Robust positioning for efficient C2

Final report

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Sammanfattning

Rapporten sammanfattar det arbete som genomförts inom projektet *Robust positionering för effektiv ledning* ur ett tekniskt perspektiv. Forskningen i projektet har fokuserat mot att utvärdera prestanda för olika tekniker i realistiska scenarion. Arbetet har därmed huvudsakligen varit experimentellt baserat, där experimentsystem har utvecklats och därefter utvärderats under så realistiska omständigheter som möjligt.

GPS-mottagare är känsliga mot interferenser och avsiktlig störning. Olika metoder för att detektera störningssignaler, innan mottagaren påverkas negativt av dessa, har utvärderats. Olika prestandamått har även undersökts i syfte att erhålla förbättrade osäkerhetsestimat av GPS-mottagarens positionsnoggrannhet i urbana miljöer.

Realiserbarhetsanalyser har genomförts rörande möjligheten att införa s.k. *assisted-GPS* även i militära system.

När felet från en GPS-mottagare är större än vad som acceptabelt så bör en GPS-mottagare varna för detta. Standardavvikelsen av latitud och longitud som erhålls i standardmeddelandet från kan ge bra estimat av positionsfelet under såväl bra som riktigt dåliga förhållanden. I situationer med kraftig flervägsutbredning, såsom nära byggnader, så är det däremot svårt att tillförlitligt estimera positionsfelet.

Det går i många fall att detektera GPS-interferenser innan de påverkar mottagaren. Energidetektion är en konceptuellt enkel detektor som ger goda resultat. Detektorer som baseras på signal-till-brus förhållandet för de olika satelliterna är olämpliga i mobila urbana scenarion eftersom de inte kan särskilja mellan en ökning av interferens- och brusnivån eller minskning av GPS-signalernas energi.

Befintliga soldatpositioneringssystem kan inte tillförlitligt estimera vilket våningsplan eller motsvarande vilket rum en soldat befinner sig i. Även om fotmonterade tröghetsnavigeringssystem är betydligt robustare och noggrannare så förväntas de inte ge önskad noggrannhet under längre inomhusoperationer. Ytterligare stöttande sensorer är nödvändiga för att kunna medge ett positionsfel som understiger tre meter efter 30 minuter inomhus, i realistiska situationer.

Positionsnoggrannheten kan förbättras genom att införa kooperativ lokalisering, men det är då kritiskt att de olika delsystemens osäkerheter kan estimeras på ett tillförlitligt sätt. Signalstyrkemätningar på multipla frekvenser kan vara användbara i ett multisensorsystem, exempelvis genom att de medger möjligheten till lopslutning då soldaten återkommer till tidigare besökta platser. Genom att integrera kamerabaserade med fotmonterade positioneringssystem kan robustheten och noggrannheten förbättras avsevärt. Förmågan att generera 2D och 3D kartor i okända miljöer är dessutom en intressant ny förmåga som ett kamerabaserat system kan medge.

Nyckelord: Positionering, multisensorsystem, GPS, interferensdetektion, osäkerhetsmått, fotmonterad TNS, SLAM

Summary

This report provides a summary of the main activities performed in the project *Robust positioning for efficient C2*, from a technology perspective. The research performed within the project has focused on evaluating the potential performance of different technologies in real-world scenarios. Hence, the work has been mainly experimentally-based research, where experimental positioning systems have been developed and evaluated in as realistic settings as possible.

There is a need to provide warnings when the position estimates from the GPS-receiver are larger than what is acceptable. The standard deviation of latitude and longitude delivered by the NMEA GST message can be used as an estimate of the position error. The position error is estimated quite well during good and bad conditions. However, in areas with heavy multipath propagation, such as close to buildings, reliable estimation of the position error is difficult.

It is in many situations possible to detect GPS frequency interference before the receiver is affected negatively. Energy detection is a conceptually simple detector that provides good results. Carrier-to-noise (C/N_0) based detectors are unsuitable for mobile urban scenarios, since they are not able to distinguish between an increased noise-plus-jammer-power and a decrease in the received GPS signal power.

It is possible to improve critical parameters in several military applications, e.g. the TTFF and the possibility of performing direct P(Y)-acquisition, by providing military GPS receivers with assistance data.

Existing soldier positioning systems will not be able to provide room- or floor-level position accuracy. Although significantly more robust and accurate, single foot-mounted INS are not expected to provide room-level position accuracy during extended indoor operations. Dual foot-mounted INS cancels much of the systematic errors, as well as provides a higher robustness towards crawling and other irregular movement types. However, additional supporting sensors are required in order to keep the position error below three meters after time periods of 30 minutes.

The position accuracy can be improved through cooperative localization approaches; however, it is crucial that the sub-systems uncertainty estimates are reliable when cooperative localization is applied. Furthermore, it was shown that multi-frequency RSS measurements could be useful to aid a multisensor indoor positioning system, for instance by allowing the system to perform loop-closure. Also, by integrating camera-based localization with foot-mounted INS it is possible to significantly improve the robustness and accuracy since the two systems are both likely to run into situations where the performance is insufficient and where the other system in those situations can provide high accuracies. The capability to generate 2D and 3D maps of unknown indoor environments is appealing.

Keywords: Positioning, multisensor systems, GPS, interference detection, uncertainty metrics, foot-mounted INS, SLAM

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1 Introduction

This report provides a summary of the main activities performed in the project *Robust positioning for efficient C2*, from a technology perspective. The details of these results can be found in separate publications. The report is the formal project delivery[1] for Q4, 2013.

The main application for the work presented herein is a soldier positioning system, with a focus on urban operations which also includes transitions between outdoor and indoor environments. Currently, such systems are mainly based upon stand-alone GPS (Global Positioning System) receivers. However, soldier positioning systems based on multisensor approaches are under development and first-generation systems are expected to become available on the market within a few years. Most of the work is relevant also for the development of future positioning systems for small unmanned aerial/ground vehicles (UAVs/UGVs) and vehicles operating in urban environments.

1.1 Project description

Accurate and reliable localization of soldiers in all environments, including urban and indoor operations, is a challenge that has not yet been solved. Existing systems are not able to provide sufficient accuracy while simultaneously fulfilling the stringent size, weight and cost requirements.

GPS receivers can provide sufficient position accuracies in many environments. However, the GPS signals are very weak at the surface of the earth and they can easily be jammed. The GPS signal experiences reflection, scattering and attenuation in urban environments, and these effects may cause large position errors. Thus, the position accuracy and availability is often insufficient in urban environments, especially in indoor operations.

By integrating the GPS receiver with additional positioning sensors, e.g. inertial sensors, magnetometers, barometric and/or imaging sensors, it is believed that the problem with providing an accurate soldier positioning system can be solved.

The project *Robust positioning for efficient C2* is a R&D project financed by the Swedish Armed Forces. The project started in 2011 and it ends in December 2013. The overall focus of the project has been to address research problems that are considered to be key areas for increasing the robustness and accuracy for military positioning systems. The aim is to demonstrate new technologies and possibilities for localizing soldiers and vehicles, with a particular emphasis on soldier positioning systems in urban environments.

1.2 Overview of project activities

An overview of the main project activities is provided in Figure 1.1. The main activities related to GPS are detection of unintentional interference and hostile jamming, evaluations of performance metrics for improved reliability in position uncertainty estimation and work on assisted GPS approaches for military applications. All GPS activities have bearing on both soldier and vehicle applications.

There is a consensus in the research community that a multisensor fusion approach is required in order to provide an accurate, robust positioning system with indoor capability. As described in [1], GPS receivers, inertial sensors, radio-based ranging, magnetometers, barometric altimeters, ultrasonic sensors, Doppler radars, and imaging sensors have been studied within this context. An overview of sensors and characteristics is provided in Table 1.1, see [1] for more details.

[1] Swedish Armed Forces reference number – AF.922.0207

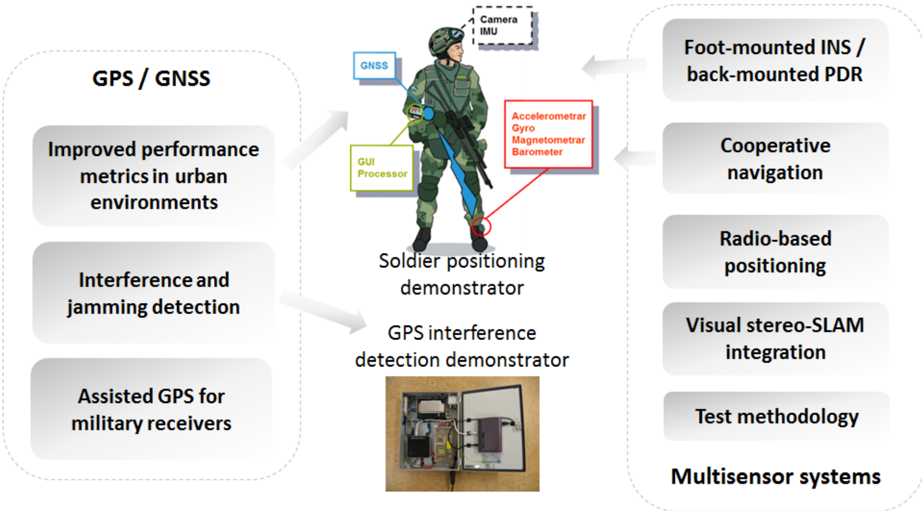

Figure 1.1: Overview of the main project activities.

Regarding the choice of sensor technologies, we have primarily focused on evaluating the strengths and potential vulnerabilities with foot-mounted inertial navigation systems (INS), radio-frequency (RF) based technologies and imaging sensors. Regarding multisensor systems, the main focus has been on the signal processing and sensor fusion aspects, using commercially available sensors.

Cooperative navigation is expected to constitute a key component when considering the long-term development of military positioning systems, including soldier applications. In contrast, foot- or back-mounted inertial sensors, complemented with magnetometers and barometric altimeters, will be integrated with GPS receivers already in next generation soldier positioning systems. Hence, in the development of test methodology we have focused on describing how the latter technologies could be evaluated.

