The Eins3D project – Instantaneous UAV-Based 3D Mapping for Search and Rescue Applications

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Abstract— **The overview of a situation in a search and rescue disaster is the key aspect of an effective assistance. In the recent years the utilization of multicopter with various photogrammetry systems is an upcoming trend and an open field of research. This paper discusses the technical aspects of an automated integral system that will support rescuers during the strategic mission planning and will give situational awareness by instantaneous 3D mapping. The approach combines sensors including a 3D Laserscanner, a thermal camera and an attitude system as a payload unit on an Multicopter. The continuous data fusion and the down link are providing an instant 3D environment map that is continuously revised and updated.**

I. Introduction

The classification of a situation in Urban Search and Rescue (USaR) missions is often a challenging task due its complexity. The general view of a scenario is the key aspect in strategic mission planning. It is necessary to priories urgencies in a situation of danger. Staying on top of things in a constantly changing situation requires also regular scenario monitoring. Nowadays the assessment of disaster situations is done by visual inspection through rescuers, a dangerous and time costly strategy. This process is aided with surveying by aerial photo- and thermography taken from a helicopter. The search and rescue of victims is often a trade off between the urgency and the danger for rescuers. New technologies in this field should reduce risks and facilitate missions.

Recently unmanned aerial vehicles (UAV) with optical and thermal cameras are introduced for this purpose. Such systems are more flexible and provide a higher level of availability. However, the data acquisition during a manual flight is a complex task and the evaluation, especially of video footage, is quite time demanding. Optical inspections done by such an UAV does not provide spatial information of the environment.

The project Eins3D (*Luftbasierte Einsatzumgebungsaufklärung in 3D*) is aimed at the development of a single drone 3D mapping solution. The intended automated approach expedites the operation, the data acquisition and the evaluation process of USaR missions. During an autonomous flight the operational area is scanned by the optical and laser sensors of the payload. The acquired sensor data is fused to a 3D map in an instant fashion. Real-time mapping enables regular situation update of 3D maps. This is beneficial especially in USarR applications for example to improve strategic planning for coordination, enhance situation awareness for firefighters and rescue workers and to support structural inspections.

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II. Related Work

Recently the use of UAVs in disaster response is an active field of research. Scherer et al. propose a modular multirobot system supporting a heterogeneous set of UAVs and camera sensors [1]. As a search and rescue application they demonstrate the detection of victims. In [2] a small fully autonomous UAV is presented also used for victim detection. However both approaches do not focus on mapping.

UAV based approaches to 3D mapping often rely on structure from motion techniques. They usually do not provide 3D maps immediately, as dense mapping has high computational requirements [3]. This time consuming step often takes several hours to complete. Photogrammetric approaches are therefore mostly applied to large scale scenarios, e.g. earthquakes [4]. In the TRADR (Long-Term Human-Robot Teaming for Disaster Response) project 3D point clouds are generated from camera images and combined with 3D point clouds from laser scanners carried by ground robots [5].

Within the project Mapping on Demand [6] a 3D laser scanner is used to build a local map of the environment for navigation tasks. However the actual mapping is then achieved by structure from motion.

In contrast to those approaches the solution developed in Eins3D focuses on a single UAV system, applicable for small to medium size sorties. By relying on a Light Detection and Range (LiDAR) sensor the environment is instantaneously available.

III. System Overview

The system, presented in this paper, is functionally classified in ground segment, aerial segment and payload. A sketch of the elements and the interactions are shown in figure 2. The ground segment is a mobile control station implemented in a fire fighter command vehicle as shown in figure 3. It communicates with the aerial segment via a custom build radio interface. The aerial segment is a medium-sized multicopter. With the frame arms of the copter fold up, it is loaded in the fire fighter command vehicle.

