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Review article

A review of predictive modelling and drone remote sensing technologies as a tool for detecting clandestine burials

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ABSTRACT

The search for missing people is a complex and intensive undertaking. Predictive models (such as RAG mapping and geographic profiling) in combination with drone-mounted technologies can improve these searches by driving down time and monetary costs, gathering new types of data and reducing the need for investigators to expose themselves to dangerous environments. Promising technologies to discover traces of clandestine burials in the landscape are LiDAR, RGB photography, multispectral and hyperspectral imaging, as well as infrared/thermal photography. This review covers the existing literature on these techniques and discusses future opportunities and directions.

1. Introduction

The localisation and detection of clandestine burials is a challenging but important issue. Discovering a grave gives new investigative or prosecuting opportunities and helps the family of the missing to gain closure. In addition, in many legal systems, it is extremely difficult or impossible to gain a conviction for murder without the presence of a body [5].

Finding clandestine graves has traditionally been a time consuming and resource demanding task, requiring many person-hours spent in potentially dangerous and difficult to access landscapes. Remote sensing techniques are promising to narrow down search areas and increase the efficiency of field search.

Most traditional methods such as search lines, cadaver dogs and ground penetrating radar (GPR) require an approach over the ground, near and sometimes even on top of the burials, which can damage potential trace evidence on the surface.

A drone based approach has the potential to alleviate these problems. A small but experienced team of two can prepare and complete a drone flight within as little as 20 min, with the flight itself taking as little as 5 min depending on the height of the flight and the size of the area to be recorded. Since a drone flight does not disturb the ground beneath it the destruction of potential evidentiary traces is prevented. Drone surveying provides affordable and high resolution images. Centimetre spatial resolutions allow fine alterations to the soil's surface to be identified. In addition, the digital measurements taken by the sensors mounted onto the drone can be stored and later shared and reviewed by multiple teams worldwide at any time.

While drones are increasingly used in forensic sciences [50], research into drone-mounted technologies and their ability to detect clandestine burials is sparse. This is likely because such research is time consuming and expensive. Land needs to be available and approved for the burial of humans or (more commonly) domestic pigs which can be challenging due to cultural sensitivities and laws such as those designed to preserve the integrity of ground water [44]. The equipment itself can be expensive to purchase as well, although prices drop quickly as new technological advances are made in the field. This suggests that drone technologies will become more widely available for such forensic purposes.

Keeping costs in mind, it is important that any research undertaken does so with a clear research question in mind which adds to or improves upon the current body of knowledge. A duplication of efforts, unless done with intention, created due to the lack of awareness of previous research initiatives, is inefficient. This review of the state of the art with

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respect to drone-based detection of clandestine burials will hopefully help prevent such inefficiencies and identify new directions to explore.

Remote sensing techniques commonly employed via drone include RGB photography, Multispectral imaging (MS), Thermal imaging (TI), Hyperspectral imaging (HS), and Light Detection and Ranging (LiDAR). This paper will review the key research publications on these technologies and aim to identify remaining research gaps. Before covering the imaging techniques, this article will describe how the search begins, how search areas are prioritised, and what it is that we are trying to detect remotely.

2. Beginning the search

The context and environment of the search determines what we are looking for and how we look for it. Focusing on specific contexts of disappearances related to armed conflict or criminal activities will outline how proposed spatial approaches could be of assistance to search teams. When someone disappears the search begins assuming that they are alive. The search usually starts from the last location where a person can be placed by the evidence at hand. This location is marked on a map and search areas are prioritized according to spatial variables like roads and paths. Localisation techniques using technologies such as mobile phones, connected watches, GPS trackers or other localisation beacons (Recco, avalanche, etc.) assist the emergency search, as do behavioural or predictive models tailored to the individuals involved and the timing of the incident. Such models have the potential to allow investigators to target the most probable locations to deploy field teams and potential remote sensing technologies effectively. Whenever possible, multidisciplinary teams strengthen the efficient use of different techniques [53].

The geoforensic search strategy encompasses a detailed process divided into pre-search, search and post-search stages [22,63]. The pre-search for clandestine graves starts with desk study [22,63]. In line with this strategy, the proposed approach is to gather information on the case and area of interest, such as different types of maps (topography, geology, roads, etc.) and images (satellite, aerial) to, in combination with predictive models, narrow down the search area.

2.1. Predictive modelling of disappearances

When someone is lost in the wilderness their chance of survival decreases rapidly with time while the search area increases with the person's potential movements [30]. In US natural parks, the dynamic behaviour of lost hikers were modelled using data from previous incidents to assist search and rescue operations [30]. Similar operations in the Swiss mountains are supported with technologies adapted to the environment, such as helicopters and the Rega drone, equipped with RGB, infrared imaging and a mobile phone localisation system.[1]

With disappearances related to armed conflicts or criminal activities, the behaviour of offenders becomes important. An offender's modus operandi helps define search areas where burial sites are most likely to be found. In the context of the exhumations of almost 11'000 victims [27] from graves related to the Spanish Civil War (1936–1939), Congram [15] studied how civilians were killed by the Falange paramilitary group in a planned and systematic manner. He studied several spatial variables that may influence where the offenders bury their victims, among which the most impactful were the distance to urban areas, the visibility and usage of the site, the road type and the distance of the killing site from the road. These variables are used to create a deductive model of the Castilla-Leon region that outlines high, medium and low probability areas. In doing so, it seeks to strike a balance between efficiency (reducing probable search areas) and accuracy (correctly categorising sites). Maps like this are meant to help prioritise the search for clandestine graves.

