Micro indoor-drones (MINs) for localization of first responders *

Claudio Paliotta†
SINTEF Digital, Trondheim, Norway‡
claudio.paliotta@sintef.no

Klaus Ening
SINTEF Digital, Trondheim, Norway
klaus.ening@sintef.no

Sigurd Mørkved Albrektsen
SINTEF Digital, Trondheim, Norway
sigurd.albrektsen@sintef.no

ABSTRACT

In this paper, we describe our approach to the localization in GNSS-denied and risky unknown environments of first responders (FRs). The INGENIOUS project is an EU funded project which is developing a new integrated toolkit to support the operations of FRs. The micro indoor-drones (MINs) developed within the INGENIOUS project represent a component of the toolkit which will support the localization of FRs in search-and-rescue (SAR) operations. In this paper, the concept behind the MINs and the current achievements are illustrated.

Keywords

Micro indoor-drones, Indoor localization, swarm.

INTRODUCTION

Natural and man-made disasters are events that unfortunately hit society causing thousands of deaths every year. In 2019 it is estimated that more than 10000 people have lost their lives in natural disasters like earthquake and floods *Our world in data* 2021.The first responders (FR) have crucial roles to save lives in this dangerous situations while putting at risk their own lives. It is then clear that it is important to develop technologies that can allow for faster, more efficient, safer, and possibly cheaper search-and-rescue (SAR) operations. Robotics technologies can play a fundamental role in this regard. In particular, the introduction of autonomous aerial or ground vehicles gives the possibility to amplify the capacities of teams of FRs by carrying heavy but important sensors and tools that could enhance the perception and action capacities of FRs, e.g., high resolution or thermal cameras may aid visual capacities of human rescuers invaluably helping the identification of victims in dangerous areas.

The robotics community all over the world has been focusing on the development of solutions for SAR applications for many years now. The EU in particular has funded several research projects to develop robotic solutions to address SAR problems, e.g., the CADDY project (2014–2016) Mišković et al. 2015, the INACHUS project (2015–2018) Athanasiou et al. 2015, the Centauro project (2015–2018) Schwarz et al. 2016 just to name a few.

The INGENIOUS project is also funded by the European Commission (grant agreement No 833435) and it is focusing on the development of an innovative toolkit for FR. The toolkit will be based on several components which will enhance the perception capabilities of the FR acting on the field and of those participating from the operation centers. A glance of the toolkit is given in Figure 1.

The INGENIOUS toolkit is made up of several components, e.g., smart uniforms, smart boots, different aerial drones. All the components are meant to be integrated in order to deliver enhanced information to the end users

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†corresponding author

‡https://www.sintef.no/en/

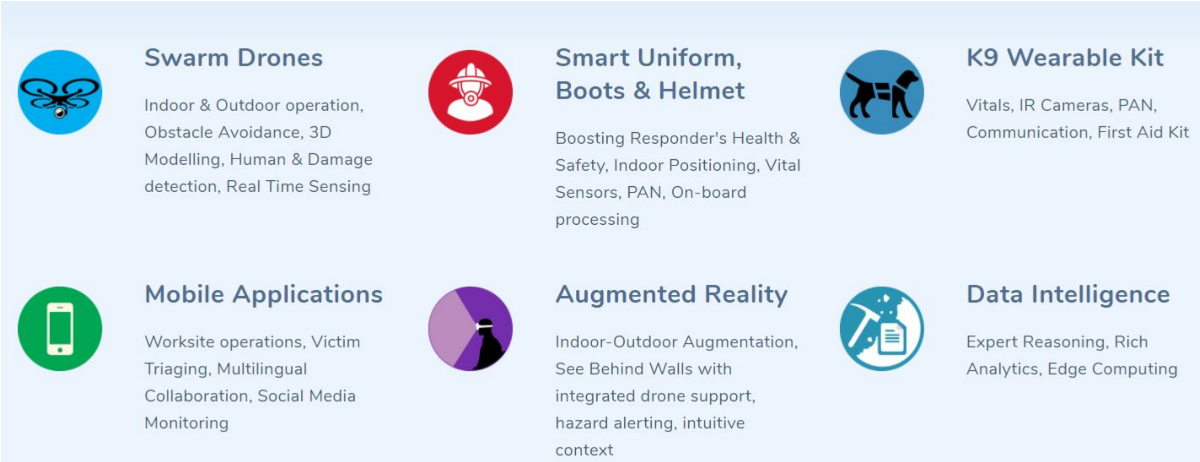

Figure 1. The INGENIOUS toolkit at a glance, from *INGENIOUS web page* 2021.

