Development of a High-Precision, Portable and Automated Mobile Laser Scanner for the Recording and Digitation of Texture and Micro-marks in Archaeological and Heritage Stone

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Abstract. The use of laser tools to digitise cultural heritage items is becoming more widespread but is generally limited to manual systems that rely on the user's movement or expensive automated equipment that is designed to scan large items but is not always able to accurately measure or reproduce specific details of small size. In this paper we present the novel high-precision system PALLAS, which allows the automatic digitisation of three-dimensional detailed surfaces. The equipment has been built using a set of motors and linear axes, control electronics and a line laser scanner that can be moved along the XY working plane. It is battery-powered for ease of use in the field and uses a standard laptop to communicate via Wi-Fi network. Custom software has been developed to automatically calculate paths, control the movement and store the profiles generated by the scanner. The software can also be used to reconstruct the surface from the set of scanner profiles, allowing the XYZ coordinates of any point on the surface to be measured and to obtain areal roughness parameters to characterise the finish and texture of the stone surface. Preliminary results obtained from masons' marks, rock engravings and petroglyphs are presented.

1 Introduction

Currently, multiple techniques exist for measuring or reproducing elements of cultural heritage. Among these, laser technology stands out as a particularly innovative and rapidly expanding approach. Like other optical techniques, such as photogrammetry [1], laser scanning offers the significant advantage of being contact-free. Its interaction with the sample relies on the reflection or incidence of light, ensuring no alteration to the artifact and allowing for measurements at a distance, even through transparent materials, within the laser's wavelength range. Another key benefit of laser scanning is its exceptional precision compared to conventional methods. Affordable equipment is available that can achieve measurements with accuracy down to hundredths of a millimetre. However, despite these advantages, most automated tools currently available for heritage conservation, particularly those suitable for field use, primarily focus on scanning large structures like facades or entire buildings [2, 3]. Smaller artifacts and intricate details, especially those with complex geometries, are often relegated to laboratory settings for high-precision digitation [4]. This involves either transporting the artifacts, which may be impractical or damaging, or manually scanning them in situ using handheld laser scanners or other techniques. Both approaches suffer from reduced precision and require a considerable time investment from conservation personnel. This issue becomes particularly critical when digitising heritage elements like petroglyphs. These archaeological markings, often found on exposed stone surfaces susceptible to erosion and located in difficult access areas, should ideally remain *in situ* [5]. Furthermore, their delicate nature and potential for faint markings require high-precision scanning to ensure accurate documentation. In order to address this challenge, this study presents a novel, low-cost, portable system designed and built by the authors. This system enables in-situ digitation of cultural heritage elements with laboratory-equivalent precision, operating autonomously to minimise user effort and maximise efficiency.

2 Methodology

In the design and manufacturing process of the equipment, the main criteria related to its use have been taken into account, specifically: light weight for easy transport, size suitable for its use in confined spaces, capable of measuring at any angle, precision equivalent to that achieved in a laboratory setting, automatic functioning during data collection in both smooth

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surfaces and surfaces with protrusions or indentations, and low-cost or easily accessible components for assembly and operation, whenever possible.

2.1 Hardware

The hardware components that comprise the system are listed below, along with their respective functions. Upon completion of the prototype, a system with a mass of 10.4 kg and an effective scanning area of 500 mm × 160 mm was achieved. This system can be oriented in any direction and achieve a working speed of 5 mm/s while displacing a mass of up to 1 kg, with an XY plane displacement resolution of 0.05 mm, a repeatability of 0.1 mm and a surface measurement precision of up to 0.005 mm. Furthermore, the equipment is versatile and can operate when connected to any power supply system with an output of 12-24 VDC or 220 VAC.

Fig. 1. Prototype of the PALLAS system

2.1.1 Structural frame

A rectangular structural frame was fabricated using custom-cut T-Slot aluminium profiles, which enabled a straightforward assembly process with a cost-effective and widely available material. Threaded holes were machined into each of the four corners, allowing for the optional installation of legs equipped with embedded interior nuts. These legs were designed and 3D-printed in PLA for integration into the prototype. The aforementioned nuts enable the anchoring or movement of a threaded rod through the leg, which features a rubber anti-vibration stop installed at the end oriented towards the sensor's measurement direction. These threaded rods, when installed, serve as a spacer and reference system, ensuring a consistent and known distance is always maintained between the equipment and the measurement surface. This configuration enables precise control over the measurement setup, allowing for accurate and reliable data collection. A mounting plate was secured to the rear face of the profiles, providing support for components associated with the control system. Additionally, an attachment element was mounted on the exterior of this plate, enabling the equipment to be secured to a tripod for measurements at varying heights and angles.

