Height measurement in seamless indoor/outdoor infrastructure-free navigation

Jesperi Rantanen, Laura Ruotsalainen, Martti Kirkko-Jaakkola, Maija Mäkelä

***Abstract* — Using barometer for height estimation often requires the use of external reference to correct biases in measurement. These biases are often caused by the change of ambient pressure environment. Barometric height estimation is especially challenging in tactical and rescue applications where high temperatures or sudden large pressure shocks can change the pressure rapidly. We assess the suitability of barometers for infrastructure-free navigation in tactical applications. First, this article investigates the effect of transition in seamless indoor/outdoor navigation. Second, we measure the effects of pressure shocks, caused by explosions or firearms, on low-cost and light weight microelectromechanical barometers to ensure that the sensors are capable of operating under these conditions. Finally, we investigate the use of sonar measurement to estimate vertical speed as an alternative to reference barometer for infrastructure-free navigation. Fusion of barometer and sonar achieved on average 0.46 m Root Mean Square Error (RMSE) while simple barometric height estimation had RMSE 0.65 m. Fusion method had no errors over 1.5 m during the test. This accuracy is generally sufficient to find the correct floor level which is crucial for tactical situational awareness. The goal of our research is to develop methods for seamless indoor/outdoor navigation and therefore the most important result of this work is that the error caused when transitioning between outdoor and indoor environments is visibly reduced.**

***Index Terms* — Altimetry, pressure measurement, indoor navigation, sensor fusion, sonar navigation**

I. Introduction

PROVIDING rescue and military personnel with indoor navigation tools is a challenging but important topic [1]-[4]. The goal of our research is to provide rescue and tactical operations infrastructure-free, seamless indoor/outdoor three-dimensional localization using sensor fusion [5], [6]. In infrastructure-free navigation preinstalled systems cannot be used so the user must be able to carry all the required sensors.

This paper discusses seamless vertical navigation. Height is an important part of any indoor navigation solution. When navigating outdoors the height coordinate might be ignored because the user can determine their height from their horizontal position with a terrain height model. In indoor navigation determining the height is more challenging. In a multistory building or in an underground tunnel the height of the user cannot be derived from the ground elevation. In fact the vertical accuracy requirement may be more stringent than the horizontal. A three meter error in horizontal position may still result to the user's location being in the correct room. However, a three meter error in vertical position would result in a location on a wrong floor which may cause unacceptable delays in time critical missions such as first responder and tactical operations.

Achieving better than half the floor height accuracy is rather demanding. Consumer grade Global Satellite Navigation System (GNSS) receivers cannot usually achieve vertical accuracy better than a few meters although this is rarely a problem outdoors. Air pressure on the other hand has long been used to determine height with relatively good accuracy [7]. Microelectromechanical Systems (MEMS) have made it possible to create relatively low-cost, small barometers only millimeters in size [8]. Usually in a barometer a small membrane is pushed from one side by the ambient pressure change. In a MEMS pressure sensors the deflection can be measured using for example the change in resistance of a piezoresistor attached to the membrane or using capacitive detection of position [9]. Barometers and other MEMS sensors such as Inertial Measurement Units (IMU) are attractive for navigation because of the small size that enables mounting them easily anywhere, for example the foot of the user [10].

MEMS barometers have been used in navigation in many works either as a standalone measurement or fused to other sensor measurements (see for example [11]-[15]). However, barometer measurement is prone to bias and drift due to simplified atmospheric models, weather change during measurements, and other environmental effects.

For indoor and pedestrian navigation applications barometric height has several noticeable drawbacks that are often mentioned. Firstly, portable and cheap MEMS barometers have large measurement noise and averaging is often necessary to achieve the desired precision [16], [14]. In [6] relative precision was found to be 0.15 m in barometric height difference estimate due to the measurement noise and other factors using the Xsens MTi-G-700 barometer. This instrument is a light weight portable MEMS GNSS/INS device with integrated barometer. Fortunately the sampling rate of MEMS barometers can be relatively high, for example 50 Hz for the barometers in Xsens MTi-G-700 and Xsens

The work has been originally submitted on Feb. 16. 2018. Work was resubmitted after the review on May 4. 2018 and again on Jul. 6. 2018.

This work was supported by the Scientific Advisory Board for Defence of the Finnish Ministry of Defence [project INTACT (INfrastructure-free TACTical situational awareness)], and the Finnish Geospatial Research Institute (FGI).

The authors are with the Finnish Geospatial Research Institute, Geodeetinrinne 2, FIN-02430 Masala, Finland (email: name.lastname@nls.fi).

Awinda sensor also used in this study to represent lightweight and low cost MEMS barometer [17]. Large sampling rate makes filtering and smoothing of the measurement possible. Moreover these sensors are small enough that they are easily carried by a pedestrian. They can be controlled through a miniature PC and powered with lightweight batteries making the system very portable.

In addition to usually noisy measurements barometric height often has an error caused by the change of the ambient air pressure during the operation. This change occurs naturally over time. For example there exists a regular daily variation of the air pressure comparable to the ocean tide. The variation is dependent on the latitude and its amplitude is approximately 30 Pa in Polar Regions and up to 300 Pa in the tropics [18]. This change in air pressure leads to approximately 2.7 – 26.5 m difference in barometric height estimate. In addition to this, there exist high and low pressure systems and local weather phenomena such as gusts of wind. Day to day changes in the air pressure are complex and variable, and floor level accuracy cannot be achieved if these variations are not taken into account.

Because of the change in ambient air pressure most studies suggest using a reference barometer at a known height [12]–[14], [19], [30] or multiple reference barometers in each floor of a building [20]. In [14] the absolute error was found to be bounded by 0.2 m but only after correction from reference barometer was made to account for changes in ambient pressure. Floor level accuracy was achieved with smart phone pressure sensors in [29] only after calibration with current sea level pressure from meteorological office and height from smart phone satellite navigation system. Using reference barometers requires both setting them up before measurements and a data connection between the barometers. Additional information, such as floor level from Wi-Fi positioning, is needed to calibrate the barometer in single barometer height estimation [21]. This kind of solution is not suitable for infrastructure-free applications, where the user cannot rely on preinstalled equipment on site or pre-existing knowledge of the location.

Changes in local environment can also present problems that cannot be solved with the use of a reference barometer. Simply opening doors or windows near the sensor can cause air pressure to change causing significant errors in the height measurement [5], [19]. In [13] errors were observed up to 1.4 m, caused by doors and windows opening in a building and people moving around the sensor. Also ventilation conditions cause noticeable errors: sensors placed inside a car experience errors when the windows are opened or the blower settings are changed [19]. Also extreme conditions, in which military and rescue personnel operate, create even more challenges to barometric height measurement [1] that have not been widely investigated. It is even stated in [22] that barometers are not recommended for applications such as rescue operations using self-contained localization in buildings.