Congram et al. [16] analyse spatial relationships related to detention, transport, execution, and body disposal. Based on their experience in Central Africa, East Asia, and Europe they describe recurrent patterns and make recommendations regarding key factors that enable proper mapping and spatial analysis. During armed conflicts, people are often buried where they are killed in battle or, when circumstances allow for the bodies to be moved, at the nearest local cemetery. Regarding non-combatants, they are likely to be killed at their home, after which their relatives or neighbours bury them nearby. Congram et al. [16] outline the importance of adopting standards in data collection and coding in order to increase the quality and homogeneity of information, which depend on language use and stakeholders' practices. Geographic Information Systems (GIS) are an excellent tool for mapping and comparing geographic variables with which to help achieve this. GIS offer the advantage of integrating:

- Places of interest like last seen location, hospitals, cemeteries, burial sites, battles or shelling,
- Open government data (road networks, land-use, geology, demography, historic maps, etc.), public data generated by witnesses, protagonists or third parties (open-source maps, digital elevation models (DEM) and imagery, etc.),
- Satellite images of kill sites and burial sites,
- Localised data from devices equipped with GPS or other localisation systems (cameras, mobile phones, etc.),
- Attribute tables to add biometric data of missing persons or coded witness testimonies.

Congram et al. [16] explain that mapping available information allows for the visual detection of spatial patterns. They highlight the importance of local expertise for pertinent data collection (overcoming language and culture barriers) and the interpretation of spatial patterns, as local experts would have knowledge of customary and statutory burial practices, land use, and specific events. They provide the example of a ceasefire allowing the repatriation of the dead from the front lines to families, resulting in burial sites hundreds of miles away from the killing site.

Silván-Cárdenas et al. [69] studied spatial patterns related to organised crime and clandestine graves in Mexico. They developed a predictive model based on data from field investigations of potential grave sites in the state of Guerrero. They compared actual grave locations (143) and non-grave locations (281), where graves were searched for but not found. They demonstrate that accessibility and visibility are key variables that influence the distribution of grave locations; 94 % of grave locations showed a travel time from urban settlements of under one hour and 92 % of them had less than 50 % visibility. Another study by the Quipo Argentino de Antropología Forense and Centro de Derechos Humanos de las Mujeres [26] confirmed these findings with 51 known grave locations in the Veracruz region. All these graves were less than one hour's drive away from urban areas and had a visibility of less than 30 %.

The idea that perpetrators choose clandestine spaces with good accessibility and a lot of privacy agrees with Congram's [15] observations that the Falange paramilitary group tended to shoot their victims less than 13 km from their abduction point, look for low cover area, and operate at night. These similarities between large-scale killings of the Spanish Civil War and enforced disappearances in Mexico shows that predictive models have the potential to support the search for clandestine burials in regions and countries with different social, cultural and physical characteristics.

Mondragón and Cárdenas [53] highlight several studies which confirm that accessibility, clandestineness and diggability are key variables in the choice of burial sites (e.g. in Guatemala and in Colombia).

In serial homicide cases, which are related to a single prolific offender, Berezowski et al. [5] propose a search method with the use of

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[1] https://www.rega.ch/en/our-missions/cutting-edge-technology/rega-drone, accessed on the 06.05.2024

geographic profiling to define initial search areas and further reduce these areas by using LiDAR and geophysical methods. Berezowski et al. [5] describe the combined use of various types of information: case-specific (vehicles, telephones, etc.), spatial, temporal, the offender profile and the victim's profile to create a geographic profile in cold cases.

The use of RAG[2] maps that represent the suitability for grave location as high, low or medium has been proposed in the UK [21], and in Italy [70] for homicide cases. The UK study details geological variables like type of soil, diggability and geomorphology. Somma et al. [70] describe how to combine variables like accessibility, slope, diggability and visibility in GIS to produce RAG maps and prioritise search areas. Somma and Costa [71] refine the use of visibility for a specific case considering the houses' balconies as viewpoints in additions to points located along roads.

Most graves are found via witness statements, but in their absence other approaches can be used [71]. Winthropping is a technique based on developing an offender's psychological profile, analysing the landscape, and extrapolating actions from their synthesis [39,40,55,57,72]. First developed in order to find weapon cashes in Northern Ireland [33], the *Winthropping* tool invites investigators to enter the mindset of the offender and reason from there. For instance, when driving on a certain road, what landmarks might catch their eye, or what locations may fulfill certain criteria to be an attractive hiding place for the offender. In addition, Moses [55] introduced the concept of least effort to *Winthropping*, which is the idea that offenders will minimise effort and use routes and methods that are familiar to them.

The search for a grave should be iterative and refined as more information comes in. The challenge for investigators is to gather the available information and use it to guide them in searches for further graves. With each new discovery and subsequent analysis, the tools that can be used to facilitate discovery become increasingly refined and effective. As predictive models prioritise and narrow down probable locations, drones can take to the sky and search them quickly, safely and with a variety of technologies. As new technologies become increasingly proficient at helping to detect small traces associated with clandestine burials, it becomes crucial to limit the size of the survey area and to understand the traces we are looking for.

3. What are we looking for?

Clandestine graves are defined as all those places where burials, sepulchres, or holes in the ground have been made to bury one or more corpses secretly [53]. In order to effectively deploy drone-based techniques to find clandestine graves, we need to know what we are looking for in a landscape.

A grave has an interconnected nature and is part of an open and complex ecosystem. As such, a wealth of variables are expected to influence how a burial affects the landscape. The process of soil aggregation and stabilization, as described by Vereecken et al. [73], illustrates this complexity. It is difficult to define a characteristic specific to clandestine graves for which drones and associated technologies could be used to search.

Research into technologies such as hyperspectral imaging, show that, in experimental settings, graves can be clearly distinguished from the surrounding environment - but this is not the same as employing a drone over kilometers of jungle where missing people may or may not be buried. While in a limited experimental setting one can look for parts of the ground which simply stand out, this approach is likely to be impractical in practice where huge areas of land might be searched. Instead specific characteristics should be identified or parameters developed for which technologies can be used to perform an efficient and targeted search. Unfortunately, again due to the interconnected nature of a grave, this is difficult to achieve. Specific characteristics found in one climatic region or soil type may not translate to the next. This makes it challenging to perform useful and practice oriented research to gather data on such human grave specific traits. One challenging aspect is that there is limited knowledge of how greatly the environment influences grave specific traits. While it is known from theory and case studies that differences exist, these have not been quantified.

