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Metody pro zpřesnění údajů navigačních systémů

Methods for improving the accuracy of navigation systems

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Summary

Applicability of cost-effective navigation systems is wide not just in areas of aerial navigation on UAVs or small aircrafts, but also in terrestrial navigation, for instance in automotive industry or robotics. As long as cost-effective navigation systems utilize low-cost inertial sensors manufactured by MEMS based technology and thus they are not autonomous in providing a navigation solution in long terms, their application generally require integrating external measurement systems. These external systems compensate and stabilize the navigation solution (position, velocity, and attitude) obtained based on processing measured acceleration and angular rates. A disadvantage of external systems is their combined dependency on flight conditions plus on environmental influence affecting their principle of operation. In contrast, inertial sensors do not suffer from this property, but they alone do not provide a stable navigation solution.

The lecture therefore introduces methods improving accuracy of cost-effective navigation units by means of external aiding system (for instance GPS, magnetometer) integration and data fusion. Furthermore, it extends its content about methods used for signal/data processing and calibration of inertial sensors to conceive the area of improving navigation system performance as wide as possible and thus provide common overview of modern methods in this area. The lecture will be supported by obtained experience in the area of navigation systems and reached results of R&D activities.

Souhrn

Aplikovatelnost levných navigačních systémů je široká a to nejenom v oblasti letecké navigace na bezpilotních prostředcích či malých letadlech, ale i v oblasti terestriální navigace např. v automobilovém průmyslu či robotice. Jelikož cenově dostupné navigační systémy využívají levné inerciální senzory vyrobené MEMS technologií a nejsou tudíž autonomní, je nutné pro zajištění dostatečné přesnosti a s časem se nezvyšující chyby použít externích měřicích systémů, pomocí nichž mohou být výstupy navigačních rovnic (pozice, rychlost a orientace) kompenzovány a stabilizovány. Nevýhodou použitých externích systémů je vždy jejich ovlivnitelnost okolními podmínkami vycházejícími z principu jejich funkčnosti, což v případě inerciálních senzorů nenastává. U inerciálních senzorů je výstupní hodnota principiálně ovlivněna jen samotným pohybem prostředku.

Přednáška proto představí nejen metody používané pro zpřesnění navigačních jednotek, které využívají externích měřicích systémů (např. GPS, magnetometrů) a následnou fúzi dat, ale zaměří se na tento problém šířeji. Budou popsány i metody zpracování signálu/dat inerciálních senzorů, které pozitivně ovlivňují přesnost měření, i včetně kalibrace samotných senzorů. Přednáška se bude opírat zkušenosti získané v této oblasti a bude se zakládat na výsledcích, které v daných oblastech byly dosaženy.

Klíčová slova

Navigační systém; inerciální senzor; akcelerometr; senzor úhlové rychlosti; zpracování signálu a dat; fúze dat; kalibrace.

Keywords

Navigation system; inertial sensor; accelerometer; angular rate sensor; gyro; signal and data processing; data fusion; calibration.

Contents

1. Introduction

Navigation systems providing the tracking of an object attitude, position, and velocity play a key role in a wide range of applications, e.g. in aeronautics, astronautics, robotics, automotive industry, underwater vehicles, or human body observation. A common technique to do so is via a dead reckoning. One form of a dead reckoning technique is using an initial position, velocity, and attitude related to a predetermined coordinate frame and consecutive update calculations based on acceleration and angular rate measurements. These measurements are generally provided by 3-axis accelerometer (ACC) and 3-axis angular rate sensor (ARS) or gyroscopes (gyros) forming so called Inertial Measurement Unit (IMU). According to required accuracy of navigation and economical aspects suitable inertial sensors have to be chosen. It is clear that basic accuracy is manly dependent on the choice of the sensors; however, consecutive signal and data treatment can also improve the performance. Of course, it cannot go beyond the sensors' capabilities. As long as the sensors and the environment are a major source of errors in navigation systems; the type of an application should be considered as well. The sensors' performance is not just about their resolution but also their stability plays a key role. Nowadays technology with its stability is related to potential application in Fig. 1 for angular rate sensing and in Fig. 2 for acceleration.

