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PROJECT DESCRIPTION

State Estimation

AIS2202 Cybernetics

Bachelor in Automation and Intelligent Systems
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Department of ICT and Natural Sciences (IIR)
Faculty of Information Technology and Electrical Engineering (IE)
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Acronyms

CAD computer-aided design.

FTS force/torque sensor.

IMU inertial measurement unit.

1 Background

For an industrial robot to interact with the environment, a force/torque sensor (FTS) must be attached between the robot flange and the end effector tool. Most robot end effector tools are designed using computer-aided design (CAD), and their geometry, mass and center of mass can be calculated by the CAD program. However, tools that have been hand-made, or tool attachments that are otherwise *unknown*, must be be calibrated prior to use with the robot.

The FTS measures all forces and torques acting on it, including contact with the environment and the effects of gravity, robot motion and mechanical vibrations. Similarly, an inertial measurement unit (IMU) attached to the end effector will measure the same acceleration effects as the FTS, except contact with the environment.

The mass parameters of the end effector tool can be estimated, and the IMU combined with these parameters can be used to compensate for gravity, motion and vibrations in the FTS measurements.

2 Objectives

The aim of this project is to learn how to:

- Calibrate a FTS and IMU.
- Use least squares to estimate the (constant) mass and mass center of an *unknown* robot end effector tool.
- Use the Kalman filter and sensor fusion to reduce noise and compensate for the effects of gravity, vibrations and inertia (robot motion) in the FTS measurements.

The project is based on a dataset and two papers:

1. Accelerometer and Force/Torque Sensor Measurements for Parameter and State Estimation of an Unknown Robot End Effector [1].
2. Bias Estimation and Gravity Compensation for Force-Torque Sensors [2].
3. A Linear Discrete Kalman Filter to Estimate the Contact Wrench of an Unknown Robot End Effector [3].

Implement the least squares estimation, Kalman filter and sensor fusion algorithm as described in the papers without using existing libraries (e.g., Matlab *toolboxes*) other than for linear algebra. In other words, libraries for linear algebra types and operations are permitted, such as the C++ library `Eigen`, numpy's `linalg`, basic Matlab functions and syntax, or similar.

Objective 1: Sensor calibration and parameter estimation

This objective can be summarized by:

1. Estimate the FTS and IMU measurement biases.
2. Estimate the mass and mass center of the end effector tool attached to the FTS.

Implement the methods and equations from "Bias Estimation and Gravity Compensation for Force-Torque Sensors" [2] using the sensor measurements in `0-calibration_fts-accel.csv` from the dataset [1].

O.1 a) Estimating the sensor measurement bias
The FTS measures six values, a force vector and torque vector with three components each, and the IMU measures three values, an acceleration vector with three components. (In reality, the IMU also measures angular velocity, but this was not included in the dataset.) Each vector component from these sensors will have a constant deviation from the true measurement, called the sensor bias, which must be estimated and compensated for.

Once the biases have been estimated, they must be subtracted from all subsequent sensor measurement samples. For the FTS samples, the bias must be subtracted from the samples prior to mass and mass center estimation.

O.1 b) Estimating the mass and mass center of an end effector tool
The FTS measures the sum of force and torque from all effects acting on it, including gravity and the robot motion. In order to model the effects of gravity in the sensor measurements, the mass and mass center of the

unknown end effector tool must be estimated. These parameters will be used in the Kalman filter model to compensate for gravity.

Objective 2: Estimate the contact wrench between the robot and the environment

The objective can be summarized by:

1. Estimate the FTS and IMU signal variances.
2. Implement the Kalman filter.
3. Implement the state space model for estimating the contact wrench.
4. Optional: expand the model for estimating the contact wrench.

The contact wrench (force and torque) between the robot and the environment can be estimated by subtracting (1) the wrench arising from from gravity, (2) the robot motion, and (3) vibrations from the unbiased FTS measurements.

The effect from gravity can be modeled using the end effector orientation (a rotation matrix), the mass, and mass center of the end effector. Noise in the sensor signals can be represented by the signal variances at rest, whereas the IMU measurements and the estimated mass parameter can be used for sensor fusion to compensate for the wrenches arising from tvibrations and robot motion.

O.2 a) Estimate the FTS and IMU signal variances.
Noise is present in all sensors and signals. An assumption about noise when using the Kalman filter is that the noise is statistical white (following a normal distribution) with zero mean. As such, the noise can be described by its *variance*. Estimating the variance in a signal requires a system in rest, or steady state.