For infrastructure-free navigation, barometer still needs supporting sensor to give accurate height estimate for extended time. This supporting sensor might be INS which can also estimate height change from starting location. However, fusing IMU and barometer height estimates has usually been done to limit the cumulative error of the INS and not the other way around [14], [23].

The goal of this paper is to show that the challenges arising from environmental conditions in first responder or tactical operations can be overcome to achieve a floor level accuracy. The error caused by the transfer to a different environment in seamless indoor/outdoor navigation is studied in detail to determine the magnitude of this error. We also study the effect of explosions or firearms near the barometer in order to find out if the sensors are capable of operating in this kind of environment. As far as we know MEMS barometers for height navigation have not yet been tested for large pressure shocks caused by for example explosions. Finally the barometer height estimate is fused in a seamless indoor/outdoor navigation test with sonar range finder. We develop further the combination of sonar and barometer presented in [5] improving it now with new fusion method and testing it in a navigation scenario. Fusion of barometer and sonar for pedestrian navigation has not been extensively tested. Combination of sonar and barometer is studied also in for example [24] for drone altitude keeping but with two notable differences. Firstly, they use the barometer and sonar height estimates as complementary methods while we create a fusion of both. Secondly, like most other studies on barometric height estimation the barometer had a reference to account for changes in ambient pressure. We test the method to determine if the floor level accuracy from starting point can be achieved for extended time despite the challenges and without reference barometer. In infrastructure-free navigation the floor height may be unknown or difficult to define. In rescue and tactical operations the users may even be climbing on the walls or rooftops of buildings so height may have to be measured in meters instead of floor numbers. In any case, we aim for accuracy of 1.5 m or better which is half of a typical floor height.

Section II explores the background of barometric height estimation and sonar sensors. Section III describes the methods used to study and test the barometric height in seamless indoor/outdoor navigation and fusion with sonar. Section IV discusses the test setup and the results. Finally the Section V discusses the achieved result and concludes this work.

II. Background

This section presents the formulas that can be used to estimate the height from air pressure and we discuss some issues with the effect of temperature. On the second subsection the background of sonar in indoor navigation is briefly studied.

A. Barometric height

Using the Standard Atmosphere model [25] the relation between pressure p and height h is determined with the equation

$$p(h) = p_b \left(\frac{T_b}{T_b + L_b(h - h_b)} \right)^{\left(\frac{g_0 M}{L_b R^*}\right)} \quad (0)$$

if the height is between sea level and 86 km. Pressure p_b is the pressure at the bottom of the reference height in pascals, h_b is the height at the bottom of this reference height in meters, T_b is the temperature at the reference level in Kelvins, L_b is the temperature lapse rate in Kelvins per meter, g_0 is the magnitude of the gravitational acceleration, M is the molar mass of air and R^* is the universal gas constant. Different layers of the atmosphere have different values for temperature lapse rate but for indoor navigation purposes only the lowest layer of the standard atmosphere (from 0 to 11 km) is considered here.

If the temperature T in the layer is constant the temperature lapse rate equals zero and according to the atmospheric model used the relation between p and h may be presented as

$$p(h) = p_b \cdot \exp\left(\frac{-g_0 M (h - h_b)}{TR^*} \right) \quad (0)$$

Height h can be resolved if both the pressure p and p_b and temperature T and T_b at the current height and at the reference height level are known – the solution which is used in all barometric altimeters. Equations (1) and (2) solved for h are presented below in (3) and (4) respectively. For further information on the atmospheric model see [25].

$$h(p) = \frac{T_b}{L_b} \left(\left(\frac{p}{p_b} \right)^{\left(\frac{L_b R^*}{M g_0}\right)} - 1 \right) \quad (0)$$

$$h(p) = -\frac{TR^*}{Mg_0} \cdot ln\left(\frac{p}{p_0} \right) \quad (0)$$

In troposphere the temperature lapse rate according to this standard atmosphere model is approximately -0.0065 K/m so the temperature decreases when height increases. However, indoors the opposite may be true because warm air tends to stay in the upper levels of the building if air conditioning does not prevent this from happening. Therefore, the use of standard value for the temperature lapse rate in indoor navigation may lead to larger errors than simply using constant temperature.

The difference between (3) and (4) above is not significant when height differences are low. In Fig. 1 the difference between the height estimates obtained from (3) and (4) using the same reference level pressure is plotted as a function of barometric height from (3). Nominal pressure 101325 Pa, temperature 288 K and temperature lapse rate -0.0065 K/m are used in (3). The difference is negligible for the first 100 m, being only approximately 0.11 % when the sensor is 100 m from reference level. The difference increases more rapidly the higher the distance from the reference level. Therefore, outdoors the temperature lapse rate should be used, if the current height is far from the calibration height, but it can lead to slightly erroneous results if the assumption of the standard atmosphere does not hold.

Correct temperature needs to be used in the formula, otherwise the result may quickly become unusable, because in warm air the pressure decreases slightly less per meter when moving upwards. For example, nearly 1.5 m error at height 20 m from 0 m if 20°C is used instead of 0°C using (4). This effect is even higher in extreme environments in which first responders may operate, such as house fires.

Barometer bias, especially in low cost MEMS barometer measurements, needs to be removed. The bias is easily observed by comparing the measurements of several barometers placed next to each other (see for example [19]). Also in the temperature tests presented in this paper there is on average a 40 Pa systematic difference in the measurements of different barometers before bias correction. Bias can be determined by comparing the barometer measurements to an accurate reference barometer or calibrating the barometer at a known height.

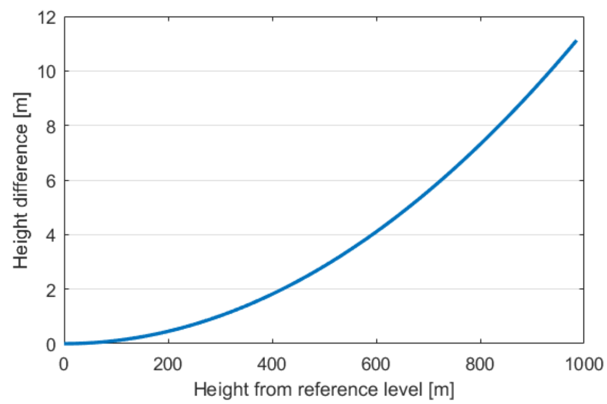

Fig. 1. Height difference of results from equations (3) and (4) at the same pressure height. The horizontal axis is the pressure height from (3) using lapse rate -0.0065 K/m and nominal sea level pressure and temperature.

B. *Sonar in navigation*

Sonar sensor uses sound waves to make a range measurement to an object based on the time of flight of the sound signal. Sonars are commonly used in underwater applications but have been used also successfully in navigating indoor spaces, for example in [24] and [26]. Sonar measures relative distance but the measurement is self-contained so they can be used for infrastructure-free navigation. Size of the sensor can be only some tens of millimeters and they are easily powered by portable batteries, while giving a measurement range in the order of ten meters.

