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DRONES AND "BUTTERFLIES": A LOW-COST UAV SYSTEM FOR RAPID DETECTION AND IDENTIFICATION OF UNCONVENTIONAL MINEFIELDS

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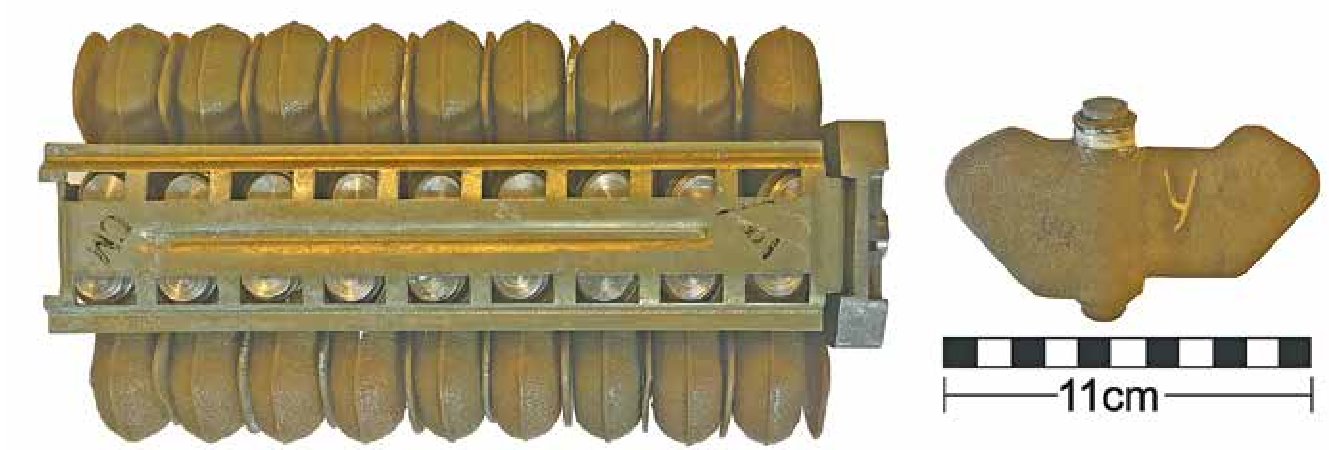

Figure 1. KSF-1 dispersal cassette and PFM-1 landmine.
All figures courtesy of the authors.

Aerially-deployed plastic landmines in post-conflict nations present unique detection and disposal challenges. Their small size, randomized distribution during deployment, and low-metal content make these mines more difficult to identify using traditional methods of electromagnetic mine detection. Perhaps the most notorious of these mines is the Soviet-era PFM-1 "butterfly mine," widely used during the decade-long, Soviet-Afghan conflict between 1979 and 1989. Predominantly used by the Soviet forces to block otherwise inaccessible mountain passages, many PFM-1 minefields remain in place due to the high associated costs of access and demining. While the total number of deployed PFM-1 mines in Afghanistan is poorly documented, PFM-1 landmines make up a considerable percentage of the estimated 10 million landmines remaining in place across Afghanistan. Their detection and disposal presents a unique logistical challenge for largely the same reasons that their deployment was rationalized in inaccessible and sparsely populated areas of the country.

In an attempt to address the PFM-1 challenge, researchers at Binghamton University developed a protocol based on remote assessment of unique thermal signatures associated with the PFM-1 and its aluminum cassette casing. In field tests, researchers were able to successfully identify and recover all elements of a randomized PFM-1 minefield. While this methodology cannot fully replace traditional manual clearance to categorically declare an area clear of mines, remote thermal detection of PFM-1 fields allows accurate assessment of minefield presence, orientation, and any overlap between two or more minefields. Available low-cost commercial UAV platforms equipped with thermal cameras allows accurate assessment of minefield presence, orientation, and potential minefield overlap. Constraining these parameters can significantly reduce search areas in wide-area assessment (> 5 acres/hour at cm pixel resolution) of at-risk regions, potentially reducing associated risks and costs.

As landmines evolved from a weapon of strategic warfare during large-scale armed conflicts of the 20th century to weapons of modern unconventional warfare, their technological development followed two complementary vectors: a calculated reduction of explosive charge and a reduction in mass and metal content. Deployed from the air, either via special artillery shells or from specially equipped aircraft, the PFM-1 contains few metal parts. Although the individual mines can be detected with laborious metal detecting surveys the minefields can be hard to detect.

Figure 2. 3DR Solo quadcopter with FLIR Vue Pro R camera attached to a fixed mount.

With its detonator fully encased in the mine's polyethylene body and its liquid explosive charge not containing any metallic shrapnel elements, remnant PFM-1 minefields are poorly defined in terms of their location and orientation. Moreover, if deployed in a remote area, they can remain in place for decades following the cessation of hostilities, as is the case in Afghanistan.[1] The irreversible detonator of the PFM-1 is set to react to cumulative pressure of roughly 25 pounds, earning it another unfortunate nickname: "the toy mine." As a result, many of its victims are children who happen to find remnant PFM-1 mines and play with them as toys until tragedy strikes.[2]

Demining experts working in Afghanistan estimate that there are currently more than 10 million landmines remaining in the country.[3] The vast majority of these are anti-personnel mines deployed during the Soviet-Afghan War (1979–1989), like the PFM-1 and PMN. At the height of the conflict, Soviet forces dropped as many as 100,000 mines per month and with no existing documentation as to specific areas or number of mines deployed during individual missions.[4] These minefields largely remain in place because the mines were dispersed by helicopters in remote areas that are difficult to access, like mountain passes that are logistically critical for transportation. The minefields are difficult to detect and individual mines are dangerous to remove relying on traditional electromagnetic (EM) methods of detection and physical spike-probing.[5] Furthermore, even when a PFM-1 field is located, removing these mines is painstakingly slow and exceptionally expensive; removal estimates are as high as US$1,000 per mine.[6] Critically, in remote areas of Afghanistan, large-scale demining efforts are not likely to happen in the foreseeable future due to high-logistical costs and ongoing conflict.