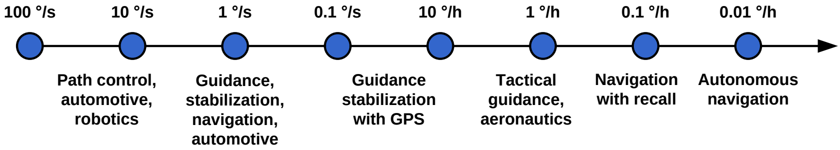


Fig. 1 – Required precision of sensed angular rate related to applications [1]

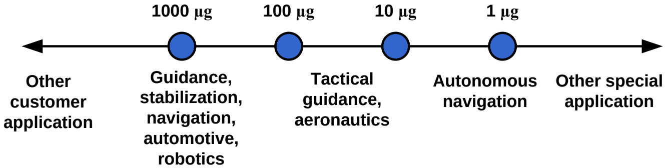


Fig. 2 – Required precision of sensed acceleration related to applications [1]

When a stand-alone application is required, only the most precise sensors have to be used. These sensors in navigation systems are ring laser gyros with their stability better than 0.1 deg/h and the resolution better than 10^{-6} deg/s and servo accelerometers with the resolution better than 1 μg. For aircraft navigation it is, according to Fig. 1 and Fig. 2, required to employ gyros with the stability better than 1 deg/h and in the case of the ACC not more than 10 μg, so these sensors serve well. Nevertheless, the higher accuracy, the more expensive the device is. Therefore these sensors would have been ideal for all applications, if they were not so expensive. Due to this reason other systems, such as Micro-Electro-Mechanical-Systems (MEMSs), have been used in cost-effective applications, such as on UAVs or small aircrafts. MEMSs are typically defined as microscopic devices designed, processed, and used to interact or produce changes within a local environment. MEMSs offer reduced power consumption, weight, manufacturing and assembly costs, and increased system design flexibility. Reducing the size and weight of sensors allow multiple MEMS components to be used to increase functionality, device capability, and reliability. In contrast, MEMS performance has many weak aspects, such as for precise navigation purposes low resolution, noisy output, worse bias stability, temperature dependency and so on. No matter these imperfections, their applicability in navigation is wide due to fast technology improvements, applied data processing algorithms, and used aiding systems. A typical chain of signal/data treatment is depicted in Fig. 3.

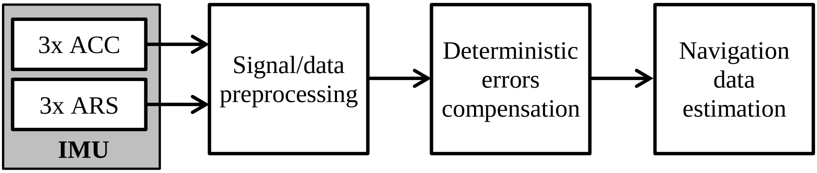


Fig. 3 – Typical chain of signal/data treatment in navigation systems

According to Fig. 3 it is possible to address two possible ways to improve the navigation system accuracy. These are:

1. choosing “the best” sensors no matter the application,
2. choosing “the best suited” sensors for a particular application and applying signal/data processing methods to provide suitable and bounded accuracy.

In the first case only there is no need of aiding systems and the approach primary relies just on calculating the navigation equations. A principle structure of this approach is shown in Fig. 4. In this case the accuracy is primary dependent on the sensors; therefore, the most precise sensors have to be used. All measured quantities are transformed to the navigation frame via a direction cosine matrix ***C*** and compensated for the Earth rotation and gravity influences.

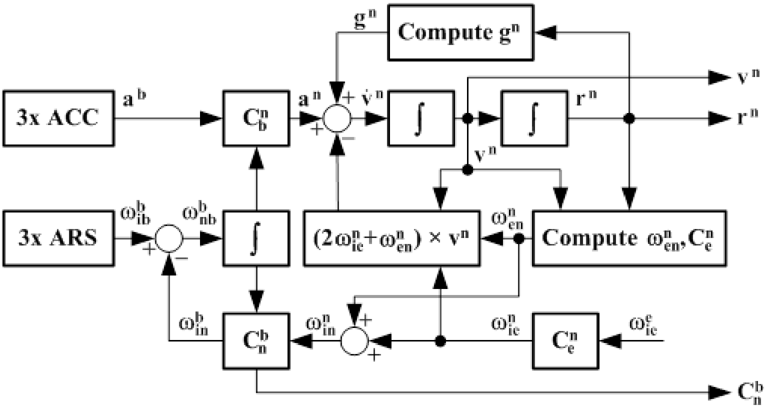


Fig. 4 – A principle scheme of navigation equation calculation [2]

The other case utilizes cost-effective solutions in which special signal/data treatment is supposed to be applied. This lecture therefore address only the second case which improves the accuracy of navigation systems via different methods suitable for different MEMS based solutions and applications. Such methods can be grouped as follows:

a) calibration techniques,
b) signal/data preprocessing, modeling, and threshold leveling,
c) data fusion and aiding systems integration.

All three groups will be closely described in following sections. Generally, in navigation systems all these three different signal/data treatment methods need to be performed and applied to reach the best navigation solution as possible.

