Detection of Gas Clouds with Cellular Sensor Network and Drone Based Deployment System

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***Abstract*—Within this document the studies, methods and research results for using multi rotor Unmanned Aerial System (UAS) with deployable sensor probes to detect hazardous gases (HG) are discussed. The studies shows the effects of propeller downwash, the prototype implementation used to read sensor information, the mechanism used to deploy the sensor to a specific target location and how the processed sensor information is sent to ground control in real time.**

I. Introduction

Nowadays many industries from pharmaceutics to small bakeries depend on chemical products, also known as dangerous goods (DG).

The handling and transportation of DGs is always a venture as in case of an accident the chemicals can get released into the environment and either damage the environment and wildlife or vaporize to hazardous gases (HG).

These vapours are especially dangerous for the emergency response units (ERUs) as they get in direct contact with the potentially life threatening gases. [1] Vaporizable chemicals exposed to air are either lighter than air in terms of weight and therefore diffuse to the atmosphere or heavier than air (heavy gas) forming dangerous clouds at surface level which are more potent in terms of perilousness because of the close proximity to humans. The dynamics and movements of big scale heavy gas clouds are affected by environmental conditions like landscape, wind direction, obstacles as well as temperature and sun light [2]. The dispersion of clouds of this kind is already well documented by Ermark[2] as well as P. Kumar[3] and described in multiple models like SLAB and SCREEN-3 [4].

Large industries are therefore required to install wireless gas detecting sensor systems to minimize the risk for first line employees and to improve the early detection for incidents [5]. A recent paper displays algorithms for monitoring and tracking dense air clouds using sensors interconnected with mobile adhoc networks (MANETs). These sensors are carried by drones or unmanned ground vehicles to the dangerous zones. [6]

This paper combines the mentioned concepts into a working system for active sensors which are attached to a UAS for registering heavy gas clouds with a delay of less than 10s and in midair. Furthermore, the system itself is also able to deploy those sensors on ground level for punctual environment monitoring of strategic measurement points. A prototype for this sensor platform was designed, implemented and tested on several aspects. The system can be used as a MANET agent for further research on tracking heavy gas clouds. The devices were designed as disposables with cost in mind, as they could potentially get lost or destroyed by deploying them too close to a danger zone. Therefore, this prototype could be utilised as low budget first line of defence device for ERUs. The proposed modular design allows easy replacement of every component.

The paper is structured as follows. In Section II a summary of recently published studies is discussed. Section III contains a detailed summary as well as description of all electronic parts used within the scope of this paper. Section IV the system itself as well as all accomplished test cases are described and discussed in retrospect. Finalizing by prospecting further research topics in Section V and concluding this work in Section VI.

II. Related Work

One problem of heavy gas clouds is their unpredictable nature. Only by calculating every environmental aspect moderately accurate predictions can occur as shown in [3]. For example the estimation of heavy gas cloud boundaries has been proposed in [7]. A MANET of mobile sensors is used to track and estimate the boundaries of the gas diffusion. The mobile sensors themselves are self aligning on the clouds boundaries based on the sensor values. When the sensor detects a higher level of concentration it moves away from the estimated center point and vice versa for lower concentrations. The estimation of the center point and the boundaries is accomplished by a centralised sensor network or by combining several sensors to smaller distributed self managed batches. A benchmark of these estimations is outlined in [7]. Whereas several other researches are focused on comparing the wide varieties of MANETs systems [8], [9].

The need for UAS based airborne support for ERUs is shown in [10] where multiple accomplishments focusing on this topic are compared and discussed. One of the discussed attempts is [11], where a fleet of small inexpensive UASs is used to monitor the fire front contours in an ongoing wildfire. This is accomplished by attaching temperature probes to each UAS. Combined with the location information of the vehicles the data is processed on a centralised endpoint. To estimate the wildfire propagation behavior a recent paper [12] describes the usage of a Kalman Filter[13] on the collected data to improve this prediction. According to these papers, the usage