Two demonstration systems have been developed; GPS interference detection based on energy detection software implemented in a commercial software defined radio (USRP B200) and a multisensor system for soldier positioning[2]. The interference detection algorithms are based on signal strength measurements, similar to the work described in Section 2.2. In the soldier positioning demonstration several different sensors have been integrated and tested (although all sensors are not currently implemented in the demonstration system) including civilian (u-blox) and military (DAGR[3]) GPS-receivers, foot-mounted inertial navigation systems based on tri-axial accelerometers, gyros and magnetometers, and ultra-wideband (UWB) ranging and communication transceivers. The different sub-systems, and the cooperative localization approach, used in the demonstrations are described in Chapter 3. The soldier positioning demonstration system has simultaneously served as a platform for obtaining realistic data on which algorithm development has been based.

The research performed within the project has been focused on evaluating the potential performance of different technologies in real-world scenarios. Hence, the work has been mainly experimentally-based research, where experimental positioning systems have been developed and evaluated in as realistic settings as possible. The project has contributed with, or participated in, six scientific publications [1,4-8], two presentations at international technology workshops [2-3], nine FOI reports [9-16] and six FOI MEMO. The latter documents provide status reports and descriptions of the major demonstrations that have been performed.

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[2] J. Rantakokko, *Beskrivning av demonstratorsystem för soldatpositionering*, FOI MEMO 3798, December 2011. (in Swedish)

[3] Defence Advanced GPS Receiver, called GPS08 in the Swedish Armed Forces.

Table 1.1: Possible sensors, and their main characteristics, in indoor positioning applications [1].

Sensor	Function	Positioning support	Meets sensor requirements	Comments
GPS	Measures travel-time (yields pseudo-ranges) for radio signals emitted from GPS-satellites	Distances to four or more satellites can be used to estimate receivers' position and time	Yes	Modern high-sensitivity receivers can yield position estimates in many indoor environments, but error can be large (> 50 m). Provides global coordinates Susceptible to jamming, interference detection/suppression techniques required
Impulse-response UWB	Measures round-trip time delay for radio signal between two transceivers	Distance between soldiers' can, in conjunction with their position and error covariance estimates, used in cooperative navigation	No, size and cost should be decreased	Transmits very short (ns) pulses, with GHz bandwidth, yields high ranging accuracy Good penetration through walls, but short range due to regulatory limitations in Tx power
Radio-based ranging as part of software-defined radio waveform	Round-trip delay estimation or time-synchronized receivers	Opportunistic ranging to units within range Time-difference-of-arrival (TDOA) estimation with at least three receivers and multilateration yields 3D position	Yes, if integrated in communications waveform	Limited bandwidths expected (< 10 MHz), limits possibility to accurately detect direct component in typical multipath indoor environments through conventional techniques (correlation), intelligent multipath mitigation techniques required TDOA requires accurate synchronization (ns-level)
Gyro (three-axis)	Measures local (IMUs) angular rate vector	Transform accelerations from sensor to earth-bound coordinate system (orientation), and apply models of earth gravity to eliminate it from accelerometer data	Yes, but additionally improved accuracy is desired	Small, low-cost (MEMS-based) sensors, suitable for foot-mounting, have large noise contribution and bias drifts that need to be compensated Gyro performance limiting factor for foot-mounted inertial navigation
Accelerometer (three-axis)	Measures difference between true acceleration vector and acceleration due to gravity (a.k.a. specific force)	By removing gravity effect and integrating data velocity is obtained, a second integration yields movement	Yes	Error increases with time (unbounded), e.g., gyro drift causes erroneous orientation and insufficient removal of gravity effects, aiding through zero-velocity updates crucial to limit error accumulation so that a few minutes of stand-alone positioning can be obtained with meter-level accuracy
Magnetometer (three-axis)	Measures magnetic field density (vector)	Model for earth magnetic field yields sensors orientation, or change in orientation, which gives direction of movement	Yes	Large local variations in magnetic field indoors, due to e.g., metallic objects and electronic equipment Efficient for aiding gyro sensors outdoors, indoor use requires reliable exclusion of data when local noise sources dominate
Barometric altimeter	Measures air pressure	Air pressure varies with height and can be used to estimate height changes, reference barometer increases reliability	Probably	Air pressure varies due to unknown disturbance sources such as weather conditions, wind, temperature, air conditioning units, smoke-ventilation fans, turbulence due to fires, etc. Reliable detection and exclusion of noisy data essential for indoor use
Doppler radar (three-axis)	Sensing axes aligned so they all reflect signal from ground or floor during normal walking	Provides 3D velocity vector	Uncertain, power and cost information not available	Observation is combination of velocity and attitude error, need for excluding returns from moving targets, clutter, and distant reflections
Ultrasonic sensors	Measure time for reflected pulses to return to transmitter Measure distance between two ultrasonic devices	Measure changing distance to, e.g., wall when person moves Support to foot-mounted inertial navigation by estimating distance between IMUs	Yes	Line of sight required, short range (~10 m) Robustness in typical operational environments somewhat uncertain
Imaging sensors (camera, IR, night-vision)	Identifies distinct points (landmarks) in environment, follows their movement between picture frames when sensor is moved	SLAM: change in camera position and orientation estimated between frames, estimates of building layouts can be generated Gyro-aiding: aids gyro in estimating change in orientation	Yes	High computational complexity for soldier applications, cameras unsuitable during some conditions (smoke, darkness, etc.) Low-resolution implies short range and sensitivity to large open areas, stereo cameras enable more accurate distance estimation Infrared sensors for indoor SLAM applications not verified

2 GPS-related activities

The three main activities related to GPS are: (1) evaluations of GPS performance in urban environments, focusing on evaluations of performance metrics for improved reliability in position uncertainty estimation, (2) development and evaluation of techniques for detection of unintentional interference and hostile jamming, and design of demonstrations, and (3) feasibility studies on assisted GPS approaches for military applications.

2.1 On the use of GPS receivers in urban environments

GPS-receivers form the core of all existing, as well as future, soldier positioning systems. In most situations they provide highly accurate positions; however, GPS-receivers have a few significant vulnerabilities.

2.1.1 Vulnerabilities

The availability of modern receivers has improved during the last decade, especially when considering civil high-sensitivity receivers using the C/A (coarse acquisition) code signal. The result is that they provide position fixes also in many indoor environments, and they may also perform re-acquisition in these low signal strength environments. The drawback is that the position error, due to multipath and signal attenuation typically experienced indoors, can be several tens of meters. Another major weakness of GPS receivers is, due to the very low signal strengths, their vulnerability to hostile jamming and spoofing. Hence, there is a need for augmenting additional sensors in order to enable accurate positioning in all scenarios.

Current hand-held military receivers, utilizing the encrypted P(Y)-code, have lower availability but the new generations of SAASM (Selective Availability Anti-Spoofing Module) chips are expected to improve their availability and accuracy also in low signal strength environments. Military receivers can detect (some) interference signals, which is important in military applications.

The main vulnerabilities of GPS-receivers are illustrated in Figure 2.1, with an emphasis on urban operations where the GPS-signals can be significantly attenuated, or completely blocked, by buildings, and where the receivers are subject to multipath propagation where they receive multiple distorted copies of the GPS signals.

Figure 2.1: Illustration of the vulnerabilities of GPS-receivers.

2.1.2 Performance

The estimated positions from a civilian high-sensitivity receiver are shown in Figure 2.2 for a short urban scenario with outdoor and indoor parts. A total station provided accurate reference positions from which the position error for the GPS receiver can be accurately evaluated [13]. The receiver continuously delivers position estimates and in these tests the maximum position error was approximately 10 to 15 meters. A military hand-held DAGR receiver was also used in the same measurements and the results can be found in [14].

As an illustrative example, a longer indoor test is shown in Figure 2.3 where the person walked into a four-story office building, walked a long corridor and then took the elevator up to the fourth floor. The receiver did not succeed in providing position estimates inside the elevator but it performed re-acquisition directly when the person stepped out of it. The availability was good, but the resulting position error was several tens of meters [17].

2.2 Interference and jamming detection

A survey of the basics of detection theory and previous work on GNSS (Global Navigation Satellite Systems) interference and hostile jamming detection is presented in [8,12]. A few simple, yet effective, detection methods were also evaluated based on measurements of real GPS and jamming signals.

The focus was on detectors that makes no assumption on the signal type of the interference. Detectors based on received energy, automatic gain control (AGC) levels, and receiver carrier-to-noise ratio (C/N_0) estimates are able to detect many different types of signals, ranging from very narrowband (continuous wave) to wideband (20 MHz) signals. The challenge with all of these detectors is to decide how to choose the decision threshold, so that interference and hostile jamming can be detected reliably whilst at the same time maintaining a low false alarm probability.

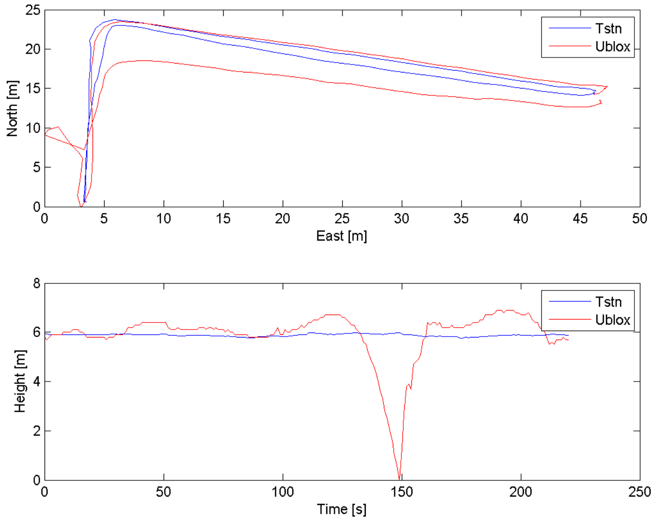
Energy detection is a conceptually simple detector that provides good results. However, in order to estimate the energy, the algorithms need to have access to raw IF (intermediate frequency) samples. These are generally not available in an off-the-shelf product. AGC values could be available and therefore an AGC based detector could be an alternative to the energy detector. The AGC gain is quantized, which may reduce the detection performance.