2. Calibration of inertial measurement units

A calibration is a standard procedure within which ACC and gyro triads' imperfections and datasheet deviations need to be estimated. Those imperfections usually reflect their scale-factors, non-orthogonalities/misalignment errors, and offsets [3,4] as described for both sensor types in (1) and (2).

$$\begin{aligned} \boldsymbol{u}_a = \boldsymbol{T_a}\boldsymbol{S}_a(\boldsymbol{y}_a - \boldsymbol{b}_a) = \\ = \begin{bmatrix} 1 & 0 & 0 \\ \alpha_{xy} & 1 & 0 \\ \alpha_{zx} & \alpha_{zy} & 1 \end{bmatrix} \begin{bmatrix} S_{ax} & 0 & 0 \\ 0 & S_{ay} & 0 \\ 0 & 0 & S_{az} \end{bmatrix} \left(\begin{bmatrix} y_{ax} \\ y_{ay} \\ y_{az} \end{bmatrix} - \begin{bmatrix} b_{ax} \\ b_{ay} \\ b_{az} \end{bmatrix} \right), \end{aligned} \tag{1}$$

$$\begin{aligned} \boldsymbol{y}_g - b_g = \boldsymbol{S}_g\boldsymbol{T}_g\boldsymbol{M}_g\boldsymbol{u}_g = \\ = \begin{bmatrix} S_{gx} & 0 & 0 \\ 0 & S_{gy} & 0 \\ 0 & 0 & S_{gz} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ \alpha_{xy} & 1 & 0 \\ \alpha_{zx} & \alpha_{zy} & 1 \end{bmatrix} \boldsymbol{M}_g \begin{bmatrix} u_{gx} \\ u_{gy} \\ u_{gz} \end{bmatrix}, \end{aligned} \tag{2}$$

where the subscript a corresponds to ACCs and g to gyros, $\boldsymbol{y}$ is the vector of a measured quantity, $\boldsymbol{b}$ corresponds to the vector of offsets, $\boldsymbol{S}$ represents the matrix of scale factors, $\boldsymbol{T}$ transforms a vector from the non-orthogonal coordinate system to the orthogonal one and conversely, $\boldsymbol{M}$ represents the alignment matrix transforming the referential system frame to the platform frame, and $\boldsymbol{u}$ is the vector of compensated acceleration in the case of ACCs and referential angular rates when gyros are under observation.

A key issue in calibration procedures is having correct and precise referential information about the load applied on the IMU being calibrated. That generally requires expensive specialized means [5]. Therefore, much effort has been put into R&D of calibration approaches using different algorithms and referential systems. In the ACC case, the most of current methods still utilize the fact that ACC is affected only by the gravity under static conditions. Then measurements collected at predetermined various attitudes are sufficient for the estimation of the ACC error model using various optimization techniques [4-6]. On the other hand, in the case of gyros the Earth rate is usually under the resolution and thus estimating their error model generally requires expensive rate tables as the reference. Due to these facts our main motivation lied in the development of an All-In-One calibration platform enabling the calibration of entire units including both ACCs and gyros to be performed by a cost-effective measuring setup and appropriate optimization techniques. The All-In-One platform concept, as shown in Fig. 5, utilizes a setup which consists of a manually driven single-axis rate table supplemented by a referential system, and a gimbal structure allowing 3D rotation of a sensor being calibrated. The referential system uses a dual-axis inclinometer HCA528T and a single-axis fiber optic gyro (FOG) DSP-3100 placed along the vertical axis. A detailed appearance of the referential system is also depicted in Fig. 5.

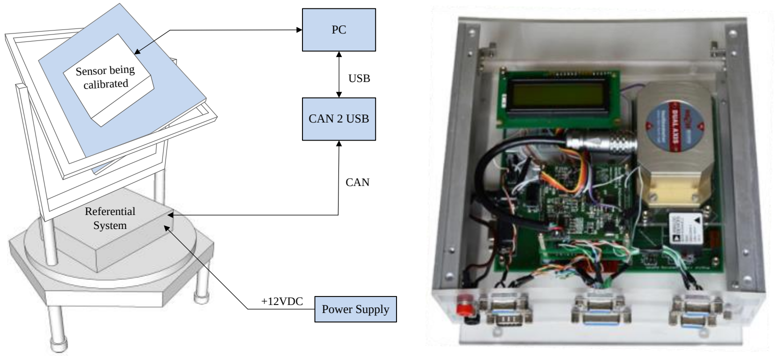
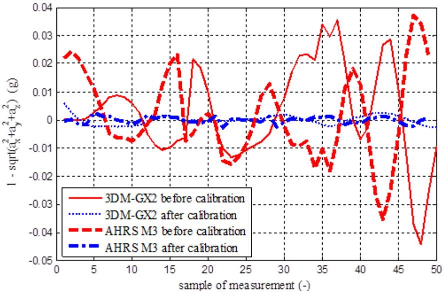


Fig. 5 – Concept of All-In-One calibration platform (left),
the referential system (right)

