Science of the Total Environment 803 (2022) 150041

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Honeybee-based biohybrid system for landmine detection

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HIGHLIGHTS

- Honeybees and organic semiconductor films can indicate explosive contamination.
- Conditioned honeybees can subsequently be used to locate explosive plumes.
- Reconditioning prolonged interest of honeybees for target odour.
- Camera-equipped UAVs can remotely track the honeybee trajectory.
- Computer vision algorithms can detect landmines by analyzing honeybee movements in video.

GRAPHICAL ABSTRACT

Passive sampling

Placing feeders around the minefield and preconcentrators at the hive entrance

Collecting and analyzing samples

Detection using organic semiconductor thin films

Active search

Conditioning honeybees to search for TNT vapor

Imaging conditioned honeybees over landmines and georeferencing using RTK GPS precise localization

Video processing using convolutional neural networks and detection of suspicious areas

Results

Passive sampling

Active search

ARTICLE INFO

Article history:
Received 10 June 2021
Received in revised form 25 August 2021
Accepted 26 August 2021
Available online 1 September 2021

Editor: Yolanda Picó

Keywords:
REST sampling
Organic semiconductors
Unmanned aerial vehicles
Convolutional neural networks
Humanitarian demining

ABSTRACT

Legacy landmines in post-conflict areas are a non-discriminatory lethal hazard and can still be triggered decades after the conflict has ended. Efforts to detect these explosive devices are expensive, time-consuming, and dangerous to humans and animals involved. While methods such as metal detectors and sniffer dogs have successfully been used in humanitarian demining, more tools are required for both site surveying and accurate mine detection. Honeybees have emerged in recent years as efficient bioaccumulation and biomonitoring animals. The system reported here uses two complementary landmine detection methods: passive sampling and active search. Passive sampling aims to confirm the presence of explosive materials in a mine-suspected area by the analysis of explosive material brought back to the colony on honeybee bodies returning from foraging trips. Analysis is performed by light-emitting chemical sensors detecting explosives thermally desorbed from a preconcentrator strip. The active search is intended to be able to pinpoint the place where individual landmines are most likely to be present. Used together, both methods are anticipated to be useful in an end-to-end process for area surveying, suspected hazardous area reduction, and post-clearing internal and external quality control in humanitarian demining.

1. Introduction

Landmines are non-discriminatory weapons that, similar to other explosive remnants of war (ERW), can stay buried and active for

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https://doi.org/10.1016/j.scitotenv.2021.150041
0048-9697/

decades, presenting danger to human lives across the globe in conflict and post-conflict areas. They pollute the environment and prevent farming, trade and communication between communities. As of January 2021, 61 countries and areas have a known threat of antipersonnel mine contamination (International Campaign to Ban Landmines, 2021). According to International Campaign to Ban Landmines (2020), in 2019 "at least 5554 casualties from mines/ERW were recorded, more than half of which were caused by improvised mines (2949)." The majority of casualties, 80%, were civilians, and children accounted for 43% of civilian casualties.

Demining techniques vary from manual mine clearance, where the detection phase relies heavily on metal detectors and/or sniffer dogs visually monitored by a trained deminer, to mechanical equipment and tools, to robotized solutions (Habib, 2008). Also of interest are biological and biomimetic systems for landmine detection, reviewed in Habib (2007).

The most important but, unfortunately, the slowest phases of the demining process are landmine/ERW detection and post-clearance inspection, i.e. quality control. The time and effort to survey an area for suspected landmines are large, incurring high costs. Therefore, a less expensive method to survey a large area prior to deploying a targeted detection method, confirming the location of individual mines, would be an advance in humanitarian demining with enormous impact worldwide (Sieber, 2000). Similarly, quality control relies on sampling, the process of re-clearance of a part of the area that has already been cleared. Sampling is typically performed manually implying a time consuming, costly and dangerous process (Gilbert and Larsson, 2013; Ekenberg et al., 2018). In addition, important issues, such as costs, upkeep, and temperament, are associated with using sniffer dogs (Porritt et al., 2015) for these tasks.

The possibility to use honeybees as chemical biosensors is well known (Bromenshenk et al., 2015; Quigley et al., 2019). While flying, honeybees become electrically charged (Vaknin et al., 2000), causing them to collect particles from the environment and bring them back to the hive. Therefore, by analyzing the contents of the hive it is possible to confirm the presence of a variety of chemicals from various sources: explosives, pesticides, drugs, fungi, microplastic, etc. (Barisic et al., 2002; Calatayud-Vernich et al., 2018; Dżugan et al., 2018; Gajger et al., 2019; Gillanders et al., 2019; Murcia-Morales et al., 2020; Edo et al., 2021).

Remote Explosive Scent Tracing (REST) (Fjellanger, 2004) is a method based on collecting air samples in the mine-suspected area. The samples are subsequently assessed by sniffer dogs for the presence of explosives. However, it is a slow and costly procedure. Photoluminescent organic semiconductor polymers have been proposed as a viable alternative to using dogs for explosive detection (Gillanders et al., 2017, 2019; Glackin et al., 2020). In Gillanders et al. (2021) honeybees were used for sampling in the suspected area and presence of explosive vapors in a hive was confirmed using organic semiconductor sensing films. This gives a very promising surveying method to indicate landmine-contaminated areas for targeted detection methods.