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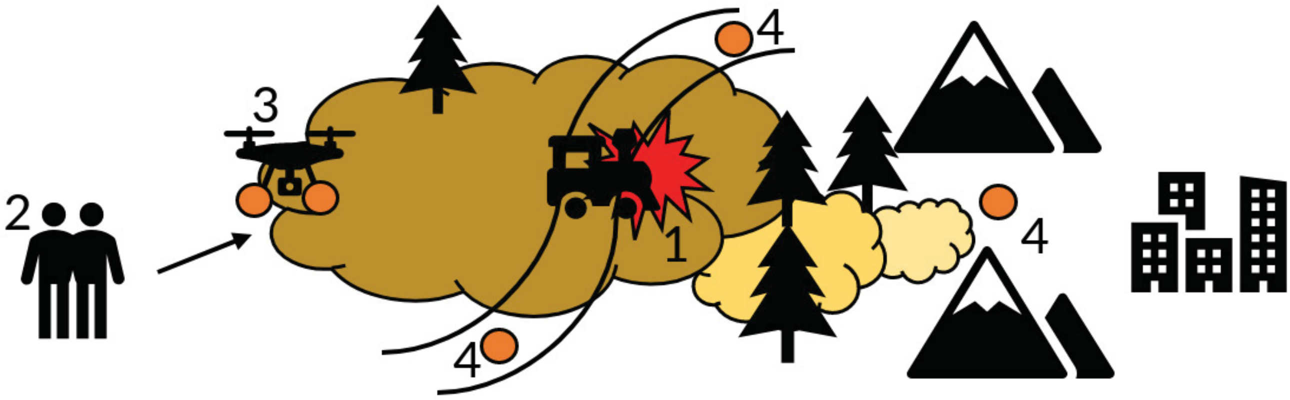

Fig. 1. Overview of the basic concept. 1: location of a train accident with DG forming HG involved, 2: Ground Control for drone operation, 3: UAS detecting boundaries of gas cloud in midair with the sensor; 4: Deployed sensor on strategic locations. Details described in Section III

of several low cost mobile sensor systems combined with a ingenious solution for centralised post processing works well for atmospheric real time measurements.

The monitoring of atmospheric environment conditions such as air pollutions is usually acquired by fixed ground based sensor stations [14]. In [15] a UAS was designed to analyse air conditions in midair. A sensor platform prototype was built and attached to the airframe of the UAS. To overcome the low range of the UASs data channel a 4G mobile network module was introduced to send the monitored results to a centralised processing server in realtime. Their results are promising for air quality monitoring of remote regions.

All referenced research is either measuring with static stations or in midair on a drone. The goal of this work is to combine static and dynamic measurements within a deployable sensor system.

III. Hardware and Development

Designing hardware for a UAS can be challenging, since the weight severely impacts the overall performance in terms of energy consumption and thus flight time. Hence, every additional component must be optimized for minimal weight. Several gases which are categorized as ”heavy” are forming dense and sometimes lucid clouds at surface level. This is because the molecular weight of the these gases is higher than air binding the molecules together. As humans can easily get in direct contact with these gases without visually noticing they are considered as especially dangerous [4]. Detecting hazardous gases (HG) with a drone is possible when big clouds are formed as they are essentially immune to the downwash of the UAS. The detection of lower concentrations of HGs on the edges or outside of clouds by UASs is especially challenging as the downwash introduces lots of fresh air of upper air layers which could dispel the HG concentrations to a undetectable ratio. Therefore the implemented sensor platform was designed to get deployed in flight by a special deployment system of the UAS. Deployed sensors are staying on ground level and are not affected by the downwash as the UAS is moved away from the deployment zone. This approach solves the downwash problem and reveals the opportunity to strategically position measuring points during emergency services.
A basic scenario of a fire service enhanced by the proposed sensor system is visualised at Fig. 1. As imaginary use case a train accident with DG leakage and forming HG clouds is assumed. Depending on the weather conditions, a nearby city could potentially get contaminated. The dedicated drone team operates from a save distance to the accident. With midair measurements the rough cloud boundaries and shape are determined. Then sensors are deployed to strategic locations outside of the contaminated zone to act as early alarm system when for example the cloud advances in the cities direction. To further support the first line ERUs images and measurements of inside the cloud are utilised to locate the leakage.

