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RESEARCH ARTICLE

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Fluorescence-based detection of field targets using an autonomous unmanned aerial vehicle system

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Abstract

1. Here we describe a proof-of-concept autonomous unmanned aerial vehicle (UAV) system that utilizes the fluorescence characteristics unique to different materials to scan and acquire targets in the field that includes fossils, rocks and minerals, organisms and archaeological artefacts. This is possible because these targets are often highly fluorescent against lower fluorescence backgrounds and may exhibit different colours. To detect these targets from a moving UAV, we utilize laser-stimulated fluorescence. This involves an intense laser beam that—unlike regular UV light—can project greater distances and generate sufficient fluorescence for targets to be detected on the UAV camera many metres above the ground.
2. The system involves a lightweight UAV programmed to fly a waypoint pattern autonomously at night over the area of interest. LIDAR maintains its height above the terrain. A near-UV laser is projected across the ground as a horizontal line directly below the UAV. Co-mounted with the laser is a small highly sensitive video camera stabilized on a motion-controlled gimbal that records the laser line during the flight. An intermittent, powerful white light strobe flashes during the flight to record the UAV's ground position in the scanned area. The UAV returns with the laser video at the end of each autonomous mission. This video is post-processed, extracting the laser line data into a long continuous scan image showing the fluorescing ground targets.
3. Initial analysis determines what colour the targets fluoresce so that a specific colour range can be extracted from the image to identify the locations of the detected targets. The white light strobe images are then used to quickly follow-up on the detections.
4. This system holds the promise of becoming the lowest 'ground truth' layer in the mix of high-altitude map data produced by satellite- and airplane-based Geographic Information Systems. With centimetre resolution and the geochemical differences shown via fluorescence, this system will increase the scale and efficiency of data collection involving fossils, rocks and minerals including mineable materials, fluorescent organisms including biogenic mineral producers like shellfish as well as archaeological artefacts. Thus, the fields of evolution, ecology, Earth and planetary science, archaeology and other subjects involving fluorescent targets would all benefit from this new system.

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KEYWORDS
applied ecology, community ecology, conservation, evolutionary biology, microbial ecology, population ecology

1 | INTRODUCTION

Many field-based disciplines have traditionally been strictly human endeavours. The introduction of satellite- and airplane-based mapping has proven useful at the macro-scale in predicting where fossil localities may exist (Anemone, Emerson, & Conroy, 2011; Conroy, 2014; Conroy, Emerson, Anemone, & Townsend, 2012; Emerson & Anemone, 2012; Emerson, Bommersbach, Nachman, & Anemone, 2015; Malakhov, Dyke, & King, 2009; Oheim, 2007; Stucky & Krishtalka, 1991; Stucky, Krishtalka, & Dawson, 1989; Wills, Choiniere, & Barrett, 2017), where living species and their habitats may occur (Norberg et al., 2019; Rushton, Lurz, Fuller, & Garson, 1997; Sperduto & Congalton, 1996; Tucker, Rushton, Sanderson, Martin, & Blaiklock, 1997; Van Manen & Pelton, 1997), where minerals may be mined (Carranza, 2009) and where archaeological artefacts may be discovered (Kohler & Parker, 1986; Kvamme, 1992; Mehrer & Westcott, 2019). This 'upper layer' technology can determine where to send ground-based investigations. However, they do not have sufficient resolution at the centimetre scale to verify specific targets. While field crews can always be deployed to search for and find any targets, funding constraints usually preclude sending teams large enough to search extensive areas based solely on satellite data. Here we use palaeontology as an evolution-related proof-of-concept case study to illustrate how a newly developed fluorescence-based autonomous unmanned aerial vehicle (UAV) detection system interfacing at the lowest level of a tiered GIS system could improve the efficiency of fossil collection. Building on this proof-of-concept, we suggest other potential applications of the UAV system in the fields of ecology, Earth and planetary sciences and archaeology.