2.1.2 Motion system

The system consists of two motorised linear guides equipped with limit switches to determine the working area. Specifically, four magnetic reed-switch position sensors, model SMC D-A96, have been installed. For the X-axis movement, the low-cost, ultralight Fuyumotion FSK30J linear guide model, with a 500 mm stroke and an integrated low-power Nema11 stepper motor of 0.06 Nm, has been selected. A universal support, designed and 3D-printed in PLA with integrated magnets, has been installed on the carriage of this guide to enable the attachment of the scanning equipment and the activation of the position sensors related to the X-axis limits. The base of this guide has been coupled to both linear axes bolted to the infrastructure, which add rigidity and prevent potential bending of the linear guide, and the second linear guide, which has been bolted to the infrastructure to provide additional rigidity to the entire assembly and enable the movement of the first guide along the Yaxis. For this second guide, the low-cost Fuyumotion FSK40 model with a 160 mm stroke and a Nema23 stepper motor of 1.2 Nm has been chosen. Between the two linear guides, an anchoring spacer, designed and 3D-printed in PLA with integrated magnets, has been installed to enable the activation of the position sensors related to the Y-axis limits.

2.1.3 Control system

To carry out the control tasks, low-cost electronics that can be programmed with open-source tools have been selected. Specifically, an ESP32 microcontroller is used to send the signals that enable the control of the stepper motors, determine if the working area limits have been reached and send a signal that acts as an external trigger to control the timing of surface profile acquisition. In order to convert the signals into stepper motor movements, two drivers have been selected and installed: the Stepperonline DM320T, which controls the first linear guide, and the Stepperonline DM542T, which controls the second linear guide. Additionally, all the necessary electronics for signal conditioning and power supply have been incorporated.

2.1.4 Laser scanner

Auxiliary structures for holding various models of laser scanners on the previously mentioned universal support have been designed and 3D-printed using PLA. This level of adaptability allows for the selection of the most appropriate scanner to be used for the digitation process based on the required precision for the measurement of the surface. The functionality of the equipment has been tested with three commercial industrial-grade laser scanners, which operate by projecting a laser line onto the surface to be measured and then detecting the reflected light using a camera, to calculate the coordinates of the points forming the laser line in the scanner reference system based on the angle of refraction. Specifically, the models P+F VLE350-F280-B12-1100 (X:40-160 mm Z:60-350 mm, 960 points), MicroEpsilon scanCONTROL 2500-25 (X:23.4-29.1 mm Z:53.5-78.5 mm, 640 points) and MEL M2DW-75/30 (X:30-40 mm Z:90-165 mm, 256 points) have been used. All these scanners have the capability to use an external trigger, which causes the scanner to obtain a profile when an activation pulse is sent, allowing for the programming of a sequence of measurements at a series of known coordinates. A critical angle of approximately 30 degrees has been identified, beyond which shadowing effects can occur, resulting in point loss, for holes, protrusions or indentations on the surface.

2.1.5 Auxiliary systems

A low-cost Wi-Fi router has been incorporated to enable communication between the control system, the laser scanner and a conventional laptop, allowing for the sending of control command sequences and the collection of surface data. Specifically, the N300 Mini Wireless Router model has been installed. A battery-based power system has also been included to allow for the use of the equipment outdoors in uninhabited areas. The VTOMAN Jump 600 has been selected for testing, offering a battery life of over 4 hours with intensive use. Finally, a tripod has been added to fix the equipment in the required position during the measurement process, allowing for the scanning of marks or elements on vertical surfaces and ceilings or at awkward angles. Specifically, the Nedo Heavy-Duty Wooden Tripod 200513 model has been chosen.

