Application

2015-03-31

2015-05259	Skog, Isaac	NT-14

Information about applicant

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Project site: Avdelningen för Signalbehandling

Information about application

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Project title (english): Signal Processing for Large Arrays of Motion Sensors

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Keywords: Signaler, System, Sensorer, Signalbehandling, Rörelsemätningar

Funds applied for

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Descriptive data

Project info

Project title (Swedish)*

Signalbehandling för stora system av rörelsesensorer

Project title (English)*

Signal Processing for Large Arrays of Motion Sensors

Abstract (English)*

Motion sensing is an essential capability in many systems to achieve a high level of autonomy. Nowadays, motion sensors are therefore ubiquitous in everything from industrial manufacturing equipment to consumer electronic devices. This widespread usage of motion sensors has become possible thanks to the last decade's micro-electrical-mechanical-system technology development, which has revolutionized the motion sensing industry. Motion sensors can now be manufactured at unprecedented volumes and and at low price.

Even though the development has also pushed the performance boundaries of the motion sensing technology, contemporary low-cost sensors still cannot fully meet the needs of many applications, e.g., navigation applications. Therefore, significant research efforts have been undertaken to by the aid of signal processing techniques enhance the sensing performance. These efforts have been mainly focused on systems incorporating one, or at most a handful of sensors, and the possibilities related to the use of arrays with a large number of sensors have not yet been thoroughly studied. However, by capitalizing on the decreasing price, size, and power-consumption of the sensors, it is now realistic to construct arrays with hundreds of sensing elements, and combine their measurements to create virtual high-performance sensors. Such sensor arrays would not only provide a higher measurement accuracy, but also higher system reliability thanks to component redundancy and for certain array configurations also a dynamic measurement range that extends beyond that of the individual sensors; properties of great importance in high-dynamic and safety critical applications like navigation systems for humans, robots, and vehicles. But before these sensor array based motion sensing systems can become real, new signal processing methods to fuse measurements from hundreds of low-cost motion sensors must be developed; methods that are robust against the time and environment dependent errors that current low-cost sensors exhibits. Furthermore, since these systems produce large amounts of data that are costly to communicate, sensor-near methods to extract relevant motion information from large amounts low-quality sensor data, must explored and developed.

The four year research project Signal Processing for Large Arrays of Motion Sensors aims to study fundamental signal processing issues related to the processing of the signals from the latest generation of motion sensors, and especially signals from arrays of these sensors. In other words, this research will enable the development of next generation motion sensing systems needed for vehicles, robots, humans, and gadgets to achieve high levels of autonomy.

The project lead by I. Skog (30% activity level) will be organized into three work package: sensor modeling and calibration; measurement fusion, fault detection, and fault isolation in sensor arrays; and information extraction and compression in sensor array systems. Two Ph.D. students will be allocated to the project with an activity level of 50% and 25%, respectively.

An analyses, theories, implement, and evaluate methodology will be applied in the research project. That is, the behavior and shortcomings of the current low-cost motion sensors will be analyzed using signals and systems, system identification, and estimation theoretic concepts. From this analysis, stochastic models of the sensor behavior will be built, allowing contemporary information fusion, data analytics, and data learning theories to be applied to the problem. The theories developed within the project will also be implemented and experimentally evaluated using the Dept. of Signal Processing, KTH, experimental test beds for motion sensing. Even though not pure basic research, this brings a unique credibility to the theoretical results obtained in the project.

Dissemination of the research results will occur through journal and conference publications. The rules for Open Access and reproducible research will be followed.

Popular scientific description (Swedish)*

En grundförutsättning i många system för att kunna fatta intelligenta beslut och uppvisa en hög grad av autonomi är förmågan att kunna mäta sina egna rörelser och position. Därför är idag allt ifrån industrimaskiner till konsument produkter utrustat med rörelsesensorer med vars hjälp de kan beräkna sina egna rörelser och förflyttningar. Denna vidsträckta användning av rörelsesensor har möjliggjorts av de senast årtiondenas utveckling inom mikro-elektro-mekaniska-system område, vilket har revolutionerat rörelsesensorindustrin. Det är idag möjligt att tillverka en endast några få kvadratmillimeter stora sensorkretsar som innehåller en accelerometrar, ett gyroskop och en magnitometrar till en kostnad av mindre än en tio kronor.

Även om sensorutvecklingen också har förbättrat rörelsesensorerna noggrannhet, så har dagens lågkostnadssensorer svårt att uppfylla de noggrannhetskrav som ställs i många system, t.ex. navigeringssystem och biomedicinska analyssystem. Effekten är att dyrare, större och mer energikrävande sensor måste användas eller att systemets prestanda reduceras. För att övervinna problemen med dålig noggrannhet hos sensorerna har ansenliga forskningsresurser används för att med hjälp av digitala signalbehandlingsmetoder, dvs. matematiska modeller och datoralgoritmer, kompensera för sensorernas mätfel och förbättra mätprestandan. Fram till dagens dato har forskningen i stor utsträckning riktat in sig på system med en eller ett fåtal rörelsesensorer, och de möjligheter som kan tänkas fås av att använda system med ett stort antal (hundratals) sensorer har inte undersökts; storleken, kostnaden och energi förbrukningen hos sensorerna har tills nu begränsade användningen av sådana system. Men genom att utnyttja den senaste generationen sensorer är det nu realistiskt att skapa system innehållande hundratals sensorer och kombinera deras mätningar för att skapa virtuella högkvalitativa sensorer. Sådana system med en stor uppsättning sensorer förespås inte bara ge en högre mätnoggrannhet, men också högre driftstillförlitlighet och ett dynamiskt mätområde större än det hos de individuella sensorerna i systemet. Egenskaper av stor betydelse i högdynamiska eller säkerhetskritiska system, så som navigeringssystem för robotar och fordon. Men innan dessa rörelsemätningssystem kan bli verkliga måste nya signalbehandlingsmetoder för att fusionera mätningarna från hundratals lågkostnads sensorer utvecklas, metoder som är robusta mot de tids och miljöberoende felen som dagens lågkostnadssensorer uppvisar. Vidare, då dessa system producera mycket stora mängder data som är kostsamt att kommunicera, måste sensornära metoder för att extrahera och komprimera relevant rörelse information från stora mängder lågkvalitative sensordata, undersökas och utvecklas.

Forskningen inom projektet ”Signalbehandling för stora system av rörelsesensorer” har som mål att studera grundläggande signalbehandlings frågor kopplade till behandlingen och bearbetandet av mätningar från den senaste generationen rörelsesensorer, och speciellt mätningar från system innehållande stora mängder rörelsesensorer. Med andra ord, att möjliggöra utvecklandet av nästa generation rörelsesensorsystem som behövs för att fordon, robotar, och annan utrustning ska kunna uppnå en hög grad av autonomi.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months

Career age: 62

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*	2. Teknik > 202. Elektroteknik och elektronik > 20205. Signalbehandling 2. Teknik > 202. Elektroteknik och elektronik > 20207. Inbäddad systemteknik

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Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