C/N_0-based detectors are unsuitable for applications where the received satellite signal strength varies, such as in mobile platforms in urban environments. These detectors cannot distinguish between an increased noise-plus-jammer-power and a decrease in the GNSS signal power. Moreover, this type of detectors cannot detect jamming signals when the receiver has completely lost track of the satellites.

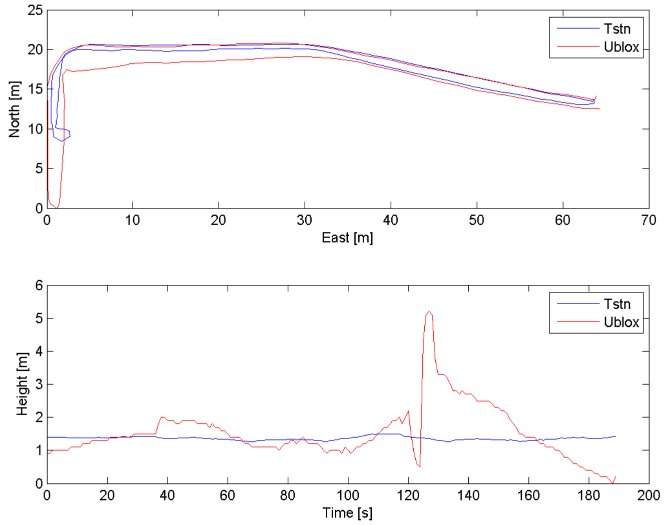
2.2.1 Demonstrations

A demonstration system has been designed, based on a hardware platform that was developed for monitoring interference levels in the GPS frequency band to protect critical infrastructure[4]. A form of energy detection algorithm is implemented. A graphical user interface was designed, which provides an alert when the interference level increases over a chosen threshold value. Also, the position estimates from the GPS receivers can be displayed on a map of the area, using the u-blox center software which also can display receiver parameters such as C/N_0 estimates for each satellite. For the examined jamming signals, the demonstration confirmed the possibility to actually detect GPS interference prior to the GPS receiver positions were affected.

[4] M. Alexandersson, P. Eliardsson, B. Gabrielsson, P. Stenumgaard, P. Weilow, and A.-K. Larsson, ”Portabel detektor för övervakning av radiostörningar i samhällskritisk infrastruktur,” *Proceedings of TAMSEC*, Stockholm, Sweden, November 2013.



(a)



(b)

(c)

Figure 2.2: GPS-receiver (u-blox 5) position estimates in urban environment with mixed outdoor and indoor movements. Bottom: True positions, obtained with a total station, for the two tests are overlaid on satellite imagery.

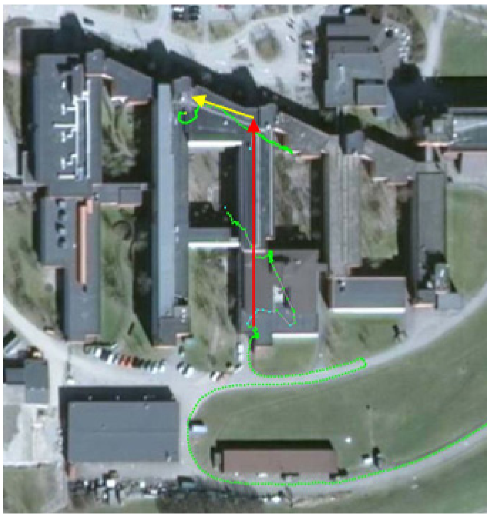


Figure 2.3: Example of GPS-receiver (u-blox 5) position estimates during mixed outdoor and indoor movement. The person started outdoors and walked indoors along a corridor (according to the red arrow), entered an elevator, exited on the fourth floor, and walked according to the yellow arrow.

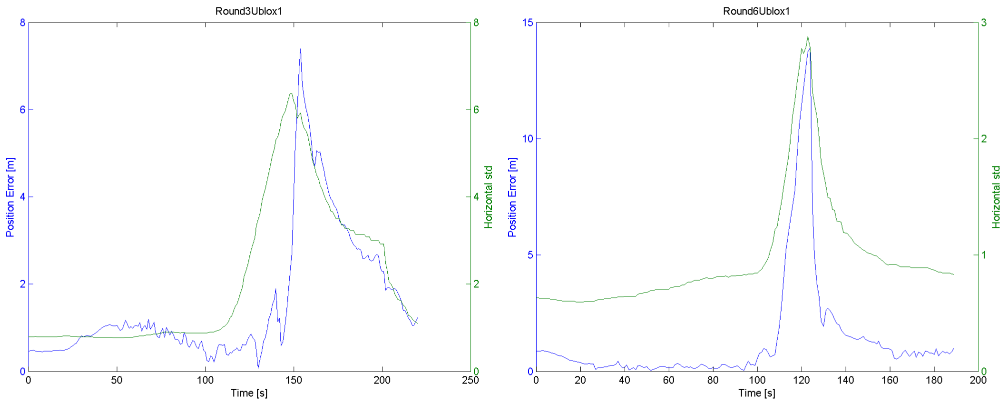


Figure 2.4: Horizontal standard deviations, calculated from standard deviation in latitude and longitude, compared to the GPS receiver position error. Same scenario as in Figure 2.2.

2.2.2 Discussion and recommendations

The evaluations points out that in many situations it may be possible to detect the interference before the receiver is affected negatively [12], for instance by using energy detection. It is strongly recommended that all GPS receivers should be equipped with state-of-the-art interference detection capability. Many military receivers have such a capability built-in, but their performance is not always satisfactory. The developed detection algorithms could be integrated into the receivers directly by the vendors, or an external device could be used.

Small, lightweight and low cost GPS interference detectors could be available on the market soon (e.g. integrated on a single chip). The potential market for these devises could be hundreds of millions considering military and first responder applications, and for protection of critical infrastructure, provided that the cost and form factors are low.

2.3 Improved performance metrics in urban environments

The GPS signal experiences reflection, scattering and attenuation in urban environments, and these effects may cause large position errors. Thus, the position accuracy is often insufficient in urban environments, especially considering indoor operations.

The long-term objective is to examine if it is possible to develop metrics that reliably determines, and informs the user or system, 1) whether or not a GPS position is reliable enough when used as a stand-alone navigation solution and 2) whether the GPS receiver should be used in a multisensor navigation solution or be excluded from the sensor fusion filter.

The standard deviation of latitude and longitude delivered by the NMEA GST message can be used as an estimate of the position error, as shown in Figure 2.4. In these examples the horizontal standard deviation successfully captures the large errors in the GPS receiver. Also, there is a strong correlation between the position error and numerous other parameters, and these can also be used to estimate the position error. However, we have not been able to exploit these to make a significant improvement in terms of the estimation and classification performance, as compared to using the horizontal standard deviations only. More advanced estimation and classification methods could potentially better exploit the parameter correlations.

The position error is estimated quite well, using the NMEA GST standard deviations, during benign and malign conditions (such as indoors). However, in areas with heavily varying channel conditions and multipath propagation, such as in urban areas, the estimation becomes more difficult.

2.3.1 Discussion and recommendations

Considering the use of hand-held GPS receivers as a stand-alone position sensor in urban environments, we recommend that the standard deviations in latitude and longitude, provided in the NMEA GST message, are used to estimate the horizontal standard deviation, which then is compared to a pre-defined threshold in order to provide a warning to the user in situations with large position errors.

When performing sensor fusion it is crucial that accurate estimates of the errors in the different sensors/sub-systems are available. Otherwise the errors from one sensor or sub-system may cause a large position error for the complete multisensor positioning system. Hence, the large position errors of the GPS receiver estimates caused by multipath and signal attenuation that occur in urban and indoor environments must be estimated reliably.

The recommendation, when considering integration of a GPS receiver with other sensors, is to use the horizontal standard deviations when available to determine if the GPS receiver positions should be used in the solution. It could also be useful to use simple thresholding of signal quality measures such as the average C/N_0 and number of used satellites. Thorough testing is strongly recommended to evaluate the performance of the integrated system, primarily in troublesome environments with strong multipath effects but also under ‘easier’ conditions with good or very bad signal quality.

2.4 Assisted GPS for military receivers

Modern civilian GPS receivers use assisted GPS (A-GPS), mainly to improve start-up performance and reduce the so-called time-to-first-fix (TTFF) which is the time it takes for the receiver to provide an initial position estimate. The assistance data transferred from an assistance server, via radio, to a mobile-station assisted A-GPS receiver often include [18]: precise GPS satellite orbit and clock information, initial coarse position and time estimate, and possibly suggestions for what satellites the receiver should initially try to track, and information about range and range-rate. A-GPS also is an enabler for high-sensitivity algorithms that use massive correlators and long integration times in the process of acquisition and tracking of weak GPS signals.

In military receivers this technology has not been implemented widely. The goal with the measurements in [9] was to evaluate the feasibility of including A-GPS approaches in select military systems, and evaluate what the performance benefits would be. Lab-tests were performed with the DAGR and a GB-GRAM[5] card. The time for transfer of assistance data, the TTFF and the possibility of performing direct P(Y)-acquisition were evaluated in different scenarios.

2.4.1 Discussion and recommendations

A-GPS can improve critical parameters in several military applications, see [9]. It is recommended that specific studies are initiated to evaluate the performance gains and user requirements for these platforms.

[5] Ground-Based GPS Receiver Application Module, mounted in the Explosive Resistant GPS Receiver (ERGR).