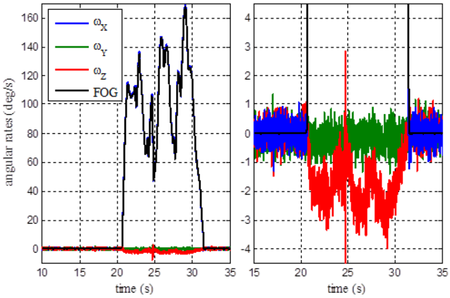
The referential system is needed only for gyro frame calibration in which it measures the attitude and the angular rate applied along the vertical axis. The ACCs are calibrated with respect to measurements taken under static conditions applied in different attitudes, which is provided by the gimbal structure. Since the FOG has a high resolution, about 3×10^{-5} deg/s, it is necessary to exclude the Earth's rate projected to its readings as precisely as possible. For that reason it is required to transform the rate from the Earth frame to the platform frame according to the evaluated attitude. Attitude accuracy thus also plays a key role; in our case it is about 1×10^{-2} deg, which satisfies our needs. The calibration begins with the ACC frame. ACCs data, measured with respect to Thin-Shell method defining suitable number of measurements, are processed by the Levenberg-Marquardt optimization algorithm, for more details see [4], to obtain the error model. When ACCs are calibrated, the calibration of gyros can take place. Since the platform is manually driven it is not necessary to apply constant angular rates. The calibration method relies on three arbitrary rotations, each along particular gyro axis performed one by one. Before each rotation the gyro axis has to be aligned in order to coincide with the platform rotation axis. The alignment should be with the accuracy better than 0.5 deg, which can be easily reached by compensated accelerometer readings. After the data are preprocessed, the optimization is performed in the angle domain. It uses the Cholesky decomposition and LU factorization to distinguish particular error model matrices [3]. Resulting behavior and error models for two 3DM-GX2 and AHRS M3 navigation units are shown in Fig. 6 and Fig. 7.



ACCELEROMETER ERROR MODELS
SCALE FACTORS, NON-ORTHOGONALITIES, OFFSETS

3DM-GX2		
S_a (-)	T_a (-)	b_a (g)
0.9974	0.0014	0.0083
1.0026	-0.0569	0.0072
0.9982	0.0039	-0.0158
Total RMSE before calibration		Total RMSE after calibration
0.0167 g		0.0017 g
AHRS M3		
S_a (-)	T_a (-)	b_a (g)
1.0064	-0.0167	0.0009
0.9968	0.0527	-0.0057
0.9937	0.0032	0.0139
Total RMSE before calibration		Total RMSE after calibration
0.0157 g		0.0008 g

Fig. 6 – Deviations of acceleration magnitudes before and after the calibration (left), resulting accelerometer error models of 3DM-GX2 and AHRS M3 units (right)



GYROSCOPE ERROR MODELS,
SCALE FACTORS, NON-ORTHOGONALITIES, ALIGNMENT MATRIX

3DM-GX2				
S_g (-)	T_g (-)	$\boldsymbol{M}_g$		
1.0099	0.0142	0.9999	0.0096	0.0086
1.0022	0.0021	-0.0089	0.9980	-0.0623
0.9954	-0.0656	-0.0092	0.0617	0.9981
AHRS M3				
S_g (-)	T_g (-)	$\boldsymbol{M}_g$		
0.9962	-0.0126	0.9999	-0.0110	-0.0123
1.0000	-0.0312	0.0111	0.9999	0.0065
1.0038	0.0012	0.0125	-0.0067	0.9999

Fig. 7 – Angular rates measured by 3DM-GX2 calibrated unit and the referential system (left), resulting gyro error models of 3DM-GX2 and AHRS M3 units (right)

Calibration is necessary for each navigation system to be performed. Basic calibration is often done by the manufacture. Nevertheless, its precision does not need to be good enough, and therefore the additive one left on a customer is often useful. Since precise knowledge of the error model increases final accuracy of the navigation system, a customer needs to manage it him/her-self to reach better accuracy in the estimation of the IMU error models.

3. Signal/data preprocessing

The motivation for using signal/data preprocessing lies in the variability of the environmental conditions observed on aircrafts as can be seen in Fig. 8 and Fig. 9. Total forces applied to inertial sensors are composed by a combination of forces originating from the flight conditions and maneuvers, and vibratory forces rising from the aircraft structure. These total forces influence the sensor readings as well as a sensor noise it-self. The influence of vibratory forces can be reduced by low-pass filtering whose bandwidth varies according to a carrier, e.g. UAV, large aircraft, terrestrial vehicle. It can be done when it is possible to distinguish and separate the bandwidth of vibrations and the carrier dynamics. Nevertheless, according to Fig. 8 and Fig. 9 unambiguous determination of those boundaries is sometimes hard to make and it depends on the application.

