User Manual

1. Goal

Researchers can use this dataset to perform benchmarking studies related to orientation estimation with magnetic and inertial measurement units (MIMUs) using sensor fusion algorithms (SFAs). Notably:

1. This online repository gathers more than 35 SFAs for estimating the 3D orientation of MIMUs. You can see a comprehensive review of SFAs in [1].
2. This online repository provides data of an experimental study (see description of experimental data in Section 3.2.) with nine participants where signals of three MIMUs were recorded. Also, a camera motion capture system was used to record the true orientation of the MIMUs.
3. Using the provided codes and data, one can find the optimal set of parameters for each SFA to achieve robust and accurate estimation.

Data included in this online repository was part of an experimental study performed at the University of Alberta (by Milad Nazarahari (nazaraha@ualberta.ca) as a part of the Ph.D. thesis under the supervision of Dr. Hossein Rouhani (hrouhani@ualberta.ca)). The result of a benchmarking study with these codes and data can be found in [2].

1.1. How to Cite

The codes and their associated data can be used subject to proper citation and only for non-commercial purposes. For commercial purposes, contact Milad Nazarahari (nazaraha@ualberta.ca) or Dr. Hossein Rouhani (hrouhani@ualberta.ca).

The codes of SFAs contain the information of the original papers that introduced the SFA as well as the link to the source codes (if the code was obtained from an online repository).

2. Copyright

3. Description of Data

The Research Ethics Board Committee at the University of Alberta approved the study protocol, and written consent was obtained from all participants. The experimental study included nine able-bodied participants (all male, 26±2 years old, 74±6 kg, 177±4 cm).

3.1. Measurement Setup

Three MIMUs (MTws, Xsens Technologies, The Netherlands) were attached to a rigid plastic plate equipped with four/five retro-reflective markers and fixed over the thigh, shank, and foot using double-sided medical tape. The MIMUs included a tri-axial accelerometer (range: ±16 g), a tri-axial gyroscope (range: ±2000 deg/s), and a tri-axial magnetometer (range: ±1.9 Gauss). The MIMUs recorded data with a sampling frequency of 100 Hz and transferred wirelessly to a computer. Also, a camera motion-capture system (VICON, Oxford Metrics Group, UK) with eight cameras was used as the reference system to record the 3D position of the plate markers, synchronized with MIMUs.

3.2. Experimental Data

The experimental protocol included two phases:

- **Phase I (MATLAB File: DataShort.mat):** quiet standing (60 seconds), straight walking (5 meters), turning, straight walking (2.5 meters), vertical jumping (two times), straight walking (2.5 meters), turning, hopping with both legs for 5 meters, turning, walking the 5-meter corridor back-and-forth three times with U-turns at the end, quiet standing (30 seconds). Also, participants were instructed to have 2 seconds of quiet standing between every two tasks (one complete trial was 131±7 seconds on average).
- **Phase II (MATLAB File: DataLong.mat):** quiet standing (60 seconds), walking (normal-pace) the 5-meter corridor back-and-forth for 75 seconds with U-turns at the end, walking (normal-pace) the 5-meter corridor back-and-forth for 75 seconds making an ∞-shape, quiet standing (5 seconds), repeating the above two walking periods with a fast pace, quiet standing for 30 seconds (one complete trial was 393±3 seconds in average). The first participant's data were discarded in Phase II as the MIMU data were not recorded correctly.

After loading "DataShort.mat" or "DataLong.mat", a MATLAB structure containing data all participants (called "Subj1", "Subj2", etc.) will be load into the MATLAB workspace. Data of each participant include the following:

- MoCap: Motion-capture data.
  - MoCap.StaticH: MIMUs were placed horizontally on the level ground surface for a few seconds and MIMU and motion-capture data were recorded (Figure 1a).
  - MoCap.StaticV: MIMUs were placed vertically on the level ground surface for a few seconds and MIMU and motion-capture data were recorded (Figure 1b).
  - MoCap.Walking: Main experimental data (Figure 1c).
    - MoCap.Walking.Thigh/Shank/Foot: trajectory of three markers attached to plates (labeled with a, b, and c in Figure 1a).

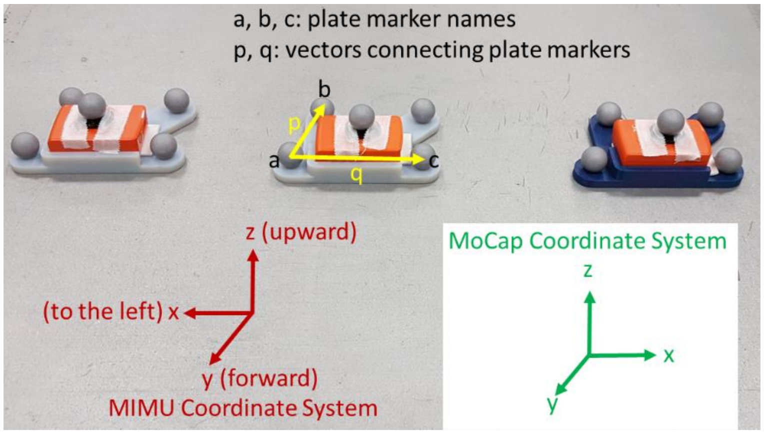

Figure 1a: MIMUs were placed horizontally on the level ground surface.

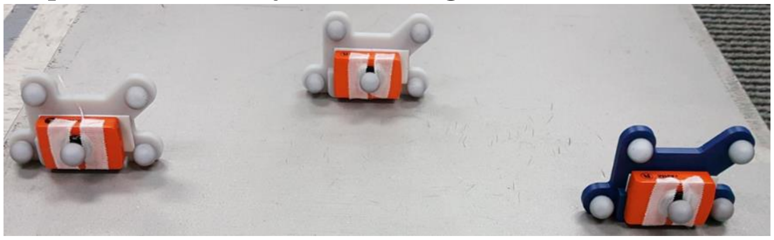

Figure 1b: MIMUs were placed vertically on the level ground surface.

