CZECH TECHNICAL
UNIVERSITY
IN PRAGUE

F3

Faculty of Electrical Engineering
Department of Control Engineering

Master's Thesis

Indoor localization system for automated vehicles based on Ultra-Wideband technology

Bc. Jitka Hodná
Cybernetics and robotics

May 2021

Datavision s. r. o.
Supervisor: Ing. Tomáš Novák

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Hodná Jitka**
Personal ID number:	**439565**
Faculty / Institute:	**Faculty of Electrical Engineering**
Department / Institute:	**Department of Control Engineering**
Study program:	**Cybernetics and Robotics**
Branch of study:	**Cybernetics and Robotics**

II. Master's thesis details

Master's thesis title in English:

Indoor localization system for automated vehicles based on Ultra-Wideband technology

Master's thesis title in Czech:

Interiérový lokalizační systém pro autonomní prostředky s využitím technologie Ultra-Wideband

Guidelines:

1. Study the state of the art data fusion principles used for pose estimation. Study principles of Inertial navigation systems (INS)
2. Propose a localization system for autonomous vehicles based on fusion of data from Ultra-Wideband (UWB) positioning system and on-board dead-reckoning sensors such as Inertial measurement unit (IMU)
3. Evaluate proposed localization system for use in industrial environments.

Bibliography / sources:

[1] THRUN, SEBASTIAN, WOLFRAM BURGARD, AND DIETER FOX - PROBABILISTIC ROBOTICS, 2005 - Massachusetts Institute of Technology, USA (2005)
[2] GREWAL, MOHINDER S., ANGUS P. ANDREWS, AND CHRIS G. BARTONE - GLOBAL NAVIGATION SATELLITE SYSTEMS, INERTIAL NAVIGATION, AND INTEGRATION - John Wiley & Sons, 2020
[3] KELLY, ALONZO - MOBILE ROBOTICS: MATHEMATICS, MODELS, AND METHODS - Cambridge University Press, 2013
[4] MOORE, THOMAS, AND DANIEL STOUCH - A GENERALIZED EXTENDED KALMAN FILTER IMPLEMENTATION FOR THE ROBOT OPERATING SYSTEM, Intelligent autonomous systems 13. Springer, Cham, 2016. 335-348
[5] HOL, JEROEN D., et al. - TIGHTLY COUPLED UWB/IMU POSE ESTIMATION, 2009 IEEE international conference on ultra-wideband. IEEE, 2009
[6] LI, JIAXIN, ET AL. - ACCURATE 3D LOCALIZATION FOR MAV SWARMS BY UWB AND IMU FUSION, 2018 IEEE 14th International Conference on Control and Automation (ICCA). IEEE, 2018.

Name and workplace of master's thesis supervisor:

Ing. Tomáš Novák, DataVision s.r.o., Ukrajinská 2a, Praha 10

Name and workplace of second master's thesis supervisor or consultant:

Ing. Martin Hlinovský, Ph.D., Department of Control Engineering, FEE

Date of master's thesis assignment: **15.01.2021** Deadline for master's thesis submission: __________

Assignment valid until:
by the end of summer semester 2021/2022

Ing. Tomáš Novák Supervisor's signature	prof. Ing. Michael Šebek, DrSc. Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

Acknowledgement / Declaration

Lorem ipsum sit amet

I hereby declare that I wrote the presented thesis on my own and that I cited all the used information sources in compliance with the Methodical instructions about the ethical principles for writing an academic thesis.

....

Prague, May 21, 2021

Abstrakt / Abstract

Lorem ipsum sit amet

Klíčová slova: ultra-wideband, imu

Překlad titulu: Interiérový lokalizační systém pro autonomní prostředky s využitím technologie Ultra-Wideband

The most awesome abstract

Keywords: ultra-wideband, imu

/ Contents

Chapter 1
Introduction

Lorem ipsum sit amet

1.1 Section 1

Lorem ipsum sit amet

Chapter 2
Indoor localization methods

Lorem ipsum sit amet

2.1 Section 1

Lorem ipsum sit amet

Chapter 3
Sensors

In chapter 3 the overview of used sensors and their properties is given. The main aim is to describe an ultra-wideband technology(UWB), an inertial measurement unit (IMU) and an odometry.

