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# Conceptual approach to community-involved, drone-assisted meteorite searching: a strategy to find fusion-crusted meteorites

**Alyona Glazyrina[1,2], Zeno Hamers[1,3,5], Quinn van der Schaar[1,4] and Sebastiaan J. de Vet[3,6,7]** [2] **University of British Columbia**
[3] **Delft University of Technology**
[4] **University of Twente**
[5] **ETH Zürich, Swiss Federal Institute of Technology**
[6] **Meteor Section, Royal Netherlands Association for Meteorology and Astronomy (KNVWS)**
[7] **Naturalis Biodiversity Centre, Leiden**
s.j.devet@tudelft.nl

Meteorites offer valuable insights into the composition of asteroids and geological processes contributing to planet formation inside the solar system. Their rapid retrieval after fireball sightings allows this science potential to be used. Finding new meteorites is notoriously difficult due to various complicating factors. A promising search strategy can involve the aerial vantage point of drones (aka: UAV, RPAS). However, drone regulations by the European Union Aviation Safety Agency (EASA) and complex zonation of airspace will impact flight operations, which makes drone-assisted searching in Europe more complex than in e.g. desert environments. Here we present the results of an interdisciplinary desk study, which aimed at proposing a conceptual framework for drone-assisted meteorite searching. We propose the development of an open-source detection and coordination tool to improve aerial assistance by drones during field searches. The design provides drone enthusiasts (referred to as 'community drones') and researchers with a platform to coordinate joint drone-based search operations. Image processing is envisioned to take place via a convolutional neural network pipeline, after which high-likelihood locations are identified and manually verified to recover a potential meteorite. This approach will require the development of multiple models to account for variations in soils and vegetation. The tool supports multi-drone coordination, providing path planning functionality and support for a broad range of (commercially) available drone models (e.g. DJI) and sensor types (e.g. RGB, thermal). Considering EASA drone regulations, the use of the DJI Mini 3 Pro is favoured as an accessible community drone. Follow-up research, implementing the proposed conceptual approach, should validate the design presented here and highlight practical areas of improvement.

## 1 Introduction

Impressive fireballs can herald the impact of a new meteorite. The rapid retrieval of meteorites after fireball observations helps limit terrestrial contamination and degradation of meteorites and allows their full science potential to be used. To alert us to potential new falls, fireball camera networks such as FRIPON (Colas *et al.,* 2020) and many others continuously monitor the skies for meteorite-dropping fireballs. In the Netherlands, six meteorites have been found to date, which include the Uden (LL7), Utrecht (L6), Diepenveen (CM2-an; Langbroek et al., 2019), Ellemeet (diogenite; de Vet, 2015), Glanerbrug (L-LL5) and Broek in Waterland (L6). However, observations during the past decade suggest that for the Netherlands meteorite-dropping fireballs occur more frequently, at a rate of every two years on average. Conventional field searches with teams operating on foot have experienced that finding new meteorites is difficult due to various complicating factors, such as the large extent of search areas, limited access to agricultural fields, and obscuring effects of vegetation. Stakeholders are now looking into other methods to support and augment their search campaigns.

A promising search strategy can involve the aerial vantage point of drones, as various studies have shown before (Zender et al., 2018; Citron et al., 2017, 2019, 2021; Anderson et al., 2020; 2022). However, drone regulations set by the European Union Aviation Safety Agency (EASA) and the complex zonation of airspace (Figure 1) will impact flight operations, which makes drone-assisted searching in Europe more complex than in e.g. uninhabited desert environments. Previous work (Anderson et al., 2022; Citron et al., 2021) has primarily focused on locating meteorites in arid environments (e.g. Western Australia and Nevada). The vegetation cover in the Netherlands can pose challenges for the convolutional neural networks (CNNs) involved in the vision-based detection of meteorites. As research by (Hill et al., 2023) in a Canadian snow-covered strewn field demonstrates, different sensors and CNN models might be needed for different soil and vegetation types.

We recognize the potential of community involvement in drone-assisted meteorite searches. Amateur drone pilots in the Netherlands provide a pool of people who could assist during field search operations with on-site drones. Simultaneously connecting scientific research with contributions by local communities creates an outreach potential. Through an interdisciplinary desk study during the 2023 LDE NL Space Campus Summer School, this paper analyses the possibilities for community involvement and aims to propose a conceptual framework for drone-assisted meteorite searching in the Netherlands.