There are however signs which, although not unique to graves, can indicate the presence of one. Local surface alterations that are associated with the presence of graves or disturbed soil can be separated into the following categories (see also fig. 1):

- Soil colour changes caused by mixing different soil horizons [14]. The surface appears lighter or darker because underground soil horizons have been brought up to the surface through digging and refilling. These soil horizons are paler in colour because they contain less organic matter, or darker because looser soil can hold more moisture;
- Abnormal accumulation of leaves, tree branches or other debris used to hide the grave [14];
- Vegetation anomalies like: the absence of vegetation, different growing rates or specific species appearing on top of or around graves [29,9], or unusual changes in the vegetation coming from botanic transfers in the backfill [31,7];
- Traces of unusual wildlife activities [31];
- Moisture changes coming from different moisture retention capabilities [31], disturbed soil retaining more moisture [7];

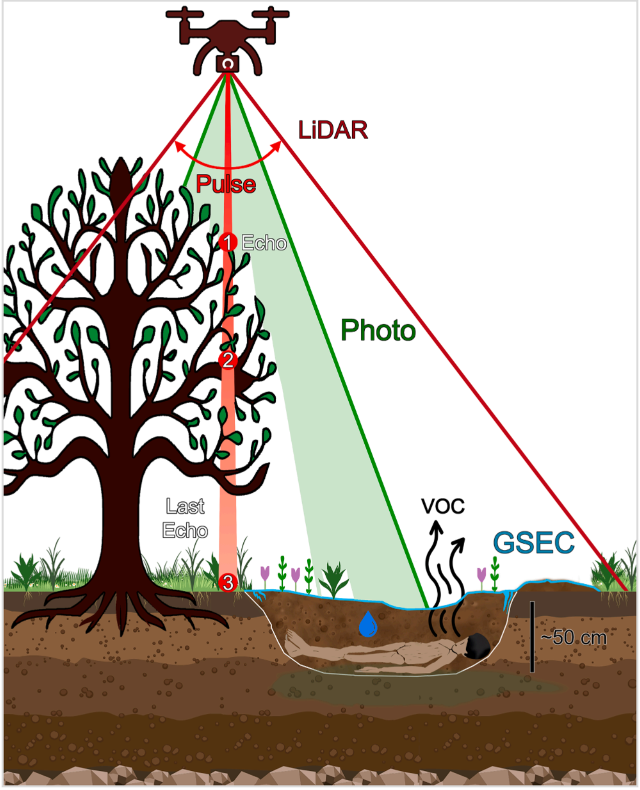

Fig. 1. Drone survey of a clandestine grave that stands out from the landscape because of local surface alterations in the vegetation, soil layers and GSEC (topographic features like cracks, depressions and back-fill mound); photography in green measures what is observed from above while the last echo of the LiDAR pulse measures the ground under the canopy.

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[2] Red, Amber and Green colors like traffic lights represents the high, medium and low probabilities of grave presence.

- Temperature changes provoked by different heating dynamics at sunrise and sunset [67];
- Topographic changes like cracking around the grave, depressions and mounds [17,36,14,6]; cracks can appear due to the swelling and shrinking of clays in soils with high clay content.

These changes are observed at different times after burial, ranging from days to months or even years. Rocke and Ruffell [62], who study older burials in graveyards, show that topographic anomalies tend to outlast local vegetation changes. Other traces of activities such as track marks from a backhoe may also indicate the presence of graves [7]. For a detailed study on how to highlight specific objects like military or transport vehicles and activity patterns from satellite images, see [61].

An example of a topographic change is the grave soil elevation change (GSEC) over time. As a grave is dug, a body is placed, and the grave is backfilled, the backfilled soil tends to form a mound (see fig. 1). This mound is formed because the disturbed soil has greater aeration and is not as packed down as the surrounding earth. Over time this mound compresses due to environmental factors such as rainfall and gravity, and sinks down. As the body decomposes in the grave there is also a loss of material volume which can be filled by the sinking soil, eventually forming a ground depression.

These depressions are now being used as a marker to find clandestine graves with LiDAR mounted on drones, but a natural landscape is not a uniform plane and contains variations in elevation. In order to distinguish a grave soil depression from the natural rise and fall of the landscape specific data is needed, such as the volume and shape of grave soil depressions. Very little of such data exists, and what exists is from extremely small sample sizes in varying conditions. As a result we know that differences between soil types do exist - but we do not know how great such differences are, or even how much the data varies within one soil type. The need for such basic data collection is great to achieve more standardised and translatable research, and for the application of drone based remote sensing technologies like LiDAR to practice.

4. LiDAR

Light Detecting and Ranging (LiDAR), also known as Laser Scanning, is an active remote sensing technology which emits a pulse of light and measures the reflection of this light to the sensor [24,25]. Common lasers operate in the green (≈ 530 nm) or in the NIR (≈ 1060 nm, ≈ 1550 nm) spectral regions [60,10]. Some key characteristics of LiDAR sensors that dictate how they should be applied are:

- Maximum measurement range [m]
- Accuracy and precision [cm or mm]
- Angular resolution of the laser beam in [°] (related to the size of the beam footprint at a given distance from the sensor)
- Field of view [°] (the angle covered by the sensor)
- Laser pulse repetition [kHz] (the number of pulses per second). This affects the density of measured points [points/m^2].
- Number of echoes or returns per pulse

Time-of-flight, echo digitization and waveform analysis are used to measure the distance from the laser, the intensity of the reflected light and the number of echoes per pulse [35]. The position of the laser is determined using reference points, a global navigation satellite system (GNSS) or a simultaneous localization and mapping (SLAM) algorithm [60]; mobile sensors usually require an inertial measurement unit (IMU). Terrestrial laser scanners are usually operated from fixed positions on the ground while airborne lasers are attached to aircrafts. In the search for clandestine graves, we focus on the use of airborne LiDAR as it allows to survey larger areas in a shorter time. Knowledge of the position of the scanner and the distance travelled by the laser allows for the calculation of the exact position of a scanned point. The collection of millions of these points is used to get dense 3D data in the form of point clouds. These point clouds in turn are used to classify points based on properties such as reflectance and their geometric relationships to each other (to isolate ground points, vegetation and buildings for example) and to create 3D models of the scanned surface. A standard format (LAS) and classes have been proposed for point clouds [3].

