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Marine measurement and real-time control systems with case studies

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ABSTRACT

Measurement, data transfer, modelling, controller systems are the main subjects of interdisciplinary area during prototyping of marine automatic control systems. Experimental parameter identification is an essential step for modelling and control system design are in question for various marine applications. The selection of variables to be measured, type of measurement sensors, type of control algorithms and controller systems, communication, signal conditioning are all important topics for parameter identification and real-time control applications in maritime engineering. The objective of this paper is to present a brief review of these important topics based on our case studies, such as ship roll motion reduction control, optimal trim control of a high speed craft, and dynamic position control of underwater vehicles. These projects involved extensive dynamic modelling, simulation, control algorithm design, real-time implementation and full-scale sea trials. In this paper, the presented methods, and the required characteristics of the marine control systems are demonstrated with the results obtained by the simulation studies and full-scale sea trials. Also, insight into the selection of hardware and software components for mechatronic applications in marine engineering is provided.

1. Introduction

Automatic control systems' applications in marine engineering include many differences, compared to other engineering controller systems. It is important to identify the features of sensors, type of communication, control algorithm, and controller systems for real-time control processes according to the specifications of an application in the maritime industry. Hence, measurement, signal processing, communication, modelling, and prototyping for marine vehicles' control systems were reviewed respectively in the following subsections.

1.1. *Marine vehicles' motion and position measurement*

Determination of sensors for marine vehicles' motion and position measurement depends on the application such as sea surface and underwater vehicles. In addition to these, tank and open sea test types are other criteria to select the sensors.

1.1.1. *Sea surface vehicles' motion and position measurement*

Sensors are used as feedback signals in closed-loop controller systems, and/or observe variables in open control systems. Global Positioning System (GPS), gyroscopes, Inertial Measurement Unit (IMU), Attitude and Heading Reference System (AHRS), a ship's speed measurement relative to the water, wind direction, wind speed, echo sounder are utilized in the maritime industry.

Accuracy, resolution, bandwidth, features of a sensor must be evaluated according to the system requirements. The system requirements are such as a system's response time, a closed-loop controller time, sampling time and error tolerance value. A high-performance sensor should have a fast response time, stable output, and immune to noise.

IMU sensors are used for measuring ship motions, linear acceleration, angular rate, and angular position. Low drift, and high reliability features of an IMU sensor must be considered. Numerical integration may cause the drift of an IMU sensor. There are many low price IMU sensors in industry, but they may have high drift during long run hours. The high reliability feature of an IMU shows that it can be run over a long period.

There are two types of IMU sensors. The first type of IMU consists of accelerometers and gyroscopes. Typically, each sensor has two or three degrees of freedom defined for x, y, and z axis. Combining both sensors will total up to four or six Degrees of Freedom (DoF). Angles (pitch, roll) can be measured from both sensors, so both data can be calibrated to get more accurate data. Yaw angle can only be measured by a gyroscope. The

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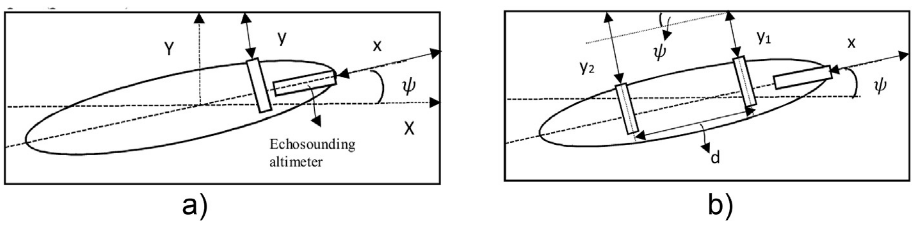

Fig. 1. a. 2-echosounding altimeter integrating to AUV localization. **b**. 3-echosounding altimeter integrating to AUV localization.

advantage of this type IMU is that it is not be affected by external magnetic fields. However, depending on two type of sensors, it may not be enough to increase the accuracy of output data, due to the sensors' noise, and the drift of the gyroscope. The second type of IMU consists of an accelerometer, gyroscope, and magnetometer to obtain measurements in three different axes, making a total of 9 DoF. The magnetometer is used to measure yaw angle rotation, so yaw angle can be calibrated by both a gyroscope, and a magnetometer (Ahmed et al., 2013).

The key difference between IMU and AHRS is that an AHRS has the addition of on-board processing system. Non-linear estimation such as an Extended Kalman Filter is typically used to calculate attitude and heading information. Global Positioning System (GPS) provides global position of x- and y-axes, and relative speed of a ship. However, it gives about 2–3 s delayed result, and its nominal accuracy is about 5–10 m. Differential Global Positioning System (DGPS) uses a network of fixed ground based stations, so its nominal accuracy is improved about 5–10 cm, but it can be used only in the coast areas.

