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

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ABSTRACT Detecting and clearing legacy landmines, Improvised Explosive Devices (IED), and Unexploded Ordnances (UXO) using a force made up of humans or animals is extremely risky, labour- and time-intensive. It is crucial to quickly map millions of buried landmines/IDE/UXO, and remove them at a reasonable cost to minimise potential risks and make this labour-intensive task easier. Using unmanned vehicles and robots outfitted with various remote sensing modalities appears to be the ideal way to carry out this task in a non-invasive manner while employing a geophysical investigative method. In this study, a small-scale customised drone – the so-called Maggy – was developed to simplify and automate the procedures of cleaning explosive devices. It was instrumented with innovative intelligent automated techniques and magnetometer sensor technologies. Maggy's performance was assessed in field tests conducted in Latvia and the United Kingdom. The outcomes, obtained in the open-air minefields and the benchmark assessments, verify the viability of the technologies, methods, and approaches integrated into Maggy for the efficient and economical detection of legacy landmines and IDE/UXO. This research provides the related research community with fundamental design and implementation parameters (e.g. flight speed, flight altitude) in building and using magnetometer-integrated Unmanned Aerial Systems (UAS). The improved versions of the developed easy-to-use compact technology are aimed to be deployed by humanitarian demining teams to expedite their clearing operations safely and efficiently.

INDEX TERMS Landmine detection, unmanned aerial vehicles (UAVs), ground penetrating radars (GPR), UAV-supported detection of landmines, aerial-supported detection of explosives, airborne demining, magnetometer, magnetic field (MF) detection.

I. INTRODUCTION

Detecting and clearing legacy landmines (anti-tank (AT) and anti-personnel (AP)), Improvised Explosive Devices (IED), and Unexploded Ordnances (UXO) using a force made up of humans or animals is extremely risky and labour- and time-intensive [1]. When these explosives come into contact with, are near to, or are in the presence of a person or vehicle, they explode. In particular, AP landmines cause long-term casualties and psychological effects by mutilating, rather than killing. More than 1,000 deminers have lost their lives or suffered injuries while performing demining operations between 1999 and 2012 [2]. All around the world, there are approximately 100 million buried landmines [3] due to the low-cost manufacturing [4] and simplicity of deployment across wide regions. 61 states worldwide are severely impacted [5] by the slow demining process [6]; these include, but are not limited to, Croatia, Bosnia and Herzegovina, Serbia, Afghanistan, Montenegro, Libya, Syria, Iraq, and most recently, the war-torn regions of the west of Ukraine and Azerbaijan. By the end of 2005, Bosnia and Herzegovina declared that there was a possibility that over 4% of their territory was contaminated with landmines [7]. In 1997, two years after the war ended, 23% of Croatian territory was thought to be mine-suspected [7]. 10.413 people in Colombia, one of the nations most affected by landmines worldwide, lost their lives to landmines between 1990 and 2013 [8]. Over 35,000 amputees in Cambodia have been impacted by a landmine explosion [2]. The average number of people killed or maimed annually is 26,000 [9] and 80% of this figure is children [5]. Ten mines are placed for every mine removed, despite recent efforts to reduce their use [10]. The precise locations of legacy landmines that have been buried are unknown, and landmines can shift slightly depending on the features of the land and the time they were buried. Using conventional methods to remove millions of landmines/IDE/UXO would take more than a century [11] with potential risks and high costs [12], which will have a long-term, significant impact on these nations in a variety of ways. Their presence continuously puts communities in danger, obstructs economic growth, and makes it difficult for infrastructure, agriculture, and resettlement to have safe access to land. The development of a landmine/UXO/IDE detection system that is quick, safe, and economical is urgent. Land-based vehicles face a number of challenges, including accurate navigation over rough terrain despite being supported by various mechanisms like wheeled, legged, and dragged robots [13]. Furthermore, it takes a while to scan larger terrain with those slow, heavy vehicles. Autonomous drones have recently been deployed to accomplish a diverse range of missions (e.g. logistics [14], smart cities [15], agriculture [16]), due to their efficient and effective use. Drones can expedite surveying and provide better access to challenging terrain with tough and hard-to-reach topography and thick vegetation [17], [18], [19]. Unmanned Aerial Vehicles (UAVs) suited to covering a large area for the purpose of easing labour-intensive mine clearance have been used in numerous studies with different detection approaches. These studies are analysed in Section II.

Magnetometers consume very little power in addition to their affordable and lightweight features and drone applications can benefit from using magnetometers in a diverse range of applications efficiently and effectively. This work, by developing a magnetometer-integrated Unmanned Aerial Systems (UAS) has been focused on landmine/UXO/IDE detection, primarily, for supporting the humanitarian clearance challenges and constraints around the world – such as the need to operate in unforgiving, undulating terrain, which may be overground with vegetation. The contributions are listed below to make the novelty of this paper clear.

1) A bespoke, low-cost, small footprint, easy-to-use, and autonomous robotic drone – the so-called Maggy (Figs. 14, 15) – integrated with magnetometer sensor modalities (Fig. 10) was developed to detect landmines/IDE/UXO locations rapidly and safely. Low mass, small size, and lightweight Maggy with low energy consumption is capable of inspecting fields at low altitudes through pre-programmed routes with extreme height precision and terrain following mode for revealing the probable landmine/UXO/IDE spots.
2) A tablet/smartphone application (Fig. 16) was developed and integrated with Maggy to i) manage Maggy, ii) process real-time data streaming from Maggy to locate landmines/IDE/UXO, iii) perform detailed survey analysis considering varying magnetic fields (MF), and iv) communicate with the landmine/UXO/IDE clearing team for reporting exact landmine/UXO/IDE locations.
3) The developed small, lightweight and robust aerial platform can be carried in a backpack and rapidly deployed by humanitarian demining teams in supporting their humanitarian landmine/UXO/IDE clearance activities safely and efficiently.
4) This research provides the related research community with fundamental design and implementation parameters (e.g. flight speed, flight altitude) in building and using magnetometer-integrated UAS.

The rest of the paper is organised as follows. The literature survey is conducted in Section II. The developed approaches and techniques in this study are explored in Section III. The results within the experimental setup are presented in Section IV. Results and findings are discussed in Section V. Section VI draws conclusions followed by the limitations in Section VII. Finally, Section VIII provides directions for potential future works.

II. RELATED WORKS

Metal detector technologies, electromagnetic (e.g., ground-penetrating radar (GPR), microwaves, nuclear quadrople resonance (NQR), infrared (IR), electrical impedance tomography, X-ray backscatter, neutron methods, sound and ultrasound), acoustic/seismic, biological (e.g., rats and dogs, bacteria, bees, antibodies, chemical methods), mechanical methods (e.g., prodders and probes, mine-clearing machines) are the main non-invasive methods employed in landmine detection [10]. Among these, metal detectors are the most commonly used tools for detecting landmines in humanitarian demining [7]. The capabilities and limitations of metal detectors are analysed by Dieter *et al.* [7] for determining which detector is appropriate to be used under what circumstances. The ever-evolving technology of landmines poses a significant obstacle to clearance efforts [20]. Existing metal detectors require the user to be physically close to the scan area, and that presents a real risk of injury or fatality when the area has emplaced ordinance either buried or scattered on the surface. Such systems tend to give an audio warning when a detection is made, and it is not recorded or geo-stamped. Detecting new landmines is more difficult because they contain fewer or no metals [2]. Stated differently, there are numerous varieties of landmines composed of diverse materials, including plastic, glass, wood, and metal, and they come in a range of sizes [21], most of which are undetectable by conventional electromagnetic-induction (EMI) methods used in metal detectors.