3 Activities related to multisensor positioning systems

3.1 Inertial sensors in dismounted soldier positioning systems

Inertial sensors are a natural choice for integration into soldier positioning systems intended for use in GPS-challenged environments. Inertial measurement units (IMUs) are composed of tri-axial accelerometers and gyros, often complemented by tri-axial magnetometers, and they provide measurements of accelerations and angular velocities (in three dimensions). Magnetometers, accelerometers and gyros based on micro-electro-mechanical systems (MEMS) are lightweight, have low power consumption, and they are small enough to allow integration with soldier equipment. However, these sensors are of low quality and they only allow accurate positioning during a very limited time (typically a few seconds) when performing (non-aided) inertial navigation, due to large noise contributions and sensor bias drifts [19]. Other approaches must therefore be pursued to enable the use of inertial sensor as the core technology in soldier positioning systems.

3.1.1 Pedestrian dead-reckoning

Existing indoor positioning systems targeting the soldier, and first responder, markets are based on pedestrian dead-reckoning (PDR) approach. The IMU is then mounted on the back, or torso, of the soldier. PDR-type of systems typically use the accelerometer data to estimate when the soldier takes a step and to estimate the length of the individual steps, while the gyro data is used to estimate in what direction the soldier is moving. Due to the weaknesses with PDR-type of positioning systems, we have chosen not to spend our limited resources on this technology; however, a literature survey is provided [16]. The focus is on the vulnerabilities of the existing products complemented with a discussion on research efforts that are targeting different ways to increase the robustness of these systems towards realistic soldier movements. Existing PDR-type of systems do not provide sufficiently accurate position estimates. Product data sheets typically claim that the position error grows 1-2 % of the travelled distance; however, this is true only during benign conditions, e.g. where the soldier walks forward with a fixed step length, but the error can increase dramatically during realistic soldier movements.

3.1.2 Foot-mounted INS

Another interesting approach is to place the IMU on the foot, or integrate it directly into the boot of the soldier; alternatively, a separate in-sole could be used where the sensors are integrated directly. If the inertial sensors are mounted on the foot, some of the sensor errors can be estimated and compensated for using knowledge about the foot at stand-still (the stance phase), where the IMU experiences a velocity that is approximately zero. Even though the soldier is certainly a low-dynamics platform, a fully-equipped soldier seldom moves faster than 5 m/s, the foot experiences surprisingly high accelerations and angular velocities. The maximum accelerations often exceed 10 and even 15 m/s^2 while angular velocities well over 1000 degrees per second have been recorded. Hence, the dynamic range of the inertial sensors must be carefully chosen. For the used low-cost MEMS-based inertial sensors, these high dynamics are also believed to result in sensor errors larger than specified in the data sheets and it is important to choose IMUs that perform well also during these conditions.

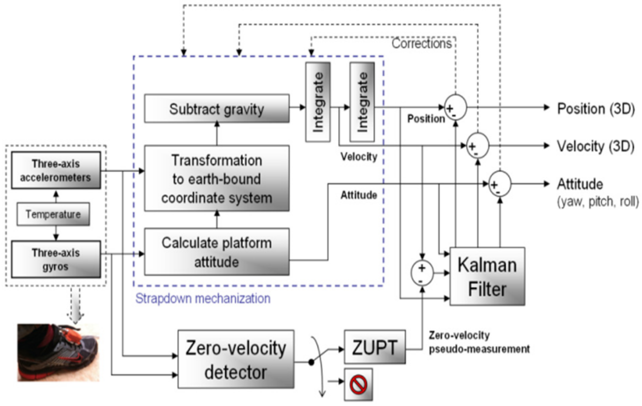


Figure 3.1: Block diagram view of the inner workings of a (strap-down) foot-mounted INS.

The first experiments using a zero-velocity-aided foot-mounted inertial navigation system (INS) were published already in 2005 [20]. Since then, several research groups have demonstrated high accuracies with experimental foot-mounted inertial navigation systems in controlled environment tests, highlighting the possibilities with the technology in safety and security applications (see for instance [21] and [22]).

3.1.2.1 Algorithm description

The principle of operation for a zero-velocity-aided foot-mounted INS, using a Kalman Filter integration approach, can be summarized as (see Figure 3.1):

- A foot-mounted IMU measures the accelerations and angular rotation rates with orthogonal three-axis accelerometers and gyros, respectively. These sensors, together with temperature sensors that are used for calibration purposes, are co-located in the IMU.
- A zero-velocity detection algorithm is applied to detect if the foot is at stand-still (where the IMU has a zero-velocity) or not. If a zero-velocity has been detected a zero-velocity pseudo-measurement is sent to the Kalman filter.
- Simultaneously, the angular rates are used to calculate the transformation from the foot-mounted sensors coordinate system to an earth-bound coordinate system, which also yields the platforms attitude.
- A model of the earth's gravity is then used, combined with a rough estimate of the position of the person, to eliminate the effect of gravity from the accelerometer measurements.
- By (mathematically) integrating the accelerometer signals once the velocity of the foot is obtained, while a second integration yields the new position (displacement) of the foot.

The above steps are performed each time new measured angular rates and accelerations are available. The calculations are normally performed using an Extended Kalman filter (EKF).

Foot-mounted inertial navigation is performed in a local frame (e.g. North-East-Down). This requires initialization of position, velocity and heading. A coarse alignment with gravity during a period of stand-still can give the initial roll and pitch estimates, but the heading has to be defined by some other method (magnetometers or GPS can be used when such are available and deemed reliable).

The navigation algorithm in our foot-mounted inertial navigation system (INS) is based on an Extended Kalman Filter (EKF) using 9 states. It estimates the 3D position, velocity, and orientation of the IMU [23]. Sensor biases are not estimated in the filter. The foot-mounted INS is computationally lightweight, and can be used in real-time on almost any hardware.

3.1.2.2 Zero-velocity detection and aiding

When a zero-velocity has been detected this information is sent to the EKF. Unfortunately, all (error) states are not observable based on the zero-velocity-updates (ZUPTs). First of all, the velocity is observable but the position (error) is not. Secondly, the roll and pitch are observable while the heading (yaw) of the system is not [24].

The key for achieving an accurate foot-mounted INS is the ability to reliably detect a stance phase using data from the foot-mounted inertial measurement unit (IMU). It is also important that spurious zero-velocity-updates (ZUPTs) are not performed when the foot is actually moving (a low false-detection rate).

A typical walking cycle can be roughly separated into the following phases: heel-strike (heel hits the ground), foot stand-still (zero-velocity), push-off (heel lift-off) and toe-off (foot completely leaves ground), and a swing phase. The walking cycle is somewhat different depending on the person, but the stand-still phase occurs approximately once per second during walking and it often lasts for over 200 ms. During running the stand-still period is shorter and the step frequency is higher. The accelerations are higher, and this also results in a higher noise level in the sensor. Furthermore, the heel-strike can be significantly less pronounced in the accelerometer signals when a person is walking downstairs compared to walking upstairs.

Zero-velocity detection is easy to perform when the person is walking, but the performance of zero-velocity detection algorithms depend on the user motion. Also, during some movements, such as when the person is crawling, the foot may not even be at stand-still during longer periods of time.

Prior work within this area has often been based on applying empirically determined thresholds on accelerometer and/or gyro readings. In [25] a statistical framework based on the general likelihood ratio test was developed, into which previously presented work fits. A statistical binary hypothesis test, based on combined information from gyro and accelerometer data, for determining whether or not the foot is at stand-still was evaluated. The results indicate that it often suffices to use only the gyro information.

We have used a simple threshold-based method for detecting foot stand-still [5]. The threshold level was determined empirically. However, the optimal threshold level can be affected by the motion of the person (e.g. walking vs. running), weight carried, surface (e.g. asphalt, sand, mud, gravel, indoors), shoe type, and if the person moves in stairs (up- or downwards).

3.1.2.3 Performance evaluations

The performance of foot-mounted zero-velocity-aided inertial navigation systems is described based mainly on the technology evaluations that have been performed using an in-house developed experimental soldier positioning system.

The overall position error can be categorized into position/displacement errors and attitude/orientation errors [26]. Typically, the heading (yaw) error is the dominating error source for a foot-mounted INS. The position error is highly influenced by the shape of the traveled path.

The results obtained during a scenario-based evaluation of the experimental system, which included realistic movements during a building-clearing exercise, are presented in [5]. The maximum horizontal position error was below 3.5 meters (evaluated at positions where visual markers where detected by the camera that was mounted on the soldier helmet or on a backpack) during four separate high-tempo building clearing operations that lasted almost three and a half minutes each. At the end of the measurements the position error was between one to three meters.

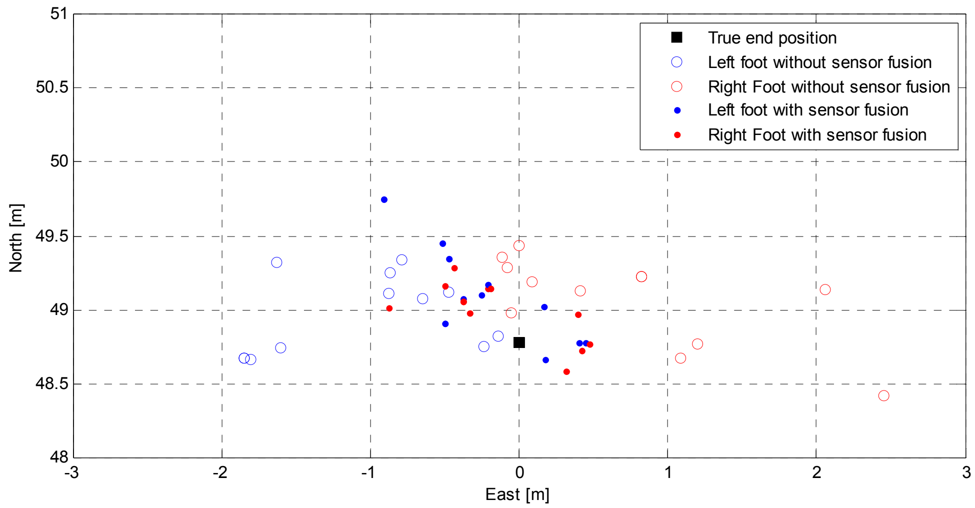


Figure 3.2: Straight line walk analysis. Comparison of left and right feet end positions using standard INS with zero-velocity updates, and after sensor fusion. Blue and red circles represent stop position for left and right feet, respectively. Similarly, blue and red dots represent the end positions after sensor fusion.