Because LiDAR emits its own beam of light and does not rely on reflected sunlight it is an *active* remote sensing technique. This bears some advantages. The technique can be used at different times of day (or even night) without the angle of the sun influencing the measurements and the laser beam can penetrate vegetative cover to give some information on the ground below [48]. Canopy penetration may vary according to the type of forest (coniferous, broad-leaved, etc.), the tree density and the LiDAR sensor [32], but, regardless, LiDAR is the technique of choice to survey covert areas like forests. LiDAR, however, struggles to measure transparent (glass) or specular reflective materials (mirrors, glossy metals).

LiDAR can be used to search for GSECs in a landscape. Mention has been made of grave soil depressions in the literature [64,36,17,6], but little research focused on this phenomenon and gathered data to accurately describe it. With remote sensing becoming more prevalent data like this increases in value. In order to use LiDAR in the search for clandestine burials, information on these soil depressions and further elevation changes which might distinguish a human burial from other anthropogenic alterations and the general environment is vital, but, to date, it remains unknown.

A distinction is made between primary and secondary depressions. A primary depression is also referred to as a 'soil compaction site' [64] and is believed to be caused by the slow compaction of the back-filled soil over time. This compaction can be caused by rainfall, the movement of animals, or the growth of vegetation. Rodriguez and Bass [64] report that these primary depressions take "anywhere from a week to a few months to occur". They also report that deeper burials (0.6 and 1.2 m deep) tend to create deeper primary soil depressions compared to shallow burials (0.3 m deep).

Although primary depressions are not specific to burials and are more indicative of disturbed soil, the area, shape and depth of these primary depressions could still distinguish a clandestine grave from the general environment. In order to achieve this - or learn whether this is possible - a large sample size of accurate measurements of primary depressions above graves, controls (empty graves) and untouched soil is necessary. From such data, variability in shape, size and depth can be calculated and the overlap of graves with the general environment and controls can be assessed.

Secondary depressions form later within the bounds of the primary depression and are thought to be caused by more advanced decomposition of the body and the collapse of the abdominal cavity [31]. Rodriguez and Bass [64] found that their 1.2 m, 0.6 m and 0.3 m deep burials formed a secondary depression. Out of their six human burials only one failed to form a secondary depression. This was explained by the staggering in burial dates of their subjects. While five of the subjects had been buried a minimum of 2,5 months before examination, the grave which failed to form a secondary depression had only been buried for one month before it was dug up and examined. At this point the body had not reached a sufficiently advanced stage of decomposition. The abdominal cavity was bloated and had not collapsed to make room for the soil to sink into. No measurements of either the primary or the secondary depressions were made.

Few studies have explored the use of LiDAR for the detection of clandestine burials. The first was Corcoran et al. [17] (see also [36]), who monitored four graves - one was empty, a second grave contained one human body, the third contained three human bodies, and the fourth contained six bodies. Each grave varied significantly in size with the exception of the mass grave containing six bodies and the control, which were dug to be roughly the same size. All four graves were dug to a depth of 60 cm. Four scans were made using a tripod-mounted Riegl VZ-400 with a pixel resolution of 5 cm over the span of 21 months. For all, graves and control, Corcoran reports a gain in elevation between the pre-burial and first post-burial scans (potentially caused by the overburden), followed by a loss in elevation between the first and second post-burial scans (108 days apart). They report that around the second post-burial scan the soil elevation above the graves and control resembled that of pre-burial values. Between the last two scans (535 days apart) they report no noticeable elevation changes.

Corcoran et al. [17] note that the grave containing 6 bodies had an uneven elevation loss, where the greatest loss was in the area right over where the bodies were placed. They also observed that the general undisturbed soil around the graves had much smaller elevation changes in more amorphic patterns while the disturbed soil saw greater elevation change in spatial clusters and elongated shapes. They also found that the grave containing 6 interred bodies showed volumetric changes directly over the bodies which are not shown by the similarly sized control grave.

Blau et al. [6] mimic the sample design used by Corcoran et al. [17] with the addition of two control graves with the same dimensions as the graves with three and one interred bodies. Where Corcoran used graves with a consistent depth of 60 cm to reduce the number of variables in the study, Blau created graves at different depths. They placed temperature loggers in each grave and collected weather data on-site. Three airborne LiDAR scans were conducted, one on the day of burial, a second 11 months after burial and a third 16 months after burial.

No measurements of any grave soil elevation changes (GSECs) were made. Instead a LiDAR specialist who was unfamiliar with the burial locations of the graves was given the processed 3D model to try and locate them. From the LiDAR data collected during the flight made 11 months after burial the specialist was able of identifying four out of six graves. 16 months after burial the specialist located five out of six graves. The only grave they failed to locate was the single burial, although interestingly they were able to locate the control grave of a similar size.

Blau et al. [6] report the depression volume of one mass grave to be $0.42m^3$ sixteen months after burial. They observe that this volume, divided by the average volume of the human body, estimates the number of bodies in the grave.

Both the studies by Blau et al. [6] and by Corcoran et al. [17] were able to locate graves and controls in a natural landscape. They also indicate that the detection of graves through LiDAR and ground soil elevation changes (GSECs) does not have the power to separate filled graves from disturbed soil (controls). However it may be that more detailed knowledge of the dimensions and development of these GSECs will make it possible to do so.

Silván-Cárdenas et al. [67] attempted to study GSECs via photogrammetry on their site in Yautepec, Mexico but found that photogrammetry, which does not take measurements of the ground through vegetation the way LiDAR can, has some important limitations. They had difficulties removing vegetation from their point cloud and were unsuccessful in extracting a bare earth digital terrain model from their data. GSECs measured were hence due largely to the growth and subsequent mowing down of grass, rather than the subsidence of soil. In addition their first scan of the landscape, to which all subsequent scans were compared, took place two weeks after burial when the initial compaction of the refilled soil had already occurred.

Somma and Costa [71] carried out an Open Source Intelligence (OSINT) analysis of thirty cases in Italy and other countries to characterize how graves are created as well as the shapes (ellipsoidal, rectangular, irregular) and depth of clandestine burials. They found that the median depth of burials was 50 cm and that graves deeper than 150 cm with sharp angles indicated the use of an excavator. No measurements of GSECs were provided.

