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Innovative Humanitarian Demining: A Novel Low-Cost UAV System for Anomaly Detection via Pulse Induction Metal Detector

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***Abstract*— Unexploded landmines continue to pose threats in post-conflict areas, and the need for mine clearance has been exacerbated by the negative impacts that the presence of these landmines has on the affected communities and the environment. However, the process and cost associated with landmine clearance in such regions have been extensive and pose risks to the clearance teams. This research proposes a cost-effective system using a UAV with a Pulse Induction metal detector and a LiDAR terrain-following system capable of autonomous flight at low altitude. The system proposes the application of a digitized process that eliminates manual marking in the detection process and offers a Virtual Minefield Map to be used by the clearance ground team once a mine has been located through the automated system. The system was tested in a field experiment consisting of buried landmine substitutes and identified 9 out of 10 landmine targets at an accuracy level of 87 percent. The data we obtained confirms the system is a scalable solution for preliminary mine detection surveys, which can be provided to ground teams as reliable data to speed up clearance operations safely.**

***Index Terms*— Humanitarian Demining, Unmanned Aerial Vehicle (UAV), Pulse Induction (PI), Landmine Detection, Digital Georeferencing, Low-cost Surveying, Virtual Tagging.**

I. INTRODUCTION

A. The Humanitarian Challenge of Landmine Contamination

Unexploded landmines and explosive remnants of war remain a persistent threat to mankind. All of these horrific devices to remain in the ground waiting for the innocent, civilian victims even decades after the wars have ended. Internationally, it has been estimated that more than 60 million people in more than 60 countries worldwide are living in the face of such threats on a daily basis [9]. The cost of this conflict has been horrendous. According to the Landmine Monitor, unfortunately, civilians represented 84% of all recorded casualties in 2023 [10].

It can be seen that the effects are not confined to the initial wounding or deaths. According to the ICRC, mines cause the deaths of livestock and make agricultural land unusable.

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This wrecks the local food systems. Fear prevents people from going out, from accessing the market or even the water source. This paralysis locks communities into poverty. They are left to leave their places of residence not because of the fighting but because the land is not safe [12].

B. A Review of Current Detection Technologies

There are two types of demining technology in general: either ground-level or aerial surveying. These would provide trade-offs between safety and precision. The ground-level teams are now using the services of handheld detectors. Pulse Induction (PI) or Very Low Frequency (VLF) detectors are cheap and highly sensitive; unfortunately, these would alert to all objects made of even scrap metal indiscriminately. Ground Penetrating Radar (GPR) is more intelligent; it could detect plastic "minimum-metal" mines that other detectors would not. However, all ground-level detectors have one fatal weakness: they are slow, laborious, and require the operator to stand within the danger area.

Unmanned Aerial Vehicles (UAVs) would resolve the safety problem. UAVs can survey a broad area in a short time. They usually carry magnetometers to outline ferrous anomalies or thermal cameras to detect soil disturbance. These aerial devices would be safer but may not provide the same level of precision as a human operator on the ground.

C. Proposed Solution and Contribution

To fill the gap between dangerous manual work and costly military equipment, we have designed a specialized "Detect-and-Map" aerial platform. Our platform incorporates a Pulse Induction (PI) sensor, designed and built by us, on a heavy-lift hexacopter. This is helpful in integrating the soil-neutralizing properties of the Pulse Induction sensor with the stability of a hexacopter.

The innovation in this project is the logic between the analog sensor and the digital flight controller. Unlike traditional surveys, which involve complex post-processing, our system is real-time. The moment the sensor detects a metallic object, the onboard computer sends a "digital interrupt," which records the exact GPS location to a mission file.

Although our original design proposal included a "Physical RFID Dispenser" for RFID-tagging targets for the ground operations team, the current prototype uses a "Virtual RFID Dispenser". The simulation is used to test geolocation logic, which does not require the complexity of a physical dispenser and provides a detailed "Virtual Minefield Map" of the suspected targets. The removal of the physical planting of the flag has enabled the system to allow demining teams to evaluate a threat area from a distance. In this paper, we will explain the engineering that has gone into this integrated process.