## 2 Methods

The research methods that have been employed during this research consisted of an interdisciplinary desk study of relevant drone regulations and peer-reviewed research articles from the last 10 years. After removing duplicates and extraneous articles from the literature review, we identified five key articles. These include cases from Western Australia covering the development of a machine learning system that we used as our baseline (Anderson et al., 2020), (Anderson et al., 2022), Canada (Hill et al., 2023), Nevada, USA (Citron et al., 2021), and from the United Arab Emirates, UAE (AlOwais et al., 2019). All articles describe the neural networks responsible for image identification as well as the physical construction of their drones. Differences in vision-based detection pipelines, drone hardware and field deployment were analyzed. Based on the findings of the literature review, this paper proposes a practical approach to community-involved drone-assisted meteorite searching, facilitated by group discussions and expert interviews during the 2023 LDE NL Space Campus Summer School.

## 3 Literature Review Findings

### Vision-based meteorite detection

The utility of convolutional neural networks (CNNs) in the detection of fusion-crusted meteorites on RGB image data has been effectively shown in (AlOwais et al., 2019) (Citron et al., 2021) and (Anderson et al., 2022). Anderson et al. demonstrated the viability of drone-assisted meteorite searches with an average area survey speed of 1.3 km$^2$/day. Previous work by (Hill et al., 2023) has also noted the potential of combining thermal with visible imagery for meteorite detection (e.g. on snow-covered fields in Alberta). For proper imaging, Anderson et al. used a ground sampling distance of 1.8 mm/pixel, making the meteorites appear at an apparent size between 15 and 65 pixels. Hill et al. concluded that a ground sampling distance below 26 mm/pixel was sufficient for the efficient identification of meteorites on thermal images. With drone altitudes heavily affecting image resolution, both authors stress the importance of managing the drone's flight altitude above ground level (AGL). However, current CNN drone detection models

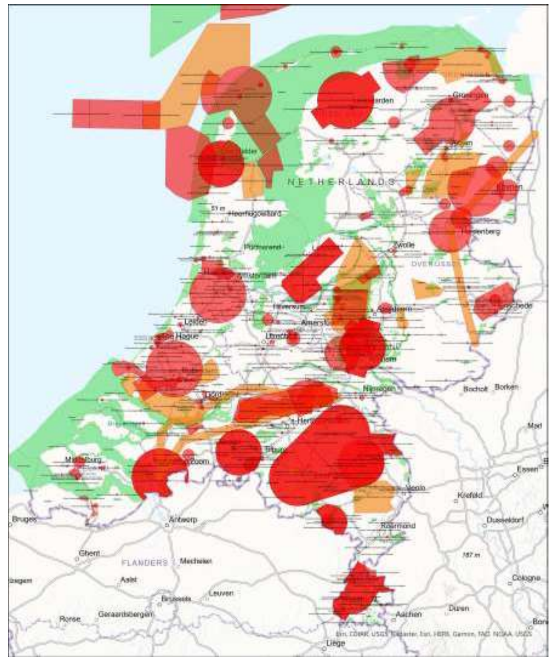

*Figure 1* – Map showing airspace zonation and no-drone zones in the Netherlands. Red: airports and no-zones; orange: limited access; green: Natura 2000 (effectively no-drone zones, or exempted under permits). Data: Air Traffic Control the Netherlands (LVNL) retrieved via PDOK.

are not perfect. In (Anderson et al., 2022), it was noted that their image processing pipeline effectively created an anomaly detector, instead of the desired meteorite-specific detector. They encountered many false positives, like tin cans, bottles, snakes, kangaroos, piles of bones, and research equipment. More training data, and especially data including more background varieties are necessary to improve the model's performance.

The above-mentioned studies were primarily conducted in clear soil and regulatory plane environments. Drone-assisted meteorite searching in the Netherlands poses additional challenges because of the high soil and vegetation diversity in addition to the presence of Dutch and European drone regulations. Successful operations in the Netherlands require more complex CNN models, trained on a high quantity of (meteorite) images, present in a variety of soils and vegetation types. On top of that, drone types, flight height and no-fly zones should be actively considered in operations.

