Collaborative Indoor Navigation for Emergency Services Personnel

Aiden Morrison, Nadezda Sokolova
SINTEF ICT Communication Systems
Strindveien 4,
7034 Trondheim, Norway
Aiden.Morrison@sintef.no

Trym V. Haavardsholm, Ove K. Hagen, Thomas O. Opsahl, Kjetil B. Ånonsen,
Norwegian Defence Research Establishment (FFI), P.O. Box 25
NO-2027 Kjeller Norway
Trym.Haavardsholm@ffi.no

Kapteinløytnant Erik H. Eriksen, Norwegian Battle Lab and Experimentation (NOBLE), Bodo, Norway
Erik@noble.mil.no

Abstract— **First responders and other emergency services personnel must often enter buildings which prevent the use of GPS or other satellite navigation signals for positioning. Loss of navigation capability combined with the fact that the buildings are often unknown to the personnel in question makes it more difficult for individual team members to coordinate with one another, and difficult or impossible for the team leader to monitor and direct the actions of each team member. While inertial navigation or pedestrian dead reckoning provide for some degree of navigation in GPS signal denied environments, these solutions degrade with time and may require prohibitively large and expensive inertial solutions to navigate over extended periods, while also allowing each individual user to accumulate independent positioning errors and thereby appearing to 'drift away' from one another. This paper presents an implementation of a collaborative navigation system utilizing each of user-to-user radio links, Global Navigation Satellite Systems (GNSS) when available, inertial navigation, pedestrian dead reckoning, as well as camera based Simultaneous Location and Mapping (SLAM) to provide a team of users with absolute and relative situational awareness for themselves and their team. The application of collaborative navigation to such a team provides the triple benefits of providing improved absolute navigation accuracy, improved relative navigation accuracy, and greatly enhanced situational awareness for all cooperating team members.**

TABLE OF CONTENTS

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1. INTRODUCTION

This paper presents the extension of a collaborative navigation project originally undertaken in 2014 between SINTEF and NOBLE, the results of which have been published [1][2][3]. During the original 2014 project the objective was to demonstrate the performance and situational awareness capabilities of a collaborative navigation system in the context of a team of users entering a building which completely eliminated GNSS coverage for a duration of 5.5 minutes. A further constraint on the scenario was that no fixed infrastructure within the building could be relied on during the entry operation as a building to be entered by emergency services or defense personnel cannot be instrumented ahead of the entry, and may not have power at the time of entry. The potential lack of power also precluded the use of signals of opportunity in the scope of the original project.

The 2014 project achieved its initial goals and demonstrated the ability of a collaborative navigation system to deliver performance and situational awareness benefits to the users in a practical operational setting, and led to a 2016 follow on project, which had the objective to extend the operating envelope of the system while also improving performance and usability.

In order to improve system performance, enhancements not present in the original version were added based on other successful indoor navigation systems, such as a foot based sensor similar to that popularized by researchers at KTH [4][5], navigation based on an optical flow camera [6] and methods for Visual Odometry and Visual Simultaneous Localization and Mapping [7]. Initial design work on deployable Micro aerial vehicles (MAVs) [8] as reference and communication nodes was also conducted.

In the following sections of the paper the collaborative navigation motivation and concept of operation is introduced. This is followed by an overview of the augmentation systems added to this version of the system which are discussed in terms of their design, processing algorithms, and performance contributions. The main shoulder mounted system hardware and software design is reviewed, as is the system test plan and intended future work on the collaborative navigation concept.

2. THE COLLABORATIVE NAVIGATION MOTIVATION AND CONCEPT

The motivation behind the use of collaborative navigation is to provide reliable indoor navigation performance in environments where infrastructure cannot be set up specifically to allow navigation and where approaches such as signals of opportunity may not be relied upon due to the potential for loss of power to the building. Such scenarios are regularly faced by emergency services and security personnel, though these user groups have the notable advantage of operating in teams.

Collaborative navigation functions using three simple assumptions about the members of such a team:

i. That each user has the ability to estimate their position and position uncertainty over time.
ii. That each user is equipped with a means to estimate or measure range to other cooperating users.
iii. That each user can communicate with the users they can measure or estimate range to.