Figure 1 shows a picture of the payload, the major element of our system. This sensor unit is an integral system specifically developed for the environment mapping application

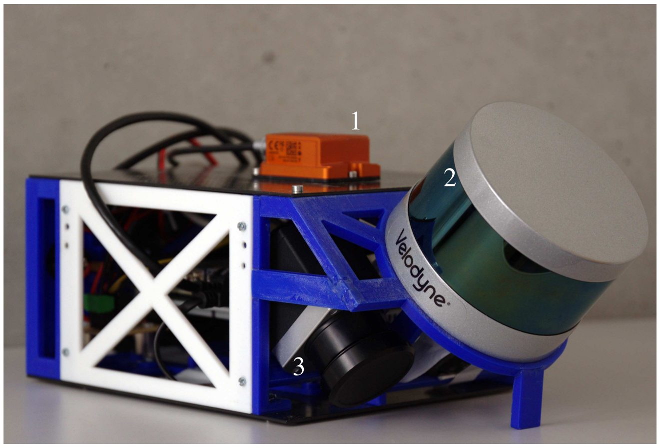

Fig. 1: The sensor unit featuring a Xsens Mti-G 700 (1) IMU, a Velodyne VLP16 Lite (2) laser scanner and an Optris PI 640 LW (3) thermal camera.

and for search-and-rescue missions. Its main sensors are a 3D LiDAR, a thermal camera and an attitude sensor. Additionally a RGB camera is mounted. Sensor data logging and flight control is done by a single-board computer running Robot Operating System (ROS). The final sensor unit will be equipped with a wireless radio control and communication unit capable of streaming sensor data to the ground station. The following section gives an overview of the system and discusses the key features of the components and the sensors.

A. Ground segment

The main part of the ground segment is a system control station. It is used for mission planning, flight monitoring and data evaluation. The concept of a German standard fire fighter command vehicle (ELW 1 – DIN14507-2) is refined, for the upcoming utilization of UAVs in search and rescue missions. The ground segment is implemented in this vehicle. There are two work areas with a standard desktop computer, a network connected to the Internet and a radio control system.

B. Radio system

A pilot is compulsory due to aviation restrictions during scan-flights. Task of the pilot is to monitor an ongoing mission and to take over control in case of an unexpected situation. Therefore two independent radio systems are implemented.

Firstly a master system, commonly used in the radio control (rc) community, enables the pilot to take over control, to interrupt an ongoing mission and to continue in a manual flight mode.

Secondly a high bandwidth, low energy radio system is under development specifically for the project purpose. The up-link embrace control and mission commands, the down-link UAV house keeping information and sensor data. The required throughput of the down-link is several orders of magnitudes greater than the up-link. The reason is the high data rate of the sensors used for mapping. First range experiments of the transceiver system showed a throughput rate of 326.5 Mbits at a distance of 300 m.

C. Aerial segment

The aerial segment is a medium size off-the-shelf professional grade multicopter, namely a DJI S1000+. It features a octorotor configuration, a frame weight of 4.4 kg and a maximum takeoff weight of 11 kg. The UAV provides a sufficient lifting capability for the sensor unit. This unit is fitted at the gimbal mount of the UAV. A picture of the configuration is presented in figure 4. The entire system has a takeoff weight of 9.5 kg is powered by a 6 S battery with 18 Ah. Under optimal conditions it is capable of a maximum flight time of 15 min.

The UAV is controlled by the A3 Pro of DJI, a flight control unit (FCU) for multirotor aerial platforms. This control system fuses three sets of redundant sensors, each of them including an IMU, a barometer and a GPS sensor. Therefore it gains failure safety and a higher accuracy through internal sensor fusion. The FCU is linked via a serial connection and an API interface to an onboard computer. The API is a communication wrapper providing attitude and status information and a UAV flight control interface. The master radio controller, discussed previously, is directly connected via S.Bus.

D. Sensors

The core part of the system presented is the sensor unit, as depicted in figure 1. The main sensor of our mapping system is a Velodyne Puck VLP16 Lite laser scanner. With its low weight of 830 g and typical power consumption of 8 W, the sensor is appropriate for aerial mapping. It provides full 360° scans at a frequency of 10 Hz with a maximum range of 100 m. The vertical FoV of 30° is sparsely covered by 16 line laser scans with an angular resolution of 2° vertically and 0.2° horizontally.

As a second sensor the system features a Optris PI 640LW thermal camera to enrich the map with registered temperature information. In order to maximize the overlap with the laser scanner a wide angle lens with a FoV of 90° x 64° is used. Thermal images are captured at VGA resolution with a frequency of 10 Hz. Additional sensors are mountable on the system. Temporarly a Logitech Brio rgb camera is tested to enrich the optical spectrum. The rolling shutter of the system and the high frequency vibrations of the UAV resulted an a non-satisfying video output.