Modern UAV systems offer highly sophisticated and transportable aerial platforms able to autonomously fly detection instrumentation (Krajník, Vonásek, Fišer, & Faigl, 2011; Saska, Krajník, Faigl, Vonásek, & Preucil, 2012; Figure 1). Ariel surveying is now common and 3D scanning systems are coming into regular use (Anemone, Emerson, Jones, Liu, & Henderson, 2018; Bindemann, Fysh, Sage, Douglas, & Tummon, 2017; Floreano & Wood, 2015; Gao, Xu, Klinger, van der Woerd, & Tapponnier, 2017; Petti et al., 2018; Romilio et al., 2017; Siebert & Teizer, 2014). Many of the once heavy instruments like compasses and inertial sensors are now down to the chip level allowing for greater payloads but still having advanced capability similar to full-size aircraft. Current UAV technology allows for affordable, sophisticated, autonomous aerial reconnaissance with a variety of instrumentation.

FIGURE 1 Unmanned aerial vehicle (UAV) starting autonomous mission over fossil-rich badlands in Wyoming, USA. Flight path is verified during the day and flown in detection mode at night. The UAV maintains height over the rolling hills using LIDAR

Laser-stimulated fluorescence (LSF) uses high-power lasers to stimulate fluorescence in fossils (Kaye et al., 2015; Wang et al., 2017). This technique has revealed signatures of previously unseen soft tissues in famous fossil lagerstätten (Falk, Kaye, Zhou, & Burnham, 2016; Kaye, Pittman, Marugán-Lobón, et al., 2019; Kaye, Pittman, Mayr, Schwarz, & Xu, 2019; Vinther et al., 2016; Wang et al., 2017; Yang et al., 2018). Ultraviolet (UV) lamps have traditionally been used on fossils (Frey, Tischlinger, Buchy, & Martill, 2003; Hone, Tischlinger, Xu, & Zhang, 2010; Tischlinger & Arratia, 2013; Tischlinger & Unwin, 2004), but the laser's higher photon flux per square centimetre produces higher levels of fluorescent signal making the same fossil glow brightly when little or no fluorescence is visible when using lamp-based UV (Croft, Kaye, & Panko, 2004; Kaye et al., 2015; Kaye, Pittman, Marugán-Lobón, et al., 2019; Kaye, Pittman, Mayr, et al., 2019). The laser's higher intensity allows it to be projected over much greater distances than UV with little reduction in power (inverse square law = intensity $\propto$ 1/distance^2). The laser's ability to be utilized at distance is the basis for current airborne laser fluorometers used to detect organic matter in water systems (Rogers, Webster, & Livingstone, 2012). The use of a true UV laser would be greatly preferred as it incorporates both the benefits of a collimated light source and the specific UV wavelength, but at this time UV lasers are only commercially available in the lower milliwatt range.

The fluorescence of rocks originates from contamination in the mineral lattice (Shopov, 2003, 2009). This can be detected even when the contamination is in the parts per million level (deNeufville, Kasdan, & Chimenti, 1981). Differences in fluorescent colour are indicative of a change in the underlying geochemistry. While the colour is not diagnostic by itself (Shopov, 2009), unusual colours indicate outliers in need of further investigation. If the target is rare, such as fossils, economic minerals, gemstones, archaeological artefacts, stony meteorites or particular microbes, it will often show up in the scan images as a rare colour that makes the target easily detectable.

Here we describe the first viable autonomous system to detect fossils in the field arising from the intersection of UAV technology

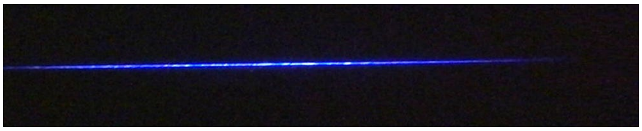

FIGURE 2 Laser line projected from beneath the unmanned aerial vehicle. Flight height was 4 m above the ground. The line is approximately 3 m wide. Dots in the line are fluorescing fragments. Flight speed was 1 m/s