METHODOLOGY

We saw the challenge of detecting the plastic design of the PFM-1 as an opportunity to test a different approach to detection and identification. Our approach is based on the mine's long-wave infrared (LWIR) thermal **heat signature**, which contrasts greatly with the LWIR signatures of the surrounding host environment and the aluminum casing of the PFM-1 dispenser.[7] In a recent study, we demonstrated that a thermal camera mounted on a low-cost, commercial unmanned aerial vehicle (UAV) could successfully detect the presence of a PFM-1 from an elevation of 10 meters above ground level. We further demonstrated that the orientation of the PFM-1 plays little role in our ability to detect these devices.[8] In this article, we present the results of a series of field studies that demonstrate our ability to detect and identify all elements of a dispersed PFM-1 minefield. We complement our findings with results of stationary experiments meant to identify the optimal environmental conditions for the application of this methodology.

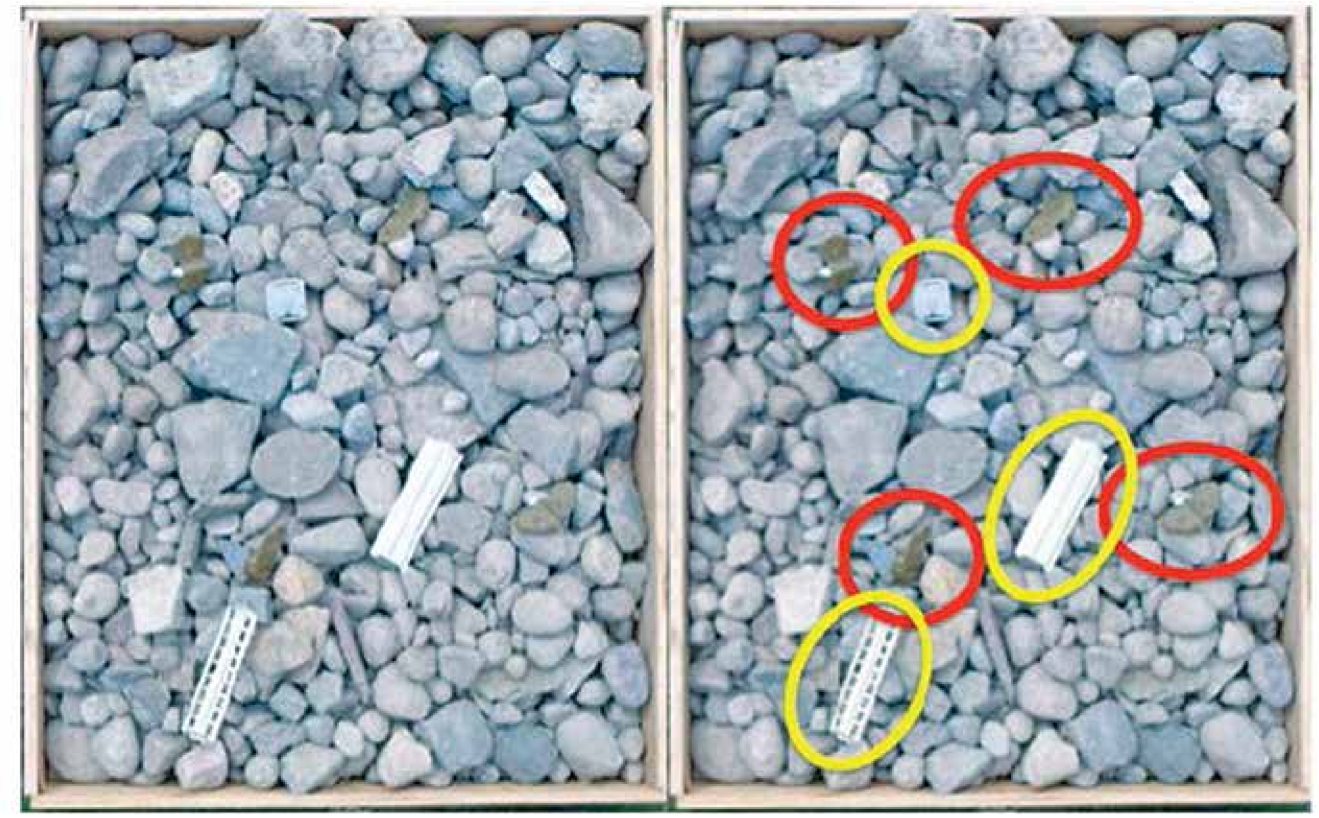

Figure 3. Trials 1 and 2, photogrammetry of cobble environment with PFM-1 landmines circled in red and the KSF-1 cassette casing elements circled in yellow in the second image.