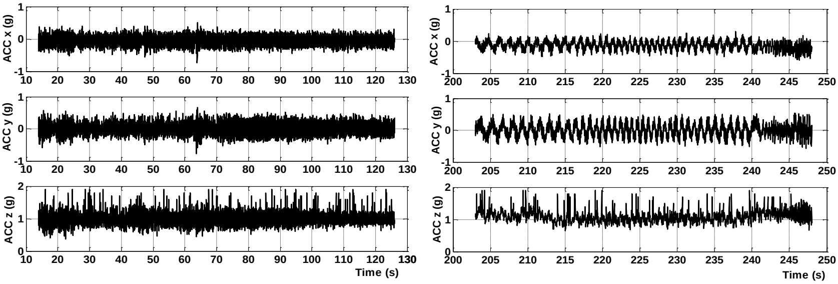


Fig. 8 – Measured acceleration
during parking with the engine on (left), engine RPM suppression (right)

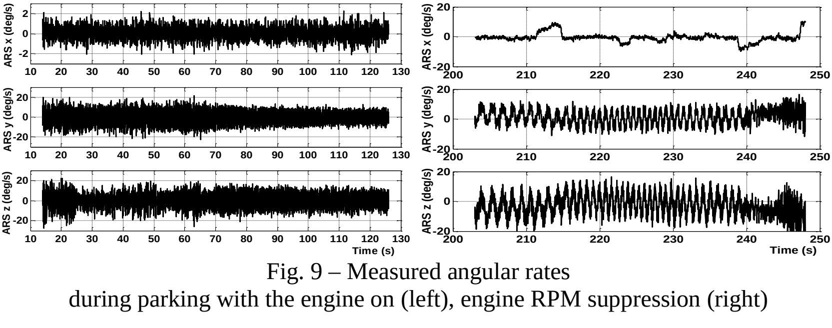


Fig. 9 – Measured angular rates
during parking with the engine on (left), engine RPM suppression (right)

Another issue in signal/data preprocessing is a sensor noise it-self. We have proposed a method improving resolution of MEMS based ACCs via the modification of their sensing framework and a special treatment of their analogue outputs. Our motivation was in the improvement of a useful signal to noise ratio, which increased the resolution, plus in the reduction of ACC readings dependences on temperature and power variation. The method utilized a modified ACC framework which used the properties of differential configuration. That occurs in the simplest case when a biaxial ACC is used and has its initial position tilted by 45 deg with respect to the original vertical axis. To complete the whole framework two of these ACCs need to be employed [7] and placed the way as shown in Fig. 10. Characteristics of this modified configuration were determined according to sensitive analyses. They confirmed that the modified configuration improved performance in contrast to a typical one when the emphasis was put on the horizontal flight conditions. A principle scheme and the real appearance of a navigation system using the modified configuration are depicted in Fig. 11.

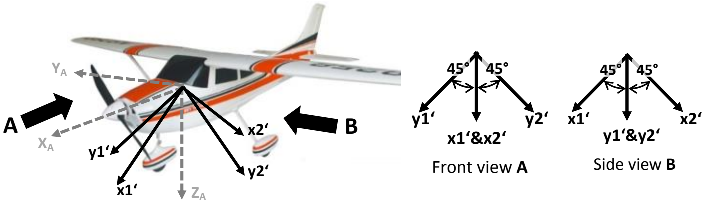


Fig. 10 – Modified framework using two biaxial accelerometers [12]

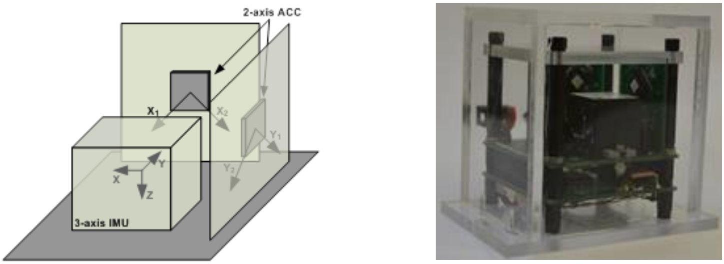


Fig. 11 – Principle scheme of a navigation system using the ACC modified configuration (left) and its real appearance (right)

When the biaxial ACC is aligned as suggested its sensitivity to small attitude changes from the initial alignment can be assumed equal for both sensitive axes. This fact enables the application of differential signal processing method. Due to the same sensitivities but with opposite signs of changes the biaxial ACC behaves as a differential sensor. A differential signal processing improves a useful signal to noise ratio, i.e. the useful signal is doubled while a mean square root of combined noises from both axes increases only by the factor of √2. Furthermore, the differential processing positively affects the sensor dependence on temperature and power variation. Experimental results which confirmed the method are shown in Fig. 12.