The above assumptions may initially seem onerous but on closer inspection they can apply to very inexpensive platforms such as a smart phone. Current smart phones almost universally include GPS support as well as rudimentary inertial sensors that satisfy the requirements of point one above, while internal radios such as Bluetooth low energy can meet the requirements of point two with modest uncertainty in the estimate. Since smart phones are intrinsically communication devices, they obviously meet the requirements of point three to be able to communicate with other cooperating users.

When collaborative navigation is used, the effect of the system is a threefold benefit to the users.

i. Since the noise and accumulated position errors of each individual user can be considered uncorrelated, the measurement/estimation of user to user ranges combined with the exchange of estimated user positions and uncertainty allows all collaborating users to improve their absolute navigation performance.
ii. Since a one dimensional distance constraint is applied between cooperating users via the range and uncertainty exchange process, the relative navigation performance will have a bounded error over time, even as the absolute navigation performance continues to degrade.
iii. Implicit in the exchange of position information the cooperating users gain substantial situational awareness about the approximate location of their teammates without the need for verbal or other communication of this status.

Under operating conditions where some users in the cooperating network have access to an absolute position reference (e.g. GNSS), are experiencing a continuous Zero Velocity Update (ZUPT, with or without a simultaneous Zero Angular Rate Update (ZARU), and therefore have a bounded position uncertainty, additional benefits emerge. If as few as two users in a team equipped with barometers simultaneously meet these criteria, the error growth of the other users can be bounded. In order to increase the occurrence of such beneficial synergies, additional augmentation sensors which provide additional information or serve to limit error growth can be incorporated by some or all of the users.

3. AUGMENTATION SYSTEMS CONSIDERED

In the scope of the original project, the collaborative navigation units utilized strap-down inertial navigation as their primary method of propagating system state estimates from epoch to epoch. The system leveraged several sources of information when they were available, such as GNSS and magnetic compassing during system initialization, barometric pressure throughout operation to aid in altitude estimation, as well as the user-to-user data links and range measurements for the collaborative aspects. To this, an attempt was made to add a form of step detection, which was complicated by the location of the system on the users bodies, as they were designed to be carried on the shoulder or carried in the hand during testing. As a consequence of these carriage options, the ability of the shoulder unit to reliably detect and characterize user footfalls was limited, and commensurately the quality of the information provided to the system was also limited.

To work around this limitation of the original system design, it was decided to revise the system design to support the use of dedicated external sensor pods including shoe mounted dead reckoning units similar to those popularized by the openshoe initiative [4] and used in many prior pedestrian navigation applications [5].

A second source of information, which was compatible with the desire to maintain the self-contained nature of the individual user, was identified as camera based navigation. An initial effort at using optical flow cameras to track displacement and rotation was undertaken using off the shelf components, but when performance of these sensors proved unreliable, a custom Simultaneous Localization and Mapping (SLAM) system was implemented by researchers at FFI. The FFI designed SLAM system was architected to provide the benefits of optical flow based displacement and pose estimation while also providing dynamic map generation and the potential for loop closure.

A third source of additional information used to evolve the capabilities of the system was the inclusion of a MAV borne reference node. This drone carried reference node is based on the desire to keep the system self contained within assets that can be brought in by the team of users, but also by the desire to enhance performance. By placing a collaborative navigation package on an agile airborne platform performance is enhanced both by the inclusion of an additional user, but also by the ability to employ this user in a way that is best suited to the situation at hand. For example if the building walls are sufficiently thin that the radio links from the outdoor users can frequently reach the indoor users, then the drone can hover above or beside the building at an optimal location to provide a reference point while still in GNSS coverage. If on the other hand the building is structured in such a way that a hovering outdoor reference point would not be particularly useful, then the drone can be brought in and deployed as a fixed reference point indoors which benefits from continuous ZUPTs simply by having it land at a selected location.

4. PEDESTRIAN DEAD RECKONING PODS

Since the collaborative navigation systems in this application are used by individuals entering a building, the use of pedestrian dead reckoning (PDR) techniques for estimating displacement and constraining error growth are an excellent match. In the original collaborative navigation project with NOBLE in 2014, the information driving the PDR processes was provided by the shoulder mounted/handheld navigation systems. While research in to the use of such data sources [9] has demonstrated the feasibility of the approach, in general the performance available from PDR based on non-foot located sensors is reduced relative that available when a sensor package can be mounted directly on the foot of the user [10]. One obvious reason for this performance differential is that the foot will frequently come completely to rest, allowing ZUPT application while other parts of the human body do not.