Honeybees have a very developed sense of smell (Menzel et al., 1974; Arenas et al., 2007; Mas et al., 2020) and can detect vapors at a ppt level (Bromenshenk et al., 2003). Pelz et al. (1997) presented that high concentrations of odorant support stronger associations than lower concentrations, especially with high reward. Previous research (Rodacy et al., 2002; Kezić et al., 2013; Bromenshenk et al., 2003) has shown that it is possible to train honeybees to search for explosive odor. Honeybees learn very quickly, and the duration of conditioning is from four to five days. However, they can also abandon the search for a specific smell in a day or two after the conditioning, and orient to other food sources in nature (Gruter et al., 2011). Nevertheless, they remember the learned odor for a long time and may return to it in the future. In order to use this ability for landmine detection, methods for prolonging the interest in a specific odor are needed. To the best of our knowledge, the main disadvantage of using honeybees for landmine detection was the lack of a method for their precise localization and tracking of bees during flight.

Detection of free-flying honeybees is one of the highest challenges in the process of their use as active biosensors (Ćosović Bajić, 2014) and many methods for detecting and tracking insects have been extensively studied. A review of pre-2000 approaches was given in Reynolds and Riley (2002). Spatial maps of flying honeybees for landmine detection were obtained using thermal infrared imaging (Ćosović Bajić et al., 2003) and Light Detection and Ranging (LiDAR) (Shaw et al., 2005; Repasky et al., 2006; Hoffman et al., 2007; Carlsten et al., 2011). Other notable examples include using fluorescence LiDAR for insect detection (Brydegaard et al., 2009; Guan et al., 2010), radio-frequency identification (RFID) (Streit et al., 2003; Nunes-Silva et al., 2019), harmonic radar (O'Neal et al., 2004), reflective UV dyes (Bextine and Thorvilson, 2002), and high-frame rate video (Shimasaki et al., 2020). The main limitations of these methods are the need for special imaging techniques and/or attaching tags or antennae to honeybees, which is time consuming, expensive, and could interfere with normal honeybee behavior.

Visual detection and tracking of unmarked honeybees and other insects in RGB video, is not a trivial task, even in laboratory conditions (Kimura et al., 2014). In Romero-Ferrero et al. (2019) a system for tracking small animals based on convolutional neural networks (CNN) was proposed. However, the method is trained on videos with uniform background and good contrast between the insects and background, which makes it inapplicable to detection of free-flying honeybees. An approach for visual tracking of small animals in natural environments was proposed in Risse et al. (2017). There are some efforts (Campbell et al., 2008; Chen et al., 2012; Chiron et al., 2013; Babic et al., 2016; Rodriguez et al., 2018; Marstaller et al., 2019) to analyze the behavior of honeybees based on visual information at a hive entrance. However, honeybees in videos captured at the hive entrance have more prominent visual features compared to the honeybees in videos of free-flying honeybees, making the task easier. Detection and tracking of honeybees in uncontrolled conditions was investigated in Estivill-Castro et al. (2003). Unfortunately, the proposed approach is sensitive to movements of tree foliage resulting in false positive detections.

Unmanned aerial vehicles (UAVs) have recently been used to investigate honeybee drone congregation areas in difficult terrain (Cramp, 2017). However, only manual inspection of the recorded video was performed. More similar to our work, Stumph et al. (2019) proposed usage of computer vision techniques for detection of invasive insects in videos recorded using an UAV with ultraviolet light source and video camera. Recently, a method for detection of small moving objects in UAV videos was shown to be suitable for detection of flying honeybees (Stojnić et al., 2021).

In this paper we propose a biohybrid system for detection of landmines and other unexploded ordnances, based on honeybees as biosensors in combination with photoluminescent organic semiconductor polymers as indicators of the presence of explosives, as well as UAVs with mounted cameras and video analysis for honeybee behavior monitoring. The proposed system uses two complementary detection methods, passive sampling and active search.

The passive sampling aims to confirm the presence of explosive materials in a mine suspected area and is based on foraging honeybees flying freely in a mine-suspected area and subsequent non-invasive analysis of the contents of the hive using organic semiconductor-based explosive vapor sensing films, making it possible to draw conclusions about the presence of explosive particles in the area visited by honeybees.

Using honeybees for passive sampling can indicate the existence of contamination within the range of bee flight, but it is not possible to find the locations of the sources of explosive particles. To this end, we developed the active search method, which relies on trained honeybees and their monitoring using UAV-mounted cameras and video analysis using computer vision techniques to detect flying honeybees and produce spatial density maps of honeybee detections. In our experiments, peaks of detection counts were visible in the obtained spatial density maps at locations of landmines, so they can provide a good indication of presence and location of landmines in the surveilled area.

The main contributions of this paper are: (1) a biohybrid system for landmine and other unexploded ordnance detection that can be applied for suspected hazardous area reduction and/or to confirm the completion of the demining process in internal and external quality control, is proposed, (2) we show that analysis of the samples from beehives using organic semiconductor-based explosive vapor sensing films can confirm explosives contamination in the area where honeybees foraged, which provides information on areas to concentrate landmine detection activities, (3) the possibility of prolonging the interest of the bees to search for specific odor with re-conditioning was shown, and (4) showing that using UAV-mounted cameras coupled with computer vision techniques for video analysis can be used for detection of locations where conditioned honeybees spend more time, therefore indicating the presence of landmines.

