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'OPEN' ARCHITECTURE OF UAVIMALS PROTOTYPE AND ITS ARCHAEOLOGICAL USE

1. Introduction

The benefits of using aerial scanning systems to explore sites and territories for the purpose of identifying archaeological deposits, structures, and contexts that are imperceptible to the human eye are widely acknowledged in scientific literature. The anomalies, colours, and patterns visible in remote sensing scenes are the result of interactions between natural phenomena and human activities, which ultimately shape the landscape (Küçükdemirci *et al.* 2021). It is now possible to identify certain types of buried archaeological deposits based on their ability to produce various proxy indicators visible on the ground, despite physical and micro-topographical changes that may not be visible from an aerial view (Optiz, Cowley 2013).

The UAVIMALS project focuses on identifying archaeological deposits in areas with sparse and low-trunk vegetation. This system, is the result of interdisciplinary research between archaeology and biorobotics, carried out between the Sapienza University of Rome and the Scuola Superiore Sant'Anna of Pisa, which led to the creation of a small size aerial laser scanner prototype, useful for light archaeological investigations[1]. One important aspect of this project is the identification of 'soil marks' (Fig. 1), which are micro-relief anomalies caused by buried deposits; the project aims to use a drone for this purpose.

The existing tools (e.g. DJI Matrice 600, Elios 3) used for this type of investigation are expensive, though based on established technologies and are not yet fully suitable for environmentally unfriendly areas subject to flight restrictions. Additionally, they are equipped with a hardware, and often associated software, that has confidential ownership, preventing users from making changes to the source code. Although market-responsive and compliant with current UAS flight regulations, this feature limits the user's ability to calibrate the machine to their own research needs. For instance, a drone that can be adapted to different levels of archaeological visibility in an area of high vegetation cover could enable faster and more effective investigations. To achieve this, the project placed research objectives at the forefront of development. The UAVIMALS project aimed to develop a prototype with a highly customisable open source modular structure, allowing for different

[1] The project was funded by a National Geographic Society grant awarded in September 2018, with an Early Career Grant (Grant No. EC-50761T-18) by Federica Vacatello (Principal Investigator and Post Doc Researcher in Archaeology and Post-Classical Antiquities at Sapienza University of Rome) who coordinated an interdisciplinary research team made up of archaeologists, engineers and biorobotics technicians.

configurations depending on the degree of visibility and survey objectives. This paper discusses the configuration of the UAVIMALS instrument for surveying 'micro-relief' traces in the archaeological context of Cencelle (VT).

2. Analysis context

The city of Leopoli-Cencelle was founded by Pope Leo IV in the Tolfa Mountains area on 15 August 854 CE. The name of the city was Leopolis (Duchesne 1981, II, 132). Archaeological investigations conducted by the Chair of Medieval Archaeology and Topography at Sapienza University of Rome over the past 30 years have confirmed the city's multiple phases of occupation from the 9th to the 14th century CE (Stasolla 2012). However, most of the intramural area remains unexplored (Fig. 2). In the late 1990s, S. Del Lungo surveyed aerial photographs taken by the British RAF (Royal Air Force), and SIAT (Studio Italiano Aereofotogrammetria e Topografia) between 1944 and 1995 in search of the archaeological features visible on the top of the Cencelle plateau (Del Lungo 2003) (Fig. 3). The detected anomalies were identified as 'mediators' of a vegetal nature that defined the footprints of individual structures and sometimes entire urban districts (Fig. 3). After over thirty years, the primary urban centres was uncovered. The vegetation that once shaped neighbourhoods and environments has been completely altered due to continuous animal grazing and changing climatic conditions.