Straight line tests constitute the worst-case scenario for a foot-mounted INS [24]. By performing repeated straight line tests it is possible to evaluate both distance-scale and heading errors, of which both can be concealed to a large extent if only closed-loop trajectories and start/stop position analysis are performed. Hence, by performing repeated straight line tests with different test subjects, movement patterns and surfaces it is possible to compare the performance of most foot-mounted INS.

Straight line tests using dual foot-mounted INS also reveal interesting properties about the error characteristics; when mounted on the right and left feet, the systems tend to drift towards right or left, respectively. The results from such tests are shown in Figure 3.2, where the two foot-mounted INS also have been integrated into a single system [7]. Using dual foot-mounted INS and sensor fusion efficiently reduces the systematic errors, and this fact shows that the sensor fusion of two INS can actually improve the performance to a higher extent than earlier was believed.

Other approaches have been proposed for reducing the heading error, such as magnetometer aiding or imposing models (constraints) on how the person moves indoors (see e.g. [27]). However, magnetometers may suffer from large local perturbations of the magnetic field in indoor environments which may be difficult to handle [5,28]. Furthermore, the movements of the soldiers can hardly be modelled as following the dominant building direction approximation (where it is assumed that a building is usually composed of straight corridors and 90-degree turns, and the person actually moves straight according to these). Finally, it might be possible to improve the foot-mounted INS algorithms by more sophisticated error modeling.

3.1.3 Discussion and recommendations

Existing soldier positioning systems do not fulfill critical user requirements concerning position accuracy. For instance, they will not (even during shorter indoor operations that involve realistic movement patterns) be able to deliver reliable height estimates that are usable for determining what floor the soldier is on, nor are they expected to provide room-level accuracy.

Next generation soldier positioning systems that are expected to become available on the market within a few years are expected to include either improved PDR-type of system or foot-mounted INS, integrated with GPS receivers. Hence, a sound knowledge about the strengths and weaknesses with both the PDR-type and foot-mounted INS technologies are crucial in the development of test methodologies for future multisensor positioning systems, as well as for future requirements definition and system evaluations.

The results concerning foot-mounted INS presented in [5,7] clearly indicates that a single foot-mounted INS will not provide room-level position accuracy during extended (e.g. exceeding 20 minutes) indoor operations. Dual foot-mounted INS are recommended, since they cancel much of the systematic errors. Magnetometers can, if reliable pre-filtering is applied, reduce the heading errors that occur in a foot-mounted INS. A foot-mounted INS can reliably estimate when the user moves in stairs, but a barometric altimeter could still provide some extra information. However, although the foot-mounted INS algorithms can still be improved, it is still believed that additional supporting sensors are required in order to keep the position error below 2-3 meters after time periods of 30 minutes.

3.1.4 Other uses of inertial sensors

Inertial sensors will also be integrated into other soldier sub-systems, such as simultaneous localization and mapping (SLAM) based on imaging sensors and direction estimation applications. Furthermore, in order to allow soldiers to quickly and securely input targets or other landmarks into a soldier C2 support system, it is crucial that they also have a robust means of estimating heading (of weapon, head/helmet, or other devices) to the object. This capability is needed in all environments, also in situations where the magnetic field is severely disturbed. Hence, in these situations inertial sensors (gyros in particular) could be used and integrated with other sensors (such as magnetometers and imaging sensors) to provide accurate heading.

3.2 Radio-based positioning and cooperative localization

Numerous approaches have been proposed for performing radio-based positioning. Most of the technologies are not feasible for use in typical military operations where the use of pre-installed infrastructure is prohibited. In this project we have examined two different approaches for using radio signals to aid the multisensor soldier positioning system:

- Evaluations of the accuracy of ultra-wideband (UWB) ranging transceivers as a means to perform cooperative localization.
- Received signal strength (RSS) measurements on carefully selected set of signals-of-opportunity as a means to enable loop-closure.

3.2.1 UWB and cooperative localization

UWB transceivers can both provide accurate ranging as well as communications at short ranges. In our work we have evaluated the possibilities with impulse radio UWB (IR-UWB) for mobile indoor applications, as a means to perform cooperative localization. IR-UWB transceiver transmit very short pulses (few ns), which occupy large bandwidths (3.1 to 5.3 GHz). Due to regulatory reasons, to avoid intersystem interference for other radio systems operating within the frequency used by the UWB units, these systems can only transmit pulses with very low energy and there are some restrictions on the applications and environments where they can be used. As a consequence, the system can only operate at relatively short distance.

The new P410[6] transceivers provide ranging accuracies down to a few centimeters. Multipath propagation has little effect on the accuracy as long as the direct path is strong enough to be detected. Due to the wide bandwidth, the signals also penetrate walls; in

[6] TimeDomain P200, www.timedomain.com.

earlier measurements we have performed ranging through two concrete walls or three plaster walls [23]. In these non-line-of-sight (NLOS) conditions the range estimate is overestimated with up to one meter, depending on the number of, and material in the, walls. A larger potential error source is however situations where the direct path is too weak to be detected in the receiver, due to NLOS signal attenuation, and where it instead may lock on to multipath components. The ranging error is then unpredictable; it can be several tens of meters in indoor environments [23,17].

Several demonstrations have been performed showing the possibilities with cooperative localization. Two persons have been equipped with foot-mounted INS and a UWB transceiver. The position estimates and uncertainties are then exchanged between the persons using the UWB transceiver, which also estimates the range between them. The position accuracy is improved through this cooperation [1,23]; however, in situations where the position error is significantly larger (more than 10 meters) than what one of the foot-mounted systems uncertainty estimate tells, the algorithm has had problems to recover from these errors and the error may also propagate to the other unit. Hence, it is crucial that the sub-systems uncertainty estimates are reliable when cooperative localization is applied. Thus, the estimate of the ranging uncertainty must also be reliable, and one possibility is to only use the UWB-transceivers in LOS conditions. Through analysis of the received signal, such as the slope of the received pulse, channel impulse response analysis or a simple comparison of estimated range versus received signal strength, it is possible to discriminate between LOS and NLOS conditions (see e.g. [29] and the references therein).

The first (openly available) live indoor experiments using cooperative localization in real-time for small tactical units was performed at the Royal Institute of Technology, KTH, in October 2013. Two smoke divers and a smoke diving leader was then equipped with dual foot-mounted INS and (synthetically generated) UWB-ranging. Initial analysis shows position errors of a few meters[7] during an operation that lasted approximately 8 minutes, which involved both walking, climbing and descending stairs and realistic motions typically used in smoke-filled environments (crawling, room-search with hands and legs, etc).

3.2.1.1 Discussion and recommendation

In a dismounted soldier indoor scenario the soldiers are not expected to have constant LOS conditions, or even full connectivity when allowing the use of NLOS paths, to the other units in the squad. Hence, the cooperative localization must be designed so that it can use information from other units when the opportunity arises. The opportunistic approach also dictates the use of a decentralized cooperative localization scheme.

The UWB transceivers used in these tests were too bulky and expensive for the soldier application; however, several industries[8] are developing single chip implementations of two-way ranging UWB radios, including Irish DecaWave and a joint effort by French BeSpoon and Leti. DecaWave's DW1000 chip uses the IEEE 802.15.4a standard, the size is 6x6 mm and it has a price tag of around €2 in high volumes. Although these are not as capable and accurate as the TimeDomain P410 transceivers, the price and form factors are appealing. If the UWB units are to be used only in LOS conditions, these UWB chips could provide an alternative. However, their immunity towards multipath and interference must be examined thoroughly.

Cooperative localization will not be available in soldier positioning systems until perhaps 2020. However, it is a technology that is likely to be required in order to fulfill the soldiers accuracy requirements fully. It is also of interest for other military applications, and it is

[7] http://www.youtube.com/watch?v=Qtyq86tJrZ8 (accessed at 2013-11-29)
[8] www.decawave.com / www.bespoon.com / www.leti.fr

recommended that the possibilities and challenges with cooperative localization approaches in military scenarios and platforms are studied further.

3.2.2 Received signal strength measurements

Received signal strength (RSS) measurements utilizing signals of opportunity has been examined as a means to provide additional information to a multisensor soldier positioning system in indoor environments. RSS measurements on single frequencies are subject to fading, where multipath components are constructively and destructively combined depending on the location. The signal strength in indoor environments, for single frequencies, will have similar values at multiple positions; however, when combining a set of RSS values measured at different frequencies they provide a unique match between location and RSS vector. However, apart from the spatial variation of the RSS values that are exploited, they also exhibit a variation with factors such as time, antenna rotation and mounting. These variations can in some situations be larger than the spatial variations, which then make it more difficult to use the RSS values.

As described in [11], there is typically no possibility in military applications to create a database with geo-referenced RSS values prior to deployment. Only when a soldier, or another platform, is revisiting an old position during the operation they will be able to know that they are close to a previously visited position. Hence, the soldiers must themselves collect and store RSS values while entering a building, together with location information from the soldier positioning system, and then compare the current RSS values with those stored in the database. When these values are sufficiently close to what is stored in the database, this yields information about the current position which can be used to improve the performance of the integrated multisensor system.

Measurements were performed on signals from FM radio, TV, mobile and TETRA transmitters. The selection of frequencies is crucial for the performance. In summary, the feasibility study indicates that RSS measurements could be useful to aid a multisensor indoor positioning system, for instance by allowing the system to perform loop-closure. However, due to the possible ambiguities in the matching function between RSS vectors and positions, the RSS approach must be implemented and evaluated in the multisensor solution before it is possible to state with certainty that multi-frequency RSS measurements do improve the results [11].

3.2.2.1 Discussion and recommendation

RSS measurements can be combined with other information, such as on the local magnetic field, to provide more reliable decisions on when the user is at a previously visited position; hence, it is recommended that magnetic field measurements are integrated into the RSS approach and also integrated into a multisensor positioning system in order to evaluate the accuracy improvements that can be obtained. This could be performed for other platforms, such as micro-/nano-UAV applications, if funds become available.