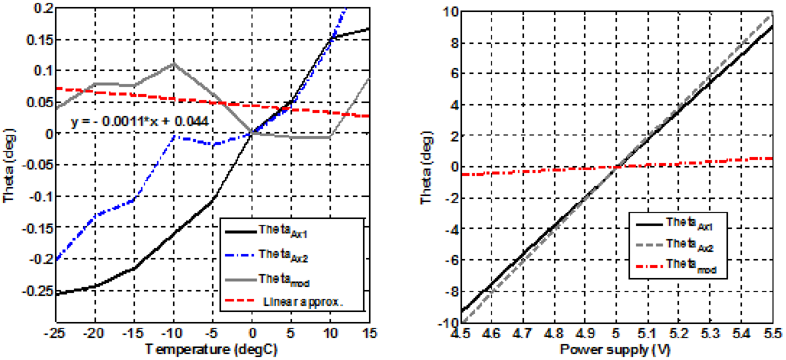


Fig. 12 – Resultant pitch angle dependencies on temperature (left) and power (right) variation

A basic idea used in the modified ACC frame configuration with the differential analogue signal processing was further extended into the form used in a 3-axial ACC frame. A principle scheme and shape of such a navigation system is depicted in Fig. 13.

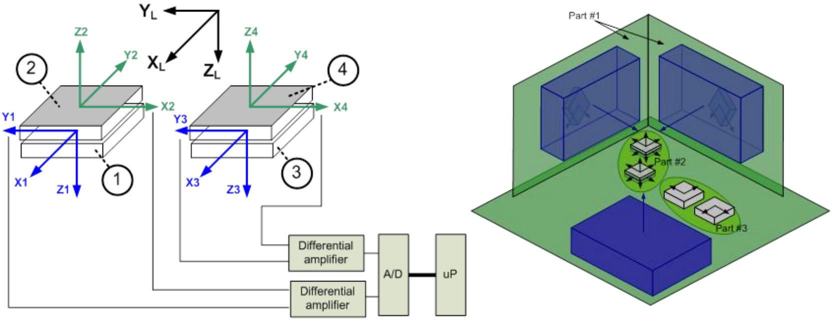


Fig. 13 – Differential principle in 3-axis configuration (left),
new concept of a navigation system in multi-sensor configuration, ARSs with their axes – blue, ACCs with their axes – grey (right)

Even if the signal/data preprocessing positively affects a final accuracy, MEMS based navigation systems still cannot be used as stand-alone. It can just extend the time of operation which is still not long enough without aiding systems integrated.

4. Data fusion in navigation systems

Even when MEMS based inertial sensor frame is calibrated and its readings preprocessed, it still cannot ensure correct operation for longer time than a couple of minutes. To provide long term operation the inertial sensors are supposed to be supplemented by aiding systems which might be for instance GNSS based positioning, magnetometer based compassing, tilt sensor leveling etc. A general approach is to fuse data obtained from as many information sources as possible, which of course depends on the application. Potential aiding systems for aerial vehicles are shown in Fig. 14. A main issue of their usage is to bound errors in navigation outcomes (position, velocity, attitude) to predetermined boundaries by means with zero mean value of the error and known its variance. However, there is always a danger in utilizing any other data source than inertial sensors that the data might be negatively affected by environmental conditions other than flight conditions them-selves. Even if this danger exists it can be handled by data validation process to recognize it and reduce its effect on the decrease of accuracy. It is always on a designer choice how the data fusion is performed. Data fusion is commonly provided by Kalman filtering (KF) or complementary filters (CF).

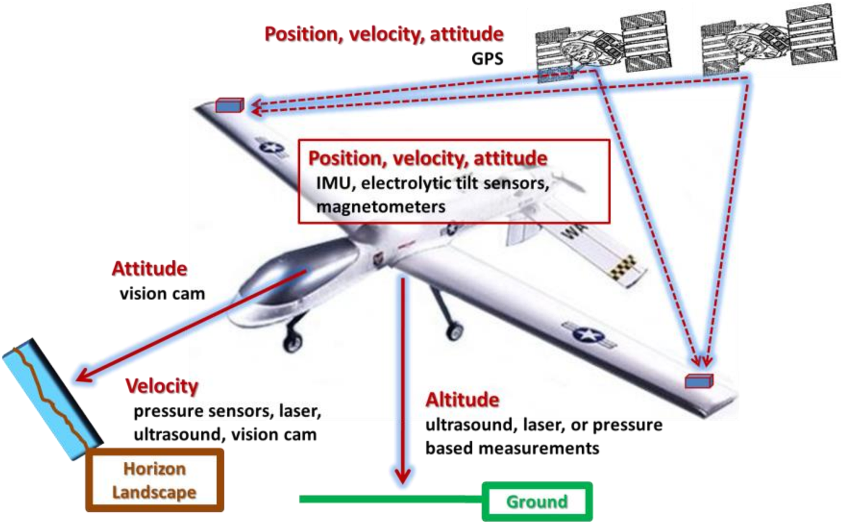


Fig. 14 – Aiding systems in aerial applications

Often used example of the CF is its usage in the attitude estimation process. A basic principle of the CF uses a low-pass filtering on attitude estimates obtained from ACC data and a band-pass filtering on a biased attitude estimates obtained by the integration of angular rates [8,9] as shown in Fig. 15.

