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D 2.3 System specification

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Abbreviations

WP: Work package

M: Month

UNIPI: Universita di Pisa

UBM: Université Bordeaux Montaigne

UoY: University of York

INRAP Institut National de Recherches Archéologiques

AMZ: Arheoloski Muzej u Zagrebu

QB: QBrobotics Srl

HUJ: The Hebrew University of Jerusalem

MIN: Miningful srls

KCL: King's College London

IIT: Fondazione Istituto Italiano di Tecnologia

UB: Universitat de Barcelona

CL: Culture Lab

AI: Artificial Intelligence

ML: Machine Learning

Executive summary

Deliverable 2.3 outlines the system specification for the AUTOMATA project, a robotic system designed to automate the digitisation of archaeological artefacts, specifically ceramics and lithics. This document builds upon the discussions in D2.1 (*Methodologies, Scenario, and User Requirements*) and the review conducted in D2.2 (*State of the Art on Enhanced Digitisation*). It provides a detailed description of the prototype robotic workstation, including its components, safety measures, and motion control mechanisms for handling archaeological objects. Additionally, it explores sensor integration for 3D scanning and material analysis alongside the automated workflow for collecting the necessary data to generate the 3D models and feed the post-processing phase.

Sections 2 to 4 focus on the robotic system for digitisation, highlighting its adaptability and the end effectors designed to safely handle artefacts. The document details safety measures, workspace layout, and weight distribution control while addressing environmental considerations such as dust protection, vibration mitigation, and specific lighting requirements. The motion control systems ensure the precise handling of fragile artefacts, incorporating intelligent path planning and integrated safety protocols for efficient operation.

Section 5 delves into the protocols for integrating sensors for 3D scanning (including photogrammetry, laser scanning, and structured light) and material analysis (using hyperspectral imaging, pXRF, and handheld Raman spectroscopy). It discusses the calibration and accuracy of these methods, along with challenges in data acquisition, while emphasising the use of compact devices for effective material analysis.

The final section (Section 6) describes the automated digitisation workflow, explaining the object positioning techniques employed for 3D model creation and the process of combining hyperspectral imaging with 3D models. These tasks are supported by AI tools for calibration and model refinement. The system aims to digitise each artefact while automating data processing, with outputs stored in the RIS3D system. Finally, the document addresses object labelling protocols and cloud integration for secure storage and sharing of digitised data.

1. Introduction

The AUTOMATA system seeks to enhance the digitisation of archaeological artefacts by using advanced technologies to improve efficiency, precision, and adaptability. Central to its operation is the robotic handling system, designed to securely manipulate fragile objects using adaptive end effectors equipped with soft-grip technologies and force control. This ensures the physical integrity of artefacts is preserved throughout the digitisation process, addressing the inherent challenges posed by their diversity and delicacy.

A strong emphasis is placed on tackling practical challenges, including lighting synchronisation, protocol standardisation, and processing times. These aspects are carefully evaluated through rigorous testing and real-world case studies, allowing for continuous refinement of the system based on technical feedback. By systematically addressing these hurdles, AUTOMATA ensures that each component contributes to a streamlined and reliable workflow.

The system also highlights the importance of multimodal sensor integration, encompassing advanced techniques for 3D scannings, such as LiDAR, structured light, and photogrammetry, alongside material analysis methods like hyperspectral imaging (HSI), pXRF, and handheld Raman spectroscopy. Testing of these sensors is currently underway to define precise protocols that optimise their performance in terms of accuracy, speed, and technical efficiency. Furthermore, efforts to miniaturise sensors are advancing, enabling their seamless incorporation into the system and enhancing its adaptability. Case-specific applications, including the detailed analysis of ceramics and lithic artefacts, provide insights into the functionality and validation of these approaches.

An intelligent and structured approach to data registration further supports the system's efficiency. Sensor data is recorded to enable immediate processing without overloading the robotic arm's computational capabilities. This information is later integrated with 3D datasets during post-processing, taking advantage of the RIS3D system to ensure precise alignment and efficient workflow execution. Automation also plays a crucial role in optimising 3D model cleaning processes, with existing software solutions delivering rapid and reliable results, particularly for tasks such as LiDAR scanning.

Through the integration of advanced technologies, practical design elements, and systematic testing, AUTOMATA offers a structured approach to the digitisation of archaeological artefacts. Its workflow aims to improve the accuracy and efficiency of data acquisition, supporting documentation, analysis and interpretation of cultural heritage materials.

2. Mechanical and structural components

The robotic work cell serves as a fundamental component of the AUTOMATA system, designed to facilitate the efficient and accurate digitisation of archaeological artefacts. In this document, the term "artefacts" specifically refers to ceramic fragments and lithic objects, as these represent the primary focus of the AUTOMATA system's digitisation and analysis workflows. Given the diverse nature of artefacts in terms of size, shape, material composition, and fragility, the system incorporates a modular and adaptable architecture to accommodate these variations. This adaptability ensures that artefacts can be handled with precision and care.

By integrating advanced automation and robotic control mechanisms, the work cell enhances digitisation workflows while maintaining compliance with conservation best practices. The system's customisable parameters allow operators to fine-tune handling processes, ensuring minimal risk of damage while maximising data acquisition quality.

2.1 Role of end effectors in object handling

At the heart of object manipulation within the robotic work cell are end-effectors, which perform essential functions such as gripping, supporting, and positioning artefacts during digitisation. These components must be carefully engineered to account for the delicate nature of archaeological materials, some of which may be fragile not only due to age-related deterioration but also because of their intrinsic material properties, such as thinness, brittleness, or surface instability.

To address this challenge, the AUTOMATA system incorporates **adaptive end effectors** equipped with (Fig. 1):

- **soft gripping technology** to grasp objects, evenly and automatically distributing the contact pressure on fragile surfaces;
- **adjustable multi-fingered robotic grippers** that conform to different shapes and textures;
- **vacuum-assisted suction systems** for securely holding artefacts without direct mechanical contact can be evaluated.

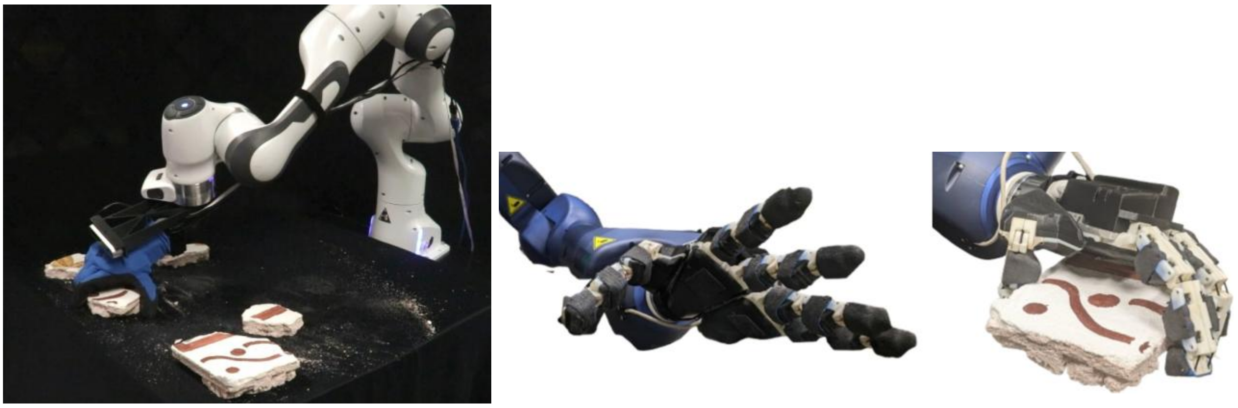


Fig. 1. SoftHand used in the RePair Project to grasp delicate artefacts such as pieces of frescoes.

This combination of technologies enables safe and controlled handling of artefacts while ensuring that each object remains securely positioned and manipulated throughout the digitisation process. To further enhance artefact safety, the project will implement standard precautionary measures, such as pedestals or support wedges, to stabilise items during handling. While manual handling may be preferred initially for particularly fragile items, the system will include a restraint setup to protect artefacts as they are positioned for scanning.

In line with user requirements and the constraints of the robotic work cell, gripping devices will be designed and tested to handle artefacts weighing up to 1 kg and measuring approximately between 10 and 120 mm. The fragments to be digitised will be placed by a human operator into containers whose dimensions are defined by the workspace of the system, rather than by archaeological practice. Although archaeological excavations often employ 20 to 40-litre boxes to store hundreds of artefacts, these are typically repacked into plastic bags, which require manual opening before processing. For digitisation, the operator will transfer the fragments into a container compatible with the work cell and will ensure they are properly arranged, cleaned, and associated with relevant metadata (e.g., inventory numbers, excavation context, SU number, material, size, weight). This preparatory phase is essential to optimise the recognition and manipulation of individual fragments by the system. To prevent simultaneous grasping of multiple items, end-effectors must be capable of selectively isolating and grasping a single fragment, even when in contact with adjacent ones. From a mechanical standpoint, the design must minimise contact pressure and reduce the risk of scratching or breaking objects during both pick-up and placement. These requirements apply across the full range of object shapes and sizes, making adaptability and versatility of the gripping mechanism central to operational reliability. Furthermore, since repositioning of a fragment is needed during the process, the system must preserve the association between different data and positions by accurately managing the release and re-grasping phases, maintaining a consistent reference to the object's position and orientation.

Technical analyses, in accordance with process requirements, will define the evolutions of these systems in terms of reliability and precision.

2.2 Defining the work envelope

The work envelope represents the physical space within which the robotic system operates. Its dimensions and constraints are carefully designed to accommodate both small and large artefacts, ensuring optimal efficiency without excessive motion complexity.

The heterogeneity of the fragments and their handling requires dexterity, which can be achieved by adaptive grippers and an anthropomorphic robotic arm with at least 6 degrees of freedom. The workspace for a robotic arm is approximated with a sphere limited by the workbench, constraints related to acquisition devices and other support frames that will be integrated into the system. Moreover, the workbench will have movable support on the lateral sides to place the boxes for fragments before and after the digitisation (Fig. 2).

