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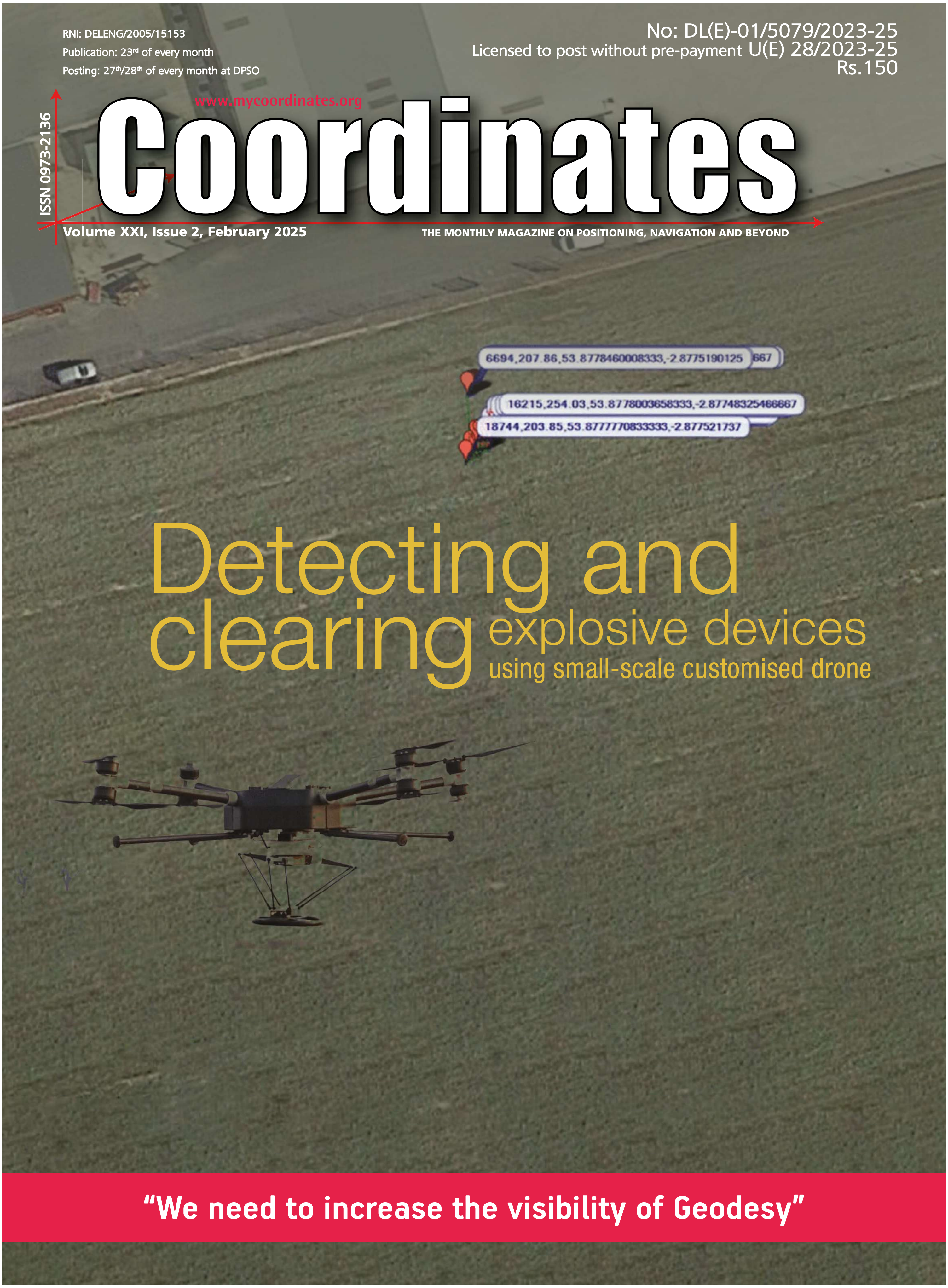
THE MONTHLY MAGAZINE ON POSITIONING, NAVIGATION AND BEYOND



Detecting and clearing explosive devices using small-scale customised drone

"We need to increase the visibility of Geodesy"