A. Unmanned Aerial System (UAS)

The carrier platform for the proposed hardware is a multi rotor system. It was selected for several reasons. It is portable, able to start and land without a runway and can hover in midair. In this research a custom built quad copter with 16 inch propellers in X configuration is used. It is powered by a 6 cell (6S) lithium polymer (LiPo) battery packs with a capacity of 5.000mAh. As main processing unit the UAS is equipped with a Pixhawk4 flight controller (FC) with ArduPilot firmware. This controller uses an accelerometer, a gyroscope, Global Navigation Satellite System (GNSS) and compass modules for stabilizing flight and provides navigation on waypoint mission basis. Waypoints are data points containing information about coordinates, elevation, facing direction and other commands. The mission is planned in advance by combining multiple waypoints with a ground control program (e.g. QGroundControl) and uploaded to the FC. Once the operator activates the mission the UAS autonomously flies to all waypoints sequently and performs all defined tasks. These auto pilot waypoint missions are part of the open source ArduPilot FC firmware (https://ardupilot.org/). The drone used as carrier platform utilise four T-Motor 4006 380KV. The KV rating describes the revolutions per minute (RPM) of the motor per input voltage. Each motor is equipped with a 16 inch fixed pitch propeller. With this current configuration the prototype UAS is able to lift payloads up to 1.5 kg with a maximum take off mass of 3.5 kg and a flight time of approximately 12 to 15 minutes.

B. Sensor Platform Prototype

With the conceivably harsh conditions for the sensor platform during the deployment process in mind, as the platform has to endure a release within midair on any surface from several meters above. Its casing also has to be permeable enough, that the HGs can get in contact with the sensor module. These mentioned aspects led to the most promising design for the platform, where a icosphere which reduces the impact force, shaped in a wireframe model to expose the gas mixture to the sensor, is used as frame. The electronic components are mounted right at the center point of this frame. As the shape closely resembles a ball, the platform is called Sensor Ball System (SBS). See Fig. 2. After deployment the sensor has to operate autonomously for at least several hours as it may be used as monitoring device as described in Section III and visualised in Fig. 1. So an additional small Li-Ion cell is included to the design. To allow charging the device with a single USB cable a battery supply unit (BSU) is integrated. A short circuit protection and deep discharge protection to improve battery live is included on the BSU. As most sensor modules are not capable to detect the vast bandwidth of HGs it is essential to have a modular system, where sensor modules can easily be changed. Alternatively different versions of the sensor platform equipped with different sensor types can be produced. This is important as every incident with DG consists of different gases. For the prove of concept the SBS were equipped with a temperature and humidity sensor. In order to process the collected data, every data set is annotated with the global position where it was recorded. The combined data of GNSS location, sensor values, battery status, network information, and an unique identifier, is sent via GSM/GPRS and processed at a centralised server which will be described in section III-D.

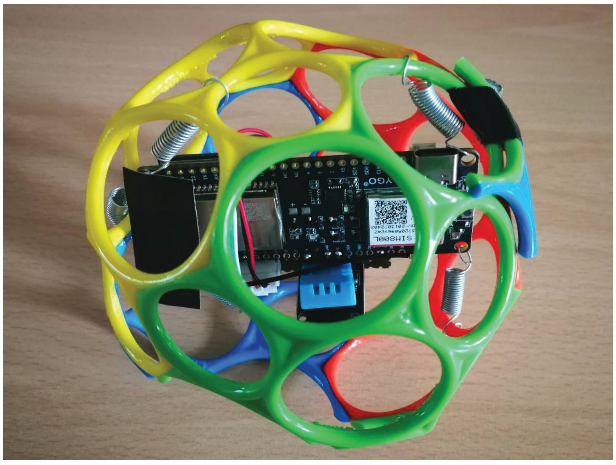

Fig. 2. Image of "Sensor Platform" prototype

The SBS includes these specific electronic components: (i) A LILYGO TTGO T-Call development board as it already includes the SIM800L GSM/GPRS module with antenna, a BSU and the ESP32 micro controller which acts as the central processing unit (CPU) of the sensor platform (ii) A Beitian BN220 Dual GPS/GNSS module with integrated passive GNSS antenna (iii) A generic 900mAh 18350 type Li-Ion cell (iv) A DHT11 sensor module for temperature and humidity readings. As mounting structure for the electronics a toy grab ball was misused where all components could easily fit inside and are secured by several springs. On the software side the SBS was implemented with the following procedure. At startup the prototype goes into the initialize state indicated by a LED blinking scheme (three long flashes with a duration of 1000ms per cycle) for some visual feedback at field tests, where it performs several system checks and waits for the GNSS and GMS to establish a stable connection. As soon as the modules are reporting valid data values the ESP32 advances to the working state indicated by another LED feedback (two short flashes with a duration of 500ms per cycle). Within this state the micro controller periodically processes a working cycle, where it collects the values of all sensor modules. The data is translated into a Javascript Object Notation (JSON) encoded information bundle and transmitted to the server. The bundles structure is shown on listing 1. At the end of a successful working cycle a status code is indicated by two long LED flashes. Two short flashes signalize a failure. The source code of the SBS is available on Github https://github.com/robsl2314/deployable-gas-sensor.