A ship's speed measurement before GPS is important to the navigation system. Dead reckoning position calculation depends on a ship's heading and speed. A ship's speed can be measured relative to either the seabed or to the water flowing past the hull (water reference speed). The speed logging methods are the pressure tube log, electromagnetic log, and Doppler speed log (Tetley and Calcutt, 2001).

1.1.2. Underwater vehicles' localization system

Localization and dynamic position control of Autonomous Underwater Vehicles (AUVs) are very important subjects while AUVs are operated as hover style and flight style such as path following, target tracking control applications for underwater construction, maintenance, also underwater mapping. Other important subject, energy efficiency can be obtained by using successful localization and dynamic position control because of preventing drifts.

Data fusion of sensors for navigation was studied extensively in the literature, because localization of AUVs is ongoing problem. The most common underwater navigation includes Doppler Velocity Log Sensors (DVL), Ultra Short Baseline (USBL)/Long Baseline (LBL) with IMU. The integration of DVL/IMU for underwater vehicle was studied in (Lee et al., 2005) using multisensor Kalman Filtering (KF). DVL-based navigation causes drift in the position estimate, and this becomes even worst in AUV navigation with range longer than 300 m. So, a DVL is hardly used alone for underwater navigation. It is combined with other sensors for example acoustic sensors (Bandara et al., 2016). USBL and LBL-based navigation systems of AUVs are explained comparatively, and indicated drawbacks of USBL during an AUV's docking, and flight style operation beneath sea ice (Plueddemann et al., 2012). A survey researches about localization, navigation and mapping of AUVs are reported (Chen et al., 2013; Paull et al., 2014).

Localization of AUVs was calculated online based on Kalman Filtering by using IMU and a laser-based vision system. These experimental studies were applied in a tank, but the measurement range of the laser-based vision feedback was very short distance such as from 30 cm up to 5 m. Also, computer vision feedback was carried out at low frequency (Karras et al., 2011; Cain and Leonessa, 2012).

USBL/LBL acoustic position measurement system does not work correctly for localization of AUVs in the tank tests, because of wall effects. Also, range of localization of AUV by using vision feedback is very short and vision feedback frequency is very low. Dead reckoning method including DVL/IMU may cause drifts of AUV motion. Consequently, integration of 2 or 3-echosounding altimeters to IMU and pressure depth sensor on AUV can be used to localize of AUV in the tank tests. 2-echosounding altimeters adding on AUV enable to measure positions of X-, and Y-axes. Hence, localization of AUV can be obtained. It is shown in Fig. 1 a. Frequency range of an altimeter is 1–4 Hz, and distance range feedback of it is 5–100 m if a magnetometer has big drifts during the tank tests, 3-echosounding altimeters can be used to measure yaw angle, as well Fig. 1 b. Also, an echo sounding altimeter has lower price than DVL.

In addition to these, USBL measurement system may not work correctly near shore, and shallow water. Hence, an echo sounding altimeter would be used to keep distance control on AUVs during flight style operation of AUVs in shallow coastal and under ice areas, also during docking of AUVs. These would be provided collision avoidance of AUVs from fix and dynamic targets.

1.2. Noise, derivative problems, and filtering methods

In real-time, closed-loop control applications, there are problems such as noisy measurements and derivative processes. A variety of filtering methods are available to reduce the noise in the literature. Averaging the sampling data is a simple filtering method. Butterworth filters are frequency based digital filters. They include low-pass, high-pass, band-pass, etc. The common problem encountered in using Butterworth filters is the phase delay problem (Butterworth, 1930).

Furthermore, the Kalman Filter is widely used in time series for signal processing. The Complementary Filtering (CF) may be another method to be obtained accurate and stable data from an AHRS based on low-cost MEMS (Micro-Electro-Mechanical Systems). High frequency such as 100 Hz should be applied for the CF application (Wang et al., 2014).

The Kalman Filter is applied not only in signal processing but also in the estimation of velocity. The derivation of position signal data may be needed not having another sensor for measuring velocity. A general derivative process is the Euler method, but this method may not give accurate results. An efficient velocity estimation algorithm is given in the literature as the Enhanced Differentiator (ED) (Su et al., 2006).

1.3. Data transfer and communication types

The sensors feature different means of communication such as analog, RS232/RS485, USB, NMEA 0 183/2000, Ethernet. Although most of these communication types are the same as general engineering applications, NMEA is a specific protocol for the maritime industry. A digital signal is preferred to an analog signal, because an analog signal has a disadvantage for long distances during transferring data between a controller and feedback signals. Data transfer time of a common communication must be fast enough for the sampling time, and the closed loop time of a real-time application.

Communication systems in a maritime application are CANopen (CAN), NMEA, MODBUS, PROFIBUS, PROFINET, Ethernet TCP/IP, EtherCAT protocols. A maritime automation system can be very complex. It is generally structured into three hierarchical levels such as field-level networks, control-level networks, and information-level networks