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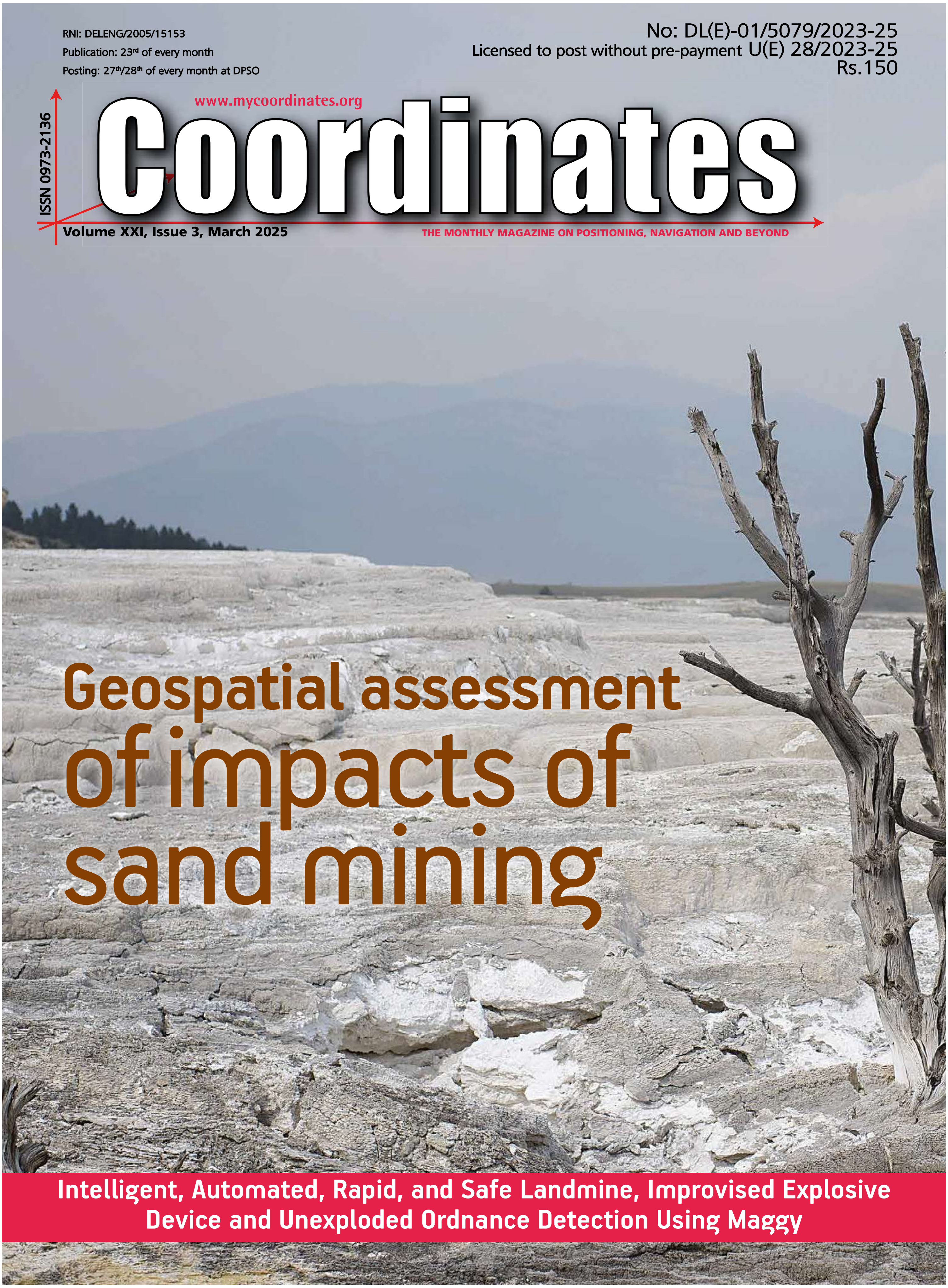

Geospatial assessment of impacts of sand mining

Intelligent, Automated, Rapid, and Safe Landmine, Improvised Explosive Device and Unexploded Ordnance Detection Using Maggy

Intelligent, automated, rapid, and safe landmine, improvised explosive device and unexploded ordnance detection using Maggy

In this study, a small-scale customised drone – the so- called Maggy – was developed to simplify and automate the procedures of cleaning explosive devices. Readers may recall that we publsihed the first part of the paper in February issue. We present here the concluding part

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Experimental Results

The functions of the prototype magnetometer-integrated autonomous drone – Maggy – were improved in the lab environments with numerous trial iterations and its viability in realising aforementioned targets was validated in the benchmark test fields with benchmark outputs as explicated in the following subsections. The use of the tablet application (Fig. 16) for the streamed data and old survey analysis is explained in [67] with a video.

A. Lab Tests With Maggy

In the lab environment, design of sensors and their integration with the drone components were extensively tested to find out i) the ideal component integration that avoids extreme magnetic interferences and ii) ideal configuration that ensures that subsequent sensor trials are reliable with repeatable and valid values under similar conditions. The acquired test data set was used to establish the classification and clustering algorithms with respect to the chosen MF threshold value (Fig. 16) as elaborated in Section III-B2.

The results obtained from the earlier trials in the lab environment with 1 m/s, 2 m/s, and 3 m/s flight speeds and 0.5, 1 m, and 2 m altitudes demonstrated that 1 m/s flight speed and 0.5 m altitude outperformed other parameters, namely, 2 m/s, and 3 m/s flight speeds and 1 m, and 2 m altitudes. More specifically, the detection accuracy of MF decreases significantly, primarily, for the explosives with less metallic parts, as the flight/sensor

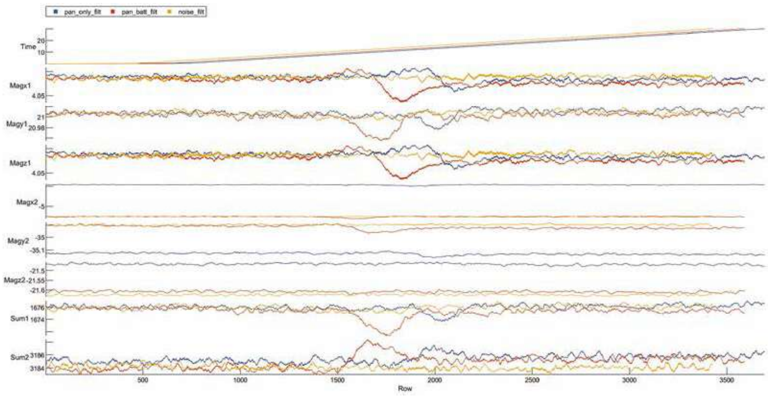

FIGURE 17. Change of MF values in the three axes with the two magnetometers when encountered a high MF. The total magnetic strength/intensity is shown at the bottom for two magnetometers.

