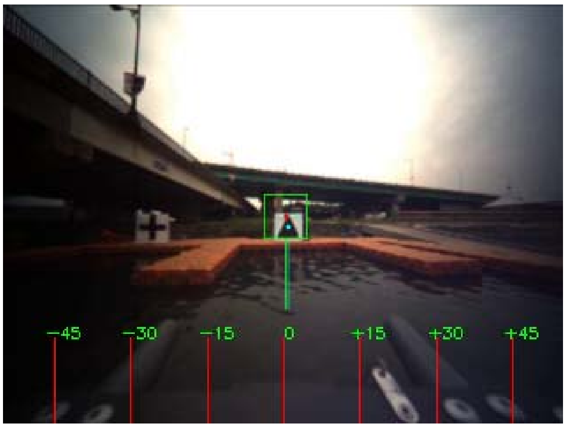

Figure 11. Identification of the symbol on the bay using adaptive template matching and EKF-based tracking filter.

3.4. Task 4: Observe and report

In this task, the USV conduct an observation of the light buoy to determine the sequence of the light pattern on the buoy displays. In order to find the color sequence, the USV is required to identify the position of the light buoy which is in a random location in the search area. The lidar system is used to find the relative distance between the vehicle and the buoy post for approach and position-keeping maneuvers.

Once the buoy is found, the detection algorithm is applied to determine the color sequence using the computer vision system. To detect the color sequence of the light panel, three algorithm features are designed and implemented: 1) an algorithm for robust color detection under environmental changes, 2) the decision tree to classify the color sequence correctly and 3) the voting algorithm for efficient decision making on the color sequence.

In detecting the color sequence, it is very challenging to deal with color distortions under varying lighting conditions that depend on weather conditions and the camera's pose relative to the sun. In our approach, YCrCb color space is applied instead of RGB color space for more robust color detection performance. In YCrCb color space, Y is the luminance component and Cr and Cb are the red-difference and blue-difference chroma components, so that the effect of light variation can be minimized. Using the Cr and Cb components with certain threshold values, we can distinguish red and blue colors of the LED panel.

To separate the green color, we merge Y, Cr and Cb components by setting Y values to zero and convert it back to the RGB color space. Then, we obtain the green color space that does not contain the luminance component. Without separating the luminance component, it is difficult to distinguish the background image from LED panel emitting green color, since the green color space is sensitive to the intensity of light. The resulting image from the experiment test shown in Fig. 12.

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(Cr(Current/Avg), Cb(..), G (..))
(70.9/115.7, 135.5/133.5, 76.4/28.0)
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Figure 12. Extracting the LED panel region from the light buoy: camera view (top), extracted ROI (bottom)

According to the competition rule [5], there exist twelve different color sequences. In order to determine the correct one among these twelve sequence cases, the structure of a decision tree considering all possible color states (i.e., red, green, blue and idle) and all twelve color sequences are introduced. Then, a voting algorithm is applied to make a decision regarding the detected color sequence.

While detecting light tower, the ROI in pixel coordinates is adaptively updated in every time receiving the relative bearing and distance of the USV with respect to the light tower. The size of ROI is selected using the prior information of the head size of the light tower. Figure 13 shows all possible sequences of the light colors. Each color component is confirmed to be detected when the sum of all pixels of the ROI is over the threshold in each color space. A moving average filter is applied to keep the mean value of the color components, and each threshold is settled when the sum of all pixels of the ROI is higher than the mean value with some margin. Then, we track the changes of the color sequences.

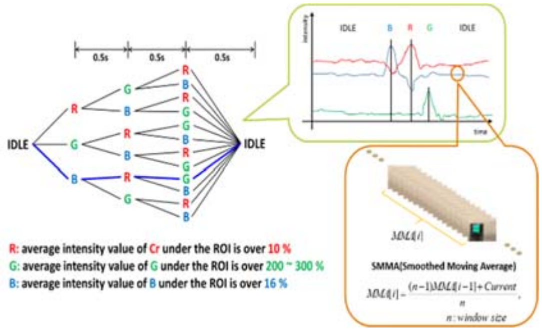

Figure 13. Decision tree for determining the color sequence using a moving average filter based on the intensity changes for each color

It is important to report the correct color sequence quickly to the judge station. To reduce the computation time in determining the correct sequence without overly compromising the accuracy of the color sequence detection, we use multiple decision criteria. That is, the system is designed to report the color sequence in any of the following cases: 1) when the number of votes for a certain sequence exceeds the prescribed threshold, 2) when a specific sequence is declared to be the winner regardless of the rest of the votes, and 3) when the same sequence is detected more than three times consecutively.

3.5. Task 5: Detect and Avoid Obstacles

The objective of this task is to traverse the course passing the correct entry and exit gates, avoiding all the obstacles without colliding to any of the gates buoys. In order to complete the task, the USV needs to recognize the start and goal gates and select the entry and exit point, in addition to obstacle detection/avoidance capability.