For pose estimation we primarily we rely on the attitude sensors of the FCU. However we mounted an additional Xsens Mti-G 700 to enable the usage of the sensor unit independent of the UAV. This sensor fuses IMU and GPS data to increase the longterm stability of the orientation measurements and provides position data with 400 Hz.

An important design decision is the disposal and orientation of the mounted sensors. Considering the narrow vertical FoV of the Velodyne laser scanner, it needs to be inclined to enable measurements on the ground. Depending on the flight altitude, the effectively horizontal FoV is reduced to

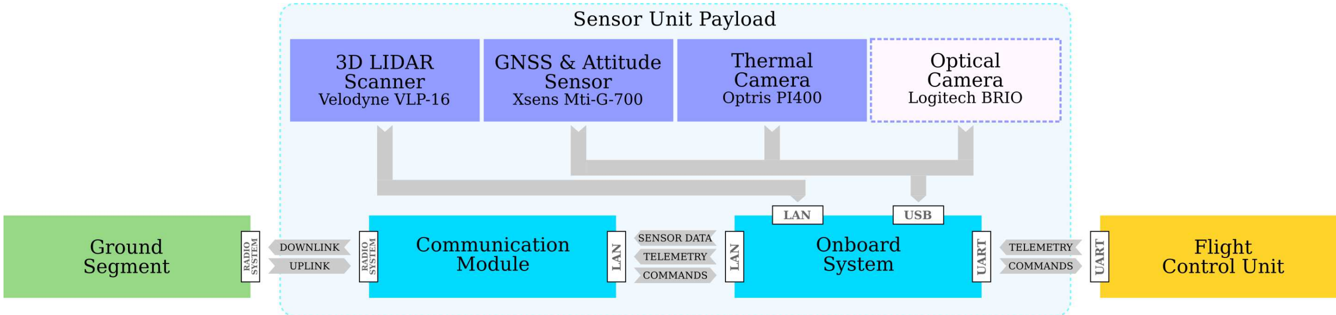

Fig. 2: Sketch showing the classification of the Eins3D system configuration.

Fig. 3: Fire fighter command vehicle and ground segment equipped for this project (courtesy Hensel, Waldbrunn, Germany)

Fig. 4: Multicopter equipped with the sensor payload at the landing field during a test mission.

less than 180° though. As Zhang and Singh [7] pointed out, the registration of laser scans without additional attitude information tends to fail in tilted configurations due to cumulative drift.

As a trade off we tilted the laser scanner by 45° along the pitch axis. The thermal camera is oriented in flight direction such that the overlay with the laser scanner is maximised. This configuration enables the mapping of restricted areas, no-fly zones likes houses on fire, without the necessity of an overflight. However the resulting FoV of all sensors needs to be taken into account during flight planning and pattern generation to gain maximum area coverage.

Besides the mapping sensors, the sensor unit features a single-board computer running ROS for data logging and a radio module for communication and data transmission. The hardware selection and the structural design is based on the demand of a maximum weight of 2.5 kg.

IV. Instantaneous Mapping

A. Initial Pose Estimation

As mentioned above we use the navigation data of the FCU to unwind the data from the laser scanner to build an initial map.

When running independently of the UAV the Xsens Mti-G 700 provides the pose estimate. Although this sensor internally runs an EKF filter, it turned out that the filtered position information is not continuous. To deal with this problem we run an additional EKF to fuse velocity and position, to get a smooth trajectory.

A second issue is the timing between the IMU and the laser scanner. As either the Xsens and the FCU are connected via USB they suffer from delays. We applied the method of [8]. Assuming an online data stream we only used forward synchronization.

B. Point Cloud Optimization

As the VLP16 deliverers sparse point clouds in the vertical direction, registration with the common iterative closest point (ICP) approaches on two consecutive scans will fail. [9] address this problem of sparseness by detecting features like edge points and planar patches that are present in multiple scan lines. Another approach is to make assumptions about the underlying surface. [10] therefore create a simple quad mesh in order to estimate the point normals.

The registration approach used in this setup is based on the work in [11], [12]. Using the initial trajectory we group several consecutive sparse scans to a dense submap, a so-called meta-scan. The submaps are registered rigidly with ICP. Afterwards the transformation is locally distributed to all individual scans of that submap. Although not constrained, a linear distribution of the translation and SLERP interpolation shows to be sufficient for small errors. This resembles a semi-rigid ICP algorithm, which can also be called continuous-time ICP [13]. Additionally we implemented a loop closure detection based on the same linear distribution of the errors.