To date no further literature on the measurements and volumes of GSECs have been found, indicating a severe lack of data upon which to base practical applications of LiDAR. For LiDAR to be properly applicable to real world cases, data on the variability, range, and averages of GSECs as well as on the volume of subsequent soil depressions and soil compositions are required. This would enable practitioners to create targeted remote sensing surveys and provide an indication of the false positive and false negative rates which such a survey may produce.

There are serious limitations to the use of LiDAR data however, many of them related to the processing and interpretation of data. Low vegetation can be mistaken for ground points. While algorithms for the removal of taller vegetation like trees exist, grasses and low shrubbery are often missed and it is difficult to verify that the ’ground points’ are indeed ground points. When it comes to relatively small height changes like when searching for GSECs, this is a very important limitation to keep in mind.

In addition, while LiDAR has the unique advantage of being able to record ground points through tree canopies, it is not necessarily fruitful to deploy a drone with LiDAR equipment over a forest in the search for clandestine graves. The density of points acquired is greatly reduced under tree cover, so that smaller GSECs may no longer be detected [32]. In some parts of the world one could wait for winter when the canopy cover is thinned or gone, but then one must be mindful of fallen leaves collecting in the exact depressions one is hoping to record, as Corcoran [36] experienced. It is unsure how viable it is to locate single burials under tree canopy with the reduced point cloud densities, but Brede et al. [10] successfully used drone based LiDAR to determine the diameters of individual tree trunks at chest height in forests, indicating that smaller shapes can still be described. As opposed to small graves, larger ones (i.e. mass graves) tend to be dug away from forests [15], as roots interfere with excavating larger holes.

It is worth noting that studies using LiDAR to investigate GSECs use pig or human remains. Pig remains in general are often used to model human remains, as in many countries there are fewer ethical and legal complications. However, more recently it has been questioned whether they are a suitable model at all [49,19,18,41]. When it comes to the study of GSECs and LiDAR it would seem that the use of a pig is unnecessary. The factors of importance are the displacement of soil, and the presence of a decomposing volume. This could be achieved with cheaper and less problematic materials, as the use of pigs can cause religious and cultural discomfort. In some countries, burying any large animal would go against groundwater preservation laws (such as in Switzerland: [44]). It could be more practical and accessible to use cheap animal feed or potatoes to create a similar sized volume of decomposing materials.

When conducting multispectral or hyperspectral studies in parallel it could be that such plant based materials are less suitable, due to the impact of specific decompositional nutrients leaching into the surrounding soils. To date however most studies have been unable to distinguish between filled graves and disturbed soil (controls), but only between disturbed soil and undisturbed soil, indicating that other organic material would be as appropriate as animals or humans bodies. The exception to this is the study by Kalacska and Bell [37], who suggest that their single control can be distinguished from their graves through a degree of vegetative regrowth, which is reflected in their reflection spectra. They theorise that the lack of vegetative regrowth on their graves are due to a toxicity of the soil caused by the leeching of decompositional products.

The next section focuses on the potential of imaging techniques to characterise the spectral properties of graves.

5. Imaging techniques

Imaging techniques are passive remote sensing techniques that measure the sunlight reflected by the earth’s surface in different spectral regions (fig. 2).This section will begin by discussing studies using multispectral and hyperspectral imaging, then moves on to visible (RGB), infrared (NIR) and thermal (MWIR, LWIR) imaging.

Imaging techniques are characterised by their resolutions:

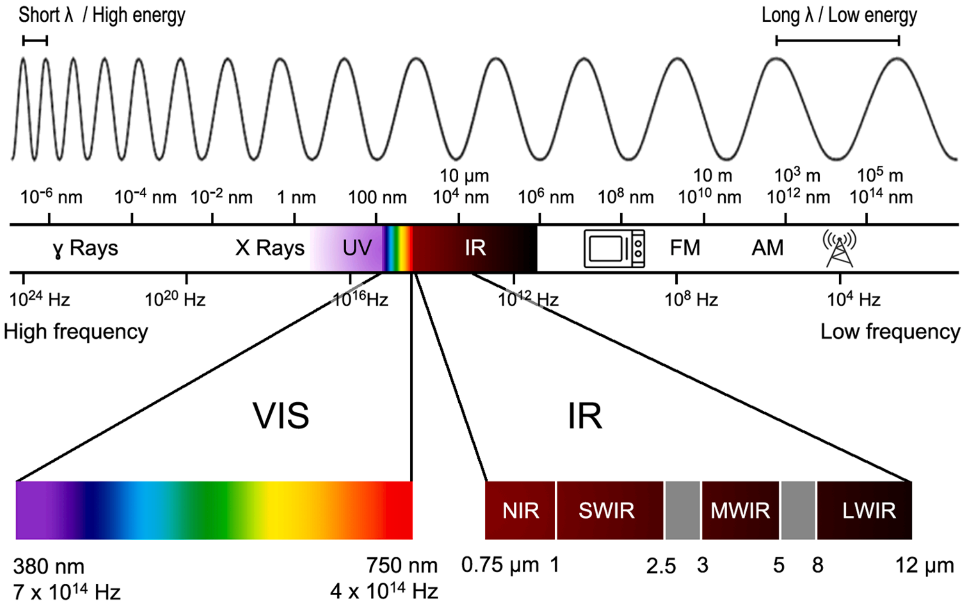

Fig. 2. Electromagnetic spectrum with wavelengths, energy and frequency of the sensing wave; the visible (RGB) and infrared portions are enlarged to distinguish the short (SWIR), medium (MWIR) and long wavelength infrared (LWIR).