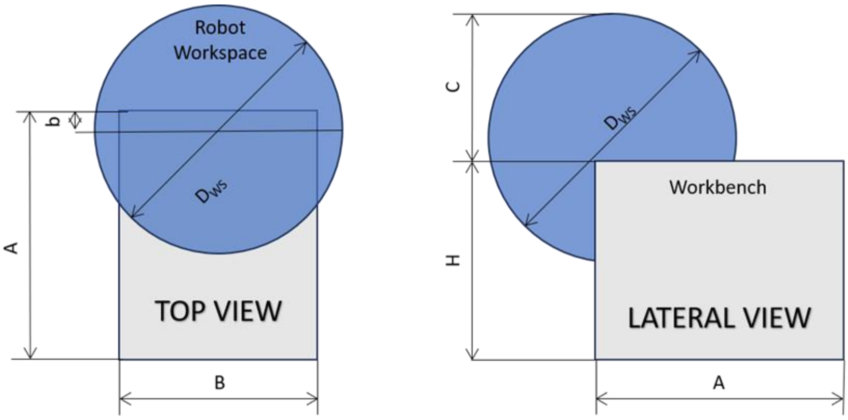


Fig. 2. Scheme of robot workspace and workbench.

In the following, the key factors influencing the work envelope are reported.

- **Reach and range of robotic arms** – ensuring the coverage of the handling area with a Diameter of workspace Dws≤1800mm.
- **Fixed and variable workspace elements** – the stationary elements will be related to the acquisition systems with known position and orientation on the workbench. Variable elements are basically the objects to be digitised, other support for lamps to be arranged depending on the environment illumination and lateral support for the containers where the finds are placed.
- **Safety zones and operational clearance** – the workstation's perimeter will be equipped with safety systems that detect the distance of the operator and consequently limit/stop the movements of the robot

By optimising these parameters, the robotic work cell can adapt to different artefact dimensions while maintaining high precision and repeatability in movement and object interaction. The best dimensions of the cell and positions of all the elements will take into account the specifications of each acquisition device and the space requirements for moving the artefacts. The starting dimensions for the workbench (see Figure 1) will be: A=1200mm, B=600mm, H=800mm without extendable surfaces that can be placed on lateral sides.

2.2.1 Safety considerations

When using portable X-ray fluorescence (pXRF) instruments, ensuring safety is paramount due to the ionizing radiation they emit. Adherence to the ALARA (As Low As Reasonably Achievable) principle is essential, which involves minimising exposure through careful management of time, distance, and shielding. Operators must follow established protocols, such as employing shielding attachments, ensuring proper sample positioning, and maintaining appropriate distances. For user protection, dosimeter rings are commonly worn, and surrounding individuals should remain at least 1 meter away from the device (depending on the specific sensor). The pXRF is equipped with a red light indicator to signal when X-rays are active, reinforcing the need for caution. In addition, the instrument should be powered off when not in use and stored securely to prevent unnecessary exposure.

Compliance with radiation safety standards specific to the operating country or region is crucial. Operators must undergo radiation safety training, which is often required by academic institutions and government agencies, ensuring familiarity with regulations and best practices. As with all safety protocols, it is important to periodically refresh training, especially when new users are involved or when safety practices may have lapsed over time. Moreover, the robotic arm used for automated scanning must also comply with safety regulations, including European standards, to ensure both operator and equipment safety.

For effective radiation protection, the use of shielded test stands is recommended, as they can block stray X-rays. Some systems are equipped with interlocks that stop the X-ray emission if the shield is removed, providing an additional safety measure. However, when using a portable system without a shielded stand, extra care must be taken with positioning and distance to mitigate exposure. Practising proper safety protocols and being mindful of safety features in pXRF instruments can significantly reduce radiation risks (Frahm, 2024).

2.3 Load capacity and stability

The load capacity of the robotic system is a crucial factor in balancing stability, weight distribution, and artefact safety. The system is engineered to handle artefacts of varying weights without compromising accuracy or structural integrity. It is assumed that the robotic arm is more than sufficient to lift the objects. The recommendations to end-users should not include objects outside the above-mentioned specifications (e.g. low-capacity gripping systems such as suction cups).

Design considerations include:

- **Dynamic weight distribution control** prevents imbalances that could affect precision. Controlling the robot dynamics is essential to achieve smooth movement and minimise inertial effects, which cause vibrations and disturbances to data acquisition and fragment handling procedures.
- **Structural reinforcements** ensure that the system remains stable under varying loads. The cell will be provided with wheels for transportation and extendable levelling feet with anti-vibration contact surfaces.
- **Automated force adjustment mechanisms** modulating grip strength based on artefact weight. This specification will be met by using self-adaptive grippers, featuring both low- and high-level controls to manage the overall contact force, combining the information from the gripper and the vision system that defines the fragment to be manipulated.

By integrating these features, the AUTOMATA robotic work cell can efficiently process lightweight pottery and heavier stone artefacts, enabling a versatile and scalable approach to archaeological digitisation.

3. Power and environmental considerations

The system will address practical concerns, such as dust management, to maintain equipment and sensor functionality during the handling and digitisation process. Although engineering limitations may prevent the guarantee of absolute artefact safety, a thorough assessment of acceptable handling standards will be established to ensure potential risks are minimised, keeping mishandling rates to a very low level. By focusing on power supply, portability, and environmental stability, the AUTOMATA system is designed to operate efficiently and safely in different settings, offering a robust solution for archaeological digitisation in a variety of environments.

3.1 Power supply requirements

The AUTOMATA robotic work cell is designed to operate in laboratories, research centres, museums and storage facilities with a reliable power supply. To ensure operation in various environments, the system is engineered to be compatible with:

- **Standard laboratory power sources:** supply voltage 110V/240V with replaceable power connector according to the standard used in the destination country.
- **Uninterruptible Power Supply (UPS) systems:** built-in buffer battery to protect the electronic devices from fluctuations and brief interruptions of the power supply and offer backup power during digitisation tasks. The system will be able to detect a prolonged power failure, initiate the safe shutdown procedure and save the work in progress.

The flexibility in power options allows the system to maintain consistent performance regardless of the operational setting, protecting CPUs and other electronic components.

3.2 Compact and portable design

A key requirement of the AUTOMATA system is its compact and portable design, allowing for easy transport and deployment in diverse archaeological settings. Given the spatial constraints of museum storage areas and research laboratories, the system must be lightweight, modular, and adaptable. To achieve this, the robotic work cell features a modular structure that enables quick assembly and disassembly, facilitating relocation and setup. Foldable or collapsible components minimise bulk, while lightweight yet durable materials ensure ease of transport without compromising structural integrity. The following picture (Fig. 3) shows the proposed solution.

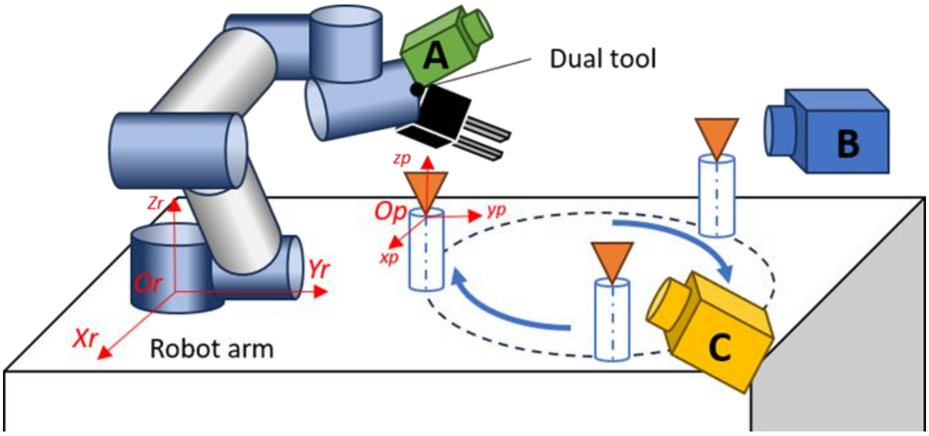


Fig. 3. Work cell layout with robotic arm equipped with gripper and data acquisition systems: A, B and C.

The system includes a robotic arm equipped with a dual-tool gripper, a 3D model/HSI acquisition system (A), and two additional data acquisition stations: pXRF (B) and handheld Raman spectrometer (C). The gripper, mounted on the robotic arm, picks up the artefact from its tray, places it on a support, and performs the initial data acquisition (3D/HSI) using the robot's degrees of freedom. The data acquired at this first station will determine whether pXRF and handheld Raman spectroscopy analyses are needed and will pinpoint regions of interest for subsequent analyses. HSI can provide effective and fast support for the classification of materials, based on the comparison of spectral data obtained in real-time from the system and spectral libraries that will be optimised for the purpose. The support, equipped with a rotating vertical axis, then moves the artefact to the pXRF station and subsequently to the handheld Raman spectroscopy station. At the end of the sequence, the artefact returns to the first station, where the gripper picks it up and places it back in its tray. For example, when step A is completed, the fragment moves to the next step and at the same time the fragment that has just completed the overall cycle arrives. At that point, the robot removes that fragment, places a new one and immediately begins the digitisation. A total of three supports will rotate in synchrony, meaning the cycle time will be determined by the longest acquisition phase, allowing, at the same time, the parallel digitisation of different artefacts.

The use of supports that move the sample from one station to the next without repositioning ensures that the same reference system is maintained throughout the procedure.

The use of a dual tool on the wrist of the robot will allow it to exploit the available degrees of freedom for the first step, and at the same time to immediately switch from the movement phase to the digitisation phase without changing the tool and therefore increasing the cycle time. Instruments B and C will exploit the vertical rotation axis of the support and the movement organs they will be equipped with, to approach the analysis point of the fragment, identified in the first phase. These organs will be designed and tested in the early stages of the project, jointly with the partners who deal with such analyses and taking into account the specifications of each instrument.

A major advantage of this design is its ability to support lab digitisation, allowing artefacts to be documented directly at their location rather than being transferred to a separate facility. This is

particularly valuable for institutions where object movement is restricted or requires formal authorisation, as well as for fragile or immovable artefacts. Instead of relocating objects, the system itself can be transported between storage areas, museum collections, and archaeological centres, streamlining the documentation process.
To enhance usability, the system will be designed to fit through standard doors and elevators and will likely be mounted on a wheeled platform for smooth navigation within controlled spaces.

The construction of the robotic work cell allows for:

- **quick assembly and disassembly**, facilitating deployment in field environments;
- **foldable or collapsible components**, reducing transportation bulk;
- **lightweight materials**, ensuring portability without compromising durability.