Despite significant scientific progress, there are still many questions regarding the chronological and topographical aspects of the urban layout, particularly in the NW and NE areas of the site. The archaeological visibility has been compromised by the presence of tall and medium vegetation, as well as conspicuous tangles of brambles and weedy thistles, particularly in the portions

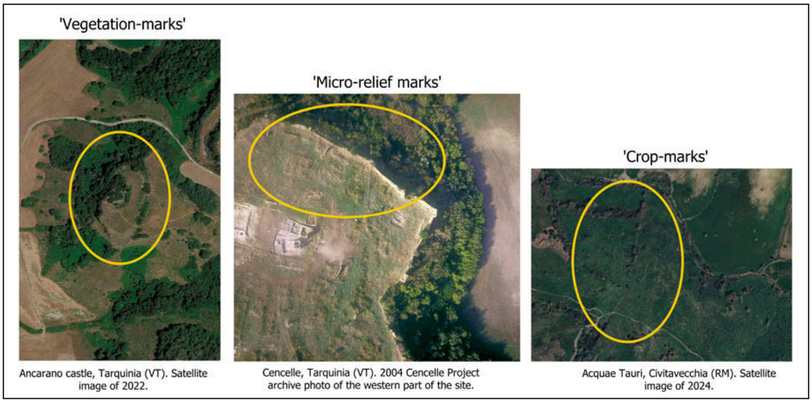

Fig. 1 – Types of archaeological anomalies visible with aerial instrumentation (Satellite image from Landsat/Copernicus 2015).

not yet affected by the excavation. This makes aerial and satellite imagery observations superfluous and surface physical reconnaissance ineffective. Subjective evaluations have been excluded unless clearly marked as such. Within this context, the UAVIMALS prototype was tested to explore the limits and potential of an instrument equipped with a LiDAR sensor. The sensor is capable of recording beams of points on 3 channels, distinguishing high vegetation (trees and shrubs), low vegetation (brambles and tall grass), and ground surface.

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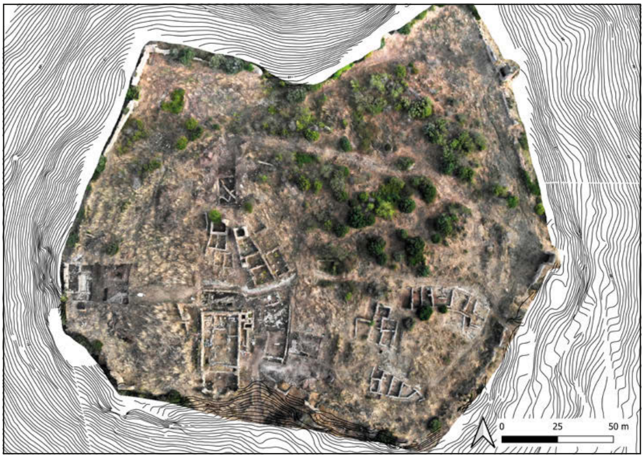

Fig. 2 – Drone orthophoto of the archaeological site of Leopoli-Cencelle (VT).

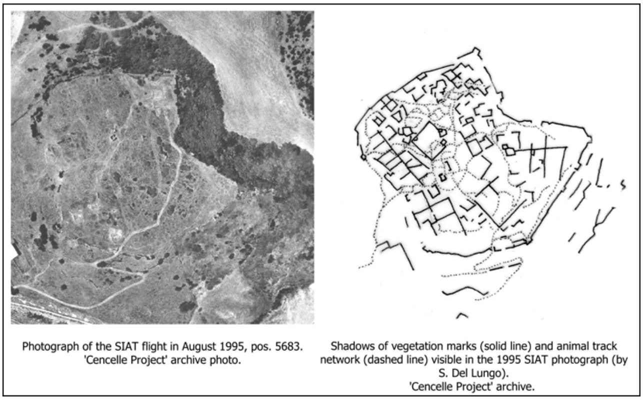

Fig. 3 – Anomalies detected by SIAT flights in the aerial surveys conducted at the Cencelle site between '94 and '95 (graphic re-elaboration by F. Vacatello from Del Lungo 2003).

3. System architecture

Our initial challenge was finding a sensor for microrelief detection that balanced portability and cost. We repurposed a car sensor meeting our needs. Next, we considered operational components (voltage regulators, computer) and the crucial factor: weight. With the payload defined, we sized the remaining drone components (motors, propellers). This ensured optimal performance and stability for the specific payload weight. Precise calculations are essential for efficient multirotor design, balancing power usage with flight duration and preventing overloading. To help us in this process we use a software XcopterCalc which allows simulating various drone configurations (motor types, propellers, battery size) through a user-friendly interface.