and LSF. As a proof-of-concept prototype, the new system is not meant to be fully capable of extended missions covering square kilometres but serves as a test platform to validate key concepts and gather insights to inform future system design. It is based on a half metre diameter 6-rotor UAV (hexacopter) assembled from off-the-shelf parts. The commercial flight control system allows 'missions' to be pre-programmed including GPS waypoints, speed and altitudes. Data downlink allows real-time observation of all flight parameters including current position on Google Earth. During flight, the gimbal mounted video camera and near-UV laser are used to record the laser line projected onto the ground below the UAV (Figure 2). A strobe light flashes once a second to record precise location information. Laser and video recording start at the beginning of the flight and continue until the flight ends. The 405 nm laser diode used in this system is only 10 nm away from 395 nm UV and produces comparable results under practical applications, but is available up to a higher 1 W output power. For many test flights, a 450 nm 7W laser was used at 3 W to effectively demonstrate how laser power increased the detection distance between the UAV and the ground. The data are post-processed to reveal target locations (see Supporting Information). The system was successfully tested in the Oligocene-aged White River Group of the Chadron Formation of Wyoming, USA. There it detected fossil mammal specimens down to ~20 mm in size flying at 1 m/s airspeed at a height of 4 m above the ground.

2 | MATERIALS AND METHODS

The flowchart shown in Figure 3 outlines the methodology adopted by this UAV-based system (Figure 3). The first step in determining whether the target area will produce clean detections of fossils (as opposed to false-positive signals) is to fluoresce a typical fossil-containing area at ground level. If it can be determined that the fossils have a unique fluorescent colour, then the area is suitable for UAV surveillance. This initial analysis phase uses a small test area to compare ground-based and UAV LSF images. These images are processed and target specimens identified and associated with a particular fluorescent colour range. Once the initial analysis is complete, a mission is programmed and the UAV flies an autonomous path while recording video. Upon landing, the video is downloaded and post-processed according to the protocols from the initial analysis to produce a 'scan strip'. The scan strip is visually searched for promising targets. Once likely targets are

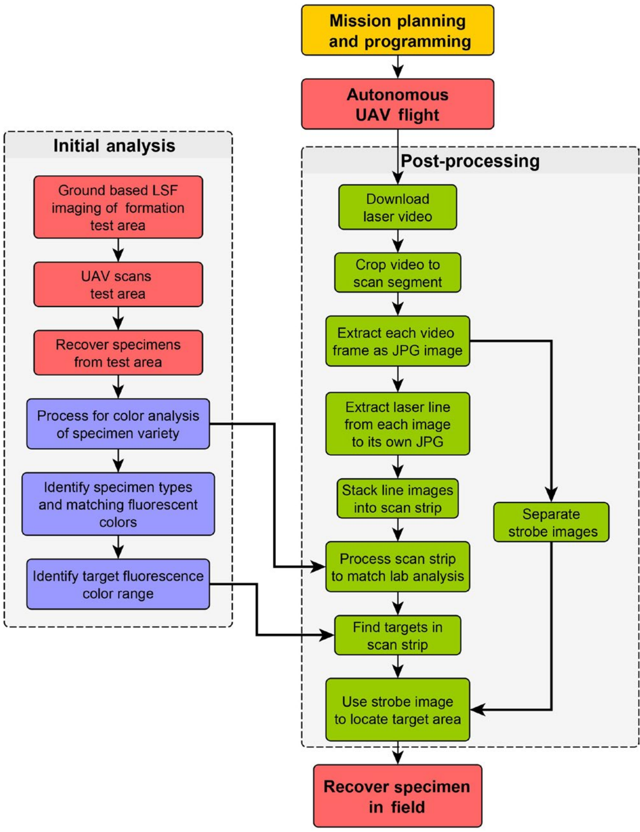

FIGURE 3 Flowchart showing the methodology used to detect targets using the autonomous fluorescence-based unmanned aerial vehicle (UAV) system. Red, field work; Purple, lab work; Yellow, mission planning; Green, post-processing

identified, the white light strobe images are used to identify their precise location in the field where the targets can be recovered. For flight hardware and post-processing software description, see Supporting Information.