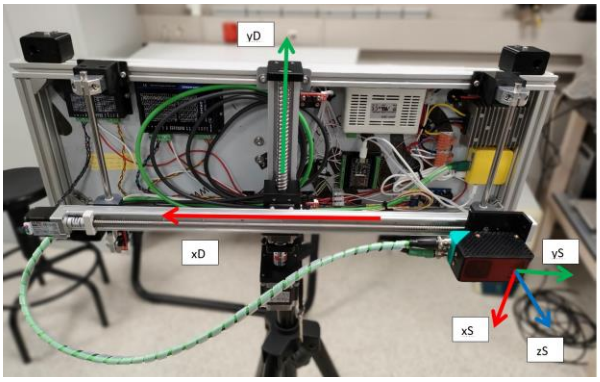

Fig. 2. Detail of the setup with linear guides and laser scanner reference axes overlaid

2.2 Firmware and software

The system's operation relies on open-source firmware installed on the control electronics and custom-developed software. This software suite enables path planning, command transmission to the laser scanner, reading, visualization, and storage of the digitized surface data. Furthermore, the software converts the acquired data into an open 3D representation format, promoting accessibility and interoperability

2.2.1 Control firmware

FluidNC, an open-source firmware, was selected for its ability to use G-code commands to control the linear guides' movements and trigger the laser scanner to capture profiles. This firmware, designed for the ESP32 microcontroller, features a graphical user interface for system management and status visualisation. It also enables remote command reception via a wireless network connection. Parameters defining the resolution, acceleration and maximum speed of each linear guide, as well as the digital inputs and outputs connected to magnetic sensors and the laser scanner, have been configured.

2.2.2 Custom software

A Python-based software has been designed and implemented to control the equipment via a wireless network connection, utilising a conventional low-end laptop. The software employs a communication socket to monitor the system status and transmit G-code commands, receiving responses accordingly. Upon establishing the communication channel and specifying the area to be measured, the application calculates the coordinates of each necessary path to scan the selected surface and generates the required command sequence. If the surface to be scanned exceeds the laser line width of the tool, multiple sweeps are generated to measure it completely, with overlapping regions according to a specified percentage. This overlap percentage is a programmable parameter whose optimisation can contribute to eliminating noisy points and shadow zones caused by the scanner's orientation relative to the piece, facilitating the merging of the different profiles obtained. The software calculates the coordinates and time intervals in which a uniform speed is maintained, based on the scanner's displacement speed and maximum acceleration configured in the firmware. During this interval, the tool's activation command is sent, enabling the transmission of a trigger sequence at a previously established frequency. Although the scanner's displacement speed can be selected based on the installed sensor model and its maximum working frequency, the software proposes a speed value that maintains a homogeneous distance between the obtained points that define the surface in the XY plane, facilitating subsequent data processing. During this interval, the application establishes a connection to receive profiles from the scanner and stores them in HDF5 format along with the linear guides' coordinates where the aforementioned profiles have been obtained, enabling grouping and conversion to the equipment's reference system coordinates.

After executing all planned paths, the software processes the stored points using various algorithms, eliminating outliers, merging sweeps and calculating the best approximation of height value for points in overlapping zones. The processed points are used to construct a triangle mesh, which is stored in PLY format. This open 3D format has been selected because it can be processed and visualised using multiple free or proprietary software tools in a straightforward manner. Additionally, it has the advantage of allowing the storage of colour information that can come from other sources. Furthermore, to facilitate the sampling task, the application allows for the visualisation of profiles as they are obtained and of the entire set using the Plotly library.

It is important to note that, in accordance with the current equipment features, when storing multiple scans, it is recommended to include auxiliary reference elements on the surface to optimise their merging, as they facilitate determining the relative position between them and allow for automatic processing through software. Furthermore, since the scanner always remains oriented in the same direction relative to the surface, if there are shadow or hole areas caused by surface protrusions or indentations that the overlap cannot resolve, it will be necessary to manually displace and rotate the equipment, perform a new sequence of sweeps that can add additional points and incorporate the previously mentioned ones. Using automated software in the conducted experiments, we achieved a percentage of valid points exceeding 90% (with an approximate average of 95%), which is greater than the required amount for a proper characterisation of the surfaces. In terms of time savings compared to manual scanning, a time savings of approximately 83% was calculated. It is important to note that the yield calculations were performed in comparison to tools previously developed to test the equipment, as no commercial software exists to perform the described set of tasks in a fully integrated manner.