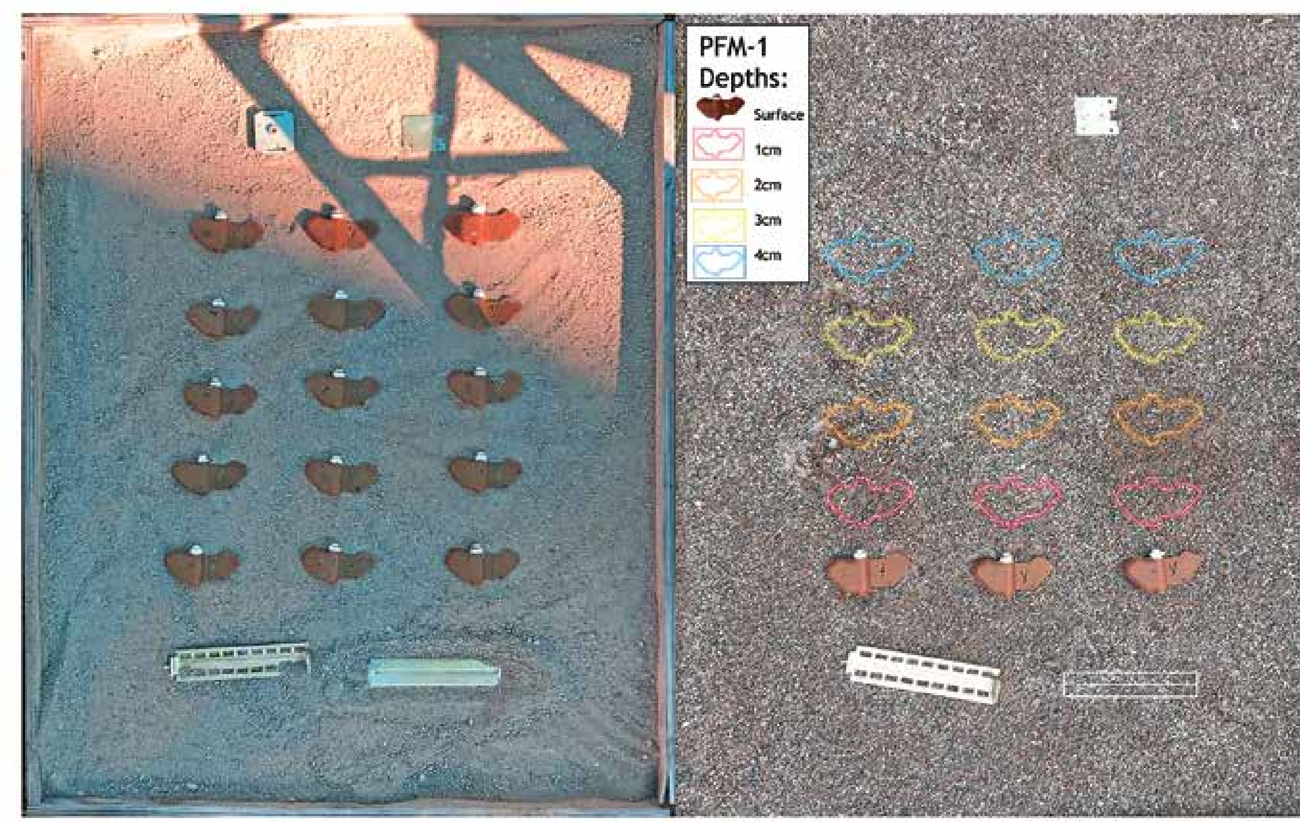

Figure 4. Sand environment for trials 3 and 4 with 9 PFM-1 mines and KSF-1 cassette casing elements.

