IPIN 2023 – Tutorial

Pedestrian Inertial Navigation with ZUPTs: From History to Algorithmic Enhancements

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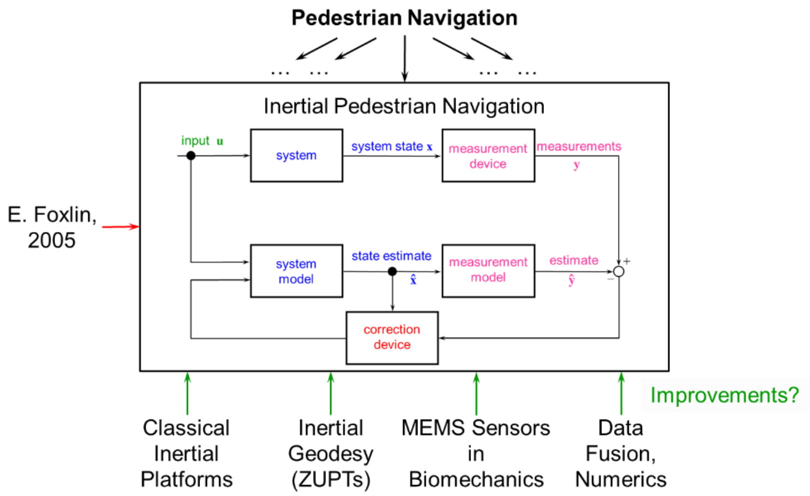
Abstract

ZUPT-based pedestrian inertial navigation is a very popular method for indoor positioning and navigating. Its pure form does not depend on any kind of infrastructure and benefits from the growing availability of small, low-cost inertial measurement units (IMUs) based on MEMS technology. It became especially popular during the last 12 to 15 years after the publication of only a few papers which provided a compact, easily practicable algorithmic basis for processing the IMU signals and which paved the way for numerous research activities on improving and applying this method.



The roots of ZUPT-based pedestrian inertial navigation are, however, much older. Initiated by the invention of the gimballed gyro in 1810, an important technology of gyro instruments emerged about 100 years later and led to high-performance inertial platforms in the middle of the 20th century. These navigation instruments carried gyroscopes and accelerometers on a horizontal, aligned frame, they were masterpieces of precision mechanics, and they represented in principle analog computers. To reduce the weight and costs of these platforms as well as to increase their reliability, a transition to digital technology with optical gyroscopes took place in the following decades: Mechanical platforms were replaced by the so called strapdown technology with inertial sensors directly fixed to the respective vehicle and with specially designed algorithms.

The advent of the MEMS technology with consumer grade IMUs and the increasing packing density of microelectronics effected a drastic miniaturization of strapdown systems. This reduction increasingly enabled biomechanical applications of inertial technology since about two decades. ZUPT-based pedestrian inertial navigation is a prominent example of this development, and a look is worthwhile on the tradition of inertial technology being still present in this kind of indoor navigation.

The first aspect of this view is that the processing of the IMU data for indoor navigation is almost exclusively based on algorithmic features that originate from strapdown systems with high-grade sensors, i.e. accelerometers and gyroscopes of significantly higher accuracy as usual in pedestrian inertial navigation. The second aspect is the fact that the ZUPT approach in these pedestrian navigation systems was originally designed for a very different application, namely inertial geodesy, i.e. for surveying with mechanical platforms of also high-grade sensors. Therefore, neither the ZUPT approach nor the algorithmic features mentioned were designed for the accuracy level of the IMUs used normally for pedestrian navigation, and the question arises about the consequences of this circumstance.

Against that background, the tutorial aims at a reflection of the historical roots, the algorithmic features and the related state of the art of ZUPT-based pedestrian inertial navigation. On this basis, possible algorithmic improvements are introduced and tested using real measurement data of two different research groups with different experimental equipment. The improvements concern the system design, i.e. error states versus total states, the inclusion and modeling of the inertial sensor biases, and the numerical integration of the required ordinary differential equations.