3.1 *Pre-flight and post-flight software*

The ground station software is divided into pre-flight and post-flight components. Mission Planner, an open source tool, defines flights and assists in mission planning, telemetry visualization, and UAV parameter configuration for ArduPilot autopilot systems. It supports firmware updates, data logging, and offers a user-friendly interface. Operators utilize Mission Planner for mission planning, telemetry monitoring, and post-flight analysis. Additionally, a Python program aids in verifying that mission is correctly loaded in the Pixhawk autopilot, checks software functionality onboard the UAV, and monitors the state machine during flight to alert pilots of any issues. Together, these tools streamline mission execution, ensure safety, and enhance performance for both novice and experienced operators. After landing, the drone sends its data to the ground station. A Matlab program processes the raw data, removing errors and emphasizing micro details. Through a user-friendly interface, operators can select areas of interest, view the 3D point cloud, and colorize it for clarity. Results can be exported in open formats like csv, las, ply, obj, compatible with software like Cloud Compare, Meshlab, and QGIS.

3.2 *Flight software*

The underlying software for the flight is Ardupilot, a firmware that runs on the FCU which directly controls the hardware components of the drone. It is a sophisticated open source autopilot system, providing a robust platform for autonomous vehicle control. In this case we were able to minimize the vertical movements, from the plane perpendicular to the zenith of the drone while taking-off. To do this we deactivated the terrain following by acting on all the parameters made available by the Ardupilot, excluding the barometer and the laser altimeter from the calculation of the EKF (Extended Kalman Filter). In the first case, the reason is that acquisition quotas (10/12 m) cannot accurately determine the flight height; in the second one, reading the heights below the objects it flies over induces the drone to rise and lower based on what it sees below. Then we correct the height at which to fly the drone through, our state machine (SM) to minimize errors introduced by terrain elevation changes.

3.3 *ROS, MAVROS and State Machine (SM)*

Unmanned Aerial Vehicles (UAVs), commonly known as drones, require specialized onboard computers for flight control, the Flight Control Unit (FCU), the central nervous system of a drone, responsible for maintaining stability and manoeuvrability. It gathers sensor data from gyroscopes, accelerometers, and other sensors to determine the drone's attitude, position, and motion. By processing this data in real-time, the FCU calculates and transmits appropriate control signals to the motors and actuators, ensuring the drone maintains stability. In addition to the Flight Control Unit (FCU), a secondary computer, an Nvidia Jetson TX2, was integrated into the system. This computer arm boasts a powerful programmable GPU, enabling the creation of a digital terrain twin. The Jetson TX2's low power consumption (only 15W) makes it ideal for drone applications. To allow the two computers to communicate and exchange data we used an UART serial port. UART (Universal Asynchronous Receiver-Transmitter) is a serial communication protocol enabling byte-by-byte data exchange between devices using dedicated transmit and receive lines.

The Flight Control Unit (FCU) relies on the MAVLink protocol for data exchange with other computers via serial ports. MAVLink (Micro Air Vehicle Link) is a lightweight messaging protocol specifically designed for drones. It defines a standard format for messages carrying sensor data, control commands, and critical flight information. This low-overhead and reliable protocol is ideal for resource-constrained drone applications. Using standard computers with a Linux (Ubuntu 18.04) operating system enabled us to utilize the ROS software framework (https://www.ros.org/). ROS (Robot Operating System) serves as a fundamental tool for us in developing robotic systems. We rely on ROS to streamline the complexities of robotics by providing a flexible framework for communication between various components fostering a modular and scalable approach to robotic development. Moreover, ROS facilitates real-time data exchange, enhancing our robots' responsiveness and adaptability to dynamic environments. The standardized message-passing system ensures seamless interoperability among diverse hardware and software components.