A key issue in scan registration is the search for closest point pairs. The search trees in 3DTK [14] are optimized for small memory footprint and fast search operations. Due to its compact representation in memory they do not allow for dynamic extension. Thus, in sequential registration the entire map needs to be rebuilt for each inserted submap. The registration process is speed up by maintaining and querying several search trees of already merged submaps in parallel, thus reducing the frequency of map rebuilding. To further speed up the process we use a keyframe approach based on the distance moved since the last keyframe. Especially when flying at low speed, the registration of all acquired laser scans does add only little information to the map anyways.

After the optimization the improved trajectory is used to geolocate the final point cloud. The optimized trajectory is rigidly aligned the original GNSS measurements, considering correspondences from time stamps.

C. Thermal Mapping

As mentioned before, thermal information is used by firefighters to detect either temperature hot spots that may indicate hidden fires or to detect humans and animals in search and rescue scenarios.

1) Calibration: For projection of thermal data to the point cloud a precise transformation between camera and laser scanner needs to be known. Previously Borrmann et al. [15] proposed a method to estimate the extrinsic calibration between a thermal camera and a surveyor grade 3D laser scanner. A board with clearly defined heat sources, e.g. small lightbulbs, that are positioned in a grid, similar to corners of a chessboard is used as calibration target. After applying upper and lower thresholds the pattern is extracted from the thermal images. The board is then detected in the laser scans by finding the most prominent plane with RANSAC and registration of a point cloud representation of the board. The extrinsic calibration is then estimated from N images and scans of the calibration pattern with M point correspondences by minimizing the reprojection error

$$\sum_{i}^{N}\sum_{j}^{M}\left\| \mathbf{p}_{i,j} - \mathrm{proj}(\mathbf{K}, \mathbf{D}, \mathbf{R}_L^C, \mathbf{t}_L^C, \mathbf{P_{i,j}}) \right\|^2 \tag{1}$$

where proj is the projection of the point P from the laser scanner coordinate system L on the image plane with intrinsic matrix $\mathbf{K}$, distortion parameters $\mathbf{D}$ and the estimated rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$ from L into the camera coordinate system C. This approach works well for dense point clouds. However in case of sparse point clouds e.g. from a Velodyne VLP16 as used in our setup, a rectangular flat board is problematic since the pose of the board cannot be determined unambiguously due to the coarse resolution in vertical direction. Therefore we mounted the lightbulb pattern on a cuboid structure which enables distinct pose estimation.

Timing is crucial in a mobile mapping context. We extended the approach to enable the estimation of the sensor clock offset. In contrast to [15] we collect data while moving the sensor unit in front of the target during data acquisition. We then compute the trajectory of the laser scanner by sequential registration where the origin of the calibration target defines the global coordinate system. For a thermal image with successfully detected pattern we compute the interpolated corresponding scanner pose from the previously computed trajectory and establish the correspondences. The extrinsic calibration is then computed by minimizing Eq. 1. The calibration of the clock offset is done by rerunning the calibration with binary search in a predefined interval of clock offsets.

2) Data Projection: During flight data is acquired for all sensors simultaneously. The determined extrinsic calibration is used to directly assign temperature values to points. Suppose a scan was acquired at time i and the image to be projected on the point cloud at time j. Using forward projection proj from Eq. 1 the laser scan is first transformed from its local coordinate system L at time i to the global coordinate system W and then to the camera coordinate system C at j:

$$\mathbf{p}_{C,j} = \mathbf{T}_L^C \mathbf{T}_{W,j}^L \mathbf{T}_{L,i}^W \mathbf{p}_{L,i} \tag{2}$$
$$= \mathbf{T}_L^C \mathbf{T}_{L,i}^{L,j} \mathbf{p}_i \tag{3}$$

The temperature values are assigned by projection to the image plane, before back transforming the scan to L at i. Although not restricted to, we select the closest image in time for projection.

Considering the field of view of laser scanner and thermal camera, with this forward projection approach not all points of a laser scan are assigned with a temperature value. This produces a This issue could be resolved by backprojecting the images on the final global point cloud. However this computational more complex as raycasting is needed for each pixel of an image. We decided for the fast forward projection. We instead address this issue in a postprocessing step after the trajectory optimization. Therefore we again exploit our octree structure by assigning the median of all valid temperature measurements of a voxel to the points of that particular voxel.