Signaler

Keyword 2*

System

Keyword 3*

Sensorer

Keyword 4

Signalbehandling

Keyword 5

Rörelsemätningar

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

Inga etiska frågor är aktuella

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

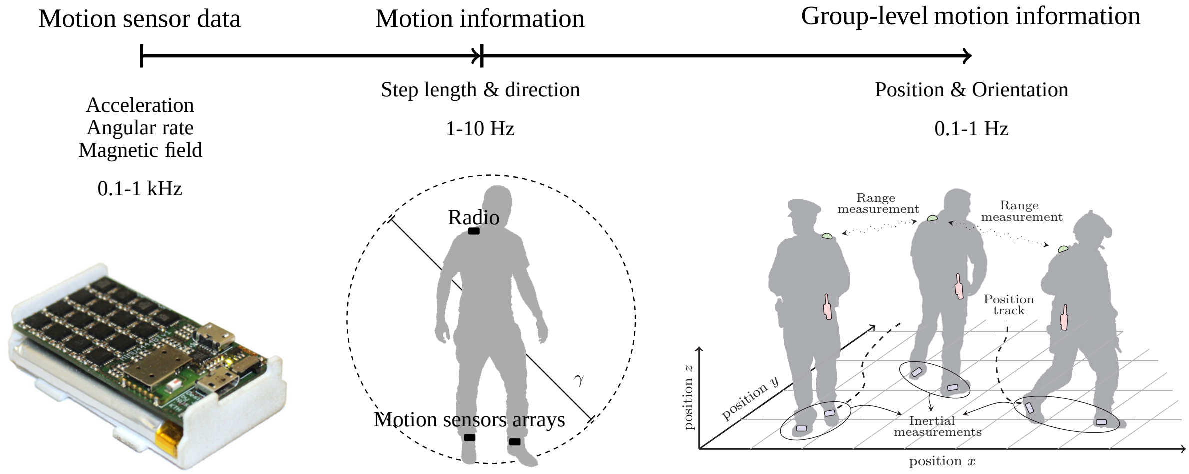
1 Purpose and aims

Motion sensing is an essential capability in many systems to achieve a high level of autonomy. Nowadays, motion sensors are therefore ubiquitous in everything from industrial manufacturing equipment to consumer electronic devices. This widespread usage of motion sensors has become possible thanks to the last decade's micro-electrical-mechanical-system technology development, which has revolutionized the motion sensing industry [A1]. Motion sensors can now be manufactured at unprecedented volumes and and at low price [A2].

Even though the technology development has also pushed the performance boundaries of the motion sensing technology, contemporary ultra-low-cost sensors still cannot fully meet the needs of many applications; especially applications where the sensor signals have to be integrated over time. These applications still suffer from the bias instability, drift, nonlinearities, and thermal instability of the ultra-low-cost sensors [A1]. Therefore, significant research efforts have been undertaken to by the aid of signal processing techniques enhance the performance of the sensors, see e.g. [A3, A4]. These efforts have been mainly focused on systems incorporating one, or at most a handful of sensors, and the possibilities related to the use of arrays with a large number of sensors have not yet been thoroughly studied. However, by capitalizing on the decreasing price, size, and power-consumption of the sensors, it is now feasible to construct arrays with hundreds of sensing elements, and combine their measurements to create virtual high-performance sensors. In figure 1a, an example of a sensor array holding 288 sensing elements is shown. This type of sensor arrays will not only provide higher measurement accuracy, but also higher system reliability thanks to component redundancy and for certain array configurations also a dynamic measurement range that extends beyond that of the individual sensors; properties of great importance in high-dynamic and safety critical applications, such as motion sensing systems for humans, robots, and vehicles. But before these sensor array based motion sensing systems can become real, new signal processing methods to fuse measurements from hundreds of ultra-low-cost motion sensors must be developed; methods that are robust against the time and environment dependent errors that current ultra-low-cost sensors exhibits [A5]. Furthermore, since large sensor arrays produce vast amounts of data that are costly to communicate, sensor-near methods to extract relevant motion information from large amounts low-quality sensor data must also be explored and developed. See figure 1 for an illustration of the transformation of low-level motion sensor data to high-level motion information in a system for cooperative tracking of a group of rescue agents.

The research project *Signal Processing for Large Arrays of Motion Sensors* research project aims to study fundamental signal processing issues related to the processing of the signals from the latest generation of motion sensors, and especially signals from the arrays of these sensors. In other words, this research will enable the development of next generation motion sensing systems needed for vehicles, robots, humans, and gadgets to achieve high levels of autonomy.

The principal investigator (PI) behind this proposal, Isaac Skog, is a promising young researcher, as manifested by some 800+ citations; a top 10% ranking in KTH Royal Institute of Technology young researchers bibliometrics index survey; a Best Survey Paper Award in the prestigious IEEE Transactions on Intelligent Transportation Systems; and extensive international experience, as outlined in his CV. The main purpose and outcome of this basic research will be to educate the supported Ph.D. students Johan Wahlström (GPA 4.9/5) and Robin Larsson (GPA 4.75/5), supervised by the PI.



(a) In-house designed motion sensor array [IS15, IS16]. The array consists of 32 motion sensor chipsets, each with nine sensing elements.

(b) Agent level motion information is calculated from several sensor arrays on the body of the user and fused using constrained filtering [IS7].

(c) A group of agents are cooperatively localizing themselves using motion information from a multitude of sensor systems and inter-agent ranging radios [IS5].

Figure 1: Illustration of the transformation of low-level motion data recorded by body mounted motion sensor arrays (figures 1a and 1b) to high-level motion information in a system for cooperative tracking of a group of agents (figure 1c). Even though only three agents are included in this example, motion data streams from more than 1700 sensors are used in the localization of them, and the need for sensor-near signal processing methods for extraction and compression of relevant information from large amounts of low quality sensor data is obvious.

2 Survey of the field

Motion sensing is an instrumental capability for a large range of applications and motion sensing related research is conducted in a variety of fields. Here, a few well cited articles from the fields of navigational and biomedical engineering are considered, together with a few recent articles dealing specifically with signal processing for motion sensor arrays.

2.1 General survey of the topic

The automotive industry was, in the early twenty-first century, one of the first to adapt the MEMS motion sensor technology on a large scale, where the sensors first made their way into the air-bag deployment detection systems, and then into the vehicle stability control and in-car navigation systems [A6]. In the in-car navigation systems, the motion sensors are used to bridge the GPS-signal outages, but the imperfections in the sensors only allow for gaps of a few seconds to be bridged if the sensors are not calibrated first, and the measurements enhanced through digital signal processing. Research has therefore been, and still is, focused on developing different sensor calibration methods [A3, A4] and sensor error models [A5, A7].

As the motion sensing technology developed and the sensors got smaller, cheaper, and more power efficient, the motion sensors made their way into the consumer electronics market.

They also started to attract the attention of several other research fields, with the pedestrian indoor navigation and biomedical engineering research fields being two of them.

Since current ultra-low-cost motion sensors are not good enough be used for the purpose of inertial navigation for time periods longer than a couple of seconds (as in the case of the in-car navigation systems), their use in pedestrian indoor navigation has taken two main directions. The first direction is to use the motion sensors to extract human motion information, such as stride frequency and gait type (forward, sideways, upstairs, etc.), together with gait models to track how a user is moving through so called dead-reckoning [A8]. The second direction, which springs out of the paper [A9], is to mount the motion sensors on the foot of the user and use them for traditional inertial navigation. To reduce the severe position error growth rate caused by sensor imperfections, the sensors and the system are recalibrated whenever the foot becomes stationary. Foot-mounted motion sensor based navigation has been identified as key technology in the development of indoor navigation systems for first-responders [A10].