A critical component in our projects is Mavros, a package that facilitates communication between our state machine, running on tx2, and the FCU. Mavros acts as a middleware for communication with MAVLink-based autopilots, significantly enhancing our capabilities in unmanned aerial vehicle (UAV) development. It establishes a communication bridge for real-time exchange of telemetry and control commands with UAVs. Our ROS configuration comprises several nodes:

– Mavros node: Initiates communication with the FCU.
– Lidar data acquisition node: Collects LIDAR data and synchronizes it with GNSS and FCU IMU data for point cloud generation.
– State machine (SM): Manages all flight phases, including emergencies.
– Point cloud management node: Creates, saves, and sends the point cloud.

The state machine is tailored to our specific needs, such as managing flight altitude during waypoint navigation, a feature not adequately provided by Ardupilot at the time of experimentation. The system ensures redundancy in control during emergencies and adapts to challenges like sensor acquisition issues. The point cloud node processes data for point cloud creation, storing it on the drone's memory, and transmitting it to the ground station upon an state machine signal. For a comprehensive understanding of the difficulties encountered and the solutions implemented, we refer readers to the Data Acquisition section of the full text.

4. Data acquisition

Adapting a sensor not designed for remote sensing but rather for obstacle detection and automatic vehicle braking (ADAS) was a challenge that involved finding specific software solutions. Specifically, the chosen sensor returns only distance measurements along 16 cones (Fig. 4a), that are aligned on a straight-line (Fig. 4b) and thus producing a one-dimensional GF ground footprint. The amplitude A_gf of GF i.e., the distance between bin 1 and bin 16 measured in a plane, is directly proportional to the distance of the measured surface and can be calculated as:

$$A\_gf = 2 * H * \tan(FoV / 2)$$
$$H = flight\ height\ [variable]$$
$$FoV = field\ of\ view = 19° \ [fixed]$$

The A_gf is extremely important because it determines the number of passes required to cover a given area and thus the duration of the flight for point cloud creation and its resolution on the ground. The first variable we had to solve was the height of the flight H to keep during the acquisition. After numerous tests carried out at the training camp, we decided that an H between 10 m and 12 m was the best compromise between flight duration and resolution on the ground. One strength of this sensor, which led to its selection, is its ability to return up to 3 measurements in the same bin associating them with a reliability index based on the quality of the measurement performed. In Fig. 4c, we have schematized an example of how we used this peculiarity of the sensor. Acquiring 3 distances: the distance from the tree in blue, the distance from the tufts of grass in green and the distance from the soil in red. By filtering vegetation information, we were able to measure distances from the ground more accurately. In order to transform these lengths into points in a three-dimensional space, it is necessary to have fixed external points so that they can be used as a reference and a common coordinate system CCS.

The first fixed point for each flight is the take-off and landing point of the drone (ground origin HOME CCS→ HCS home coordinate system). The others are instead the set of points which form the perpendicular plane to the straight line passing from the HOME and its zenith, distant from HOME the chosen flight altitude. On this Plane it was necessary to control the movement of the drone in order to minimize its vertical deviation. We have therefore specialized a state of our state machine. The ‘Reaching Waypoints’ state leverages data acquired from onboard sensors, including the GNSS system, Inertial Measurement Units (IMUs https://en.wikipedia.org/wiki/Inertial_measurement_unit), laser altimeter, and lidar sensor. This state is responsible for managing navigation along a predetermined path consisting of waypoints generated using mission planning software. Through continuous analysis of sensor data, the system implements real-time altitude corrections to ensure adherence to the Plane previously describe.