The 'scan strip' image is now a fluorescent representation of the flight path with periodic white stripes denoting the strobe flashes. Colour is balanced in *Photoshop CS6* to provide maximum colour differentiation (Figure 4). Initial analysis specifies which colours in the scan strip are target specimens (Figures 3 and 5). The white light shots can then be referenced to determine where the target specimens are located on the ground.

The UAV system was flown 2–6 m above the ground. The laser intensity falls off as predicted by the inverse square law, causing the detection efficiency to fall off in turn. The exposure time per frame is limited by the frame rate. The Sony camera records a minimum of 25 frames per second (FPS) so no efficiency gains were possible through slower frame rates and longer exposure times. However, this could be improved with cooled astronomical cameras. Increased height was compensated for by reducing the spread of the line lens from 30° to 12° in the case of the 0.6 W 405 nm laser. This concentrated the laser flux and made detections possible at 3 m aboveground. Experimentation showed that 3 m height with a 10° line lens was optimal for detection, but limited field of view. The more powerful 450 nm laser at 3 W provided clean detections at 4 m with a 90° lens.

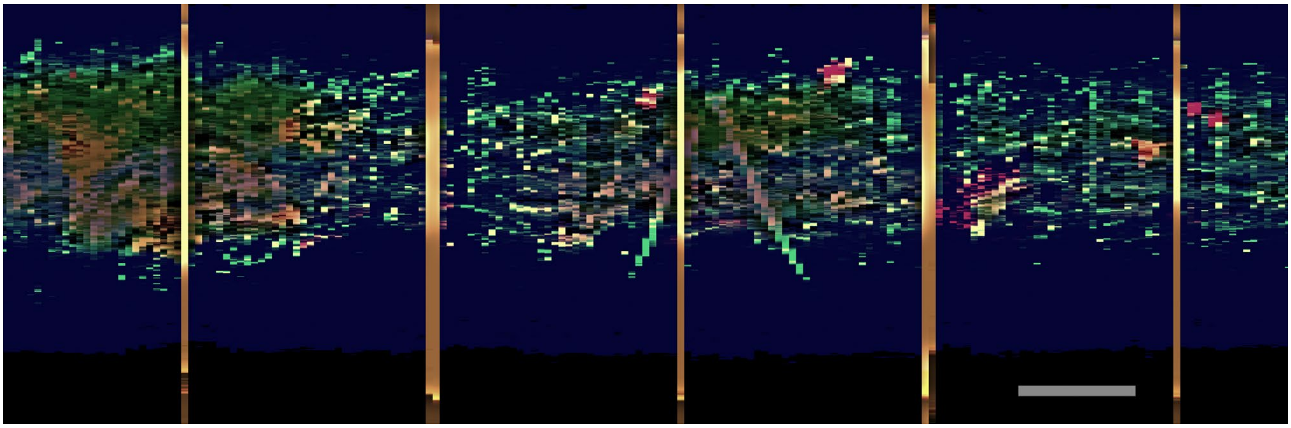

FIGURE 4 Colour balanced unmanned aerial vehicle scan strip. Laser lines from each frame is assembled into a long 'scan strip'. The vertical lines represent the strobe images at 1 s intervals. Scale = 500 cm

