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Towards 3D-Motion Tracking of Instrumented Flow Followers in Large Vessels

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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 permanently, even under high acceleration, which interferes the attitude estimation because it is based on measuring the gravitational acceleration. Experimental results show, that using the ESKF for attitude estimation is giving accurate results even under high body acceleration.

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 in the presence of a permanently disturbing high acceleration. High in this context means that the acceleration is about 85% higher than in 90% of the vessel volume. The validation is based on the following experimental method.

Method

To investigate the developed algorithm, the inertial measurement unit BNO055 from Bosch Sensortec and an Arduino Due were strapped as a unit to a rotating table, as shown in fig. 1. The setup measures body acceleration, angular velocity and the earth magnetic field with a sampling rate of 100 Hz. These measurements were fed into the algorithm, which filtered the input data and corrected the initial bias, inherent to all sensors. The noise characteristics of all sensors were identified beforehand and are listened in [2]. All these quantities were then used by the ESKF to estimate attitude and the acceleration in vessel coordinates.

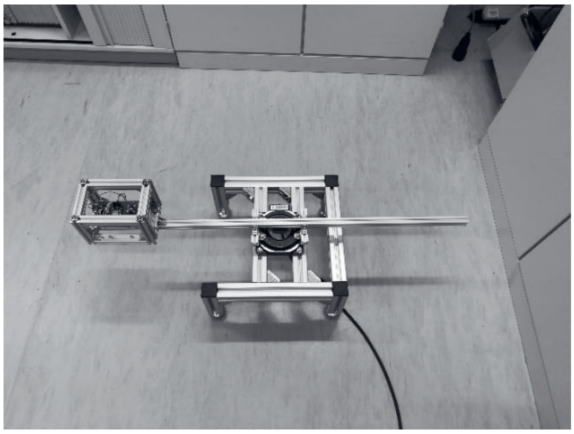

Fig 1: Experimental setup for circular motion of sensor particles on a rotary table.

As an example of a typical motion one can find in round vessels a circular motion was chosen. The radius of the circle was 42.5 cm and the angular velocity of the motor was 180 °/s, which results in a radial acceleration of 4.2 m/s² and a measured body acceleration of $\boldsymbol{a_m^B} = [4.2, 0, 9.81]$ m/s². The measurement time was 10 minutes. The motion was started after about 70 seconds, to estimate the initial bias of the sensors. The motor was set to make 120 turns and the start and end position were identical, making it easy to identify the correct attitude estimation of the filter. The prefiltered body acceleration is depicted in fig. 2.

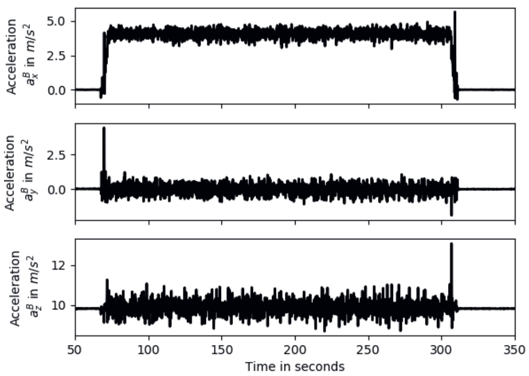

Fig 2: Extract of the filtered body acceleration $\boldsymbol{a_x^B}, \boldsymbol{a_y^B}$ and $\boldsymbol{a_z^B}$.