Listing 1. Example of JSON data packet

```
{'actuators':
    {'22c8a393-aa14-481b-...': {
        'latitude': 47.56606,
        'longitude': 12.12695,
        'altitude': 482.1,
        'satellites': 7,
        'speed': 0.22224,
        'temp': 33,
        'humi': 40}
    }
}
```

C. Deployment System

To compensate the downwash issue mentioned in Section III and open the possibility for sensor distribution a deployment system was implemented shown on Fig. 3. The schematic of the deployment system with all components is shown on Fig. 4. The designed system is fully decoupled from the UAS and consists of the following components.

Fig. 3. Prototype "Deployment System"

- Two distinct custom build release mechanisms
- Down facing camera
- Analog 5.8 GHz video sender (VTX)
- RC radio receiver
- Small LI-ION battery

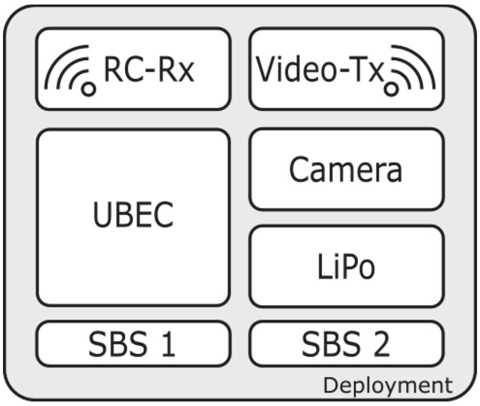

Fig. 4. Schematic of all components of the deployment system

To prevent the pilot from being distracted the release mechanism is controlled by an expert for HGs. With the video stream of the down facing camera, which is provided by the analog video transmitter (VTX) with a delay of less than 20ms the operators are able to locate the optimal deployment location. The deployment system prototype is equipped with two deployable SBSs. Therefore it is possible to distribute multiple sensors as mentioned in Section I or keep measuring in midair after deploying a single SBS. The release mechanism utilise a 9g metal gear servo motor to drive a shaft into a casing where the payload can be attached. Besides the servo motor every component is designed to keep the overall weight at a minimum. The casing and shaft are produced with a fused deposition modeling (FDM) 3D printer using polylactic acid (PLA) printing filament. The 3D model of the release mechanism is visualised in Fig. 5 and can be downloaded on Thingiverse https://www.thingiverse.com/thing:3368497.