It is well documented that a user position and heading can be well constrained under certain conditions through the application of dual foot mounted sensors [10][4]. While designs and algorithms for well-designed foot mounted sensor pods are freely available from sources such as the openshoe consortium, it was decided to produce a tailor made solution within this project that would differ from the openshoe hardware in a number of ways.

The first hardware implementation difference was the use of a dedicated 2.4 GHz radio link, which is architected to allow simultaneous connection to up to six peripheral sensors rather than using Bluetooth, which in the current system design is reserved for potential communication with a user handset. The second hardware implementation difference was the use of a single MPU-9250 Micro Electro Mechanical System (MEMS) sensor assembly, which is newer than the MPU-9150 used in the available openshoe design, though the latter does include four identical MPU-9150 sensors to improve performance. The use of a single sensor rather than an ensemble of four sensors is in part responsible for the battery life of the designed system exceeding 3.5 hours compared to the 1.5 hours advertised by the openshoe system. The third hardware implementation difference was the design of the sensor enclosure to include a 3D printable 'clip' designed to allow the sensors to easily attach to boot laces, or another convenient mounting point on the users foot, while the openshoe based sensor enclosures have no such facilities.

Figure 1. Side on view of pedestrian dead reckoning food pod encapsulated in a 3D printed enclosure with outer dimensions 39 x 29 x 25 mm including clip for attaching to boot/shoe laces.

Additional considerations affecting the design of the foot-mounted sensors within this project were related to the selection and formatting of data sent over the RF interface to the shoulder unit from the foot based pod. Given the high dynamics of the user foot, a sampling rate of 500 Hz was selected which produces too much raw data to be reliably streamed to the shoulder unit. Part of the challenge in the case of a foot-mounted sensor communicating results to a shoulder mounted system relates to the periodic obstruction of the line of sight between the two devices during the normal walking stride of the user. This periodic obstruction requires either substantial local buffering, or careful design of the transmitted data packets. To address the challenges posed by this operating configuration, the processing algorithm and output data format used in the foot mounted sensor pod was designed to address both the throughput restrictions and frequent communications dropouts expected in normal operation.

The algorithm operating within the PDR foot pods functions as follows:

i. Samples are mechanized at the full sensor provided rate of 500 Hz.

ii. ZUPT and ZARU events are detected over a lagging window of 15 and 128 samples (at 500 Hz) respectively.

iii. In the common event that a ZUPT event is detected, the velocity states of the system are zeroed.

iv. In the case that a much rarer ZARU event is detected, the attitude and sensor biases estimates are updated. The estimated position, velocity and attitude of the sensor are also reset to be consistent with a static user facing north at surface of the earth at the equator.

v. Every 250 samples the following data are produced by the processing algorithm:

   a. The magnitude of the lateral displacement of the pod

   b. The vertical displacement of the pod

   c. The heading direction of the foot

   d. The direction of motion of the foot relative to the axes of the pod body (distinct from the heading direction of the foot)

   e. Flags indicating the accumulated number of ZUPTs and ZARUs over the preceding interval, and implicitly indicating the continuity of the heading estimate.

While the data output by the processing algorithm is very compact relative to the input 500 Hz data stream from the MEMS inertial measurement unit (IMU), the output data packet is specially designed to support operating in the expected challenging environment without substantial communication overhead to negotiate retransmission. This is achieved by naively transmitting the previous two observations and flag sets along with a current sequence number at every epoch. In effect this makes individual transmissions longer than they need to be, but eliminates the need for protocol level negotiation over retransmission (this is handled at the hardware level for limited retry attempts). Since data are presented as triplets of displacements it becomes possible to form a continuous estimate of user displacement and velocity as long as no more than any two out of three consecutive samples are lost.

The displacement performance of the system implementing these algorithms was determined by map matching evaluation over a controlled 280 m trajectory to be approximately 2% of distance travelled laterally. This is not comparable with some estimates of stride-length estimation performance such as those referenced in [10]. It is important to note that the efforts of [10] utilized tethered sensors which did not need to contend with data loss caused by normal user motion, which the protocol developed and implemented in these custom pods partially but not completely overcomes.

5. OPTICAL FLOW CAMERA

An additional sensor system that was considered for inclusion in the evolution of the collaborative navigation system was an off the shelf optical flow camera of the type that has been popularized by drone hobbyists. These compact and inexpensive optical flow cameras function similarly to an optical computer mouse and use the translation and rotation of the image seen by the camera sensor to estimate the displacement and rotation of the platform carrying the camera.