### European and Dutch UAV regulations

There are many rules and regulations which must be adhered to in order to operate a drone in the Netherlands. Drone flight operations are dependent on the drone's operational risk category, as specified by the drone regulations of the European Union Aviation Safety Agency (EASA). There are three main categories: open, specific and certified. Since this paper focuses on community-involved drone operations, all drones discussed in this paper are consumer-drones and their operations and CE certification will fall in the open category. This category is divided into 3 sub-classes (A1, A2 and A3) depending on the risk level of their operations, which places drones in these classes depending on factors such as the weight (MTOW, maximum take-off weight), it sets a maximum flight altitude and imposes a safety distance between the drone and buildings and people that the operator should adhere to. As of 2024 EASA regulations require all drones operated in the European Union to be marked with a Class identification label (CE label), with some legacy drones without CE label to be reclassified to a higher risk catagory (A3). (COMMISSION, 2019; Netherlands Enterprise Agency, 2023). Locally in the Netherlands, all drone operators of drones that contain an onboard camera need to be registered with the Netherlands Vehicle Authority (RDW) and the drone registration number should be displayed and visible on their drones. Futhermore, the Netherlands has several restricted areas and no-fly zones where additional rules can apply compared to other EU countries (Figure 1). The operational areas for meteorite searching will thus depend on the drone's category (OPEN A1/A2/A3) and optional granted zonation exceptions (e.g. for research purposes).

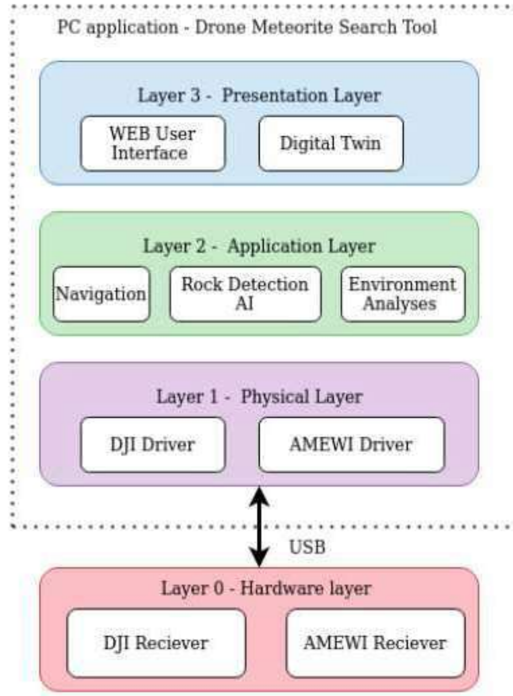


*Figure 2* – Recommended Software Architecture for the drone base station. The Drone Meteorite Searching tool encapsulates layers 1, 2 and 3, layer 0 is the physical radio receiver which communicates with the drone. Layer 1 incorporates the API (e.g. DJI API) which is required for the communication to that receiver

## 4 Community-involved drone-assisted meteorite searching tool

Fast recovery of freshly fallen meteorites is paramount for accessing their scientific potential as this prevents terrestrial contamination or loss due to environmental exposure (De Vet, 2015). Here we propose and outline a community-involved search strategy that enables fast drone-assisted meteorite searches by leveraging the on-site use of drones from drone enthusiasts residing in areas near strewn fields. To make this search strategy possible, a structured drone-imaging approach is necessary. We propose that a key step needed to improve drone-assisted meteorite searching is the development of a software tool, designed to coordinate the flight paths (search areas) of multiple drones, capture and analyse aerial images and communicate these with drone operators and researchers. This tool has the potential to automate most of the crucial steps of drone searching, making search operations more agile and increasing the meteorite recovery rate. Figure 2 displays the layered software stack architecture of the tool. The layered architecture enables developers to create interfaces which can be used by different implementations of the tool. For instance, this architecture makes seamless support of different drone models and camera sensors (RGB, infrared) possible.

Based on the considerations above, the following criteria were considered in the search strategy design: (i.) Community Involvement; (ii.) Search Efficiency; (iii.) Research Group Compatibility; and (iv.) Minimization of Physical Labour. Based on these optimization criteria, we constructed a conceptual framework for drone-assisted meteorite searching. The following subsections will focus on key parts of the tool's architecture.

### Open source framework

To get the conceptual framework for drone-assisted meteorite searching off the ground, the drone-searching tool should be developed as an open-source project. While starting locally, this can eventually provide the project with volunteers from all over the world, connecting different research groups, developers and drone enthusiasts around rapidly recovering meteorites with drones. This appraoch also has the potential to create and strengthen relations between research groups, allow (drone) enthusiasts to contribute and put drone-assisted meteorite searching on the map. This will increase community involvement in the project (criterion i.) and improve research group compatibility (criterion iii.). An additional advantage is that this approach satisfies the need for big datasets in machine learning operations. When research groups and volunteers can contribute to the platform, data availability will be increased, leading to improved meteorite recognition models (criterion iii.).

