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Development of USV Autonomy for the 2014 Maritime RobotX Challenge

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Abstract: The inaugural Maritime RobotX Challenge competition was held in Marina Bay, Singapore between October 20-26 in 2014. The competition composed of five mission tasks in which intelligence is the single most important factor, and all the mission tasks were required to be performed autonomously with no human intervention. We participated in the competition as the KAIST team with our own unmanned surface vehicle integrated with various sensors for autonomous navigation and perception. All the software algorithms for vehicle autonomy including mission management, environmental perception, path planning and control were developed and applied in the actual competition. This paper describes the given mission tasks of the competition and how the vehicle intelligence and control algorithms were designed in order to perform those mission tasks autonomously.

Keywords: Unmanned surface vehicle, vehicle autonomy, navigation, perception

1. INTRODUCTION

Recently, 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 various missions in marine environments such as environmental monitoring, hydrographic survey, coastal security, search-and-rescue, etc.

In line with this, the inaugural Maritime RobotX Challenge (http://www.robotx.org) was held in Marina Bay, Singapore between October 20-26, 2014, organized by AUVSI Foundation and sponsored by US office of Naval Research (ONR). The competition was composed of five mission tasks which are closely related to practical applications for USVs. Intelligence is a key factor and all the mission tasks were required to be performed autonomously with no human intervention. The five mission tasks are summarized in the following:

Task 1 - Navigation and control: The boat should traverse a linear course bounded by two sets of gate buoys with different colors (red on the port side and green on the starboard side) at the start and end points whose position coordinates are not provided.

Task 2 - Underwater search and report: The boat should find and report the location (position and depth) of an acoustic sound source (i.e., pinger) in a search area. The pinger is hidden underwater and periodically emits acoustic signals at a frequency between 25∼40 kHz.

Task 3 - Symbol identification and docking: The boat must identify symbols on a placard and enter the designated docking bay. Three marker symbols are circle, triangle, and cruciform, which are placed on each docking bay whose arrangement is not provided in advance.

Task 4 - Buoy observation and report: A light buoy is placed somewhere in a search area and the buoy emits light signals with three different colors (red, green, and blue) in a randomly arranged sequence. The boat should find the location of the buoy and report the correct color sequence.

Task 5 - Obstacle detection and avoidance: The boat should enter the course through a designated entry gate, navigate the course area filled with different sizes of obstacle buoys without collision (or contact), and complete the course by passing through a designated exit gate.

We developed a 4m-long USV system to participate in the competition using a 16-foot long catamaran hull platform (i.e., WAM-V by Marine Advanced Research). The specifications and configurations of the electronics and propulsion systems were designed and integrated using commercial-off-the-shelf (COTS) components. In particular, various sensors were installed on the USV for autonomous navigation and perception. To be more specific, an integrated IMU/GPS system was used for navigation. A camera and a lidar were for environmental perception and a hydrophone array for the underwater search task. Then, the computer algorithms for fusing the measure-

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ments from the above-mentioned sensors were developed considering the given mission requirements. The computer codes were implemented in C/C++ for real-time operation and hardware/software interface towards the developed USV system. The performance of the algorithms were demonstrated with experimental tests and eventually at the on-site competition.