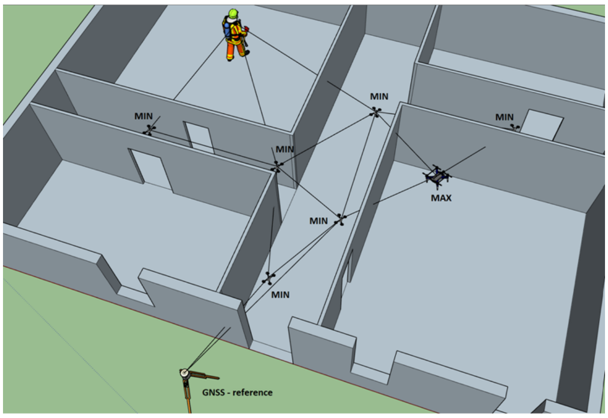

Figure 2. Mesh network built by the MINs.

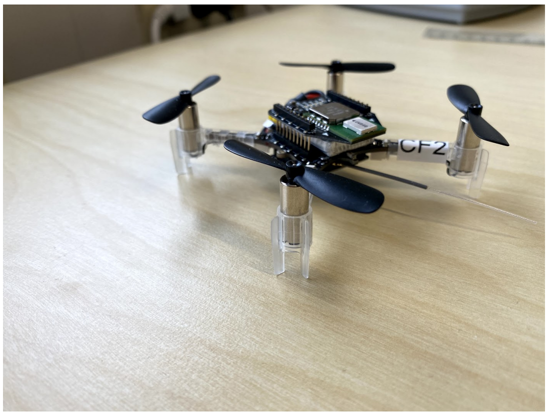

Figure 3. The Crazyflie 2.1.

working on the field. This paper will mainly focus on the development of one component of the toolkit, the micro indoor-drones (MINs). The MINs are one of the different autonomous aerial vehicles that are being developed in INGENIOUS. The main goal of the MINs is to support the localization of FR moving in indoor dangerous and GNSS-denied environments. The idea is to use the MINs to build an indoor mesh-network such that they could be used as beacons to obtain the position of FR carrying a specific device (tag), see Figure 2. Finally, it must be remarked that the function of the MINs within the INGENIOUS toolkit is tightly connected to the integration of the MINs with the other components which, due to space constraints, will not be discussed in this paper.

The literature is rich of results about the use of unmanned aerial vehicles (UAV) for SAR operations, concerning mainly the use of drones for the localization of victims by the use of cameras and on the development of novel algorithms to optimize SAR operations by using one or multiple UAVs Alotaibi et al. 2019; Erdos et al. 2013; Hatazaki et al. 2007; Kulkarni et al. 2020; Jiang et al. 2018. Since SAR applications are very diverse and also the UAVs category encompasses very different kind of vehicles (e.g., quadrotors, fixed wings), the robotics community has focused on different problems to be addressed by different kind of UAVs. For instance, Erdos et al. 2013 focused on the development of outdoor UAV starting from off-the-shelf products. They realised a low-cost UAV by using standard hobby remote-control air-frame that is modified for autonomous flight, GPS-based navigation, ground image acquisition and moreover, the system integrates several off-the-shelf systems to provide search and rescue capabilities. The work in Rivera et al. 2016 deals with the implementation of a human detection and geolocation system using aerial drones for outdoor scenarios. In particular, the authors present a system based on the use a dual-camera system where a termal camera aids localisation of vicitims outdoor in night time scenarios, while a more traditional optical camera is instead used for day time scenarios. Indoor applications present also a challenge connected to the lack of GNSS signals to aid the vehicle localization. To overcome this problem simultaneous localization and mapping (SLAM) algorithms have been developed and used for autonomous navigation in GNSS-denied environments, see for instance Cui et al. 2015; Chen et al. 2017; Aznar et al. 2018. The work in Cui et al. 2015 presents a solution for search and rescues operations for image collection of the outdoor environment and indoor mapping by SLAM algorithms. The contribution of their paper lies in the implementation and testing of robust image stitching algorithms for reconstruction of the outdoor scenario. At the same time, they present also an interesting implementation of a SLAM algorithms that accommodates the limited computational resources of their UAV. Also the work presented in Chen et al. 2017 presents a work based on SLAM algorithms to support SAR operations. In particular, Chen et al. 2017 presents a SLAM approach for a ground vehicle using a monocular camera. As a result, they can generate a map which is good enough to support the remote control of the vehicle and give information about the environment to the rescuer operating outdoor. Although a lot of work has been done in the field of SLAM, the implementation of SLAM algorithms requires to equip the drone with camera and/or lidar sensors, implying heavy payload for the vehicles and demanding computational resources to run which often small UAVs cannot accommodate.