Within the field of biomedical engineering, motion sensing is used for various types of monitoring, diagnosis, and rehabilitation applications [A11]. For example, in the field of ambulatory gait analysis, foot-mounted motion sensors have been used to calculate things, such as the center of mass displacement, the center of pressure, and the ground reaction force of a walking subject [A12]; parameters that are important when assessing energy expenditure and the stability of human walking. In [A13], foot-mounted motion sensors are used to quantify the gait of several control subjects, with the aim of developing ambulatory gait analysis systems to detect and diagnose neurological disorders.

In the area of signal processing for motion sensor arrays, about a hundred publications exist, but the subject is far from fully explored. Most studies have focused on arrays involving only a small number (6-12) of accelerometer sensors, see e.g., the recent papers [A14, A15, A16, A17, A18, A19], and no studies on large arrays (hundreds of sensing elements) of motion sensors exist. The focus of the research about accelerometer arrays have been on algorithm development [A14, A15], sensor placement optimization [A18, A19], and experimental evaluations [A15, A16]. Few of publications have looked at the fundamental properties of the motion estimation problem from a signals and system oriented perspective. One exception is [A17], where the observability conditions for when the orientation of a system can be tracked using an array of only accelerometers is studied.

Only a handful of publications exist about sensor arrays consisting of different kinds of motion sensors. In [A20], the theoretical performance gain of using multiple motion sensors is studied, but the important and unavoidable spatial separation of the sensors was not taken into account. In [A21] and [A22], the problem of fault detection and isolation is studied. In [A23], the sensor placement and how it can be used to cancel out the g-sensitivity of the gyroscopes is discussed. The problem of fusing the measurements in motion sensor arrays built out of multiple inertial measurement units, a.k.a. sensor assemblies consisting of three accelerometer and three gyroscopes, is studied in [A22, A24] and [A25]. Their results indicates that a significant accuracy gain can be achieved using multiple inertial measurement units.

2.2 Previous work by the applicant

The PI I. Skog and his colleagues at the Dept. of Signal Processing started to conduct research in the field of motion sensing with application to in-car navigation technologies around 2005, and worked on a variety of topics from low-level signal processing problems such as motion sensor calibration [A26, IS26] and motion sensor time synchronization [IS8, IS32], to high-level signal processing problems, such as the multi-sensor information fusion [A27]. The research work culminated in the writing of the two book chapters [IS34] and [IS35], as well as the survey paper [IS33] that was awarded a *Best Survey Paper Award* of the IEEE Transactions on Intelligent Transportation Systems as one (out of three) of the best survey papers published during the 10 year span from 2000-2009 [A28].

Around 2009, the PI and his colleagues started to apply their knowledge about in-car navigation systems and the motion sensors used therein, to the emerging field of indoor localization of humans, based on body-mounted motion sensors. Here, they established themselves as a world leading group within foot-mounted motion sensor based navigation. Together with their colleagues at the Indian Institute of Science, Bangalore, they within a Indo-Swedish Vinnova research project developed the OpenShoe platform; an open-source platform for research on foot-mounted motion sensor based navigation, available online at `www.openshoe.org`. The research leading to the development of the OpenShoe platform generated several well cited research publications on problems related to the processing of information from foot-mounted motion sensors, see e.g., [IS9, IS20, IS21, IS24, IS25], as well as off-the-shelf products on the market provided by GT Silicon Pvt Ltd[1].

With the OpenShoe platform as a stepping stone, several open basic research problems have been studied both theoretically and experimentally. The activities have to a large extent been basic research, mainly funded by the Swedish Research Council via the Framework ICT project 2009-4004 (2009–2012). Still, the application of the basic findings have been instrumental in validating the activities and identifying novel and fundamental questions. Accordingly, in 2011, we set out to build the indoor navigation system demonstrator TOR (Tactical Locator) to demonstrate the possibility of doing infrastructure independent navigation and tracking of first responders. The construction of TOR reached its final phase during the second half of 2013, and at the end of 2013 we were able to perform the first full scale tests with fire fighters. Thereby, we became one of the first, if not the first, in the world to demonstrate the possibility of doing infrastructure independent navigation and tracking of first responders under realistic conditions with fully equipped fire fighters. The research that led up to the construction of TOR is summarized in the recent publications [IS5, IS6, IS14].

In parallel with the final work on the TOR demonstrator, the PI and his colleagues, during the construction of the motion sensor arrays shown in figure 1a, conducted some initial research studies on signal processing issues related to motion sensor arrays [IS4, IS15, IS16]. The preliminary results of these studies are discussed in section 5.

3 Project description

3.1 Theory, methods, and dissemination

An analyses, theories, implement, and evaluate methodology will be applied in the research project. That is, the behavior and shortcomings of the current low-cost motion sensors will be analyzed using signals and systems, system identification, and estimation theoretic concepts. From this analysis, stochastic models of the sensor behavior will be built, allowing contemporary information fusion, data analytics, and data learning theories to be applied to the problem of extracting and compressing relevant information from large quantities of low quality sensor data. Since the Dept. of Signal Processing through the KTH R1 indoor navigation system test facility and the TOR demonstrator has unique possibilities to test the performance of motion

[1] `http://www.gt-silicon.com/`

sensor platforms when used for infrastructure free indoor navigation, the theories developed within the project will also be implemented and experimentally evaluated. It is the PI's belief that such a targeted implementation and experimental evaluation, even though not pure basic research, bring a unique credibility to the theoretical results obtained in the project.

Dissemination of the research results will occur both through specialized journals, such as IEEE Transactions on Instrumentation and Measurements and IEEE Transactions on Biomedical Engineering, as well as conferences and journals devoted to generally applicable methodologies, such as the IEEE International Conference on Information Fusion and IEEE Transactions on Signal Processing. The rules for Open Access and reproducible research will be followed.

3.2 Project structure, project participants, and roles

The span of the proposed project is four years, with a planned start in Jan. 2016. The project aims to partially support two Ph.D. students, Johan Wahlström and Robin Larsson, as well as the PI Isaac Skog. The participation of J. Wahlström and R. Larsson will be 50% and 25%, respectively, which leaves time for department duties (e.g., teaching) and more targeted research funded through EU, VINNOVA, and industry. (By engaging the students in more targeted research efforts during parts of their PhD studies, the students will gain valuable experience in addition to the basic research conducted in the VR project.) The PI is assigned a 30% activity grade in the project, which leaves room for active participation in the research and research supervision of J. Wahlström and R. Larsson.

I. Skog has conducted signal processing related research in a variety of fields, such as vehicle navigation [IS8, IS32, A26, A27, IS33], pedestrian indoor navigation [IS5, IS6, IS9, IS14, IS21, IS20, IS24, IS25], insurance telematics [IS1, IS2, IS13, IS17], etc. The common denominator for all of this research has been the usage of motion sensing and motion sensor related signal processing. The PI thus possesses both a wide and deep knowledge about motion sensing, its applications, and its limitations; knowledge well in line with the proposed research. The quality of I. Skog's prior work in signal processing, which includes several international collaborations (see table 1), is evidenced by a high number (800+) of citations.

J. Wahlström was hired as a Ph.D. student (dokorandtjänst) in February 2014 by the Dept. of Signal Processing KTH, after he got his MSc in engineering physics after only three years (nominal time 5 years), and top grades (GPA 4.9/5) throughout all of his courses. Thanks to this excellent achievement, he was admitted to the *Program of Excellence*, Doctoral program in Electrical Engineering KTH Royal Institute of Technology, which includes a grant of 1.000 tkr to (mainly) fund his course work. J. Wahlström is already actively engaged in the research at the Department, and he has already published the conference paper [IS13] and contributed to the writing of the journal paper [IS1].