V. Results

We tested our sensor unit in a flight at the robotics hall of the university of Würzburg. The UAV was flown manually in several loops alongside the building. From 137 s of flight the laser scans were extracted resulting in 285 keyframes. Figure 5 on the left visualizes the point cloud after the initial trajectory estimation. The point clouds are colored by reflectance values. The red line resembles the flown trajectory.

Visual inspection of the 3D model reveals that the most prominent errors appear in the up-axis. This is caused by the height estimation from the barometer and non ideal GNSS conditions. This is noticeable on the roof of the robotics hall (bottom left). The uncertainty in GNSS measurements also affects the heading estimation, as seen on the building in the top left corner of the figure.

After applying 4 iterations of our continuous-time ICP approach, the initial one with loop closure, the errors are

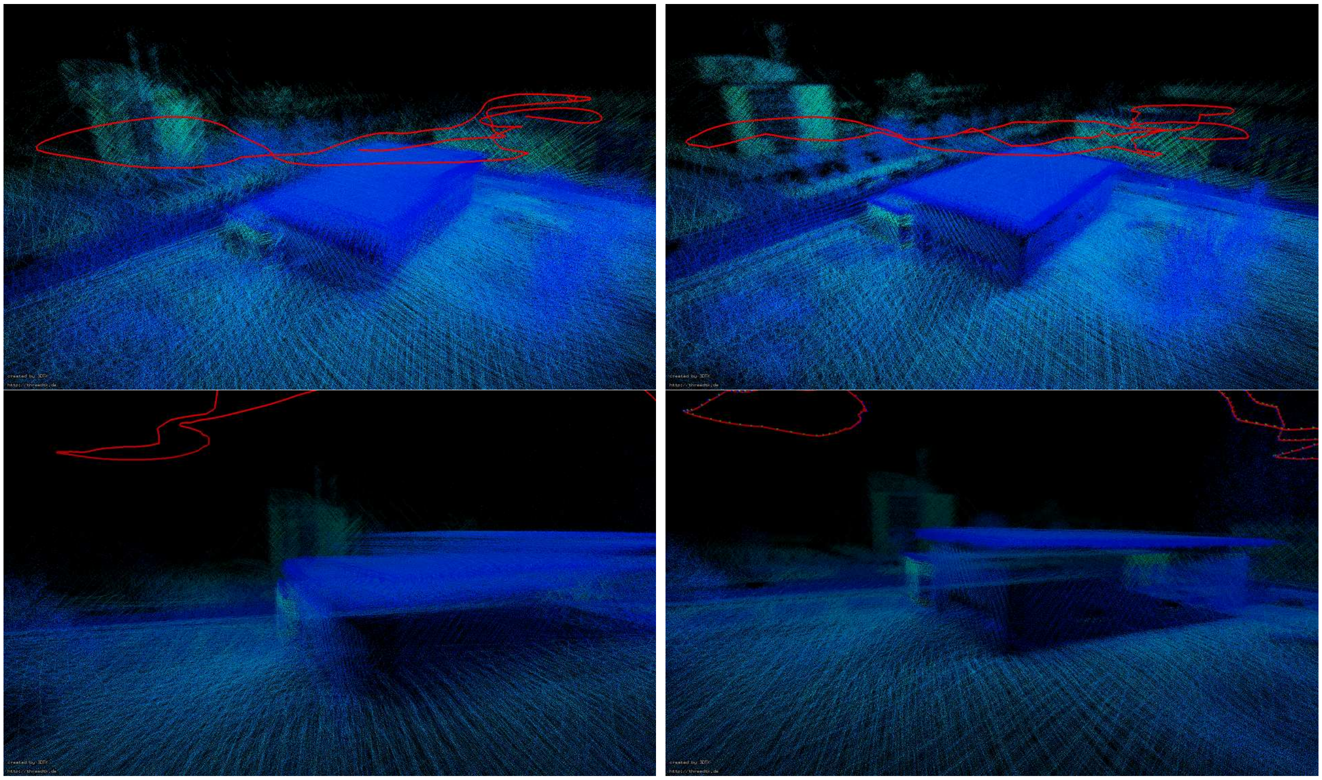

Fig. 5: Point cloud of the robotics hall from two perspectives with initial pose estimation (left) and after applying continuous-time ICP (right). The point clouds are colored by reflectance values. The red line resembles the trajectory.