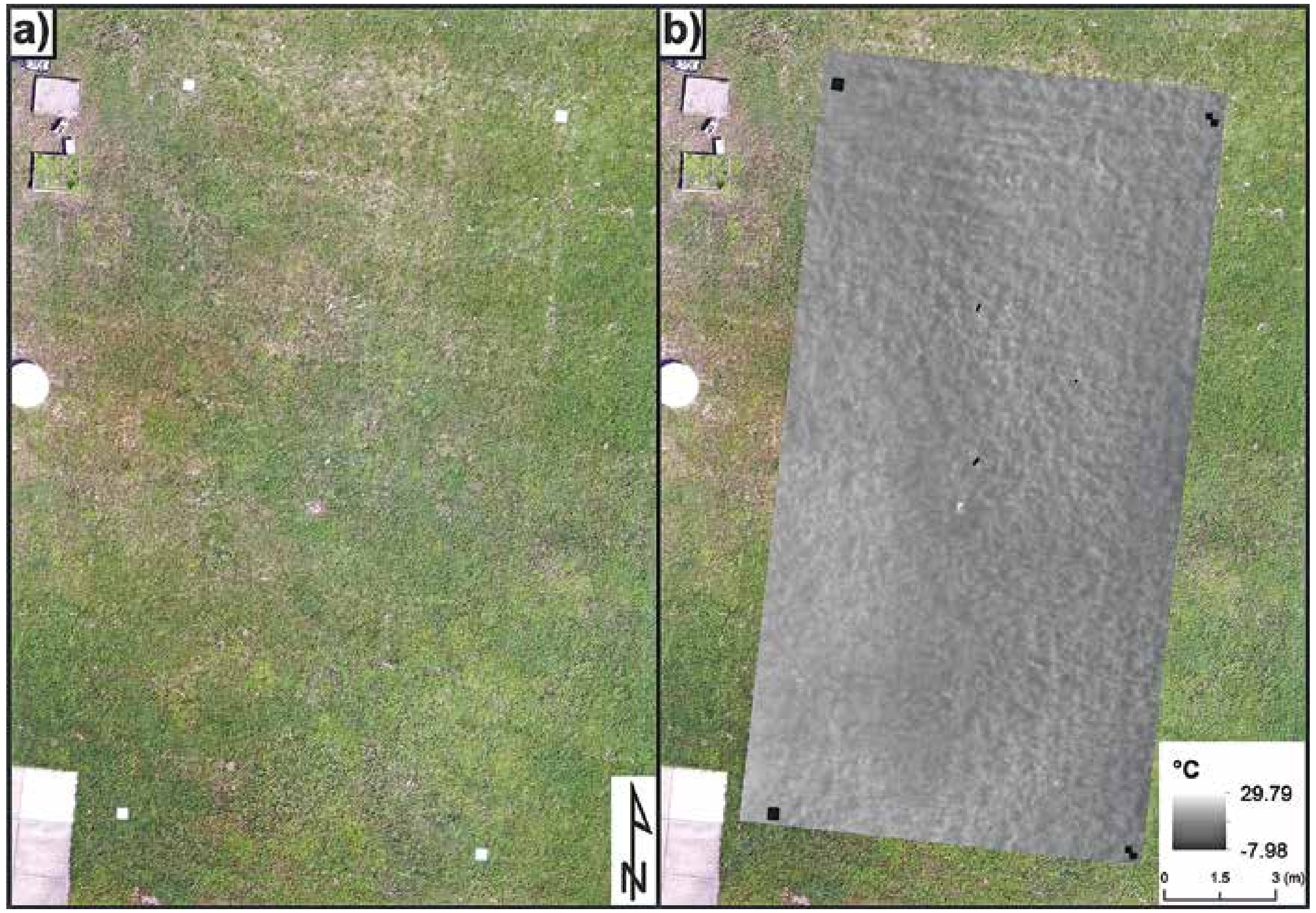

Figure 5. (a) Visible light photogrammetry model from Phantom 4 Professional, and (b) apparent temperature thermal orthomosaic from FLIR Vue Pro R from 8:16-8:23 a.m. flight. In the upper left-hand corner, the stationary experimental sets can be seen.

DYNAMIC UAV TRIAL

The aerial dispersal mechanism of the PFM-1 results in ellipsoidal minefields with dimensions governed by the angle of the initial ballistic trajectory with a range of 18 to 20 meters by 8 to 10 meters. In mountainous areas the size and footprint of the minefield has likely been dynamically changing over freeze-thaw cycles since the mines' initial emplacement. The minefield consists of old intact and inert mines in three element categories: 18 PFM-1 mines, each of which consists of two thin aluminum KSF-1 rails and a thick aluminum KSF-1 pad (Figure 1). In our prior work, we demonstrated that each of these elements has a unique thermal signature, which is largely independent of orientation.[8] For our series of field trials, we dispersed these elements randomly within a 20 by 10 meters test area in a grassy field, to mimic the grassy lowlands these mines could end up in after winter melt mobilizes them, and have previously conducted research on rocky mountainous background geology.[7,8] We conducted a blind test in the grassy courtyard of the Science 1 building at Binghamton University, New York, on 7 August 2018. This was a truly blind trial, as the mines were randomly dispersed to mimic an ellipsoidal minefield the day before so they could reach thermal equilibrium with their background environment before our early morning trials.

Thermal infrared data was collected with a FLIR Vue Pro R camera, which measures LIWR in the 7.5 to 13.5 micrometers wavelength spectral band. The camera was mounted on a commercially available 3DR Solo quadcopter UAV and flown at an elevation of 10 meters above ground level for a high-resolution ground sampling distance of 1.2 centimeters (i.e., the distance between proximate pixel centers as measured from the ground). We complemented thermal imaging with a visual light aerial photography flight at 10 meters altitude with a DJI Phantom 4 Pro 20 megapixel camera (Figure 2), which resulted in 0.24 centimeter per pixel resolution photogrammetry model orthomosaic. An orthomosaic is a georeferenced image product mosaiked from many individual photos into one single image.

STATIONARY CONTROLLED ENVIRONMENT TRIALS

We complemented our dynamic field trials with a series of stationary experiments to assess the impact of environmental conditions and sediment cover on our ability to reliably discern mines from host geology. Four 24-hour experiments were conducted to test the effects of ground composition and water saturation on the detection of intact inert PFM-1 mines among host geology; the mines were left out for over one year and no noticeable deterioration of the mine occurred due to UV exposure. In the first two trials, five randomly dispersed PFM-1s along with an aluminum KSF-1 casing were placed in 0.915 by 1.07 by 0.15 meter sand boxes filled with cobble-sized stones that ranged from 64 to 256 millimeters (Figure 3). In trials three and four, nine horizontally oriented mines, (three placed on the surface with the KSF casing, three at a 1 centimeter depth and three at a 2 centimeter depth) were placed in the sandbox filled with sand less than 10 millimeter (Figure 4). Data was collected using the FLIR VUE Pro thermal infrared camera, with spectral bands between 7.5 and 13.5 micrometers, with a resolution of 640 megapixels attached to a 3DR Solo, propped 2 meters above the sandboxes. Thermal infrared imagery data was taken every 15 seconds throughout the 24-hour duration starting at 12:00 a.m. in order to capture the optimal time of day to detect the PFM-1s based on differences in the thermal inertia of the PFM-1s and surrounding environment.