2. Material and methods

2.1. Test sites

Data acquisition for an experimental evaluation of the proposed methods was organised by the Croatian Mine Action Centre – Centre for Testing, Development and Training (HCR-CTRO) and carried out at test sites (minefields) in Benkovac and Cerovac, Croatia, Fig. 1a. Benkovac test site is situated in the coastal region of Croatia. It covers 10000m^2 with three different types of soil and offers the opportunity to test and validate equipment, techniques and methodologies. It contains 1000 landmines buried at various depths. The site is divided into 47 lanes, which are then divided into 1 × 1 m squares. The aerial image of the Benkovac test site is shown in Fig. 1b.

Cerovac test site is located near Karlovac, with a total area of 55000m^2. It is used for testing of demining machines, mine detection dogs and handlers, as well as for development and training in demining. For testing and certification of mine detection dogs and handlers, 66 testing boxes of 10 × 10 m have been set up according to IMAS 09.42: Operational testing of Mine Detection Dogs and Handlers. For the same reason the exact locations of landmines in this test site are kept secret. Therefore, for our tests of the active method we chose two boxes with partially visible landmines. These boxes are labelled C4 and G5, and we will use these labels in the rest of the paper. The aerial images of the part of the Cerovac test site with marked testing boxes is shown in Fig. 1c.

2.2. Preparation of honeybee colonies

For both the passive sampling and active search Carniolan bees (*Apis mellifera carnica*) were used. We selected healthy bee colonies, well developed, with a sufficient amount of pollen. We provided the hive with enough space to accommodate sugar syrup. The preparation of honeybees for the passive sampling was done according to the procedure described in Gillanders et al. (2019) and Gillanders et al. (2021).

For the field trials in the active method we used seven colonies. For conditioning, two colonies were transferred to the 120m^2 mesh tent shown in Fig. 2a. Colonies were conditioned consecutively. In order to avoid visual cues two types of feeders were used for conditioning. Targets were composed of a 20 cm diameter Petri dish with odor of raw military TNT covered with soil from surrounding, on the top of the soil feeder made of 10 cm diameter Petri dish with glass, filled with light sugar solution, was placed, as shown in Fig. 2b. Controls were the same but without the odor of raw military TNT and food source.

After the first day, when the bees adjusted to the tent space and started visiting the targets, we set up the same number of targets and controls. Targets and controls were repositioned regularly every hour and dishes were replaced to avoid footprint pheromone (Giurfa and Núñez, 1992). Conditioning success in a tent was tested every day. We exchanged positions of feeders containing target odor with controls. When bees found feeders with a TNT odor immediately after relocation, it was anticipated that bees had successfully learned to recognize the target odor. Honeybee colonies were kept in the tent for four to five days. Afterwards, hives were transferred to the test minefield.

In order to prolong the interest of the bees to search for the odor of TNT reconditioning is needed. Conditioned colonies were set up with the hive entrances facing the minefield, at a distance of 30–50 m, as shown in Fig. 2c. First two days targets and controls were placed in front of the hive. Next days targets and controls were placed in front of the test minefield. After about one week of adaptation of the bees to the new environment, we started recording honeybee flights on the test minefield. During that period controls and targets were relocated every hour, and all feeders were replaced in order to avoid the presence of footprint pheromone. Targets were set up every morning before the bees started flying and refilled with food. The feeders were removed 1 h before conducting recordings of bee flights. Reconditioning success was tested in the same way as in the conditioning phase.

In all our experiments the number of honeybees in the surveilled area was significantly larger than the number of other flying insects of similar dimensions, the grass was cut and there were no flowers attractive to honeybees and other pollinators.

2.3. Passive sampling for site identification

The methodology for passive sampling has been described in detail previously (Gillanders et al., 2019, 2021). Briefly, preconcentrators for explosives were prepared from the commercially-available fluoropolymer Aflas (AGC Chemicals Europe Ltd), which was dissolved in Tetrahydrofuran (Sigma Aldrich) at a concentration of 155mgml^{-1}. The solution was then blade-coated onto canvas sheets prior to cutting into squares of approximately 2.5 × 2.5 cm giving the final preconcentrators. The

(a) (b) (c)

Fig. 1. (a) Locations of the test sites. (b) Aerial photo of the Benkovac test site. (c) Aerial photo of the Cerovac test site with testing boxes marked with white strips.


(a) (b) (c)

Fig. 2. (a) Mesh tent used for conditioning of honeybee colonies. (b) Target feeder used in the field experiments. (c) Position of the colonies at the test site.

preconcentrators were then rolled into a tube of diameter 1 cm and inserted into Lexan plates, in cartridges of four tunnels each. Two cartridges were inserted into the colony entrance – one for returning bees and one for exiting bees, as shown in Fig. 3. After one day on-site the preconcentrators were removed, sealed, and shipped for analysis.

To detect the explosives, fluorescent sensors were fabricated by dissolving Merck Super Yellow in toluene at a concentration of $6.5 \mathrm{mg ml}^{-1}$ and spin-coating onto cleaned glass slides in a clean room environment. The sensor was then placed in a chamber, aligned parallel to a preconcentrator at 1 cm distance, and nitrogen was flowed for 30 s to flush the chamber prior to measurement and reduce effects from photo-oxidation. The sensor was then excited by a 405 nm CW laser (Photonic Solutions), and the photoluminescence was measured using a CCD spectrophotometer for 30 s, before the preconcentrator was heated to release the stored molecules of explosives for 100 s at 100 °C. The released explosives molecules interact with the sensor film causing a quenching of the photoluminescence. The photoluminescence intensity was monitored for a total time of 300 s to detect the presence of molecules released from the preconcentrator. A reference measurement was made every four preconcentrators with a Super Yellow film in the chamber without a preconcentrator, but with the same heating procedure, to ensure measurements were not affected by latent contamination.