- *Spatial* resolution is related to the smallest detail that is recorded by the sensor. For airborne sensors it is usually expressed as the ground sampling distance (GSD), which is the distance on the earth surface represented by two adjacent pixels. It is a function of altitude, sensor's size (dimensions and number of pixels) and focal length; several drone GSD calculators can be found online.[3] The sensor's GSD needs to be finer than the surface features we want to detect. Kovanič et al. [42] summarise the GSDs of commercial drone based LiDAR and cameras used for photogrammetry.
- *Spectral* resolution is related to the sensor's bands, their number and their bandwidth. Multispectral sensors record several broad bands like Blue (≈ 480 nm), Green (≈ 550 nm), Red (≈ 670 nm), Red Edge (≈ 710 nm) and NIR (≈ 800 nm), with bandwidth around 32 nm [67]. Hyperspectral sensors have higher spectral resolutions: they record a large number of narrow bands (≈ 1 nm) across a large region of the visible and IR spectrum. Hyperspectral cameras record many discrete bands, capturing a complete reflectance spectrum for each pixel in the image, as presented in Silván-Cárdenas et al. [67] for simulated graves and controls.
- Temporal resolutions is related to the time interval between different recordings of the same portion of the earth's surface by a sensor; it is usually used for satellites whose orbital movement allows repetitive recording [1].

5.1. *Multispectral & Hyperspectral Imaging*

Multispectral imaging (MS) registers data from several bands of reflected electromagnetic radiation, often in the visible and the infrared region. Hyperspectral imaging (HS) registers data from a near continuous range of wavelengths. As such it is ideal to try and find which exact spectral regions are best for discriminating clandestine graves from disturbed soil (controls) and their environments. The techniques will be discussed together as they attempt to detect clandestine graves via the same principles and the findings for one technique should apply to the other. In essence, the difference is in spectral resolution. The amount of data generated with hyperspectral sensors is much larger, since images, also called hypercubes, hold a complete reflectance spectrum for each pixel.

The dependence on reflected (sun)light makes multi- and hyperspectral imaging passive remote sensing techniques and brings limitations. No measurements can be taken behind obstacles like from the soil under a tree or from surfaces which are not reflecting light, such as areas of dark shade. The angle of the sun in the sky can influence the measurements, as the intensity of different parts of the electromagnetic spectrum shift and change as the sun moves through the sky. Naturally, when relying on sunlight, measurements must be taken during daylight hours.

Scrutinising reflectance values of the landscape in specific bands of wavelengths has allowed investigators to distinguish graves from the natural landscape in controlled studies [37,38,36,68,28]. Let's take a closer look at the most useful spectral bands for distinguishing clandestine burials from the environment, as this is paramount to helping investigators select appropriate cameras for better results.

Regarding vegetation, the NIR reflectance of the spectrum is influenced by the leaf structure of vegetation. The SWIR reflectance is diminished by water content (specific absorption features 1400 & 1900 nm) and organic compounds. The soil spectral signature depends on its composition: inorganic (reflective) versus organic content (absorbent), air and water content (absorbent). A finer granularity is also more reflective than a coarser one. Kalacska and Bell [37] could not distinguish a mass grave from individual ones and controls after one month because of the absence of vegetation; five months after this experimental burial, vegetation was present on the controls but absent on the graves, possibly because of the soil toxicity following decomposition.

Using HS, Dozal et al. [23] could successfully distinguish graves containing pig carcasses from control graves six months after their creation in Yautepec in Mexico. The authors outline the best distinction is achieved after three months of burials using spectral bands influenced by the vegetation and plants' water content. The most distinctive bands were 970 nm and 1546 nm, both influenced by the leaf water content, 2216 nm informing about vegetation species (cellulose or lignin) and 2368 nm related to calcium carbonates.

Using HS ranging from 400 to 1000 nm and monitoring a grave containing a rabbit and a control grave in a dry arctic environment over 6 weeks, Ruotsala [66] could distinguish both from the environment but

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[3] https://github.com/scarnecchia/GSD_calc, last visit on the 01.10.2024

measured only slight spectral differences between the grave and control over 750 nm.

Table 1 shows a summary of the most useful spectral bands as found by different studies into the detection of clandestine burials.

Multispectral sensors are also useful to detect traces of vehicular motion, tracks or other activities that disturb vegetation and ground cover. If the GSD is small enough, tire tread marks can be distinguished using satellite images [61].

5.1.1. *RGB cameras*

Satellite images with a larger swath (field of view) also have a larger GSD. For the same satellite, the panchromatic (levels of greys) and RGB images have usually a smaller GSD than the available multispectral bands [47]. [37] were able to distinguish a large mass grave in Guatemala using a 15 m spatial resolution image. Commercial satellites operating at lower orbits can have a GSD of under one meter, reaching GSDs as small as 30 cm. This spatial resolution could make it possible to distinguish surface alterations created by individual graves. Aerial image are usually associated to smaller GSD, like for instance Swisstopo,[4] which provide images with 10–25 cm GSD every three years. Drake describes the use of satellite archives covering different periods of time to search for clandestine graves or other traces of criminal activities [26]. Aerial images, for instance unclassified military imagery in conflict areas like the Balkans in the 90 s, have outlined machine activities and large graves in the surroundings of Srebrenica [7].

The elevated and top-down perspective of aerial or drone images allows the detection of surface anomalies that cannot be seen during field surveys on foot [63]. Photogrammetry enables the creation of orthophotos and digital surface models (DSM) of the survey area to measure anomalies and outline elevation changes. Alvarez-Vanhard et al. [1] outline the advantages of satellite and drone imaging: drone techniques being more flexible, independent of cloud coverage (but sensitive to wind and precipitation) and cheap (for a small GSD), but demanding in data management and pre-processing tasks. The authors also describe synergies between both systems for image analysis and interpretation, such as data fusion techniques to increase spatial or spectral resolution. Calleja et al. [12] combined the resolutions and spectral bands of both satellite and drone systems to detect crop marks and micro-topographic features associated with buried archaeological remains. Combining data from heterogeneous sensors is demanding in processing time, but has the potential for greater improvement than the simple addition of different techniques.

According to Evers and Masters [28] RGB images can provide valuable information with which to find clandestine graves. Subtle colour changes in vegetation and soil can be used to identify disturbed soil, and geomorphology can be analysed and worked into predictive models [65]. Colour changes may be difficult to use after long periods of time, as Molina et al. [52] could not detect their eight simulated graves with RGB images after eight years of burial.