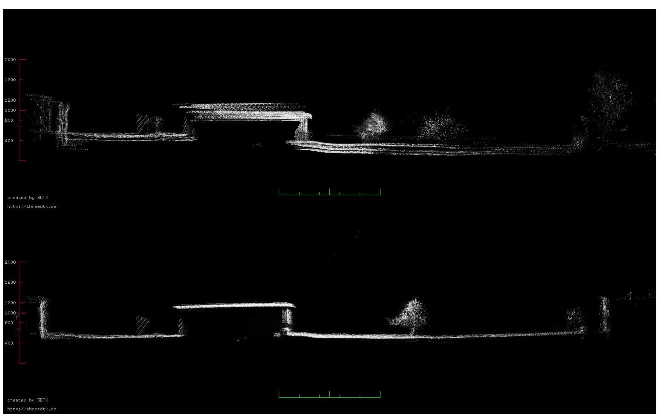

Fig. 6: Cross section of the initial (above) and the optimized point cloud (below)

reduced. The height was corrected, visible in the reduced thickness of the roof. The cross section of the point cloud shown in figure 6 also visualizes the improvements. The point cloud optimization was finished after 117 s.

In a second flight we tested the instantaneous projection of thermal data to the point cloud. Here the UAV was flown in the same manner as before alongside the so called Food Court, part of a former mall. (see figure 7 above) Due to better conditions compared to the first flight, the initial point cloud contained only little noisy, thus producing a precise optimized map. During data acquisition, the thermal images

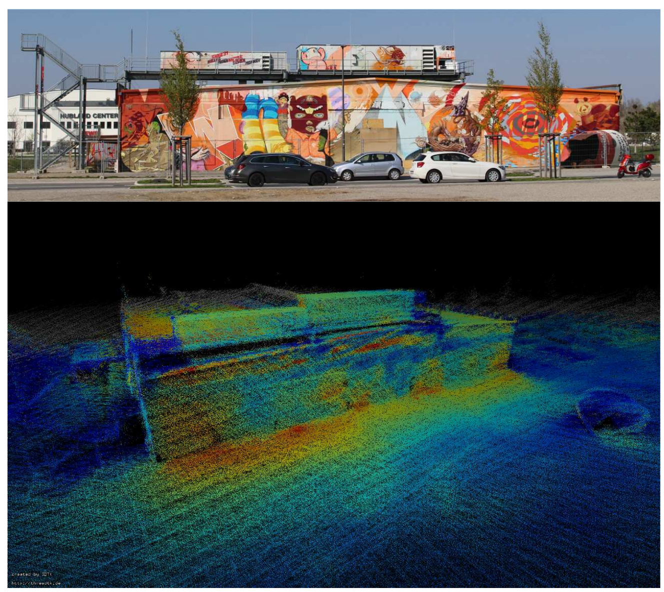

Fig. 7: The Food Court, Würzburg a former mall. The building is covered with graffiti (above), also apparent in the point cloud colored by temperature (below). Red color indicates higher temperatures, blue color lower temperatures

were projected on the laser scans as described in section IV-C. The final point cloud is shown in figure 7 below. As expected, the ground in front of the building shows higher temperature values, compared to areas far away from the building, due to reflection of sunlight.

VI. Conclusions and future work

In this paper we presented our approach of an accessible application-orientated solution of a 3D mapping tool for USaR missions. The overall system is presented and the mayor aspects are discussed. To number among the hardware of the integral system, the sensor data processing pipeline, the automated trajectory planing and flight execution. It presents the current results at an intermediate state in the life span of this research project.

Subjects of future work are the elaboration and field tests of the automated path planning.

Furthermore we plan to work on a monitoring system of the mapped environment to aid the situational awareness during a mission. This also includes the enhancement of the model with additional information from semantic analysis of point cloud and thermal data.

The presentation of the 3D map in a demand oriented way, will be part of the mission control software.

A key part of the overall system that needs to be done, is the integration and evaluation of the high bandwidth radio system, to enable instantaneous mapping while the UAV is still airborne.

Further milestones are performance test in association with firefighters under simulated operational conditions.