3.3 Integration of GPS and foot-mounted INS

A number of possible schemes exist for integrating GPS with inertial navigation systems, such as ultra-tight, tight or loose integration approaches. These are applicable also for future GNSS-receivers which also encompasses signals from the Galileo and GLONASS navigation satellites.

Loose (or loosely-coupled) integration is a technique where the position and velocity as calculated by an external GPS-receiver is used to correct for the drift in the INS. Technically this is a suboptimal solution, but it is a simple and pragmatic approach. The loose-integration represents a good trade-off between accuracy and complexity. GPS is intended mainly as an aid when the soldier is outdoors. In indoor scenarios GPS-receivers may experience very large position errors, and the position uncertainty is difficult to calculate reliably. The gain of using tight or ultra-tight integration is currently deemed to be limited, in our view, particularly considering indoor environments and the lack of reliable performance metrics for individual pseudo-range measurements. A loose integration approach has therefore been adopted in our work [16].

3.3.1 Example of loose-integration

A foot-mounted Inertial Navigation System is often based on a Kalman filter. Kalman filters have two main steps, “System Update” and “Measurement Update”. In the “System Update” step of the Kalman filter the measured acceleration and angular velocity of the IMU is calculated to position, velocity and orientation by means of numerical integration. This occurs at the rate of which the IMU sensor provides data. When a zero velocity is detected the Kalman filter is updated (in the so called “Measurement Update” step). Based on the ZUPT-measurement the Kalman filter will correct the position, velocity and orientation (and possibly sensor error states).

Integration with GPS can be done similar to the ZUPT-measurement update. The Kalman filter uses the position and velocity as obtained from the GPS to improve the estimates (position, velocity, orientation and possibly sensor errors). This is a straight forward approach reported in standard literature on GPS/INS integration [19].

3.3.2 The challenge when integrating GPS and foot-mounted INS

Since the INS (even foot-mounted) is affected by (mainly heading) drift, integration with GPS is beneficial for most cases. The integration can however have issues when walking close to buildings where the GPS-receiver is affected by multipath (signal reflects on e.g. walls). This causes the GPS-track to be shifted several meters and will, unless detected by the integration filter, slowly force the navigation solution towards the (erroneous) GPS-track. Similar issues will occur when moving indoors. The reason for this is that no appropriate GPS position error model exists. Innovation Filtering can, to some extent, be used to handle GPS position outliers due to short term multipath effects.

3.3.3 Handling “bad” GPS data

GPS receivers may have large position errors in urban environments. These position errors will propagate into the integrated position solution if the uncertainty estimates of the GPS positions do not reflect the size of these errors. Contrary to what is often stated by researchers that analyze GPS/INS integration algorithms, it is *not* the case where GPS is lost that should be considered as the worst case scenario. During favorable GPS reception conditions, with unobstructed views to the satellites, it is relatively straightforward to device the sensor fusion filter. Similarly, when GPS is lost the integrated system will resort to using only the foot-mounted INS. However, the difficulties arise in urban and indoor environments when the GPS receiver still provides position estimates, but these are affected by multipath and signal attenuation that causes large position errors. As discussed previously, the receiver provides insufficient position uncertainty metrics in urban environments. Until such metrics are developed, we instead propose to use cruder metrics which indicates when the GPS positions should be used in the sensor fusion or if it instead should be discarded. These GPS “cut-off” metrics are based on the results presented in [13].

In [16], a set of GPS receiver cut-off metrics were proposed and initial evaluations are provided. The cut-off metric was based on the following procedure

- stop using GPS when the standard deviation in latitude and longitude (horizontal standard deviation) grows above 1.6 or the average C/N_0 ratio (of all used satellites) falls below 35dB, and

- start using GPS again (a form of "re-acquisition") when the horizontal standard deviation falls below 1.6 and the average C/N_0 has been over 35dB for more than 5 seconds.

3.3.4 Discussion and recommendations

These metrics works well in some scenarios but not in all. Evaluations are ongoing in order to find and evaluate the performance of an integrated GPS and foot-mounted INS based on these criteria. It is recommended that thorough testing is performed, in many different environments, in order to evaluate the performance of the integrated system.

Note also that the error characteristics do to some extent depend on the receiver, such as the tracking sensitivity, Kalman filter and possibly by motion models imposed in the position solution calculation. Hence, the performance metrics, and cut-off criteria, needs to be re-evaluated if a new GPS receiver is to be used. This is particularly the case when integrating the military hand-held DAGR [14].

3.4 Increased robustness and accuracy through integration of imaging sensors

An imaging-based SLAM system can be integrated with the foot-mounted INS to provide an increased robustness and accuracy. Through sensor fusion, high accuracies can be obtained also in environments and scenarios where one of the systems is unable to operate by itself, as shown in [6].

3.4.1 The Chameleon system

The camera-based system, Chameleon, is shown in Figure 3.4. Chameleon[9] is composed of two thermal infrared cameras (black: FLIR A35), a stereo camera (golden: Point Grey Bumblebee2), and an inertial measurement unit (orange: Xsens MTi-10 IMU) [30,31].

Chameleon navigates by tracking a number of landmarks as the stereo camera moves through a scene. Landmarks are added and removed dynamically as they enter and exit the field of view. Up to 30 landmarks are typically tracked.

A stereo camera can measure the distance to observed landmarks, in addition to their bearing. This makes initialization of new landmarks easier, as their full 3D position is estimated at the first observation.

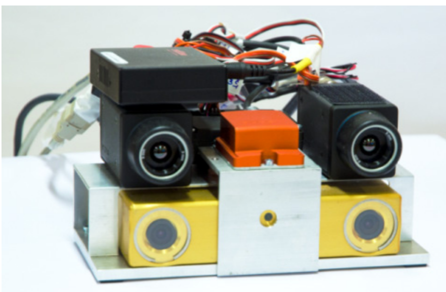


Figure 3.4: The experimental system Chameleon, composed of a visual stereo-camera, dual thermal IR cameras and an IMU.

[9] The visual stereo-camera sub-system has been developed in the R&D project *Surveillance systems*, funded by the Swedish Armed Forces, while the thermal IR camera sub-system is mainly being developed in civilian projects targeting firefighter localization and mapping in smoke-filled and dark environments. The development and evaluations of sensor fusion algorithms for integration of Chameleon with the foot-mounted INS is performed in the R&D project *Robust positioning for efficient C2*.

The field of view of the cameras are large, approximately 100 degrees horizontally, to provide a good view of landmarks close to the system. It would be possible to use a monocular camera, but then the distance to new landmarks would be unknown until they had been observed from multiple directions. However, if active illumination is feasible from a tactical point of view, then a laser which emits structured light could be combined with the monocular camera and then provide a performance equal to, or better than, the stereo camera system can provide.

Chameleon fuses the inertial measurements with landmark observations from the camera using an (15-state) EKF. The filter estimates the 3D position, velocity and orientation, as well as the IMU error states (the accelerometer and gyro biases). Data from the IMU is used to predict the navigation solution and the observed positions of the landmarks. The actual landmark observations from the camera system are thereafter used to correct the prediction error and this enables estimation of sensor biases. When no landmarks are visible, the positioning system resorts to free inertial navigation.

3.4.2 Mapping capability

The stereo camera enables estimation of the distance and direction to observed points in the environment. This information, along with the position and orientation of the Chameleon system, can be used to construct a global point cloud which contains all points observed by the camera along its path. Hence, the camera-based system can create 3D models of the environment through which it moves [30]. A horizontal projection of the point cloud can be used as a 2D map.

3.4.3 Examples – SLAM with visual stereo-camera

Figure 3.5 shows the trajectory estimated by the visual stereo camera system when exploring a mock-up apartment of a building [30], where the measurement was performed at the new military training facility in Spång. The number of associations, i.e. tracked landmarks which were observed in the camera images, at each point along the trajectory are also shown. Points where no associations occurred are marked with red circles. Typically, few associations are found when the system is rotated quickly or when moving through dark areas. Still, since inertial data is available, navigation performance does not degrade noticeably, even if no landmarks are observed and associated in a few consecutive frames. These measurements were performed with a low quality IMU, and performance has been improved further by inclusion of the Xsens MTi-10 IMU.

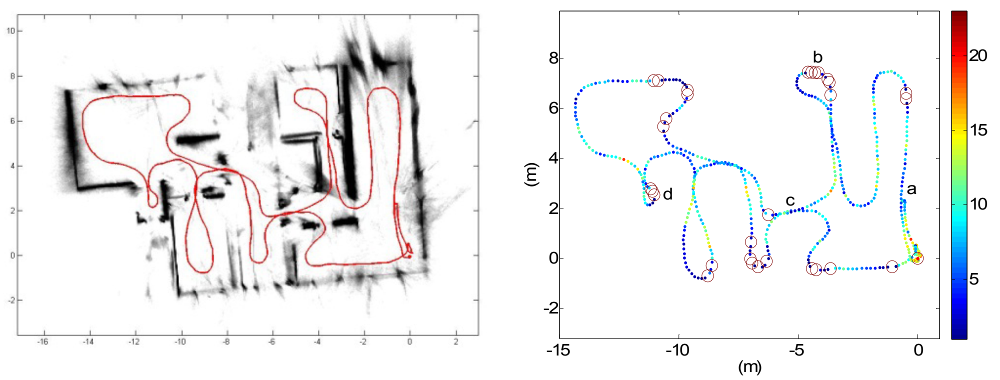


Figure 3.5: Left: Estimated trajectory and horizontal projection of the recorded 3D point cloud. Right: The number of associations along the trajectory. Points without associations are marked with red circles.