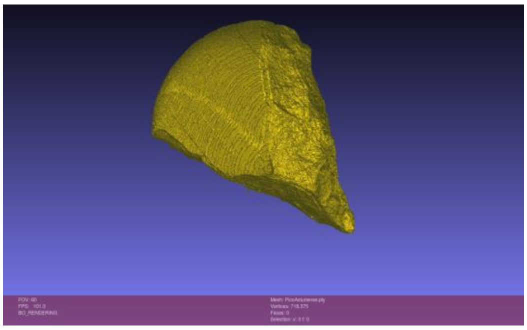

Fig. 3. Scanned hand axe saved in PLY format

3 Results

A series of laboratory tests have been conducted on the current prototype, with the dual purpose of calibration and verification of compliance with the predetermined design criteria. Following the successful outcomes of these tests, the equipment is presently undergoing field validation on heritage pieces located outdoors. It is noteworthy that preliminary results from ongoing field tests suggest that the automatic system yields measurements with enhanced precision, speed and accuracy compared to manual scanning and post-processing. While the approaches described in the referenced articles are adequate for obtaining statistical data on general roughness and determining the limits of medium-sized marks, the equipment presented in this work is necessary for a rapid and efficient processing of large areas with sub-millimetric precision. Further validation of the equipment and analysis of the results are necessary to complete the comparison.

The following text presents a series of results obtained during the tests already performed.

3.1 Calibration Grating

The test was conducted on a grid with known dimensions in order to determine the equipment's precision and perform a partial calibration of the equipment using different scanner models. The complete element has a size of 300 mm × 400 mm and a thickness of 9.5 mm, with gaps of 15.0 mm × 15.0 mm, the width of the bars being 2.5 mm.

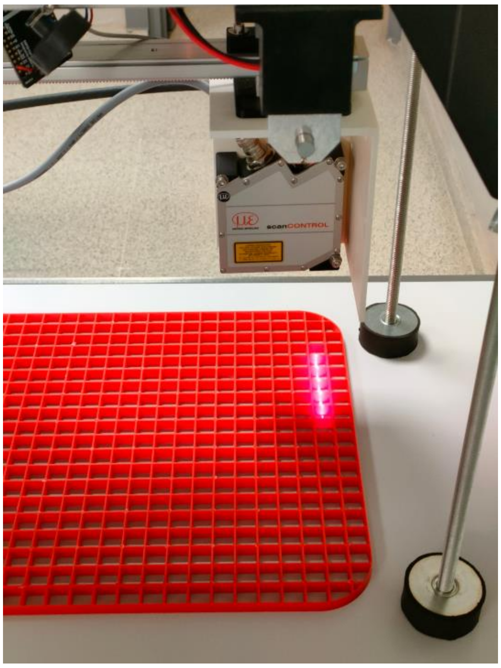

Fig. 4. Calibration grating scanning process

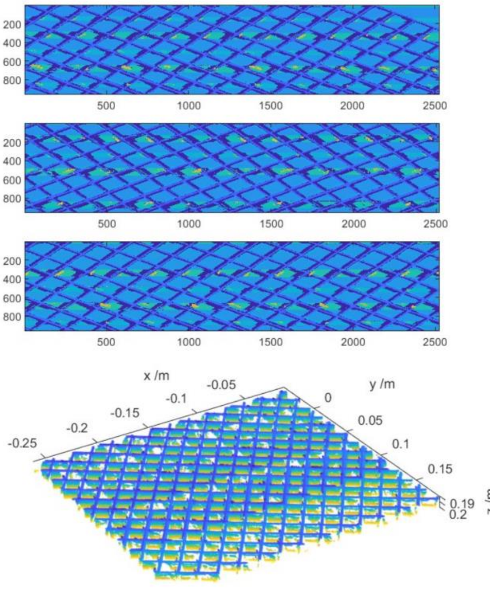

Fig. 5. Calibration grating measurements

3.2 Theatre Neutral Mask

The test was conducted on a mask similar to those used in classical theatre. It was selected due to its size, large enough to require multiple sweeps, its height and the level changes in the surface that allow for the completion of the equipment's calibration with different scanner models across the entire working range along the Z-axis. Furthermore, this example is considered representative of the types of surfaces commonly found in cultural heritage made of stone, due to its round shapes, the representation of a human face and the presence of cavities that create shadows. Additionally, it is considered an interesting example because it enables the validation of the system's capability to digitise individual pieces from other areas of cultural heritage with high precision.