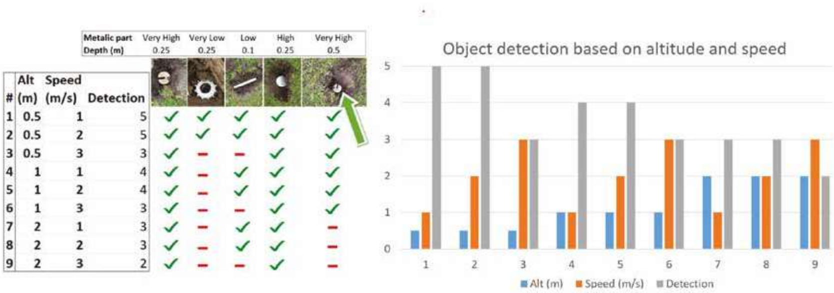

FIGURE 18. Nine test scenarios: The test results of Maggy for 5 different types of landmines with varying features. The green arrow shows the direction of Maggy during testing for each landmine separately. Maggy operates with high detection accuracy at low altitudes and speeds (i.e., 0.5 m, 1 m/s).

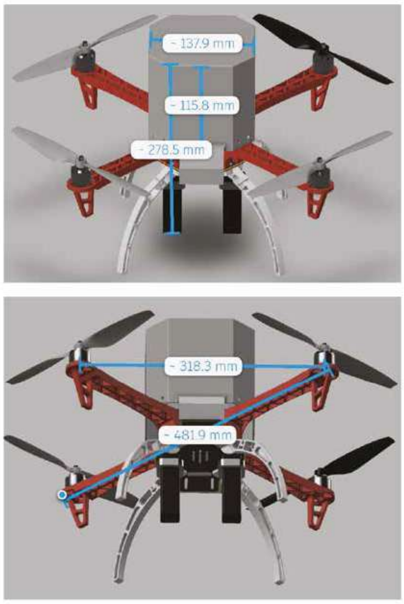

FIGURE 19. Shielded Maggy.

FIGURE 20. Autonomous use of Maggy in the UCLan landmine field. All data points.

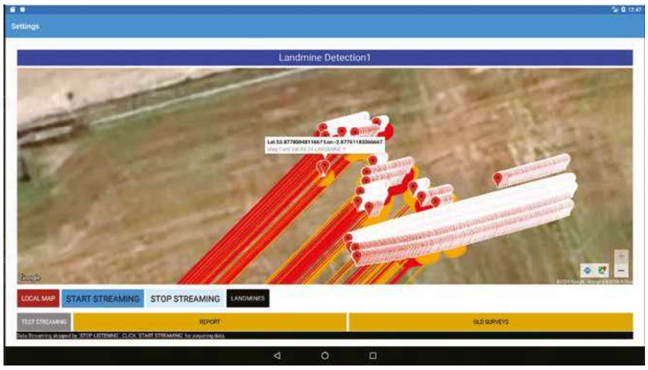

FIGURE 21. Landmine locations, until the current scanned point in the route, shown by user during data streaming while Maggy is still in operation.

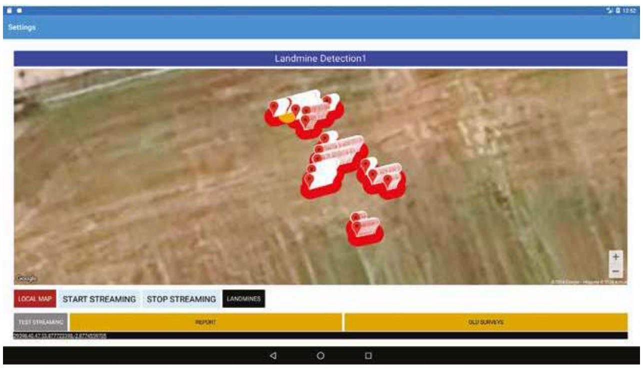

FIGURE 22. All landmine locations, with "very high" MF (red), shown by the user.

FIGURE 23. Landmine locations, with "very high" (red) and "high" (orange) MF, shown by the user.

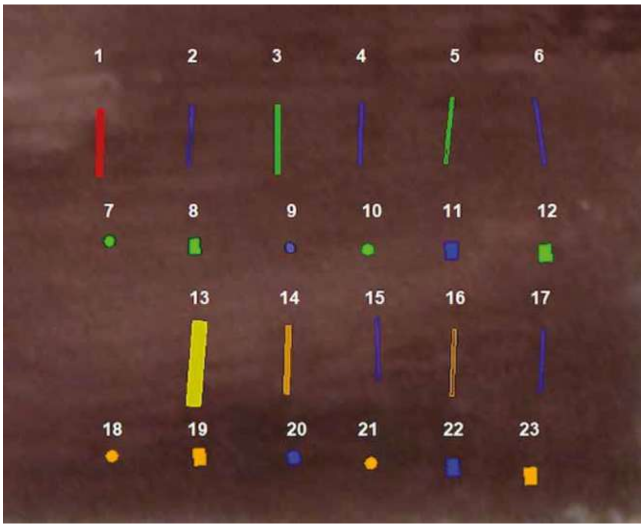

FIGURE 24. Latvia landmine/UXO/IDE field locations (Table 5).