Figure 6. Apparent temperature from (a) 8:16-8:23 AM flight and (c) 9:18-9:24 AM flight before and after direct heating from sunlight, and (b) visible light color photos over the same area. Aluminum KSF-1 casing can be seen in the top left and PFM-1 landmine in the bottom right.

Figure 7. Close up of a single PFM-1 mine apparent temperature at (a) 8:16-8:23 AM flight and (c) 9:18-9:24 AM flight, and (b) visible light color photos over the same area.

RESULTS

DYNAMIC UAV TRIAL

The results of our dynamic field trials are presented in Figures 5–7. In order to spatially control the resulting photogrammetry model orthomosaics to the centimeter, we placed four aluminum ground control points (GCP) at the perimeter of the approximately 10 by 20 meter area. Shiny aluminum has a low emissivity and can easily be detected by a thermal camera, which can be seen in Figure 3; however, the low apparent temperatures are radiometrically-inaccurate. The location of the GCPs was measured with a subcentimeter Trimble Geo 7X Global Navigation Satellite System (GNSS). We also visibly geolocated the randomly placed PFM-1 landmines with the same GNSS after conducting the thermal surveys. Anecdotally, we were only able to visually locate 15 of the 18 landmines from the cassette on our first walking pass of the area. We likely missed the mines upon our first visual inspection because their dull, green plastic body blends in with the long grass. The fact that we were unable to locate all of the 18 newly-deployed mines on a first pass in our 10 by 20 meter elliptical minefield highlights that this was a true blind trial and the great difficulty

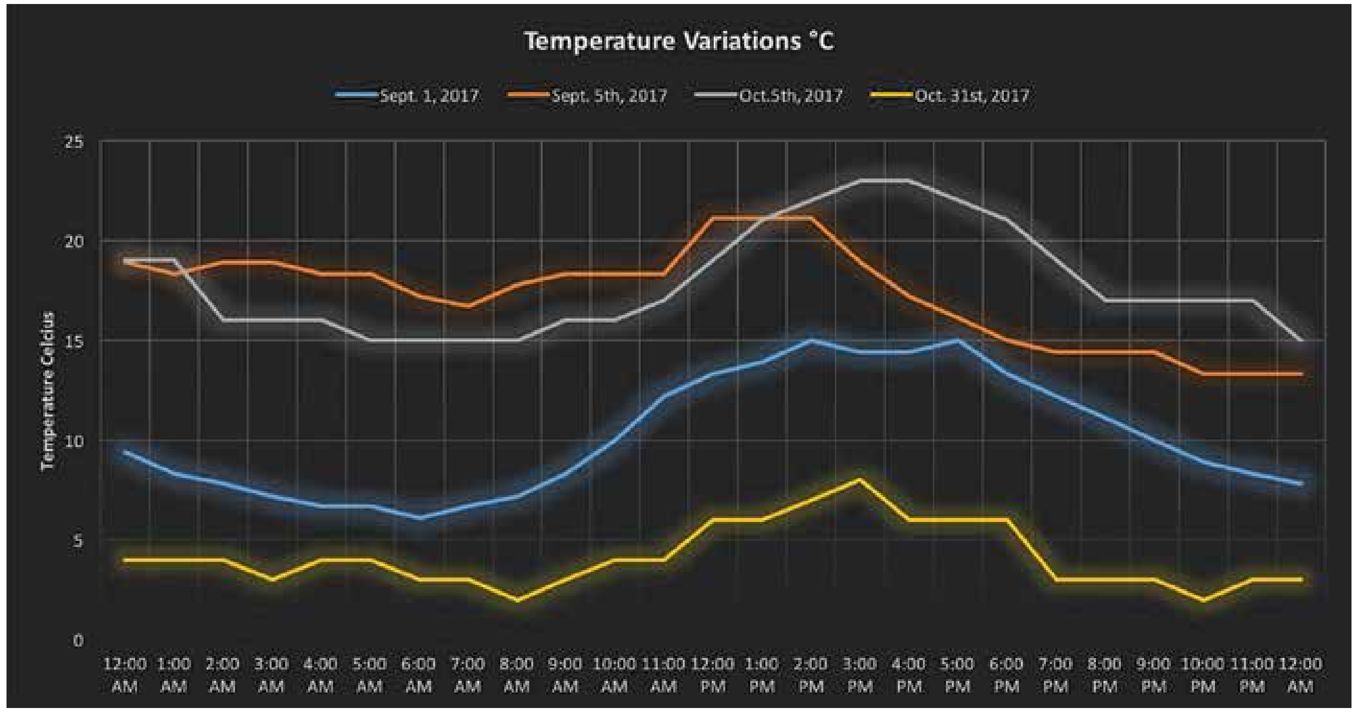

Figure 8. Temperature variation throughout the day for controlled environment trials.

involved in visually locating these small mines in the field even when their general location is known.