Figure 1c: MIMUs attachment during trials.

- IMU: MIMU data. For all MIMU data, data are recorded in an N-by-13 matrix (N: number of samples). The first three columns are accelerometer data (normalized by gravity), the second three columns gyroscope data, the third three columns are magnetometer data, and the last four columns are orientation obtained by Xsens proprietary Kalman Filter presented with quaternion parametrization (reference coordinate system of MIMUs is not known).
    - IMU.StaticH.Thigh/Shank/Foot: MIMUs were placed horizontally on the level ground surface for a few seconds and MIMU and motion-capture data were recorded (Figure 1a).
    - IMU.Thigh/Shank/Foot: MIMUs were placed vertically on the level ground surface for a few seconds and MIMU and motion-capture data were recorded (Figure 1b).
    - IMU.Walking.Thigh/Shank/Foot: Main experimental data (Figure 1c).
- SA2PM.Thigh/Shank/Foot: The fixed misalignment between MIMU and plate local frames due to the attachment inaccuracies and was calculated according to [3], [4]. StaticH and StaticV trials of MIMU and motion-capture were used to calculate the fixed misalignment (in quaternion parametrization).
- True.Thigh/Shank/Foot: True (reference) orientation of the MIMUs tracked with the motion-capture system using plate markers with respect to motion capture reference coordinate system presented with quaternion parametrization.
- True_EA.Thigh/Shank/Foot: True (reference) orientation of the MIMUs tracked with the motion-capture system using plate markers with respect to motion capture reference coordinate system presented with Euler angles parametrization.

3.3. Optimal Sensor Fusion Algorithm Gains

After loading “SFA_Gains.mat”, a MATLAB structure named containing the optimal gains for all sensor fusion algorithms will be load into the MATLAB workspace.

- SFA_Gains.SFA_NAME: Contains three sets of optimal parameters for the sensor fusion algorithm named SFA_NAME for obtained via three-fold cross-validation. You can use these parameters to evaluate the sensor fusion performance.
    - These parameters are for the foot MIMU. For thigh and shank MIMUs, you must conduct a search (as described in Section 4 under Code name: “Optimization.m”) to find parameters.

4. Description of Codes

Code name: “SensorFusion_Assessment.m”

- This script can be used to load the data (Section 1) and evaluate sensor fusion algorithms for orientation tracking with MIMUs in the following sections. Each section evaluates one sensor fusion using optimal parameters obtained via optimization and plots the estimated orientation against true (reference) orientation obtained from the motion-capture system.
    - You can load “DataShort.mat” or “DataLong.mat” to see results for Phase I or Phase II of the experimental study, respectively.
    - Keep all the functions (sensor fusion algorithms and utility functions such as quaternion product) and data files in the current directory of MATLAB.

Code name: "SFA_Performance.m"

- This script receives the estimated orientation by a sensor fusion algorithm and returns the (1) root-mean-square of the error between estimated orientation and true orientation (by the motion-capture system) for both Euler angler and quaternion parametrizations; (2) plot of the orientations for Euler angler parametrization. This script uses the initial quiet standing period at the beginning of the experiment to transform the MIMU reference coordinate system into the motion-capture reference coordinate system. See [5] for more information on this procedure.
- This script also presents similar results for the estimated orientation by Xsens proprietary Kalman Filter.

Code name: "Optimization.m"

- This script can be used to find the optimal parameter of a sensor fusion algorithm by comparing the estimated orientation for a set of parameters with true orientation (by the motion-capture system); see [5] for more information.
    - This script can be used to find fixed optimal parameters or optimal parameters and thresholds for adaptive parameter tuning (the implemented examples use a two-level hard-switch for adaptive parameter tuning, see [5] for more details).
    - This script uses Particle Swarm Optimization to conduct the search. You require the "Global Optimization Toolbox" in MATLAB to use function "particleswarm" which implements Particle Swarm Optimization.
    - This script contains two examples of defining the optimization problem (for sensor fusion algorithms named Madgwick2011_MIMU and Nazarahari2020). You can use these examples to create the required functions to find your sensor fusion algorithm's optimal parameters.

5. References

[1] M. Nazarahari and H. Rouhani, "40 Years of Sensor Fusion for Orientation Tracking via Magnetic and Inertial Measurement Units: Methods, Lessons Learned, and Future Challenges," *Inf. Fusion*, vol. 68, pp. 67–84, 2021.

[2] M. Nazarahari and H. Rouhani, "Sensor Fusion Algorithms for Orientation Tracking via Magnetic and Inertial Measurement Units: An Experimental Comparison Survey," *Under Rev.*, 2021.

[3] M. Nazarahari and H. Rouhani, "Semi-automatic Sensor-to-Body Calibration of Inertial Sensors on Lower Limb Using Gait Recording," *IEEE Sens. J.*, vol. 19, no. 24, pp. 12465–12474, 2019.

[4] M. Nazarahari, A. Noamani, N. Ahmadian, and H. Rouhani, "Sensor-to-body calibration procedure for clinical motion analysis of lower limb using Magnetic and Inertial Measurement Units," *J. Biomech.*, vol. 85, pp. 224–229, 2019, doi: 10.1016/j.jbiomech.2019.01.027.

[5] M. Nazarahari and H. Rouhani, "Adaptive Gain Regulation of Sensor Fusion Algorithms for Orientation Estimation with Magnetic and Inertial Measurement Units," *IEEE Trans. Instrum. Meas.*, vol. 70, 2020, doi: 10.1109/TIM.2020.3033077.