2.4. Video acquisition using UAVs

Acquisition of videos, required to analyze the movement of bees over a certain area is the first step of the active approach for marking of suspicious areas. There are some challenges, which need to be addressed for these videos to be usable in the automatic processing. First, a substantial resolution or pixel count needs to be achieved, which is not a difficult condition to meet, since it is easy to record in 4 K video standard. However, there are also some obstacles, related to the duration of each video sequence and geographical reference which links the visible area to the exact place in nature. The duration of each video needs to be substantial so that honeybees can be tracked over a longer period of time, which will provide better results in terms of pinpointing the area with higher possibility of containing a land mine or other type of unexploded device. The limiting factor for this is the power supply of a conventional battery-powered UAV which can hover and carry a high resolution camera. The only possible choice of an UAV at the moment are conventional multirotors, which do not have a very large endurance, and we could achieve only around 25 min of video recording of each location, before we needed to land and replace the battery. Georeferencing in our case is very important due to rather small areas of observation and the required accuracy, which is sub-meter. Achieving this by using a conventional satellite-based position system, even by adopting signals from multiple constellations, is not possible, because the achieved accuracy would be much worse than required. Therefore, we used an upgrade to a standard positioning system of an UAV, called RTK (Real Time Kinematic) which uses an additional ground station for achieving high positioning accuracy through phase correlation of the L1 carrier in GPS. Using this system, we were able to achieve horizontal accuracy of around 5 cm in real-time and provide very accurate flight patterns producing rather good georeference of captured videos, Fig. 4.

The equipment used for providing videos for the automatic analysis consisted of two different types of UAVs and cameras, able to provide various levels of quality of recorded videos. To test the resolution-related requirements we used a commercial UAV supplied with a high-quality large-sensor camera with interchangeable lenses, the DJI Inspire 1 v2.0 with the X5R camera. This camera uses a micro 4/3" sensor able to provide a good dynamic in various lighting conditions and the camera itself is capable of storing videos in different compression formats and even without compression at all. This UAV does not have a precise RTK position upgrade for its satellite positioning system and is usable only for defining the optimal capturing conditions. Because of the significant wind, which larger UAVs produce, we decided to fly and capture from a height of around 10 m above the ground, which proved to be a good compromise between rather low wind disturbance and swath captured by a camera equipped with a 50 mm (equivalent to 35 mm system) lens. Capturing in non-compression mode did not provide significantly better results and the tradeoff between the size of captured sequences towards the image quality was not enough for it to be favored. Therefore, we used H.264 compression and 4 K resolution of 3840 × 2160 pixels. Another UAV, built specially for this task, is a large hexacopter capable of carrying different camera sizes, equipped with the Here+ RTK GPS positioning upgrade. This system allows longer flight times, depending on the used batteries, and precise hovering

Fig. 3. Preconcentrator cartridges in the colony entrance. The “In” cartridge for returning bees is on the left and is fully inserted into the beehive to provide a landing site for the incoming bees, with the “Out” cartridge on the right visibly protruding from the hive.

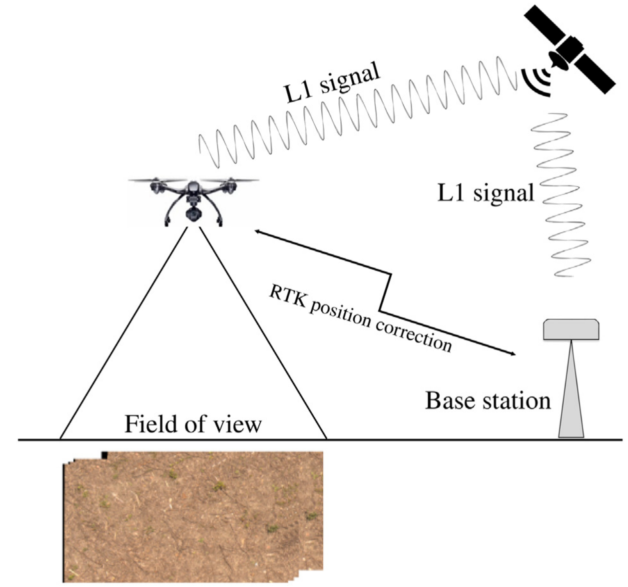


Fig. 4. UAV-based system for capturing 4 K georeferenced videos using GPS-RTK enhancement for achievening positioning accuracy at centimeter-level.

over the observed area with high stability and low wind generation. For capturing, we used a GoPro 6 Black camera with 1/2.3" sensor, modified with a narrow angle lens of 47 mm equivalent to 35 mm system and capturing in the same 4 K resolution. This system provides up to 30 min of hover time and a constant capture with a high positional accuracy and rather small file sizes at the output, which saves time for the data transfer and processing of videos.