II. Design Methodology and System Architecture

A. The Aerial Platform

For this research, we designed a UAV using a Tarot X6 960mm frame as its core structure. Unlike quadcopters, the six-rotor design ensures safe landing or return-to-home even if a single motor fails in a hazardous minefield.. We ensured an unobstructed field of view for the downward-facing sensors, by equipping the drone frame with a retractable landing gear. We ensured extended flight times even with the heavy payload by utilising Tarot 5008 340kV brushless motors paired with 18-inch (1855) carbon fibre propellers. Power was supplied by a high-capacity Tattu 22,000mAh 6S (22.2V) LiPo battery, which provided the necessary current for both the heavy-lift propulsion as well as the high-pulse current required by the metal detector coil. For the autonomous flight planning and navigation, we used the Mission Planner GCS software and a Cube Orange+ flight controller. We deliberately selected this Flight Controller Unit (FCU) for its triple-redundant IMU and industrial-grade reliability, even though it was more expensive than the basic Pixhawk 2.4.8 FCU. We ensured precise positioning by using a standard Holybro M10 DroneCAN GPS module. We opted for this option instead of an expensive RTK GPS device considering the low-cost constraints for our project. For low-altitude flight, we used a dual LiDAR system, although not very expensive but very efficient, including a Benewake TFmini Plus for terrain-following altitude lock and a Benewake TF02-Pro for anti-collision detection in the forward direction. Main command and control, especially for long ranges, were achieved using a RadioMaster TX16S MKII transmitter supporting an ELRS ExpressLRS link, connected through an RP3 Nano receiver. The telemetry link for data transmission to ground control used a 915MHz SiK Telemetry Radio. We had an engineering design problem for protecting the sensitive metal detector coil from the electromagnetic interference generated by the drone components. To overcome this, we developed an optimized-deployment scissor arm mechanism, actuated by a JGY-370 high-torque geared motor connected to a 300mm T8 lead screw, extending the metal detector coil from 1.5 meters below the aircraft immediately following drone liftoff. The assembly featured a linear guide rail and brass lead screw nut for smooth, vibration-free deployment. This system was placed at the base of the drone.

B. The "Detect" Subsystem: High-Fidelity Pulse Induction Payload

We needed to maximise the signal integrity and to isolate sensitive analog lines from high-speed digital switching. So, we engineered the detection payload using a split-architecture approach. Unlike standard single-board detectors or hobby circuits, our design physically separates the signal chain into two dedicated PCBs:

- Analogue Front-End (AFE) PCB: The AFE is a custom board centred around the OPA1644 quad operational amplifier. We selected this specific component for its low noise floor and high slew rate. These are necessary for resolving the rapid decay transients of the PI signal. We use this stage to handle the amplification and damping of the raw return signal from the search coil. We then send this conditioned signal to the next stage which is the digital stage.
- Digital Signal Processing (DSP) PCB: This is the core of our detection system. We designed this dedicated PCB using an STM32 microcontroller. We chose the STM32 for its high-speed internal Analog-to-Digital Converter (ADC) that comes with a very high sample rate (MSPS).This allows the system to generate the precise timing for the transmit pulse and, most importantly, to digitize the return signal's decay curve with exceptional temporal resolution. The STM32 captures the full shape of the decay curve and pre-processes the data to extract key signal features. This high-bandwidth data stream is then transmitted to the payload computer. Here, the ability to discriminate between metals is possible based on the curve information we are able to glean.
- Payload Computer and Analysis: In doing the analysis, we utilized a high-level payload computer, which is a Raspberry Pi 4 Model B. Its function is to get the pre-processed signal data from an STM32 through a serial interface. On this computer, we have a Python script for signal analysis that runs to check for metallic anomalies in real-time signal characteristics. In real-time signal detection, it sends a signal for a high-resolution image capture of the terrain right below our UAV through a command for a Raspberry Pi Camera Module 2. Geotagged photos are taken for post-mission assessment. Even if a typical GPS positioning system may not provide location accuracy at a level beyond a meter, with an anomaly heatmap created through this data and imagery obtained, ground personnel can accurately pinpoint risky zones.

C. The "Mark" Subsystem: Virtual Geotagging

In an ideal world, dropping a physical marker on the mined location would have been the function of our drone. However, due to a couple of operational constraints, we ended up with the option to virtually mark this study. The logic is simple. When a valid target, or in other words when the anomaly score passes the threshold, a "simulated RFID tag drop" is carried out. Rather than the RFID tag payload being sent to the detect location, we have included a function to immediately access the GPS Module and record the exact latitude, longitude, and time to a file.

This leaves a "digital tag" on the map. The latter approach does, however, have the advantage of enabling us to test the detection and georeference workflow without actually having the possibility of jamming a real dispenser. In a real-world test later, this same signal will be used to power a servo to dispense an RFID tag.

III. System Integration and Workflow

This section details the signal processing chain and the logic used to create the digital minefield map.

A. Mechanical Integration and Deployment Mechanism

We ensured that our primary concern was stability in flight and EMI isolation.

We packaged the Analog Front End (AFE) and STM32 PCBs in two separate shielded enclosures that are mounted on the battery tray of the UAV.