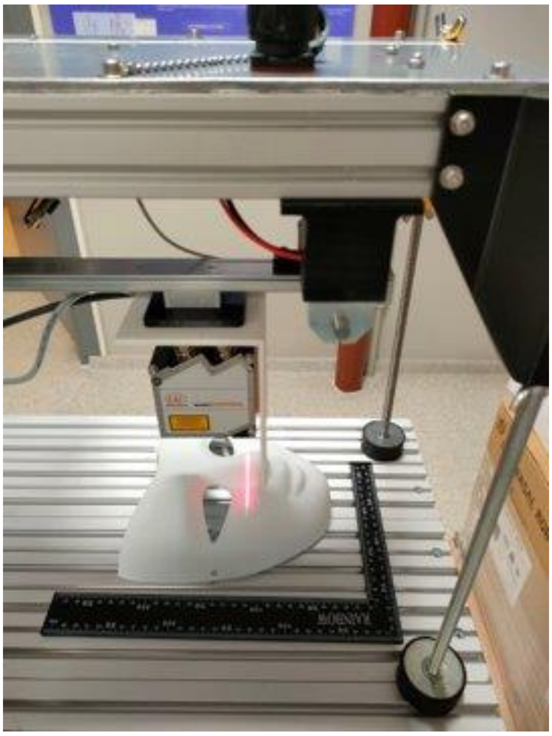

Fig. 6. Theatre neutral mask scanning process

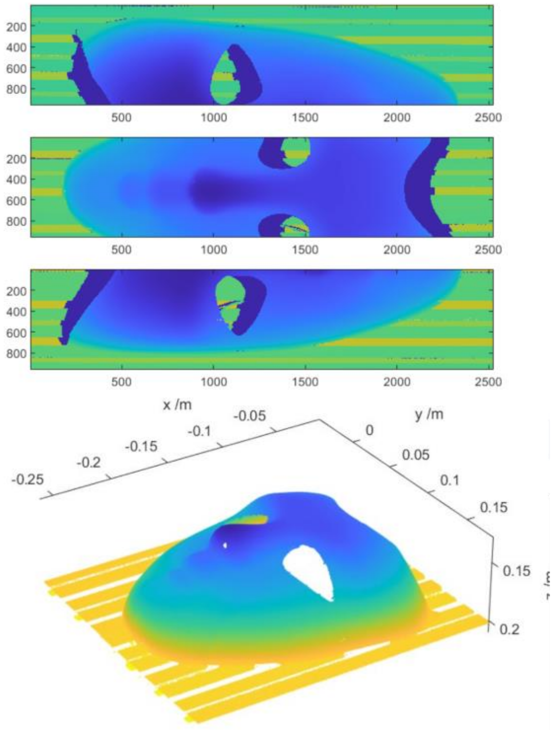

Fig. 7. Theatre neutral mask measurements

3.3 Reproduction of Granitic Stone Frieze

The test was conducted on a representative element of the stone heritage in the geographical area where the authors are carrying out most of the field tests. In this case, a granite piece was selected, as it is a very abundant material in the northwest region of the Iberian Peninsula, widely used in both archeologic stones with petroglyphs and cultural heritage buildings. Furthermore, it is a material that the authors have extensively studied in previous works and, due to its durability and heterogeneity, it presents a wide variety of wear marks, defects or interesting surface changes that should be recorded for conservation and treatment purposes. The example used is a reproduction of a simple frieze handcrafted by a stonemason, with a relief and depth equivalent to those commonly found on the façades of churches and manor houses. The surface was painted with blue graffiti paint and partially cleaned with a laser, emulating the restoration of the piece after being subjected to vandalism, to determine the level of detail that the equipment records before and after the treatment.