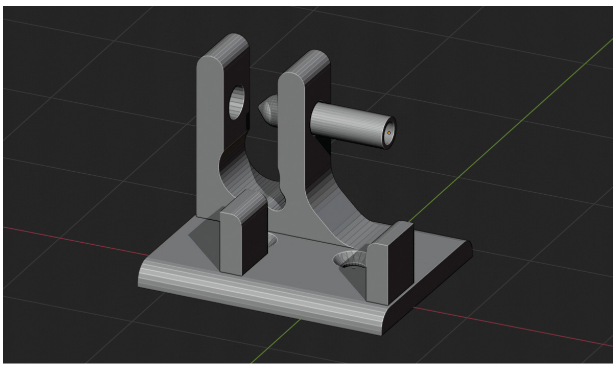

Fig. 5. 3D model of the release mechanism

To minimize the cameras weight while keeping an appropriate performance a first person view drone racing camera (Rumcam Swift2) is utilised. With a focal length of 2.1mm and a field of view (FOV) of 135°a large area can be observed. This camera system is capable to operate within a wide range of supply voltage (5-36V) and could therefore potentially be powered directly with the battery pack of the carrier drone. However, a decoupled power supply is important because the noise created by the UASs motors would negatively impact the recording of the camera and the video transmitting. The video feed to the operators is created with a 5.8 GHz VTX. For testing the maximum output power within the legal boundaries of the country the tests were conducted of 25mW was used. To control the servos a radio control link (RC) is established by a small 3 channel FlySky receiver combined with a FlySky FS-i6X radio sender. As only 2 of these 3 channels are used, the system could potentially get upgraded with another release mechanism or other features. For example a controllable camera gimbal. To complete this system, a ultimate battery eliminator circuit (UBEC) which is in general a high performance DC-DC converter combined with a small 2 cell LiPo pack is added to the platform. The rotation speed of each individual motor of the UAS is calculated with a PID control algorithm by the FC in a rate of 8 kHz. As the FC usually has no information about the weight distribution of the vessel a centric weight distribution is assumed. By attaching the SBS with a string the dangling pulls the UAS from many different angles thus shifting the center of mass constantly. As the PID rates are defined for a static object they are not dynamically adjustable. This could causes the PID controller to constantly overshoot, resulting the UAS getting instable and crash. To overcome this issue the string has to be either very long, that the pulling angle of the sensors mass is constant or by mounting the SBS directly to the deployment system. As long strings are problematic when used in close proximity to drone motors, as they can wind up within the propellers which leads to fatal crashes the sensors were attached directly.

D. Data processing

As in the previous section III-B described, the sensor information is transmitted to a centralised web service. This endpoint provides several functionalities and is implemented in PHP (https://www.php.net/). First, the received information is logged and archived for further inspections. Secondly, it acts as middleware for a websocket service (WSS), which is used to forward the data to a realtime data visualisation application.

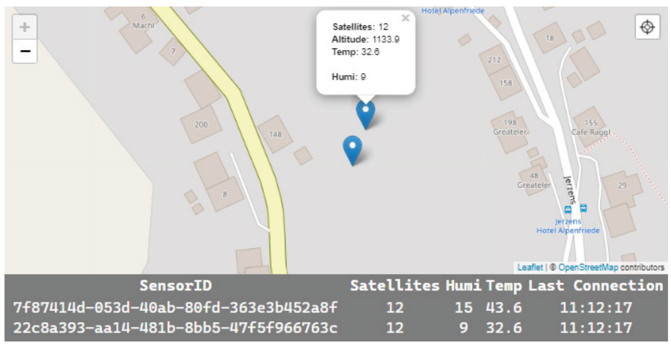

Fig. 6. Data visualisation with table and map view

Another important aspect is to define the area of operation of UASs. Here a novel data centric JSON based geographic model, *SpatialJSON*, described in [16] is utilised. This data type allows for an efficient modelling of three dimensional areas and data enrichment. Thus, the final function of this service is to integrate the collected data in such a spatial model. The visualisation application shown on Fig. 6 consists of a NodeJS https://nodejs.org/ data broadcasting websocket server and a rudimentary client web application which is displaying the received data on a table as well as showing the sensor information directly on an interactive map. This map application is designed to provide crucial information for the drone operator and enable a strategic SBS deployment.

Furthermore, a simulation tool was implemented to utilise the created the log files of the endpoint. Here, the recorded data can re-fed with arbitrary rate into the WSS to replay the visualisation on the web application. With this tool operations can be audited in retrospect.

E. Communication Layers

In this section, the communication between the drone operators and all system components (UAS, deployment system, SBS and web services) is described. A visualisation is shown on Fig. 7. At first, the pilot controls the UAS with a radio control (A). This connection is full duplex, meaning that log information of the drone is send back to the pilots radio control where it is displayed. This information contains flight relevant data for example battery status, current position, speed, altitude and mission data like the id of the current waypoint. The down facing camera is connected to the VTX sending video back to the operators (B). This video is displayed on a screen visible to the dangerous goods expert (DGE) and pilot to improve the scouting results for the best deployment location. Once this location is discovered, the DGE controls the deployment system with another RC connection (C) to initiate the release mechanism. In midair as well as in deployed state the SBS sends information to the cloud service (D1). After the centralised postprocessing described in Section III-D the web application instantly receives the sensor data from the WSS(D2), presenting it to the DGE.

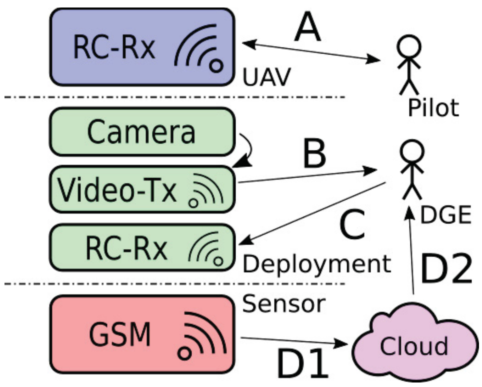

Fig. 7. Communication and operation schema

IV. Evaluation

This section discusses the accomplished tests and evaluates the results from the testing procedures of individual components.