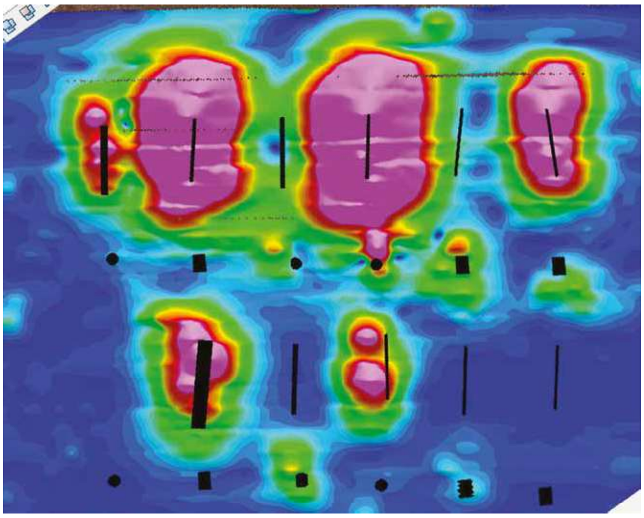

FIGURE 25. Geometric measurement of MF of the objects depicted in Fig 24) using the MagArrow Magnetometer[8].

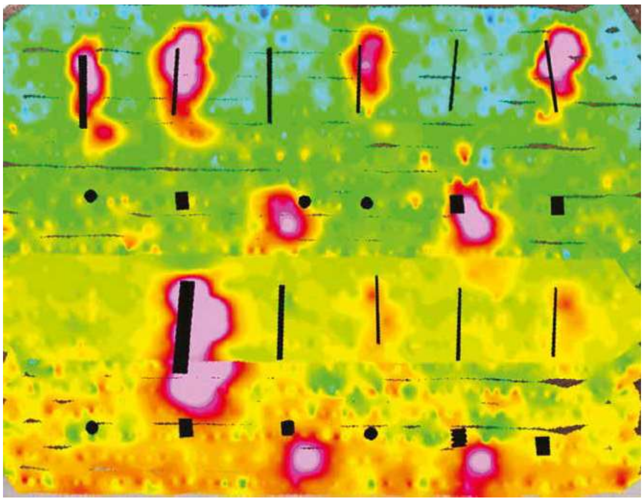

FIGURE 26. Geometric measurement of MF of the objects depicted in Fig 24) using the metal detector[9].

altitude increases and the flight speed increases. The MF values of various landmine/UXO/IDE were measured by Maggy and one of the acquired results is presented in Fig. 17. The change of MF values in the X, Y, and Z axes with the two magnetometers are demonstrated. The MF values of the targeted object can be distinctively noticed when encountered a high MF. The test results of 9 test scenarios for 5 different types of landmines with varying features are presented in Fig. 18. The noise level considerably rises with the speed increase. The increase in altitude hinders the ability to detect buried objects at deeper depths. The lesser the metallic parts the lesser the magnetic field. Operating at a height of less than 0.5 m (e.g. 0.25 m) not only puts operation safety at risk despite the terrain following capability of Maggy, but the echoed acoustics from the ground also significantly increase noise levels, making the detection impossible. Maggy operates with high detection accuracy at low altitudes and speeds (i.e., 0.5 m, 1 m/s). Maggy was tested in real benchmark test fields as explained in Section IV-B after it passed its tests in the lab environment. To summarise, the test results in the lab environment were instrumented to determine the ideal parameters for Maggy considering its design and configuration.

B. Real Field Tests With Maggy

Maggy was covered with a shield as shown in Fig. 19 to protect the electronics from bad weather conditions, especially, from rain. In this way, Maggy can function under rainy conditions. It is noteworthy to emphasise that Maggy cannot resist heavy windy conditions due to its lightweight design. Maggy operated with 1 m/s flight speed and 0.5 m altitude. The ability to fly under 1 m altitude and very low speed increases the magnetometer sensor performance significantly as explained in Section IV-A. Maggy was tested in the UCLan landmine field and the Latvia test field.[7] The results of these tests are explained in the following subsections.