### Considerations for a CNN pipeline

RGB images (extendible to e.g., multispectral, hyperspectral or thermal image data) are processed via a Convolutional Neural Network pipeline. The pipeline outputs high-likelihood locations which can be manually verified to recover a potential meteorite. This approach requires the development of multiple ML models to account for variations in soil and vegetation (possibility of transfer learning). Two approaches are possible: Eusing (i.) one vegetation-independent model or (ii.) multiple models for different types of vegetation. Which approach yields the best results is a topic of future research. Currently, exploratory field studies are being performed at TU Delft's Faculty of Aerospace Engineering (supported by a Paneth Meteorite Trust Award) to study the use of ML models for detecting meteorites in Dutch field settings.

**Multi-drone coordination**

An important aspect of the framework is that it supports multiple (commercially) available drone types. The program will require drone registration so that the drone's legal classification can be verified. Once verified, *geofencing* based on Dutch and European drone regulations can be activated within the platform, automatically avoiding no-fly zones and taking into account any difference in regulations based on drone type and its corresponding CE label. The ground sampling distance (which depends on camera resolution and flight height) is determined based on the parameters input into the framework, and can be derived from dark flight predictions of fragment sizes in a given area. If multiple drones are available in one search region, the platform coordinates flight planning and facilitates the transfer of collected image data to a central dataset. Based on our desk study, the DJI Mini 3 PRO is proposed here as a *community drone* (i.e., a drone model accessible for a boarder public). The model is affordable; it can be operated in the A1 category with less restrictions compared to A2 and A3; it is equipped with a gimbal-stabilised 4K camera and GPS system and has a average flight time to 30 minutes per battery. As such, the DJI Mini 3 PRO is a favourable option that can be initially used during the development of the project. Figure 3 illustrates the proposed community drone. In the end, the open-source nature of the project makes it possible for the community to use and support any drone model (even self-made drones).

**Graphical interface - false positive sorting**

The envisaged graphical interface is designed to efficiently identify false positives from the classified images and is inspired by (Anderson et al., 2020; Anderson et al., 2022). A 3x3 grid is shown to the user, who can identify tiles of interest (a tile that might contain a meteorite) by pressing the corresponding keys (1-9) before progressing to the next set of images. The selected tiles will be moved to the next pool, while the others are moved to the False pool. The second pool allows the user to pan and zoom into the image. After another round of selection, the GPS coordinates of the remaining interesting images will be used to create a survey flight path to each location of interest. At the location, the drone will go lower and take more images closer to the ground. Once the drone is returned, the collected images will be inspected and the remaining interesting candidates will then be inspected in person. It was determined by (Anderson et al. 2020; 2022) that this process takes about 20 hours of work from one person assuming 150,000 detections per meteorite search area. This time could be reduced by having more people working at the same time, as well as limiting work sessions to 20 minutes at a time to reduce decrements in vigilance. Additionally, (Anderson et al. 2020; 2022) included a set of test sets, of which 0, 1, or 2 would appear in each 3x3 grid. If the user did not correctly identify the members of the test set two times in a row, the program would force the user to take a break. In addition to this, all images should be reviewed by at least two people.

*Figure 3* – Proposed hardware configuration for a community drone: the DJI Mini 3 Pro, with DJI RC RM330 Smart Controller. The controller shows a recent meteorite embedded in the soil of a grassy field, yet still visible from above (fragment of the Saint-Pierre-le-Viger). Image sources: DJI, FRIPON/Vigie-Ciel).

To summarize, the automated false positive sorting process consists of four phases, listed here and shown in Figure 4.

1. Primary sorting - based on initial images, with a test set to ensure the user identifies meteorites correctly.
2. Secondary sorting - zooming in on the images to identify promising candidates.
3. Tertiary sorting - identifying promising candidates in the field via GPS and requesting enthusiasts to take close-up pictures at the coordinates to go into a final sorting stage.
4. In-person inspection - the last stage requires people to go in person to inspect the final candidates.

This process of false positive sorting yields itself to gamification, encouraging enthusiasts to come back to

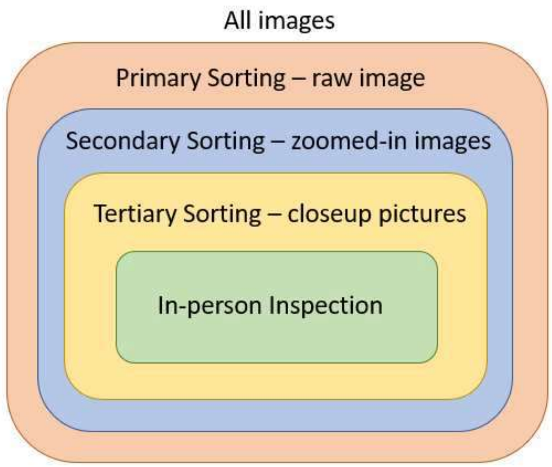


*Figure 4* – Proposed false positive classification process.

the platforms and continue sorting the images, with trackers on the user's performance.