A. Downwash

The thrust needed to lift a multi rotor vehicle is created with the propellers by pushing the air from above with rotational force and the propellers angle downwards. The more thrust, the more air is moved, therefore more turbulence are produced. In case of normal flight this behavior is not problematic. When trying to measure minimal amounts of HGs in midair the induced air has the potential to impair the sensor results. The downwash effect of multi rotor systems is discussed in detail here [17], [18]. In the scope of this work, several downwash tests where conducted by flying through a fog cloud created by a fog machine. This was tested it with a variety of different sized drones. An indoor environment was used to accomplish these tests. Unfortunately, this setup is not optimal for the following reasons. First, the produced fog may not behave like heavy gas clouds so only common air movements are detected. Secondly, are moving rotors inducing air channeling effects on the indoor test environment. The air is pushed to the floor by the UAS where gets deflected by the walls and finally dragged back under the ceilings by the vehicles propellers. This creates an accelerating stream of rotating air inside the room. The air movement is visualised on Fig. 8. Ceiling fans create the same effects in a smaller magnitude as described in [19]. These effects are inflict the test results as the fog is moved before the actual downwash occurs. The stream of air can become strong enough to push the UAS on the floor, forcing it to land or even crash. Lastly, a fog machine is not capable to produce

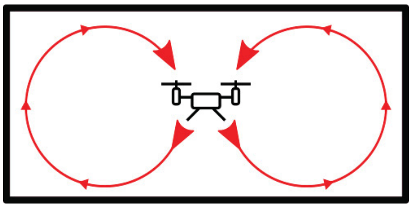

Fig. 8. Air circulation of a UAV within indoor environment

clouds big enough to become relevant for ERUs. Atmospheric conditions like wind are dispersing small clouds in a short period of time. According to an expert of DG of the local fire department, relevant clouds are huge. Sometimes not even an incoming emergency helicopter is capable to disperse those clouds. Therefore the SBSs should be capable to evaluate the gas composition of huge visible HG cloud.

B. Deployment System

Technical range limitations of the VTX and RC system are the most critical aspects of the deployment system. The camera system uses an analog 25mW 5.8GHz wireless module as described in section III-C. As its antenna is usually located on a high position within line of sight (LoS) the transmitting video signal can be carried a long distance as no obstacles interfere the connection. Within our testings with high gain directional antennas, readjusted to the UAS at the receiving end the signal could be retrieved at any point, even around 200m into the distance. The weak point of this system lays on wet, rainy and foggy weather conditions as water molecules are absorbing radio signals the better the higher its frequency [20]. At any point when the video signal is lost, the pilot can pull back to areas where the video signal stabilises. The other range dependent component is the RC Link which has accordingly to the manufacturer a range of 200m on ground level. When taken on air as no obvious obstacles are between transmitter (located at the operator) and receiver (located at the UAS) this range is increased. In a real scenario special long range modules can be used which can cover distances of several kilometers. Within the testing scope of the prototype the transmitter never lost connection. In case of a lost RC link the receiver has to handle this situation properly. As the deployment zones clearance can not be confirmed the release mechanism for the SBSs is disabled by default. The so called "failsave protocol" of the receiver was configured to hold the servos where the sensors are attached in a closed position whenever the signal is lost. Subsequent implementations of the deployment system will be equipped with either more powerful communication components e.g. antennas with higher gain.

C. Sensor Ball System (SBS)

Examining the SBS two distinct use cases are defined. Monitoring and transmitting the collected sensor values in midair and on ground level. And the physical stress induced during the deployment process which is also part of the investigation. During the various tests the GSM connection worked flawlessly and was able to transmit every captured data frame via GSM/GPRS to the cloud system. With the redirection performed by the WSS the visualisation web application was able to display all sensor readings accordingly. As already disclosed in Section III-D the sensor locations are visualised with map markers whereas the provided data is presented with a table as well with popups directly at the sensors position within the map. The second aspect to examine is the physical stress of the SBS during the deployment process. None of the components has rating for impact forces, also in a real world scenario the sensor platform would usually be treated as a disposable device, therefore, it is only necessary that the electronics resist the impact forces of a single deployment. Because of that the testing was focused on wether the impact destroys the device on impact. The tests where structured on surface hardness and deployment hight. Tests where performed for falling distances of 1m, 3m, 5m, 10m, 15m and 20m above ground on a mown grass surface as well as 1m, 2m, 3m on concrete tiles. The results for the soft surface showed, that deployment procedures higher than 15m could damage the electronics irreversible. To cover all evaluations the SBSs were reused when no obvious defect at its function occurred. The impact on the hard concrete tiles was documented with a 960 frames per second camera resulting in a 32 times slow motion. This test reviled that on a 3m high impact the SBS-frame could not sufficiently protect the electronics. The deformation of the SBS is depicted in Fig. 9.