Within INGENIOUS, the development of the MINs is aiming to define an innovative use of autonomous micro indoor-drones. The main difference and also innovation with respect to the results currently present in the literature is the use of micro indoor-drones to support indoor localization of FR. The MINs' purpose is finalized to overcome the lack of GNSS positioning in indoor environments by using the MINs as beacons to triangulate the position of the FR. This innovative approach brings important challenges to be overcome which will be discussed in more detail in the remainder of this paper.

THE OBJECTIVE OF THE MINS & ITS CHALLENGES

In this section the main objective of the MINs will be introduced before the challenges that micro drones have to face in connection with the specific objectives of INGENIOUS will be discussed. Finally, the discussion will lead to the introduction of the robotic platform that was chosen to be used as MIN in the INGENIOUS project.

The main objective of the MINs

The use of multiple UAV systems in indoor environments has been already proposed, for instance in Aznar et al. 2018; Queralta et al. 2020; Scherer et al. 2015; Luo et al. 2011 where a multi-robot systems are generally proposed to aid mapping, monitoring, surveillance, and situational assessment operations. In fact, aerial systems represent an important resource in SAR operations where disasters have affected large areas, involved many people and the terrain presents locomotion challenges (e.g., floods, semi-collapsed buildings, earthquakes). Clearly, the specific objectives to address during the development phase of unmanned aerial systems for SAR operations depend on the context. In particular, the main objective that has been identified and assigned to the developed of the MINs is the following:

Objective. *The MINs have to aid the indoor localization of FR operating in semi-collapsed and dangerous, GNSS-denied building and have to self-deploy by navigating* autonomously *in the environment.*

The main objective of the MINs is to create an indoor ultra-wide band (UWB) station network to aid indoor localization of a FR. UWB is a radio frequency technology which in the last years has emerged as a reliable and accurate technology for localization systems. In particular, each MIN will behave as a beacon and each FR will wear a receiver device, a tag, that will be able to triangulate its moving position based on the MINs' location and signals. More information about UWB systems for drone applications can be found here Shule et al. 2020.

A possible scenario

The support of the MINs to aid the indoor localisation of FR can be applied to several scenarios characterized by GNSS-denied environments. However, the development has focused more on the application to earthquake situations hitting large populated centers. When a high-magnitude earthquake (>7.0 Richter Scale) affects a large urban area, the collapse or semi-collapse of many inhabited buildings and the interruption of communication and electricity systems is common. In this case, victims can be located mainly in the affected buildings and the intervention by unmanned systems which could navigate through dangerous and narrow spaces may be of tremendous help. Although within the overall context of the NGIT toolkit, the MINs are conceived to support such operations by entering semi-collapsed building in creating a mesh network which can support the operations of the FRs. The MINs will not be able to operate alone, and a careful integration with the other components of the toolkit is needed to obtain relevant information which will support also the operation of the MINs, e.g., obtaining an external and an internal map of the building will help the indoor navigation task of the MINs.