Fig. 8. Granitic stone frieze scanning process

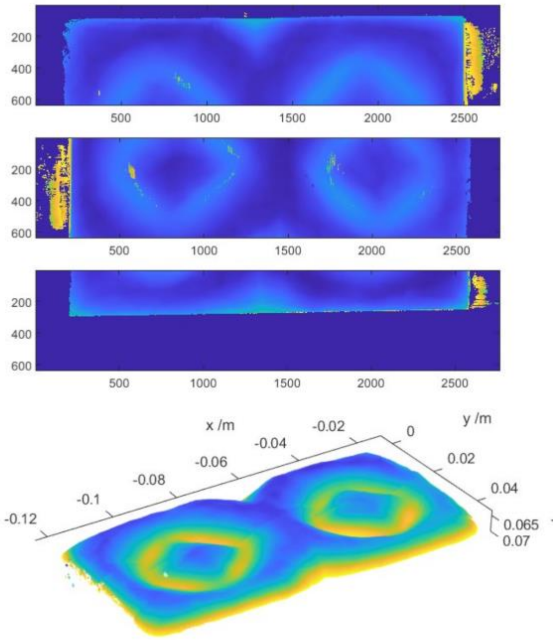

Fig. 9. Granitic stone frieze measurements

3.4 Rock with Engravings

A test was conducted on a fragment of a rock with engravings from the Valcamonica archaeological site due to its challenging nature for precise digitation *in situ* using conventional methods. The sample presents shallow marks and signs of wear caused by prolonged exposure to the environment. The marks are difficult to discern with the naked eye, not only due to erosion but also due to the material's discoloration. The use of the prototype enables the visualisation of all existing marks, which appear to represent a set of lines and an arrow, as well as measuring their depth and length. Additionally, the surface data obtained from the scanning process allows for the partial determination of the texture differences between the marked areas and the base material, providing supplementary information that can be useful for archaeologists when analysing the type of tool used for engraving or searching for similarities between these marks. Ultimately, this sample has validated the equipment's level of precision allows for satisfactory results in the use cases for which it was designed.

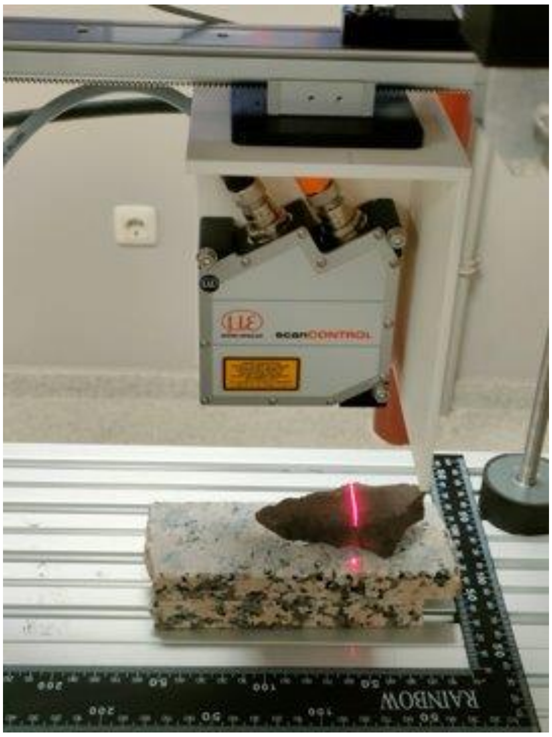

Fig. 10. Rock with engravings scanning process

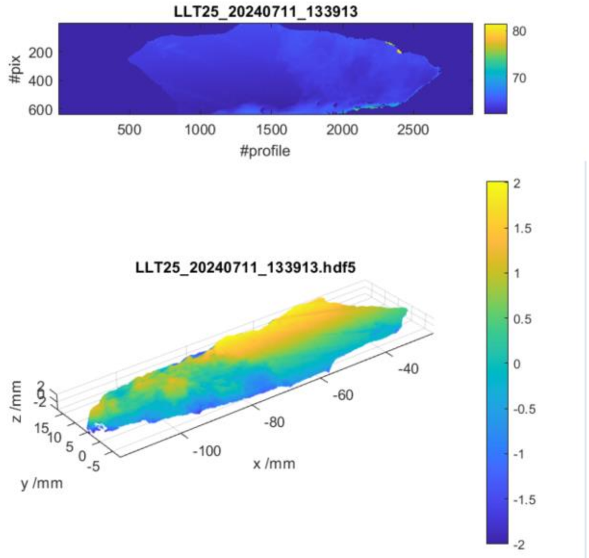

Fig. 11. Rock with engravings measurements

4 Conclusions

A novel method is presented that enables the acquisition of high-resolution data from archaeological stone *in situ*

with laboratory-grade precision, using a device and software developed by the authors. It is based on a lightweight positioning system with two motorised linear axes XY that enable the scanning of the surface with different laser scanner models. A 3D model of the entire surface within the working area without holes can be generated by merging different scan sequences, but it requires auxiliary reference markers and manually rotating the device.
Future work will focus on enhancing the prototype's performance. While the current prototype functions correctly and executes its intended processes effectively, potential improvements include the incorporation of a rotating scanner, the addition of encoders to the motors and the extension of the software. These modifications are expected to improve usability and reduce the time required for surface scanning.

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