A number of other diverse approaches have been employed to mitigate the shortcomings and constraints of the metal detectors. The use of GPR seems a viable option to support metal detectors and increase the detection accuracy of a demining system [9], [22], [23], [24] where it can detect a wide range of landmines, especially, in detecting non-metallic objects at depth, even though it is susceptible to various localised ground inhomogeneities and surface roughness [22], [20]. In addition to being sensitive to local inhomogeneities of the ground, the small electromagnetic (EM) radar cross sec-

FIGURE 1: **MANTA Mine Kafon[1]: GPR and metal detectors.**

tions for non-conducting materials make it challenging to detect buried explosives made of dielectric or polymer-based materials (plastics) [25], [26]. Moreover, regarding sensing capabilities, high-priced GPR systems have limitations due to strong random clutter at rough air-soil interfaces [27], the size of targeted objects (<10 cm) [28] and soil moisture and flight height [29]. To overcome these deficiencies, there have been numerous attempts to employ various other sensor modalities as mentioned earlier different from metallic detectors and GPR to reduce the false alarm rate (FAR), increase the chance of detection, and expedite the landmine/UXO/IDE clearing operations safely. Every technique used in these attempts has shortcomings. For instance, Lihan *et al.* [21] and Ishikawa *et al.* [30] assess dual sensor approaches that make use of both EMI and GPR sensors to compare the effectiveness of dual sensors and metal detectors. These approaches are particularly effective in differentiating between landmines and metal fragments and extending the detectable range in the depth direction. Donskoy *et al.* [31] use remote measurements of soil surface vibration (using laser or microwave vibrometers), processing of the measured vibration, and vibration (using seismic or airborne acoustic waves) of buried objects to extract the "vibration signatures" of mines.

Thanks to cyber-physical systems (CPSs) and enhanced Artificial Intelligence (AI) techniques, recent years have seen an increase in the intelligence of the "everyday things" in our environments considering Internet of Everything (IoE) [32], [33] enabling them to make decisions with an increasing degree of autonomy and little to no help from humans, leading to the development of advanced robotics systems. In addition to using different types of sensor modalities, there are various initiatives to speed up the demining process and prioritise safety using robotic systems. For instance, Aoyama *et al.* [3] propose a land vehicle robot with a mine detector; Yijun *et al.* [23] propose a mine detection using a land vehicle on which a forward-looking GPR (FLGPR) is mounted. In particular, to more quickly detect landmines on larger fields, vision-based remote sensing (VBRS) modalities

FIGURE 2: **Binghampton University (NY) – De Mine Research Group[2]: Bigger and less manoeuvrable platform; real-time sensing and detection.**

FIGURE 3: **Sensys R4 System[3]: Larger platform but offer full solutions and software.**

FIGURE 4: **F5 PRO quadcopter[4]: invested by NATO, 20-30 mins flight time, no real-time data processing,**

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

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

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

[4] https://www.smithsonianmag.com/innovation/a-ukrainian-teenager-invents-a-drone-that-can-detect-land-mines-180980826/

are becoming more and more popular as a solution to the drawbacks of the currently in use of off-the-shelf conventional techniques. These methods are founded on various physical principles, e.g., vapor/builk detection, electromagnetic detection, and optoelectronic imaging [34]. Nonetheless, a number of factors, including the type of soil, weather, lighting, and ambient conditions, must be taken into consideration when applying these techniques successfully [34]. More specifically, over the past 20 years, spectral remote sensing technology has made great strides and is now being utilised more and more in lab-scale applications (such as forensic, biomedical, industrial, biometric, food safety, and pharmaceutical process monitoring and quality control) [35]. Increased and sustained agricultural yields, water resource management, food safety and quality evaluation, disease diagnosis, artwork authentication, forensic analysis of disputed documents, military target detection, and counterterrorism have all benefited from the use of hyperspectral imaging [36]. By exploiting this technology, Asmish *et al.* [37] suggest combining an aerial minefield imaging system with multispectral (multiple wavelengths) sensors as part of a morphological approach to automatic mine detection. Anderson *et al.* [38] analyse the multispectral photos to look for landmines on the basis of histograms. Differentiating the thermal properties of the soil and the buried objects is how the detection is made [34]. Thanh *et al.* [34] suggest a finite-difference approximation of generalised solutions to the thermal model as a 3-D linear forward thermal model for buried landmines. Among the technologies in use, the dynamic thermal infrared technique (IR images of the soil surface obtained at multiple time instants) appears to hold promise for the detection of non-metallic landmines that are shallowly buried and for differentiating them from other buried objects by utilising the differences in thermal properties between the buried objects and the soil [39] [34], [39]. In other words, the existence of buried objects influences the soil's ability to conduct heat, leading to variations in soil temperature above the objects compared to areas that have not been disturbed; an IR imaging system situated above the soil area can measure this temperature signature [39].

The use of UAVs is clearly suited to covering larger minefields without the danger of triggering landmines/IDE/UXO during humanitarian clearing activities. The incorporation of UAS equipped with various sensor modalities into clearance operations has recently become popular. Fernandez *et al.* [40] propose a synthetic aperture radar imaging system for landmine detection using a GPR integrated with a drone. Measurements in controlled and real-world scenarios validate the algorithms and the UAV payload, demonstrating the viability of the suggested system. Mine Kafon integrated both a GPR and a metal detector with an aerial vehicle as shown in Fig. 1. Fernandez *et al.* [41] suggest using an aerial Synthetic Aperture Radar (SAR) imaging system to obtain complete three-dimensional (3D) radar images from below the ground. Markus *et al.* [42] carried out airborne landmine detection with a circular synthetic aperture radar. Garcia-Fernandez *et al.* [43] analyse airborne multi-channel ground penetrating radar for landmine/UXO/IDE detection. The use of GPR systems, with their large size and heavy weight, on UAS is extremely restrictive, especially, on lightweight drones with smaller payloads (Fig. 5). Badia *et al.* [4] suggest a blimp-based UAV outfitted with a widely tuned metal-thin oxide chemo-sensor through the use of a bioinspired detection architecture where employing trained animals is still one of the most widely used techniques for explosive detection. Julian *et al.* [13] suggest a UAV-based system that recognises and processes images of partially buried landmine-like objects.

According to a market research report by MarketsandMarkets, the global magnetometer market was valued at around USD 2.44 billion in 2023 and was projected to reach USD 4.34 billion by 2032, growing at a compound annual growth rate (CAGR) of around 6.60% during the forecast period [44]. These figures indicate the market's significant size and potential for expansion. The active detection of small UXO by measuring electromagnetic responses is analysed in [45] using a magneto-inductive sensor array, in [46] using broadband electromagnetic induction sensors, and in [47] using fluxgate sensors. The detection and classification of subsurface UXO using a magnetic field with a magnetometer is analysed in [48], based on a set of landmine or UXO sensor signatures. It is concluded in these studies that since many target signatures are site-dependent and variable based on the features of UXO, obtaining trustworthy priori training data in advance of designing an algorithm is frequently challenging. Considering this conclusion, the techniques developed in our research employ field-dependent data sets, without requiring a priori training set. The self- and user-selective threshold classification and clustering mechanisms help reveal MF distinctive from the rest of the Area of Interest (AoI) as elaborated in Section III.

The integration of magnetometer sensors with small UAS is carried out by various studies to realize different objectives such as [49], [50] in increasing the quality of magnetic field by reducing the permanent and induced interference magnetic field generated by the drone. We aim to increase the quality of the magnetic field in our novel drone and sensor integration design as explicated in Section III-B. The effectiveness of drones equipped with magnetometers in detecting buried metallic explosives, in particular, AP and AT landmines, was demonstrated in various studies [51], [52], [53]. We analysed the initiatives of using drone-mounted magnetometer systems in the market. The magnetometer-mounted UAS have been developed to provide an integrated solution to demining operations as demonstrated in Figs. 2, 3, 4. The features of these UAS are summarised in their legends. These systems are yet to provide an ideal compact system that the market demands as elaborated in Section V (Table 6). Millions of buried landmines still need to be found and removed manually, despite significant efforts to identify landmines using automated remote sensing approaches and using these manual techniques, it would take hundreds of years to fully demine all of these mines. It is now critically necessary to

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develop landmine/UXO/IDE detection and removal systems quickly [3] where their removal is very risky, expensive, and time-consuming [4]. The incorporation of aerial surveying supported by drones and multiple sensor modalities seems to be the most viable option to expedite the demining, specifically, in tough terrains. In this paper, regarding the previous promising studies on magnetometer sensor modalities, we have built a new integrated holistic system to detect landmines/IDE/UXO automatically in large terrains using UAVs. To the best of our knowledge, this research is the first attempt to determine the likely locations of potential landmines/IDE/UXO autonomously, rapidly and safely using a bespoke, lightweight, small and intelligent aerial-based, integrated, and easy-to-use compact drone (quadcopter) system equipped with a magnetometer sensing system and live sensor data telemetry link, which meets most of the market demands as explicated in Section V (Table 6).