In our datasets, we were consistently able to visibly detect both the PFM-1 landmines and the KSF-1 cassette casing elements by inspecting the correlation of visible light and thermal infrared imaging in our field trials. Although the sun rose at 6:03 a.m. on the morning of 7 August 2018, the landmines still could not be seen at our 8:16–8:23 a.m. flight (Figure 5b) because a nearby building blocked direct sunlight from reaching the courtyard until approximately 8:30 a.m. Although the landmines themselves are not visible in the flights before direct heating from the sun, the KSF-1 casing elements are clearly visible in the center of the simulated elliptical minefield as low apparent temperature anomalies (Figure 5b). Upon closer inspection, the KSF-1 casing elements maintain their radiometrically low apparent temperature because of their low emissivity, even after exposure to direct sunlight heating (Figure 6). The landmine's body and wing in Figure 6 (bottom right) heats up faster than its background during early heating from direct sun exposure. Individual PFM-1 landmines that are invisible before direct sun exposure (Figure7a) rapidly heat and can be detected in both visible (Figure 7b) and thermal (Figure 7c) imagery by their distinctive shape and thermal properties.

STATIONARY CONTROLLED ENVIRONMENT TRIALS

In all stationary trials, the aluminum KSF casing was highly distinguishable in both cobble and sand environments and high and low relative moisture. This is important because the KSF casing is an easily detectable indicator of an area impacted by PFM-1s, likely within a 10 by 20 meter range; although as stated previously, in mountainous areas these mines can become mobilized after snowmelt. These controlled experiments provide insight regarding variables associated with plastic landmine detection using thermal infrared imaging.

TIME OF DAY

For differential apparent thermal inertia (DATI) data, PFM-1s were most visible 30–120 minutes after sunrise and sunset.[4] For raw thermal data (trials 3 and 4), PFM-1s were most visible at peak sunlight time from 12:00 to 2:00 p.m. (Figure 8).

HOST ENVIRONMENTAL CONDITIONS

The cobble environment of trials 1 and 2 made detection of PFM-1s more difficult, as the cobbles increased the likelihood of false positives (Figures 9 and 10) and is most like the remote areas where these are dispersed in Afghanistan. In the sand environments of trials 3 and 4 (Figures 11, 12, Table 1), the mines were easily distinguishable in the thermal conductivity and inertia dataset due to extremely low chance of false positives, and the size difference between the PFM-1s and sand environment. This shows PFM-1s are easiest to detect in fine-grain environments like sand, silt, or clay and most difficult to detect in cobble size environments where the grain size is similar to the mines (assuming all thermal properties of the environment remain constant).

MOISTURE CONTENT

High moisture content in the sand environment during trial 4 (Figure 12) greatly improved the visibility of the surface mines in the sand environment.[5] Compared to trials 1 and 3, trials 2 and 4 had higher moisture content (with trial 4 having the highest because the sand more readily retained moisture than the cobbles), increasing the temperature difference and differential apparent thermal inertia between the sand and the PFM-1s.

DEPTH OF BURIAL

Mines buried at depths of 1 or 2 centimeters in trials 3 and 4 failed to emit heat signatures detectable with our equipment. In Figures 11 and 12, none of the 12 buried mines can be identified at any depth below the surface due to the layer of sand above the mines having dominate thermal properties on the surface, muting out the mines' thermal signatures below.

ORIENTATION OF SURFACE-LAID MINES

Statistically, the most likely orientation of the mine for a flat surface is lying flat horizontally as shown in sandbox trials 3 and 4 (Figure 4). This proves useful for detectability in that the flat orientation has signature shape and size that can be identified. Thermally, the most visible part of the PFM-1 is the aluminum cap; when the cap is visible, the mine is easier to detect than when it is not visible. Additionally, orientations that display maximum surface area of both the fluid body and the thin wing were more distinguishable from the surrounding environment, as each has separate thermal properties.

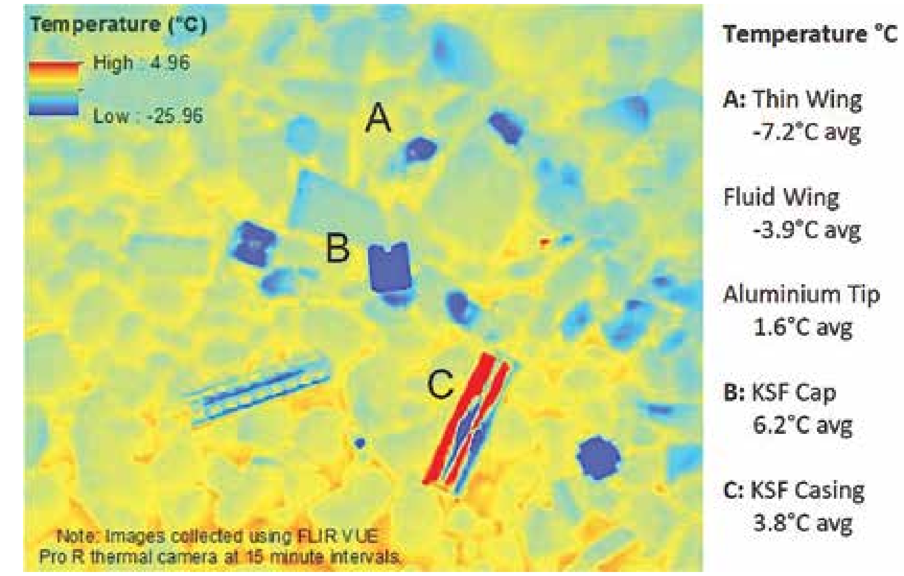

Figure 9. Trial 1, differential apparent thermal inertia taken every 15 minutes of PFM-1s and KSF-1 casing in cobble environment 1 September 2017 (°C/hour).