The challenges of the MINs

The MINs are micro drones to operate in indoor, GNSS-denied, and dangerous environments, specifically, semi-collapsed buildings. Before we achieve Objective we need to address several challenges. The main four are listed and discussed here:

C1) **The MINs will have to move in an unknown environment:** micro drones are characterized by limited payload and therefore cannot carry advanced and precise sensors that could aid obstacle detection. In other words, the MINs will have to fly in an environment where there will be obstacles due to the nature of the mission (i.e., semi-collapsed buildings) but at the same time the perception capabilities of the micro drones are limited due to physical size of the vehicles.

C2) **The MINs will have to move in a GNSS-denied environment:** the MINs will have to build a mesh network to support the localization and tracking of FR moving within the semi-collapsed building. Therefore, the MINs will have to work in substitution of a GNSS system. However, in order to do this, the MINs will have to communicate their final position within the building with good accuracy in order to being able to use them as reference points (i.e., beacons) for the localization of the FR.

C3) **The MINs will have to move autonomously within the building:** the MINs will have to be able to self-navigate and move within the environment in order to support the work of FR. The situation in which an FR or any other external person manually operates the MINs would be time consuming while time is a precious resource in SAR operations. Therefore, the MINs will have to be able to operate with very limited support of an external operator.

C4) **The MINs will have to guarantee a good coverage of the whole building where they operate:** the MINs will spread all over the area within a semi-collapsed building. Each MIN will be equipped with UWB modules and other radio that could allow the MINs to communicate with each other and with a base station outside the building. Since the communication range of the radios that allow the MINs to communicate with each other and with the external station is limited, the MINs will have to hop messages to guarantee that also the information from the furthest MIN can be relayed to the outdoor station. This aspect clearly poses a constraint on the final disposition of the MINs and must be taken into account during the design of the exploration strategy.

The Crazyflie 2.1

An important aspect is the choice of the robotic platform to be used for the MINs. The four challenges introduced in the previous subsection give a first general idea of what is needed from the MINs in terms of sensor capacities. That is, a MIN shall be able to carry:

- a UWB sensor
- a module to allow for radio communication with other MINs in a given range
- a sensor capable to detect the presence of obstacles in its way

Furthermore, the INGENIOUS consortium includes several end users that have been precious for the definition of technical and non-technical requirements that have been driving and supporting the technical development of the various components of the NGIT toolbox. In the specific case of the MINs, the discussions with the end users have resulted in a number of requirements that due to space limitation constraints will not be reported in this paper. However, can be summarised as follow:

- The MINs shall aid the indoor localisation of FR and victims while not representing an obstacle for the movement of the FR.
- The precision of the localisation system made by the MINs shall reach an accuracy that indicates the area of the building where a FR is moving.

The technical constraints and the technical requirements discussed with the end users have been driving the development of the MINs. After a careful investigation, SINTEF decided to use the Crazyflie 2.1 as platform for the MINs. The Crazyflie 2.1 (Figure 3) is an off-the-shelf (OTS) micro indoor-drone commercialized by Bitcraze, *Bitcraze webpage* 2021. The Crazyflie 2.1 is open source guaranteeing complete flexibility concerning SW and

Drone	Weight	Payload	Battery time	Build-in sensors	Price
CRAZYFLIE 2.1 	27 g	15 g	7 min	3-axis gyrosope and 3-axis accelerometer (BMI088), high precision pressure sensor (BMP388).	195 $

Table 1: Crazyflie 2.1 specs

HW development. Moreover, Bitcraze commercializes a series of sensor modules among which some of them are particularly interesting for the MINs applications. Table 1 sums up the specifications and performance of the Crazyflie 2.1.

In particular, the relevant sensor modules for the MINs are:

- **Multi-ranger deck:** it is made of five laser sensors to measure the distance in five orthogonal directions. Measurement range is up to four meters.
- **Flow deck v2:** it includes the PMW3901 optical sensor that allows the Crazyflie to measure its movement with respect to the ground and a laser sensor to accurately measure distance from the floor. In addition, it has also the VL53L1x ToF sensor to measure distance with respect to the floor. The VL53L1x sensor is a laser sensor with 4 m range with a precision of a few millimeters depending on light conditions.
- **Loco Positioning deck:** it is a UWB module based on the Decawave DWM1000 module and provides range measurements to other UWB modules which can be mounted on the other drones and/or carried by the FR. This module is expected to offer an accuracy of 10 cm.