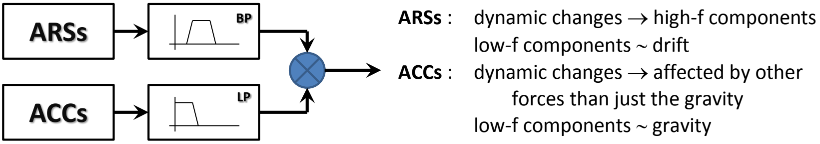


Fig. 15 – Principle scheme of the complementary filter

The other approach to fuse data is via the KF. As long as it is based on non-linear equations the extended KF is utilized and integrated in loosely, tightly, or ultra-tightly coupled scheme. The form of the KF depends on a design. We have compared several designs which differed in applied algorithms. It was related to our modular navigation system design for UAV applications; its appearance is provided in Fig. 16. It consisted of an IMU supplemented by an electrolytic tilt module, magnetometer, single-antenna GPS receiver, and pressure based sensors. The reference position and attitude were obtained from the multi-antenna GPS receiver to which estimated data were related.

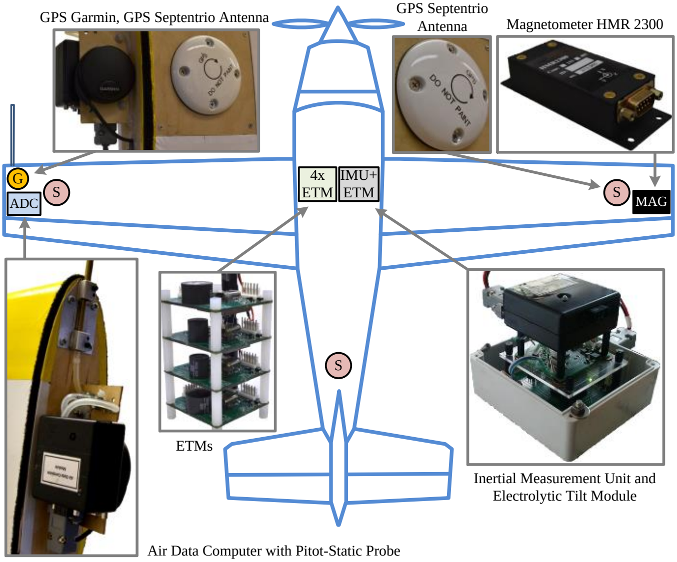


Fig. 16 – Modular navigation system used on a UAV

The first used approach has implemented a loosely-coupled INS/GPS integration and provided a 9-dimensional state vector containing position, velocity, and attitude using the extended KF, for details see [10]. The advantage of this approach is a straightforward implementation and satisfactory navigation performance. However, even when properly tuned, the estimates strongly rely on the GPS signal, which is its disadvantage. The second approach has implemented Gauss-Newton algorithm providing updates for the extended KF. A principle scheme of this approach is depicted in Fig. 17. The performed flight experiment and its results are shown in Fig. 18 and Tab. 1.