III. METHODOLOGY

A. BACKGROUND

This research is based in The University of Central Lancashire (UCLan)'s Engineering and Innovation Centre, a 35m building bringing together additive manufacturing, software simulation technologies, advanced composites and a host of interdisciplinary engineering teams. UCLan has been testing multiple sensor modalities for 12 years in a diverse range of projects (e.g. [54], [55], [56], [57], [58]). UCLan received an investment of £1.3M in 2021 to procure drone equipment to support local businesses and enable new research [5]. Many commercially available geophysical ground scanning sensors were procured and bespoke ones were developed. These have been utilised and evaluated over the last few years in helping solve real-world problems intelligently. UCLan has developed many bespoke autonomous small, lightweight, compact quadcopters equipped with sensors for different types of objectives (e.g. for agriculture [59], [60], landmine/UXO/IDE detection [1], collision avoidance [17], beyond visual line of sight (BVLOS) teleoperation [61], [62]). UCLan has been collaborating with the Cambodian Army and several landmine-cleaning-based NGOs to develop new approaches and improve the pre-developed techniques for detecting and demining landmines. The Aerospace and Sensing Research (ASR) team at UCLan tested drone-mounted magnetometers with Cambodia's Armed Forces Peacekeeping Division.

TABLE 1: Properties of Fluxgate sensor — HWT3100-485.

#	Features	Properties
1	Output	MF and heading angle
2	MF range	-800uT — +800uT
3	Heading angle range	-180 — +180
4	Sensitivity	13nT/LSB
5	Return rate	can be adjusted between 0.2-100Hz
6	Components	Built-in sensor chips: 2*Sen-XY-f(pn13104) and 1*Sen-Z-f(pn13101) geomagnetic module; 1*Mag12C(pn13156) control chip
7	Resolution	16 bits for each axis
8	Voltage	5V—36V
9	Current	<10mA
10	Volume	83mm*25mm*25mm
11	Data interface	485 serial port (the specific level depends on the selection, the baud rate
12	Casing	Waterproof and vibration-resistance aluminium casing

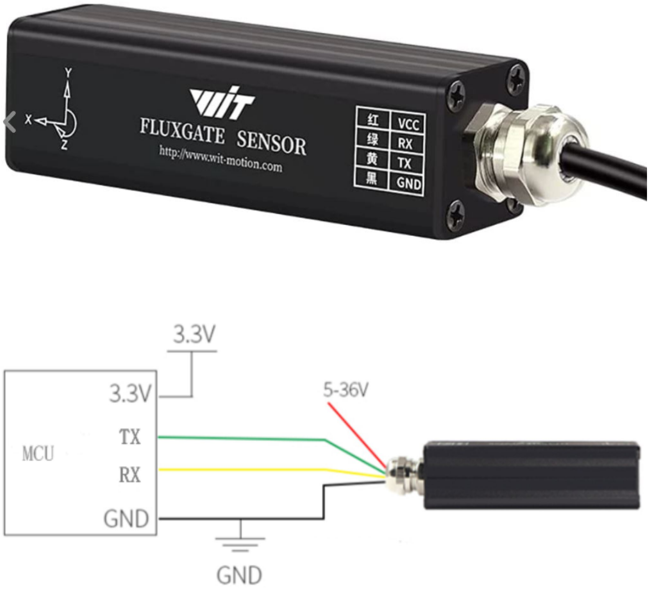

FIGURE 10: Fluxgate sensor with three-axis MF output. Model: HWT3100-485.

The ASR team was previously funded by both the Global Challenges Research Fund (GCRF) in 2018 and the Internal Engineering Research Centre Fund in 2021 in developing landmine/UXO/IDE applications. The performance of particular remote sensing sensor modalities such as GPR, magnetometers, infrared (IR), a Longwave Infrared (LWIR) camera, and a multispectral camera has been evaluated in-field tests. The fusion of data obtained from the integrated GPR and magnetometer sensor modalities mounted on an autonomous UAS (Fig. 5) has already accomplished satisfactory results with very high accuracy rates in finding landmines [1] (Figs. 6), 8). Initial datasets using vision-based remote sensing sensor modalities (i.e. IR, LWIR camera, and multispectral camera) were collected in Croatia in 2018 [63]. Later, the developed sensor-integrated UAS were tested in Cambodia in larger mine-affected areas in cooperation with the Cambodian Army and NGOs to quantify the observed results in difficult scenarios. Two landmine sites (UCLan Hawkins yard and Myerscough site (Figs. 8, 9) were already designed with landmines/IDE/UXO for scanning by drones in Preston, UK. Recently, UCLAN and Qatar University have

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[5] https://www.uclan.ac.uk/business/support-for-smes/lancashire-innovation-drone-zone

FIGURE 5: Onboard sensors: Magnetometer and GPR.

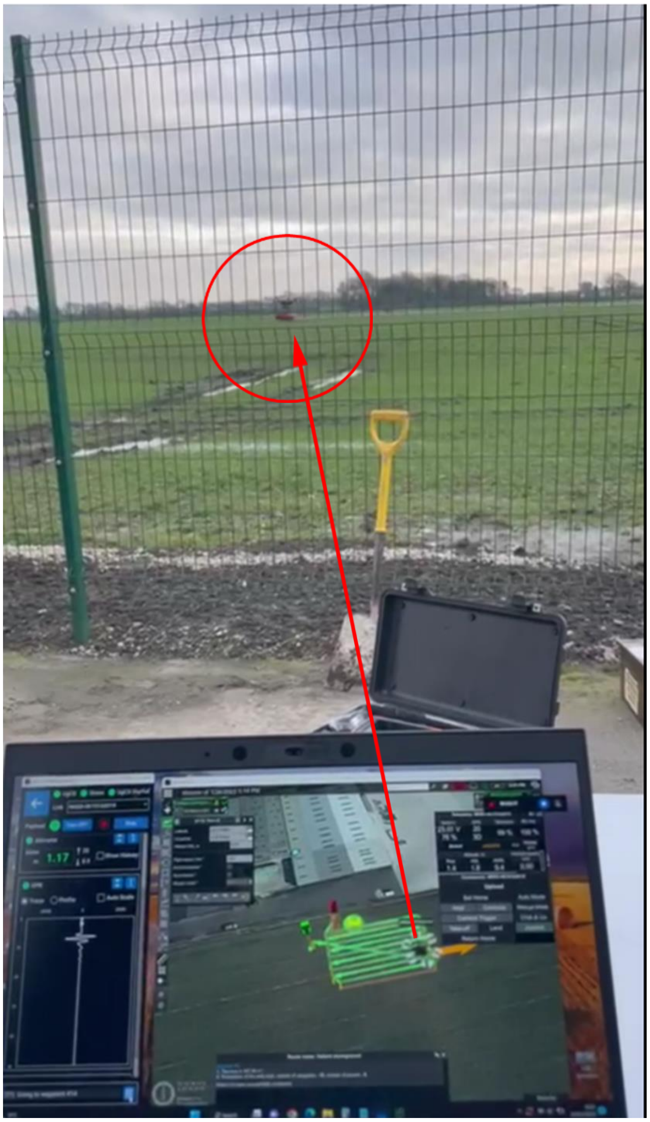


FIGURE 6: Autonomous mission monitoring in the UCLan landmine field. The drone (Fig. 5) is flying with an altitude of 1 m at a 1 m/s flight speed.

