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Underwater Navigation System Based on Inertial Sensor and Doppler Velocity Log Using Indirect Feedback Kalman Filter

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This paper presents a hybrid underwater navigation system for unmanned underwater vehicles. The navigation system consists of an inertial measurement unit (IMU) and a Doppler velocity log (DVL) along with the magnetic compass and depth sensor. A navigational system error model is derived to include the bias errors of accelerometers and gyros in the IMU, the scale errors of the DVL, and the bias errors of the compass and depth sensor. An extended Kalman filter is used for the error model in indirect feedback, where the measurement equation is composed of the navigational state errors and system parameters. This paper demonstrates the effectiveness of the inertial-Doppler navigation system through a lawn-mowing mode in simulation and circular motion with rotating arm tests in the experiments. The hybrid navigation system equipped with a low-quality IMU sensor improves navigational performance, where the bias error of the accelerometers and the gyros of the IMU are 1.0 mg and 1.0 deg/h, respectively. The tracking error is less than 1.0 m for 10 min of circular motion from the experiments.

INTRODUCTION

Since a radio wave cannot pass through the operating environment of underwater vehicles, acoustic positioning systems such as LBL (long baseline), SBL (short baseline) and USBL (ultra short baseline) are widely used for underwater vehicles (Milne, 1983). These acoustic positioning systems have no accumulative error, while they have a low update rate and limited accuracy in position estimation. In general, the LBL system is widely used to localize underwater vehicles for its reliability and relatively higher accuracy, but we have to install acoustic sensors at a predetermined position on the sea bottom, and the working range is limited by the distance of the deployed sensors. On the other hand, the USBL system can be used conveniently for the tracking and monitoring of far-reaching AUV; however, the position accuracy rapidly deteriorates as slant range increases. It is hard, then, to use the USBL alone for the positioning and control of an underwater vehicle (Trimble, 1998).

Inertial navigation systems are widely used for navigation, guidance and control of vehicles in land, air and sea, because they are small and self-contained in mobile vehicles. An inertial navigation system has exponentially increasing error due to the integration of the inherent bias errors in the inertial sensors. Inertial navigation systems give accurate position information for a short period, while the bias error accumulates with time. This accumulation leads to very large position error (Titterton, 1997; Larsen, 2001). Auxiliary sensors are needed to compensate for accumulative bias errors. For application to underwater vehicles' navigation, various hybrid positioning systems have been proposed based on the inertial navigation sensor, together with a Doppler velocity logger (DVL), magnetic compass, depth sensor, inclinometer, acoustic sensors and GPS sensors, to enhance the performance of the navigation system near the seawater surface.

Surface navigation systems have been developed successfully by integrating GPS with inertial sensors. However, introducing GPS to underwater navigation systems is limited to the case of shallow water vehicles repeatedly surfacing to update position information (Marco and Healey, 2001; Yun et al., 1999; An et al., 1996). Larsen (2000 a, b), Beiter et al. (1998) and Uliana (1997) have proposed hybrid navigation systems based on an inertial sensor combined with acoustic velocity sensors. Recently, Kinsey and Whitcomb (2003) proposed a navigation method integrating a DVL signal with an LBL system to enhance position accuracy in the deep sea.

In this paper, we propose a new hybrid underwater navigation system based on a strap-down inertial measurement unit (IMU) accompanied by depth sensor, magnetic compass and DVL. A dynamic error model and a measurement model for the inertial-Doppler hybrid navigation system are designed to implement the extended Kalman filter in indirect feedback form. The bias and scale errors of the inertial and auxiliary sensors are modeled in the system matrix of the navigation algorithm. The measurement equation is modeled with the navigational state errors and system parameters. The navigation system predicts the errors of the navigational state with the extended Kalman filter, while the bias and scale errors are updated indirectly whenever external measurements are available.

This paper demonstrates the effectiveness of the navigation system through simulation and experiments. Rotating arm tests of an AUV were conducted in the Ocean Engineering Basin at KRISO to compare the estimated position of the inertial-Doppler underwater navigation system. The hybrid navigation system equipped with a low-quality IMU sensor improves navigational performance. In addition, this paper surveys the effect of the sample rate of the inertial and Doppler sensors on navigational performance.

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