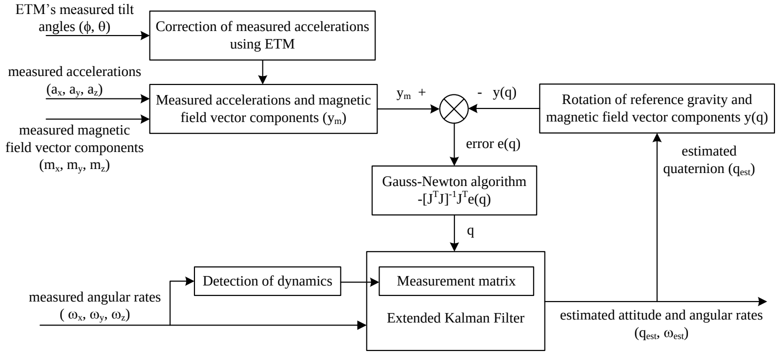


Fig. 17 – Extended KF with the Gauss-Newton optimization algorithm

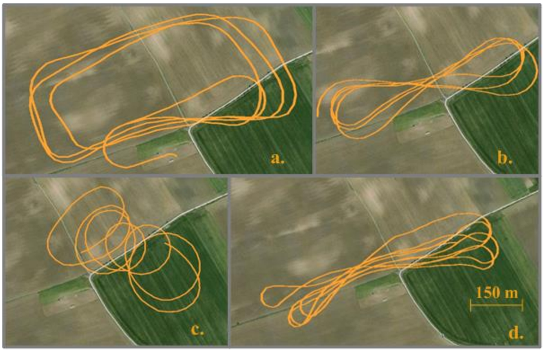


Fig. 18 – Flight experiment

	Position INS/GPS EKF (m)			**Attitude INS/GPS EKF (deg)**			**Attitude EKF + Gauss-Newton Algorithm (deg)**		
	North	East	Down	Roll	Pitch	Yaw	Roll	Pitch	Yaw
RMSE	4.54	4.89	5.94	1.17	1.98	5.17	2.28	3.07	6.07
1 σ	2.96	3.40	4.67	1.09	1.75	4.41	2.12	2.87	5.58

Tab. 1 – Evaluation results of the flight experiment

5. Conclusion

This lecture is devoted to problems concerning methods and algorithms applicable in navigation systems to improve their accuracy. These methods are primary aimed at estimating deterministic sensor error sources via calibration, improving signal/data conditioning via preprocessing, and providing long term stability via data fusion and implementation of aiding sources. It is clear that the design of navigation systems is generally a complex issue and requires profound knowledge in navigation principles, sensor technology, signal/data processing, and calibration procedures as well as knowledge in measurement system modeling, fusion, and implementation. The design to design can vary and is often unique based on the designer. Many R&D activities and related papers describe a unique solution more or less theoretically based and confirmed by laboratory experiments. Despite they reach good results, until it is applied under real outer conditions, the solution cannot be really confirmed. Real flight conditions are key aspects and reasons why proposed solutions may not work properly and have to be modified and tuned. That is why challenges concerning navigation systems are still ahead.

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Work experience

09/2004 –

Assistant professor and research fellow
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05/2004 –

Training manager of modules 5, 13, 15, the regulation JAR-66 (intended for airman-technicians) – recognized by Civil Aviation Authority of the Czech Republic

05/2004 – 08/2004

Technician and research fellow at the CTU-FEE,
Dept. of Measurement

09/2001 – 04/2002

Research associate at Shizuoka University,
Research Institute of Electronics, Hamamatsu, Japan

Education and trainings

03/2000 – 10/2005

PhD. degree in Measurement Technology at CTU in Prague-FEE, Dept. of Measurement

06/2008

1 week course: Applied Kalman Filtering taught by Dr. Patrick Hwang (Rockwell Collins), Mr. Michael Vaujin (Raytheon)

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1 week course: Application of Kalman Filtering to GPS, INS, & Navigation taught by Mohinder S. Grewal, PhD, PE (Kalman Filtering Consultant Associates)

09/1994 – 02/2000

Ing. (= MSc.) degree in the study branch Aircraft Information and Control Instrumentation at CTU in Prague, FEE

Research interests

Test and measurement systems, their modeling and simulation, measurement methods for electrical and non-electrical quantities, avionics, embedded systems, navigation systems and sensors, methods of signal/data processing, data validation and verification.

Research achievements

- Author or co-author of 8 journal papers with impact factors, 3 papers in reviewed international journals, more than 16 international conference papers, 2 patents, 1 scientific book
- H-index = 2 (based on WoS) – 15 international citations, 11 national citations

Research projects

- SGS10/288/OHK3/3T/13: Modular system for attitude and position estimation, internal CTU grant (2010-2012)
- SGS13/144/OHK3/2T/13: Modern methods in development of inertial navigation systems, internal CTU grant (2013-2014)
- TA02011092: Research and development of technologies for radiolocation mapping and navigation systems, grant of the Technology Agency of the Czech Republic (2012-2014)
- VG20122015076: The survey points range-finding system utilization for perimeter security (screen), grant of the Ministry of the Interior of the Czech Republic (2012-2015)

Professional activities

- Deputy Head of the Czech Aeronautical Society
- Representative of the CTU in Prague in the PEGASUS Network
- Representative of the CTU in Prague in Airbus-PEGASUS internship program
- Reviewer of papers published in: Elsevier-Measurement, IEEE Transactions on Instrumentation & Measurement, Sensors and Actuators A: Physical, Cybernetic Letters

Pedagogical activities and achievements

- Lecturer of bachelor and master degree courses concerning aircraft and spacecraft avionics, its principles of operation, sensors, and internal processes
- Member of committees for bachelor and master degree state exams – CTU in Prague, FEE study program: Cybernetics and Robotics, FTS programs: Air Transport, Professional Pilot, Technology of Aircraft Maintenance
- Supervisor of 5 PhD students, a supervisor of more than 10 master degree final theses successfully defended
- Accreditation of the study branch Aircraft and Space Systems