Reliable EKF Algorithm For Low-Cost AUV Navigation
Method Integrates Initialization, Outlier Rejection and State Noise
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Reliable navigation is critical for AUVs, not only for the sake of safe operation and recovery, but also for scientific surveys. AUVs are now being used for a variety of tasks, including oceanographic surveys, demining, and bathymetric data collection in marine and river environments. AUV navigation is a challenging problem, primarily due to the rapid attenuation of high-frequency signals and the unstructured nature of the undersea environment.

Acoustic EKF navigation systems are still a popular method. The field is in the midst of a paradigm shift from old technologies, such as long baseline (LBL) that require predeployed and localized infrastructure, toward dynamic system approaches that allow for rapid deployment and flexibility with minimal infrastructure. Other systems, like ultrashort baseline (USBBL), are employed to track and locate underwater vehicles. However, the EKF navigation algorithm of AUVs is challenging because it is difficult to design an effective online processing procedure for travel time measurements, which may be affected by noise, drops outs and outliers. Although the inertial navigation unit with high accuracy would perform well in the heading measurement, it costs much more than an electronic compass and consequently leads to a high expenditure in AUV development.

We equipped an AUV with a PNI Sensor Corp. (Santa Rosa, California) TCMS electronic compass and a 300-kiloherz acoustic Doppler velocity log (DVLo) developed by the Institute of Acoustics, Chinese Academy of Sciences, as heading and velocity sensors.

As part of its sensor suite, a customized, multiple-beacon navigation system was equipped on the AUV.

(Top) The error of initializing methods. The x-axis is the time sequence of sampling, and the period is 24 seconds. (Bottom) Vehicle track comparison of two navigation algorithms (without outlier rejection versus with outlier rejection).

To estimate the vehicle position reliably using low-cost sensors and acoustic ranges from multiple beacons, we designed a novel EKF navigation algorithm that integrates an initialization, outlier rejection and state noise set method. The
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output error of the Kalman filter will increase rapidly and even diverge. Although the real noise value is difficult to obtain for the actual model, we can determine the noise parameters that are most likely to occur based on the technology indicator and principle of the actual equipment with the working environment. For example, the error consists of the TCMS electronic compass and a 300-kilohertz acoustic Doppler instrument for the dead reckoning system. The error of the 300-kilohertz acoustic Doppler instrument is only 0.5 percent of the real speed v, and the error of the TCMS electronic compass is 3°. The latter is far larger. Thus, the position error caused during the unit time is approximately sin(5°) v T, with T as the period of acoustic pinging.

Experimental Results
The experiments were carried out in March and June 2013 in the South China Sea. In the experiments, T was 24 seconds, the maximum and minimum velocities were four minutes per second and zero minutes per second, respectively, the maximum area was 0.5 meters per second squared, and the threshold for outlier rejection was 9.21. The cruise speed was one minute per second. There were four acoustic beacons deployed at the sea bottom.

The correct initiation point could be obtained by both the fixed computation and estimation methods, but the estimating method consumed much more time. The time-delay resolver error converged rapidly with the state of small error range (approximately 120 seconds), and the time for the estimation method error was 720 seconds. Thus, the time-delay resolver method is the better choice for more accurate navigation in the presence of at least three beacon signals; otherwise, the estimation method would be a better choice.

When plotted out, we can directly see that the track estimated with proposed outlier rejection is much smoother than without outlier rejection. The plots indicate that the travel time measurements are able to correct the vehicle position, while the false measurements are dropped out to avoid disturbing the estimates. In contrast, the track estimated without outlier rejection produces more significant jumps. The reason for these jumps is primarily that outliers from raw measurements have not been rejected, and as a result the estimates are contaminated.

The TCMS electronic compass was used as a heading sensor for navigation, but unfortunately the sensor was badly calibrated, and the results deviated from the real value. After we got the sea trial data and analyzed the data offline, we found that a 9° deviation existed. The error of the estimated position using small state noise (the value was 0.2) is very large, and the error using large state noise (the value was 21) is relatively small, except some fluctuations. The results tell us that when we use EKF as a navigation algorithm, if the system model is not accurate or there is a relatively large error in the calibration of sensors, we can set a large noise for the system state, which makes for better filtering results.

Conclusion
EKF is a very important algorithm in autonomous navigation systems. Although it is not a new algorithm, there are still some problems remaining to be addressed regarding low-ac-