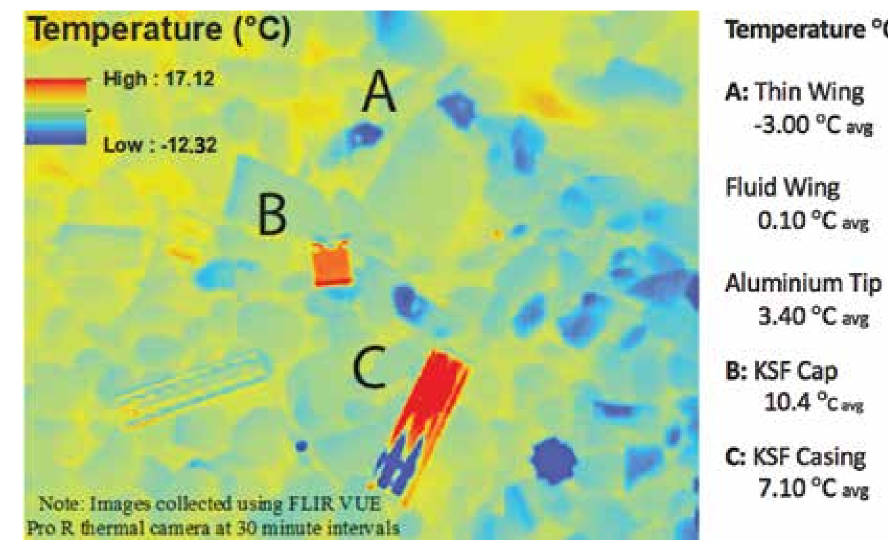

Figure 10. Trial 2, differential apparent thermal inertia taken every 30 minutes of PFM-1s and KSF-1 casing in cobble environment S4 eptember 2017 (°C/hour).

DISCUSSION AND CONCLUSIONS

The use of cost- and time-efficient, remote-sensing techniques to locate direct evidence of PFM-1 contamination from UAVs has great potential that warrants further study. Our preliminary results indicate that the proposed remote-sensing methodology can positively and immediately impact efforts to identify remote high-altitude areas, where aerially deployed plastic mines were most commonly used. In these settings, the design of the PFM-1 and its military role as an efficient tool to restrict and deny the use of remote passages work against it in terms of our ability to detect and identify PFM-1 minefields. In other words, remote thermal detection of PFM-1 minefields would work particularly well in remote areas that are otherwise free of anthropogenic waste and combat artifacts. These are precisely the areas that most PFM-1 mines remain in place in Afghanistan. Conversely, this method would have limited use in urban areas or in areas where plastic and metal debris would produce prohibitive false positives.

We are careful to point out that remote assessment of PFM-1 contamination should be seen as a non-technical and technical survey tool for initial assessment of mine presence and minefield orientation, rather than a methodology to conclusively declare an area free of landmines. It is possible that a PFM-1 minefield may not contain the full 18 mines, as anecdotal evidence suggests that PFM-1 mines may become mobile due to weather (being carried downslope after winter thaw). Furthermore, it is highly likely that not all mines can be detected in a specific field due to a unique orientation, sediment cover, UV exposure, or other unknown factor that might mask a given PFM-1. Finally, it is possible that a PFM-1 minefield may contain other types of mines within its boundaries that are not discerned by remote thermal assessment. Moreover, low emissivity aluminum objects of similar size and shape could cause false alarms. However, despite these shortcomings, remote thermal and visible light assessment would significantly limit the search zone in wide-area assessments of areas impacted by past deployments of PFM-1 landmines. The low cost, small mass, and relatively easy-to-operate system demonstrates significant potential for the NGO demining toolkit. Future research on the detection of the PFM-1 and other similar anti-personnel mines will consider a greater suite of environmental variables (diurnal temperature variation, altitude, host geology, UAV flight altitude, mine orientation) at larger–scale, controlled test sites. This methodology shows great potential for wide-area assessment to rapidly locate remote minefields for subsequent clearance. Eventually, we hope to develop a fully autonomous system of UAVs that can use machine-learning algorithms (e.g., supervised learning classification) to detect and remove anti-personnel mines in difficult terrain without requiring human exposure.

The ultimate goal of this project is designing and implementing a low-cost landmine detection technology that we intend to transfer to NGOs focused on demining efforts in post-conflict countries. We anticipate that the technology and knowledge base that emerge as a result of our ongoing research efforts will allow us to structure a training program focused on efficient and safe deployment of drone-based landmine detection platforms in different environments. This project aims to increase the efficiency and decrease the risk associated with landmine removal to allow previously inaccessible minefields to be located. In this effort, we hope to positively impact communities that remain divided by an artificially introduced threat to their lives and future development.