Table 1
The most useful wavelengths with respect to detecting clandestine graves in a landscape varies with time as soil settles, the body decomposes, and vegetation regrows. See fig. 2 for the wavelengths' corresponding regions of the spectrum.

Time after burial	Wavelengths
Before vegetative regrowth	850 nm [28,37]
1 month	400–550 nm [37,38,67], 850 nm [37,38], 2000–2500 nm [37,67]
3 months	500–700 nm [67], 700–1000 nm [68,23], 1001–1800 nm [68,23], 1500–2500 nm [23,67]
5 months	450–550 nm [37,38], 970 [23], 1500–2500 nm [23,67]
13 months	707 nm [36], 761 nm [36], 1440–2200 nm [36]
16 months	550–700 nm [38]

5.1.2. *Infrared & thermal imaging*

Infrared cameras have been of interest in the search for missing persons for decades, as shown by earlier works such as Dickinson [20], who used such a camera mounted on a helicopter to attempt to locate the body of a missing hitchhiker in New Zealand and showed that animal remains as old as 17 days could still be located with this technique.

Thermal imaging is of continued interest with drones. The sensors required are relatively cheap, and the specialised processing needed is less than that with techniques like LiDAR or hyperspectral scanning. While of special interest to the search for living missing people and surface remains [11,8,46,56,2], thermal imaging has also been applied in the search for clandestine graves [11,28,56,43,67].

Evers and Masters [28] used a customised Go-pro to capture NIR wavelengths. NIR imaging is not actually thermal imaging, the difference being that thermal (wavelengths from about 8000–14000 nm) captures also the radiation produced by the temperature of an object itself (with the idea that higher temperature = brighter image), while NIR imaging captures reflected NIR radiation that comes from very hot objects (notably the sun).

Healthy vegetation tends to reflect NIR very strongly as it is not used in photosynthesis, while unhealthy or disturbed vegetation reflects it less [74]. Soil tends to be even less reflective of NIR radiation, and can be made even less so by high moisture content leading to increased absorption. This can help us find clandestine graves, since back-filled soil tends to hold more moisture than the surrounding, compacted soils [34]. This in combination with the removal of vegetation of soil cover could create a large contrast between the natural environment and the clandestine grave in NIR wavelengths.

Evers and Masters [28] studied a natural burial ground in England with 138 buried individuals buried in willow, wooden or cardboard coffins. They found that they were able to identify graves with NIR that they were unable to identify with visible wavelengths. All these graves were more recent graves however, and they specify that they were only the graves where vegetation had not fully recovered that were located. They also found that some graves could be identified on the colour images (due to small changes in vegetative colour and species) but not on the NIR images.

Larson et al. [43] claim that thermal scans are effective only on relatively fresh shallow burials, but that the back-filled soil can be two to three degrees centigrade warmer than the surrounding soils.

Butters et al. [11] looked at both surface and at shallowly buried pig remains in Queensland, Australia. They were able to easily pick out the freshly buried remains with thermal imaging taken at midday for up to two weeks. The greatest heat signals from all remains both buried and surface was during the early decomposition stages with peak insect activity. Meanwhile Bodnar et al. [8] used four pigs, one left on the surface and three buried at different depths, and found that thermal imaging is most effective between 6 and 29 days of burial. The difference between the results is theorised to be due to a difference in rate of decomposition as the experiments were hosted in different climates and potentially different seasons [11].

Silván-Cárdenas et al. [67] used thermal images recorded at dawn and at noon to measure the heating pattern of the soil where experimental graves were present. Seven months after burial, the authors measured a slightly lower temperature for six out of seven of the experimental graves. This difference with the untouched soil was attributed to the pit creation process that promoted the vegetation regrowth rather than to the presence of buried pigs. They also observed that voids caused by the decomposition of several bodies and thermal barriers like plastic bags increased the detectability of graves using thermal imaging.

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[4] https://www.swisstopo.admin.ch/fr/orthophotos-swissimage-10-cm

5.2. Spectral indices

Spectral indices or vegetation indices (VI) are derived from a combination of spectral bands to measure a number describing the intensity of a complex quality of which the individual contributing factors are unknown or undefined [4]. There are many VI and those are typically used to study the biosphere and monitor vegetation [54]. VI allow a comparison between the strength of reflectance in different spectral bands. Using ratios for comparison minimizes the effects of illuminations changes in images. The most commonly used VI, Normalized Difference Vegetation Index (NDVI), is a comparison between the NIR and red bands generally used to assess how healthy observed vegetation is. Healthy photosynthesising plants absorb light from red bands and largely reflect NIR bands. As such they appear bright on NIR bands and dark in red bands.

The NDVI has been used to identify clandestine graves in a study by Leblanc et al. [45]. Instead of using it to identify healthy vegetation, it was used to locate bare soil which is characterised by low NDVI values. This approach was based on the assumption that disturbed soil has less vegetative cover. While this approach was successful and is probably more robust to illumination changes over the survey area, Evers and Masters [28] could also successfully identify bare soil as an indicator for burials using NIR aerial images directly. Norton [58] monitored a pig and an empty grave for 121 days; their distinction was possible through vegetation coverage up to 65 days, but no distinction was possible afterwards.

Norton [58] used NDVI derived from satellite images to distinguish large mass graves from empty graves up to five years after burial. Even many years after an incident, the exploitation of archive images allows the comparison of spectral information before, during and after burial to outline anomalies from regular seasonal changes.

Corcoran [36] also attempted to locate graves using NDVI but found that no patterns with respect to the burials could be observed. The graves did not show as anomalies after application of NDVI to their multispectral data. They have similarly negative results with the application of six other vegetative indices on their hyperspectral data (REPI, MRENDVI, MRESRI, RENDVI, SIPI, SGI). Terrestrial multispectral data identified as useful for the distinction between disturbed and undisturbed vegetation came from red, NIR, and SWIR - all of which can be greatly influenced by the presence of bare soil. These bands no longer distinguished disturbed soil from undisturbed soil when scaled up to aerial remote sensing, although this could be caused by reduced spatial resolution.