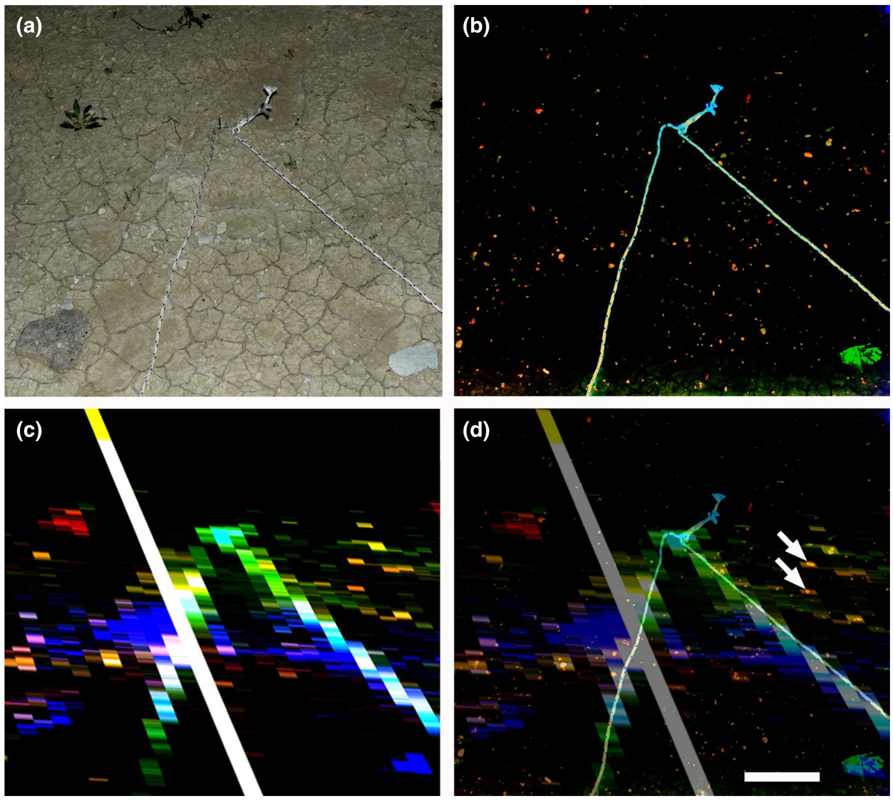

FIGURE 5 Test area identification of fluorescence colour range. (a) White light image of test area. (b) High-fidelity LSF image taken with a tripod-based DSLR camera setup. (c) Unmanned aerial vehicle (UAV) overflight of test area transformed to match ground image. (d) DSLR and UAV images overlapped. Images were studied first hand to identify targets and their associated fluorescence colour range. Arrows are ~15 mm wide fossil fragments verified by first-hand observation. The specific light brown fluorescence colour of these fossils tells us the fluorescence signal for fossil bone in this part of the White River Group in the Chadron Formation. Scale = 200 mm

3 | RESULTS

3.1 | Initial analysis

A small representative test area of the White River Group of Wyoming, USA was chosen to include typical rock and fossil varieties likely to be encountered in the UAV flights. Marker rope was laid out for positional reference in the images. High-fidelity white light and LSF images were taken with a tripod-mounted Digital Single Lens Reflex (DSLR) camera setup to show the range of fluorescing targets in the test area (Figure 5). Next the UAV was flown over this test area at night to obtain flight scan data that could be compared to the DSLR LSF images. Lastly, specimens seen to fluoresce in both the DSLR and UAV images were collected.

The ground-based images and UAV scan were identically processed to maximize colour differentiation. The fluorescing colour ranges of the fossil specimens were identified in both the DSLR image and the UAV scan to confirm detectability. A small percentage of fossil bone exhibited a light yellow fluorescent colour but most of the bone in the test area had an unusually low fluorescence signal and was not detectable. In contrast, fossil teeth fluoresced very brightly and it was determined that in the green RGB channel the intensity was above all other targets. This allowed a specific 'bright green' methodology to be adopted to identify them with the UAV.

3.2 | Tooth-specific UAV scan

The detection of rows of teeth, which is possible with this setup, often leads to the discovery of fossil skulls which contain a wealth of anatomical and phylogenetic information. The UAV equipped with the 450nm laser and flying at 4 m aboveground with an average airspeed of 1 m/s recorded a ~65 m long scan strip of a randomly chosen straight line path across the badlands.