Finally, the Crazyflies are able to communicate among each other in a *peer-to-peer* fashion thanks to an integrated nRF51822 module from Nordic Semiconductor.

THE FIRST RESULTS

The main strategy that it has been elaborated by SINTEF is based on a progressive autonomous self-deployment of the MINs. In other words, the deployment strategy of the MINs can be summed up as follows:

1. The first MIN will fly towards the entrance of the building and move inside the building as long as it does not lose connection with a base station
2. The successive MINs will fly towards the entrance and use the already deployed MINs to support their own localization within the building
3. Each MIN shall not fly too far from the others in order to guarantee connectivity of the mesh network
4. Each MIN shall be within communication range of a given number of other MINs to guarantee a minimum degree of connectivity of the mesh network
5. When all the area is covered, the MINs will stop entering the building

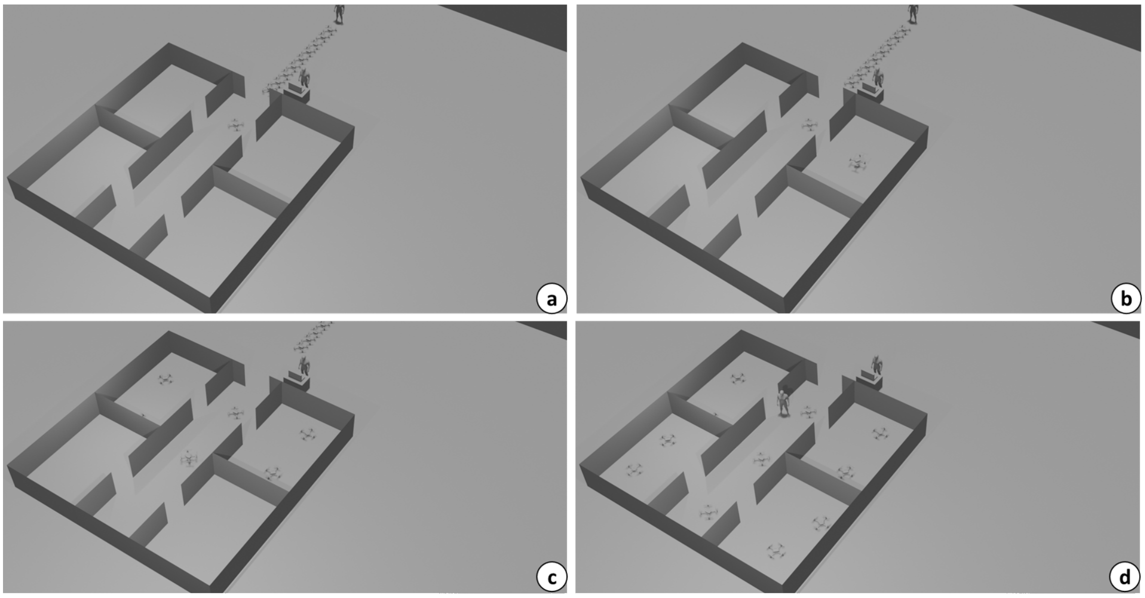

Figure 4. Visual illustration of MINs autonomous self-deployment.

Figure 4 gives a visual illustration of the deployment phase of the MINs. It is important to remark that the requirement of a minimum connectivity degree of the mesh network is fundamental for two main reasons:

1. **Triangulation:** as mentioned previously, once all the MINs have landed and have formed a mesh network, they will work as beacons, that is, reference points emitting UWB signals to estimate the position of the FR that will be carrying a tag, i.e., a UWB receiver. In order for this approach to work, the tag will have to receive UWB signal from at least three MINs at all time to allow for triangulation algorithms to work.
2. **Robustness:** an high connectivity degree allows to have redundancy to stream information through the network. That is, consider the situation in which two MINs that stand too far apart from each other to have direct communication and they need to exchange a message. If they had only one other MIN between them bridging the communication, the solution would not be robust since if the MIN bridging the communication would stop working, then the other two would not be able to communicate, risking also to cut off a part of the network. A high degree of connectivity then implies also a certain degree of fault tolerance. This same reasoning applies for the communication between the base station and the MINs, i.e., there will be more than a MIN next to the base station and within its communication range to guarantee some tolerance to faultiness of the MINs in the network.