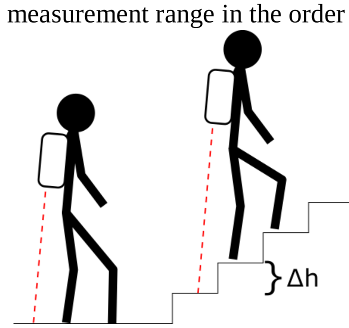

Fig. 2. The average distance measured by sonar (red dotted line) mounted under a backpack increases by Δh when ascending steps. Similarly it decreases when descending steps.

In [5] single sonar rangefinder carried by the user points downwards and measures the distance to the floor. They show that this distance stays relatively constant except when ascending or descending, for example in stairs, in which case the distance increases or decreases respectively. The method is illustrated in Fig. 2.

III. Methods

This section of the paper describes a mathematical model for combining barometer measurement with sonar measurement. This model will be used in tests to assess the accuracy of our infrastructure-free height estimation. Later in this section the measurement noise of barometer and sonar are discussed.

A. Kalman filter fusion of sonar and barometer observations

In this section we discuss an algorithm to combine sonar as an independent sensor to the height estimation based on barometer measurements during seamless indoor/outdoor navigation. Here the sonar is used in a similar manner as in [5], in a sense that it is used to detect whether the user is ascending or descending. This is illustrated in Fig. 2. However, the fusion method used here is different.

The model used in this study to combine barometric height estimate with sonar observations is based on Kalman filter. The model makes an assumption that there is a bias in the barometric height measurement that is caused mostly by moving from one pressure environment to a different one for example when moving in to a building. These changes are relatively fast. To detect the bias in the barometric height, sonar is used to obtain a speed measurement that is independent from the barometer. In short, if the barometer measures a sudden change that would indicate height change but the sonar observes no change in the vertical speed, the bias term changes and the true height can be obtained from the difference of barometric height and the bias term. This fusion algorithm is presented as a flowchart in Fig. 3.

The state x_k that is estimated in the model at time k is

$$x_k = \begin{bmatrix} h_k \\ b_k \\ v_k \end{bmatrix} \tag{0}$$

where h_k is the true height from the reference level, b_k is the bias in the barometer height estimate and v_k is the vertical speed. The system matrix A which predicts the next state is

$$A = \begin{bmatrix} 1 & 0 & \Delta t \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{0}$$

where Δt is the length of the time step.
The true height cannot be directly measured but the barometric height can and in the model the barometric height is the sum of true height and a bias term. Vertical speed can be estimated from the sonar measurement based on the change in measurement illustrated in Fig. 2. The measurement vector y_k

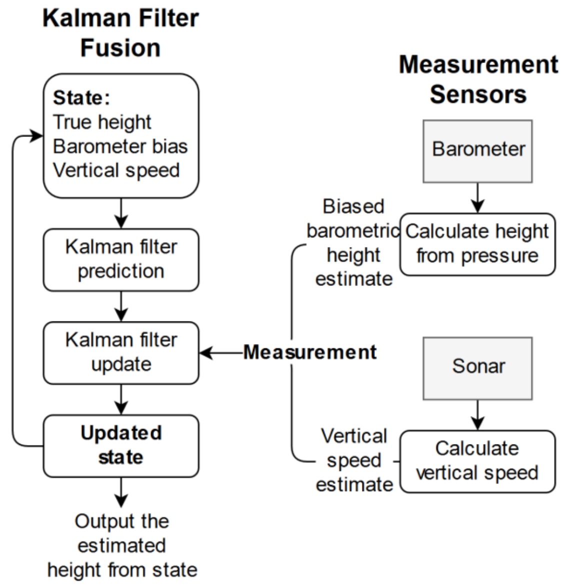

Fig. 3. Flowchart of the presented Kalman filter fusion for height.

at the time k is

$$y_k = \begin{bmatrix} h+b \\ v_s \end{bmatrix} \tag{0}$$

where $h+b$ is the biased height estimate from barometric pressure and v_s is the speed estimate from sonar. The measurement is related to the state via (8)

$$y_k = Hx_k \tag{0}$$

where the measurement matrix H is

$$H = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{0}$$

These are processed with Kalman filter equations. For further information on the Kalman filter see for example [27]. The algorithm developed here will be tested in an indoor navigation test scenario where test person moves between indoor/outdoor environments on different levels of a building.

B. Barometer and sonar measurement noise

In the scope of this article we make the fusion of barometer and sonar as an intermediate step to reduce the time to compute the final 3D position solution. For fusing the barometer and sonar, Kalman filter is adequate and fast solution. Our final goal is to use these methods to produce 3D-position. For 3D-position we will fuse the results of the Kalman filter in another fusion algorithm such as the particle filter presented in [28].

In the Kalman filter the error distribution should be Gaussian. To validate this assumption we measured the difference of two MEMS barometers placed next to each other. Measurements were made for 300 seconds with 50 Hz rate. We then calculated the difference in measurements of these two sensors which removes the environmental effects from the measurements and only the noise of both sensors is left. The histogram of differences in measurements of the two

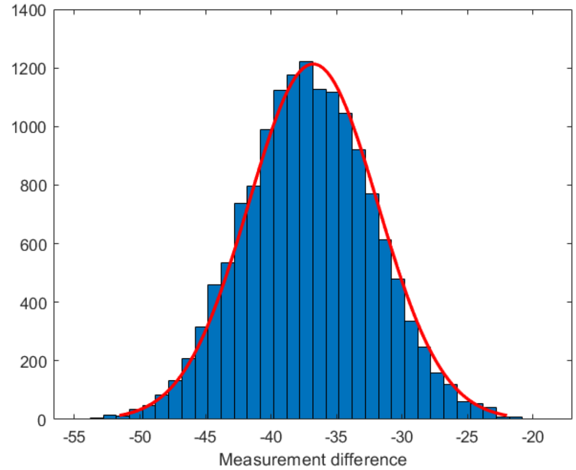

Fig. 4. Histogram of barometer noise obtained by calculating the difference of two barometers measuring side by side in indoor environment. Plotted in red is the normal distribution fitted to data.