The sensor selected for this purpose was the PX4FLOW camera whose design and algorithms are presented in [6] to provide an independent source of user translation and heading change as they maneuvered indoors.

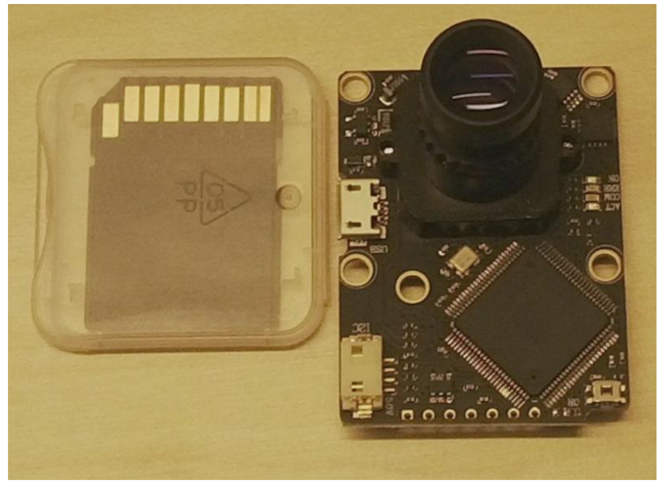

Figure 2. The PX4FLOW optical flow sensor module with SD card for scale comparison.

While the intended operating mode of the camera is to be positioned on the underside of a drone facing the ground or floor, the belief was that by pointing it upward towards the ceiling it would be possible to achieve much the same results for a user operating indoors under sufficient illumination conditions. Unfortunately testing of the concept revealed that even under generous lighting conditions the PX4FLOW camera had difficulty isolating features in the ceiling under multiple representative ceiling materials and layouts. While it is not entirely surprising that this type of low cost off the shelf sensor did not perform, it made the inclusion of the FFI developed visual navigation system all the more important to the overall system performance.

6. VISUAL NAVIGATION

With Structure-from-Motion (SfM) techniques [11][12], we are able to recover both camera poses as well as the scene structure in 3D from correspondences between 2D images. We may find such correspondences by matching keypoint features such as SIFT [13] and ORB [14], which typically are very robust to variations in viewing geometry and image intensity. Alternative approaches are the so-called direct methods [15], which estimate structure and motion directly from photometric comparisons between images. These methods are typically very precise and more robust in feature-less and blurred indoor scenes, but they often require that the geometric changes between the images being compared are relatively small.

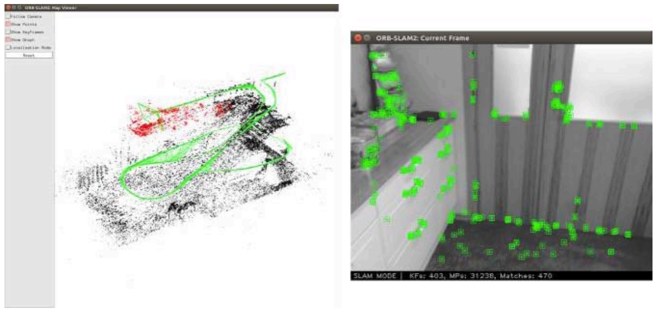

Figure 3: Example of VSLAM with ORB-SLAM2 [21]. Left image shows the 3D map and camera trajectory, while the right image shows the map points recognized in the last frame.

By relying on a number of local correspondences, it is possible to make both approaches relatively robust to outliers and moving objects in the scene by analyzing the consistency between samples. This is typically performed by applying random sample consensus (RANSAC) [16] in some form.

SfM may be solved through global optimization, where all images and cross-correspondences can be taken into account to minimize the global re-projection error, or locally over a subset of images, which enables real-time performance at the possible expense of larger drift in pose and scale. Visual Odometry (VO) methods [17][18][19] are often based on local SfM over the last *m* frames, which enable less drift and better robustness through localization in a local map, and re-localization when tracking is lost.

SfM may also be performed hierarchically in global structures based on keyframes and local maps, which enable global corrections of maps and trajectories in real-time. Such schemes are often employed in Visual Simultaneous Localization and Mapping (VSLAM) [20][21]. By detecting loop-closures when revisiting areas using image recognition techniques [22], drift in both the global map and camera trajectories may be reduced, leading to a more consistent global map. Such maps may also be stored and used for localization [21] or 3D visualization of the scene (see Figure 3).