2.5. Video analysis

The video analysis is based on the method for detection of small moving objects in UAV videos proposed in Stojnić et al. (2021). The main steps of this method are video stabilization, background estimation and subtraction, frame segmentation using a CNN, and thresholding the segmentation result. Since videos are captured using an UAV hovering over a specific place, video stabilization is performed by estimating an affine transform between the current and first frame of the sequence and then warping all frames into the common reference frame. For background subtraction, a temporal window of frames is used for estimating the means and standard deviations of all pixels across the frames. The obtained means constitute an estimate of the frame background. It is pixel-wise subtracted from each frame and the difference is divided by the estimate of standard deviations. The groups of five background subtracted frames are then fed to a CNN trained to segment the small moving objects. Finally, the segmentation result is thresholded.

The frame segmentation CNN was trained on groups of background subtracted frames extracted from synthetic sequences. Those sequences were generated by adding artificial honeybees, modeled as elliptical blobs, to real-world background sequences containing grass and bare soil. The background sequences were recorded using an UAV mounted camera in the same setup as was used for honeybee monitoring at the test site. Finally, the threshold value was chosen in such a way as to maximize the F1-score obtained for synthetic validation sequences. Each connected component in the thresholded frame is considered as a single detection. We accumulated all the detections in each video with regards to their locations to obtain a spatial density map of honeybee detections. Having in mind that landmines are much larger than individual honeybees, we divided the frames into spatial bins of the specified size and considered all detections within the same bin to be at the same location. In this way, we reduced the amount of data while maintaining the resolution of a spatial density map comparable to the size of landmines. We used elevated detection counts in spatial density maps as predictors of the presence of landmines.

We monitored the behavior of honeybees over the test area using UAV-mounted cameras recording 4 K video at 25 fps. From the available video recordings, we cut sequences with length of 90 s in which we performed detection of honeybees. We used the publicly available code, trained CNN model, and hyperparameter values from Stojnić et al. (2021). By monitoring the area during the recording, we did not observe a significant presence of other flying insects. Therefore, although the used detection method responds to all small flying objects, we may assume that the flying objects in the recorded sequences are indeed honeybees. The detections are accumulated for the complete duration of the analyzed video sequence resulting in a spatial density map of honeybee detections. The monitored area was split into bins of size 64 × 64 pixels, corresponding to roughly 128 × 128 mm and the number of detections in each bin was determined. Having in mind that anti-personnel landmines typically have diameters ranging from 60 mm to 140 mm (Keeley, 2003), the chosen bin size is sufficient to significantly reduce the area that should be manually examined. We visualized the obtained spatial density maps using heatmaps resized to the size of the original frames. For resizing the heatmaps we used nearest neighbor interpolation.

Honeybees were detected independently in each frame and tracking was not performed so the same honeybee could be detected multiple times in different frames. In this way we obtained the information about honeybees spending a prolonged period of time in a certain area which could be an indication of the presence of TNT odor and, consequently, an unexploded landmine.

3. Results and discussion

3.1. Passive sampling for area surveying

Results of fluorescence sensing measurements of preconcentrator samples collected at the Benkovac test site in September 2019 are shown in Fig. 5. The black bars represent control samples, where a sensor is monitored over the same heating procedure as outlined above, but with no preconcentrator in the chamber. This provides a check against contamination in the chamber that could lead to false positives. The red bars indicate the remaining photoluminescent emission from

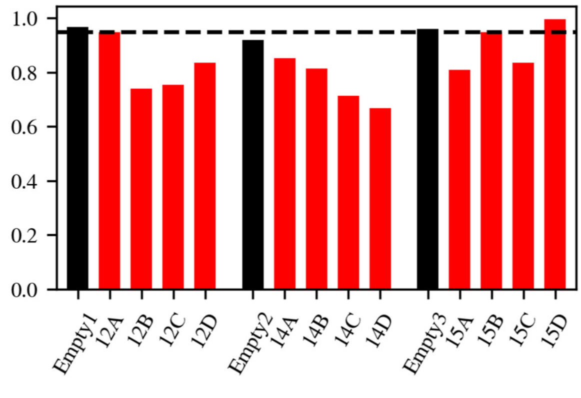


Fig. 5. The remaining photoluminescence from the explosives sensor after exposure of colony entrance preconcentrators to Merck Super Yellow films are shown with red bars. Black bars show reference measurements between every four sample measurements. The horizontal black bar shows the average loss in photoluminescence of the reference samples (from a normalised initial fluorescence signal of 1 a.u.). This result indicates that the tested area has explosives contamination, and so should be investigated by the active search. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Super Yellow films after exposure to explosives desorbed from the preconcentrator strips. The spread in results, from minimal quenching to approximately 35% loss, indicated a different load on each strip, likely due to variations in number of bees passing through each tunnel, and the explosive load carried by individual bees. This result indicates the site is contaminated with landmines, and that the active search should be next deployed to identify individual mines in the field.

3.2. Active search for landmine detection

3.2.1. The first field experiment

The first field experiment took place at the test site in Cerovac on August 27th, 2020, between 11.00 AM and 2.00 PM. The temperature was 29 °C, humidity 48%, pressure 1014 mbar and wind speed 3kmh^{-1}, as recorded by the weather station of Croatian Meteorological and Hydrological Service in Karlovac. The goal of the first experiment was to test the ability of the system to localize landmines.

Conditioning procedures used in our experiment are based on the natural mechanism of bees associating odor with food source. Composition of feeders is simulation of the flower, targets with food reward and controls without reward. Conditioning on colony level is complex, so to avoid influence of surrounding food sources and to force bees to connect target odor with food reward we conditioned bees in a semi-controlled environment (mesh tent), as described in Section 2. TNT is produced artificially, consequently it is not naturally related to the food source.