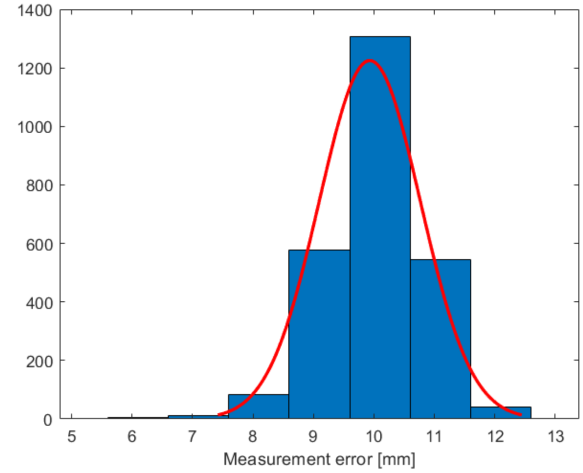

Fig. 5. Histogram of sonar measurement noise obtained by measuring a distance of 1.4 m to a wall in static conditions. Non-zero mean is mainly due to bias in sensor location inside the device.

sensors is presented in Fig. 4. A normal distribution fitted to this data is drawn in red in Fig. 4 and represents this histogram well. The distribution is not zero mean because systematic difference was not removed. The dominant component of noise is nevertheless Gaussian.

To validate the error distribution of sonar we also measured constant distance with our sonar range finder. We measured a distance of 1.4 m with the sonar for 311 s at approximately 8.3 Hz. Histogram of error is plotted in Fig. 5 with fitted normal distribution. The sonar has resolution of 1 mm and the noise standard deviation is in the same order which makes the histogram difficult to interpret but the noise appears to be approximately Gaussian. The error is not zero mean since there is approximately 10 mm bias in that is mainly due to sensor placement inside the measurement device but this can be largely ignored for distance difference measurement.

In practice, the measurement noise in dynamic conditions is much higher than what could be estimated from the variance in static conditions. The measurement noise values used in the Kalman filter were estimated based on experimentation with the data. In navigation tests that are presented in the chapter IV-C below we noticed a lot of errors that were not properly estimated only with sensor measurement noise or the barometer height estimate bias in the calculations. For sonar this error is probably due to movement of the person carrying the device. As explained later in chapter IV-C we attempt to exclude outliers from the sonar calculation to ensure Gaussian error distribution. Nevertheless, we increase the variances in measurements based on experimentation.

IV. Test results

This paper studies two barometric height estimate error sources in detail: how temperature difference and large but short pressure shocks affect seamless indoor/outdoor navigation. We performed three distinct tests. First, we test the effect of temperature difference in transition between indoor and outdoor spaces to seamless barometer height measurement. Second, the effect of large pressure shocks produced by explosion or firearms is studied. Third, a seamless indoor/outdoor navigation test is conducted to estimate the accuracy of our barometer sonar fusion. This infrastructure-free fusion method should solve the issues tested in first two tests.

A. The effect of transition between indoor and outdoor spaces

We investigate the effect of temperature difference to seamless barometer height measurement in indoor/outdoor navigation in three tests with different outside temperatures. Test setup and location in each test was the same. We deliberately did not change other things in the test surroundings to find if the temperature has systematic effect. The setup consisted of three wireless Xsens Awinda IMUs [17] that also have an integrated barometer inside. The sensor units were wirelessly connected to a laptop recording their pressure measurements. One sensor unit was deployed inside the building, another one outside the building, and then third sensor was mobile, namely carried by the user navigating indoors and outdoors. The objective was to find how much the barometric height increases or decreases when moving from one environment to another when true height does not change. We want to discover if this observed height change would be related to the temperature difference between the environments. If this effect was in some way regular then it could be corrected for and used to detect the current environment.

The tests lasted approximately 40 minutes each. Because there is a bias in each sensor, the difference in measurement between sensors was determined by measuring the pressure indoors at the same height at the beginning of the test. Thereby, we obtained an average value of three sensors during five minutes of measurement that was used as a reference value. Then two sensors, the outside pressure reference sensor and mobile sensor were taken outside. After another five minutes, the mobile sensor was taken inside and left static for five minutes. It was then taken outside twice more, for at least

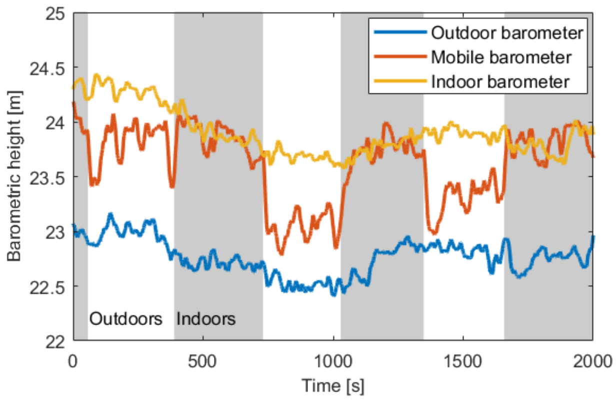

Fig. 6. Barometric height from three different sensors at constant altitude but different environments. Outdoor (white background) and indoor (grey background) areas refer to the location of the mobile barometer.

TABLE I

Temperature [°C]		Measurement difference [m]	
Outdoors	Indoors	Outdoor sensor – indoor sensor	Mobile sensor – indoor sensor
-1	21	1.1	0.6
10	20	1.6	0.6
24	25	1.4	1.7

five minutes each time to observe the change caused by moving the barometer from one environment to another.

Similar tests were repeated on three different dates with different outdoor temperatures. Indoor temperature stayed relatively same for all tests. Temperatures during the tests can be seen in the Table 1 below. The outside temperature -1 °C in the first test was actually one degree below the recommended use temperature but the sensors seemed to function normally during the whole test [17]. The test site was not in direct sunlight except in the third test. During the third test reflected sunlight from high glass windows of the building may have caused higher than expected temperature reading. Temperature was measured right next to sensors. The sensors were kept far enough from the door in both locations so that draft was not an issue.

Fig. 6 shows barometric height plot from three different sensors in the first test. Yellow and blue plots show the height observed using the static sensors indoors and outdoors, respectively. Red plot shows the measurements from the mobile sensor kept at nearly constant height. There is a clear difference between the outdoor and indoor sensors and a clear drop in calculated height when the mobile sensor is moved outdoors. The drop is due to the higher pressure. The mobile sensor does not quite reach the level of the outdoor barometer. This may be because temperature inside the sensor did not have time to equalize with the outdoor environment. The average results from all tests are presented in Table 1.

There is approximately 0.5 m change in estimated height in the indoor sensor estimate between the last and the first measurement. This is due to change in ambient indoor pressure. This change is probably due to ventilation, air conditioning, or similar reasons. Removing this effect is not possible due to it being different than the effect caused by weather change. Change in ambient pressure is the problem

Fig. 7. Practice ammunition used in pressure shock tests.

why additional sensors are required to ensure stability of height measurement.

Objective of the test was to see if the difference in barometric height would be related only to the temperature difference between the environments. However, there does not seem to be a clear relation. Other factors such as air conditioning inside the building are likely a more significant factor than the temperature change. This test shows that another sensor or method is needed to estimate the error caused by environment change.