3.3 Environmental controls

To ensure both the protection of delicate artefacts and the quality of analysis during digitisation, it is essential to implement environmental control measures. The system will be designed to operate in moderately dusty environments, typical of storage facilities and archaeological centres, while maintaining optimal conditions with a temperature range of 10°C to 50°C and a relative humidity between 30% and 70%. In addition to safeguarding the objects from potential damage, it is crucial that the environment is controlled to ensure accurate and reliable analysis. Therefore, key considerations include dust protection, vibration reduction, and light control, all of which are vital for preserving the artefacts and ensuring high-quality digital data.

- **Dust protection**. To address dust protection, the system will evaluate the use of sealed enclosures or controlled airflow mechanisms to minimise dust accumulation. Artefacts are assumed to be clean prior to processing, and users will receive guidance on regular maintenance and cleaning procedures for the system. Additionally, anti-static coatings may be applied to prevent fine particles from settling on delicate surfaces.
- **Vibration reduction.** For vibration reduction, shock-absorbing mounts will be employed to stabilise the system and prevent micro-vibrations. Precision motion control algorithms will be developed to enable smooth robotic movements, supported by intelligent path planning.
- **Light control.** Lighting in the acquisition areas must be carefully controlled and aligned with the specific requirements of each instrument used in the AUTOMATA system (see Section 5). Proper illumination enhances data quality by optimising surface detail capture and minimising noise. While different digitisation technologies may have slightly varying needs, all require stable, well-distributed lighting to ensure accurate data collection and minimise interference.

For photogrammetry, even and diffuse lighting is essential to prevent harsh shadows, overexposed areas, and distortions in texture that could affect image-matching and feature detection. The use of soft light sources, such as softboxes or ring lights, helps maintain colour consistency and texture accuracy across the model. Laser scanning, including miniature LIDAR scanning (e.g. iPhone LIDAR), requires low ambient light and controlled conditions to prevent interference with laser pulses. Strong external light sources, such as direct sunlight or bright spotlights, can reduce accuracy by affecting the scanner's ability to capture fine surface details. Similarly, structured light scanning relies on projecting a controlled light pattern onto the artefact's surface, meaning that bright or direct illumination can distort the data. Scanning will therefore be performed in a dimly lit environment to ensure that only the structured light from the scanner interacts with the object.

Hyperspectral imaging (HSI) demands carefully controlled illumination, typically using halogen lamps positioned at a 45° angle relative to the object, with the camera placed centrally. Maintaining a stable acquisition setup, including a consistent distance of approximately 50 cm and a Spectralon tile for calibration, ensures reliable spectral data across multiple wavelengths.

Since both 3D scanning and hyperspectral imaging will be mounted on the same arm, a shared lighting system must accommodate both techniques. Halogen lamps provide a practical solution, as they offer stable and diffuse illumination suitable for 3D scanning, hyperspectral imaging, and other optical methods. Diffused lighting is crucial in all cases, as excessive shadows or uneven illumination could compromise data quality across different acquisition processes.

pXRF and handheld Raman spectroscopy have no specific lighting requirements. pXRF emits X-rays and detects fluorescence from the object's surface, making ambient lighting irrelevant to the measurement process. Similarly, handheld Raman spectroscopy relies on laser illumination to induce Raman scattering, meaning external light sources do not interfere. Nevertheless, correct artefact positioning is crucial for accurate readings: the sample must be in direct contact with the analyser window, covering it completely.

One possible solution is to mount the lighting units directly onto the robotic arm, supported by a fixture at the base of the hyperspectral camera. This setup would keep the lamps at a fixed distance from the camera and positioned at a consistent 45-degree angle to the artefact. In this way, uniform illumination would be maintained across all acquisitions, regardless of the arm's movement, reducing the need for lighting adjustments.

Below is a table summarising the lighting conditions for each technique and instrument used in the digitisation and analysis process (Tab. 1).

Tab. 1. Summary of lighting conditions for each technique and instrument.

Technique	**Preferred Lighting**	**Avoid**	**Reason**
Photogrammetry	Uniform, well-distributed light	Shadows, uneven lighting	Prevents texture distortion
Laser Scanning	Low ambient light	Sunlight, strong lights	Prevents external interference
Structured Light Scanning	Dim, controlled light	Bright, direct light	Avoids pattern distortion

HSI	Halogen lamps, natural sunlight	Uncontrolled lighting	Ensures spectral consistency
p-XRF	No specific requirement	-	X-rays are unaffected by ambient light
Raman Spectroscopy	No specific requirement	-	Uses its own laser

4. Motion control and automation

Motion control is a critical component of the AUTOMATA system, enabling precise, adaptable, and safe handling of artefacts during the digitisation process. Given the diversity in sizes, materials, and fragility levels, the system must ensure that all movements are highly controlled and repeatable to prevent damage while maintaining data accuracy.

By integrating advanced automation techniques, the system can efficiently manage object positioning, scanning, and handling tasks with minimal manual intervention. This reduces human error, enhances consistency, and improves overall workflow efficiency.

4.1 Optimising movement for accuracy and efficiency

To ensure efficient and high-precision object digitisation, the AUTOMATA system employs various motion control strategies, including:

- **high-resolution encoders and sensors** for real-time position tracking;
- **multi-axis robotic control** to allow complex yet stable object manipulation;
- **smooth trajectory planning algorithms** to reduce abrupt or jerky movements that could affect artefact stability.

A key aspect of optimisation is intelligent path planning, which:

- **enhances efficiency** by reducing unnecessary movements;
- **improves scanning accuracy** by maintaining consistent object orientation!
- **minimises redundancy** to speed up digitisation while preserving data quality.

The system will consist of fixed motion trajectories for the robotic arm, which include the initial trajectories where items are picked up from boxes or trays and the final trajectories where the reverse operation is performed. Additionally, there will be trajectories that are highly dependent on the type of analysis required for the artefacts and the ongoing acquisitions of previously scanned artefacts. This is because, to save time and accelerate the artefact acquisition process, a path planning strategy must be devised that accounts for already occupied scanning stations and selects optimal trajectories to ensure continuous movement.

Furthermore, the grasping of the artefact with the soft end-effector must be planned to ensure an appropriate pose on the object, considering a trade-off between the object's shape and a grasping configuration that facilitates placement near the next station. Additionally, it will be preferable to adopt softer movements based on the artefact's specifications - dimensions, weight conformation and fragility. This adaptability ensures that both delicate ceramics and more durable lithics can be digitised effectively while maintaining high-quality data acquisition. For example, when handling a thin and elongated lithic artefact, excessive speed could cause the object to rotate due to air resistance, an undesirable outcome. The robot must account for the object's pose to maintain

measurement precision across different stations.
To accommodate this, the AUTOMATA system includes adjustable speed controls, allowing:

- slow, precise movements for fragile ceramics;
- faster processing for robust stone objects.

By dynamically adjusting these movement sequences, the system ensures that artefacts are scanned from optimal angles. This approach minimises excessive repositioning, which could otherwise introduce errors or prolong processing time.

4.2 Safety mechanisms: collision avoidance and adaptive responses

Given the fragile nature of many archaeological artefacts, collision avoidance systems play a crucial role in preventing accidental contact between the robotic system and objects. Other safety considerations include proper use of the system by users and accidental impacts on them. The AUTOMATA system incorporates the following features.

- **Real-time obstacle detection sensors** to identify potential hazards. The high-level control that manages the system's kinematics combines the real-time position of the robot and end-effector (gripping or data acquisition device if needed) with all the layout constraints. Devices such as pXRF and handheld Raman spectrometers, which require minimal handling during operation, will have fixed positions within the system and well-defined dimensions and shapes. After the system validation tests, the integration of specific contact and/or distance sensors will be evaluated in redundancy with the open loop controls.
- **Force-feedback mechanisms** to adjust grip strength dynamically. The peculiarity of soft grippers explained in paragraph 2.2, with the automatic force distribution and current consumption control during the grasp, will avoid damage to artefacts. The integration of additional sensors and contact force controls will be evaluated following preliminary handling tests on samples, in the first year of the project.
- **Safety sensors for humans.** The system will be equipped with perimeter sensors that detect the distance of nearby operators and will allow the integration of the necessary safety protocols.
- **Automated emergency stop protocols** that activate upon detecting unexpected resistance or obstructions. The information coming from the external and internal distance or pressure sensors of the system layout will be used to activate appropriate safety protocols that will slow down the robot's movements and, if necessary, stop it. These states will be identifiable by the operator through signal lights and will also affect the acquisition tools that are operating before the stop.

These features protect delicate artefacts by ensuring that robotic movements remain within safe operating limits while responding adaptively to environmental conditions.

5. Sensor integration

As detailed in D2.1 (*Methodologies, Scenario, and User Requirements*), the AUTOMATA system will integrate a comprehensive suite of sensors, including 3D scanning technologies (such as photogrammetry, laser scanning, structured light scanning), as well as hyperspectral imaging for material analysis. Additionally, portable X-ray fluorescence (pXRF) and handheld Raman spectroscopy will be used for compositional analyses. These technologies are crucial for capturing enriched models of archaeological artefacts, and each method is integrated into the system to support the digitisation pipeline. This section outlines the integration of these technologies, highlighting their strengths and challenges, while ensuring efficiency, accuracy, and the preservation of artefacts.

5.1 3D scanning protocols

The selection of 3D acquisition technology has not yet been finalised, and ongoing tests are being conducted to assess different sensors for integration into the AUTOMATA system. The evaluation includes LiDAR, structured light, and photogrammetry, each following a specific methodological approach. To ensure a systematic assessment, a standardised protocol is being developed for all three techniques, defining their requirements and integration procedures. Since each method presents distinct advantages in terms of resolution, portability, and applicability to different types of artefacts, these protocols are currently being tested through iterative prototyping and comparative analysis to determine the most suitable solution for the system. Importantly, whichever protocol is ultimately selected will need to be integrated into an automated pipeline — from object positioning and data acquisition to model reconstruction and post-processing — capable of supporting efficient, consistent, and scalable digitisation within the AUTOMATA framework. Based on the preliminary results, the following section outlines the key characteristics of the acquisition protocols for each sensor.

Given that one of the key requirements of the AUTOMATA system is its compact and portable design, the **iPhone LiDAR system** has been chosen as an initial approach for laser scanning. The iPhone LiDAR (Light Detection and Ranging) system employs laser-based technology to capture the geometry of objects with high precision. When scanning ceramic fragments, the process follows a structured workflow (tab. 2).