The files `0-steady-state_accel.csv` and `0-steady-state_wrench.csv` contains data sampled from the IMU and FTS, respectively, in steady state. These measurements can be used to find the sensor variances.

O.2 b) Implement the Kalman filter.
The algorithm and equations for the Kalman filter, as described in "An Introduction to the Kalman Filter" [4], are general and do not depend on any specific application or state space model. As such, the Kalman filter can be implemented as a class with functions for each equation/step in the algorithm, without considerations to any specific model.

O.2 c) Implement the state space model for estimating the contact wrench.
Unlike the Kalman filter itself, the sensor fusion logic depends on the state space model, in this case the model described in "A Linear Discrete Kalman Filter to Estimate the Contact Wrench of an Unknown Robot End Effector" [3].

For each experiment described in the paper (baseline, vibrations, and vibrations + contact), the FTS, IMU and end effector orientation samples are listed in three separate files, each with *different sampling rates*.

1. Baseline: `1-baseline_{accel, wrench, orientation}.csv`
2. Vibrations: `2-vibrations_{accel, wrench, orientation}.csv`
3. Vibrations and contact: `3-vibrations-contact_{accel, wrench, orientation}.csv`

Implement a class, e.g., called `Fusion`, which constructs the state space model matrices and invokes the appropriate functions of the Kalman filter. Samples per experiment (from the three files) should be passed to `Fusion`, in order, based on the the timestamps.

O.2 d) Optional: expand the model for estimating the contact wrench.
The study in "A Linear Discrete Kalman Filter to Estimate the Contact Wrench of an Unknown Robot End Effector" [3] has some shortcomings which can be improved upon. For example, only the responses of the z-axis force and y-axis torque ($\mathcal{F}_3$ and $\mathcal{T}_2$) were investigated. Additionally, the scaling factor for tuning the filter did not distinguish between each FTS vector component.

Other expansions of the project may be to replicate the physical experiment (with or without a robot), by using or 3D-printing a *known* end effector tool, and attaching an IMU to the FTS.

3 Deliverables

The project in this course module is part of the course portfolio exam, and must be delivered in Inspera during the exam period.

Details on the Inspera submission will be posted at a later time, but the portfolio will include (possibly among other things) (1) a report describing the project work and results, and (2) the source code developed during the projects.

The report section for this project must follow the IMRaD(C) format (**I**ntroduction and background, **M**aterials and method, **R**esults and **D**iscussions with **C**onclusions) and contain the following (at minimum):

1. The estimated sensor biases, mass parameters, and variances.
2. The plots of the sensor measurements, state variables, and estimated values.
3. An interpretation and discussion of the plots (estimator responses compared to the sensor signals and state vector).

The (1) adjusted sensor signals (unbiased and, where relevant, transformed to $\{s\}$), Kalman filter (2) state vector and (3) estimates must be included in the submission as individual `.csv` files.

Since this is part of the exam, it is wise to **be conscious about the use of AI**, e.g., to generate code, text, ideas and solutions. See the appendix for the declaration form (from the IE faculty) that must be submitted alongside the portfolio report.

Instead of adding the outputs from the AI tool to the declaration form, the user input prompts and generated outputs from the AI tool can be included in the report (which will not count towards any potential page limits) as an appendix section.

References

[1] Aleksander Skrede. "Accelerometer and Force/Torque Sensor Measurements for Parameter and State Estimation of an Unknown Robot End Effector". In: Zenodo, May 2024. DOI: `10.5281/zenodo.11075229`. URL: `https://zenodo.org/doi/10.5281/zenodo.11075229`.

[2] Stavros Vougioukas. "Bias Estimation and Gravity Compensation for Force-Torque Sensors". In: *Recent Advances in Simulation, Computational Methods and Soft Computing*. WSEAS Press, 2001, pp. 82–85.

[3] Aleksander Skrede. "A Linear Discrete Kalman Filter to Estimate the Contact Wrench of an Unknown Robot End Effector". In: *2024 IEEE International Conference on Real-time Computing and Robotics (RCAR)*. June 2024, pp. 341–347. DOI: `10.1109/RCAR61438.2024.10671273`.

[4] Greg Welch and Gary Bishop. *An Introduction to the Kalman Filter*. en. 2006.

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