The video was downloaded and post-processed to only show pixels from the green RGB channel with maximum intensity. A small segment of the larger scan strip is shown in Figure 6 with the red and blue channels removed. The pixels marked H1 were identified as a small, very bright, standalone target. The white light images allowed identification of the precise area and three fossil fragments were found, one tooth fragment and two bone fragments. Figure 7 shows the location of the associated fragments. The three fragments were later fluoresced back in the lab. The bones showed very low fluorescence but the tooth fragment glowed brightly. Referring back to the UAV scan, only one target was detected of the three, showing that the bones were below the detection threshold. In this test run, a 20 mm tooth fragment was randomly detected by the UAV, demonstrating the system's detection capability at a 4 m altitude.

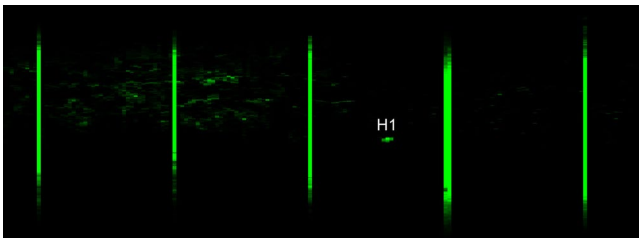

FIGURE 6 Post-processed scan image only showing maximum intensity green pixels is optimized for detecting fossil teeth. Target H1 was a small, very bright, standalone object that was suspected to be a fossil tooth. This was recovered in person and identified as a ~20 mm wide brontothere mammal tooth fragment

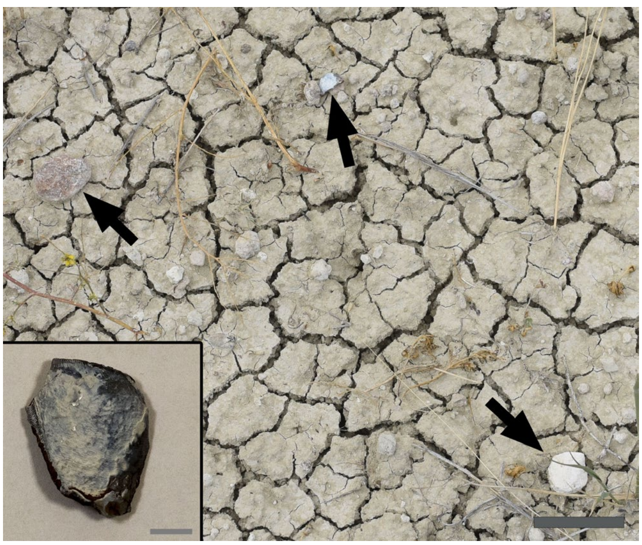

FIGURE 7 Area of the H1 fossil tooth detection. Only three fossils were found in the target zone, two bones and a single brontothere mammal tooth fragment (inset). Our lab tests revealed an unusually low fluorescence signal for local fossil bone, but a very high fluorescence signal for fossil teeth. Therefore, as expected, only the vividly fluorescing fossil tooth (H1) was detected by the unmanned aerial vehicle scan. Scale = 50 mm. Inset scale = 5 mm

4 | DISCUSSION

The proof-of-concept UAV platform demonstrated here successfully detected fossils at night using fluorescence and autonomous flight. The technology of lasers, detectors and aerial platforms has demonstrably reached the point of feasibility and can be applied using mostly off-the-shelf equipment. While palaeontology has adopted many new technologies in the study of fossils, searching for them still involves prospecting by foot. This UAV system promises to be a welcome augmentation to this tried-and-tested search method by taking advantage of the down time after sunset to search exposures, particularly in expansive areas with relatively low topography that can be covered more quickly by the UAV system. In other areas of evolutionary biology, the UAV system could potentially help to augment the identification and mapping of fossil trackways (Romilio et al., 2017) and fossilized ground surfaces (Stein, Berry, Hernick, & Mannolini, 2012) and seafloor (Anderson & Misra, 1968) more generally through additional geochemical data, if there was a fluorescence contrast (e.g. between the sediment surface and underlying sediment layers exposed by a track or trace; between the sediment surface and modern material filling the track or trace like sediment or water; between constituents of the preserved ground and seafloor like between the fossils and matrix background and between different fossilized organisms).