R. Larsson graduated from the KTH Engineering Physics program with top grades (GPA 4.75/5) in 2005 and has since then been working at OHB Sweden (formerly the Swedish Space Corporation) as a satellite attitude and orbit control system specialist. He has published 27 journal and conference papers on topics related to satellite control systems. R. Larsson was hired as a Ph.D. student (dokorandtjänst) in July 2014 by the Dept. of Signal Processing KTH.

The Dept. of Signal Processing at KTH, led by Prof. P. Händel, provides a strong research environment for work in signal processing. The Department includes 3 professors, 2 associate professors, 4 researchers (including I. Skog), 5 post docs, and 22 Ph.D. students.

3.3 Work and time plan

The research within the project have been split into three work packages (WP): (i) sensor modeling and calibration; (ii) measurement fusion, fault detection, and fault isolation in sensor arrays; and (iii) information extraction and compression in sensor array systems. The supported Ph.D. students R. Larsson and J. Wahlström will be assigned to WP1+WP3 and WP2+WP3, respectively.

3.3.1 WP1: Sensor modeling and calibration

Time period: M0-M24
Goal: To develop higher-order sensor error models that include non-linear, dynamic memory, and g-sensitivity effects.
Description: Preliminary results from the recent research studies [IS15] and [IS16], indicate that in high dynamical applications it is not sufficient to only model and calibrate the first order errors (bias and scale factor) of the motion sensors. To in reality obtain the full theoretical potential of using arrays of motion sensors, higher-order sensor error models that also includes dynamic memory and g-sensitivity effects most be developed. Further, technics to mitigate and calibrate array related artifacts such as sensor sensitivity axes misalignments, sensor location offsets, and clock synchronization errors must be investigated. The work will take its starting point in the PIs recent publications about sensor array calibration [IS4], and the recent publications on motion sensor error modeling [A3, A4, A7].

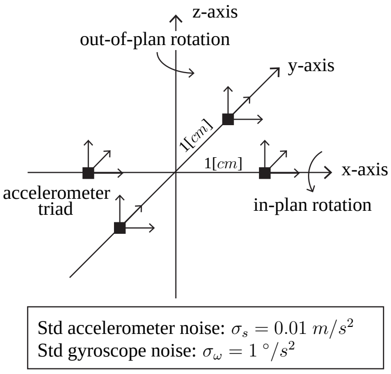
3.3.2 WP2: Measurement fusion, fault detection, and fault isolation in sensor arrays

Time period: M0-M48
Goal: To study and develop techniques for fusing the measurements in large sensor arrays.
Description: Previous studies on information fusion, fault detection, and fault isolation have been focused on arrays with only a handful number of sensors, and the proposed techniques generally only works for three dimensional arrays. Techniques for information fusion, fault detection, and fault isolation in large two dimensional arrays must therefore be studied[2]. These technics should be robust to the time and environmental dependent errors of contemporary ultra-low-cost motion sensors. The work will take it starting points in the PI's unpublished manuscript [A29] (available online) and the results presented in [A17, A24, A25]. For illustration purposes the Cramér-Rao bound for the angular velocity estimation accuracy of a small two dimensional array is shown in figure 2.

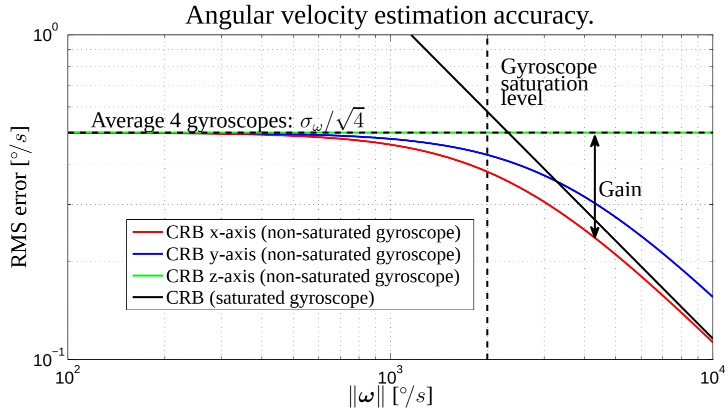
3.3.3 WP3: Information extraction and compression in sensor arrays

Time period: M0-M48
Goal: To investigate sensor-near signal processing methods to extract high-level motion information from large amount of low quality motion data.
Description: Arrays with a large number of sensors sampled at high rates produce vast amounts of data, rendering it costly to handle and communicate the data. Sensor-near signal processing methods and technics to extract and compress relevant motion information from large quantities of low quality sensor data is therefore needed. The work will take its starting point in the PI's recent publications [IS5] and [IS1], where sensor-near signal processing is used to compress high-rate sensor measurements into high-level information about the gait-motion of a pedestrian and the driving patterns of drivers, respectively.

[2] If a sensor array is to be constructed on a single printed circuit board, only a two dimensional array can be realized.



(a) Geometry of the considered sensor array.



(b) Angular velocity estimation accuracy versus angular speed during an in-plan rotation.

Figure 2: Illustration, in terms of the Cramér-Rao bound (CRB), of the angular velocity accuracy gain and measurement range extension that can be obtained using an array of four accelerometer triads and gyroscope triads. At higher rotational velocities substantial rotational information is gained from the spatial separated accelerometers. Further, even though the gyroscopes gets saturated rotational information can still be obtained from the accelerometers.

4 Significance

Motion sensing is an instrumental capability for vehicles, robots, humans, and gadgets to achieve a high level of autonomy. The research proposed within the Signal Processing for Large Arrays of Motion Sensors research project aims to study fundamental signal processing issues related to the processing of the signals from the latest generation of motion sensors, especially the signals from the arrays of these sensors. Previous studies in the field indicate that arrays of motion sensors have the potential to provide accurate, high dynamic, and fault tolerant motion sensing at low cost, size, and power consumption. The benefits of the research will thus be widespread. For examples, in the research field of navigation systems for first-responders, the ability to improve the accuracy and reliability as well as reduce the cost and size of the motion sensing systems will bring the dream of a fully infrastructure free navigation system one step closer; a type of system that could significantly increase the safety for first-responders.

5 Preliminary results

During the development of the sensor array shown in figure 1a, a few initial research studies have been conducted. Research questions related to the error characteristics and time synchronization of the sensor in the array were studied in [IS16]. These preliminary results indicate that when the arrays are stationary, the performance gain obtained by using multiple sensors is well predicted by the existing theoretical models [A24]. However, during non-stationary operations, the performance gain is reduced, due to correlations between the dynamical measurement errors of the sensors; further research about the sensor modeling and sensor measurement fusion is needed. The results in [IS16] were further confirmed by the experimental results obtained when using the sensor array in a foot-mounted motion sensor based navigation system, refer to [IS15].

A preliminary study of the problem of calibrating the sensors in the array and aligning their sensitivity axes has also been conducted, and a maximum likelihood based calibration method proposed, refer to [IS4]. The proposed calibration method works, but should be expanded to also include higher-order error terms.

During the summer of 2014, a research collaboration with Prof. A. Nehorai at Washington University in St. Louis, Missouri, USA, about measurements fusion in motion sensor arrays was initiated. Preliminary results from this research indicate that a significant accuracy improvement can be gained by using the spatial separation of the sensors in the array, see figure 2. Preliminary results are available in [A29].