Tab. 2. Step-by-step process for using iPhone LiDAR to scan ceramic fragments, from preparation and scanning to post-processing.

Step	***Description***
1. Preparation	- Select the ceramic fragments to be scanned, ensuring they are clean and free from dust or obstructions. - Place them in a controlled scanning environment, such as a green-screen box, to minimise background interference and improve object segmentation. - Ensure even, diffuse lighting to avoid shadows and reflections, which could distort the scan. - Position the iPhone at an optimal distance of 20–30 cm from the artefact to balance resolution and depth accuracy.
2. Initial scan setup	- Open a LiDAR-supported scanning app (e.g., Polycam, Reality Composer App) on the iPhone. - Select appropriate scanning settings (e.g., high-density point-cloud capture, object mode). - Adjust the frame rate and scanning resolution to match the object's level of detail.
3. Scanning process	- Slowly move the iPhone around the fragment, maintaining a steady speed and consistent distance. - Begin by capturing an overhead scan, then gradually lower the angle to cover the sides. - Ensure the entire visible surface of the artefact is recorded in a single continuous pass to prevent misalignment. - The LiDAR sensor emits infrared laser pulses, measuring the time it takes for light to reflect back, generating a real-time depth map of the fragment.
4. Addressing blind spots	- Since LiDAR scanning captures only what is visible from a single angle, repositioning the object is necessary to ensure full coverage. - For small or flat fragments, place them on a non-reflective rotating stand to capture all sides efficiently. - For larger fragments or curved surfaces, perform two or more scans, flipping the object between scans while ensuring reference points remain consistent.
5. Data processing	- The app processes the raw depth data into a 3D point cloud and generates a mesh model. - If using multiple scans, align and merge point clouds using shared control points or software-based registration tools. - Apply noise reduction filters to clean up irregularities caused by reflections or depth inconsistencies.
6. Post-processing	- Export the 3D model in standard formats (e.g., OBJ, STL, PLY) for further refinement. - Use post-processing software (e.g., MeshLab, Blender, QTSculpture) to refine mesh quality and fill minor gaps. - If colour capture is needed, apply texture mapping using image-based projection techniques.

While the iPhone LiDAR system offers a fast and portable solution, it has limitations in terms of resolution and fine detail capture, making it less suitable for high-precision analyses.

Structured light scanning is often the preferred method for pottery sherds due to its high resolution and ability to capture fine surface details. Structured light scanning is also employed for lithic artefacts, following a similar workflow but yielding different results in terms of resolution, accuracy, and data processing. While LiDAR scanning provides a rapid solution, structured light scanning ensures greater precision, making it more suitable for detailed morphological and metric analyses.

The Polymetric PT-M4 scanner allows for the production of detailed illustrations, including cross-sections and standard metric measurements. Lens selection (ranging from 16 to 75 mm) depends on artefact size, with smaller objects requiring larger lenses for optimal resolution. To counteract limitations with reflective, transparent, or dark surfaces, artefacts are often pre-treated with dulling spray, powder, or paint.

Each artefact is scanned from two to four positions to ensure full coverage, particularly for sharp ridges and edges. A complete scanning session typically lasts 10–20 minutes per artefact, followed by model reconstruction using QTSculpture and analysis with Artifact3-D (Grosman et al., 2022). The workflow, combining automated and manual processing, takes an additional 5–10 minutes per artefact, allowing for the completion of 3–4 high-resolution models per hour.

Beyond illustration, 3D modelling software offers various analytical tools, including the centre of mass calculation, volume and surface area estimation, asymmetry assessment, scar segmentation, ridge pattern tracing, and mean edge-angle measurement. The extracted data can be exported as a spreadsheet and used to investigate archaeological topics such as manufacturing techniques, engineering principles, cultural transmission, and cognitive processes (e.g., Muller A. et al. 2022, 2023; Richardson E. et al. 2014; Valletta F. et al. 2021; Yashuv T., Grosman L. 2024).

The scanning distance varies depending on lens choice, object size, and resolution needs. According to the manufacturer, the minimum required distance for the Polymetric scanner is around 26 cm. The Micro II scanner (by Artec), designed for small objects, operates at approximately 20 cm (±5 cm), with the object fastened to a scanning rotating arm. For larger artefacts, such as the flint hand-axe shown in Figg. 4-5-6, the standard indoor scanning distance is 100–120 cm. Lighting conditions also play a crucial role: light could be dim (for Micro II) but preferably dark (especially for flint), and never bright.

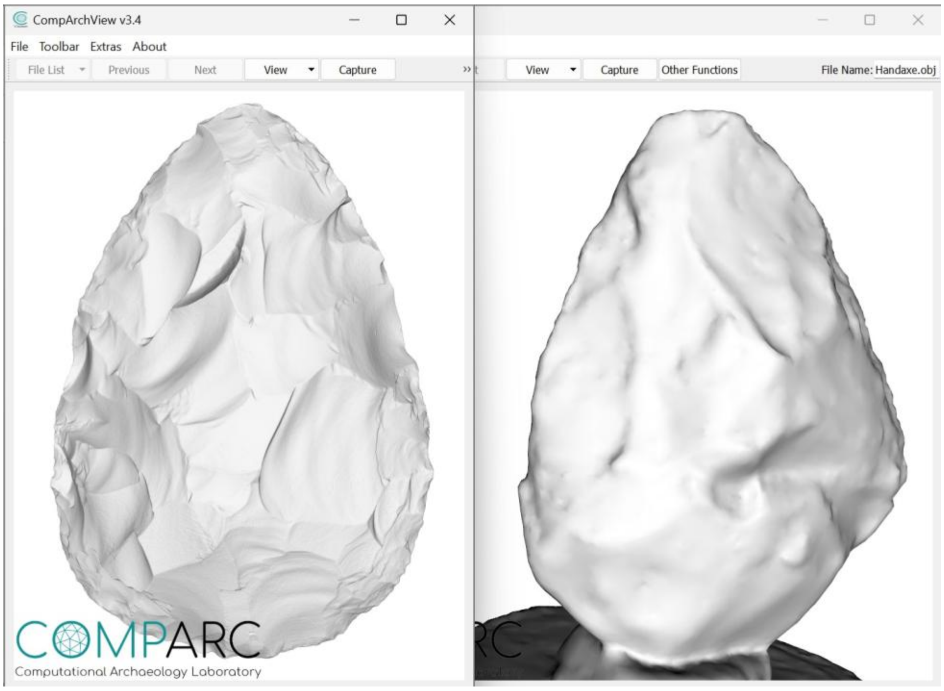


Fig. 4. Full surface comparison of 3D models of handaxes; a very high-resolution scan (structured light Polymetric PT-M4) on the left and a very low-resolution scan (iPhone 15-pro LiDAR system) on the right.

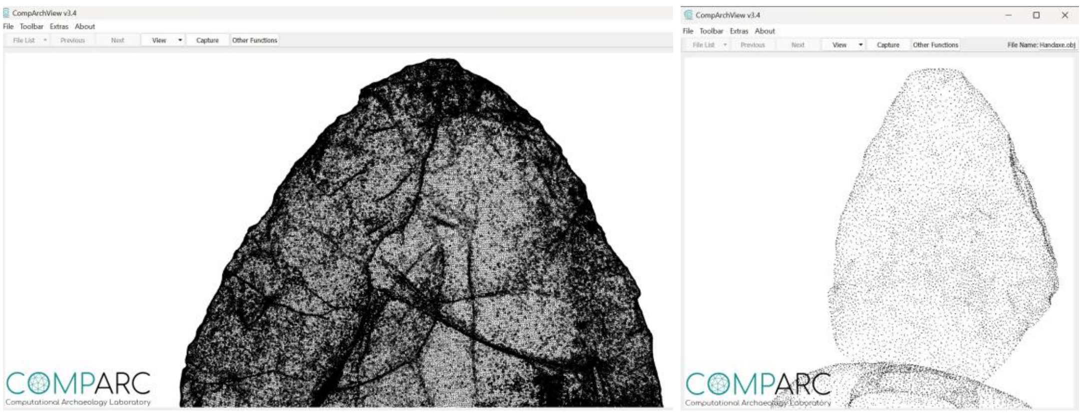


Fig. 5. Point cloud.

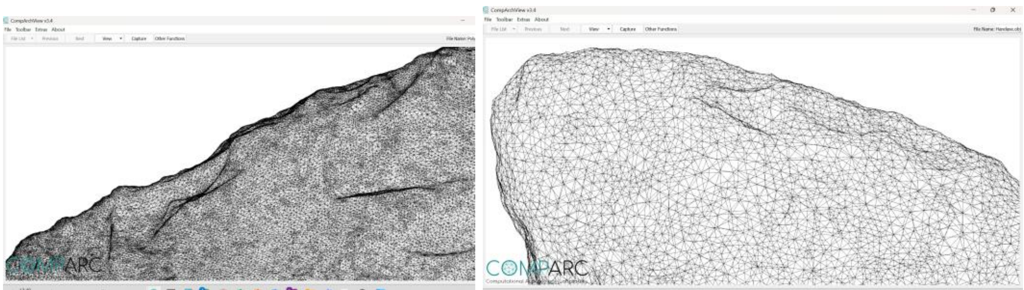


Fig. 6 Mesh.

Photogrammetry is a widely adopted method for 3D digitisation in archaeology due to its accessibility, cost-effectiveness, and capacity to produce detailed textured models. It relies on the acquisition of multiple overlapping photographs taken from different angles and their subsequent processing in specialised software to reconstruct the object's geometry and surface appearance.

Artefacts are placed in a controlled environment with a neutral, non-reflective background to facilitate image segmentation. Lighting is kept uniform and diffuse, typically using ring lights or light tents, to eliminate shadows and highlights that may interfere with the photogrammetric reconstruction. Depending on the setup, the object may be mounted on a rotating turntable or manually repositioned to ensure complete coverage from all angles. The optimal camera-to-object distance typically falls between 20 and 60 cm, depending on the object's size. For best results, a fixed-focus macro lens or a low-distortion C-mount lens with a focal length between 25 mm and 50 mm (depending on the sensor size) is recommended (Galantucci et al., 2018). These lenses provide a balanced field of view and sufficient magnification to capture fine surface details. Since depth of field can be limited at close range, using a smaller aperture (e.g., f/8 or higher) — where adjustable — is important to maintain sharpness across the object's surface. Between 50 and 150 images are typically taken per artefact, depending on its size and complexity. To achieve sufficient overlap (ideally 60–80%), images are captured in a structured pattern.