In modern ecosystems, a wide range of organisms exhibit fluorescence including among amphioxi (Deheyn et al., 2007), birds (Arnold, Owens, & Marshall, 2002; Burkhardt, 1989; Dunning et al., 2018; Mullen & Pohland, 2008; Wilkinson, Johns, & Warzybok, 2019), cnidarians (both corals and jellyfish; Alieva et al., 2008; Gruber, Kao, Janoschka, Tsai, & Pieribone, 2008; Shimomura, Johnson, & Saiga, 1962), copepods (Shagin et al., 2004), ctephores (Haddock, Mastroianni, & Christianson, 2010), cyanobacteria (Schubert, Schiewer, & Tschirner, 1989), fish (Sparks et al., 2014), frogs (Goutte et al., 2019; Taboada et al., 2017), lizards (Bajer, Molnár, Török, & Herczeg, 2011; Lisboa, Bajer, Pessoa, Huber, & Costa, 2017; Prötzel et al., 2018; Stapley & Whiting, 2006; Whiting et al., 2006), mammals (Kohler, Olson, Martin, & Anich, 2019), scorpions (Gaffin, Bumm, Taylor, Popokina, & Mann, 2012), stomatopods (Mazel, Cronin, Caldwell, & Marshall, 2004) and turtles (Gruber & Sparks, 2015). The fluorescence serves a range of functions including to make an individual easier (Gruber et al., 2016) or harder (Sparks et al., 2014) to see. It can help species to recognize one another (Sparks et al., 2014), help in signalling (Mazel et al., 2004; Stapley & Whiting, 2006; Whiting et al., 2006) and can serve in sexual communication (Arnold et al., 2002; Lim, Land, & Li, 2007). Fluorescing organisms would all be expected to generate a stronger fluorescence reaction under laser light than lamp-based UV light. The new fluorescence-based autonomous UAV system would be particularly useful in establishing the number and distribution of fluorescent animals, especially endangered ones like the hawksbill sea turtle (Gruber & Sparks, 2015) and can build upon existing UAV study practices (Rees et al., 2018). It would also be helpful in monitoring ecosystem productivity and health, especially threatened ones. For example, monitoring the cyanobacterial mats of the unique McMurdo Dry Valleys of Antarctica (Bollard-Breen et al., 2015). In any case, it would be important to thoroughly check and mitigate any potential risk the laser may pose to target organisms, in line with existing practices associated with performing research on living organisms.

In Earth and planetary science, many of the current applications of UAV systems in geological mapping and investigation (Bemis et al., 2014; Chesley, Leier, White, & Torres, 2017), mineral exploration and mining (Jackisch et al., 2019; Kirsch et al., 2018) as well as landslide and slope investigation (Hellmuth, Hunter, & Barclay, 2018; Pellicani et al., 2019) would be extendable to the new UAV system provided that clear fluorescence targets can be established. For example, calcite is highly fluorescent and so are economically important materials like fluorite. These fluorescing targets could, for example, enable investigations of carbonate rock exposures and calcite vein structure as well as exploration for fluorite seams.

Certain pottery, paints, soils and vegetation can show fluorescence-detectable geochemical differences as can weathering and erosion products. In utilizing these potential fluorescence properties, the new UAV system can be applied in archaeology to augment the mapping of field sites and excavations as well as assessments of monument condition to build upon existing UAV systems that have already been used in the field (Agudo, Pajas, Pérez-Cabello, Redón, & Lebrón, 2018; Campana, 2017; Hill, Laugier, & Casana, 2020; Smith, Passone, al-Said, al-Farhan, & Levy, 2014).

To maximize the delivery of the aforementioned applications, it will be necessary to achieve further development of the fluorescence-based UAV system:

GPS-linked video stream: is ideal for locating targets revealed in the scan. The Sony camera used in these tests has onboard GPS but this did not function due to the antenna being blocked in its position under the UAV. Currently, the prototype uses the strobe images combined with the approximate UAV location via telemetry to provide location data. In future versions, the UAV's GPS position could be fed directly into the video display. A logical improvement would be to use infrared LEDs to continuously illuminate the ground. The far red colour of the LEDs would not interfere with the fluorescence, which is usually in the middle of the visible range. This would give a rapid idea of what is creating the fluorescent response and allow quicker positive IDs of potentially fruitful locations on site.