B. *Pressure shock tests*

In this test we studied pressure shocks and their effect to height navigation. Practice rifle cartridges and thrown grenades were used to simulate pressure shock that would be caused by explosion or a firearm. Practice ammunition can be seen in Fig. 7. This test was done in collaboration with the Finnish Defence Forces. Objective was to study if large or persistent errors to barometric height measurement would be introduced in critical tactical operations. Practice ammunition has sound and the pressure blast comparable to firing an actual cartridge but causes no damage to the surroundings.

Two test persons were equipped with Xsens Awinda sensor units containing barometer sensors. Both had one sensor attached to their front chest and one on both feet. We chose this setup to be the same as when doing navigation tests. Practice ammunition was then used at a certain distance from the test persons and their sensors.

Results from open hall area shown in Fig. 8 measured by one chest mounted sensor unit are plotted in Fig. 9. This data is from the person standing near the shooter. The air pressure in millibars (mbar) is plotted with blue line and the times when the pressure shocks were caused by a firearm are designated with upward pointing triangles on the Fig. 9. The two first blasts, indicated with triangles in the image, are from 5 m from the source. The third and fourth blasts are from 15 m away. The fifth and sixth are from practice thrown grenade going off 4 m from the sensor. The third to sixth blasts are hard to detect on the pressure plot because the effect is almost buried under sensor noise.

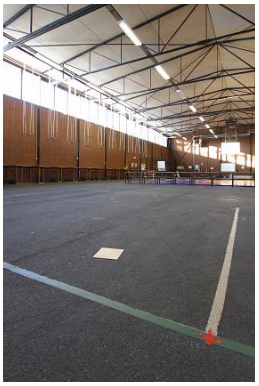

Fig. 8. Open hall area where pressure shocks were tested.

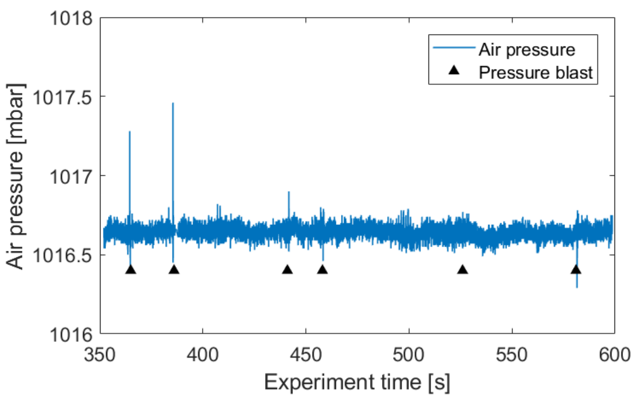

Fig. 9. Pressure measurement during large but short pressure shocks in large open hall area. The blue line plots the pressure and black upward pointing triangles mark the times of pressure shock from a firearm. First and second are measured 5 meters from the source, third and fourth 15 meters from the source and fifth and sixth 4 meters from the source.

Second part of the test was done in a confined hallway approximately 10 m in length and less than two meters wide, shown in Fig. 10. Resulting pressure measurements from one of the sensor units are plotted in Fig. 11. Again the pressure shocks are marked with upward pointing triangles. This time each instance is noticeable. The first four are from rifle cartridges and the last four are from thrown grenades but the effects are very similar. The first, second, fifth and sixth were measured 5 m from the source and the rest are ten meters from the source but the distance does not seem to have an effect in such a confined space. The effect is probably so short that the instrument is saturated and might not give an accurate reading.

The amount of testing was deemed adequate since we did not find any adverse effects to barometer measurement from the pressure shock, except the very short increase and decrease in measured pressure. Most importantly, the blasts do not cause persistent errors to the pressure measurement even when the shock happens close to the sensor. Moreover, the sensors also survived the tests unharmed. With high sample rate the outliers are relatively easy to ignore by averaging the data. As future work the result could be improved by implementing some sort of outlier detector that removes values too high to be possible such as in [20] for eliminating the quick sharp shocks caused by gunfire.

Fig. 10. Confined hallway area where pressure shocks were tested.

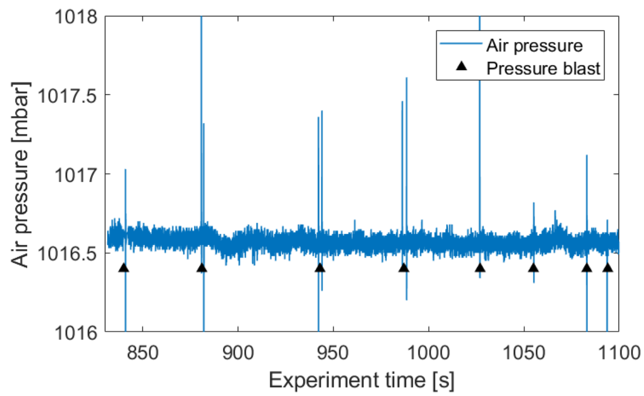

Fig. 11. Pressure measurement during large but short pressure blasts in confined hallway. The blue line plots the pressure and black upward pointing triangles mark the times of pressure blasts from a firearm. In the four first blasts two rounds are fired consecutively. First, second, fifth and sixth are measured 5 meters from the source and the rest 10 meters from the source.

C. Navigation tests

We performed seamless indoor/outdoor navigation tests at Aalto university campus area, Espoo, Finland. In this paper we discuss the vertical navigation solution. This test used Novatel navigation system consisting of tactical grade IMU, and GNSS receiver and antenna as a reference that was initialized outside. Measurement of these sensors was post processed with smoothing in Inertial Explorer software to obtain reference. The INS/GNSS system was carried in a backpack. Reference system did not have a barometer. Indoors GNSS signals are not available. We measured differences in floor levels with tape measure and presumed the surfaces nearly level. Floor levels may have some variation but we estimate that the reference has better than 0.1 m accuracy since the site was built environment. Reference level was not considered in stairs and other areas where it was difficult to determine the level accurately. Even outdoors, only places where the system could stay on a level surface were used as reference. On average, 66 % of the data had reliable reference height. The start of the test was defined as zero height level and rest of the reference heights are in relation to this zero level. In this test we measured the height in meters instead of floor numbers. The floor height in the building was over 4 m in certain places and floor detection would be simple. In addition our target application is infrastructure-free navigation where map of the building is not necessarily available.

TABLE II

Test number	Test person	Barometric height		Fused height	
		RMSE [m]	|e| > 1.5 m [%]	RMSE [m]	|e| > 1.5 m [%]
1	1	0.56	0	0.44	0
2	1	0.49	1.7	0.62	0
3	2	0.79	0.8	0.36	0
4	2	0.75	4.1	0.42	0

The test equipment consisted of a barometer for air pressure measurement and a sonar range finder for vertical speed measurement. Barometer was mounted on a left shoulder strap and the sonar was located under the backpack pointing directly downwards as was shown in Fig. 2. Relative location of the sonar and barometer does not matter since the sonar is only used for speed estimate. Relative location of the reference system and the barometer was calibrated in the beginning of the test.