Finally, this overall strategy has to imply a certain degree of autonomy, scalability and robustness to be meaningful. Scalability is particularly connectet to the communication range of the MINs. That is, a larger communication range for the MINs allows less MINs to cover the same area while being in communication with a given number of other MINs. In other words, if we define as *neighbour* of a MIN another MIN which is within its communication range, a larger communication range implies that the same amount of MINs could stant further away from each other while still being neighbours. It is then clear how a first indication of the scalability of our solution would depend on a clear estimation of the communication range of our MINs. However, during our tests we have not been able to estimate this communication range properly since the communication capabilities are highly affected by uncontrollable factorse, e.g., external noise from other communication systems as for instance Wi-Fi network. A preliminary estimate tells us that four MINs would be able to cover (in terms of communication) an area of $9x9m^2$ which gives an idea of what could be the possible covered area given a number of MINs. However, further field tests are needed to better investigate the scalability aspect.

The overall strategy presented above can be broken down in sub-objectives, a few of these are:

SO1. Definition of a communication protocol for the MINs

SO2. Definition of localization strategies using the MINs as beacons

SO3. Definition of swarm strategies for the autonomous self-deployment of the MINs

In the remainder of this paper the sub-objectives SO1., SO2. and SO3. will be discussed.

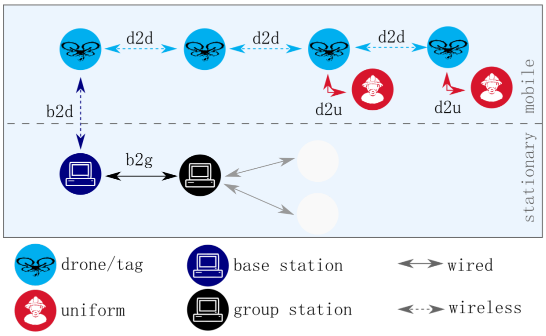

Figure 5. Communication channels for the MINs.

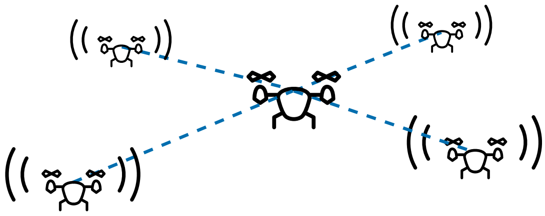

Figure 6. UWB with drones as beacons.

The communication protocols

To achieve a good distribution within the unknown environment, to be able to provide localization for the FRs and to externally provide information about the state of the system, several communication channels, as illustrated in Figure 5, are necessary. Technically the uniforms will be equipped with a localization tag instead of a drone, but as the hardware related to communication and localization of these tags is essentially the same as for the drones, it is not distinguished further. The communication between drones *(d2d)* and the base-station *(b2d)* is based on hardware (Nordic Semiconductor's nRF51822 and nRF24LU1 radios respectively) already implemented by Bitcraze.

While the provided Crazyflie firmware allows for broadcasts to all drones in reach, the far spreading of the drones makes it necessary to relay data to members of the swarm that are further away. Therefore, a general layer has been implemented on top of the provided broadcasting function that takes care of relaying data to all members. It internally keeps track of drones in direct reach, their reception of messages and the repetition of these, in cases where neighbors did not acknowledge them. This relaying layer is planned to be made available soon. Again, on top of this, an application specific layer has been implemented that allows addressing of individual drones and the definition of command- and data-messages that are needed to support the exploration, localization, and other specific tasks.

To be able to not only communicate within the swarm but also with a base-station *(b2d)* Bitcraze's crtp python-drone-communication has been extended to allow the forwarding of (for now) short versions of the application specific messages in both directions. While the goal of the drones is to explore and build the localization network autonomously, this enables a centralized overview of the swarm and allows for control or updates when needed. Any drone in reach to the base can be the access point to the swarm in this case.