The algorithms to recognize the gate buoys and maneuver the USV through the course between the gates are similar to the methods described in Task 1. However, the algorithm has been extended to deal with four buoys at each gate, instead of two in Task 1, and the constraint of the relative bearing and distances between the detected buoys has also been modified accordingly.

The nodding lidar is the main sensor for detecting obstacles in our approach. The point cloud reflected from the obstacles is clustered, and noise measurements from floating particles or wake are removed considering the geometric features such as the obstacle's size and the number of reflected points. An example result is shown in Fig. 14.

For path planning and obstacle avoidance, the A* algorithm is used as a path planner, which is known to be the optimal planner in discrete deterministic state-environment settings [6]. The path planner looks for a path which has the shortest travel distance from the start to the goal without colliding to any of the obstacles. However, the obstacle map is not given a priori and the detection process involves measurement errors and uncertainties, which leads to the need for an online path planning capability. Thus, the obstacle map keeps being updated whenever the USV detects new obstacles in the field of view.

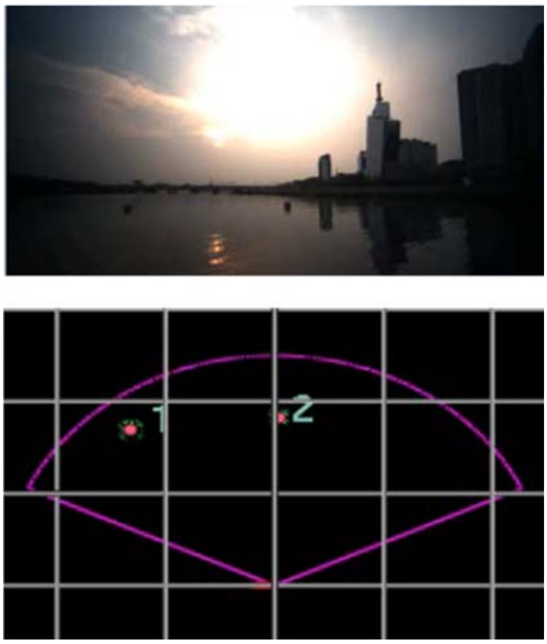

Figure 14. Obstacle detection using the nodding lidar. In the bottom figure, the violet line represents the FOV for obstacle detection and the red dots represent the detected obstacles.

The path is continuously re-planned based on the updated obstacle map to deal with erroneous sensor measurements and environmental uncertainties. The result of the path by the A* algorithm is shown in Fig. 15. The black circles represent the detected obstacles, and the magenta line is the path generated by the planner. The USV maneuvers to follow the given path by waypoint tracking control.

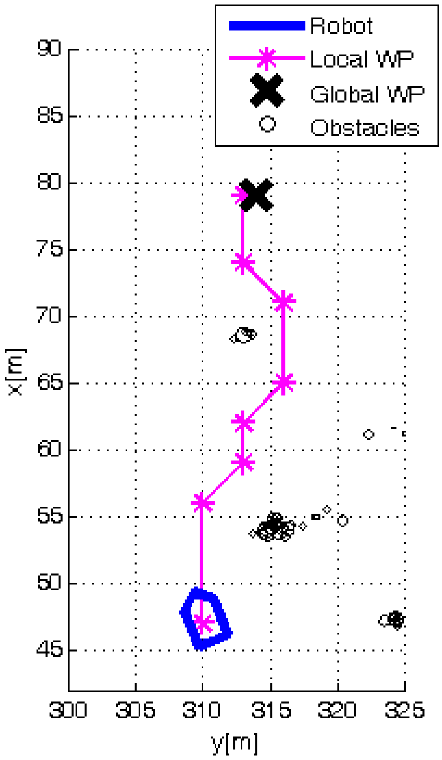

Figure 15. Obstacle avoidance path generated by the A* algorithm based on actual lidar measurements

Collaboration

Basically, all the development work has been carried out through close collaboration between the team members.

The development of the hydrophone array system for performing the underwater search task was done in collaboration with two small high-tech companies, SonarTech and Redone technologies. These companies designed and provided hydrophones and amplifier boards for our USV system. The data acquisition work and acoustic signal processing have been taken care of by our team members.

Conclusion

This paper addressed the development procedures of the Grey-duck USV system and our team strategies for the 2014 Maritime RobotX challenge competition. In order to achieve the goals of the given tasks, all the team members have been working closely together to develop the USV system which includes

- Design and installation of the propulsion/electronic systems
- Development of all the software algorithms
- Development of hardware/software interface and graphical user interface
- Experimental tests in an indoor and outdoor environment

We believe that this competition offers an exciting and unique opportunity to gain hands-on engineering experience in solving real-world problems for all the team members. Due to the time limitation to prepare for the competition, there is still much room for improving the performance of the USV system, particularly in terms of the system's reliability and robustness, toward which our future research will be directed.

Acknowledgments

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