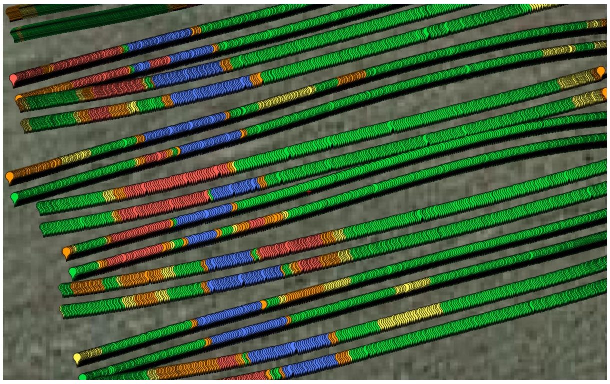


FIGURE 7: All scanned data points (Fig. 6) highlighted with 7 categorised colours which indicate the level of MF. Both magnetometer and GPR are actively acquiring data with no interference between them.

FIGURE 8: Landmine locations with very high MF points filtered from the scanned data in Fig. 7.

FIGURE 9: Examples for the plastic and metal landmines in different depths in the UCLan landmine field (Fig. 8).

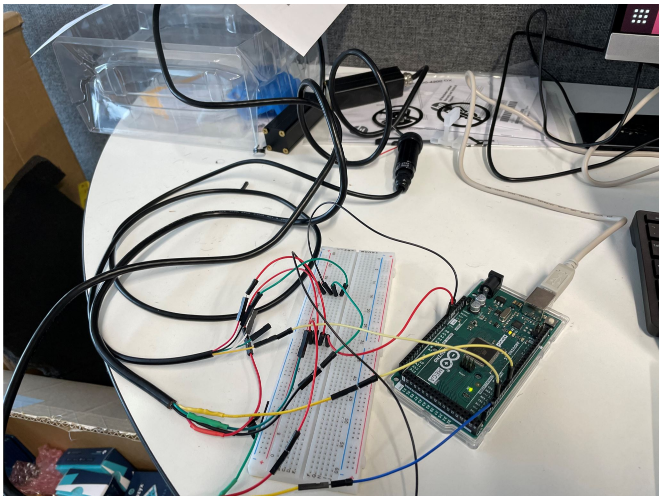
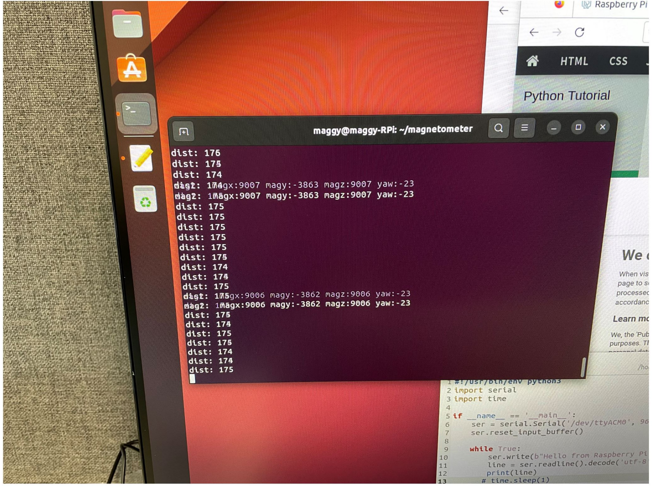
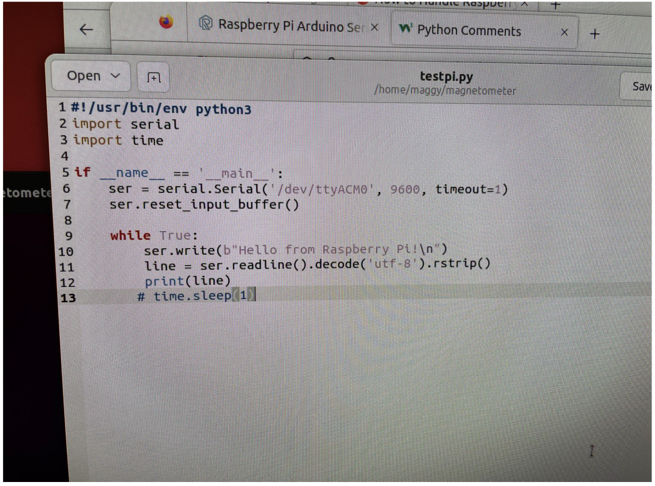


FIGURE 11: Integration of Sensors with onboard Arduino.



```
dist: 176
dist: 175
dist: 174
dist: 174gx:9007 magy:-3863 magz:9007 yaw:-23
mag2: 1magx:9007 magy:-3863 magz:9007 yaw:-23
dist: 175
dist: 175
dist: 175
dist: 175
dist: 175
dist: 175
dist: 174
dist: 174
dist: 175
dist: 175gx:9006 magy:-3862 magz:9006 yaw:-23
mag2: 1magx:9006 magy:-3862 magz:9006 yaw:-23
dist: 175
dist: 174
dist: 175
dist: 175
dist: 174
dist: 174
dist: 175
```

FIGURE 12: Acquiring the sensing.



```python
#!/usr/bin/env python3
import serial
import time

if __name__ == '__main__':
    ser = serial.Serial('/dev/ttyACM0', 9600, timeout=1)
    ser.reset_input_buffer()

    while True:
        ser.write(b"Hello from Raspberry Pi!\n")
        line = ser.readline().decode('utf-8').rstrip()
        print(line)
       # time.sleep(1)
```

FIGURE 13: Programming of sensing using Python.

established collaboration [6] in developing drone-mounted sensor systems to support the landmine/UXO/IDE humanitarian

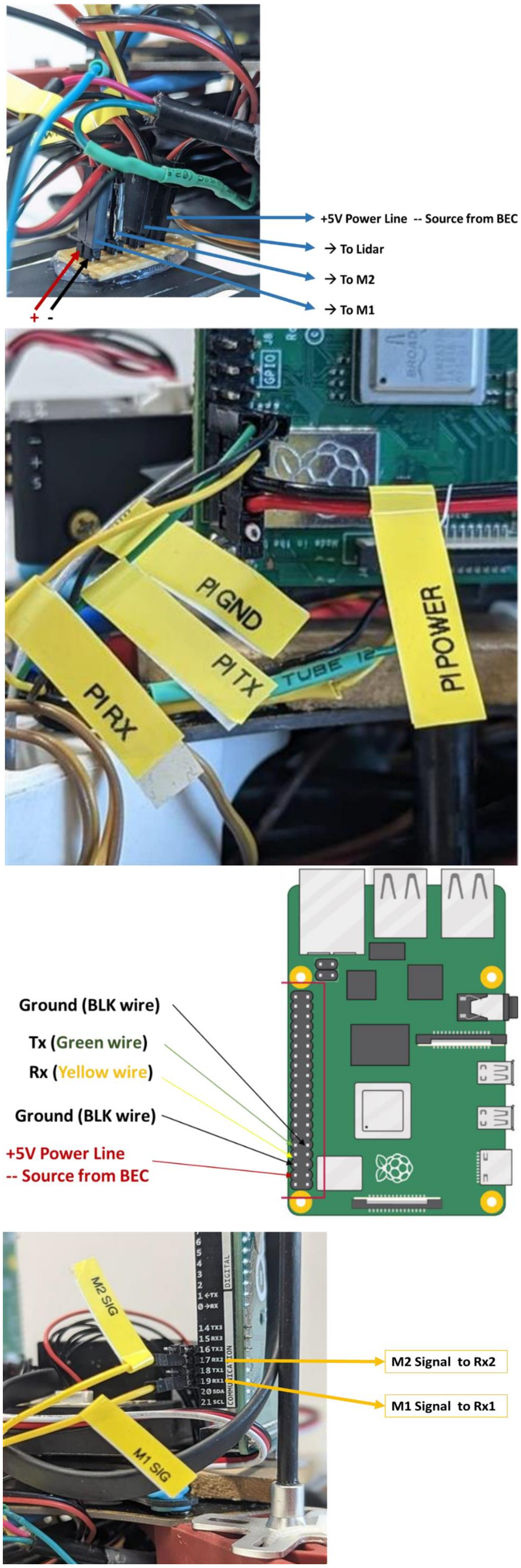


FIGURE 14: Inner component design of Maggy with detailed wiring diagram.