The test started outside the doors of a large building. The route travelled indoors, through hallways, lobby area and stairs, out of the building for several minutes and then back inside, and ended on the same height level where it started. The total length of the route was approximately 750 meters and the test lasted on average 11 minutes. Two persons performed the test and each walked through the route twice amounting to four sets of data. The sensors recorded the barometer readings and sonar distance measurements to the floor. Because the sonar is located behind the person, the distance increases when they are moving up and decreases when they are moving down and the difference from a general mean is a relatively good measure of vertical speed.

The sonar has a measurement range from 0.6 m to 5 m. Occasionally, the sonar makes an erroneous measurement due to multipath or large change of sonar angle due to user's irregular movement. These are excluded from the results because they are most likely blunders. The sonar was mounted approximately one meter from the ground so measurements smaller than 0.61 m or larger than 1.3 m were removed. This data was then averaged over one second. The sonar measurement rate is approximately 8 Hz. Average of all measurements is close to the distance from the sonar to the ground when the test person is standing on a level surface. The total average was subtracted from each measurement to get zero mean values. This was possible because the analysis was done on post processing. For real time application a moving average of most recent values or similar could be used.

Data from barometer, which operated at the rate of 50 Hz, was averaged over one second to reduce measurement noise. One second interval for averaging was chosen based on experimentation. This one second time has enough sonar and barometer observations to reduce measurement noise and is sufficient update rate for location in tactical applications. Barometric height was then calculated from the pressure values using (4). Starting height was known so the sensor was calibrated at the start of the test. These height measurements together with sonar observations were used in the Kalman filter described above in chapter III-B producing a fused height solution and estimate of the barometer bias. The fused

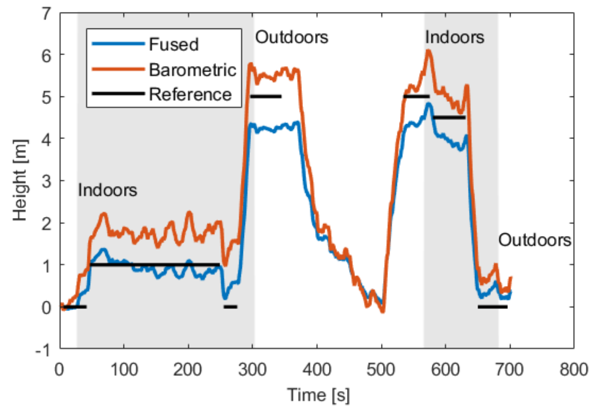

Fig. 12. Barometric height and the Kalman filtered fusion of barometer and sonar compared to reference height track in test number 4. The grey areas mark the time the test person was indoors and the rest of the time the person was outdoors

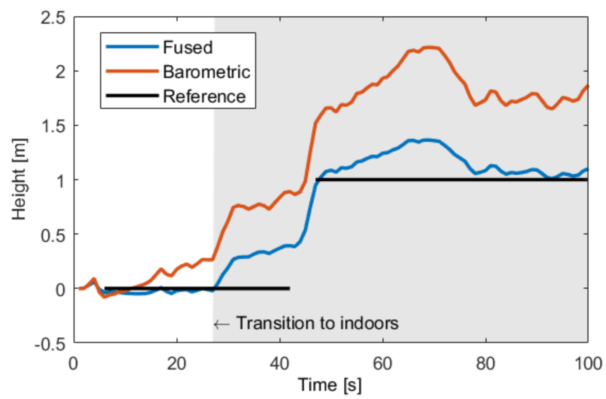

Fig. 13. Detail of Fig. 12 from the first 100 seconds. The transition from outdoors to indoors happens at the line of white and grey area. As the black line indicates, the height should not change but a bias is caused to barometer measurement.

result and simple one second average of barometric height were compared to the reference level where available. Root mean square error (RMSE) of both height measures was calculated. Also the number of measurements that had absolute error greater than 1.5 m error was considered. Errors smaller than this are usually acceptable because correct floor number can still be identified. Even in our case where the floor number is not used, the user can at least find their way back to starting level if the error remains approximately within -1.5 and 1.5 m. These RMSE and percentage of larger than 1.5 meter absolute errors from all observations that had reference are in the Table II for all four tests respectively. The fused height is slightly more accurate in all but one test case. In addition, the fused height has no absolute errors larger than 1.5 meters while in all but one test case the barometric height has them, including the test number 2 with test person 1 where barometric height is more accurate than fused height.

The vertical height plot from test number 3 is presented in Fig. 12. This height plot is an example of how the fused barometric and sonar height estimate and plain barometric height estimate differ from each other. In this figure the fused height plotted in blue is most of the time closer to the black lines of reference height levels than the barometric height estimate plotted in red is – especially indoors.

The fused height improves the overall accuracy in three cases out of four but more importantly, it reduces the error when transitioning from one pressure environment to another. In Fig. 13 is a detail from the Fig. 12 above where the test person enters the building for the first time. The barometric height increases approximately 0.5 m based on the plot even though the true height has not changed. The fusion removes most of this error. This repeats in every test and during most transitions between indoor/outdoor environments. The height accuracy is not quite as high as for example 0.2 m in [14] but comparable for the duration of the test and we achieve this without a reference barometer. Also we achieve the floor level height, which was not achieved in [29] without calibration from reference barometer information. We have not found similar results in the literature produced without a reference barometer.

It also seems that the fusion has removed some of the error related to weather change. In Fig. 12 at the end of the test the final elevation should be zero and there is larger loop closure error on the barometric height than there is on the fused height. The fused height being closer to the true height, is probably due to some of the effect of ambient air pressure change getting removed in the fusion. Also in the tests done by test person 2 the barometric height produces less accurate results than during the tests done by test person 1 while the accuracy of the fused height is not degraded. Reason for the higher RMSE in the barometric height during the tests of person 2 may be higher variation of ambient pressure at the time of the test. Changing of the test person should not affect barometric height since it is simply the height estimate from the carried pressure sensor. The fusion method is therefore working exactly when it should, that is, when the barometer only cannot provide reliable height estimate due to the environmental effects on air pressure.

In Fig. 14 the proposed fusion method in test number 3 is compared to GNSS/INS height solution indoors. This is the system that was used to obtain the reference height level outdoors and it did not have barometer for height estimation. The GNSS/INS height result was obtained using forward and backward processing and smoothing in Inertial Explorer software and was not real time solution. Fig. 14 shows why floor level heights were used indoors for reference instead of inertial navigation. The height solution of the INS has meter level errors and level surfaces are not measured level. Result is good outdoors when good post processed GNSS solution can be obtained.