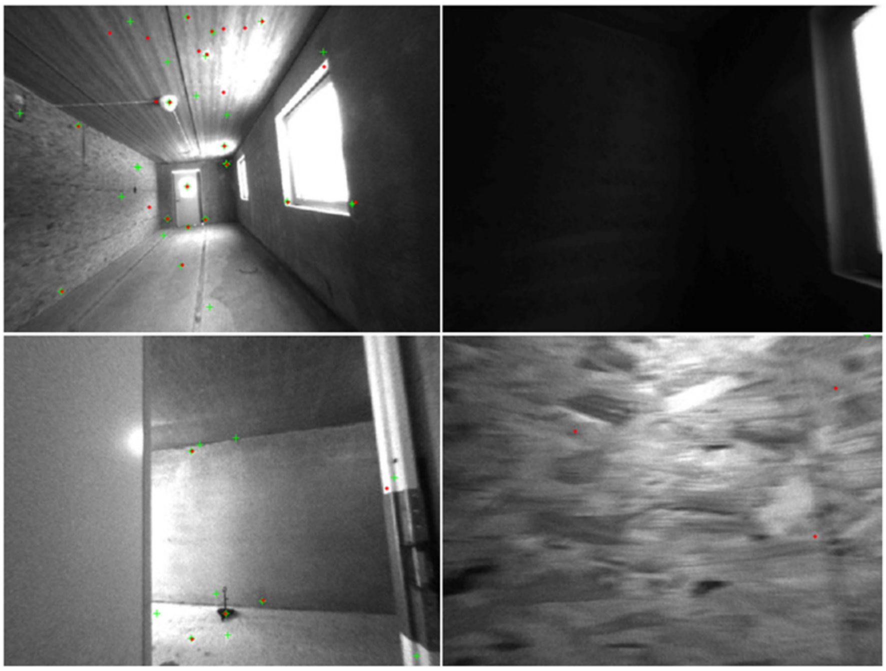


Figure 3.6: Example images along the trajectory shown above. Green markers correspond to tracked landmarks, while red markers are observations of possible landmarks in the current image.

Figure 3.6 shows image examples from the same experiment, with the intention of providing a basic understanding of what type of images the camera-based system use for positioning and mapping. The top left image (from the point marked 'a' in Figure 3.6) contain much useful information and several landmarks. The top right image (from point 'b') provides no landmarks at all due to a combination of an overexposed window and the camera-system looking into a dark corner.

The bottom left image ('c') shows the view through a doorway with a small number of landmarks due to uniformly textured walls, floor and ceiling. The bottom right image ('d') shows an image with significant motion blur, which prevent landmark extraction. The last image was acquired while rotating quickly (at approximately 150 degrees per second).

3.4.4 Challenging situations

Landmark-based navigation is difficult during rapid motion, in dark or smoke-filled environments, and in surroundings with few landmarks to track. In the case of rapid motion, the observations of the landmarks move very far between consecutive images.

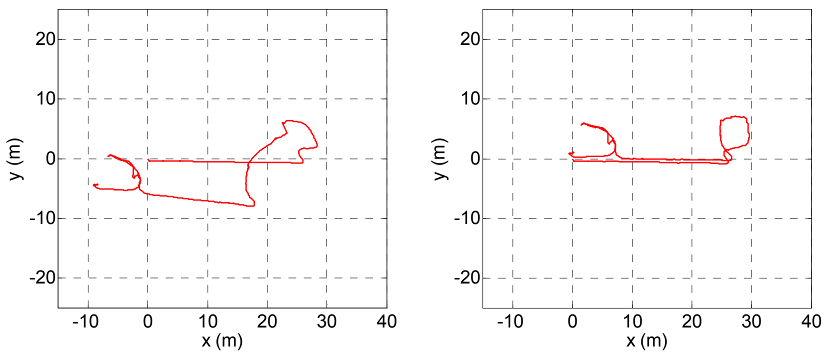


Figure 3.7: Camera-based system supported by foot-mounted INS. Estimated trajectories without (left) and with (right) fusion.

This makes data association, i.e., matching between landmarks observed in an image and currently tracked landmarks, difficult. Rapid motion may also cause motion blur, although this can be avoided in most light conditions by using a sensitive camera. While a higher frame rate solves this problem, it also causes increased computational requirements (and power usage). A higher frame rate does not solve the problems caused by darkness and lack of landmarks. During short time periods, all of these problems can be solved by using an IMU, which measures acceleration and angular velocity, together with the stereo camera [32]. The IMU enables positioning even when there are persons or other moving objects in front of the camera, as long as they do not cover most of the field of view for several seconds.

3.4.5 Sensor Fusion

The camera-based system can be integrated with the foot-mounted INS in a number of ways, where they are more or less tightly coupled to each other. In [6], a simple approach was adopted where the two EKFs of the individual systems were merged into one new EKF, where the state vector is the concatenation of the states for the foot-mounted and the camera-based systems. Additionally, three new measurement equations are used, which specify the relation between the position of the foot-mounted and the camera-based system.

As shown in [6],[16], sensor fusion can significantly improve the navigation results. The experiment contained walking through a corridor, but also included walking in a dark room for approximately 15 seconds and sitting down on an office chair that was pushed a few meters (a way to mimic a person being carried or dragged across a room) during 10 – 20 seconds. Figure 3.7 shows the horizontal trajectory as estimated by Chameleon, the foot-mounted INS and the integrated sensor fusion results. It is clear that the camera-based system does not handle the passage through the dark room (the rightmost part of the trajectory) very well without sensor fusion. Integration with the foot-mounted system alleviates the problems by trusting the foot-mounted system to a higher degree while the camera-based system is uncertain because of the darkness. During the period where no step detection was possible, the uncertainty of the foot-mounted system increased quickly and the integrated system put higher weight on the camera-based system which gave a good correspondence with the actual trajectory (see also [10]). Ground-truth estimates are not available in these tests but the start and stop positions are at $x=y=0$, and the trajectory after the sensor fusion is close to the true trajectory.

The sensor fusion results clearly point to a significant benefit of fusing data from the two systems. Essentially each system lends its strength to the other, and good results are obtained in both the horizontal and vertical directions [6,10,16]. Nevertheless, the algorithms can be improved in a number of ways [16], such as implementing inequality state constraints [24].

3.4.6 Discussion and recommendations

Very small, lightweight and low cost inertial and visual camera sensors exist, which probably could provide sufficient performance for (most) dismounted soldier indoor scenarios. Currently, the computational requirements of the positioning and mapping algorithms are prohibitive; they can be performed in real-time on fairly small and low cost computing platforms, but the energy consumption could be too high during extended dismounted operations. However, the rapid civilian development of fast, mobile and power-efficient computation hardware will help solve this problem.

Alternatively, the computational complexity of the algorithms can be reduced. One interesting possibility to reduce the energy consumption could be to explore ways to adaptively reduce the computational complexity by for instance turning off sensors when the situation or requirements so allows. For instance, camera-based positioning algorithms could be turned on only when the soldier moves into e.g. a building. Also, the camera-based system could be used to provide an accurate estimate of where the soldier enters the building, by comparing the positions of the door (or window) with its position on a satellite photo.

Camera-based systems are expected to be integrated into future soldier positioning systems, when the energy consumption issues have been solved. Although visual cameras will work poorly in dark or smoke-filled environments, they are an important sensor in other situations and can help achieve acceptable position accuracies. Furthermore, the mapping capability is expected to provide an additional benefit.

A prerequisite for successful sensor fusion is that accurate estimates of the uncertainty of the two systems are available. Continued in-depth analysis is required in order to improve the uncertainty estimation of all sub-systems of a multisensor positioning system.

It is recommended that work is initiated on adaptive positioning approaches, with the goal of conserving energy. Studies on uncertainty estimation of sub-systems are required; however, considering the current funding levels of military research this research task may be better suited for PhD students. Thus, it is recommended that we try to initiate such work on cooperating universities.

4 Test methodology and reference systems

In order to evaluate soldier positioning systems it is crucial that accurate reference systems are available that enables reliable evaluations of the accuracy of the system under test. The performance of most of the technologies, that are of interest for integration into a soldier positioning system, depend on factors such as the trajectory, type of motion, and environment. Hence, it is crucial that controlled-environment evaluations can be complemented with evaluations performed during realistic conditions. Thus, there is a need for a lightweight, low-cost position reference system that can be placed on the soldiers during for instance training exercises, which does not affect how the soldier executes the exercise.

4.1 Camera-based position reference system

In [4], a camera-based position reference system, which performs positioning by estimating its position based on a limited set of pre-installed visual markers at known positions, was developed and evaluated. It was used in scenario-based evaluations of an early foot-mounted INS experimental system, which included realistic movements during a building-clearing exercise [5].

The reference system should be able to provide reliable ground truth data in relatively large indoor environments (e.g. multistory buildings), and should require a minimum of pre-installed infrastructure. Furthermore, the requirements regarding size and weight of the reference system are stringent, in order not to alter how the soldier moves during the system evaluations. A low-cost reference system is desired. It should be possible to move and install the system quickly in new test sites or buildings, so that the evaluations can be performed during regular training exercises (where we have little influence over what buildings the soldiers actually will move through).

Marker-based camera positioning, however, is immune to drift. The position of the camera is computed using one or several markers in the field of view. The installation of the markers is easy and inexpensive. It is, however, important that markers are placed at well-known positions, with good accuracy. If sufficiently precise building schematics are available, this should not present a problem. For instance, walls close to door-openings are a good choice; the soldiers often pass though these and it is also easy to position the marker on the building map. Since the reference system is designed for evaluations of foot-mounted INS and back-mounted systems, a positioning error within 0.25 meters is acceptable for the reference system. The (horizontal) distance between the back- or foot-mounted sensors and a reference system camera mounted on the soldier helmet or backpack is then larger and will contribute more to the total error budget in the evaluation phase.

4.2 Test methodology development

In [15], a proposal is provided for the development of future testing methodology for current and next generation soldier positioning systems. As discussed previously, many different factors affect the performance of the different examined positioning technologies. Also, the sensor fusion poses several challenges that can seriously reduce the position accuracy in specific scenarios. It is crucial that the performance evaluations can capture the performance that is to be expected during realistic conditions that can be expected to occur in dismounted soldier operations, and that both the average as well as worst-case performances are revealed. These factors lead us to believe that the test methodology must be based upon a sound and deep knowledge about the strengths and vulnerabilities of different technologies, and potential pitfalls for the sensor fusion implementations. Hence, the test methodology will contain test cases that target the main vulnerabilities of the technologies/sensors that are under test [7]. This also implies that the test methodology must be adapted if new sensors or sub-systems are used in the integrated soldier positioning system.