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[6] https://qrdi.org.qa/en-us/Scientific-Research/Academic-Research-Grant-ARG

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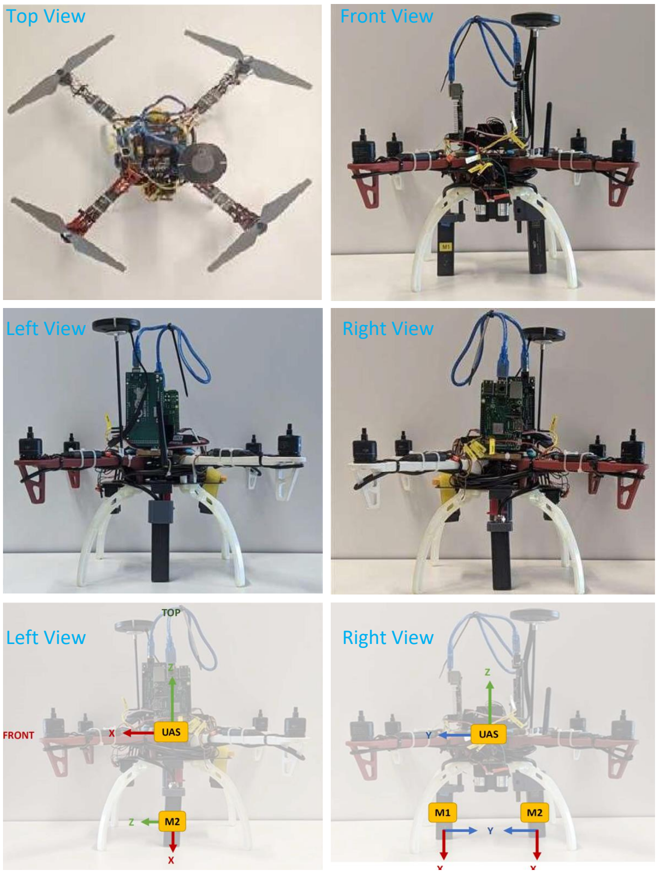

FIGURE 15: Outer design of Maggy.

clearing activities.

B. DESIGN & ROBOTICS INTEGRATION OF MAGGY

We planned to use a small single-board computer (SBC) on Maggy to process the internal management of its parts as well as the sensor components. Arduino and Raspberry Pi are both suitable to our design and development objectives. In this application, the Arduino board was selected to execute simple sensing operations from the sensors where i) it is cheaper than the Raspberry Pi, which helps us to accomplish one of our objectives – a bespoke drone as less expensive as possible and ii) it needs less current than Raspberry Pi does, which is important for us regarding the battery-constrained Maggy for the extention of flight time. This section consists of two subsections (Sections III-B1, III-B2), i) design and development of the drone – Maggy – with sensor technologies (Figs. 14, 15), and ii) development of the tablet/smartphone application (Fig. 16) to manage Maggy and process data streaming from Maggy to locate landmines/IDE/UXO.

1) Integration of Maggy With Sensors

The incorporation of the internal software and hardware components with the sensors into the bespoke Maggy system is explained in this section. Fluxgate magnetometer sensors were used to detect MF generated by the metallic parts of landmines, UXO or IDE. Magnetometer sensors should be integrated with UAS appropriately concerning the magnetic interferences relating to onboard electronics as elaborated in [64], [65], [66] even though the small electronics of Maggy help reduce the interferences significantly. The magnetometers were integrated below a lightweight drone to minimise magnetic interferences, specifically, caused by the UAS (Fig. 17). The properties of the magnetometer sensors shown in Fig. 10 are presented in Table 1. Two fluxgate sensors – magnetometers – are connected to Arduino using the serial port via the Modbus multiple connections as demonstrated in Fig. 11. One of the magnetometers is placed on Maggy to collect MF data via the Z direction and the other is placed to collect via the X direction. The sampling rate was adjusted to 10 Hz in order to reduce the noise (Fig. 17). Sensor data is read as shown in Fig. 12 and programming of sensing is executed using Python as displayed in Fig. 13.

TABLE 2: Features of Maggy in Figs. 14, 15 considering its drone components.

Component	Features
UAS/aircraft model name	DJI F-450
UAS battery packs	Tattu 4S 1800mah
UAS battery chargers	Overlander Charger
Transmitters model name	Futaba T8J
Transmitters battery packs	NiMH 4.8V
Transmitters battery chargers	Futaba Battery Charger
Ground station control model name	HP 15inch Laptop / Android Tablet + chargers
SiK telemetry	HolyBro ground side unit
Data communication	Netgear + charger
Data transfer	USB flash Drive, Arduino – Pi Cable
Propeller set	9X4.5
Software	QgroundControl, Wit-motion software

$$\begin{aligned} MF(uT) &= (Maggy_{rawdata} * Sensitivity)/1000; \\ \text{where } Sensitivity &= 13nT/LSB; \\ -800uT &< Maggy_{rawdata} < +800uT; \\ 1000 \text{ converts } nT \text{ unit to } uT &\ (micro - Tesla); \end{aligned} \tag{1}$$

$$\begin{aligned} MF_{XYZ} &= sqrt(MF_X^2 + MF_Y^2 + MF_Z^2); \\ \text{where } MF \text{ is the magnetic field with respect to axis.} \end{aligned} \tag{2}$$

$$\begin{aligned} Maggy_{heading}(degrees) &= atan2(mag_y, mag_x) * (180/pi); \\ \text{where } mag_x \text{ and } mag_y &\text{ are the magnetic field strength} \\ \text{values in the } x \text{ and } y &\text{ axes respectively;} \\ 180/pi &\text{ converts radians to degrees;} \end{aligned} \tag{3}$$

The general features of Maggy considering its drone components are presented in Table 2). The inner design of Maggy is demonstrated in Fig. 14. Each full battery can perform up to 4 min 30 sec at low speed flying (i.e. 1 m/s). An altimeter was incorporated into Maggy to make the flights accurate under 1 meter, enabling reliable terrain-following flight. The "position mode" is the easiest to fly with the centre stick configuration. Maggy uses a distance sensor (i.e. altimeter) for "position hold" below 1 m altitude. In "altitude

TABLE 3: Particular features of Maggy in Figs. 14, 15 considering operational objectives and sensor integration.

Element	Feature	Description
Magnetometer.	FGM3D/75 Fluxgate	Two FGM3D/75 Fluxgate
Operational weight	880 gr	The operational weight when mounted to the UAV is 880g including the battery.
Power supply	1V, 1,950 mAh Li-Ion	Re-chargeable battery.
Connection 1	Bluetooth	Bluetooth module is implemented into the MagDrone device.
Connection 2	Fischer connector	The Fischer connector can be used as a telemetry port.
GPS receiver 1	Internal GNSS	The GNSS receiver contains a support battery for memorising the Almanach and the configuration. The Fischer connector is used as a telemetry port becomes the GPS input.
GPS receiver 2	External GPS	The Fischer connector can be used as the GPS input while the telemetry port is Bluetooth.
Sampling	200Hz.	All three axles of every sensor are sampled at 200Hz.
Data logger	SD card	The capacity of the SD card is 2GB . This capacity is enough for about 24 hours of uninterrupted recording.
Software	MagDrone Data Tool	The MagDrone device provides a telemetry port that allows for live data output and reception of start and stop commands.
Data	Binary raw data	Moving directions, tracks and overlapping. The data can be converted into a readable format using the MagDrone Data Tool
Offset correction	Temperature offset data	Offset correction data such as temperature offset data are stored. These data are applied to the data measured by the magnetometers.

mode", Maggy will drift with the wind and is sensitive to control input. The "transmitter timer" is set to 4 min and will start to beep to notify "low battery". The particular features of Maggy shown in Figs. 14, 15 considering operational objectives are explained in Table 3. By integrating wireless communications with antennas using telemetry radios for remote control, WiFi for real-time data transmission using a 5G Netgear Router and a drone flight controller for precise navigation – we can implement a provision of real-time data which opens up many operational advantages as elaborated in next subsection III-B2. X, Y and Z component directions of the magnetometers are processed as formulated in Eqs. 1, 2, 3) to result in the total magnetic strength/intensity. A Gaussian low-pass filter as well as a high-frequency pass filter are applied to the acquired signals (Fig. 17) to suppress the background noise and accomplish a satisfactory signal-to-noise ratio (SNR) (Figs. 27, 28), which help detect small-scale MF caused by the targeted explosives with metallic objects. The autopilot control system of Maggy was optimised for flight close to the ground, integrating a radar altimeter into the drone to enable terrain following flight at a distance between 50 cm and 1 m above the ground to maximise the sensor performance.