The fusion of barometer and sonar appears to be more feasible than even a tactical grade INS. Moreover, the barometers and sonars are lighter and require less power than tactical grade INS. Sensor containing barometer and sonar weigh approximately 16 g each. Both sensors and miniature computer recording their data were powered by portable 6000 mAh battery for several hours. The whole system weighed less than 1 kg and contained also other navigation sensors not used in this test. The system was not even optimized for weight and power consumption and there is still room for improvement. On the other hand the tactical grade INS alone weighs approximately 2 kg excluding the 12V battery that was required to power it.

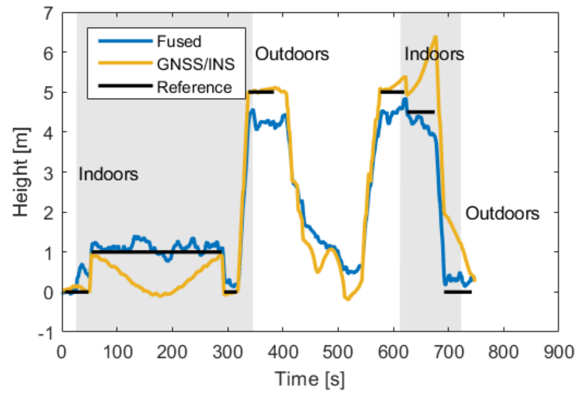

Fig. 14. Comparison of the height solution of barometer-sonar fusion presented in this paper and post processed and smoothed height solution from a commercial tactical grade INS/GNSS system. Both are from test number 3. INS/GNSS solution is obtained with commercial software and is processed both forward and backward and smoothing the end result.

V. Conclusions

MEMS barometers seem to be able to handle pressure shock and can be used in seamless indoor/outdoor navigation with sensor fusion. In this study two different barometer error sources were investigated in detail: the temperature differentials and sudden sharp pressure shocks such as the ones created by firearms. The height error that happens due to moving between indoor/outdoor spaces does not seem to be related to temperature difference of the two environments. Nevertheless, there is a definite change in pressure each time the transition is made. The change is present in all tests and leads to approximately 1 m errors in height measurement. Large but short pressure shocks were tested by using firearms close to the sensors. These do not seem to cause any harm or cumulative errors on the MEMS barometers in the test, and the effect is so short that it is effectively filtered out by averaging.

Navigation tests have shown that while a single barometer may not be enough for seamless navigation between different environments, a reference barometer is not necessarily needed. Here we presented a method to use sonar range finder for vertical speed estimation and fusing the estimate with barometric height estimate in a Kalman filter. This fusion makes it possible to estimate the error caused by the transition between indoor and outdoor environments.

The fusion of barometer and sonar showed to produce more accurate vertical position results compared to estimating height based solely on barometer. The filtered result had in four tests on average 0.19 m better RMSE than barometer only and had no absolute errors exceeding 1.5 m. While differential barometry height estimates in literature have even higher accuracy, the relative height estimate from the fusion of sonar and barometer is better than tactical grade inertial navigation system carried by a pedestrian while still being infrastructure-free solution. We tested the method in infrastructure-free navigation case where the layout and floor height of the building was unknown so height in meters is the only elevation information available. Our system does not currently calculate the floor number but this will be possible if floor height information is input to the system. However, the height in meters may be more useful than the floor number in certain situations. In rescue and tactical applications the floor number might be misleading or not available when the user is for example climbing the side of a building or on the rooftop. Either way, the presented method should provide height with more than half the typical floor height, which is 1.5 m, for at least ten minutes without any outside reference.

The method is promising for applications where infrastructure-free navigation is required such as first responder and tactical operations. Also, a large detected height difference bias can be used to determine the transition between indoors and outdoors. This enables computation of the vertical position in seamless indoor/outdoor navigation. Future work could test fusing the barometer and sonar with even more sensors such as MEMS IMUs and visual navigation that can be used to obtain 3D position.

References

[1] J. Rantakokko, J. Rydell, P. Stromback, P. Handel, J. Callmer, D. Tornqvist, F. Gustafsson, M. Jobs, and M. Gruden. “Accurate and reliable soldier and first responder indoor positioning: multisensor systems and cooperative localization,” in *IEEE Wireless Communications*, vol. 18, no. 2, pp. 10-18, April 2011. DOI: 10.1109/MWC.2011.5751291.

[2] M. Nilsson, J. Rantakokko, M. A. Skoglund and G. Hendeby, "Indoor positioning using multi-frequency RSS with foot-mounted INS," in *Proc IPIN*, Busan, Korea, 2014, pp. 177-186. DOI: 10.1109/IPIN.2014.7275482

[3] C. Fischer and H. Gellersen, "Location and Navigation Support for Emergency Responders: A Survey," in *IEEE Pervasive Computing*, vol. 9, no. 1, pp. 38-47, Jan.-March 2010. DOI: 10.1109/MPRV.2009.91

[4] L. Ojeda and J. Borenstein, “Non-GPS Navigation for Security Personnel and First Responders,” in *Journal of Navigation*, vol. 60, no. 3, pp. 391–407, 2007.

[5] L. Ruotsalainen, L. Chen, M. Kirkko-Jaakkola, S. Gröhn, and H. Kuusniemi, ”INTACT – Towards infrastructure-free tactical situational awareness,” in *European Journal of Navigation*, vol. 14, no. 4, pp. 33-38, 2016.

[6] L. Ruotsalainen, M. Kirkko-Jaakkola, L. Chen, S. Gröhn, R. Guinness and H. Kuusniemi, "Multi-sensor SLAM for Tactical Situational Awareness," in *Proc. ION ITM*, Monterey, California, USA, January 2016, pp. 273-282.

[7] M. Berberan-Santos, E. Bodunov and L. Pogliani, “On the barometric formula,” in *American Journal of Physics* vol. 65, no. 5, pp. 404-412. DOI: 10.1119/1.18555

[8] J. Judy, “Microelectromechanical systems (MEMS): fabrication, design and applications,” *Smart Materials and Structures,* Vol. 10, no. 6, pp. 1115, 2001.

[9] M. Bao, “Micro Mechanical Transducers: Pressure Sensors, Accelerometers and Gyroscopes (Handbook of Sensors and Actuators),” Elsevier Science, 2000, vol. 8

[10] E. Foxlin, "Pedestrian tracking with shoe-mounted inertial sensors," in *IEEE Computer Graphics and Applications*, vol. 25, no. 6, pp. 38-46, Nov.-Dec. 2005. DOI: 10.1109/MCG.2005.140

[11] J. Seo, J. G. Lee and C. G. Park, "Bias suppression of GPS measurement in inertial navigation system vertical channel," *PLANS* Monterey, California, USA, April 2004. pp. 143-147. DOI: 10.1109/PLANS.2004.1308986

[12] J. Käppi and K. Alanen, “Pressure altitude enhanced AGNSS hybrid receiver for a mobile terminal,” in Proc. ION GPS, Long Beach, California, September 2005, pp. 1991-1997.