Flight time: for typical consumer UAVs have been historically limited by the batteries with a maximum duration of ~30 min. With a 1 m/s average airspeed, as tested here, this translates into a scan strip about 100 m long after deducting for take-off, turnaround and landing time. New technologies are demonstrating multi-hour flight times using other energy sources like gasoline (Matheson, 2017) and hydrogen (Dutczak, 2018; Swider-Lyons et al., 2014). Such multi-hour duration platforms would make better use of the time available during an expedition between sunset and bedtime. All the technology required to develop such a long duration autonomous UAV is currently available and should be incorporated as part of future development efforts.

Detection distance: Increasing flying altitude allows the laser line to spread out more over the ground creating a wider scan strip increasing overall per square kilometre scanning efficiency while still providing sufficient laser power at ground level. Using the 450 nm laser at 3 W gives a 3 m wide scan strip. To increase detection distance, next-generation designs should incorporate multiple near-UV lasers with the lines overlapping. This concept has already been demonstrated in caves where images of entire cavern chambers up to 30 m away have been fluoresced in their entirety for the first time (Kaye & Garcia, 2017; Kaye, Garcia, & Pittman, 2019).

Predictive models: used at the 'Mission planning and programming' stage of Figure 3 could help to further increase the detection efficiency of the proposed UAV system. Such models have been established using a range of approaches in search of body and trace fossils (Anemone et al., 2011; Conroy, 2014; Conroy et al., 2012; Emerson & Anemone, 2012; Emerson et al., 2015; Malakhov et al., 2009; Mensing, Elston, Raines, Tausch, & Nowak, 2000; Oheim, 2007; Wills et al., 2017), living species and their habitats (Norberg et al., 2019; Rushton et al., 1997; Sperduto & Congalton, 1996; Tucker et al., 1997; Van Manen & Pelton, 1997), minerals (Carranza, 2009) and archaeological artefacts (Kohler & Parker, 1986; Kvamme, 1992; Mehrer & Westcott, 2019).

The current system's 4 m detection distance and 30 min flight time translates to a ground scan covering 4,500 square metres. Four batteries could provide 2 hr of flight time covering 18,000 square metres per night. Over 10 nights, the system could theoretically cover 180,000 square metres. These estimates are based on the current system with its mostly low-cost consumer equipment. However, with commercial heavy lift UAVs (10+ kg), high sensitivity cooled purpose specific astronomical cameras, custom data processing software, a high-performance laptop and an array of lasers, the area of coverage could potentially be improved by a factor of 2–3x.

5 | CONCLUSIONS

The technology to autonomously search for fluorescent targets from a flying platform exists today. This feasibility study was undertaken with consumer-level products and has proven capable of detecting fossils and would be able to detect other fluorescent targets including rocks and minerals, organisms and archaeological artefacts. These baseline data allow calculations for an improved platform that could efficiently scan large areas using larger commercial products. In addition to body and trace fossil detection, other potential field uses for the system in the areas of ecology and evolution include studies of the population and distribution of living species and monitoring of modern ecosystem productivity and health, especially those that are threatened. These applications would all provide important primary data with a wide range of upstream spin-off benefits. The fluorescence-based UAV system also has potential applications in a broader range of fields including in Earth and planetary science and in archaeology.

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CONFLICT OF INTEREST

The authors (T.G.K. and M.P.) declare no competing interests.

AUTHORS' CONTRIBUTIONS

The study was designed, performed and written up by T.G.K. and M.P.

DATA AVAILABILITY STATEMENT

All data results (LSF images) are made available in this manuscript. *IDL* code for laser line and colour extractions in the laser scan strip are available on Dryad at the https://doi.org/10.5061/dryad.9w0vt4bc3 (Kaye & Pittman, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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