3.1 Inertial measurement unit

An inertial measurement unit (IMU) is a device that utilizes measurement systems such as gyroscopes and accelerometers to estimate the relative position, velocity and acceleration of a vehicle in motion [1]. The sensor is typically integrated with an on-board computational unit and could contain more sensors as a magnetometer or thermometer.

The gyroscopes measure changes its angular velocities and accelerometers a specific forces, which can be easily transformed into linear accelerations [1]. The IMU typically contains three orthogonal accelerometers and three orthogonal gyroscopes. Because of that, it can measure angular velocities and specific force in each axis to maintain a 6-DOF estimate of the pose of the vehicle (position (x, y, z) and orientation ($roll$, $pitch$, yaw). The process of the computation can be seen in the figure 3.1.

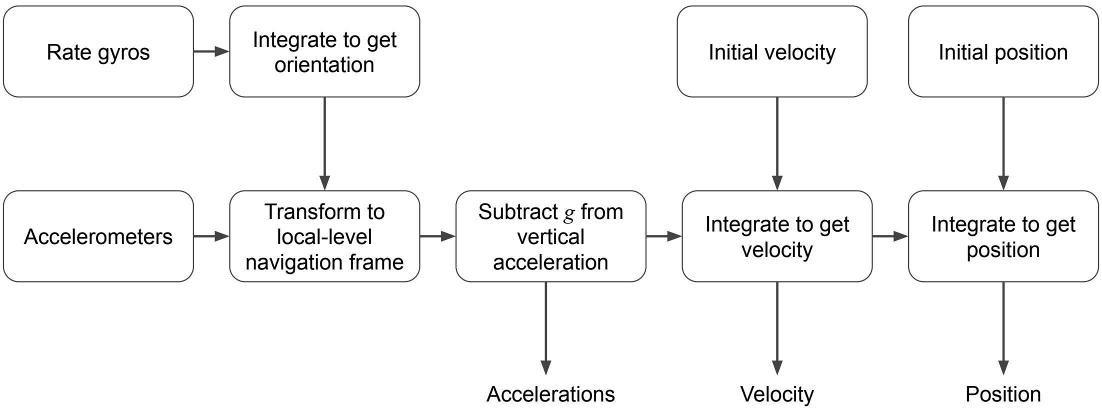

Figure 3.1. IMU block diagram [1]

There are two basic inertial navigation systems (also called mechanization architectures) [1][2] how the IMU is mounted to a vehicle.

- In **gimbaled systems**, the IMU is attached to a stabilized platform that maintains its inertial orientation as the vehicle manoeuvres.
- In **strap-down systems**, it is rigidly attached to the vehicle.

The mechanization determines which navigation equations are used during the estimation of linear accelerations and angular velocities of the vehicle.

IMU's are extremely sensitive to measurement errors given by properties of used gyroscopes, accelerometers and their mounting. As the data are once or twice integrated, any error in measurement causes a linear or quadratic error in the pose estimation. Even with a small measurement error, over time, the IMU's drift becomes significant, and it needs to be externally compensated. The IMU's provides a short-term stable solution because gyroscopes and accelerations have relatively low noise characteristics in a short period of time, and it has a high data rate (100 Hz - 200 Hz).

3.1.1 Accelerometers

Accelerometers can measure external forces acting on the vehicle. They measure a specific force relatively to a non-rotating inertial space in a specific direction. They are sensitive to all forces, including gravity and fictitious forces [1].

Mechanical accelerometers use a spring-mass-damper system. The force acts on the mass, and it causes displacement of the spring. The system is limited by, in reality, non-ideal spring and sensitivity to vibration.