[13] G. Retscher, “Altitude Determination of a Pedestrian in a Multi-Storey Building,” in Location based services and telecartography. Gartner, G., Cartwright, W.E., Peterson, M.P., Eds. Springer-Verlag, Berlin/Heidelberg, Germany, 2007; pp. 119–130.

[14] M. Tanigawa, H. Luinge, L. Schipper and P. Slycke, "Drift-free dynamic height sensor using MEMS IMU aided by MEMS pressure sensor," *5th Workshop on Positioning, Navigation and Communication*, Hannover, Germany, 2008, pp. 191-196. DOI: 10.1109/WPNC.2008.4510374

[15] M. Romanovas, V. Goridko, A. Al-Jawad, M. Schwaab, M. Traechtler, L. Klingbeil and Y. Manoli. "A study on indoor pedestrian localization algorithms with foot-mounted sensors," *In Proc. IPIN*, Sydney, Australia, 2012, pp. 1-10. DOI: 10.1109/IPIN.2012.6418886

[16] A. M. Sabatini and V. Genovese, “A stochastic approach to noise modeling for barometric altimeters,” *Sensors*, vol. 13, no. 11, 2013, pp. 15692 – 707

[17] Xsens Awinda sensor specifications, 2017 [online], Available: https://www.xsens.com/products/mtw-awinda/

[18] F. Le Blancq, Diurnal pressure variation: the atmospheric tide. *Weather*, vol. 66, no. 11, pp. 306-307, 2011.

[19] J. Parviainen, J. Kantola and J. Collin, "Differential barometry in personal navigation," *IEEE/ION Position, Location and Navigation Symposium*, Monterey, California, 2008, pp. 148-152. DOI: 10.1109/PLANS.2008.4570051

[20] H. Xia, X. Wang, Y. Qiao, J. Jian, and Y. Chang, “Using multiple barometers to detect the floor location of smart phones with built-in barometric sensors for indoor positioning,” *Sensors*, vol. 15, no. 4 pp. 7857-7877.

[21] B. Li, B. Harvey and T. Gallagher, "Using barometers to determine the height for indoor positioning," *IPIN*, Montbeliard-Belfort, France, 2013, pp. 1-7. DOI: 10.1109/IPIN.2013.6817923

[22] U. Walder and T. Bernoulli, "Context-adaptive algorithms to improve indoor positioning with inertial sensors," in Proc. *IPIN*, Zurich, Switzerland, 2010, pp. 1-6. DOI: 10.1109/IPIN.2010.5646966

[23] S. Zihajehzadeh, T. J. Lee, J. K. Lee, R. Hoskinson and E. J. Park, "Integration of MEMS Inertial and Pressure Sensors for Vertical Trajectory Determination," in *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 3, pp. 804-814, March 2015. DOI: 10.1109/TIM.2014.2359813

[24] Y. G. Yusuf and H. W. Agung, "Optimizing ultrasonic and barometric sensors for quadcopter's altitude-hold using YoHe V1.2 PID and KK V2.0 boards," 2016 *International Seminar on Sensors, Instrumentation, Measurement and Metrology (ISSIMM)*, Malang, 2016, pp. 37-42. DOI: 10.1109/ISSIMM.2016.7803718.

[25] U.S. Standard Atmosphere, U.S. Government Printing Office, Washington, D.C., 1976. [Online] (retrieved 24.10.2017), Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539.pdf

[26] F. Ijaz, H. K. Yang, A. W. Ahmad and C. Lee, "Indoor positioning: A review of indoor ultrasonic positioning systems," in Proc. *ICACT*, PyeongChang, South Korea, 2013, pp. 1146-1150.

[27] G. Welch and G. Bishop. An introduction to the kalman filter. Proc of SIGGRAPH, Course, 8(27599-23175), 41. 2001.

[28] L. Ruotsalainen, M. Kirkko-Jaakkola, J. Rantanen, & M. Mäkelä, “Error Modelling for Multi-Sensor Measurements in Infrastructure-Free Indoor Navigation,” *Sensors*, vol. 18, num. 2, 590, 2018, DOI: 10.3390/s18020590

[29] B. Shin et al., "Motion Recognition-Based 3D Pedestrian Navigation System Using Smartphone," *in IEEE Sensors Journal*, vol. 16, no. 18, pp. 6977-6989, Sept.15, 2016. DOI: 10.1109/JSEN.2016.2585655

[30] D. E. Bolanakis, K. T. Kotsis and T. Laopoulos, "A prototype wireless sensor network system for a comparative evaluation of differential and absolute barometric altimetry," in *IEEE Aerospace*

and Electronic Systems Magazine, vol. 30, no. 11, pp. 20-28, November 2015. DOI: 10.1109/MAES.2015.150013

Jesperi Rantanen is a research scientist at the Department of Navigation and Positioning in Finnish Geospatial Research Institute. He has a M.Sc. (Tech.) degree in Geomatics from Aalto University School of Engineering, Finland. He is currently pursuing a doctoral degree at Tampere University of Technology. His research focus is in developing integration algorithms for adaptive indoor navigation systems.

Dr. Laura Ruotsalainen is a Research Manager and Deputy Director of the Department of Navigation and Positioning at the Finnish Geospatial Research Institute, Finland, where she leads a research group on Sensors and indoor navigation. She received her doctoral degree in 2013 from the Department of Pervasive Computing, Tampere University of Technology, Finland. Her doctoral studies were partly conducted at the Department of Geomatics Engineering at the University of Calgary, Canada. Her doctoral research was focused on vision-aided seamless indoor/outdoor pedestrian navigation. Her current research interests cover, in addition to vision-aided navigation, adaptive integration of sensors and radio positioning means for robust navigation, situational awareness and GNSS interference mitigation.

Dr. Martti Kirkko-Jaakkola received his M.Sc. and D.Sc. (Tech.) degrees from Tampere University of Technology, Finland, in 2008 and 2013, respectively. From 2006 till 2013 he worked with the Department of Pervasive Computing, Tampere University of Technology, including research visits to the Technical University of Munich, Germany, and the European Space Research and Technology Centre, The Netherlands. Currently, he works as a Research Manager at the Finnish Geospatial Research Institute (FGI) in Kirkkonummi, Finland; his research interests include low-cost precise satellite positioning, microelectromechanical inertial sensors, indoor navigation, and GNSS-based time transfer.

Maija Mäkelä is a Research Scientist at the Department of Navigation and Positioning in Finnish Geospatial Research Institute (FGI). She received her M.Sc. (Tech.) degree in 2016 from the Department of Mathematics, Tampere University of Technology, where she also worked studying ionospheric correction methods in GNSS. She joined FGI in 2017 and is a doctoral student in Tampere University of Technology. Her current research interests include sensor-based and hybrid cooperative positioning algorithms, and machine learning in situational awareness.