6 Independent line of research

Even though the PI is still working in the same research group as where he pursued his Ph.D. degree and conducted his Post-doc studies, he has during the last years established himself as an independent researcher. This is manifested by the facts that: (i) the PI has several international exchanges as a visiting scholar; (ii) the PI has conducted several research projects independently of his previous supervisor P. Händel, which have resulted in a book chapter [IS35] and the conference publications [IS18, IS22, IS26]; (iii) the PI has for projects not involving his previous supervisor received funding from IVA Kungliga Ingenörsvetenskapsakademien, Swedish Space Agency (Rymdstyrelsen), and Stiftelsen Glödlampsfabrikernas stipendiefond; and (iv) the PI is the defacto[3] supervisor for three Ph.D. students and has supervised on graduated Ph.D. student. A grant project would allow the PI to further develop as an independent researcher and support the education of the Ph.D. students that he supervises.

The research in the *Signal Processing for Large Arrays of Motion Sensors* project will partially build upon results from the PI's Ph.D. and Post-doc projects [IS8, IS12, IS23, IS32, IS33, IS34, IS35]. The research proposed in the project is outside the PI's previous supervisors core research areas, i.e., insurance telematics and radio-frequency measurement technics.

7 Employment status

The PI I. Skog has a permanent position (*tillsvidareanställding*) as a researcher at the Dept. of Signal Processing KTH. J. Wahlström is employed as a Ph.D. students (*doktorandtjänst*) at the Dept. of Signal Processing KTH. His appointment extends to July 2019. R. Larssons is employed as a Ph.D. students with 50% activity level at the Dept. of Signal Processing KTH. His current appointment extends to July 2018, where a halftime evaluation will be conducted.

8 Equipment and infrastructure

The Dept. of Signal Processing, KTH, has via the KTH R1 indoor navigation test facility[4] and the Tactical Locator (TOR) demonstrator, cf. [IS5], unique possibilities to conduct realistic, full scale tests of indoor navigation systems for first-responder emergency scenarios. As the performance of the TOR system is highly dependent on the performance of the motion sensors used, the TOR system may be used to quantify and demonstrate the potential of using

[3] As the PI does not have an appointment as a docent he cannot officially be registered as main supervisor.

[4] The KTH R1 indoor navigation test facility is located in the reactor hall of Sweden's first nuclear reactor. The reactor hall is 25 meters below ground and represents a typical multi-storey industrial environment. The hall is equipped with a reference ultra-wide band radio positioning for the evaluation of indoor positioning systems.

Table 1: Summary of collaborations in terms of organizations and publications.

Organisation	**Joint Publications**
International	
Indian Institute of Science, India	[IS6, IS21]
Università degli Studi di Perugia, Italy	[IS11]
CSIC - Consejo Superior de Investigaciones Científicas, Spain	[IS18]
Washington University in St. Louis, MO, USA	[A29]
National	
FOI Swedish Defence Research Agency	[IS24, IS6, IS9, IS31, IS14]
Stockholm University, Sweden	[IS1, IS2, IS17]
Dept. Automatic Control, KTH,	[IS12]
Dept. Micro- and Nanosystems, KTH	[IS22]
Dept. Electromagnetic Engineering, KTH	[IS22]
Industry	
REW Insurance Consulting Services	[IS1]
Movelo AB, Sweden	[IS1, IS2, IS36, IS37, IS38, IS39, IS40, IS41]
OHB Sweden AB, Sweden	[A30]

new motion sensing systems such as motion sensor arrays. Equipment for designing and manufacturing sensor platforms, as well as temperature chambers for calibrations of sensors, are also available.

9 International and national collaboration

The Dept. of Signal Processing, KTH, has a strong tradition of international collaborations. Those most significant for the proposed research project, and where the applicant played a significant role, are the Indo-Swedish Vinnova-DST project *Development of wireless sensor based experimental prototype for estimation of position/navigation parameters of objects in a short enclosed range, using co-operative localization techniques based on multiple sensor data* (2010-2013)[IS6, IS7, IS9, IS19, IS21, IS20, IS25] and the Indo-Swedish Vinnova-DBT project *Seamless affordable assistive technology for health* (2014-2016) [IS4, IS14]. The PI's collaboration with external researchers and industrial partners are summarized in table 1.

References

[A1] D. Shaeffer, "MEMS inertial sensors: A tutorial overview," *IEEE Commun. Mag.*, vol. 51, no. 4, pp. 100–109, Apr. 2013.

[A2] M. Perlmutter and L. Robin, "High-performance, low cost inertial MEMS: A market in motion!" in *Proc. IEEE/ION Position Location and Navigation Symposium (PLANS)*, Myrtle Beach, SC, Apr. 2012, pp. 225–229.

[A3] Y. Li *et al.*, "Autonomous calibration of mems gyros in consumer portable devices," *Sensors Journal, IEEE*, vol. pp, no. 99, pp. 1–1, 2015.

[A4] G. Aydemir and A. Saranli, "Characterization and calibration of MEMS inertial sensors for state and parameter estimation applications," *Measurement*, vol. 45, no. 5, pp. 1210–1225, June 2012.

[A5] Y. Yuksel *et al.*, "Error modeling and characterization of environmental effects for low cost inertial MEMS units," in *Proc. of PLANS*, May 2010, pp. 598–612.

[A6] R. H. Dixon and J. Bouchaud, "Markets and applications for mems inertial sensors," in *Proc. of SPIE*, vol. 6113, 2006.

