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Towards standalone attitude estimation for instrumented flow followers

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Summary:
A concept for 3D-motion tracking of instrumented flow-following sensor particles, equipped with a gyroscope, accelerometer, magnetometer and pressure sensor, has been developed. Consisting of an error state Kalman filter (ESKF) the algorithm can track the attitude of the sensor particle in relation to a reference coordinate system. In this short paper we investigated if the estimated attitude returns to the reference trajectory after experiencing motion similar to a motion that is expected to be found in the multidisperse fluid flows of a biogas fermenter or a waste water treatment basin. Results show the feasibility of the proposed method. However, the strategy of the measurement update in the ESKF needs improvement.

Keywords: error state kalman filter, motion tracking, fluid dynamics, sensor particle, soft sensor

Motivation

The investigation of the fluid flow in large-scale plants or vessels like biogas fermenters or activated sludge tanks, is limited because currently applied instrumentation only measures locally. To optimize the use of energy and resources in such plants, the flow patterns inside the vessels need to be known. To overcome the limitations of local sensors, the concept of instrumented flow-following sensor particles has been developed at HZDR [1].

The aim is, to recover the acceleration, velocity and position of the sensor particle in the vessel over time, to track the flow pattern. Therefore, sensor particles are equipped with an accelerometer, a gyroscope, a magnetometer and a pressure sensor. Since the measurements are taken in body coordinates, the reconstruction of the attitude of the sensor particle in relation to the vessel is of fundamental importance. An absolute attitude is obtained by combining the measurement of acceleration due to gravitation and earth magnetic field aiding the attitude calculated from the measured angular velocity.

In this short paper, we show that an error state Kalman filter (ESKF) as presented in [2] can be used to estimate the attitude of the sensor particle after an experienced motion with a maximum angular velocity of 55.7 °/s and a maximum acceleration of 13.2 m/s².

Method

To investigate the developed algorithm, a customized inertial measurement unit (IMU) was build from an accelerometer ADXL355, a gyroscope IAM-20380, a magnetometer MMC5883MA and an Arduino Due. The IMU was strapped to a hexapod, as shown in fig. 1.

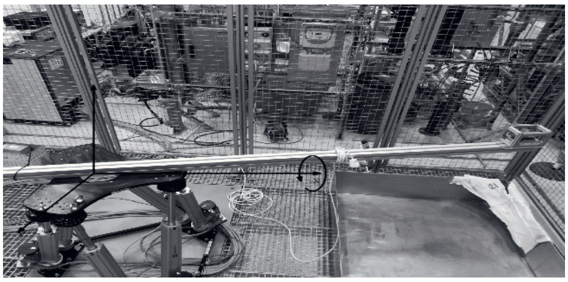

Fig 1: Experimental setup for a circular motion of sensor particles on a hexapod. The length of the arm was 195 cm.

The setup measures body acceleration, angular velocity and the earth magnetic field with a sampling rate of 500, 250 and 100 Hz, respectively and then low pass filtered with a cutoff frequency of 5 Hz. To use the local magnetic field as an aiding attitude element, a proper calibration of the magnetometer data was performed by using the initial parameter estimation for the bias and misalignment of the algorithm described in [3]. The local magnetic field reference was taken at the initial position (φ = 15 °) and was $\boldsymbol{B_0} =$

$[-12.5\ 26.6\ 23.6]$ nT. The bias of the inertial sensors was obtained by taking the mean over 5 seconds when the IMU was at rest. The inertial sensors noise characteristics was identified with the allan variance method [4].

All these quantities were then used by the ESKF to estimate the attitude in vessel coordinates.

As an example of an expected motion in agitated vessels, such as biogas digesters, a circular motion in the y-z-plane of radius 0.5 m was chosen. The motion was generated by manipulating the angles yaw (φ), pitch (θ) and roll (ψ) with a sinusoidal signal with a frequency of 0.25 Hz (φ, θ) and 0.40 Hz (ψ) and a magnitude of 15 °, 15 ° and 20 °. One motion cycle had a duration of 60 seconds with an appended pause of 12 s. This motion was repeated for 20 times. The resulting angular movement for 2 cycles is depicted in fig. 2. The ESKF was intended to perform the measurement update in the pause of the motion as soon as the norm of the measured acceleration and the norm magnetic field deviated less than 0.001% to gravity and the norm local magnetic field, respectively.

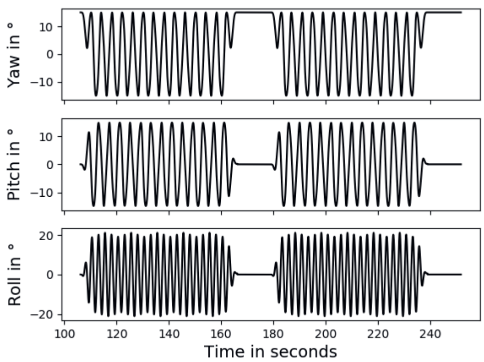

Fig 2: Extract of the attitude reference trajectory in Euler angles.

Results

To evaluate the quality of the attitude estimation, the error between the reference trajectory and the estimated trajectory and the raw integrated angular velocity, respectively are shown in fig. 3. It is evident, that the raw integrated angular velocity drifts off from the reference trajectory since the error is not symmetric with respect to the reference. The filtered result from the ESKF does not show this drift. But the error margin is still too large with a maximum deviation of Δφ=19 °, θΔ=14.3 °, Δψ=23.5 ° to obtain a valid velocity or position from the measured acceleration. Due to noise and changes of the local magnetic field in the area of motion the updates were sometimes performed at the period at the motion and not only in the pause. This then leads to a wrong attitude. The filter corrected this in the next pause.

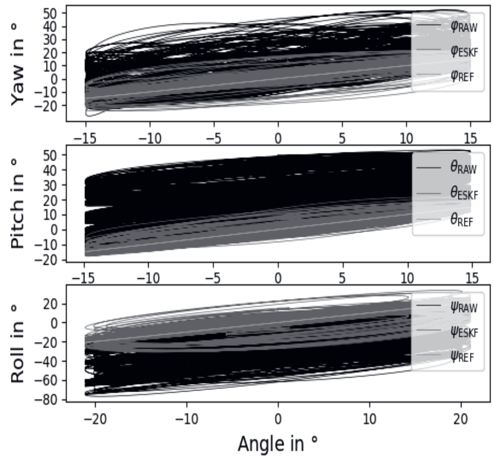

Fig 3: Error of the estimated attitude for each Euler angle.

Conclusion

The motion-tracking algorithm introduced in [2] can reconstruct the attitude of the sensor particle in relation to the vessel. This allows to calculate the acceleration in vessel coordinates and, due to the pressure sensor, allows a statistical analysis of the vertical acceleration profile. Further development will focus on a better calibration and noise estimation of all sensors. Also, we aim to develop a proper strategy for the measurement update since we expect disturbances of the magnetic field next to deviation of gravity and measured acceleration.

Acknowledgments

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