Fig. 9. Deformation of SBS on deployment test from 3m on hard tiled floor — 960 FPS - Frame count of clips 0, 1, 3, 5, 9, 17

To improve subsequent implementations of the SBS highly shock absorbing materials in conjunction with a 3D printer will be. With a special design the frame can be breathable and perfectly house the electronics within a special component bay for better access.

V. Future Work

A. Sensor fusion with Spatial Extension Model

As described in [2] and Section II gas clouds are heavily affected by landform, wind direction, obstacles and even the angle of incidence of the sun. By accumulating such information in a data centric geospatial model as described in [16] it is possible to combine the retrieved data, weather information and geoid data from multiple sources. Hence creating a digital representation of the environment which should allow accurate predictions about the movement and dispersion of the detected heavy gas clouds. If this prediction is accurate enough the civil population could get notified in case of an accident based on a highly detailed report within a very short period of time.

B. Expanding to dangerous fluid examination

As this paper only includes the gases of DG, a future work will discuss the possibilities for detecting dangerous fluids from the distance. The SBS easily can be upgraded to be water resistent by coating the critical electronic components and by adding a small floating body. Furthermore, a SBS with these upgrades could be deployed on lakes, rivers and the sea but also silos and tanks within industry.

C. Using the UAV in beyond visual line of sight (BVLoS) environments

In most states, pilots are limited by the legislative to the so called LoS flight. Requiring the pilot to operate UAS in the line of sight. Therefore, limiting the radius of action to approximately 500 meters. Depending on the weather conditions, wind speed and direction the operating pilot and DGE can get trapped inside of a HGs cloud. The LoS limitation forces the pilot to approach close to the danger zone. By introducing more safety systems to UASs these legal limitations could potentially get decreased that pilots of ERUs are allowed to fly beyond visual line of sight (BVLoS). For example the down facing camera which is used to secure the clearance of the deployment zone. In an upcoming study about flight security and safety enhancing devices for UASs the potential risks will be discussed.

VI. Conclusion

As several use cases and works discussed in Section II introduce the potential of air bourn environmental sensors this research field is indisputable very important for atmospheric measurements as well a necessity for a variety of industries and especially for rescue organization. The results of this paper a present a working, easily upgradable and highly cost efficient attempt to support the safety of ERUs during rescue missions and operation. The first iteration of the prototype has great potential for improvements and unfolds a promising foundation for further research topics.

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References

[1] M. A. Wenck, D. V. Sickle, D. Drociuk, A. Belflower, C. Youngblood, M. D. Whisnant, R. Taylor, V. Rudnick, and J. J. Gibson, "Rapid assessment of exposure to chlorine released from a train derailment and resulting health impact," *Public Health Reports*, vol. 122, no. 6, pp. 784–792, Nov. 2007. DOI: 10.1177/003335490712200610.

[2] D. L. Ermak, "User's manual for slab: An atmospheric dispersion model for denser-than-air-releases," Jun. 1990. [Online]. Available: https://www.osti.gov/biblio/6252170.

[3] P. Kumar, A.-A. Feiz, P. Ngae, S. K. Singh, and J.-P. Issartel, "CFD simulation of short-range plume dispersion from a point release in an urban like environment," *Atmospheric Environment*, vol. 122, pp. 645–656, Dec. 2015. DOI: 10.1016/j.atmosenv.2015.10.027.

[4] P. Prof.V.A.Bhosale Prof.K.I.Patil, *Study of accidental releases heavy gas dispersion comparing slab models and screen-3 model*, Jan. 2015.

[5] L. Shu, M. Mukherjee, and X. Wu, "Toxic gas boundary area detection in large-scale petrochemical plants with industrial wireless sensor networks," *IEEE Communications Magazine*, vol. 54, pp. 22–28, Oct. 2016. DOI: 10.1109/MCOM.2016.7588225.