Once the photographs have been taken, they undergo photo processing using software such as Adobe Lightroom or Darktable. Adjustments are made to white balance, exposure, and sharpness, and lens correction profiles are applied to minimise optical distortion. The processed images are then imported into photogrammetry software, most often Agisoft Metashape, where they are aligned to generate a sparse point cloud. Tie points are verified, and outliers are removed before building a dense point cloud and generating the 3D mesh. A texture map is then applied based on the original photographs. If scale accuracy is required, coded targets or scale bars photographed during acquisition are used to scale the final model.

To reduce processing time in Agisoft Metashape without compromising essential quality, both hardware usage and workflow settings will be optimised. Enabling GPU acceleration, using SSD storage, and working with a reduced but high-quality image set will make a considerable difference. During processing, selecting *Medium* quality for photo alignment and dense cloud generation, limiting key and tie point values, and generating the mesh directly from depth maps with a custom face count help streamline computation. Texture size can also be lowered to 2048 px for faster mapping.

Below is a table comparing the number of photos, the processing parameters and the processing time for different levels of accuracy for photogrammetry on 1-12 cm objects (Tab. 3).

Tab.3 Optimised Metashape Settings: High vs. Low Resolution

Processing Stage	Lower Resolution	Higher Resolution
Image Count	40–60 images (8–12 MP)	60–100 images (12–20 MP)
Alignment	Accuracy: *Low* Key points: 15,000 Tie points: 1,500	Accuracy: *Medium* Key points: 20,000 Tie points: 2,000
Dense Cloud	Quality: *Low* Depth Filtering: *Aggressive*	Quality: *Medium* Depth Filtering: *Mild*
Mesh Generation	Source: *Depth Map* Face count: ~100,000	Source: *Depth Map* Face count: ~300,000–500,000
Texture Mapping	Resolution: *1024 px* Blending: *Mosaic*	Resolution: *2048–4096 px* Blending: *Mosaic*
Estimated Time	**~10–15 min** (on mid-range machine)	**~20–30 min** (on mid-range machine)

In the final post-processing phase, the resulting 3D model is exported in standard formats such as OBJ or PLY and refined using tools like MeshLab or Blender. This may involve mesh optimisation, hole filling, and surface smoothing. Colour correction or re-texturing may also be applied to compensate for any inconsistencies caused by lighting or surface reflectivity.

Photogrammetry is particularly effective for capturing both the geometry and the visual texture of artefacts. Nevertheless, it is sensitive to lighting conditions and needs specific attention on transparent, reflective, or featureless surfaces.

5.1.1 Accuracy and calibration

The accuracy levels of different 3D digitisation methods vary based on the technology used and the conditions under which they are applied (Pamart et al., 2019).

- Laser Scanning: this technique can achieve sub-millimetre precision (~50–200 microns), with accuracy reaching up to ±0.1 mm under optimal conditions. For smaller archaeological artefacts, the recommended minimum scanning distance is around 0.5 - 1 meter, as getting too close may affect the accuracy due to improper reflection of laser pulses from certain surfaces.
- Photogrammetry: the accuracy of photogrammetry can reach up to ±0.5 mm at close distances, although accuracy decreases as the distance increases. The ideal minimum distance for high-quality results is approximately 30 to 50 cm, depending on camera quality and the number of images captured. Key factors affecting accuracy include the precision of image acquisition, proper image overlap (60–80%), and consistent, well-distributed lighting.
- Structured Light Scanning: this method provides high accuracy of up to ±0.1 mm at close distances, making it particularly effective for capturing intricate details of archaeological artefacts. The optimal scanning distance is around 20 - 30 cm, with a maximum effective

range of 3 to 4 meters. Beyond this range, scan quality diminishes. Structured light scanning is especially suitable for objects with well-defined geometries and non-reflective surfaces.

To ensure optimal performance across all techniques, it is crucial to calibrate each sensor (laser, camera, etc.) based on factors such as object size, material properties (e.g., reflectivity and translucency), lighting conditions, and background contrast. Additionally, multi-view alignment techniques are employed to minimise errors and ensure precise registration.

5.1.2 Addressing key technical challenges

Several key technical challenges must be addressed during the system prototyping phase:

1. **Surface Reflectivity**: This can interfere with laser scanning results.
   Solution: Use polarisation filters or apply surface treatments to reduce reflections.

2. **Texture Distortions**: Inconsistent lighting can cause distortions in photogrammetry.
   Solution: Employ uniform illumination techniques to ensure consistent results.

3. **Alignment Errors**: Multi-view scans require precise registration to ensure merging.
   Solution: Implement automated software corrections and use reference markers in the environment (not on the object) for better alignment.

These solutions help achieve high-fidelity digital reconstructions while maintaining the integrity of the artefacts.

Another challenge is **synchronising** the scanning system with the robotic arm's movements to guarantee full coverage without missing any areas. This involves performing multiple scans, including flipping the object to scan both sides and then merging the resulting 3D models. Only once the object is fully scanned can other analysis steps (e.g., HSI, pXRF) be performed.

A significant difficulty arises from **tracking** the object's position during scanning, as some analyses are point-based while others cover surfaces. This requires precise geolocation of the object throughout the process. Moreover, achieving high accuracy during model registration is essential to ensure the final 3D model is both accurate and consistent.

Additionally, sensor **calibration** is critical: each sensor (e.g., laser, camera) must be precisely calibrated for optimal performance, tailored to the specific characteristics of the object being digitised.

5.2 Analytical Devices

The necessary measurement devices for prototyping the materials analysis component include a hyperspectral camera, a portable X-ray fluorescence (pXRF) spectrometer, and an handheld Raman spectrometer, selected specifically to meet the operational and technical needs of the AUTOMATA system, as it is described in D2.1 (*Methodologies, Scenario, and User Requirements*). These devices will be compact and lightweight, some of them weighing only a few hundred grams and measuring just over ten centimetres, with none expected to exceed 3 kg in weight or 30 cm in length and width, ensuring optimal performance, interoperability with the robotic system, and overall efficiency within the AUTOMATA workflow. The implementation of miniaturized sensors is desirable in order to optimize the system's functions and portability. Nevertheless, the system is also expected to be tested and configured with commonly available pXRF and Raman devices, which are often already in use by stakeholders (see Deliverable 2.1). This will allow for flexibility in system management, enabling adaptation to the equipment already available to operators and stakeholders.

A key technical consideration is the possibility of reducing the working distance required by the hyperspectral camera to match it with the spatial constraints of the other devices. Aligning the working distances would enable side-by-side sensor placement, significantly simplifying the mechanical design of the prototype and final system. Hyperspectral cameras generally work at a distance of several tens of centimetres from the object, usually between 50 cm and 100 cm. In contrast, pXRF spectrometers operate just a few millimetres from the object because secondary radiation is quickly absorbed by the air, especially for lighter elements. Handheld Raman spectroscopy, while theoretically more flexible, is also typically performed as close as possible to the object to maximise the collected signal. Accurate control of the working distance between the artefact and each analytical device is essential for obtaining reliable, high-quality measurements. For example, the analytical devices can be equipped with laser-based distance sensors to enable real-time monitoring and automatic adjustment of the artefact-to-sensor positioning throughout the acquisition process (see paragraph 6.3). From a practical standpoint, the morphology of the artefact to be digitised is very important, since the devices' ability to properly analyse the artefacts is influenced by sample characteristics such as shape, size, and surface condition. Uneven surfaces, residues, and post-depositional alterations can distort readings, requiring careful cleaning and preparation. Also, artefacts with convex surfaces present challenges in positioning and maintaining proper contact with the sensor.

To ensure the analyses are of consistently high quality and reproducible over time, it is essential to regularly assess the accuracy and precision of the measurements by analysing a standard material. The creation of a multi-standard calibration is currently being considered. Alternatively separate standards will be provided for each of the sensors (e.g. a Spectralon or Teflon disc for HSI, a mineral with a strong Raman response such as gypsum for Raman spectroscopy, and a homogeneous volcanic glass with a known composition for XRF). Standards should be analysed at regular intervals, with the optimal frequency to be determined through validation protocols (estimated at every 10 or 20 analyses). Systematic acquisition of reference data will allow detection of potential drift in illumination conditions or geometric alignment, and may support correction algorithms during post-processing. Furthermore, calibration will be essential for detecting potential sensor malfunctions, which must be promptly flagged to the operator.

5.3 Case-based examples: object-specific scanning setups

As outlined in the previous section, the selection and integration of analytical devices in the AUTOMATA system requires validation through controlled, object-based testing. To this end, a limited set of artefacts has been used to test the archaeometric sensors and support the definition of key technical aspects of the robotic system. These object-specific trials have been carried out at UBM and UNIPI. The selected test cases include ceramic and lithic artefacts characterised by diverse morphological and material properties. While some tests have already been completed, others are currently in progress and continue to inform the system's development. These case studies serve multiple purposes: they enable the evaluation of sensor performance under realistic operating conditions; they provide insight into handling requirements for complex surfaces and geometries, and they contribute to defining acquisition protocols tailored to different artefact types. In particular, the tests are used to examine critical factors such as lighting conditions, working distance, sensor alignment, and the feasibility of integrating multiple analytical techniques — HSI, pXRF, and portable/handheld Raman spectroscopy — within a single, automated workflow. The outcomes of these studies play a key role in refining the system's design. By working directly with real artefacts and simulating practical constraints, the testing phase bridges the gap between theoretical specifications and field-ready implementation. Together, these test cases provide a controlled basis for assessing the performance of the AUTOMATA system under real-world conditions. By engaging with artefacts that vary in material composition, surface complexity, and morphological constraints, they offer valuable insights into sensor integration, object handling strategies, and data acquisition protocols. The results will support the iterative refinement of both the mechanical and analytical components of the system.

5.3.1 Ceramic fragments or vessels

One of the primary test cases for archaeometric sensor integration focuses on decorated ceramic fragments from Paracas culture, currently under study at Archéosciences Bordeaux laboratory (UBM). These artefacts come from the Ánimas Altas/Ánimas Bajas Archaeological Complex in Peru. This research is part of the broader Ánimas Altas Archaeological Program, supported by the French Ministry for Europe and Foreign Affairs and directed by Aïcha Bachir Bacha and Oscar Daniel Llanos. The ceramics, dating from 600/500 BCE to 100 CE, are particularly notable for their polychrome designs and post-firing resin-based pigments, demonstrating advanced pigment preparation techniques (Fig. 7).