2. USV DESIGN AND DEVELOPMENT

2.1 USV platform system

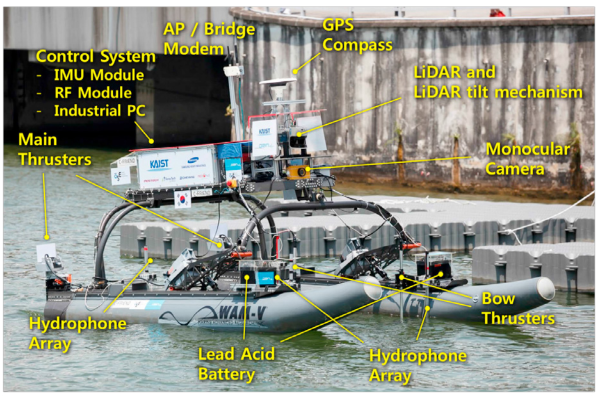

Fig. 1. KAIST USV system

In order to perform the given mission tasks, the USV required the capability of perceiving the surrounding surface-water and underwater environments. For navigation, the USV was equipped with an integrated GPS/IMU system to estimate the pose of the USV. Specifically, a GPS compass and a MEMS IMU were used. In addition to navigation sensors, the USV system was equipped with a monocular camera, two lidars and hydrophone arrays for exteroceptive sensing. The monocular camera and the lidars were 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 10 Hz. A nodding mechanism was implemented using a step motor that can tilt the lidar up and down at approximately 0.8 Hz from 20°to -20°for three-dimensional scanning of the surrounding environment. To find the location of a sound source, four hydrophones were installed on the lower hull of the USV, two on the starboard side and two on the port.

Two industrial PCs were used for autonomous perception, navigation and control. The primary PC dealt with control, navigation, underwater acoustics, and task management, and the secondary PC took charge of processing camera and lidar measurement. These two PCs are connected via a TCP/IP communication link. Work allocation between two PCs and various algorithm modules is shown in Fig. 2.

For mobility, two electric outboard thrusters were installed on the USV as a main propulsion system considering that the boat has a catamaran hull form. The USV was designed to be steered using differential thrust in nominal operating conditions. In addition, two outboard thrusters

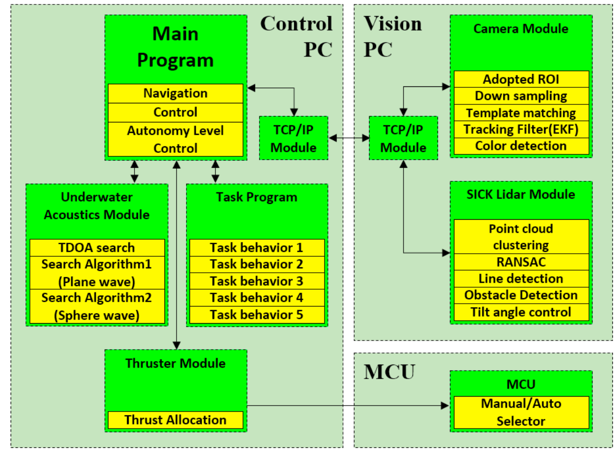

Fig. 2. Software structure of KAIST USV

are installed in the fore part of the twin hull to achieve station-keeping and parallel maneuvering capabilities. All the onboard systems of the USV including the propulsion system were electrically powered by batteries. The duration was expected to be over 6 hours, slightly varying with operating conditions.

2.2 Navigation, guidance and control

The Kalman filter algorithm was applied to the navigation filter. Three degree-of-freedom (DOF) motion composed of surge, sway, and yaw was considered for the filter dynamics. The USV's motion was estimated using position and attitude measurements provided by the the GPS-compass and IMU. The state vector to represent this 3-DOF motion can be expressed as

$$\mathbf{x} = \begin{bmatrix} x & y & \psi & u & v & \dot{\psi} \end{bmatrix} \tag{1}$$

where x, y and ψ represent the position and heading of the USV in the global reference frame. u and v are the USV's velocity in the body-fixed frame. The USV was able to localize itself and navigate the course area reliably with the 3-DOF based GPS-IMU integrated navigation system.

In fact, accurate sensor measurement such as lidar's point cloud data is important to carry out mission tasks. Because the lidar provides the point cloud data in the body-fixed frame, it is required to compensate roll and pitch motions of the USV from the sensor measurement. For this reason, these extra states were additionally measured using IMU.

For guidance and control, three maneuvering modes(course tracking, weathervaning, position keeping) were defined and different control strategies were designed and applied as decribed in the following.

Waypoint tracking: Waypoint tracking was an essential maneuvering capability for every mission task. Waypoints were predefind according to the course information or generated by the boat's planner. The waypoint tracking guidance was applied to minimize line of sight error and cross-track error (Fossen et al. (2003)). The control forces minimizing these errors were determined in the direction of surge and yaw, and control forces were achieved by operating two main thrusters of the USV. The USV was operated efficiently over a wide range of speed in this mode, however its sway motion could not be controlled due to the vehicle's underactuated properties in this mode.