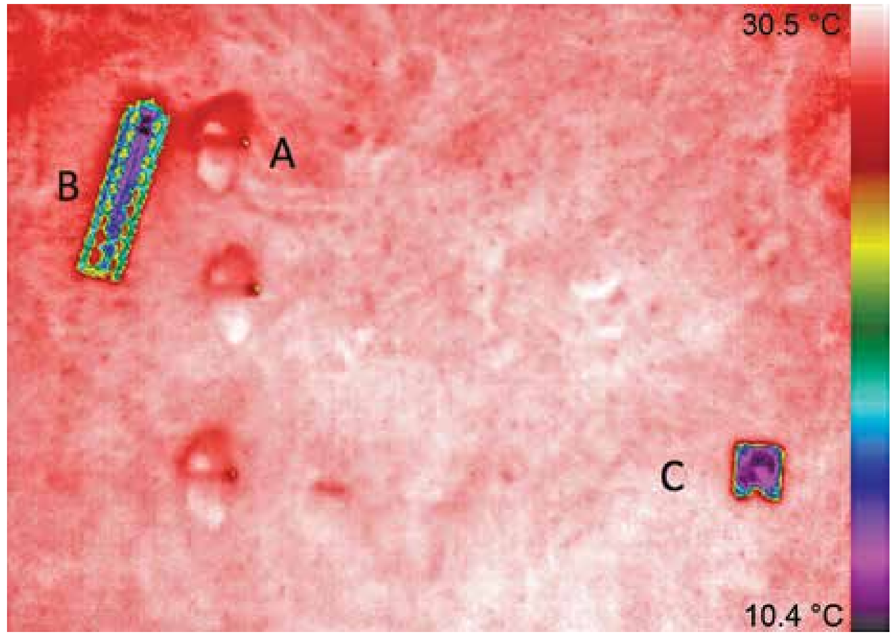

Figure 11. Trials 3 thermal images of PFM-1s and KSF casing in sand environment at 12:00 PM October 5th and 31st

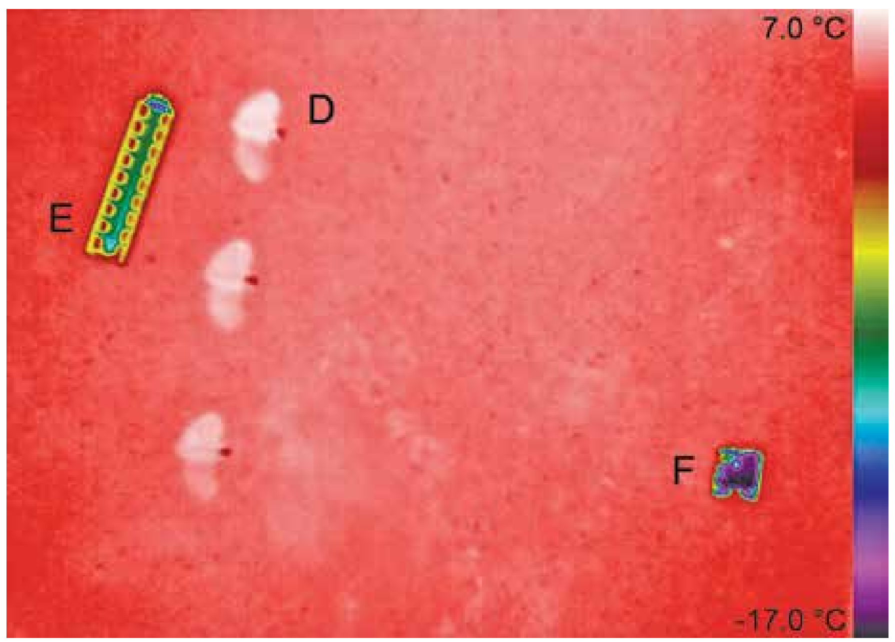

Figure 12. Trials 4, thermal image of PFM-1s and KSF casing in sand environment at 12:00 PM October 31st

Table 1 (right). Trial 3 and 4 average apparent temperatures of labeled objects seen in Figures 11 and 12.

ID	OBJECT	TEMP ° C AVG
A1	PFN-1: Thin Wing	30.39
A2	PFN-1: Fluid Wing	28.21
A3	PFM-1: Aluminum Cap	24.09
B1	KSF: Cap	12.81
C1	KSF: Casing	13.45
D1	PFM-1 Thin Wing	5.7
D2	PFM-1: Fluid Wing	6.5
D3	PFM-1: Aluminum Cap	3.33
E1	KSF: Cap	-6.07
F1	KSF: Casing	-16.75

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See endnotes page ##

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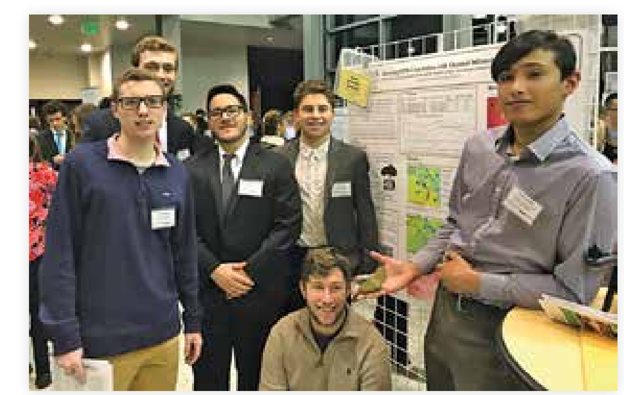

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