Honeybees learn fast but also they stop foraging activity on specific odor if food reward is diminished. In order to keep the interest of bees to specific odor continuous reconditioning is needed. Reconditioning was done at the minefield with honeybees free flying from seven hives. Success of reconditioning was tested by replacing the targets with control feeders. When bees found the target immediately after replacing, colony was ready for recording on a test minefield. Results of Gruter et al. (2011) show that volume, concentration and number of rewards increase the foraging constancy up to 98,6%, when ecologically realistic rewards are present.

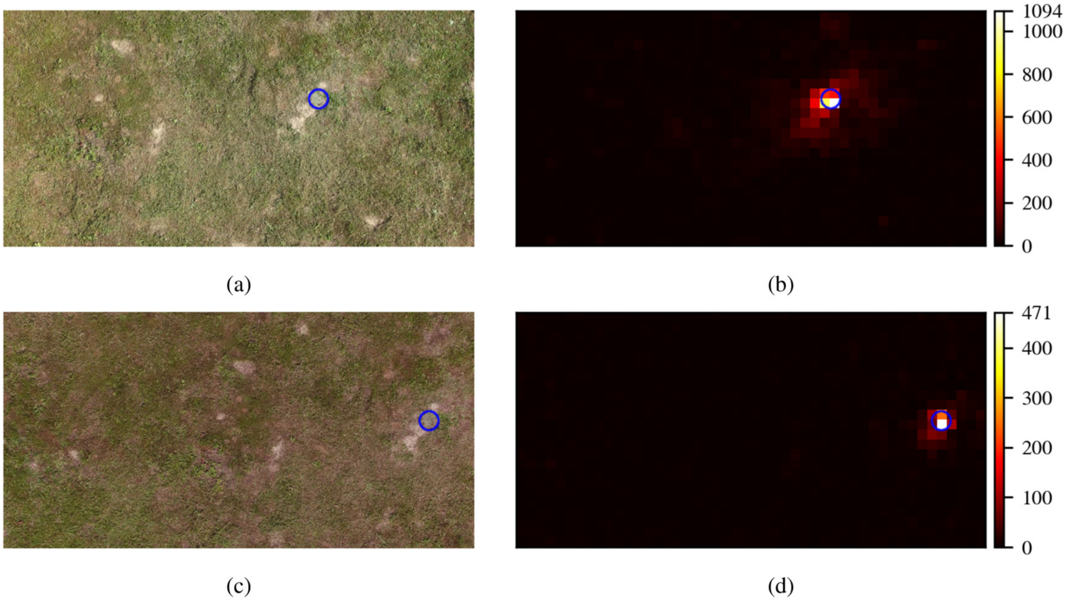
The heatmaps produced by applying the described approach on the available video sequences in the first field experiment are shown in Figs. 6 and 7. We used two recordings of both the squares C4 and G5. In each figure the example frames from the test sequences, as well as the colorbars showing the color coding for detection counts are also shown. Locations of landmines are marked with blue circles in the shown example frames and heatmaps.

The heatmaps shown in Figs. 6 and 7 indicate that there is a good agreement between the actual locations of landmines and locations where elevated honeybee detection counts are observed. In all cases the detection counts are considerably higher in the vicinity of the landmine than at distant locations. Since we detected honeybees in each frame independently of other frames and did not perform honeybee tracking, the obtained results show that the honeybees tended to spend more time in the vicinity of the landmines, which are the sources of TNT odor. It should be noted that the total count of detections is considerably larger in Figs. 6b and 7b than in Figs. 6d and 7d, resulting in more pronounced peaks in the heatmaps. This is a consequence of the larger number of honeybees flying during the specific recording sessions. It should be noted that, in general, the numbers of detected honeybees between recording sessions should not be compared because many factors, such as weather conditions, time of the day, time of the year, needs of the colony (pollen, propolis, water), and individuality, influence honeybee behavior (Eckert et al., 1994; Abou-Shaara, 2014). Nevertheless, in Figs. 6d and 7d, the honeybee detection counts in the vicinity of landmines are still several times higher than in the rest of the frame, making them a strong cue of the landmine presence. The widths of all peaks are around 4 × 4 bins, corresponding to 0.5 × 0.5 m, which provides a good localization of the landmines.

3.2.2. The second field experiment

The second field experiment took place in Cerovac on September 7th, 2020, between 14.30 PM and 17.00 PM. The temperature was 24, humidity 60%, pressure 1020 mbar and wind speed 2kmh^{-1}, as recorded by the weather station of Croatian Meteorological and Hydrological Service in Karlovac. In this experiment, our main goal was to eliminate the influence of the landmines being visible. In order to do this we covered them using grass and soil that fitted into the overall look of the field and monitored the behavior of honeybees as described previously.