Figure 4: Visual navigation camera system. It is based on two identical modules comprised of a Point Grey Blackfly S 5.0 MP camera based on a Sony IMX250 monochrome sensor and an XSENS MTi-100 IMU. The modules are shown in a stereo configuration with 185° field of view Fisheye lenses.

To experiment with different state-of-the-art methods for VO and VSLAM in the indoor navigation application, a camera system based on two Point Grey Blackfly S 5.0 MP Global shutter cameras was constructed. The use of two cameras makes it possible to collect data in a stereo configuration, and thereby avoid scale drift by observing scale directly. A flexible camera mount also makes it possible to experiment with monocular methods, as well as different multi-view configurations for better feature tracking and robustness to occlusion.

Each camera is fitted with an XSENS MTi-100 inertial measurement unit (IMU), which may be used for movement prediction and scale observation in the non-stereo configurations. A custom FPGA-based synchronization and logging board is used to log and stream IMU-data and image timestamps. VO and VSLAM is performed in real-time on an NVIDIA Jetson TX1 embedded computer.

7. DRONE BORNE PLATFORM

While each of the other augmentation sensors considered can be made self-contained within the individual user, the inclusion of drones effectively serves as an extension of the team size and allows for multiple avenues of performance enhancement.

Firstly, if the building to be entered has relatively thin outer and inner walls (e.g. two-Wythe brickwork) that the collaborative navigation radios are able to readily penetrate, then judicious positioning of one or more drones outside the building can provide an impromptu reference network for users operating within the building. In testing in a minimally obstructed area it was found that even two such reference points could in combination with onboard barometers provide sub-meter position uncertainty over periods of several minutes. By placing such a reference point on a highly mobile drone that can be commanded to hover at an optimum outdoor location where GNSS is available, the drone becomes an absolute position reference point to the rest of the network.

Alternately, if the outer walls of the building to be entered is not expected to be easily penetrated by the communication and ranging radios, it is possible for the drones to be flown or carried in with the time and deployed statically as a type of deployable constraint point and communications relay indoors.

While the benefits of inclusion of such flexible additional reference points are considerable, the design of the collaborative navigation package for such a platform must contend with the intrinsic limitations of that platform including the need to minimize size and especially weight. In this specific case, a target platform with a mass of 90 grams was selected as a minimum, which in turn implied a gross payload mass for the collaborative navigation system of approximately 25 grams and a size of only 19 cm^2.

One of the necessary trade-offs made when designing the compact and lightweight drone borne platform was the reduction in inertial performance relative to that available on the heavier and larger user borne equipment. The specific IMU selected was the same MPU-9250 utilized within the foot pods, while the remainder of the drone borne hardware was nearly identical to that utilized in the main system that is detailed in the following section.

8. MAIN SHOULDER MOUNTED SYSTEM HARDWARE DESIGN

While the paper thus far has focused on the design of augmentation sensors that have been added since the previous version of the collaborative navigation system described in [1], the core shoulder mounted unit was also upgraded. Relative to the original system, the new version is more compact, lighter, has a fully enclosed GNSS antenna, a triple constellation GNSS receiver, an added NRF24L01 based internal radio and antenna for connection to peripheral sensors. An additional interface port for connecting to and synchronizing with external systems was also added, in addition to increased processing power to allow for the extra data from the augmentation systems to be leveraged in the onboard filter. The full system hardware diagram is shown in figure Figure 5 while the enclosed and mounted unit as worn by a user is shown in figure Figure 6.