## 5 Conclusions

Meteorite recovery activities benefit from using various methodologies that can help cover the large spatial extent of strewn fields in a short amount of time. The use of drones is a promising addition to existing search strategies. Based on an interdisciplinary desk study that considered existing drone-based solutions from literature and EASA drone regulations within in the Netherlands we advocate the development of an open-source, machine-learning-based detection and multi-drone coordination tool. This tool can potentially offer an effective approach for community-involved, drone-assisted meteorite searching. Integrating these aspects enables the creation of a community that can engage in search activities to rapidly recovery meteorites. Simultaneously, this approach also stimulates the collaboration and synergies within the community, while encouraging new individuals, such as drone pilots, to join. The next steps to realising this approach includes demonstrating the strengths and user cases of a multi-drone coordination tool. Although we focused in our study initially on applications in the Netherlands, the conceptual framework and community-focused approach presented here will be of broader interest for stakeholders across Europe.

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## References

AlOwais A., Naseem S., Dawdi T., Abdisalam M., Elkalyoubi Y., Adwan A., Hassan K., and Fernini I. (2019). "Meteorite hunting using deep learning and uavs". In *2019 2nd International Conference on Signal Processing and Information Security (ICSPIS)*. pages 1–4.

Anderson S., Towner M., Bland P., Haikings C., Volante W., Sansom E., Devillepoix H., Shober P., Hartig B., Cupak M., et al. (2020). "Machine learning for semi-automated meteorite recovery". *Meteoritics & Planetary Science*, **55:11**, 2461–2471.

Anderson S. L., Towner M. C., Fairweather J., Bland P. A., Devillepoix H. A., Sansom E. K., Cupák M., Shober P. M., and Benedix G. K. (2022). "Successful recovery of an observed meteorite fall using drones and machine learning". *The Astrophysical Journal Letters*, **930:2**, L25.

Citron R. I., Jenniskens P., Watkins C., Sinha S., Shah A., Raissi C., Devillepoix H., and Albers J. (2021). "Recovery of meteorites using an autonomous drone and machine learning". *Meteoritics & Planetary Science*, **56:6**, 1073–1085.

Citron R. I., Shah A., Sinha S., Watkins C., and Jenniskens P. (2017). "Meteorite recovery using an autonomous drone and machine learning". In *Proceedings of the 48th Lunar and Planetary Science conference*, The Woodlands, Texas.

Colas F., Zanda B., Bouley S., Jeanne S., Malgoyre A., Birlan M., Blanpain C., Gattacceca J., Jorda L., Lecubin J., et al. (2020). "Fripon: a worldwide network to track incoming meteoroids". *Astronomy & Astrophysics*, **644**, A53.

COMMISSION T. E. (2019). "Commission implementing regulation (eu) 2019/947 of 24 may 2019 on the rules and procedures for the operation of unmanned aircraft".

De Vet S. J. (2015). "The 1925 meteorite fall near ellemeet and serooskerke, the netherlands". *Meteoritics & Planetary Science*, **50:11**, E1–E17.

Hill P. J. A., Tunney L. D., and Herd C. D. K. (2023). "Application of drone-captured thermal imagery in aiding in the recovery of meteorites within a snow-covered strewn field". *Meteoritics & Planetary Science*, **58:3**, 421–432.

Langbroek M., Jenniskens P., Kriegsman L. M., Nieuwenhuis H., De Kort N., Kuiper J., Van Westrenen W., Zolensky M. E., Ziegler K., Yin Q.-Z., et al. (2019). "The cm carbonaceous chondrite regolith diepenveen". *Meteoritics & Planetary Science*, **54:7**, 1431–1461.

Netherlands Enterprise Agency R. (2023). "Rules for flying drones".

Zender J., Rudawska R., Koschny D., Drolshagen G., Netjes G.-J., Bosch M., Bijl R., Crevecoeur R., and Bettonvil F. (2018). "Meteorite detection with airborne support—a study case". In *Proceedings of the International Meteor Conference*. pages 145–152.