1) Real Field Tests with Maggy at the Uclan Landmine Field

The landmines in the UCLAn landmine field (Fig. 6) were buried between 15 cm to 50 cm depth as shown in Fig. 9. Several off-the-shelf UAV-mounted sensor modalities such as GPR and magnetometer (Fig. 5) were already tested by the UCLan ASR team successfully. In those tests, the MF map of the UCLan landmine field was constructed with detailed information as shown in Fig. 7 and the disclosed landmine field spots are shown in Fig. 8. The UAS, flying with an altitude of 1 m at a 1 m/s flight speed (Fig. 6), was able to detect 21 landmine spots out of 25 successfully with an accuracy rate of 0.84. The large size of the drone, causing high noises with interferences, i.e., the echoed acoustics from the ground at an altitude lower than 1 m, didn't let us fly at lower altitudes. Consequently, 4 landmines weren't detected where 2 of them, composed of large metallic parts, were at the depths of 0.5 m and 0.25 m and the other 2 of them, composed of little metallic parts, were at the depths of 0.5 m and 0.25 m. Maggy was deployed in the same landmine field in an autonomous mode with the previously tracked waypoints to conclude if the developed approaches considering all the components of Maggy and their integration with one another were functioning as desired. The MF formation of the landmines with metallic objects is demonstrated through real-time data streaming in the IEEE DataPort [67] with a video using the earlier version of the application. All scanned points are displayed in Fig. 20. The "very high MF" locations, highlighted by red colour, are disclosed in Fig. 22 and "high MF" locations, highlighted by orange colour, are shown in Fig. 23 together with the "very high MF" locations. Maggy was found to be performing satisfactorily in revealing the pre-mapped MF locations (Fig. 8). Maggy was successful in finding 24 landmine spots out of 25. One landmine at a depth of 0.5 m with little metallic part couldn't be detected by Maggy. It is noteworthy to emphasise that "very high MF" locations (red) are surrounded by "high MF" (orange), which indicates that Maggy can show the hot/red MF spots inside orange circles when the field is scanned densely. Fig. 21 shows that the user can disclose the previous hot spots while Maggy, with multi-processing ability, is in operation. Maggy accomplished its operational objectives in these field tests in finding landmines with metallic parts, having an accuracy rate of 0,96. This field test demonstrated that the development of lightweight drones like Maggy, with reduced interferences/noise enabling low-altitude flights, improves the detection of landmines/IDE/UXO significantly.

2) Real Field Tests With Maggy at the Latvia Field

The size of the Latvia test field is 450×70 meters with permanently installed objects as elaborated in Table 5 and as illustrated in Fig. 24. The MF formation of the field was already obtained as presented in Figs. 25 and 26 using two different sensor modalities, namely, the MagArrow magnetometer and metal detector. Maggy can rapidly scan a large terrain, providing near real-time survey data. However, Maggy flew a few straight lines over known targets as displayed at the top of Figs. 27 and 28 due to the battery limit during our flight from the UK to Latvia. The battery does not last very long. Each full battery can function for up to 4 min 30 sec at low-speed flying, which restricts the scanning of larger areas, especially, at the ideal speed of 1 m/s. This testing provided us with data on the system's sensitivity to detect objects with various quantities of metal content, at various depths, in different soil/surface materials. Maggy was successful in detecting objects in this field as presented in the middle of Figs. 27 and 28. The histograms of MF values along with those straight lines are shown at the bottom of Figs. 27 and 28. The MF locations can be distinctively noticed in those graphs. Maggy completed its operations over 9 objects with metallic parts (Figs. 25 and 26) and it was successfully in spotting the pre-generated high-field areas with a success rate of 1.0. This field test demonstrated that Maggy could detect objects placed at deeper depths such as 1 m and further if these objects have larger metallic parts, enabling large MF. The real-field tests help us understand the abilities as well as the shortcomings of Maggy in operations to find out the improvement points (Table 6) in its design and functionalities, which is discussed and elaborated in Sections V, VI, VII and VIII in different perspectives.

Discussion

Landmines pose a significant threat to civilian populations and humanitarian efforts worldwide in addition to its economic loss as pointed out earlier. Heavily mined low-income countries often cannot afford high-tech landmine/UXO/IDE demining equipment to expedite the clearing activities. Despite the intensive effort spent in finding an effective and efficient approach to demining, a safe semi/fully autonomous method is yet to be realised in finding landmines rapidly and safely in a cost-effective manner. Since the end of the eighties, the start of the first humanitarian mine clearance operations in Afghanistan, the metal detector is still the only trusted sensor used in humanitarian demining [7]. Any technique still needs to be confirmed with a detector to ensure the location of landmines. Detecting and safely removing landmines is crucial for the safety and well-being of affected communities. Therefore, deploying robots for these types of work is vitally important due to their very high potential risks. Autonomous robotic applications are replacing the human force, in particular, for dangerous and labour-intensive tasks in many areas.

Cost-effective UAVs equipped with advanced sensors and AI offer a promising solution for efficient and accurate landmine/UXO/IDE detection. This research aims to develop an integrated drone system capable of detecting landmines/IDE/UXO using magnetometers, and AI-based classification and clustering algorithms ([68]). The evaluation of the developed aerial platform was carried out by processing the experimental data gathered in controlled conditions at the lab and real benchmark test sites. Successful outcomes of the tests in this research show that the platform can empower the humanitarian clearing teams towards the aforementioned challenges, particularly, the threat of explosive devices. Maggy can scan a large area quickly and provide a real-time map of MF generated by on-ground and underground metallic objects. Its compact size enables numerous applications in many demining use cases by providing real-time surveying data. The benefits are a risk reduction to the demining clearing personnel, and/or their vehicles, an increase in safety and an increase in assurance of information. Drone-mounted magnetometers are suggested to be separated from UAS to avoid magnetic interference ([64], [65], [66]) as shown in Fig. 2. But, this increases the motion noise in addition to the wind noise. Other magnetometer systems tend to be physically large, limiting their application to wider open areas with forgiving terrain, expensive, and do not give real-time results which is not desirable to promote freedom of movement. This research shows how the detection and removal of

TABLE 5. Properties of buried objects depicted in Fig 24. Di: Diameter (mm); L: Length (m); D:Depth (m).