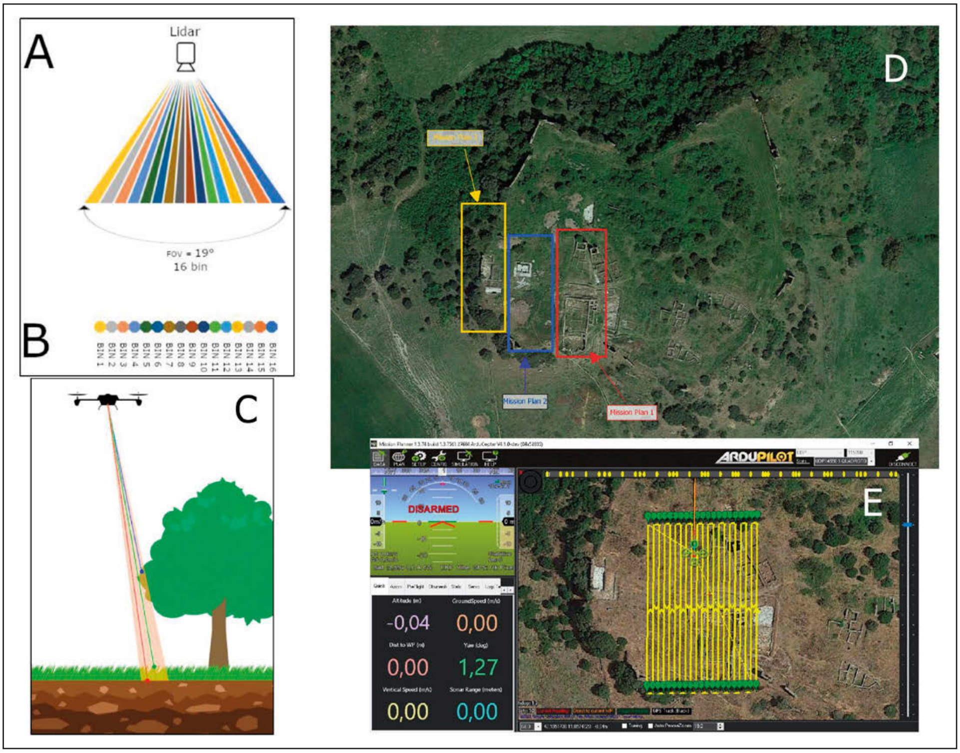

Fig. 4 – a) Front perspective of the sensor view cone; b) sensor point of view; c) example of data acquired within a single bin; d, e) satellite view of the Leopoli-Cencelle (VT) archaeological site and flight mission planning.

For the HCS (home coordinate system) we instead opted for a metric coordinate system ENU (East-North-Up) which is a local system for positioning objects in a 3D space. It uses 3 axes: positive X for East, Y for North, and Z pointing upwards relative to a specific location on Earth. In our case the origin of the coordinate system on the starting point of the vehicle. Going from a set of lengths to a georeferenced point cloud in HCS needs some trigonometry and some multiplications of inverted roto translation matrices. For each acquired length we can generate a point in the 3-dimensional space having as origin the sensor itself using the formulas:

$$x = 0$$
$$y = l * \sin \alpha$$
$$z = -l * \cos \alpha$$

l: misured lengh, α: angle on the y,z plane, enclosed between the z axis and the straight line passing through the center of the bin cone which generated the length itself. In order to merge these spaces into one common to all (HCS) we need the information generated by the FCU of the drone so we need to move each space O_sensor{k} to a new space having as its origin the center of the FCU O_drone{k}. Since the sensor is solidly mounted to the body of the drone, this transformation is calculated as a translation of the origins of x_diff, y_diff, z_diff given by the position of the sensor and the FCU. Finally each point of an O_drone{k} space can be roto translated in HCS using the information of latitude, longitude, altitude, roll angle ϕ, pitch angle θ and yaw angle φ acquired simultaneously with the length l.

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5. Results

The mapping concentrated on the top of the hill of Cencelle, where most of the public and religious buildings and quarters were found, including the Church of St Peter and the Public Palace. This area was chosen because of the presence of thin burial layers and partially exposed structures covered by shrubby vegetation. Over a period of three working days, 30 flight missions were carried out in order to survey both the structures already revealed in the religious and civil sectors, as well as any archaeological deposits not yet covered by excavations (Fig. 4d, e). This made it possible to determine the degree of accuracy of the relief of each archaeological feature visible in the Digital Terrain Model (DTM) produced by the instrument, according to the degree of coverage present on each deposit.

The system can acquire a cloud of points with centimetric precision. This allows for the extraction of a DTM that reproduces the detailed morphology of the terrain in the areas flown over. The cloud was rasterized using CloudCompare's 'rasterize' tool to create a digital terrain model with 20 cm ground resolution cells. The reference parameter set in the 'Step Grid' may vary depending on the final objective for which the DTM was created. However, in the case of archaeological analyses, a lower ground resolution of the cells will result in a more detailed mapping of possible archaeological indicators in the surveyed area (Masini, Soldoveri 2017).