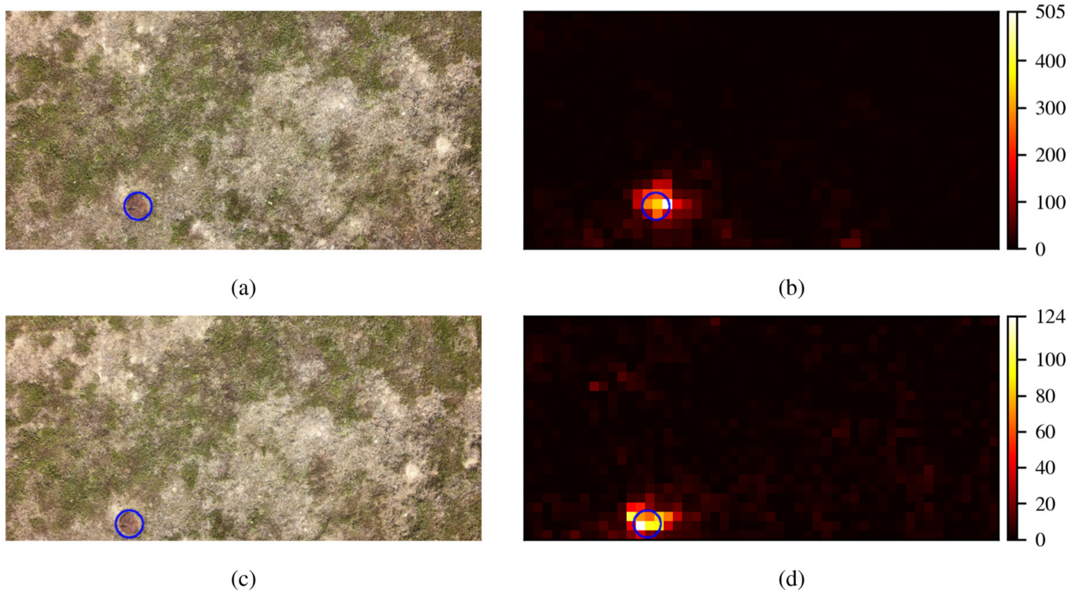
The results of this experiment are shown in Figs. 8 and 9. The locations of landmines are again marked with blue circles in the shown example frames and heatmaps. We can see that the landmines are not



(a) (b)

(c) (d)

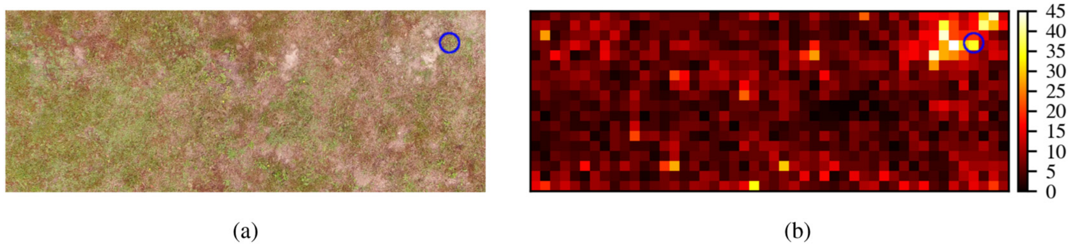
Fig. 6. Results on two sequences recorded over a segment from square C4 of the mine field on August 27th, 2020. (a), (c) Example frames. (b), (d) Corresponding heatmaps. Actual locations of the landmines are marked with blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

(c) (d)

Fig. 7. Results on two sequences recorded over a segment from G5 of the mine field on August 27th, 2020. (a), (c) Example frames. (b), (d) Corresponding heatmaps. Actual locations of the landmines are marked with blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

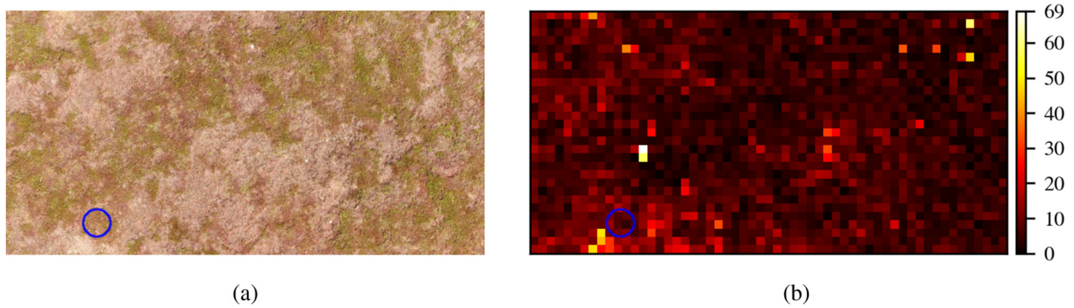


(a) (b)

Fig. 8. Results on a segment from square C4 of the mine field on 07.09.2020. (a) Example frame. (b) Corresponding heatmap. Actual locations of the landmine is marked with blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

easily visually spotted in the video anymore. On the other hand, although there is a considerable number of false positive detections, we can see that there are slightly more detections in the areas near the landmines. Nevertheless, it should be noted that this trial was done when bees had already started to prepare for winter so the total number of bees actively searching for the odor of TNT was significantly lower. It might be possible to compensate for the low number of foraging honeybees by monitoring the area for an extended period. However, as mentioned in Section 2.4, the recording time is limited by the battery capacity. Because of this limitation, in the future work we plan to investigate mitigating the problem of the low number of foraging honeybees by using more honeybee colonies.