#	Target	Di	L	D
1	Stainless steel pipe	110	6.0	0.4 - 1.0
2	Steel pipe 4.0mm wall	500	6.0	1.0 - 2.0
3	PVC pipe EMPTY	110	6.0	0.4 - 1.0
4	Steel pipe 3.0mm wall	314	6.0	1.0 - 2.0
5	PVC pipe EMPTY	160	6.0	0.5 - 1.5
6	Steel pipe 2.5mm wall	200	6.0	0.5 - 1.5
7	Plastic barrel 50L vertical (empty)	400	0.57	0.5
8	Plastic barrel 50L horizontal (empty)	400	0.57	0.5
9	Steel barrel 200 L, vertical	610	0.88	1.0
10	Plastic barrel 100L vertical (empty)	420	0.70	1.0
11	Steel barrel 200 L, horizontal	610	0.88	1.0
12	Plastic barrel 100L horizontal (empty)	420	0.70	1.0
13	Reinforced concrete pipe	1000	8.0	1.0 - 2.0
14	PVC pipe (water filled)	110	6.0	0.4 - 1.0
15	Steel pipe 3.0mm wall	60	6.0	0.5 - 1.5
16	PVC pipe (water filled)	160	6.0	0.5 - 1.5
17	Steel pipe 1.5mm wall	110	6.0	0.5 - 1.5
18	Plastic barrel 50L vertical (water filled)	400	0.57	0.5
19	Plastic barrel 50L horizontal (water filled)	400	0.57	0.5
20	Steel barrel 200 L, diagonal	610	0.88	1.0
21	Plastic barrel 100L vertical (water filled)	420	0.70	1.0
22	Steel barrel 200 L, flattened (crashed)	610	0.88	1.0
23	Plastic barrel 100L horizontal (water filled)	420	0.70	1.0

metallic explosives in humanitarian mine clearance operations can be significantly accelerated by UAVs fitted with magnetometers. The ability to fly under 1 m altitude using an altimeter and at a very low speed (i.e. 1 m/s) increases the magnetometer sensor performance significantly compared to the other flight parameters based on the results obtained from the earlier trials in the lab environment (Section IV-A). The main goal of this research is to host the sensor system on small lightweight robust aerial platforms that can be carried in a backpack and rapidly deployed by humanitarian demining teams. Our idea was born from many years of work, researching the detection of buried landmines using drone-mounted sensors. The design of Maggy has been heavily influenced by real conditions on the ground and after consultation with mine clearance organisations. This research demonstrates that MF generated by landmine/UXO/IDE substantially depend on the depth of objects and the magnitude of the metallic parts. In other words, signatures of buried explosives are site-dependent. Therefore, the developed classification and clustering techniques in this research use field-dependent data sets, without needing a priori training set. All the datasets related to this work will be uploaded to the IEEE DataPort [67] for the researchers who would like to perform similar studies, which will lead to new

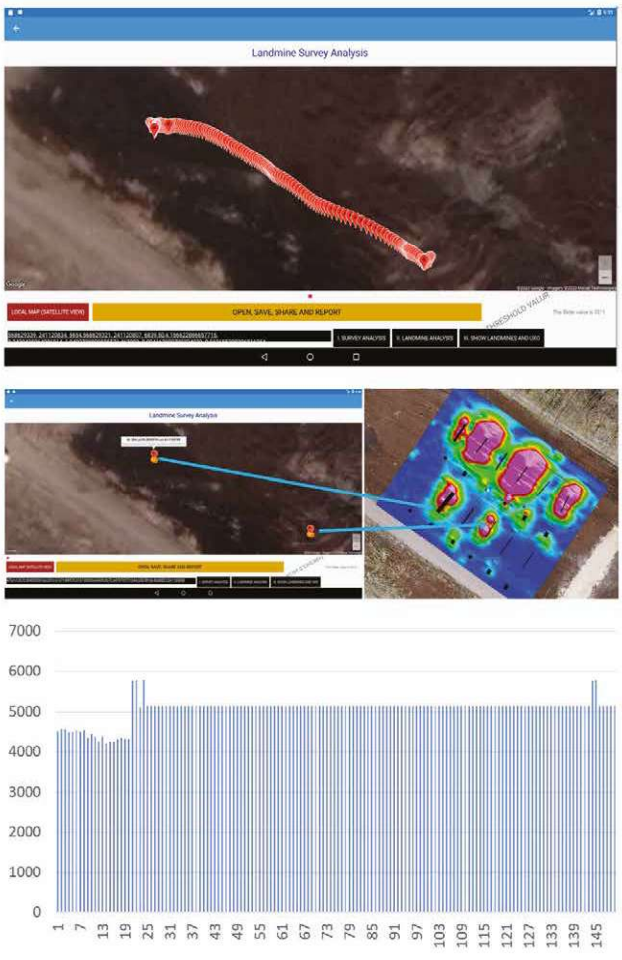

FIGURE 27. Latvia field test -III-. Top: all data points; middle: high MF; bottom: MF graph for all data points in the route depicted at the top.