The DTM was imported into QGIS 3.30 software where, to enhance visualization potential, we developed a more precise model for highlighting terrain anomalies using the QGIS slope analysis tool. The Slope Analysis algorithm can identify the steepest points on the analyzed territory (Brogiolo, Citter 2018, 601). The analysis conducted on 1 cm DTMs with a Z factor of 1,000,000 accurately identified major height differences, which occasionally coincided with dense vegetation and archaeological indicators. The adopted method outputted a slope map highlighting the remains of structures linked to a series of rooms (Fig. 5). Some of these structures had been identified during previous excavations, while others were previously unknown. The highlighted features in red with a continuous line represent the wall septa of the rooms discovered during archaeological excavations conducted between 1994 and 2019 in the SW area of the site (Stasolla 2012). The more prominent features in red hatching correspond to additional anomalies that can be identified as archaeological indicators of wall fragments of buildings belonging to the urban quarters in this portion of the site, which are only partially known today (Fig. 5a).

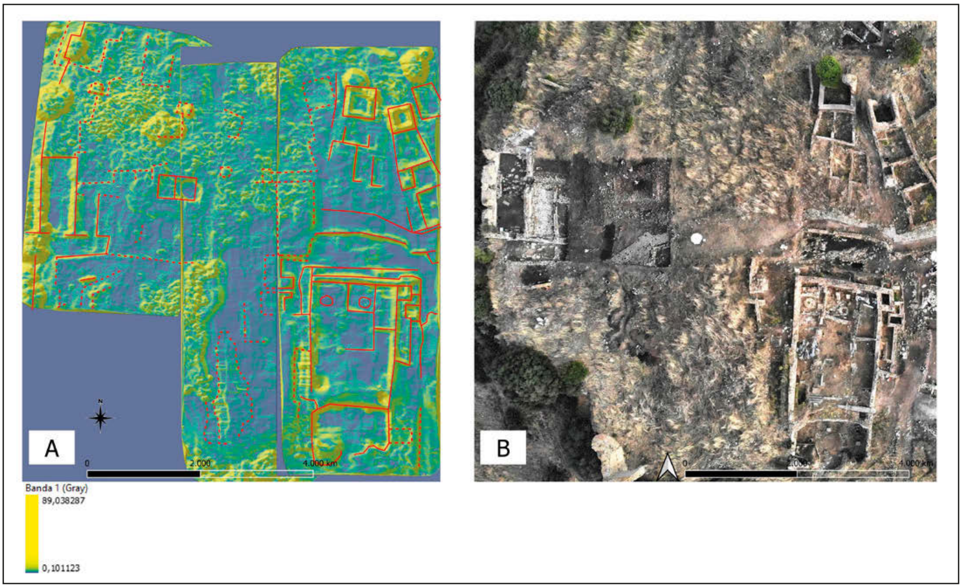

Fig. 5 – a) Slope map highlighting identified anomalies corresponding to the profiles of specific rooms (the values represent the slope degree); b) drone orthophoto of the SW area of the Cencelle site taken in September 2020.

The ongoing investigation is redefining the urban layout of the site to be denser than previously assumed. The area contains public and religious buildings alongside other urban structures, likely used for residential and artisanal purposes. The structures are divided by a main roadway with smaller roads branching off, following the contour lines of the hillside. This urban plan was already identified in the eastern area of the site between the 11th and 13th centuries CE.

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ABSTRACT

The UAVIMALS system is a small airborne laser scanner prototype resulting from interdisciplinary research conducted by the Sapienza University of Rome and the Institute of BioRobotics of the Scuola Superiore S. Anna in Pisa. The project was financed by the National Geographic Society (Early Career Grant No. EC-50761T-18). Its aim was to develop an inexpensive and open source remote sensing system, test an engineered LiDAR sensor for autonomous vehicles, and create a specific aerial system for 'micro-relief' archaeological trace detection. The experiment conducted in the archaeological context of Leopolis-Cencelle (VT) demonstrated the effectiveness of a self-built open source hardware and software system that can be adapted to different types of archaeological visibility.