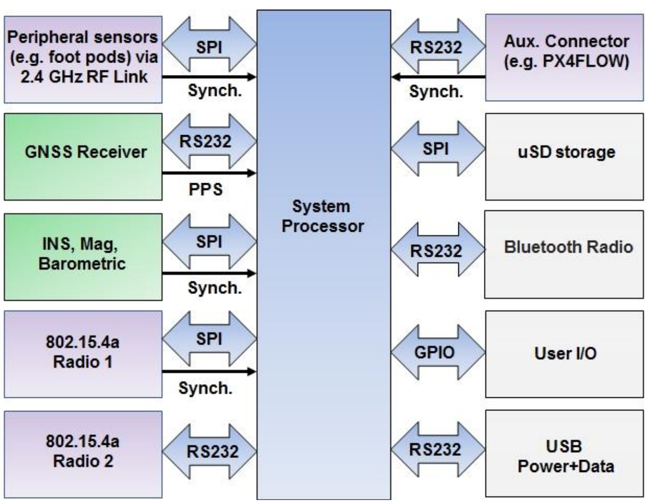

Figure 5. Collaborative navigation system hardware architecture indicating hardware interfaces and synchronization facilities. Information sources are colour coded green, while grey boxes are system interfaces and communications. Violet shaded boxes are simultaneously information sources and communications interfaces.

Figure 6. Main shoulder mounted system shown attached to a Modular Lightweight Load-carrying Equipment (MOLLE) vest via integral mounting clips in the enclosure. Outer enclosure dimensions are 13 x 7 x 3 cm.

The majority of system volume is occupied by the combination of the tactical grade IMU, and the battery pack necessary to provide a runtime endurance of the main shoulder mounted system of approximately 8 hours.

Synchronization of data is carried out by the capture of pulse-per-second (PPS) events from the GNSS receiver. These PPS events are used to characterize the offset and drift rate of the onboard oscillator, which in turn is used to time stamp all locally occurring events such as samples from the IMU as well as messages transmitted or arriving over the various RF interfaces. In the case of the collaborative navigation radios, a Time Division Multiple Access (TDMA) scheme is used to provide 16 or 32 user time slots per second. While other interfaces such as the 2.4 GHZ peripheral sensor link utilize frequency division multiple access (FDMA) to isolate communications between users and their own peripheral sensors and is therefore insensitive to oscillator drift while indoors, the TDMA guard bands require relatively tight initial synchronization to avoid overlapping transmissions. The oscillator of the system has been selected to allow 30 minutes of continuous GNSS denied operation before any overlap can arise, however this duration could be extended by incorporating existing UWB radio based timestamps to limit and correlate the oscillator drift of team members in a manner analogous to the underlying collaborative navigation.

While the original system from 2014 supported only logging and post mission processing, the firmware of the new systems was designed to support both online processing of all data excepting the SLAM data, in addition to logging all non-image data for post processing and offline analysis. The approach used for real time processing of the main and augmentation sensors is discussed in the following section.

9. DATA HANDLING AND PROCESSING ARCHITECTURE

While there are compelling performance advantages to the use of a centralized data processing approach [5], the collaborative navigation systems discussed here utilize a fully de-centralized processing approach to allow for operation in environments where the network may be bifurcated or subsets of users may be isolated for extended periods. Each individual shoulder mounted system implements an Extended Kalman Filter (EKF) with 19 states or 21 states depending on whether the system is used in loose GNSS coupling or tight GNSS coupling mode. The non-GNSS EKF states are position, velocity, attitude, accelerometer biases and scale factors, gyroscope biases and scale factors, and barometer bias.

An important consideration in the implementation of the real-time processing firmware relates to the need for a collaborative navigation system to provide the most up to date estimate of the required system states (typically position and position uncertainty) during user ranging updates. Conflicting with this desire lies in also accommodating the substantial (hundreds of ms) latency that is present in information sources such as the GNSS receiver and peripheral augmentation sensors. To reconcile these factors, the collaborative navigation main shoulder mounted system employs a strategy of short term buffering and projection. Firstly, incoming sensor data is buffered, and is only used once a fixed delay period is past. Currently this delay period is set to 500 ms to attempt to bound the worst case latency of the attached information sources. Since the calculated user state vector is then by definition 500 ms out of date, it is necessary to use velocity state information to propagate the past user position and position uncertainty to the present for transmission over the collaborative navigation radio links.

While this implementation choice does limit system performance slightly, it is considered a sensible trade-off in light of the limited computational resources available in the shoulder mounted main system. Since the SLAM data handling requires significantly more memory and processing power, it is currently processed in a dedicated computer system, and tested only in post-processing at this stage.

The measurements from the camera-based navigation described in section 6 are integrated with IMU, barometer, GNSS, and the collaborative radio ranging in the software tool NavLab4, developed by FFI. NavLab4 is an aided INS for post-processing, simulation and performance analysis, based on the same core as described in [23], but with an implementation of the Kalman filter for sensor fusion, that supports a flexible state vector. For this project, NavLab4 is redesigned to support the collaborative navigation through user to user ranging as described in section 2.