[6] M. Krzysztoń and E. Niewiadomska-Szynkiewicz, "Intelligent mobile wireless network for toxic gas cloud monitoring and tracking," *Sensors*, vol. 21, no. 11, p. 3625, May 2021. DOI: 10.3390/s21113625.

[7] M. Krzysztoń and E. Niewiadomska-Szynkiewicz, "Heavy gas cloud boundary estimation and tracking using mobile sensors," *Journal of Telecommunications and Information Technology*, vol. 3/2016, pp. 38–49, Sep. 2016.

[8] H. R. Hussen, S.-C. Choi, J.-H. Park, and J. Kim, "Performance analysis of MANET routing protocols for UAV communications," in *2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*, IEEE, Jul. 2018. DOI: 10.1109/icufn.2018.8436694.

[9] M. Parmar and S. Mishra, "Comparative analysis of mobile ad- hoc network and sensor network," *International Journal of Advanced and Innovative Research*, vol. 3, pp. 123–126, Jul. 2014.

[10] M. A. Akhloufi, A. Couturier, and N. A. Castro, "Unmanned aerial vehicles for wildland fires: Sensing, perception, cooperation and assistance," *Drones*, vol. 5, no. 1, p. 15, Feb. 2021. DOI: 10.3390/drones5010015.

[11] Z. Lin and H. H. T. Liu, "Enhanced cooperative filter for wildfire monitoring," in *2015 54th IEEE Conference on Decision and Control (CDC)*, 2015, pp. 3075–3080. DOI: 10.1109/CDC.2015.7402681.

[12] Z. Lin, H. H. T. Liu, and M. Wotton, "Kalman filter-based large-scale wildfire monitoring with a system of UAVs," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 606–615, Jan. 2019. DOI: 10.1109/tie.2018.2823658.

[13] R. E. Kalman, "A new approach to linear filtering and prediction problems," *Transactions of the ASME–Journal of Basic Engineering*, vol. 82, no. Series D, pp. 35–45, 1960.

[14] A.-S. Mihaita, L. Dupont, O. Cherry, M. Camargo, and C. Cai, "Air quality monitoring using stationary versus mobile sensing units: a case study from Lorraine, France," in *25th ITS World Congress 2018*, Copenhagen, Netherlands, Sep. 2018, pp. 1–11.

[15] X. Liu, H. Wen, A. Li, D. Xu, and Z. Hou, "Research of multi-rotor UAV atmospheric environment monitoring system based on 4g network," *E3S Web of Conferences*, vol. 165, W. Qin, L. Wang, and V. Yepes, Eds., p. 02 029, 2020. DOI: 10.1051/e3sconf/202016502029.

[16] K. Raich, R. Kathrein, M. Erharter, and M. Döller, "Spatial extension model for multimodal traffic management," in *Proceedings of the 2020 4th International Conference on Vision, Image and Signal Processing*, ACM, Dec. 2020. DOI: 10.1145/3448823.3448854.

[17] D. Yeo, E. Shrestha, D. A. Paley, and E. M. Atkins, "An empirical model of rotorcrafy UAV downwash for disturbance localization and avoidance," in *AIAA Atmospheric Flight Mechanics Conference*, American Institute of Aeronautics and Astronautics, Jan. 2015. DOI: 10.2514/6.2015-1685.

[18] Y. ZHENG, S. YANG, X. LIU, J. WANG, T. NORTON, J. CHEN, and Y. TAN, "The computational fluid dynamic modeling of downwash flow field for a six-rotor UAV," *Frontiers of Agricultural Science and Engineering*, vol. 0, no. 0, p. 0, 2018. DOI: 10.15302/j-fase-2018216.

[19] H. Wang, M. Luo, G. Wang, and X. Li, "Airflow pattern induced by ceiling fan under different rotation speeds and blowing directions," *Indoor and Built Environment*, vol. 29, no. 10, pp. 1425–1440, Nov. 2019. DOI: 10.1177/1420326x19890054.

[20] J. Luomala and I. Hakala, "Effects of temperature and humidity on radio signal strength in outdoor wireless sensor networks," in *Proceedings of the 2015 Federated Conference on Computer Science and Information Systems*, IEEE, Oct. 2015. DOI: 10.15439/2015f241.