[A7] N. El-Sheimy *et al.*, "Analysis and modeling of inertial sensors using allan variance," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 1, pp. 140–149, Jan. 2008.
[A8] A. Jimenez *et al.*, "A comparison of pedestrian dead-reckoning algorithms using a low-cost mems imu," in *Proc. of IEEE WISP*, Aug. 2009, pp. 37–42.
[A9] E. Foxlin, "Pedestrian tracking with shoe-mounted inertial sensors," *Computer Graphics and Applications, IEEE*, vol. 25, no. 6, pp. 38–46, Nov. 2005.
[A10] J. Rantakokko *et al.*, "Accurate and reliable soldier and first responder indoor positioning: multisensor systems and cooperative localization," *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 10–18, Apr. 2011.
[A11] H. Zeng and Y. Zhao, "Sensing movement: Microsensors for body motion measurement," *Sensors*, vol. 11, no. 1, pp. 638–660, 2011.
[A12] H. Schepers *et al.*, "Ambulatory estimation of center of mass displacement during walking," *IEEE Trans. Biomed. Eng.*, vol. 56, no. 4, pp. 1189–1195, Apr. 2009.
[A13] I. Tien *et al.*, "Results of using a wireless inertial measuring system to quantify gait motions in control subjects," *IEEE Trans. Inf. Technol. Biomed.*, vol. 14, no. 4, pp. 904–915, July 2010.
[A14] H. Naseri and M. Homaeinezhad, "Improving measurement quality of a MEMS-based gyro-free inertial navigation system," *Sensors and Actuators A: Physical*, vol. 207, pp. 10–19, Mar. 2014.
[A15] P. He and P. Cardou, "Estimating the angular velocity from body-fixed accelerometers," *J. Dyn. Sys., Meas., Control*, vol. 134, no. 6, p. 061015, 2012.
[A16] S. Madgwick *et al.*, "Measuring motion with kinematically redundant accelerometer arrays: Theory, simulation and implementation," *Mechatronics*, vol. 23, no. 5, pp. 518–529, 2013.
[A17] P. Schopp *et al.*, "Observing relative motion with three accelerometer triads," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 12, pp. 3137–3151, Dec. 2014.
[A18] T. R. Williams *et al.*, "Minimal spatial accelerometer configurations," *J. Dyn. Sys., Meas., Control*, vol. 135, p. 021016, 2013.
[A19] C. Liu *et al.*, "Design and analysis of gyro-free inertial measurement units with different configurations," *Sensors and Actuators A: Physical*, vol. 214, pp. 175–186, Aug. 2014.
[A20] S. Guerrier, "Improving accuracy with multiple sensors: Study of redundant mems-imu/gps configurations," in *Proc. of ION GNSS*, Savannah, GA, USA, Sept. 2009.
[A21] D. Bittner *et al.*, "Fault detection, isolation, and recovery techniques for large clusters of inertial measurement units," in *Proc. of IEEE/ION PLANS*, May 2014, pp. 219–229.
[A22] A. Waegli, S. Guerrier, and J. Skaloud, "Redundant MEMS-IMU integrated with GPS for performance assessment in sports," in *Proc. IEEE/ION PLANS*, May 2008.
[A23] H. Martin and P. Groves, "A new approach to better low-cost MEMS IMU performance using sensor arrays," in *Proc. ION GNSS+*, Sept. 2013.
[A24] A. Waegli *et al.*, "Noise reduction and estimation in multiple micro-electro-mechanical inertial systems," *Measurement Science and Technology*, vol. 21, 2010.
[A25] J. Bancroft and G. Lachapelle, "Data fusion algorithms for multiple inertial measurement units," *Sensors*, vol. 12, pp. 3720–3738, 2011.
[A26] I. Skog and P. Händel, "Calibration of a MEMS inertial measurement unit," in *Proc. XVII IMEKO World Congress*, Rio, Brazil, Sept. 2006.
[A27] ——, "A low-cost GPS aided inertial navigation system for vehicle applications," in *Proc. EUSIPCO 2005*, Antalya, Turkey, Sept. 2005.
[A28] "The top and the best: Toward excellence in ITS research and development," *IEEE Trans. on Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1033–1034, Sept. 2013.
[A29] I. Skog *et al.*, "Inertial sensor arrays, maximum likelihood, and cramér-rao bound," available at: https://sites.google.com/site/isaacskog/home.
[A30] ——, "GNSS receiver based navigation of satellites in geotransfer orbits," in *Submitted to 2015 ION GNSS+*.

Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project*

	Role in the project	Name	Percent of full time
1	Applicant	Isaac Skog	30

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Isaac Skog	30	244,300	251,600	259,100	266,900	1,021,900
2	PhD Student	Johan Wahlström	50	274,200	295,200	317,500	341,000	1,227,900
3	PhD Student	Robin Larsson	25	132,300	137,600	153,500	159,700	583,100
	Total			650,800	684,400	730,100	767,600	2,832,900

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Kontor	67,000	70,000	75,000	79,000	291,000
	Total	67,000	70,000	75,000	79,000	291,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Resor		80,000	80,000	80,000	80,000	320,000
	Total		80,000	80,000	80,000	80,000	320,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	650,800	684,400	730,100	767,600	2,832,900		2,832,900
Running costs	80,000	80,000	80,000	80,000	320,000		320,000
Depreciation costs					0		0
Premises	67,000	70,000	75,000	79,000	291,000		291,000
Subtotal	797,800	834,400	885,100	926,600	3,443,900	0	3,443,900
Indirect costs	243,000	256,000	273,000	287,000	1,059,000		1,059,000
Total project cost	1,040,800	1,090,400	1,158,100	1,213,600	4,502,900	0	4,502,900

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The VR budget covers the salary costs for the PI I. Skog (30% activity level) and one PhD-student equivalent (75% activity level). It is planned that two PhD students employed by KTH will participate in the project, but they are not to be fully funded through VR. They will be employed (doktorandtjänst) and follow the doctoral salary ladder at KTH. By engaging the students in more targeted research efforts during part of their Ph.D. studies, they will gain valuable experience in addition to the basic research conducted in the VR project. Initially, Johan Wahlström and Robin Larsson will be allocated to the project, but over the time of the project a natural renewal of Ph.D. students may take place.

Travel costs are calculated as one travel per participant per year, based on the Department's budget key. A similar budget has been prepared for the rent.

Indirect costs are specified below.

Summa högskolegemensamma: 23,76%

Summa skolgemensamma: 6,33%

Summa avdelningsgemensamma: 7,26%

Summa indirekta kostnader: 37,4%

The budget above is according to the guidelines. Funding for related activities of relevance (including procurement of equipment) will be provided by the accumulated faculty funding (positivt myndigheteskapital) according to Dnr: E-2010-0088 available at the Department of Signal Processing, KTH. If a reduced funding is granted (up to a reasonable amount), faculty funding will be secured so that the project can be adapted to the new funding level (omställningskostnader). The research outlined in this application is not covered by other funded, nor have other external project grants been applied for.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV

Curriculum Vitae – Isaac Skog (born: 1981)

1. Higher education qualification

- B.Sc. Electrical Engineering, KTH Royal Institute of Technology, Sweden (2003).
- M.Sc. Wireless Systems, KTH Royal Institute of Technology, Sweden (2005).
- Licentiate Signal Processing, KTH Royal Institute of Technology, Sweden (2007).

2. Degree of Doctor

- Ph.D. in Signal Processing (main supervisor: P. Händel, title: Low-Cost Navigation Systems – A study of four problems), KTH Royal Institute of Technology, Sweden (2010)

3. Postdoctoral positions and international visits

- Visiting scholar, Mobile Multi-Sensor Systems Research Team, University of Calgary, AB, Canada. (Jan. 2009 – Jun. 2009)
- Visiting scholar, Statistical Signal Processing Lab, Indian Institute of Science, Bangalore, India. (Sep. 2011 – Jan. 2012)
- Visiting scholar, Dept. of Electrical & System Engineering, Washington University in St. Louis, USA. (2 weeks, Aug. 2014)
- Post-doc, Dept. of Signal Processing, KTH Royal Institute of Technology, Sweden. (Feb. 2010 – Feb. 2012)

4. Qualification required for appointment as a docent

- No docent title. Docent application planned for by Aug. 2015. Fulfills all requirements.

5. Current positions

- Researcher, Dept. of Signal Processing, KTH Royal Institute of Technology, Sweden, Feb. 2012 (*tillsvidareanställding*).
- Research director (20% part time), SafeLine Sweden AB, Sweden. Mar. 2015.

6. Previous positions and periods of appointment

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7. Deductible time

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8. Supervision

Co-supervisor at KTH for the following Ph.D.-students:

1. John-Olof Nilsson, (M.Sc. Engineering Physics, KTH), Ph.D. Signal Processing, 2013, [IS5, IS6, IS9, IS11, IS15, IS16, IS19, IS21, IS20, IS23, IS25, IS27, IS35]
2. Johan Walhström, (M.Sc. Engineering Physics, KTH), *ongoing*, [IS1, IS13]
3. Farid Bonawiede, (M.Sc. Engineering Physics, KTH), *ongoing*, [IS1]
4. Robin Larsson, (M.Sc. Engineering Physics, KTH), *ongoing*

9. Scientific awards and token of excellence

- Ranked top 10% among KTHs young researchers in the KTH bibliometrics index, 2014.
- Best Survey Papers Award[1] (2000–2009), IEEE Trans. on Intell. Transp. Syst., 2013.
- PI of the project "Camera-based classification and detection of light sources", funded by Stiftelsen Glödlampsfabrikernas stipendiefond, 900' kr, 2015
- Scholarship from Hans Werthén Scholarship, IVA Kungliga Ingenörsvetenskaps-akademien, 60' kr, 2011.
- Co-founder of Movelo AB, which was ranked #2 in the Insurance Telematics Supplier Ranking 2013 provided by the PTOLEMUS Consulting Group[2], in the category Best Telematics Service Providers in Europe, segment Smartphone.
- Co-creator and developer of the OpenShoe (`www.openshoe.org`) foot-mounted inertial navigation platform, used by researchers and companies in more than 10 countries.