NavLab4 has an existing implementation for camera-based navigation through tight integration of feature-tracks using an inverse depth parameterization [24]. In this project, we develop modules for NavLab4 that support a type of loose coupling integration, by using rotation and translation increments estimated from the visual SLAM system. The integration algorithm for these measurements in the error-state Kalman filter in NavLab4 is based on the stochastic cloning technique described in [25]. For a subset of keyframes the current rotation and position are saved, their error-states are cloned, and from thereafter available for delta rotation and position updates. When interfacing visual odometry methods, the cloned states in the filter will be recycled when a keyframe is out of scope. If the users revisit places during the operation, it is possible to perform a loop closure update. To integrate this properly, the relevant cloned states for the loop closure needs to be present in the state vector of the Kalman filter. A loop closure measurement will potentially reduce the errors to the same level as when the loop closure point was first visited.

Computationally wise, it is not a problem to use this algorithm in real time, though a camera-based INS has to handle the increased latency caused by the camera processing algorithms. We still considered this solvable, either by running the Kalman filter at fixed delay, as described earlier, or through the delayed measurement processing technique used by the real-time HUGIN navigation system. The real-time SLAM loop closure problem, knowing which cloned states to save, is not considered in this scope, but is identified as part of the future real-time development needed.

10. TEST PLAN, AND PERFORMANCE EVALUATION

The test and performance evaluation plan for the evolved collaborative navigation system is similar to what was undertaken to evaluate the original system, but with several important alterations.

During the original project, the performance of the system was tested by having a team of six users equipped with the first generation hardware enter and navigate through an office building, which denied GNSS coverage to all users except for the commander who waited outside. The five remaining team users spent 5.5 minutes in a GNSS denied environment, with varying levels of motion depending on their scripted path through the building. The team was equipped with stop watches to ensure that their repetitions of the test were consistent in their execution to the point that performance could be evaluated by comparing the reported locations of the users to the available floor map of the building. The performance evaluation of the original systems was conducted by isolating the contribution of each individual information source available to the collaborative navigation users as delineated in Table 1.

Members SINTEF and FFI conducted testing of the evolved systems week 45 at Rena in Norway with the assistance of the Norwegian armed forces and NOBLE personnel.

Table 1. Performance of the original collaborative navigation systems over varying levels of sensor/algorithm integration.

	Peak error magnitude in metres during 330 second indoor navigation				
Processing options	User 1	User 2	User 3	User 4	User 5
GNSS INS only	2600	6300	16300	20200	20200
Barometer and ZUPT added	125	89	106	68	34
Basic step detection added	75	74	59	62	16
Collaborative navigation added	13	13	15	10	10

Compared to the original, the new system evaluation was modified in the following ways:

- The team size was expanded from six users to eight users.
- A simulated city environment comprising concrete and steel three level training buildings and underground tunnels replaced the office building test environment.
- One of the eight users carried the stereo vision system designed by FFI.
- Drones were not utilized in the final tests due to signal level issues with the designed drone boards.

The first direct benefit of the increased team size was found in the more reliable propagation of 3rd party situational awareness information through the network of users, reducing the average propagation interval from five seconds in the original tests to three in this effort, and eliminated any gaps in coverage within the operating area.

With the increased team size and addition of foot-mounted PDR sensors it also proved possible to achieve comparable relative and absolute positioning performance to that shown in Table 1, but with a far shorter initialization period at the start of the test, as well as a longer total duration operating without GNSS coverage. In the original tests a period of approximately five minutes was used for outdoor initialization of the systems after GNSS lock was obtained by each user, while in this test this initial alignment period was reduced to approximately 90 seconds. The GNSS denied period in the original tests was 5.5 minutes with a peak error of 15 m, while these new tests contained approximately 6.33 minutes of GNSS denied operation and a 15.8m peak user error when combining all information sources except the visual odometry information produced by the stereo vision system.

Over a similar trajectory length, the isolated VO system provided a similar positioning performance to the entire assembly of other information sources, peaking at 25 metres of error when returning to the initial starting point as indicated in Figure 7 by the displacement between the red crosses. While this level of performance is lower than initially hoped it should be emphasized that this result utilized no feature extraction and matching techniques (i.e. loop closure was not used) and therefore leaves much room for direct performance improvement.