Leblanc et al. [45] successfully used the Structure Insensitive Pigment Index (SIPI) to identify single graves. This index incorporates reflection values of blue bands to estimate the ratio of carotenoids to chlorophyll. A high value tends to be an indication of plant disease and/or stress. It is, like the NDVI, sensitive to the reflectance of bare soil and as such it may be that Leblanc et al. [45] were able to differentiate the graves from the general environment mainly through degrees of bare earth rather than through plant health. This poses limitations on the method, as older graves with recovered vegetation may not be found.

Rocke et al. [63] used Visual Atmospheric Resistance (VARI) to search for the simulated grave containing a cloth handbag with woolen clothes. VARI uses the visible spectrum (green, red and blue bands) and is minimally sensitive to the effects of the atmosphere on reflection. Unfortunately they were unsuccessful - no anomaly was found at the location of the grave. NDVI was successful in showing an anomaly - despite vegetation fully covering the grave. It is important to note that no decomposing animal remains were buried, and as such this anomaly is the product of disturbed soil and buried objects, not of a decomposing body.

Rocke et al. [63] also use VIs as part of their Geoforensic Search Strategy. Through mapping plant stress they locate areas where plants grow better and the soil is expected to be easier to dig in. This information when added to a predictive model as discussed in the earlier sections of this article, could greatly help focus search areas.

An yet unstudied use of VIs is their ability to distinguish between species of vegetation. It has been noted that the vegetation which grows over disturbed soil can be significantly different from the surrounding vegetation [75]. In search for older clandestine burials where vegetation is expected to have largely recovered, VIs might aid discovery by indicating the growth of a species in an unexpected location.

Silván-Cárdenas et al. [67] showed that spectral indices like GNDVI, NDREI or RECI,[5] which are sensitive to the vegetation nitrogen content, allow for the detection of buried pigs three or four months after burial. They posit that it took a few months for the nutrients to be absorbed by vegetation; the efficacy of these VIs more than six months after burial was not tested.

Molina and Pringle [51] followed four simulated graves containing pigs and one control grave and compared the multispectral images just before burial to 128 days (4.2 months) after burial. They display their multispectral data with NDVI, GDVI, and GCI VIs and some areas of interest can clearly be seen, but unfortunately it is unclear how they line up to the location of the graves. It would have been better to have a clear marking of the distribution of the graves on their VI images, as more than six areas of interest can be found in each.

In 2024 Molina et al. [52] flew over eight simulated clandestine graves, each eight years old, with a UAV. The simulated graves held either pigs, human cadavers, skeletal remains or a variety of objects and were 2 m x 2 m in size. Four were at a depth of 0.8 m and four were at a depth of 1.2 m. Their results indicate that all but one (the deepest) grave could still be detected with the use of NDVI and NIR multispectral data collected from a UAV flying at a height of 70 m. Using NIR they were even able to identify exact grave boundaries on three of their simulated graves.

6. Discussion and conclusion

Predictive models and GIS tools aid the systematic spatial analysis of disappearances by narrowing down search areas. Remote sensing can then be deployed in a targeted manner to look for grave associated surface alterations and support investigations efficiently.

Local surface alterations associated with the presence of graves can be detected using remote sensing techniques, but it remains a challenge to distinguish between the effect of natural phenomenon, anthropogenic activities and criminal activities. In this regard, potential graves detected via remote sensing techniques require an excavation to confirm the presence of a human body.

LiDAR, multispectral (MS), hyperspectral (HS), RGB, infrared and thermal imaging are all different tools to apply to the appropriate situations, each with their respective advantages and disadvantages.

LiDAR is a promising technique which is able to record topographic anomalies under the canopy and does not depend on time of day or, to a lesser extent, on open vegetation. However, there are only few studies with which to interpret the point clouds created with this technique for the purpose of finding clandestine graves.

A useful development in LiDAR research efforts would be to more carefully describe the shapes and volumes of the depressions recorded by this technique, and to develop algorithms to classify even low vegetation so as to better isolate true ground points. An improved understanding of the volumes and the variation therein of GSECs above graves versus controls might further help the differentiation between them.

Hyperspectral (HS) imaging is an expensive and time consuming technique but vital in discovering the optimal spectral bands with which to distinguish graves from controls and from the landscape. The results obtained with this technique can be used to choose appropriate cheaper

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[5] GNDVI=Green Normalized Difference Vegetation Index, NDREI=Normalized Difference Red Edge Index, RECI=Red Edge Chlorophyll Index

and lighter sensors with a lower processing load.

Multispectral imaging can be used to compare multiple spectral bands and compute spectral indices and VIs. It is one of the cheaper alternatives to HS imaging when we have a better understanding of which spectral bands are relevant to investigate.

NIR imaging is cheap and well used in situations where the vegetation is not expected to have yet recovered above the clandestine grave, as it is excellent at highlighting patches of bare earth in a landscape. As it is used to monitor plant health, it might be interesting to investigate whether NIR is effective in identifying tracks (either from vehicles or footwear) through a vegetation rich environment.

RGB cameras are a common accompanying technique that can help us find clandestine graves in situations where there is a contrast in top soils and different types of vegetation. Often it is automatically deployed together with one of the other above-discussed techniques. The visual appearance of objects on RGB photographs is familiar to everyday experience and helps with recognition.

As technologies continue to develop, giving rise to smaller, lighter and cheaper equipment, new drone-mounted solutions will present themselves. Those covered in this review are but a start - drone based GPRs are becoming prevalent [59,13] and are, based on the frequent use of their terrestrial counterpart to detect underground anomalies, of obvious interest to the field as they avoid direct contact with the surface. Multi-wavelength LiDAR sensors are promising as they can increase the spectral resolution of this active remote sensing technique, allowing the collection of “multispectral” measurements under the canopy [60].

It is the opinion of the authors that drone based solutions fill an important niche in the search for missing persons and that with an increasing understanding of what we can detect with them, we will be able to build an invaluable and flexible toolbox to apply to a wide variety of cases.

CRediT authorship contribution statement

Marissa Koopman: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Quentin Milliet:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Christophe Champod:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

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

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