Fig. 7. Two of the ceramic samples from Monticulo 1, under current investigation (2025).

Their complex surfaces and heterogeneous materials offer an excellent opportunity to investigate the potential applications of different sensors in the AUTOMATA system for analysing decorated pottery. A multi-analytical approach has been adopted to characterise both ceramic mineral and organic components. Initial testing has included hyperspectral imaging (VNIR and SWIR) and pXRF acquisitions on untreated samples. Preliminary results suggest the presence of two pigments: a plant-based organic pigment and a mineral-based ochre pigment. Future analyses will include Raman spectroscopy and will be complemented, including techniques such as SEM-EDS, cathodoluminescence (CL), and Fourier-transform infrared spectroscopy (FTIR).

Also, medieval glazed ceramic fragments from the S. Sisto excavations in Pisa (UNIPI) were utilised as a case study for the AUTOMATA workflow. The study primarily investigated the physical challenges posed by object curvature and stability during scanning, contributing to the improvement of sensor specifications, positioning protocols, and acquisition times for ceramic fragments.
The initial analyses were conducted on ten ceramic fragments using an Olympus VANTA C Series Handheld X-ray Fluorescence Analyzer, equipped with a 50kV silver (Ag) anode X-ray tube and an SDD (Silicon Drift Detector). The instrument operated with a two-beam “Geochem” method, which recorded 34 elements. Each beam had a live analysis time of 60 seconds (120 seconds in total), with beam conditions set to 40kV for the first beam and 10kV for the second. Depending on the fragments’ shape and size, two or three spots were analysed for each fragment, and the average composition was calculated to account for the inherent heterogeneity of clay materials. However, the presence of post-depositional surface contaminants, as well as encrustations or patinas (that often form on ceramic surfaces due to their porosity) limited the ability to take additional readings on individual fragments. These alterations, which persist even after cleaning, can complicate or obstruct surface analysis unless they are mechanically removed, such as by scraping. Surface conditions like these can significantly influence the quality of the data (see also Deliverable 2.1).
The analysis protocol also included the examination of two geological standards (Certified Reference Materials, CRMs) before analysing the fragments to evaluate the instrument's precision and accuracy. Using CRM data, linear regressions were performed to calculate the squared

correlation coefficient (R^2) for each measured element, indicating how accurately the results corresponded to the known elemental compositions of the CRMs and assessing the reliability of the instrument's measurements.
Additionally, the Bravo Handheld Raman Spectrometer by Bruker was employed to test the results. This device, lightweight and portable (1.5 kg), is a dual-laser dispersive Raman spectrometer, equipped with 785 nm and 853 nm excitation wavelengths and a spectral range of 300–3200 cm^{-1} with a resolution of 10–12 cm^{-1}. The Sequentially Shifted Excitation™ technique mitigates fluorescence interference, providing clear Raman signals by subtracting broad fluorescence features from the sharp Raman spectra. As with the pXRF analyzer, the convexity of the ceramic surfaces posed challenges for optimal positioning, as the fragments needed to adhere closely to the spectrometer's laser window for accurate results. To ensure a representative dataset, multiple measurement points - typically two or three per fragment - were analysed, covering both the composition of the glazed surface and the exterior (Fig. 8).

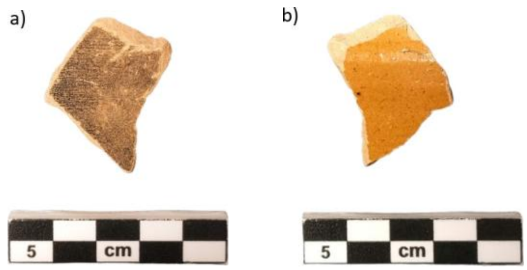


Fig. 8. Glazed ceramic fragment from S. Sisto excavation (Pisa, 2022-2023): a) exterior, with a surface patina; b) interior. An analysis of the area affected by the patina (a) would yield geochemical data influenced by the patina itself. Conversely, analysing the glaze on the opposite side of the fragment (b) would likely result in a hybrid spectrum, incorporating elements from both the glaze and the ceramic body.

From a system design perspective, these case studies provide essential insights into the physical constraints related to object shape and stability during analysis, as well as the presence of surface alterations that could limit or affect the spectra. It is important to note that, in this case, the decision was made to adopt medium-sized portable sensors, with hardware characteristics different from the miniaturised instruments that will be tested at UBM. However, these types of instruments are commonly used by archaeometry laboratories in universities and museums and could be available to AUTOMATA stakeholders. For this reason, it is essential to carry out both types of experimentation and to evaluate different instrumental solutions in order to ensure maximum usability of the system, even with equipment already owned by the users.

5.3.2 Lithic artefacts

A second case study focuses on a set of prestige lithic artefacts from the so-called "Pauilhac Treasure," currently housed at the Musée d'Aquitaine in Bordeaux, on deposit from the National Museum of Archaeology (France) (Fig. 9). Discovered in 1865 in the Gers region, France, during quarrying activities, the collection includes high-quality polished stone axes and large flint blades dated to the late Neolithic period.

Fig. 9. Polished axe (reference 60.687.2) probably in jadeite, found at Pauilhac (Gers, Occitanie region); one of a series of objects from the Late Neolithic; 25.1 x 8 x 1.8 cm, 534 gr, © Mairie de Bordeaux

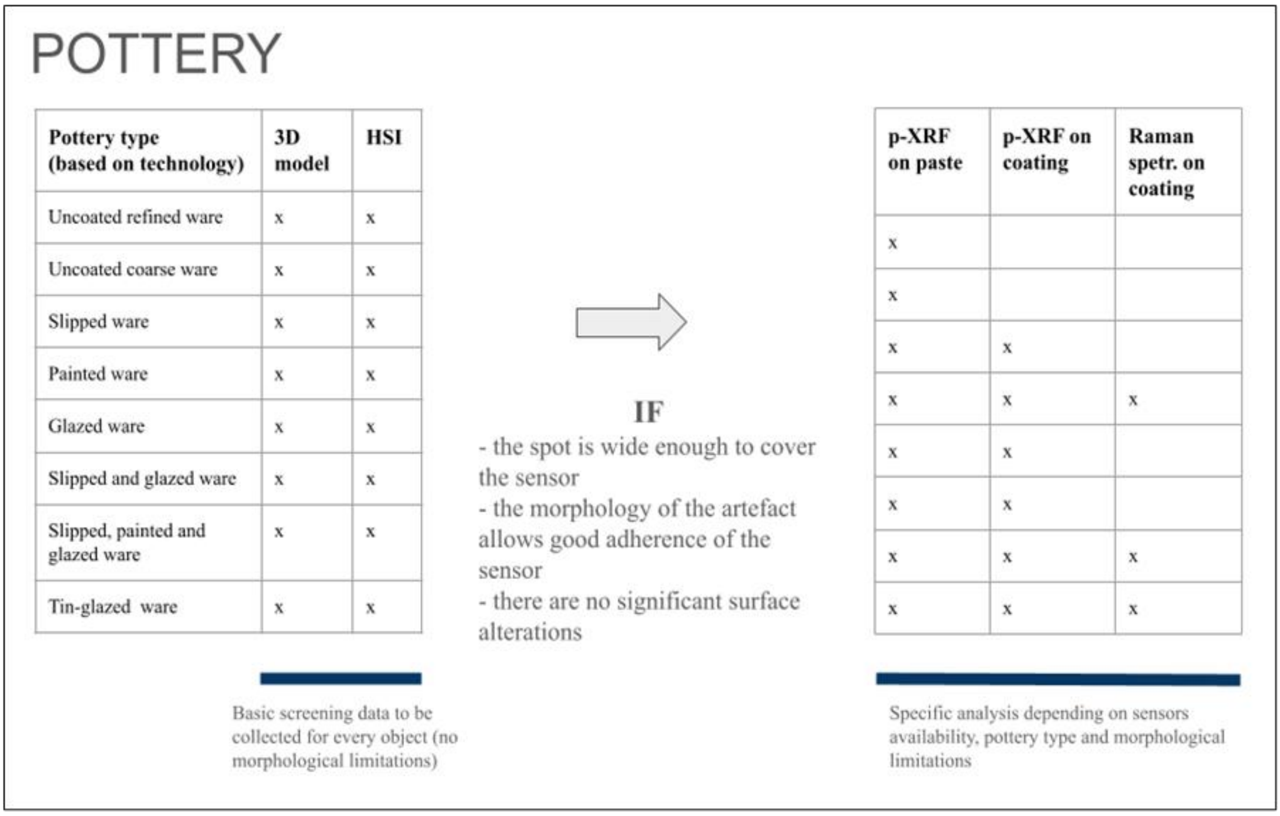
These objects serve as an important reference for evaluating the analytical challenges associated with polished lithic artefacts. Their reflective surfaces provide a meaningful testbed for assessing the performance of HSI, pXRF, and Raman sensors, specifically in relation to signal acquisition, working distance constraints, and surface response variability. On-site analyses are currently being conducted at UBM using pXRF, pRaman, and hyperspectral imaging. The objective is to obtain more detailed information about the materials and surface conditions of these objects to determine whether these artefacts constitute a coherent set and whether there are any direct relationships between them. These analyses will be complemented when necessary, by other non-destructive laboratory methods such as FTIR, ED-XRF, and SEM-EDS.

From a technical perspective, this test case contributes to assessing the limitations and requirements of spectroscopic techniques when applied to polished lithic surfaces. It supports the refinement of sensor positioning strategies, particularly where precise alignment, surface reflectivity, and restricted acquisition angles affect the quality and consistency of the analytical results.

6 General digitisation workflow

The general process of digitisation, as described below, relies on the precise positioning and handling of the object throughout the entire workflow, from initial data acquisition to final processing. In the context of AUTOMATA, this workflow is designed to be fully automated, ensuring repeatability, efficiency, and minimal user intervention. To achieve the highest quality enriched models, each sensor, regardless of the specific digitisation technology employed, should be associated with a system for recording the relative coordinates on the object. This additional component plays a crucial role in identifying and localising all relevant measurement zones on the artefact, enabling accurate data capture and optimised model reconstruction.