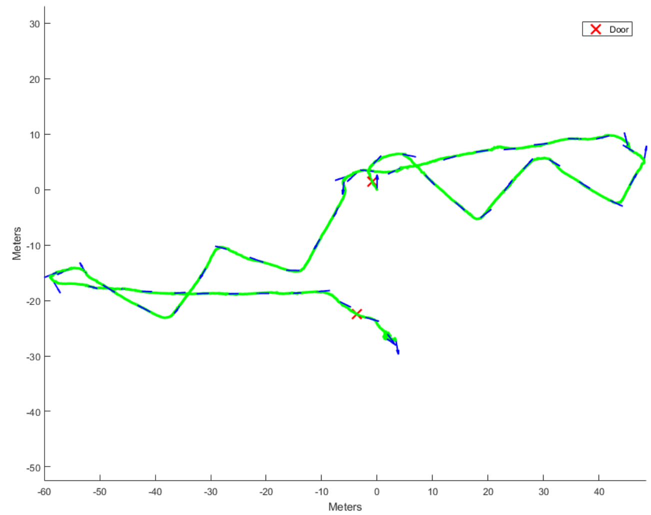

Figure 7: Output results of the isolated visual odometry system during a building traversal.

11. CONCLUSIONS AND FUTURE WORK

As expected, the additional sources of data and expanded operating network served to improve the performance of the system by allowing it to achieve similar performance to previous tests but over an extended operating duration, and with better overall situational awareness availability between users.

While it was intended that at least one drone borne system would be included in the current tests, this was cancelled at the last minute due to GNSS signal level problems in the designed lightweight drone boards. Since the collaboration of small autonomous drones with first responders and security services personnel is anticipated to be a useful technology, an internal SINTEF project will carry forward this aspect of development during 2017. It is also expected that by adding an additional peripheral sensor pod to the user helmet, the orientation of the head relative to the torso could be used to provide relative 3D audio between mobile users. The availability of 3D positional audio provides an effective way to relate situational awareness information about the distance and relative position of other cooperating team members without requiring active action on the part of any user. This method of implicitly communicating situational awareness information is considered promising and an improvement over requiring the users to view a screen or readout to gain this information.

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Biography

Aiden Morrison *received his PhD degree in 2010 from the University of Calgary, where he worked on ionospheric phase scintillation characterization using multi frequency civil GNSS signals. Currently, he works as a research scientist at SINTEF ICT, Communication Systems department.*

Nadezda Sokolova *received her PhD degree in 2011 from Norwegian University of Science and Technology (NTNU. Currently, she works as a research scientist at SINTEF ICT, Communication Systems department and adjunct associate professor at the Centre of Excellence on Autonomous Marine Operations and Systems (AMOS), NTNU.*

Trym Vegard Haavardsholm *is senior scientist at the Norwegian defence research establishment (FFI), and works primarily within the hyperspectral image processing and computer vision domains. His current research focus is leading the scene analysis activity within FFI's autonomy project.*

Ove Kent Hagen *is a scientist at the Norwegian defence research establishment (FFI). Hagen holds a master's in fluid mechanics and a bachelor's in mathematics from the University of Oslo. Since 1999, he has worked on underwater navigation of the HUGIN autonomous underwater vehicle (AUV), with special focus on terrain navigation. In 2003-2004 he was a scientific assistant on AUV navigation at NATOS' Centre of Maritime Research and Experimentation in La Spezia, Italy.*

Thomas Opsahl *is a senior scientist at the Norwegian defence research establishment (FFI), where he has focused on hyperspectral image processing, image georeferencing and computer vision. He has a master's degree in mathematics and a bachelor's degree in physics from the University of Tromsø. Since 2015 he has been lecturing a course on Computer Vision at the University of Oslo.*

Kjetil Berg Ånonsen *received his PhD degree in 2010 from the Norwegian University of Science and Technology (NTNU) with a thesis on terrain based underwater navigation. He is currently a senior scientist at the Norwegian defence research establishment (FFI), specializing in navigation for autonomous systems.*

Kapteinløytnant Erik Holthe Eriksen *is a development officer at NOBLE battle lab where they conduct concept development and experimentation for the armed forces. Currently he focuses on soldier systems and communication solutions. Apart from Norwegian military academy he holds a master´s degree in technology management from NTNU and was a visiting fellow at Massachusetts institute of technology (MIT).*