Microelectromechanical systems based accelerometers (MEMS) are made of at least three components, namely a proof mass, a suspension to hold the mass and a pickoff, which relates an output signal to the induced accelerations [3]. MEMS accelerometers are then classified by the type of converting the mechanical displacement of the proof mass to an electrical signal. In most common principles belong to piezoresistive, capacitive sensing, piezoelectric, optical sensing and tunnelling current sensing. The piezoelectric MEMS sensors can not be used for navigation because their output rate is too low [3].

3.1.2 Gyroscopes

Gyroscopes are used for estimating a rotational motion of a body, each gyroscope measures angular rate ω (inertial angular rotation) relatively to a non-rotating inertial space in one axis. There are basically three main categories of gyroscopes [1].

Mechanical gyroscopes have a mass spinning steadily with respect to a free movable axis, they are not used a lot anymore, but they can be found in very old submarines.

Optical gyroscopes are based on the Sagnac effect, which states that frequency/phase shift between two waves counter-propagating in a rotating ring interferometer is proportional to the loop angular velocity. As a light source, the laser is typically used. Currently, this technology gives the best performance. Examples can be ring laser gyroscopes (RLG) or fibre optic gyroscopes (FOG).

Vibrating gyroscopes are based on the Coriolis effect that induces a coupling between two resonant modes of a mechanical resonator. Example can be MEMS sensors [3], these are typically the cheapest, and they can be found basically everywhere, for example, in every mobile device. As MEMS gyroscopes have no rotating parts, have low power consumptions requirements, and are small, they replaced others in robotics applications.

The performace and application of each technology is perfectly demonstrate in figure 3.2.

3.1.3 IMU's errors and Allan variance analysis

IMU errors IMUs faces several error sources. In this thesis, the main focus is given to MEMS-based IMU as they are used in experiments. These sensors are typically small and low cost.

These errors can be divided into two categories [3]