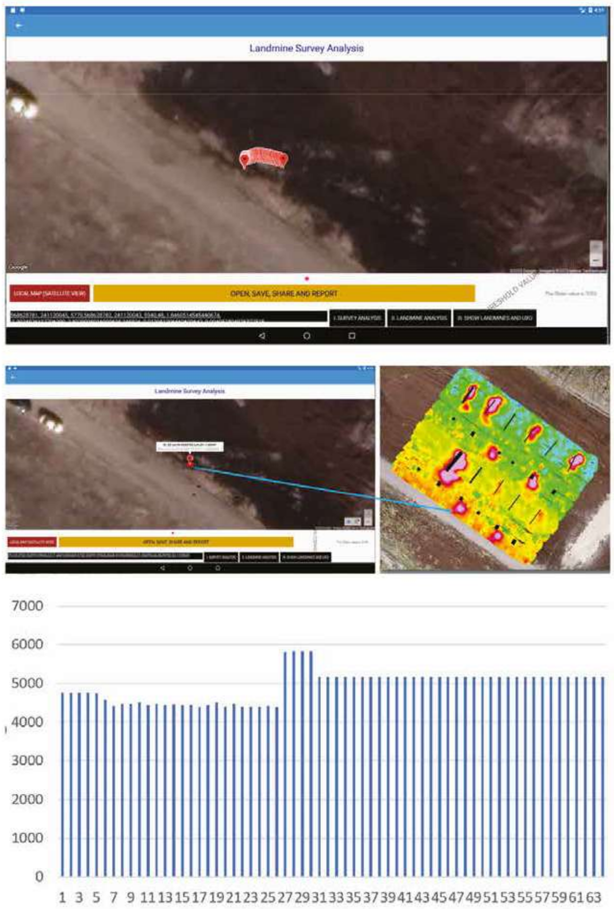

FIGURE 28. Latvia field test -I-. Top: all data points; middle: high MF; bottom: MF graph for all data points in the route depicted at the top. MF is clearly very high at the above location (middle) as shown in the histogram points between 25 and 31.

directions in this specific field. While not all ordinances will have a magnetic signature, many will and on balance risk can be reduced by deploying this system. Maggy's capabilities as well as its features are evaluated in Table 6 with multiple criteria put forth by mine clearance organisations and the current literature research. The study presents a compelling exploration into the use of drones for detecting landmines, IEDs, and UXOs. The integration of advanced sensor technologies, particularly magnetometers, shows the potential of UAVs in humanitarian demining operations, offering a rapid and efficient means of surveying large areas that are often difficult to access. One of the most imperative aspects of this research is the innovative application of UAVs in a domain that is critical for safety and humanitarian efforts. The capability of Maggy to provide near real-time data has the potential to enhance the efficacy of mine clearance operations, potentially saving lives and resources. This research effectively highlights the advantages of using drones over traditional ground-based methods, particularly in terms of speed and safety. Maggy is innovative in the following ways:

- It has been designed to be compact and lightweight.
- It can provide near real-time scanned streaming data to the user, which is displayed on a small tablet/smartphone device.
- It is low-cost compared to commercially available magnetometer systems.
- The application can filter streaming data quickly, providing the classification of MF spots as very high, high, moderate, low and very low.
- Multiple numbers of similar platforms can be deployed as a swarm to expedite the clearing process. The developed application can stream data from multiple platforms simultaneously.

TABLE 6. Evaluation of Maggy.

#	CRITERIA	✓/-	NOTES
1	Detection of all explosive types	-	only explosive objects with ferrous metals can be detected by Maggy.
2	Determination of the type and composition of metallic objects	-	only MF location of metallic objects can be detected.
3	Small and light weight	✓	Fig. 19, payload < 1 kg.
4	Manoeuvrable	✓	rotary, vertical take-off and landing.
5	Terrain following mode	✓	Maggy uses a radar altimeter.
6	Autonomous/automated mode	✓	Maggy uses UgCS system – drone flight planning software.
7	Low energy consumption	✓	Fig. 19, payload < 1 kg, most of the processing and computing is performed by the tablet application.
8	Good flight time, long battery life	-	Maggy can fly 4.5 minutes per battery
9	Robust	✓	Maggy was designed to perform robustly (Figs. 11, 12, 13, 14). The GPS component will be replaced with a robust one.
10	Accurate/reliable	✓	Maggy is tested in the benchmark test fields with the benchmark outputs.
11	Air-to-ground data streaming	✓	Maggy provides near real-time scanned streaming data to the user while in operation.
12	Real-time data processing	✓	Maggy provides real-time scanned streaming data to the user, which is displayed on a small tablet/smartphone device.
13	Easy to use/off the shelf	✓	Maggy is a compact tool.
14	User friendly	✓	30 minutes of training is sufficient to use Maggy effectively.
15	Resource friendly	✓	not resource-hungry processing. Ability to run ordinary computing device.
16	Ability to analyse old surveys	✓	AI-based tablet/smartphone application provides users with multiple decision-making abilities.
17	Classification and clustering abilities	✓	AI-based tablet/smartphone application provides users with multiple decision-making abilities.
18	Ability to fly under 1 meter	✓	to increase the efficacy of sensors.
19	Small footprint	✓	Fig. 19, payload < 1 kg.
20	Accessible, low-cost, affordability	✓	Maggy is low-cost compared to commercially available magnetometer systems.