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References

[1] J. Scherer, S. Yahyanejad, S. Hayat, E. Yanmaz, T. Andre, A. Khan, V. Vukadinovic, C. Bettstetter, H. Hellwagner, and B. Rinner, "An autonomous multi-uav system for search and rescue," in *Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use*. ACM, 2015, pp. 33–38.

[2] T. Tomic, K. Schmid, P. Lutz, A. Domel, M. Kassecker, E. Mair, I. L. Grixa, F. Ruess, M. Suppa, and D. Burschka, "Toward a fully autonomous uav: Research platform for indoor and outdoor urban search and rescue," *IEEE robotics & automation magazine*, vol. 19, no. 3, pp. 46–56, 2012.

[3] A. Martell, H. A. Lauterbach, K. Schilling, and A. Nüchter, "Benchmarking Structure from Motion Algorithms of Urban Environments with Applications to Reconnaissance in Search and Rescue Scenarios," in *Proceedings of the 16th IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR '18)*, Philadelphia, PA, USA, August 2018, pp. 1–7.

[4] S. Verykokou, A. Doulamis, G. Athanasiou, C. Ioannidis, and A. Amditis, "Uav-based 3d modelling of disaster scenes for urban search and rescue," in *2016 IEEE International Conference on Imaging Systems and Techniques (IST)*. IEEE, 2016, pp. 106–111.

[5] A. Gawel, R. Dube, H. Surmann, J. Nieto, R. Siegwart, and C. Cadena, "3d registration of aerial and ground robots for disaster response: An evaluation of features, descriptors, and transformation estimation," in *Proceedings of the IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR '17)*, Shanghai, China, September 2017, pp. 27–34.

[6] L. Klingbeil, M. Nieuwenhuisen, J. Schneider, C. Eling, D. Droeschel, D. Holz, T. Läbe, W. Förstner, S. Behnke, and H. Kuhlmann, "Towards autonomous navigation of an uav-based mobile mapping system," in *Proc. of Int. Conf. on Machine Control & Guidance (MCG)*, 2014.

[7] J. Zhang and S. Singh, "Aerial and ground-based collaborative mapping: an experimental study," in *Field and Service Robotics*. Springer, 2018, pp. 397–412.

[8] E. Olson, "A passive solution to the sensor synchronization problem," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*. IEEE, 2010, pp. 1059–1064.

[9] J. Zhang and S. Singh, "Loam: Lidar odometry and mapping in real-time." in *Robotics: Science and Systems*, vol. 2, 2014.

[10] D. Holz and S. Behnke, "Registration of non-uniform density 3d laser scans for mapping with micro aerial vehicles," *Robotics and Autonomous Systems*, vol. 74, pp. 318–330, 2015.

[11] J. Elseberg, D. Borrmann, and A. Nüchter, "Algorithmic solutions for computing accurate maximum likelihood 3D point clouds from mobile laser scanning platforms," *Remote Sensing*, vol. 5, no. 11, pp. 5871–5906, November 2013.

[12] H. A. Lauterbach and A. Nüchter, "Preliminary Results on Instantaneous UAV-Based 3D Mapping for Rescue Applications," in *Proceedings of the 16th IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR '18)*, Philadelphia, PA, USA, August 2018, pp. 1–2.

[13] A. Nüchter, M. Bleier, J. Schauer, and P. Janotta, "Improving Google's Cartographer 3D Mapping by Continuous-Time SLAM," in *Proceedings of the 7th ISPRS International Workshop 3D-ARCH 2017: "3D Virtual Reconstruction and Visualization of Complex Architectures"*, ser. ISPRS Archives Photogrammetry and Remote Senssing Spatial Inf. Sci., Volume XLII/W3, Nafplio, Greece, March 2017, pp. 543–549.

[14] J. Elseberg, S. Magnenat, R. Siegwart, and A. Nüchter, "Comparison on nearest-neigbour-search strategies and implementations for efficient shape registration," *Journal of Software Engineering for Robotics (JOSER)*, vol. 3, no. 1, pp. 2–12, 2012.

[15] D. Borrmann, H. Afzal, J. Elseberg, and A. Nüchter, "Mutual Calibration for 3D Thermal Mapping," in *Proceedings of the 10th International IFAC Symposium on Robot Control (SYROCO '12)*, vol. 10, Dubrovnik, Croatia, September 2012. [Online]. Available: https://robotik.informatik.uni-wuerzburg.de/telematics/download/syroco2012_2.pdf