For the base-station to group-station *(b2g)* a simple sockets-based communication protocol has been agreed on within the working group to exchange and fuse data and provide them to external participants. The drone to uniform *(d2u)* channel will be implemented using wired UART and is mainly used to communicate the position within the site to the uniform, from where it is to be provided to the FR.

The drones used as beacons

Although the UWB radio system can be used for communication, its primary use in this project is localization. By doing a two-way-ranging (TWR) we can estimate the time it takes for the wireless signal to travel from one drone to another, or from a drone to a tag carried by the first responder. By subtracting the processing times of the radio's transmitter and receiver we can calculate an estimate of the distance between the two radios, by dividing the calculated time with the speed of the radio signal, which is approximated to the speed of light in vacuum. Then, the drone's position can be calculated using triangulation. To calculate a position in 3D based on these measurements, at least 3 beacons in different planes must be visible, but more beacons can be used to increase the accuracy.

Unfortunately, these beacons can obviously not be placed in a disaster scenario before a first responder enters. Luckily, the radio onboard the drones can be used as a beacon as well as the normal operation as a drone. Thus, we can fly one drone into the building, land it, and then make it switch mode to become a beacon for the following drones as they explore the area.

As the first drone to enter a room does not have any other beacons to aid its navigation, the estimated position will be inaccurate. As more drones enter the building, more information is available, not only for that drone that is currently flying, but also about the previous drones that the current one sees. Thus, the estimate of the first drone can be improved and the entire navigation system is improved. To keep track of the drones' positions we can create a graph or matrix with estimated positions, estimated accuracy of the positions and how the estimated position affects the positions of the following drones. Then we can update this matrix as more drones enter the area, creating a globally optimal solution for all the drones' position estimates and feed the landed drones with the updated position estimates. This is illustrated in Figure 6.

By having this loop of updating the position estimates as more drones complete their exploration, we believe that we can create a network of drones that provide sufficiently accurate position estimates to provide valuable aid for a first responder in a risky environment.

Self-deployment strategy considerations

Although we are just starting development of the self-deployment strategy, it will in broad terms aim to make each drone try to fulfil three main goals: ensuring connectivity with the previously deployed drones, choosing its final placement be such that it can aid following drones with UWB-ranges for navigation, and extending the currently covered area. The first goal is required for the MINs to communicate their findings back to the base, and to receive updates, such as its globally calculated estimated position, from the base. Thus, the signal strength of the communication link and the number of visible drones are likely candidates to be parameters in the deployment strategy. The second goal is needed to improve the accuracy of the position estimates of both the following MINs, and finally the first responder. The third goal is required to urge the drones to cover as much of the SAR operation as possible. If this is not implemented a valid strategy would be to deploy all the MINs in a small area of the mission, which of course, is undesired.

Sub-goals can also be included in the strategy. An example is maximizing the estimated remaining battery of the MIN. As the MINs need to function as a beacon after they have landed, the remaining battery impact their maximum operational time. In addition, we can add other sub-goals, such as avoiding landing in areas where an FR is likely to step, avoiding areas that might be hazardous or places with uneven landing areas, or attempting to land in different elevations to provide better vertical accuracy for the localization algorithm.

As the processing power onboard the MINs is limited, the selected strategy must be straightforward to follow. Although there is room for some processing, large global optimizations must be avoided, as these are too costly to be performed onboard. As there is a communication network available from the drone and outside of the mission area, a possibility would be to have a more powerful processing unit that could create a strategy, but this increases the infrastructural complexity and centralizes the decisions made by the swarm, which is undesirable.

CONCLUSIONS & FUTURE WORK

In this WiP paper we have given a brief overview of the work that SINTEF has done in relation to the development of the MIN, micro indoor-drones to aid the localization of FR in GNSS-denied buildings in SAR operations. The preliminary results have been shown and discussed. Current and future work is focusing on the development and implementation of swarm algorithms to allow for the self-deployment of the MINs.

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