A preliminary summary of the required analyses for each artefact type is presented in Figure 10. It outlines the baseline digitisation requirements for ceramics, regardless of geographic or chronological context, and lithics. For all ceramic fragments, the acquisition of 3D models and hyperspectral images is mandatory, forming the core dataset for further analysis. Additional sensors will be deployed selectively, depending on the morphology of the piece and the specific analytical needs dictated by the ceramic's characteristics. In the case of lithic artefacts, the classification relies exclusively on morphology.



Pottery type (based on technology)	3D model	HSI	p-XRF on paste	p-XRF on coating	Raman spetr. on coating
Uncoated refined ware	x	x	x		
Uncoated coarse ware	x	x	x		
Slipped ware	x	x	x	x	
Painted ware	x	x	x	x	x
Glazed ware	x	x	x	x	
Slipped and glazed ware	x	x	x	x	
Slipped, painted and glazed ware	x	x	x	x	x
Tin-glazed ware	x	x	x	x	x

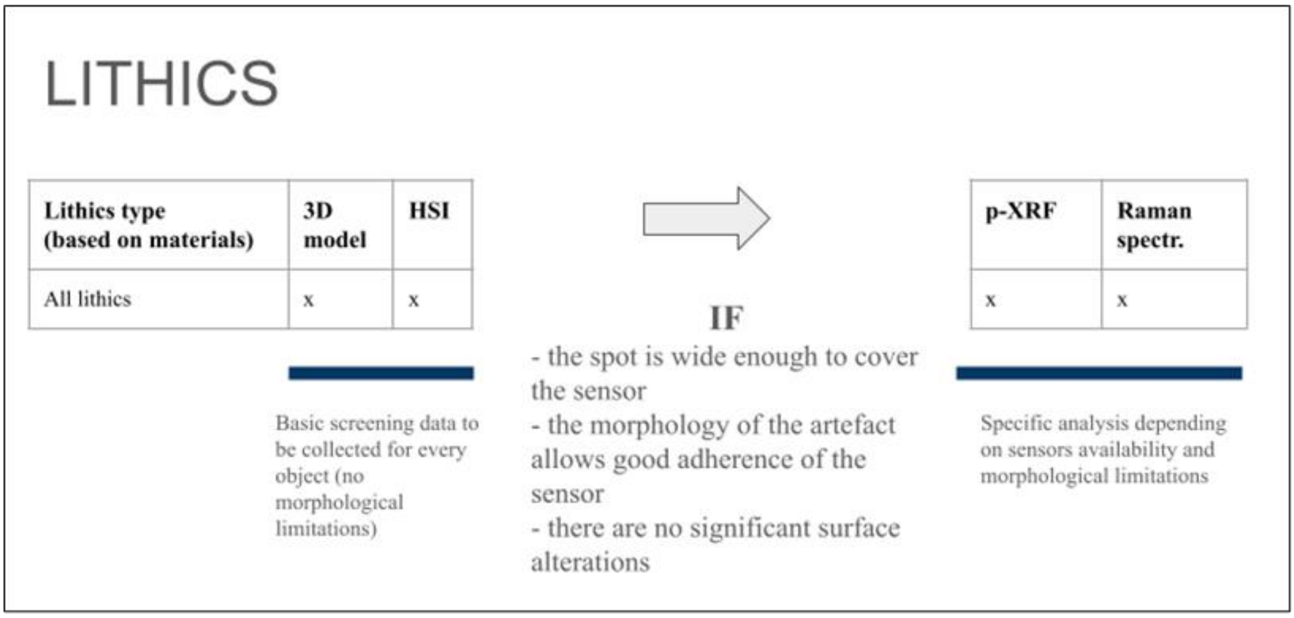


Fig.10. Summary of the required analyses for each ceramic type, based on general criteria applicable to all geographic and chronological contexts, and lithics. 3D models and hyperspectral images must be acquired for each piece, forming the core of the baseline data. Other sensors will only be applied if the morphology of the piece allows it and if the ceramic's characteristics require it. For lithics, the classification is based solely on morphology.

6.1 Object positioning and user interface

The user interacts directly with the working space and sets the digitisation process through the Graphical User Interface (GUI) of the AUTOMATA system. Designed to provide an intuitive and user-friendly experience, the GUI caters to a diverse range of users, including archaeologists, museum professionals, and researchers. Recognising the varying expertise levels of its users, the interface prioritises ease of use with a clean, accessible layout and minimal technical complexity. It will also offer customizability, allowing users to adjust settings based on different scanning tasks and artefact types. The GUI will enable adjustments to various parameters, including lighting, resolution, and scanning speed, while monitoring system diagnostics, such as error detection and calibration status.

For efficiency, the system could be set to apply a uniform accuracy level to a batch of objects rather than each individual one. The system is intended to operate automatically with minimal user intervention, enabling users to prepare a series of objects for scanning without the need to adjust each one individually.

The user interface will also allow for the entry and association of descriptive metadata, including provenance (e.g., excavation site and stratigraphic unit), material class, inventory number, and other relevant attributes. This ensures that contextual information is linked to each artefact throughout the digitisation and analysis workflow.

6.2 3D model creation

Two main approaches to generating 3D models of artefacts, using automated scanning sequences, are being explored in the context of the AUTOMATA system, both aimed at ensuring complete surface coverage and high-quality digitisation. These approaches could be applied across the three primary 3D acquisition methods under evaluation, iPhone LiDAR, structured light scanning, and photogrammetry, each of which presents specific requirements and constraints.

The first approach involves rotational scanning with object repositioning. In this configuration, the artefact is initially placed in a gripping device, and the scanning system, either mobile or mounted on a robotic arm, performs an initial pass, capturing one side of the artefact. Due to occlusions or blind spots, particularly on the underside or internal surfaces, the artefact must then be repositioned to expose the remaining areas. This approach is compatible with all three scanning methods: LiDAR benefits from the portability and flexibility of repositioning, structured light scanners can conduct multiple scans at different orientations for high-resolution reconstruction, and photogrammetry relies on systematic image acquisition from various angles. After each scan or photo set, partial 3D models are generated. The merging of these datasets is achieved through alignment algorithms based on control points or feature matching. Automation of this workflow could involve robotic repositioning of the artefact and AI-assisted registration of the scans or images, reducing manual input and ensuring consistency.

The second approach uses stationary scanning with a transparent surface. In this setup, the artefact is placed by the robotic arm on a transparent tray, such as plexiglass or polycarbonate, allowing the scanning device, typically mounted on a robotic arm, to capture the object from all sides, including the underside, without repositioning. This method significantly reduces the need for physical manipulation of the artefact, making it particularly advantageous for fragile or small objects. IIT has conducted multiple tests using this configuration which have produced high-quality scans free from noise typically associated with tray transparency. For this reason, within the AUTOMATA framework, we consider this approach technically viable. The robotic cell setup is expected to work effectively with transparent supports, thereby eliminating the need for object manipulation during the scanning process. While structured light and LiDAR scanning can be adapted to this configuration, provided the transparency of the support does not interfere with depth sensing, photogrammetry may still require specific calibration and adjustments to capture images from below the transparent tray. By ensuring minimal robotic handling, this method enhances the repeatability of scans, reduces alignment errors, and supports streamlined automation (Ahmad et al., 2025).

Based on preliminary testing and integration considerations, the second approach appears particularly well-suited to the design and automation goals of the AUTOMATA system. Its compatibility with the robotic cell layout reduced the need for mechanical intervention, and its proven ability to produce high-quality scans makes it a strong candidate for standard implementation. Nevertheless, the first approach remains valid in scenarios where object geometry, surface properties, or specific analytical requirements make repositioning more effective or necessary. Both configurations will continue to be evaluated during the prototyping phase to ensure maximum flexibility and performance across a range of artefact types.

3D digitisation is performed as the first step in data acquisition, regardless of the chosen method, whether photogrammetry, LiDAR scanning, or another approach. To maintain efficiency, the cleaning and optimisation of the 3D model must be fully automated. Existing software solutions already handle this process effectively for LiDAR scans, streamlining the workflow.

6.3 Data acquisition and alignment

Following the 3D reconstruction, hyperspectral imaging (HSI) is planned as a default step in the standard pipeline. Mounting a hyperspectral camera alongside the 3D sensor on the same robotic arm will enhance the process by combining both contactless analyses into a single solution. This integration allows for highly accurate geometric data while offering valuable insights into the artefact’s material properties and condition, providing a comprehensive, non-invasive approach to documentation and preservation. By mounting multiple sensors on the same robotic arm, the system reduces the risk of misalignment between data sets related to the same object, ensuring greater consistency and accuracy in the final 3D model. The HSI data is then processed and classified based on a spectral library, allowing for the identification of different material spectral signatures. These spectral features will guide further analyses, ensuring that pXRF and handheld Raman spectroscopy, if applicable, are conducted on the most relevant areas.

However, the robotic arm cannot operate effectively using 3D coordinates in real-time. Processing movements based on a full 3D model would be too computationally demanding and inefficient. Instead, the robotic arm will use a relative coordinate system during all the processing, in order for the spatial relationship to the 3D model to be established in a later stage. The immediate post-processing phase registers sensor coordinates, integrating them into the 3D model. At this point, RIS3D technology comes into play, ensuring accurate alignment between analytical data and the 3D representation.

To further optimise the workflow, a dedicated software tool, yet to be developed, will automatically define the spatial boundaries of the spectral signatures identified by HSI. This software will guide the robotic arm in positioning the artefact for handheld Raman spectroscopy and pXRF analyses, ensuring precise alignment while maintaining the speed and automation required for the system’s efficiency.

To ensure the reproducibility and traceability of all analytical operations, the coordinates of each analysis will be recorded and stored. A laser pointer is being considered as an additional tool to define and confirm the position of each measurement point on the artefact’s surface. These coordinates, captured within the relative 2D system used during active analysis, will later be linked to the final 3D model during the post-processing phase. This integration will be managed through RIS3D, which will associate each analytical dataset, whether obtained through HSI, handheld Raman spectrometer, or pXRF, with its precise location on the model. In doing so, the system will guarantee that all analyses are spatially contextualised, forming a coherent and navigable dataset anchored to the digital representation of the object.

6.4 AI-based support

The main contribution of AI and Machine Learning (ML) in digitisation concerns real-time processing, particularly for calibration, ensuring proper data acquisition, and identifying specific areas of interest on artefacts for sensor analysis (e.g., pigmented regions and rotation angles). Additionally, AI and ML enhance the digitisation process by increasing efficiency, accuracy, and automation. A key challenge in implementing these operations is minimising the overall digitisation time. Specific areas of concern are described in the following.