To provide sufficient isolation from the noise of the drone affecting the sensors, we designed a custom scissor arm (pantograph) system to extend the coil. This linear actuator is driven by a JGY-370 high-torque geared motor with a 300mm T8 lead screw. It has a linear guide rail and a brass nut to provide vibration-free extension. When the drone reaches its predetermined survey altitude, the system extends the search coil 1.5 meters below the drone body. This provides sufficient separation of the sensor from the magnetic noise of the motors of the drone. For the avionics, we mounted the Holybro M10 DroneCAN GPS on the top plate for sky visibility, and above all other components on the drone. We provided low-altitude protection by implementing a dual-LiDAR system: a Benewake TFmini Plus pointing downwards for terrain following, and a Benewake TF02-Pro pointing forward for obstacle avoidance.

B. Electrical and Data Architecture

The system was powered by a single Tattu 22,000mAh 6S LiPo battery. A high-efficiency Power Distribution Board (PDB) ensured a stable and noise-free voltage supply: 12V for the Analogue Front-End and 5V for the digital logic (STM32, Raspberry Pi 4). The data communication was structured in three levels:
Flight Layer: The flight dynamics were controlled by the Cube Orange+ with M10 GPS for position and TFmini Plus for altitude hold. Communication with the ground station was provided by a 915MHz SiK Telemetry Radio, and control from the pilot was provided by a RadioMaster TX16S MKII (ELRS link).
Signal Acquisition: The STM32 controlled the physics of signal acquisition. Signal acquisition was provided by the pulse timing for the coil and samples the raw analogue signal from the return using its onboard ADC.
Mission Logic: The Raspberry Pi 4 controlled the serial data stream from the STM32 via UART. The Pi ran the analysis script and controlled the camera. The payload has been designed to be electrically isolated from the flight controller, with only a shared ground connection, such that a software bug on the payload will not crash the drone.

C. End-to-End Operational Workflow

The process of the operation of the system is expected to be linear, starting from ground setup to the process of capturing the data. The process starts at the Ground Control Station (GCS), where we apply the use of Mission Planner to specify the area where the survey will take place. Through the specification of certain boundaries and a certain distance of the lanes, we are able to create a grid autonomous path that is sometimes referred to as a "lawn mower."
The pilot then proceeds to initiate take-off once the flight plan has been uploaded. The scissor arm system is then engaged after the UAV reaches a safe altitude; this is when the UAV locks the search coil to a position 1.5 meters below the aircraft. In the actual scan process, the UAV regulates the altitude using the LiDAR TFmini Plus to fly at a constant 1.8 meters AGL. This is when the detection coil hovers 30cm above the ground, which is the optimal position for the maximum detection range.
The data logging process runs uninterruptedly in the background. The STM32 component deals with the analog process, pulsing the coil, decoding the decay curves, and sending this data to the Raspberry Pi for further processing. The Raspberry Pi is responsible for monitoring the data stream for any abnormal behavior, and upon crossing our predefined threshold, it automatically transmits a "Virtual Marker."
This process asks for GPS data regarding the exact location coordinates and demands a snapshot by the camera at the exact spot.

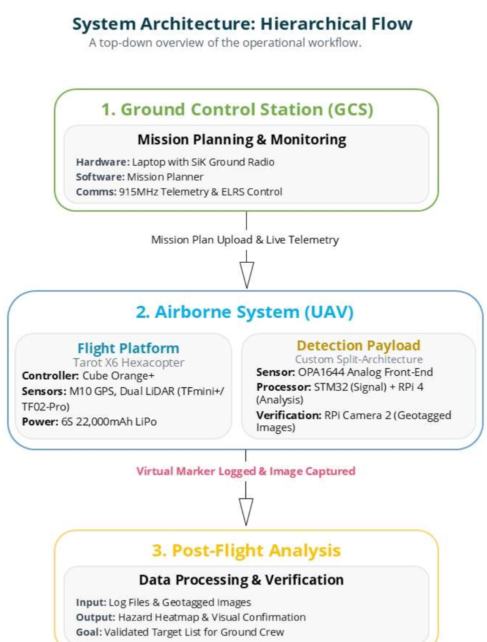

Figure 1. System Architecture: Hierarchical Flow. The diagram illustrates the top-down operational workflow involving the Ground Control Station (GCS), Airborne Platform (UAV), and Ground Team

IV. Design Methodology and System Architecture

To validate the study and the processes, we split our approach into two stages: a ground simulation and an actual aerial survey.

A. Ground-Based Validation (Handcart Trials)

We chose to check the Pulse Induction payload and data logging system functionality with the simulated ground tests before engaging the flight tests. We made an environmentally neutral, wheeled, and specially designed cart, modelled on the drone flight height, which was 1.8 meters high, as specified in the drone's hover height, because the Pulse Induction sensors are mounted 1.8 meters above the ground on the drone. Initially, the sensors, the GPS, LiDAR, and the Pulse Induction Detector were all placed on the wheeled cart, followed by actual manual movement of the cart over the 10x10 metal surrogates test grid as the drone would move during the flight tests. The Pulse Induction Detector was adjusted for maximum detection sensitivity such that the GPS logging algorithm could clearly separate metal and soil background noise on the ground tests.