10. Academic assignments

- Ph.D. thesis Grading committee at Autonomous University of Barcelona, Spain 2014.
- Reviewer for most IEEE journals in the area of Signal Processing, Instrumentation and Measurements, Intelligent Transportation Systems, and Aerospace Systems.
- Tutorial speaker at:
  - IEEE I2MTC, Pisa, Italy 2015. Tutorial title: Smartphone Instrumentation for Insurance Telematics.
  - IEEE CONECCT, Bangalore, India, 2013. Tutorial title: Zero-velocity aided foot-mounted inertial navigation.
  - GETA winter school, Aalto University, Short course on Wireless Localization, 2012. Tutorial title: Signal processing for foot-mounted navigation.
  - SP 5th International workshop on Analysis of Dynamic Measurements, Borås, Sweden, 2010. Tutorial title: Navigation with Kalman Filtering.

11. Publication output in brief

- 13 journal and review articles
- 24 international and national conference papers (20 between 2008-2015)
- 2 book chapters
- 4 granted patents + 2 filed patents
- 836 citations[3] (h-index: 13)

Top 3 cited publications

I. Skog and P. Händel. "In-car positioning and navigation technologies – a survey," *IEEE Trans. on Intelligent Transportation Systems*, vol. 10, nr. 1, pp. 4-21, Mar. 2009

Number of citations: 215

I. Skog and P. Händel. "Calibration of a MEMS inertial measurement unit," in *Proc. XVII International Measurement Confederation (IMEKO) World Congress*, Rio, Brazil, Sept. 2006.

Number of citations: 114

I. Skog, P. Händel, J-O. Nilsson, and J. Rantakokko. "Zero-velocity detection – An algorithm evaluation,". *IEEE Trans. on Biomedical Engineering*, vol. 57, nr. 11, pp. 2657-2666, Nov. 2010

Number of citations: 106

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[1] The Top and the Best: Toward Excellence in ITS Research and Development, *IEEE Trans. on Intell. Transp. Syst.*, vol. 14, no. 3, Sep. 2013.

[2] `http://www.ptolemus.com/ubi-study/`

[3] Citation count by Google Scholar on 17th of March 2015.

Publication list

Isaac Skog — Publications

1. Peer-reviewed original articles

[IS1] P. Händel, I. Skog, J. Wahlström, F. Bonawiede, R. Welch, J. Ohlsson, M. Ohlsson. "Insurance Telematics: Opportunities and Challenges with the Smartphone Solution," *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 4, pp. 57-70, Dec. 2014.

[IS2] P. Händel, J. Ohlsson, M. Ohlsson, I. Skog, and E. Nygren. "Smartphone Based Measurement Systems for Road Vehicle Traffic Monitoring and Usage Based Insurance," *IEEE Systems Journal*, vol. 8, no. 4, pp. 1238-1248, Dec. 2014.

[IS3] I. Skog and P. Händel. "Indirect Instantaneous Car-Fuel Consumption Measurements," *IEEE Transaction on Instrumentation and Measurements*, vol. 63. no. 12, pp. 3190-3198, Dec. 2014.

[IS4] J-O. Nilsson, I. Skog, and P. Händel. "Aligning the Forces - Eliminating the Misalignments in IMU Arrays," *IEEE Transaction on Instrumentation and Measurements*, vol. 63. no. 10, pp. 2498-2500, Oct. 2014. *

[IS5] J-O. Nilsson, D. Zachariah, I. Skog, and P. Händel. "Cooperative localization by dual footmounted inertial sensors and inter-agent ranging," *EURASIP Journal on Advances in Signal Processing*, vol. 163, Oct. 2013.

[IS6] KVS. Hari, J O. Nilsson, I. Skog, P. Händel, J. Rantakokko, and GV. Prateek. "A prototype of a first-responder indoor localization system," *Journal of the Indian Institute of Science*, vol. 93, nr. 3, pp. 511-520, Aug. 2013.

[IS7] D. Zachariah, I. Skog, M. Jansson, and P. Händel. "Bayesian Estimation With Distance Bounds," *IEEE Signal Processing Letter*, vol. 19, nr. 12, pp. 880-883, Dec. 2012. *

[IS8] I. Skog and P. Händel. "Time Synchronization Errors in Loosely Coupled GPS-Aided Inertial Navigation Systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, nr. 4, pp. 1014-1023, Dec. 2011.

[IS9] I. Skog, P. Händel, J-O. Nilsson, and J. Rantakokko. "Zero-velocity detection – An algorithm evaluation,". *IEEE Transactions on Biomedical Engineering*, vol. 57, nr. 11, pp. 2657-2666, Nov. 2010. *

[IS10] I. Skog and P. Händel. "Synchronization by Two-Way Message Exchanges: Cramér-Rao Bounds, Approximate Maximum Likelihood, and Offshore Submarine Positioning,". *IEEE Transactions on Signal Processing*, vol. 58, nr. 4, pp. 2351-2362, Apr. 2010.

[IS11] A. De Angelis, J-O. Nilsson, I. Skog, Händel, and P. Carbone. "Indoor Positioning by Ultrawide Band Radio Aided Inertial Navigation," *Metrology and Measurement Systems*, vol. 17, nr. 3, pp. 447-460, Dec. 2010.

[IS12] P. Händel, Y. Yao, N. Unkuri, and I. Skog. "Far infrared camera platform and experiments for moose early warning systems," *Transactions of Society of Automotive Engineers of Japan*, vol. 40, nr. 4, pp. 1095-1099, 2009.

2. Peer-reviewed conference contributions

[IS13] J. Wahlström, I. Skog, and P. Händel. "Risk assessment of vehicle cornering events in GNSS data driven insurance telematics," in *Proc. IEEE 17th International Intelligent Conference on Transportation Systems (ITSC)*, Qingdao, China, Oct. 2014.

[IS14] J-O. Nilsson, J. Rantakokko, P. Händel, I. Skog, M. Ohlsson, KVS. Hari, "Accurate Indoor Positioning of Firefighters using Dual Foot-mounted Inertial Sensors and Inter-agent Ranging," in *Proc. IEEE/ION Position, Location and Navigation Symposium (PLANS)*, Monterey, CA, USA, May. 2014.

[IS15] I. Skog, J-O. Nilsson, and P. Händel. "Pedestrian tracking using an IMU array," in *Proc. IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, Bangalore, India, Jan. 2014.

[IS16] I. Skog, J-O. Nilsson, and P. Händel. "An Open-Source multi inertial measurement units (MIMU) platform," in *Proc. International Symposium on Inertial Sensors and Systems (ISISS)*, Laguna Beach, CA, USA, Feb. 2014. *

[IS17] I. Skog, P. Händel, M. Ohlsson, and J. Ohlsson. "Challenges In Smartphone-Driven Usage Based Insurance," in *Proc. IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Austin, TX, USA, Dec. 2013.