TABLE 4: Streaming attributes of each data point.

#	Attributes	Example
1	(GPS_RAW_LAT, GPS_RAW_LON, GPS_RAW_ALT)	(538126932, -28246376, 25240)
2	(GPS_FIX_LAT, GPS_FIX_LON, GPS_FIX_ALT)	(538126938, -28246368, 25546)
3	DIST_Sensor_height	52
4	(Local_Xm, Local_Ym, Local_Zm)	(-0.8917901515960693, -3.773503303527832, 6.130475997924805)
5	(Timestamp, Roll_Euler, Pitch_Euler, Yaw_Euler)	(778899, 0.019024385139346123, 0.020649636164307594, 0.2144695520401001)
6	(mag_ID, mag_x, mag_y, mag_z, mag_yaw)	(m1,6723,-3249,4605,-25)

2) Development of the Application

An intelligent tablet/smartphone application was developed using the Xamarin.Net development platform. The Xamarin platform enable us to create an application which can run on both Android- and iOS-based devices. The functionalities of the application are explained in Fig. 16. It was fully integrated with Maggy to i) manage Maggy, ii) process data streaming from Maggy to locate landmines/IDE/UXO, iii) perform detailed survey analysis considering varying MF, and iv) communicate with the landmine/UXO/IDE clearing team for reporting the exact locations of explosives. From a technical standpoint, the application establishes an agreed-upon communication link with Maggy using either a TCP or UDP connection. Preferably, a UDP connection is suggested to be used where each data point read by Maggy needs to be readily displayed on the application without stricter protocols as in a TCP connection. Maggy can be used in an automated manner where planned waypoints can be fed into Maggy using the UgCS system – drone flight planning software. Maggy transmits MF values with related information at each data point on its waypoints to the application. The flight information and MF data are streamed to the application to be processed and monitored in near real-time. The attributes of each data point are explained in Table 4 with an example. The streaming of data was coded using Pyrton and the Pyrton script codes of streaming (Maggy_UART.py) are provided in the supplementary materials for interested readers. The streaming is communicated through 5G Netgear Router's WiFi connection as mentioned earlier. The application readily processes these values using Eqs. 1, 2, 3 for MF classification and clustering based on the MF threshold chosen by the user as explained

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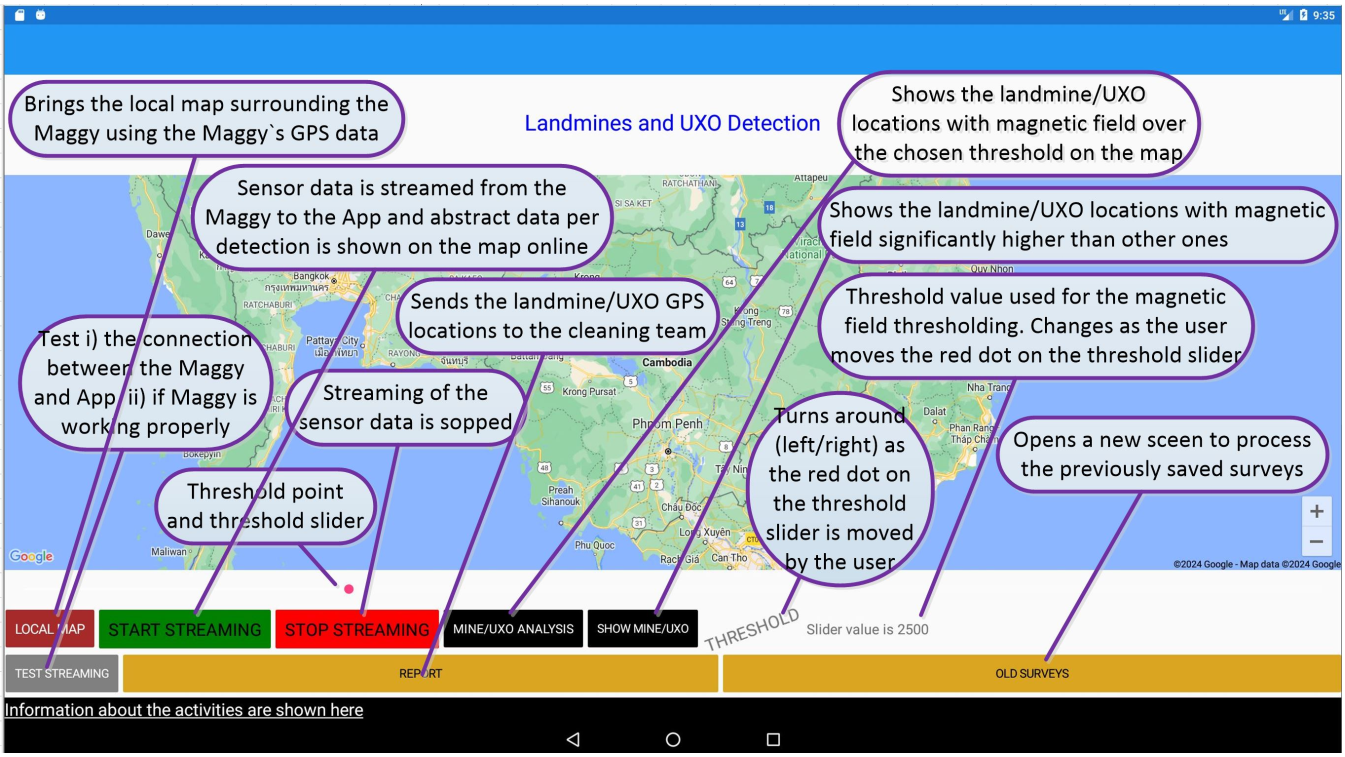


Brings the local map surrounding the Maggy using the Maggy`s GPS data

Sensor data is streamed from the Maggy to the App and abstract data per detection is shown on the map online

Shows the landmine/UXO locations with magnetic field over the chosen threshold on the map

Shows the landmine/UXO locations with magnetic field significantly higher than other ones

Sends the landmine/UXO GPS locations to the cleaning team

Threshold value used for the magnetic field thresholding. Changes as the user moves the red dot on the threshold slider

Test i) the connection between the Maggy and App ii) if Maggy is working properly

Streaming of the sensor data is sopped

Turns around (left/right) as the red dot on the threshold slider is moved by the user

Opens a new sceen to process the previously saved surveys

Threshold point and threshold slider

FIGURE 16: Main interface of the Android tablet/smartphone application and its functions.

in Fig. 16 and shows landmine/UXO/IDE GPS locations on the local map with abstract information (Figs. 27, 28) as data is streamed from Maggy. The classification of MF values is carried out based on the distribution of the MF values obtained from various landmine/UXO/IDE devices considering the "no MF" values as exemplified in Section IV-A. Regarding the clustering, values below the threshold value are ignored and clustering is executed based on these values above the selected threshold. These algorithms are employed to classify the MF values as "very high MF" represented by "red"' colour, "high MF"' represented by "orange" colour, "low MF" represented by "yellow" colour, and "no MF" represented by "green" colour. This is demonstrated in Section IV, particularly, in Fig. 27. The use of the application with its functionalities is further explained in Section IV-B with real-field implementations.