B. Autonomous Flight Trials

Once the ground-test data proved reliable, we then did a live grid survey with the Tarot X6 hexacopter. We had to configure the flight mission in Mission Planner under very stringent constraints so that we could ensure regular data collection.

The drone flew "Auto" mode at a very slow 1.5 m/s. Using the LiDAR with terrain-following kept it flying at a height of 1.8 meters AGL. The scissor arm was then deployed at its 1.5-meter extension, lowering the coil to the best detection zone of 30cm above the ground constantly.

Signal Acquisition: An STM32 microcontroller drives the detection physics. It generates the precise coil pulse timing and digitises the raw analogue return signal using its onboard ADC.

V. Results

Flight logs provided the hard numbers needed to evaluate the system's success in locating the 10 buried targets.

A. Detection Data

The Raspberry Pi recorded 12 specific detection events synchronised with GPS time and location. Out of the 10 real targets buried in the field, the system successfully flagged 9 of them. As detailed in Table I, most event logs matched the known target locations.

However, there were two events (DET-007 and DET-011) that turned out to be false positives caused by surface debris or ground mineralization. The system detected 9 out of the 10 buried targets during autonomous flight. A total of 12 detection events were recorded, of which 10 matched known target locations while 2 were false positives caused by surface clutter.

B. Accuracy Analysis

The calculated Detection Accuracy for the system turned out to be 87.25%. We compared the GPS logs against the true ground coordinates and found a lane deviation of roughly ±40 cm. This was a rather mechanical drift, perhaps because of the wind.

The suspended coil was akin to a pendulum during turns or when the car was exposed to gusts of wind. This resulted in the sensor deviating from the central path. Nonetheless, the final heatmap we obtained for high value scores indicated a clear cluster over the detection points.

VI. Discussion

A. Operational Challenges and Limitations

"Detect and Map" is working in our system as we had planned, although we did see some points of stress in our field test. Challenges: Stability was the most difficult part for us. The coil held up the drone due to the pendulum effect in the initial flights. We were able to aggressively tune the PID parameters for the Cube Orange+ drone. However, the presence of the +\- 40cm error, as mentioned, is still a problem for us.

It was quite an exercise to calibrate the Pulse Induction coil, which is very sensitive to everything and thus has to be calibrated all the time to avoid sensing the noise generated by the power distribution board of the drone. The signal processing logic is not intelligent enough; it identified the metallic trash as mines twice, and thus it requires more filtering.

TABLE I: AUTONOMOUS FLIGHT VALIDATION DATA

Event ID	Time	Lat.	Long.	Peak	Status
DET-001	17:00:45	12.780512	74.860798	0.8942	Confirmed
DET-002	17:01:32	12.780545	74.860812	0.9105	Confirmed
DET-003	17:02:15	12.780588	74.860845	0.8821	Confirmed
DET-004	17:03:05	12.780622	74.860889	0.7854	Confirmed
DET-005	17:03:55	12.780533	74.860912	0.9211	Confirmed
DET-006	17:04:40	12.780577	74.860934	0.8566	Confirmed
DET-007	17:05:22	12.780601	74.860956	0.7623	False Pos.
DET-008	17:06:10	12.780644	74.860978	0.8999	Confirmed
DET-009	17:07:05	12.780511	74.860823	0.9012	Confirmed
DET-010	17:07:50	12.780555	74.860867	0.8745	Confirmed
DET-011	17:08:35	12.780599	74.860901	0.7899	False Pos.
DET-012	17:09:20	12.780633	74.860945	0.9321	Confirmed

B. Future Work

Our project is not finished yet. There are still some things that we need to work on, such as the false positives caused by surface clutter. To compensate for our weaknesses, the future version will utilize the Raspberry Pi Camera 2 much better. Through the use of visual AI recognition, the drone will be able to “see” that the target is merely scrap metal and therefore ignore it. Aside from that, we still need to complete the RFID dropper system. This will allow the drone to drop markers on the ground, which is more beneficial to human deminers than a digital map.

VII. CONCLUSION

Manual demining is very dangerous, and most high-tech solutions are simply too pricey to be viable. Our project ends this. We were able to integrate a very accurate PI sensor with a scissor-arm system on a Tarot X6, and in actual testing, it’s already over 87% accurate. It’s a real solution that’s affordable enough to get people’s hands dirty and make humanitarian demining faster and safer.

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