[IS18] F. Zampella, A. De Angelis, I. Skog, D. Zachariah, and A. Jimenez. "A constraint approach for UWB and PDR fusion," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sydney, Australia, Nov. 2012.

[IS19] I. Skog, J.-O. Nilsson, D. Zachariah, and P. Händel. "Fusing the information from two navigation systems using an upper bound on their maximum spatial separation," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sydney, Australia, Nov. 2012.

[IS20] J-O. Nilsson, I. Skog, and P. Händel. "A note on the limitations of ZUPTs and the implications on sensor error modeling," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sydney, Australia, Nov. 2012.

[IS21] J-O. Nilsson, I. Skog, P. Händel, and KVS. Hari. "Foot-Mounted INS for Everybody – An Open-Source Embedded Implementation," in *Proc. IEEE/ION Position Location and Navigation Symposium (PLANS)* SC, USA, Apr. 2012. *

[IS22] M. Bengtsson, J. Lillieskköld, M. Norgren, I. Skog, and H. Sohlström. "Developing and Implementing a Program Interfacing Project Course in Electrical Engineering," in *Proc. 8th International CDIO Conference* Brisbane, Australia, Jul. 2012.

[IS23] J-O. Nilsson, I. Skog, A. De Angelis, C. Aquilanti, and P. Händel. "Gear scale estimation for synthetic speed pulse generation," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Prague, Czech Republic, May 2011.

[IS24] P. Strömbäck, J. Rantakokko, S.-L. Wirkander, M. Alexandersson, K. Fors I. Skog, and P. Händel. "Foot-mounted Inertial Navigation and Cooperative Sensor Fusion for Indoor Positioning," in *Proc. International Technical Meeting of The Institute of Navigation*. San Diego, CA, Jan. 2010.

[IS25] I. Skog, J-O. Nilsson, and P. Händel. "Evaluation of zero-velocity detectors for foot-mounted inertial navigation systems," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Zurich, Switzerland, Sept. 2010.

[IS26] G. Panahandeh, I. Skog, and M. Jansson. "Calibration of the accelerometer triad of an inertial measurement unit, maximum likelihood estimation and Cramér-Rao bound," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Zurich, Switzerland, Sept. 2010.

[IS27] J-O. Nilsson, I. Skog, and P. Händel. "Performance characterisation of foot-mounted ZUPT aided INSs and other related systems," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Zurich, Switzerland, Sept. 2010.

[IS28] J-O. Nilsson, I. Skog, and P. Händel. "Joint state and measurement time-delay estimation of nonlinear state space systems," in *Proc. of 10th International Conference on Information Sciences Signal Processing and their Applications (ISSPA)*, Kuala Lumpur, Malaysia, May 2010.

[IS29] A. De Angelis, J-O. Nilsson, I. Skog, and P. Händel. "UWB Ranging Hardware Platform," in *Proc. of GigaHertz Symposium*, Lund, Sweden, Mar. 2010.

[IS30] J-O. Nilsson, A. De Angelis, I. Skog, P. Carbone, and P. Händel. "Signal processing issues in indoor positioning by ultra wide band radio aided inertial navigation," in *Proc. European Signal Processing Conference (EUSIPCO)*, Glasgow, Scotland, Aug. 2009.

[IS31] J. Rantakokko, J. Rydell, K. Fors, S. Linder, S-L. Wirkander, I. Skog, and P. Händel. "Technologies for first responder indoor localization," in *Proc. Precision Indoor Personnel Location and Tracking for Emergency Responders Technology Workshop*, Worcester, MA, USA, Aug. 2009.

[IS32] I. Skog and P. Händel. "Effects of time synchronization errors in GNSS-aided INS," in *Proc. IEEE/ION Position Location and Navigation Symposium (PLANS)*, Monterey, CA, USA, May 2008.

3. Review articles

[IS33] I. Skog and P. Händel. "In-car positioning and navigation technologies – a survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 10, nr. 1, pp. 4-21, Mar. 2009.

4. Book and book chapters

[IS34] I. Skog and P. Händel, "State-of-the-Art In-Car Navigation: An Overview.," in *Handbook of Intelligent Vehicles*, Edited by: A. Eskandarin, Springer, 2012.

[IS35] J-O. Nilsson, D. Zachariah, and I. Skog, "Global Navigation Satellite Systems: An Enabler for In-Vehicle Navigation," in *Handbook of Intelligent Vehicles*, Edited by: A. Eskandarin, Springer, 2012.

5. Patents

[IS36] M. Ohlsson, P. Händel, J. Ohlsson, and I. Skog, "Larm-anordning i fordon", Swedish patent application 1130079-5, Sept. 2011. (approved)

[IS37] P. Händel, M. Ohlsson, J. Ohlsson, and I. Skog, "Avläsning och central lagring av mätarställning", Swedish patent application 1230004-2, Jan. 2012. (approved)

[IS38] P. Händel, M. Ohlsson, I. Skog, and J. Ohlsson, "Bestämning av aktivitetsgrad hos portabel elektronisk utrustning", Swedish patent application 1230015-8, Feb. 2012. (approved)

[IS39] M. Ohlsson, P. Händel, J. Ohlsson, and I. Skog, "Mobiltelefonladdare med anslutningskontroll", Swedish patent application 1230116-4, Nov. 2012.

[IS40] P. Händel, I. Skog, M. Ohlsson, and J. Ohlsson, "Anordning för att bestämma identitet hos ett motorfordon", Swedish patent application 1230137-0, Nov. 2012.

[IS41] I. Skog, P. Händel, M. Ohlsson, and J. Ohlsson, "Beräkning av accelerationssignal utifrån hastighetsmätning", Swedish patent application 1330082-7, Jun. 2013.

6. Open access computer programs that you have developed

[IS42] I. Skog and J-O. Nilsson, "OpenShoe – Foot-mounted INS for Every Foot", Available at `www.openshoe.org`, First revision released: Dec. 2011

[IS43] I. Skog, "GPS based onboard navigation of geostationary satellites simulator", Available at `https://sites.google.com/site/isaacskog/home`, First revision released: Aug. 2013.

7. Popular science articles/presentations

[IS44] "Svensk teknik hittar rätt i rökfyllda rum", Ny Teknik, 2012-12-11.

[IS45] "Smarta skor alla kan sko sig på", Elektronik Tidningen, 2012-12-10.

[IS46] "Smarta skor hjälp i äldreomsorg", Dagens Nyheter, 2014-01-04.

[IS47] "Dator i klacken ska rädda liv", Sveriges Television, 2012-12-29.

[IS48] "Sensor hjälper GPS som tappar orienteringen", Ny Teknik, 2007-12-10.

[IS49] "Den datoriserade dojan", TV4 vetenskap", 2012-10-28.

CV

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Gender: Male	**Employer:** Kungliga Tekniska högskolan

Research education

Dissertation title (swe)		
Dissertation title (en)		
Low-Cost Navigation Systems - A study of four problems		
Organisation	**Unit**	**Supervisor**
Kungliga Tekniska Högskolan, Sweden Sweden - Higher education Institutes		Peter Händel
Subject doctors degree	**ISSN/ISBN-number**	**Date doctoral exam**
20205. Signalbehandling	1653-5146 ; 2009 : 057	2010-01-22

Publications

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Skog, Isaac has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.