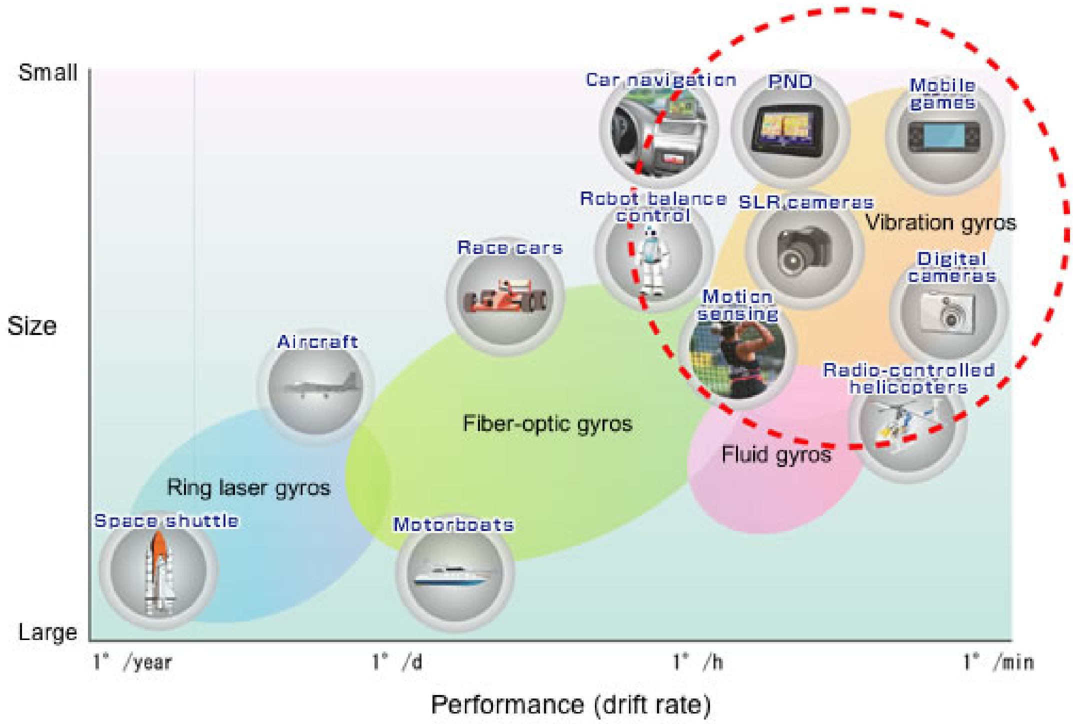

Figure 3.2. Gyroscopes technology plotted by size and performance [4].

- stochastical errors, which can be described as random processes,
- and deterministic errors, also called systematic errors, are basically caused by manufacturing imperfections or not ideal handling with IMU. These errors can be corrected by proper calibration.

Nevertheless, errors need to be analysed and reduced according to application requirements. The following errors are the most significant according to the topic of this thesis.

Biases of accelerometers and gyroscopes used in IMU are examples of systematic errors and can be divided into

- bias instability (or also called in-run bias), which represents drift of the sensor during a time,
- and initial bias (or repeatability bias), which is a static offset, which can be different during each start-up of the device, but during a run, it is static.

Biases are typically represented in $^\circ/hr$ or $^\circ/s$.

A scale factor and *a misalignment error*, both systematic errors, could also be significant. The scale factor is connected to imperfection while converting the real measurement input value and output value. The nonorthogonality of all sensors gives the misalignment error in IMU and it is caused during the production.

Angle or *velocity random walks* belong to stochastic errors. The measurement of gyroscopes and accelerometers are subject to white noises (the noise represented by Gaussian distribution). During the estimation of angles and velocities, integration needs to be done. Then the white noise starts to manifest itself by angle or velocity random walk, $^\circ/s/\sqrt{Hz}$ and $m^2/s/\sqrt{Hz}$ respectively.

Allan variance(AVAR) is widely used to analyse a random error of inertial sensors in time-domain. The AVAR $\sigma_A^2(\tau)$ is a function of the averaging time τ, computed as

$$\sigma_A^2(\tau) = \frac{1}{2(N-1)} \sum_{i=1}^{N-1} (\overline{y}_\tau(i+1) - \overline{y}_\tau(i))^2, \tag{1}$$

where N represents the number of clusters in the dataset ($N = floor(M/n)$), n is the number of samples in the cluster, M is the total number of samples in dataset, τ is the time length of the cluster ($m \times T_s$), T_s is the sampling period, $\overline{y}_\tau(i+1)$ and $\overline{y}_\tau(i)$) are mean value of certain cluster corresponding to i [5].

The confidence of the deviation of current cluster is given by

$$\delta_\sigma(\tau) = \frac{1}{\sqrt{2(\frac{M}{n} - 1)}} \tag{2}$$

and for getting more confidence, the ovelapping AVAR is used. That means, that the samples in the cluster overlapped.

The process of measuring AVAR consist of collecting 24-48 hours long dataset of static table test when the inertial sensor is not moving, and it is in not vibrating environments (no trains, subways which caused vibration). The sampling values are angular rate or accelerations

If the dataset is valid and the AVAR is correctly computed, the plot copies the example plot seen in figure 3.3. It is typically plotted on a log/log scale. A different slope of the graph describes each noise component by that the graph can be easily divided into specific parts. The most important implication for navigation purposes is the fact that until the bias instability (slope=0) is reached, the sensor model can contain only a white (Gaussian) noise [6]. By that time, the external reset needs to be done.