IV. 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 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

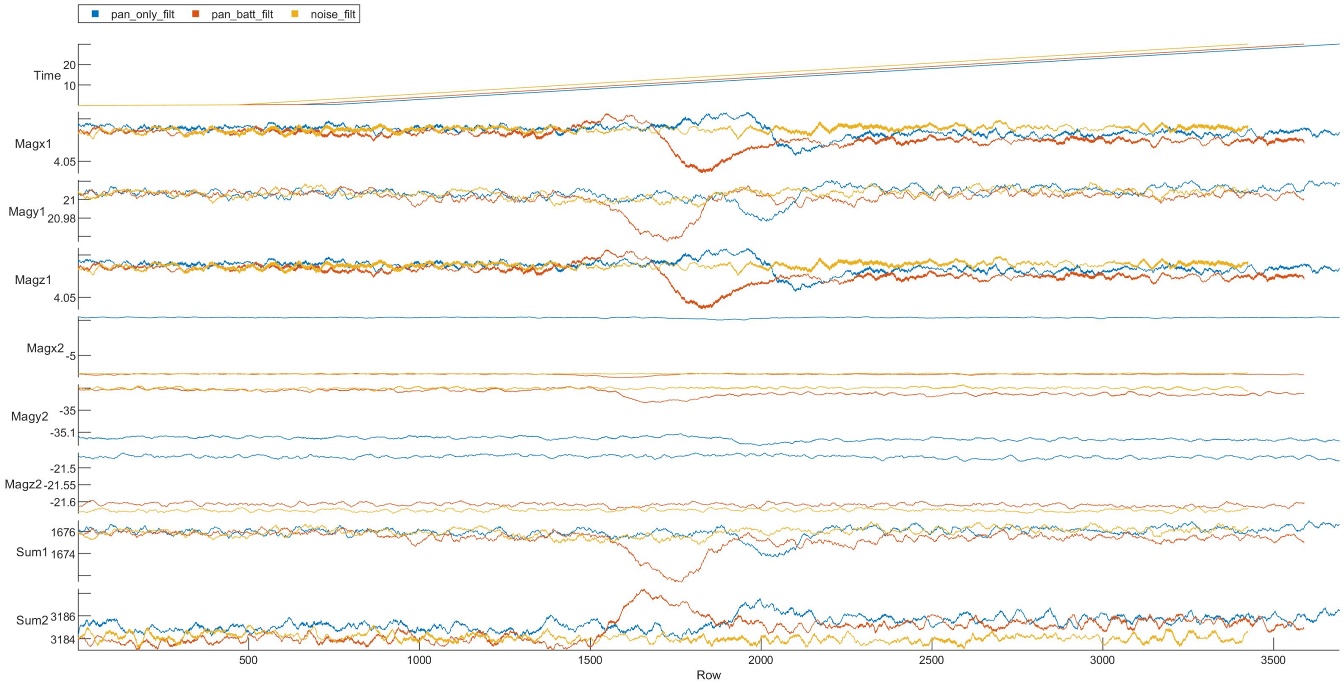
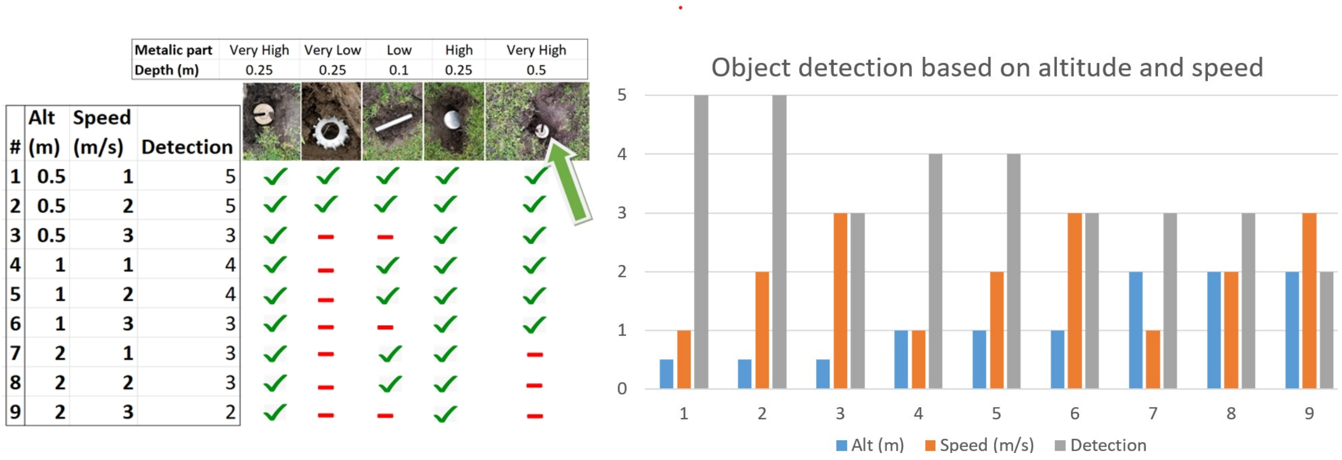


FIGURE 17: Change of MF values in the three axes with the two magnetometers when encountered a high MF. The total magnetic strength/intensity is shown at the bottom for two magnetometers.



#	Alt (m)	Speed (m/s)	Detection	Metalic part: Very High Depth (m): 0.25	Very Low 0.25	Low 0.1	High 0.25	Very High 0.5
1	0.5	1	5	✓	✓	✓	✓	✓
2	0.5	2	5	✓	✓	✓	✓	✓
3	0.5	3	3	✓	–	–	✓	✓
4	1	1	4	✓	–	✓	✓	✓
5	1	2	4	✓	–	✓	✓	✓
6	1	3	3	✓	–	–	✓	✓
7	2	1	3	✓	–	✓	✓	–
8	2	2	3	✓	–	✓	✓	–
9	2	3	2	✓	–	–	✓	–

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).

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 way-points 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.

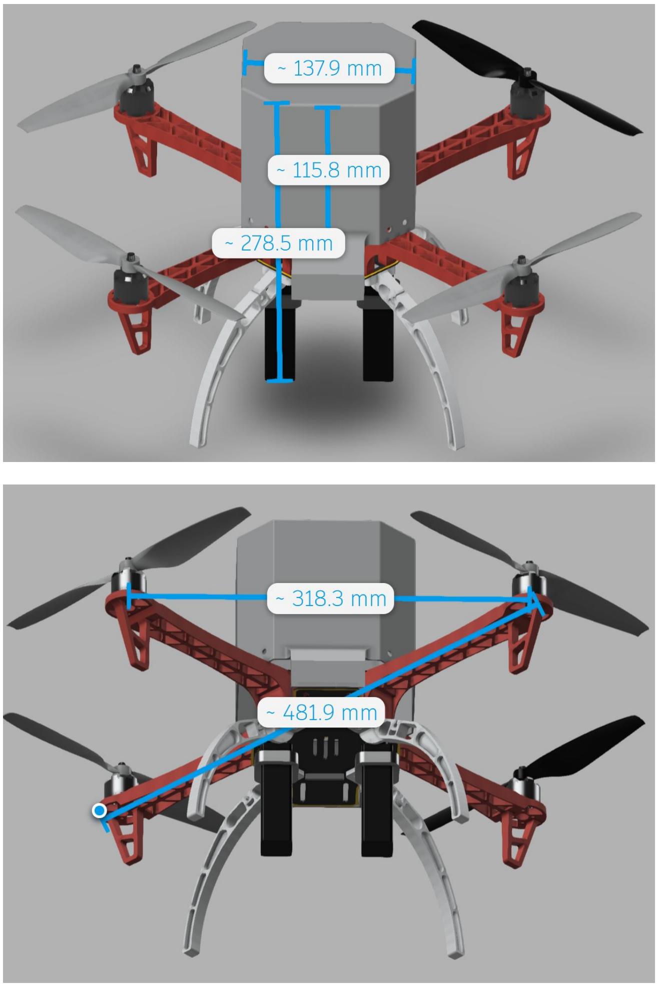


FIGURE 19: **Shielded Maggy.**

2) Real field tests with Maggy at the Latvia Field

The size of the Latvia test field is 450x70 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

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[7] https://www.sphengineering.com/integrated-systems/test-range-for-geophysical-sensors

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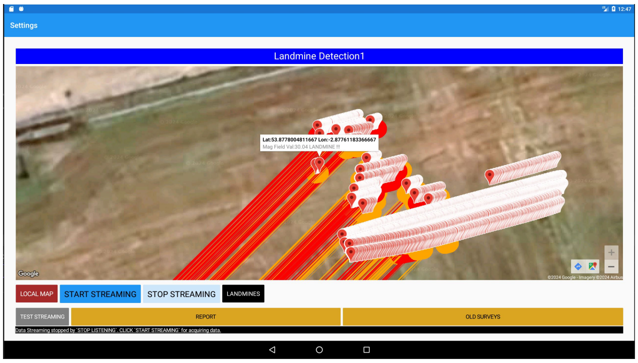
deeper depths such as 1 m and further if these objects have larger metallic parts, enabling large MF. The real-field tests help us understand the abilities as well as the shortcomings of Maggy in operations to find out the improvement points (Table 6) in its design and functionalities, which is discussed and elaborated in Sections V, VI, VII and VIII in different perspectives.