Conclusion

The cost of clearance is estimated to be USD 300-1000 per mine using conventional techniques and 1 person dies for every 5000 mines removed [69]. Mine clearing needs are in high demand all around the world. This study mainly aims to build new fully automated landmine/UXO/IDE detection systems in a time-and-cost-efficient manner. Capable of vertical take-off and landing and flying at very low altitudes with low speed makes rotary drones easy to use and efficient in humanitarian clearing operations, if equipped with effective sensor technologies and AI with proper configurations. The near real-time data provided by a UAV-integrated magnetometer system can greatly improve mine clearance operations. In this direction, the methods created in this study address the drawbacks of ground-based operations, such as high operator risk and inefficiency, and provide a quicker, safer, and more economical substitute for conventional landmine/UXO/IDE detection techniques. The developed platform in this work, the so-called Maggy, is a small, lightweight drone that can be rapidly deployed by a demining team to scan a large area for any magnetic anomalies caused by the presence of metal in landmine/UXO/IDE. It helps accelerate the speed of clearing operations across large and tough terrains or other hazardous land areas, reducing risk, increasing assurance, and improving safety for the humanitarian team. More specifically, as evaluated in Table 6, the compact, lightweight, real-time magnetometer aerial surveying system – Maggy – can scan for the presence of ferrous metal, and real-time detection information is displayed on a tablet/smartphone device (Fig. 16). The tablet/smartphone application ([67]) overlays detection information on a satellite map image of the survey site. Highly risky terrains can be surveyed by cost-effective Maggy to turn the area into low-risky areas using safer and faster scanning approaches than conventional methods. The risk to human operators can be reduced significantly with Maggy. This research provides the related research community and industry with fundamental design and implementation parameters (e.g. flight speed, flight altitude) in building and using magnetometer-integrated UAS.

Limitations

The features of Maggy are evaluated in Table 6 with its shortcomings. Maggy uses only magnetometer sensors which detect MF created by metallic objects. Therefore, landmines/IDE/UXO with no or fewer metallic objects may not be detected. Maggy cannot operate long due to its short battery life, which necessitates the use of multiple batteries for consecutive operations. The type and composition signature of metallic objects cannot be determined by Maggy. The use of Maggy is suggested in detecting explosives which consist of large metallic objects and in detecting metallic landmines. Additionally, Maggy cannot function properly under heavy windy conditions due to its lightweight feature.

Future Research Ideas

The battery life and operating time of Maggy in the field will be enhanced. We aim to develop another UAS, that is fully integrated with Maggy, to spray/paint red/high MF spots to direct clearance teams appropriately in reducing risks while Maggy is in operation. A quadrotor drone equipped with magnetometers [70] demonstrated the necessity of combining magnetometer data with other geophysical techniques to improve detection accuracy considering all types of explosives. In this direction, sensor data fusion is successful and a way to decrease the number of false alarms for detection [1], [71]. Multiple sensors can be employed simultaneously to fuse the acquired data instances at a time for better decision-making (Fig. 7). We would like to incorporate other sensor modalities such as GPR and vision-based remote sensing sensor modalities (i.e. IR, LWIR camera, and multispectral camera) into Maggy as the size and weight of these modalities decrease. UCLan and Qatar University are collaborating on a funded project to build bespoke drone systems with the major sensor modalities.

The results of this work confirm the viability of our aerial-based system. Therefore, Maggy can be deployed in real minefields in mine-plagued countries such as Afghanistan, Cambodia and Croatia to support the removal of the landmines safely. Maggy will be tested in Cambodia in larger mine-affected areas in cooperation with the Cambodian Army to quantify the observed results in more difficult scenarios. Current results show promising directions for future research ideas. Similar studies continue to be an area of active interest involving other industries. The techniques and approaches developed in this research can be exploited by various industries for a wide spectrum of application areas such as aerospace, defence, and archaeology as well, in particular, for archaeological surveys, infrastructure inspection, the detection of buried metallic objects, forensic investigations, and security applications. More explicitly, Maggy can help locate artefacts, buried structures, and archaeological sites without the need for excavation. Additionally, real-time automatic mine detection on battlefields can be carried out by Maggy.

In conclusion, while the Maggy presents a promising advancement in UAV technology for humanitarian applications, for future work, it would be beneficial to explore the implementation of a UAV swarm strategy. Utilizing multiple drones could enhance coverage and efficiency, allowing for simultaneous scanning of larger areas and potentially compensating for individual UAV limitations. Furthermore, optimizing battery performance through improved capacity or better battery management systems as well as low-power sensors ([72]) could significantly extend mission durations and enhance operational effectiveness.

Acknowledgment

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Footnotes

[1] https://www.de-mine.com/projects-1

[2] https://www.de-mine.com/projects-1

[3] https://sensysmagnetometer.com/products/magdrone-r4-magnetometer-for-drone/

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