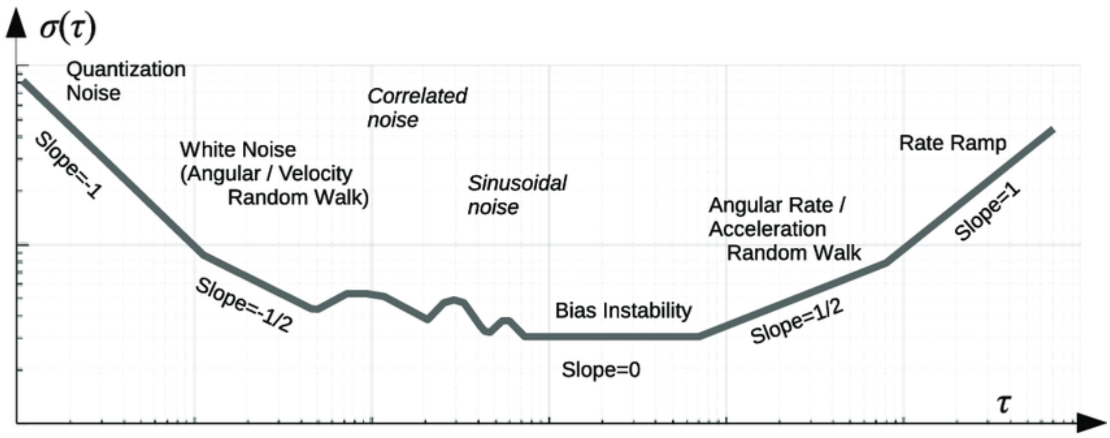

Figure 3.3. An example of Allan variance plot [7]

3.1.4 Performance of IMUs according to their application

IMUS can be used in various application, which differs by IMUs performance. The overview of each sensor's precision for a given application is nicely summarized in the figure 3.4.