23268,1,-1.75,1,2,52.63881064,53,52.66713923

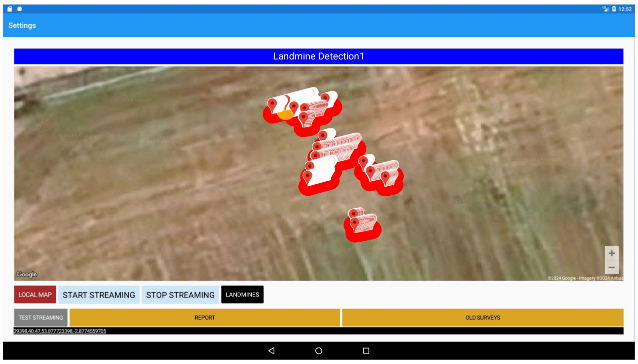
FIGURE 20: Autonomous use of Maggy in the UCLan landmine field. All data points.



Lat:53.8778004811667 Lon:-2.87761183366667
Mag Field Val:30.04 LANDMINE !!!

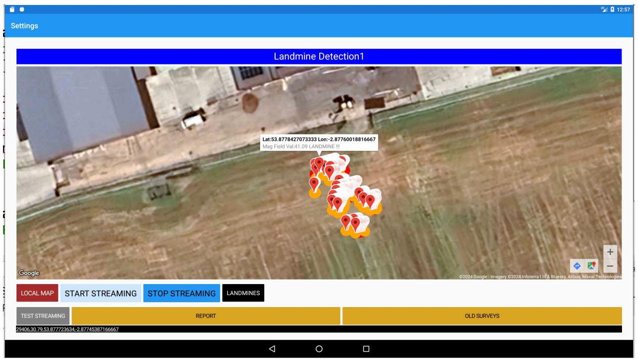
Data Streaming stopped by `STOP LISTENING`. CLICK `START STREAMING` for acquiring data.

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



29398,40.47,53.877723398,-2.8774559705

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



Lat:53.8778427073333 Lon:-2.87760018816667
Mag Field Val:41.09 LANDMINE !!!

29406,30.79,53.877723634,-2.87745387166667

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

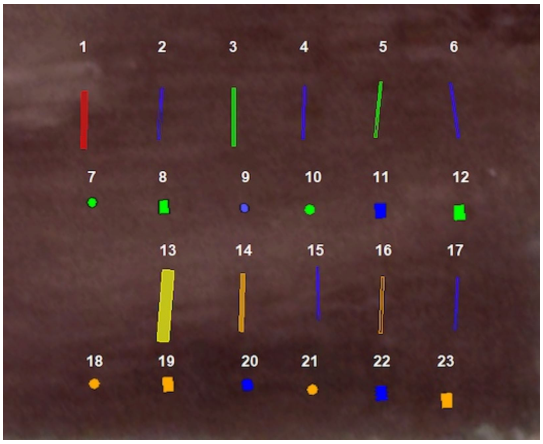


FIGURE 24: Latvia landmine/UXO/IDE field locations (Table 5)

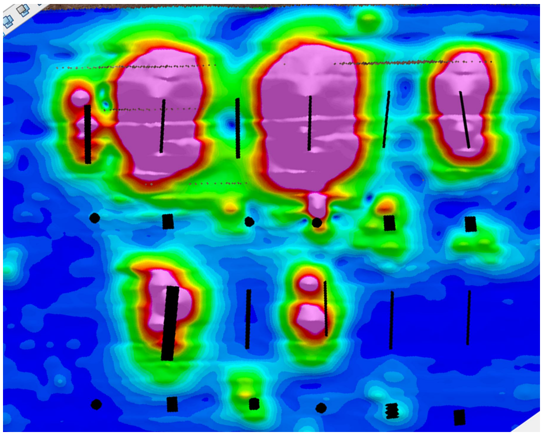


FIGURE 25: Geometric measurement of MF of the objects depicted in Fig 24) using the MagArrow Magnetometer[8].

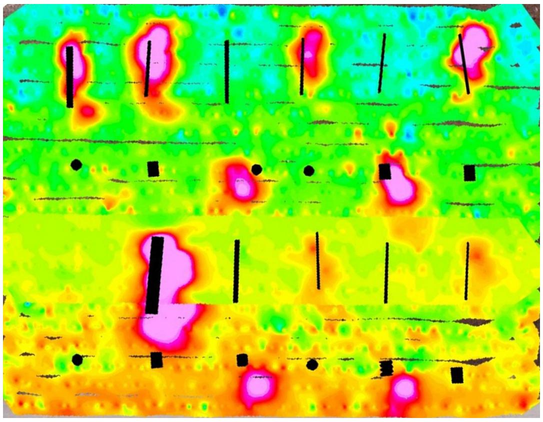


FIGURE 26: Geometric measurement of MF of the objects depicted in Fig 24) using the Metal Detector[9].

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

V. 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. t

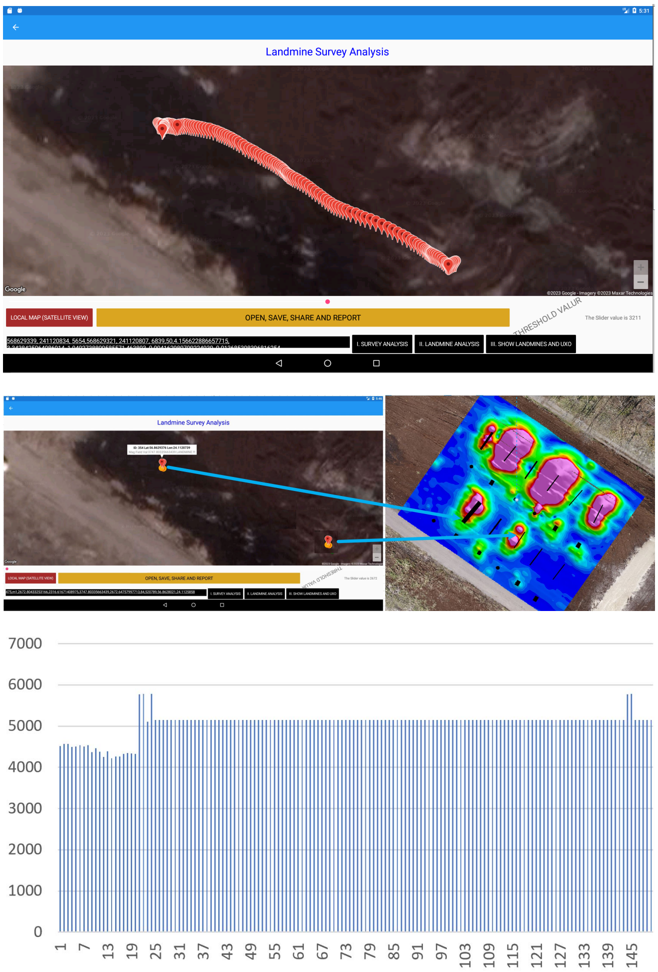


FIGURE 27: Latvia field test -III-. Top: all data points; middle: high MF; bottom: MF graph for all data points in the route depicted at the top.

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 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

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[9] https://www.geomatrix.co.uk/land-products/magnetic/magarrow/

[9] https://geonics.com/html/em61-mk2.html

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.**

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 developed 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 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, IED, and UXO. 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.

VI. 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 help in making 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 easy-to-use rotary drones, if equipped with effective sensor technologies and AI with proper configurations, efficient in humanitarian clearing operations. 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

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.

of clearing operations across a large and tough terrain or other hazardous land area, 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. 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.

VII. 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.

VIII. 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.

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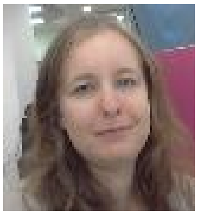

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