In contrast with the results in Figs. 6 and 7, in Figs. 8 and 9 the detection counts are more leveled. We can still observe the peaks of detection counts but they are not as pronounced as in the previous experiments and peaks of similar heights can be observed in several locations in the frame. By visual inspection of individual detections at these locations we observed that they corresponded to small flowers and tips of grass blades moving in the wind produced by the rotors of the UAV. In many cases it is hard, even for human observers, to visually distinguish between the honeybees and these irrelevant moving objects. Furthermore, many of those false positive peaks are very narrow, often comprising 1-2 bins, which is less likely to be associated with landmine presence since circles that honeybees make in the vicinity of a potential



(a) (b)

Fig. 9. Results on a segment from square G5 of the mine field on 07.09.2020. (a) Example frame. (b) Corresponding heatmap. Actual locations of the landmine is marked with blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

source of food are wider than the bin width resulting in wider peaks. Consequently, even though there are multiple locations with elevated detection counts in Figs. 8 and 9, it is important to note that elevated detection counts can still be observed in the locations corresponding to the landmines.

4. Conclusion

In this paper we proposed a biohybrid system for detecting landmines suitable for area surveying and post-clearing quality control. The system features two detection methods, passive sampling and active search, both using honeybees as biosensors. The passive sampling method relies on honeybees bringing explosive particles back to the hive and their subsequent detection using organic semiconductor sensing films. The field experiments on test sites showed that the passive method enables surveying of an extended area for explosive contamination but it cannot localize the landmines. To this end we use the active search method with honeybee colonies conditioned to search for explosive vapors during foraging flight, UAV-mounted cameras to monitor free-flying honeybees, and video analysis to detect honeybees and build a spatial map of honeybee detections. The field experiments on test sites found that the spatial maps obtained using the active search show increased counts of honeybee detections at locations corresponding to the actual locations of the landmines.

The performed field experiments suggest that the proposed system potentially enables post-clearing sampling of a larger area compared to conventional methods, opening up the possibility to improve safety and quality control. Using honeybees as chemical biosensors is a promising approach because they are present all over the world and it is possible to use honeybees from commercial beekeeping practice. Additionally, short preparation time, low costs, the ability to scan a large area in a short time without direct contact with landmines, no need for sampling of the biological material, and no need for human intervention also make them potentially good detectors. Compared to the current surveying and detection techniques, this system offers significant advantages. For instance, the costs associated with traditional surveying methods are higher than in this system. The use of honeybees reduces the risk to humans performing surveying and demining, and the practical issues with the deployment of sniffer dogs are removed. Finally, the timescale with this approach to identify contaminated areas and individual mines is much shorter – it is expected to survey and detect within two or three weeks, compared to the many months current landmine detection methods take to complete. Both methods have the potential to be scaled to surveying a larger area by increasing the number of the used colonies. Furthermore, in the case of the active method, this system can be further upgraded to allow simultaneous flight of multiple UAVs, providing better results because the video analysis step will use the videos containing honeybees spread over the large captured area.

Although the active search is effective for landmine localization it is important to note that its limitations, mentioned below, preclude its usage for large area surveying. On the other hand, passive sampling is less demanding in terms of the use of honeybees, does not require their conditioning, depends less on the nature of the terrain and weather conditions, and is able to scan a wider area for the presence of explosives. Therefore, we propose a two stage procedure in which passive sampling is first used to narrow the area where the active search should subsequently be applied.

There are limitations for using honeybees in both methods. Main biological limitations are intensive nectar flow, unfavourable weather conditions, and time of the year regarding the biological cycle of honey bees. In the passive sampling, the honeybees are limited by availability of foraging areas, local weather, and season. As for the active search, there are two main limitations. First, the recording time is limited by the battery capacity, which may result in false negatives when the total number of foraging honeybees is low. Second, it is difficult to detect and track honeybees in a terrain with medium to high vegetation because honeybees will either fly at lower altitudes compared to the vegetation height, or movements of grass or leaves, caused by the wind produced by UAV rotors, could result in false positive detections.

Potential improvements to the passive sampling method include developing preconcentrator materials with higher affinity to particular explosive materials, like 2,4-DNT. As for the active search method, in the future work we plan to focus on reducing the detrimental effects of false positive detections by training better CNN models for detection of flying honeybees. We also plan to investigate the possibility of scaling the system by increasing the number of used honey bee colonies and UAVs.

Data availability

The data presented in this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.4922817. The code used for the experiments is openly available at https://github.com/vladan-stojnic/Detection-of-Small-Flying-Objects-in-UAV-Videos.

CRediT authorship contribution statement

Janja Filipi: Methodology, Resources, Investigation, Writing—original draft preparation, Writing—review and editing. **Vladan Stojnić:** Conceptualization of this study, Methodology, Software, Investigation, Data Curation, Writing—original draft preparation, Writing—review and editing. **Mario Muštra:** Conceptualization, Methodology, Investigation, Writing—original draft preparation, Writing—review and editing. **Ross N. Gillanders:** Conceptualization, Methodology, Resources, Investigation, Data Curation, Writing—original draft preparation, Writing—review and editing. **Vedran Jovanović:** Software, Writing—review and editing, Visualization. **Slavica Gajić:** Software, Writing—review and editing, Visualization. **Graham A. Turnbull:** Conceptualization, Methodology, Validation, Funding acquisition, Writing—original draft preparation, Writing—review and editing. **Zdenka Babić:** Conceptualization, Validation, Funding acquisition, Writing—review and editing. **Nikola Kezić:** Conceptualization, Validation, Resources, Funding acquisition, Writing—review and editing. **Vladimir Risojević:** Conceptualization, Methodology, Software, Data Curation, Writing—original draft preparation, Writing—review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was funded in part by NATO Science for Peace and Security (SPS) Programme, project number SPS 985355, “Biological Method (Bees) for Explosive Detection”.

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