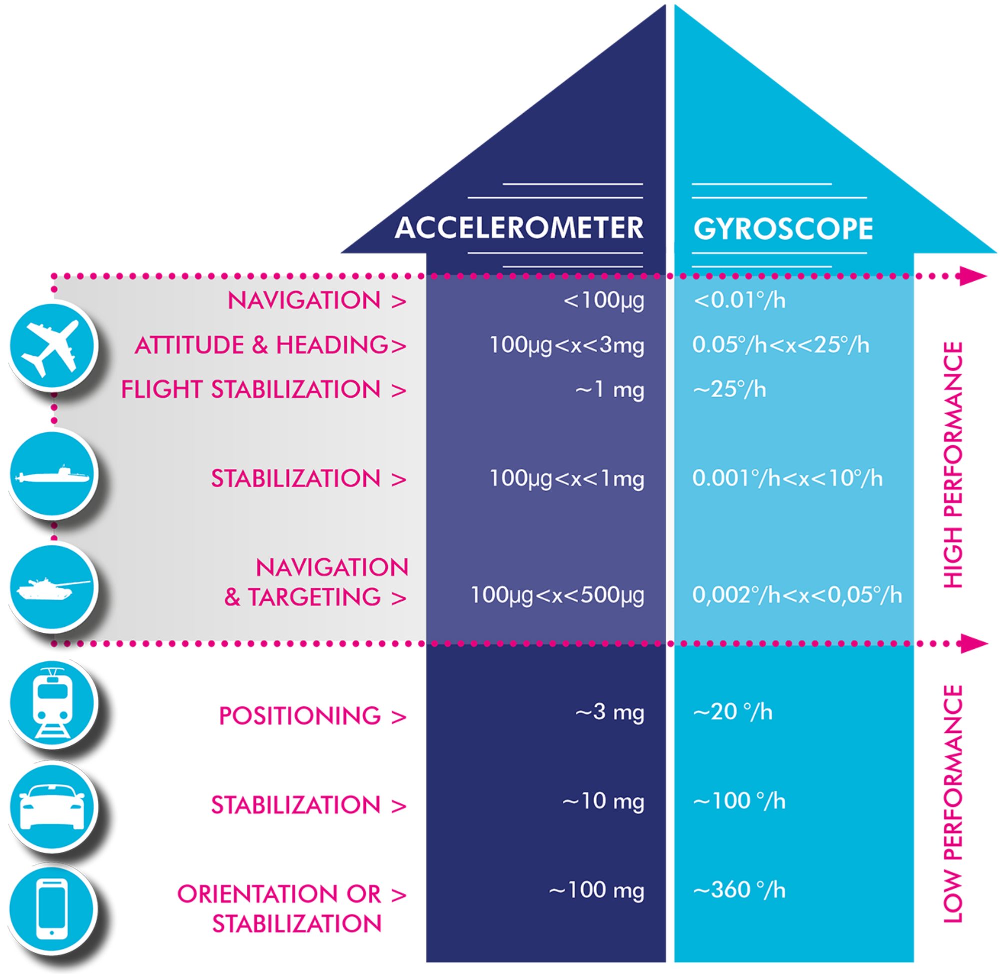

Figure 3.4. A performance of IMU per application [8]

3.1.5 Navigation (mechanization) equations

Both gyroscopes (see section 3.1.2) and accelerometers (see section 3.1.1) measure in IMU inertial frame , typically called body frame. That means they need to be converted to a reference frame. In that frame, the state (positions, orientations, velocities, ...) is estimated and it is the output of the localization method.

Navigation equations implement the transforms between the body frame and the reference frame, either a local-level frame (as North-East-Down or East-North-Up), a reference to a specific point at planet Earth, or an Earth-fixed frame as ECEF [3].

These equations are known and can be found in the book MEMS-based Integrated Navigation [3].

Chapter 4
State estimations algorithms

Lorem ipsum sit amet

4.1 Section 1

Lorem ipsum sit amet

Chapter 5
Localization system design

Lorem ipsum sit amet

5.1 Section 1

Lorem ipsum sit amet

Chapter 6
Experiments

Lorem ipsum sit amet

6.1 Section 1

Lorem ipsum sit amet

Chapter 7
Conclusion and future work

Lorem ipsum sit amet

7.1 Section 1

Lorem ipsum sit amet

References

[1] Bruno Siciliano, and Oussama Khatib. *Springer Handbook of Robotics*. Springer-Verlag, 2007.

[2] Peter Teunissen, and Oliver Montenbruck. *Springer handbook of global navigation satellite systems*. Springer, 2017.

[3] Priyanka Aggarwal. *MEMS-based integrated navigation*. Artech House, 2010.

[4] © 2021 Seiko Epson Corp. *Gyro sensors - How they work and what's ahead*. `https://www5.epsondevice.com/en/information/technical_info/gyro/`.

[5] Shuvra S Bhattacharyya, Ed F Deprettere, Rainer Leupers, and Jarmo Takala. *Handbook of signal processing systems*. Springer, 2018.

[6] Wikipedia®. *Wikipedia - white noise definition*. `https://en.wikipedia.org/wiki/White_noise`.

[7] Agnieszka Szczęsna, Przemysław Skurowski, Ewa Lach, Przemyslaw Pruszowski, Damian Pęszor, Marcin Paszkuta, Janusz Słupik, Kamil Lebek, Mateusz Janiak, Andrzej Polanski, and Konrad Wojciechowski. Inertial Motion Capture Costume Design Study. *Sensors*. 2017, 17 612. DOI 10.3390/s17030612.

[8] © Thales group. *Performance of IMU per application*. `https://www.thalesgroup.com/sites/default/files/database/d7/assets/images/thales_topaxyz_imu_infographie_copyright_thales_light_0.png`.

Appendix A
Abbreviations and symbols

A.1 A list of abbreviations

All abbreviations used in this thesis are listed below.

AVAR	Allan variance.
DOF	Degrees of freedom.
IMU	Inertial measurement unit.
MEMS	Microelectromechanical systems.
UWB	Ultra-wideband.

A.2 A list of symbols

π Lorem ipsum sit amet.