Outline

Introduction

<u>Part A: Historical and Technical Background</u>

1. From Bohnenberger's Machine to the Litton LN-3:
   150 years of mechanical gyro instrument development
2. Transition to Strapdown Systems:
   Strapdown principle, challenges and basic equations
3. Inertial Surveying with ZUPTs:
   Origin and characteristics of first ZUPT applications
4. Inertial Sensors in Biomechanics:
   Requirements and history of using inertial sensors for this application area
5. Pedestrian Motion Capture and Navigation:
   Types of pedestrian navigation systems with inertial sensors

Part A is enriched by some exhibits of historical gyro instruments.

<u>Part B: System Aspects and Algorithmic Enhancements</u>

1. Error state and total state approach:
   Origin of the error modeling,
   observer principle, interdependency of error and total states
2. Discrete-discrete and continuous-discrete Kalman filter:
   Comparison of the basic filter equations
3. Numerical solution of ordinary differential equations:
   Approaches of Euler-Cauchy, Heun and Runge-Kutta
4. ZUPT, ZARU and system observability:
   Aiding of inertial systems, observability analysis
5. Modelling of the inertial sensor bias:
   Allan Variance and Gauß-Markov model
6. State of the art of ZUPT-based pedestrian inertial navigation:
   Results from a literature survey

<u>Part C: Experimental results</u>

1. Data fusion variants:
   Stepwise changing the state of the art of ZUPT-based pedestrian inertial navigation
2. OpenShoe data
3. Data of the authors
4. Influence of the sample rate:
   Checking different sample rates against an improved numerical background
5. Influence of an IMU calibration:
   Checking the calibration influence against an improved numerical background
6. Outlook: Influence of the Earth Rotation Rate:
   Can the Earth rate be neglected for MEMS IMUs?

<u>Part D: Summary</u>

1. Conclusions and recommendations:
   Improving the state of the art of ZUPT-based pedestrian inertial navigation
2. References and further reading

Targeted Persons

PhD students, practitioners, and researchers in pedestrian navigation with basic experiences in inertial sensors or inertial navigation.

Length

150 min plus 30 min for discussion, questions, and answers as well as an optional software exercise (see below).

Planned Activities

The tutorial is organized like a lecture and has a structure which is given in the Outline of the Content. The material is mainly presented with a video projector. In addition, a blackboard is used for auxiliary calculations and to answer questions.

The slides of the presentation as shown by the video projector are provided to each participant at the beginning of the tutorial as paper copy and/or pdf file. They are intended for individual supplementary notes by the participants. In addition, participants are encouraged to ask questions during the presentation.

Based on the OpenShoe code, an optional Matlab® exercise is also introduced: An instruction is given on how to modify the OpenShoe code to implement some of the algorithmic extensions presented.

Instructor

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CV:

1985	Diploma Aerospace Engineering, University of Stuttgart
1986 - 1992	Teaching assistant and PhD student Institute A of Mechanics, University of Stuttgart
1993 - 1996	Development Engineer Aerodata Flugmesstechnik GmbH, Braunschweig, Germany
1995	Doctorate in the field of flight mechanics
1997 - 1999	Senior engineer Department of Aircraft Systems Engineering, Technical Univ. of Hamburg
2000 - 2002	Research associate Department of Mechanics and Ocean Engineering, Technical Univ. of Hamburg
2003	Habilitation in the field of Mechatronics
since 2003	Professor Chair of Flight Measuring Technology, University of Stuttgart
since 2007	Technical Advisor German SOFIA Institute, University of Stuttgart

Areas of Work:

- Mechanics and Mechatronics:
  - experimental mechanics and structural dynamics,
  - biomechanics,
  - optimization
- Navigation
  - inertial sensors and systems,
  - integrated navigation
- History of Technology