In [15], the straight line test is proposed to evaluate the baseline performance of the system. Other trajectories, especially symmetric closed-loop tests, may reduce the effects of both scale errors of travelled distance as well as the heading errors. Repeated tests should be performed, also for other movements, surfaces (indoors, concrete, sand, mud, snow/ice), and different test subjects. The distance and heading errors can then be evaluated and compared for these different tests. Trajectories with smooth curvature (horizontally and vertically) should also be examined in order to test if the system imposes movement models such as straight line walking or floor-pinning. Similar tests can be performed for foot- and back-mounted dead-reckoning type of systems, placing special emphasis on situations with repeated transitions between movement types.

It is also important to perform scenario-based tests as a complement [5], partly because the above tests are designed to examine worst-case scenarios and also to capture the effects from realistic movements not included in the prior testing. An accurate reference system is needed when performing scenario-based tests.

The performance of the IMU should be evaluated, in particular when examining foot-mounted systems with the resulting high dynamics. The effects on heading due to high dynamics can be tested by examining the heading drift on a foot-mounted IMU (w/o zero-velocity updates) with that for an identical body-mounted IMU.

The GPS/INS integration algorithms also need testing, e.g. by examining heading errors when moving into a building and examining the resulting position error in urban scenarios where the position estimate from the GPS receiver can be biased. Furthermore, test and evaluation during hostile jamming and spoofing should be included in the test suite.

5 Conclusions and recommendations

This report provides a summary of the main activities performed in the project from a technology perspective. The activities can be grouped into (a) GPS related, (b) multisensor positioning systems and (c) test methodology development.

5.1 GPS-related activities

In urban environments the GPS signals can be significantly attenuated, or completely blocked, by buildings, and the receivers are typically subject to multipath propagation where they receive multiple distorted copies of the GPS signals. These effects can cause large position errors, and the receivers currently provide poor uncertainty estimates during these occasions.

There is a *need to warn the user when the position estimates from the GPS receiver are larger than what is acceptable* (which depends on the application). The standard deviation of latitude and longitude delivered by the NMEA GST message can be used as an estimate of the position error. The position error is estimated quite well, using the NMEA GST standard deviations, during benign (unobstructed view to satellites) and malign conditions (such as indoors). However, in areas with heavily varying channel conditions and multipath propagation, such as *in urban areas, reliable estimation of the position error is difficult*. A strong correlation between the position error and numerous other parameters have also been shown; however, these parameters have not in the analysis performed so far provided significant improvements in terms of the estimation and classification performance.

Several different interference detector algorithms have been evaluated through real-world jamming tests. Energy detection is a conceptually simple detector that provides good results. An AGC based detector is a potentially simpler alternative to the energy detector, with slightly reduced performance. Carrier-to-noise (C/N_0) based detectors are unsuitable for applications where the received satellite signal strength varies, such as in mobile platforms in urban environments. These detectors cannot distinguish between an increased noise-plus-jammer-power and a decrease in the GNSS signal power. Moreover, this type of detectors cannot detect jamming signals when the receiver has completely lost track of the satellites. The evaluations points out that in many situations *it is possible to detect GPS frequency interference before the receiver is affected* negatively, for instance by using energy detection.

Assisted GPS approaches can improve critical parameters in several military applications. Through lab-tests, it has been confirmed that it is *possible to improve the TTFF and the possibility of performing direct P(Y)-acquisition by providing receivers with assistance data*.

5.1.1 Recommendations

Considering the use of hand-held GPS receivers as a stand-alone position sensor in urban environments, we recommend that the standard deviations in latitude and longitude, provided in the NMEA GST message, are used to estimate the horizontal standard deviation, which then is compared to a pre-defined threshold in order to provide a warning to the user in situations with large position errors.

The recommendation, when considering integration of a GPS receiver with other sensors, is to use the horizontal standard deviations when available to determine if the GPS receiver positions should be used in the solution. It could also be useful to use simple thresholding of signal quality measures such as the average C/N_0 and number of used satellites.

The evaluations point out that in many situations it may be possible to detect the interference before the receiver is affected negatively [12], for instance by using energy detection. It is strongly recommended that all GPS receivers should be equipped with state-of-the-art interference detection capability.

It is recommended that studies are initiated concerning the possibility to include A-GPS for selected military platforms.

5.2 Activities related to multisensor positioning systems

Existing soldier positioning systems will not be able to provide room- or floor-level position accuracy. A multisensor system approach is required in order to achieve the desired performance. We believe that a multitude of sensors are required in order to achieve the desired position accuracy and system reliability. Due to the stringent user requirements all contributing sensors must be small, lightweight and low cost. In our work we have explored GPS receivers, RSS receivers, inertial and magnetic sensors, barometer and visual cameras. All these sensors have the potential to fulfill the user requirements, since they are already available in most smart phones (although the smartphone sensors are currently of lower quality). However, next generation soldier positioning systems will not consist of all these sensors; GPS-receivers integrated with foot-mounted (or PDR-type systems) are expected to be released shortly, while camera-based positioning and cooperative localization techniques may become sufficiently mature within five to ten years.

Although significantly more robust and accurate compared to PDR-type systems, a single *foot-mounted INS are not expected to provide room-level position accuracy during extended indoor operations*. Dual foot-mounted INS cancels much of the systematic errors, as well as provides a higher robustness towards crawling and other irregular movement types. However, it is still believed that additional supporting sensors are required in order to keep the position error below 2-3 meters after time periods of 30 minutes.

The position accuracy can be improved through cooperative localization approaches; however, it is crucial that the sub-systems uncertainty estimates are reliable when cooperative localization is applied. A decentralized cooperative localization scheme should be pursued, which *opportunistically use range measurements to other units* when they become available. The development of single chip, low cost ranging and communications transceivers could soon provide a viable alternative.

Due to fading effects, the signal strength in indoor environments, for single frequencies, will have similar values at multiple positions; however, when combining a set of RSS values measured at different frequencies they may provide a unique match between location and RSS vector. Measurements were performed on signals from FM radio, TV, mobile and TETRA transmitters, and the analysis indicates that simultaneous *multi-frequency RSS measurements could be useful to aid a multisensor indoor positioning system*, for instance by allowing the system to perform loop-closure.

In urban environments, the task of integrating GPS receivers and foot-mounted INS is difficult. Different GPS receiver cut-off metrics have been analyzed and implemented.

Camera-based localization and mapping is a technology that is expected to be integrated into future military positioning and navigation systems. The capability to generate 2D and 3D maps of unknown environments, such as indoors, is appealing. Also, *by integrating camera-based localization with foot-mounted INS it is possible to significantly improve the robustness and accuracy* since the two systems are both likely to run into situations where the performance is insufficient and where the other system in those situations can provide high accuracies.

5.2.1 Recommendations

A dual foot-mounted INS should be explored as the core system for a soldier positioning system. The developed inequality constraint sensor fusion algorithm should be implemented in the real-time demonstration system and evaluated in realistic soldier scenarios. The civilian development regarding first responder positioning systems should be followed in order to maintain the current knowledge base at minimum cost.

Cooperative localization will not be available in soldier positioning systems until probably around 2020. However, it is a technology that is likely to be required in order to fulfill the soldiers' accuracy requirements fully. It is also of interest for other military applications, and it is recommended that the possibilities and challenges with cooperative localization approaches in military scenarios and platforms are studied further.

It is recommended that a camera-based real-time demonstration system is developed in order to explore the technology maturity level. Simultaneous localization and mapping technologies should be implemented, using previously developed algorithms. The system should ideally be possible to integrate with other technologies, such as thermal infrared imaging sensors, GPS receivers and possibly with foot-mounted INS. Furthermore, work should be initiated on adaptive positioning approaches, with the goal of conserving energy.

A prerequisite for successful sensor fusion is that accurate estimates of the uncertainty of the two systems are available; however, considering the current funding levels of military research this research task may be better suited for PhD students. Thus, it is instead recommended that we try to initiate such work on cooperating universities.

Finally, it is recommended that magnetic field measurements are integrated into the examined RSS approach and also integrated into a multisensor positioning system in order to evaluate the accuracy improvements that can be obtained. This could be performed for soldier as well as other platforms, such as micro-/nano-UAV applications. However, it is likely that cooperative localization and imaging sensors will provide larger impact on the performance and these technologies should therefore be prioritized at this point.

5.3 Activities related to methodology development

The performance of most of the technologies that are of interest for integration into for instance a soldier positioning system depend on factors such as the trajectory, type of motion, and environment. Hence, it is crucial that controlled-environment evaluations can be complemented with evaluations performed during realistic conditions. The test methodology should be based upon a sound and deep knowledge about the strengths and vulnerabilities of different technologies, and potential pitfalls for the sensor fusion implementations.

In the test and evaluation of next-generation of multisensor soldier positioning systems, based on GPS integrated with foot- or back-mounted inertial sensors, the following aspects are important to test: (a) the worst-case performance in terms of distance-scale and heading errors in straight line movement tests, for different movements, test subjects, weight and surface, combined with non-straight line tests to pinpoint systems that have imposed motion models (b) the quality of the GPS/INS-integration in urban environments with potentially large position errors from the GPS-receiver, (c) how the system is affected by GPS jamming signals, and if they are able to detect such signals, typical performance obtained during scenario-based evaluations and (e) the performance of the IMU during high dynamics.

5.3.1 Recommendations

The proposed test methodology should be evaluated by examining it on the next generation of soldier positioning systems that are expected to be released soon. Although these systems are not expected to fulfill the military user requirements, these tests would both help develop a long-term test capability and generate knowledge about technology maturity levels. Tests of firefighter positioning systems (which have similar requirements) could be performed at the same time, providing ample opportunity for synergy effects regarding both cost reduction and knowledge generated.

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