Results

The estimated attitude is shown in fig. 3 and represented as unit quaternion, where $\boldsymbol{q_x}, \boldsymbol{q_y}$ and $\boldsymbol{q_z}$ are the axis of rotation, $\boldsymbol{q_w}$ is the magnitude of this rotation and $|\boldsymbol{q}| = \boldsymbol{1}$. For a circular motion around the z-axis $\boldsymbol{q_x}$ and $\boldsymbol{q_y}$ are expected to be zero. The estimated attitude fits the expected one with only small deviations. Especially the start and end attitude are equal. Values of $\boldsymbol{q_x}$ and $\boldsymbol{q_y}$ are close to zero, meaning that there is only a small error introduced by the difference between $|\boldsymbol{a}|_{ref}$ = 9.81 m/s² and $|\boldsymbol{a_m^B}|$. The oscillation on $\boldsymbol{q_x}$ and $\boldsymbol{q_y}$ seen in fig. 3 occurs due to imperfect alignment of the sensor axes with the

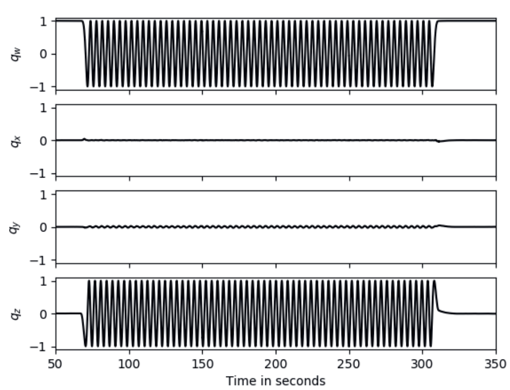

Fig 3: Extract of the estimated attitude in unit quaternion $|\boldsymbol{q}| = |[\boldsymbol{q_w}, \boldsymbol{q_x}, \boldsymbol{q_y}, \boldsymbol{q_z}]| = 1$ representation.

arm mounted on the rotation table. Besides the small deviations. Fig. 4 shows an extract of the acceleration transformed into vessel coordinates using the estimated quaternion by removing the acceleration due to gravitation and using

$$\boldsymbol{a^{vessel}} = \boldsymbol{q} * \boldsymbol{a^B} * \boldsymbol{q^{-1}},$$

where $\boldsymbol{q^{-1}}$ is the inverse of the quaternion $\boldsymbol{q}$.

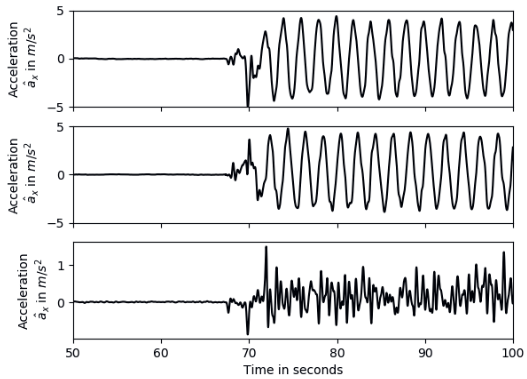

Fig 4: Extract of the estimated acceleration $\boldsymbol{\hat{a}_x}, \boldsymbol{\hat{a}_y}$ and $\boldsymbol{\hat{a}_z}$ in vessel coordinates.

As to be expected for a planar circular motion the acceleration in vessel coordinates is sinusoidal after starting the motion. The acceleration on $\boldsymbol{\hat{a}_z}$ in fig. 4 appears due to improper alignment of the accelerometer with the arm, vibration of the rotating table and measurement noise.

Conclusion

The motion-tracking algorithm introduced in [2] can reconstruct the attitude and acceleration of the sensor particle in relation to the vessel even if a high acceleration is measured which interferes with the attitude estimation. This forms the basis to extract velocity and position and, due to the pressure sensor, allows a statistical analysis of the vertical acceleration profile. Further development will focus on enhanced measurement quality of the ESKF to improve the flow tracking performance.

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References

[1] Thiele, S., Da Silva, M. J., & Hampel, U. (2010). Autonomous sensor particle for parameter tracking in large vessels. *Measurement Science and Technology*, *21*(8), 085201.

[2] Buntkiel, L., Reinecke, S. F., & Hampel, U. (2019). 3.5-Inertiale Lage-und Bewegungsverfolgung für instrumentierte Strömungsfolger zur Strömungscharakterisierung. *Tagungsband*, 52-58, DOI: 10.5162/14dss2019/3.5.