- **Instrument calibration.** Based on the analysis of an initial scan, typically using a reference fragment, the AI system identifies the necessary adjustments to the sensor's calibration parameters. This involves modifying offset values, adjusting gain factors, and applying correction curves. These adjustments are carried out automatically and in real-time, removing the need for human intervention. Calibration accuracy will also be verified through data analysis, primarily by measuring and assessing signal noise.
- **Identification of optimal viewpoints for artefact inspection.** AI algorithms are designed to determine the most relevant viewpoints for artefact examination, mainly relying on a preliminary real-time analysis of sensor data (e.g., HSI) and computer vision techniques. This enables the system to detect key features such as pigment distributions, geometric contours, and potential defects, recommending optimal locations and angles for data acquisition. The robotic arm's relative coordinate system and supports will be used to store and retrieve positions on the physical artefact (Ahmad et al., 2024).
- **Identification of meaningful data.** ML models enhance data processing by filtering and prioritising relevant information, distinguishing meaningful features from noise. In real-time, these analyses will verify the correctness of data acquisition, identifying potential issues such as acquisition errors, incorrect calibration, or sensor failures. Using anomaly detection, clustering, and feature extraction techniques, the AI system will retain only relevant information while discarding redundant or irrelevant data. This improves processing efficiency, reduces storage requirements, and ensures that subsequent analytical steps rely on high-quality, interpretable data.

6.4.1 AI-based data enhancement of 3D model quality

By applying ML algorithms, the system can **refine scanning outputs** through automated adjustments.

Integrated AI may assist in both the 3D model construction process and in improving the resulting 3D model quality. The process of creating a 3D model involves multiple stages including data acquisition, point-cloud cleaning or object segmentation, alignment, registration and fusion, various mesh optimisation procedures and more, depending on the technology and software used. Although many of these stages are automated, based on various algorithms in different software, most still require manual intervention, and the process progression is dependent on human initiative.

Beyond the data acquisition stage, which the AUTOMATA project intends to automate through the implementation of a robotic arm, we would like to explore various avenues of incorporating AI in additional stages of the 3D model construction process. For example, AI would automatically perform segmentation – identify the object, differentiate it from the background, and remove unnecessary data. In a similar process, it may be incorporated into point-cloud cleaning by identifying and removing outliers. In addition, AI could enhance the performance of alignment algorithms – as 3D models are often made up of at least two sets of scans (when a part of the object is hidden, necessitating at least one change of posture, and at least two rounds of scans, to achieve a full view of the entire exterior of the object), AI will augment the identification of recurring or shared parts of the object in all scans, and improve the alignment procedure. AI could also be employed for mesh quality assurance and optimisation, such as mending holes in the mesh or reducing point density in areas where the object has low geometry. Although AI-based data enhancement for 3D modelling does not strictly need to be performed in real-time, AUTOMATA aims to integrate key steps into the live acquisition pipeline where feasible. This will help reduce the post-processing workload and contribute to a more efficient and lightweight digitisation process.

6.5 Digitisation time

As outlined in D2.1 (paragraph 3.2), data acquisition time depends on three factors: the type of analysis, the sensors used, and the artefacts. The type of analysis influences the acquisition method and, consequently, its duration. While 3D scanning involves a sequential acquisition process that covers the entire surface of the artefact, pXRF analysis, HSI imaging, and handheld Raman spectroscopy perform image-based or point-based acquisitions, focusing on specific areas of the object. This implies that the total acquisition time depends on the number of spots to be analysed. The type of sensor selected for each analysis also has a significant impact on data acquisition. The technologies employed determine the minimum and maximum distance between the sensor and the object, the precision of the data, the resolution, and the duration of both acquisition and post-processing (see also section 5). Finally, the influence of the artefacts themselves on acquisition times depends mainly on two key factors. The material of the artefact and the presence of any decoration determine which types of analyses are feasible. For instance, Raman spectroscopy is best applied to non-glazed surfaces or objects coated with inorganic substances. Similarly, the complexity of the object's geometry and texture also affects acquisition time: the more complex the object, the longer the acquisition process. Thus, considering the system cycle described in paragraph 3.2, the digitisation time will be determined by the longest acquisition phase, allowing, at the same time, the parallel digitisation of different artefacts.

Depending on the object's complexity, required resolution, and applied analytical methods, processing times can range from a few minutes to over 15 minutes. A baseline workflow, including

3D modelling and hyperspectral imaging, averages around 4 minutes. This figure represents an optimal target under standardised conditions, typically involving regular surfaces and low-complexity acquisitions. As illustrated in the case-based scenario in Section 6.5.1, actual times may vary significantly depending on artefact morphology, resolution requirements, and sensor behaviour.

To ensure the quality and reliability of the analyses, regular calibration of the sensors used within the system is also critical, as mentioned in paragraph 5.2. Calibration helps to detect any variations in sensor performance, minimising errors that could affect data acquisition and processing. It could be considered that this calibration might be carried out during idle periods when the sensors are not actively being used for artefact analysis.

The AUTOMATA system is, therefore, designed to aim for an average processing time of around 5 minutes per artefact, balancing efficiency and data quality while retaining the flexibility to accommodate longer analytical procedures when necessary. Alternatively, a multi-sensor workflow integrates additional analytical techniques, such as portable X-ray fluorescence (pXRF) and handheld Raman spectroscopy, alongside 3D modelling and HSI, extending the process to a maximum of 12 minutes.

These estimations need to include a margin to account for the grasping and movement operations performed by the robotic arm, together with the time required for data transmission, reception and potential on-the-fly processing. To maintain operational efficiency, AUTOMATA targets an average of five minutes per artefact, achievable through optimised workflows, lower-resolution scans, and selective use of analytical techniques. The system remains adaptable, enabling rapid digitisation for general surveys while supporting extended, high-resolution analyses when necessary. This adaptability ensures that the system can meet both the conservation needs of the artefacts and the diagnostic and research purposes.

6.5.1 Case-based-example

Consider a baseline workflow, which involves the 3D modelling of an artefact enriched with hyperspectral imaging (HSI) data, as outlined in D2.1. The entire process takes approximately 4 minutes per artefact, with 180-600 seconds dedicated to 3D modelling and 30-180 seconds to HSI. However, the time between individual scans can vary significantly, depending on the real-time data processing performed by AI and the performance of the robotic arm.

At each scan, the system performs several critical checks and decisions.

- It verifies whether the HSI and 3D model scans are correctly calibrated (instrument calibration).
- It has to check whether the HSI and 3D model scans have focus issues (identify meaningful data).

- The system determines how to position the artefact relative to the sensor to acquire meaningful data. If the acquisition is compromised (e.g., excessive noise), it must decide whether to repeat the scan. If not repeated, the object may only be identifiable later if it has an assigned ID.
- The system autonomously determines when to start and stop the data acquisition process.

While each individual task is manageable, the primary challenge remains to keep the **total digitisation time below 5 minutes per artefact**, especially considering that this represents the simplest digitisation scenario. To meet this requirement, parallel digitisation may be implemented. In any case, the overall time computation, accounting for all the aforementioned elements, along with internal and external I/O communication, plays a crucial role in understanding the AUTOMATA system's performance.

These time ranges reflect realistic variations due to differences in object complexity, surface geometry, and acquisition resolution. While specific scans may require up to 10–12 minutes, particularly for high-resolution 3D modelling or detailed HSI analysis, these values are not representative of the standard operating time. Instead, they serve to define the upper bounds of the system's flexibility and performance envelope.

6.6 Data processing and integration

Efficient real-time processing is crucial for managing high-resolution 3D scans and large, complex datasets typical of archaeological materials. As described in Section 3.2, the system operates a cycle involving three rotating supports, allowing one artefact to be scanned while another is moved into place and the third is removed. This parallel management enables continuous processing and defines the effective throughput of the system, which is governed by the longest acquisition phase. As highlighted in Sections 6.5 and 6.5.1, the system must be capable of accommodating both standard and extended acquisition times, which has implications for processing load and data throughput during peak usage. To meet these demands, the AUTOMATA system will incorporate onboard computing capabilities designed to support all stages of the digitisation workflow. This includes the reconstruction of 3D artefact models, the application of AI-driven enhancements, such as noise reduction and image sharpening, and the fusion of data from multiple sensors, including photogrammetry, laser scanning, and hyperspectral imaging.

The hardware configuration required to support these operations will feature a high-core-count processor, such as an Intel Xeon or AMD Ryzen Threadripper, capable of parallel processing large volumes of data. A high-end graphics processing unit (GPU), such as an NVIDIA RTX or AMD Radeon, will be used to accelerate image rendering and model generation. The system will be equipped with a minimum of 128 GB of RAM to ensure stable performance when handling large-scale datasets. For storage, fast NVMe solid-state drives (SSDs) will enable rapid data caching and retrieval, minimising latency during processing. This robust hardware infrastructure will ensure that the digitisation process remains fluid and responsive, even under demanding operational conditions.

6.6.1 Integration into the Referenced Information System (RIS3D)

Each digitisation event will produce a comprehensive dataset consisting of a 3D representation of the artefact and a series of analytical measurements. These analyses may be either point-based, such as portable X-Ray Fluorescence (pXRF) and handheld Raman spectroscopy, or surface-based, such as hyperspectral imaging (HSI). To ensure spatial consistency across all data types, a unified reference system must be applied. This means that all 3D models and analytical measurements must share the same origin point and scale. Establishing a common coordinate system is essential to accurately associate each analysis with its corresponding location on the digital model.

The spatial positioning of each analysis will be computed based on the sensor's origin, orientation, and technical parameters at the time of acquisition. To ensure interoperability, all 3D models will be exported in standardised, widely supported formats that maintain compatibility across software platforms. Analytical data, including the coordinates of each measurement, can be recorded in structured files such as CSV or JSON. These files may either be integrated into the system during post-processing or transmitted in real-time via a local web API on the acquisition computer.

The handling of analytical files will depend on the specific instrument used, with formats ranging from CSV and plain text to ENVI for hyperspectral data. Regardless of format, the data will either be preserved in its original form or directly ingested into the RIS3D database, ensuring long-term accessibility and integration within the broader digitisation pipeline (Dutailly et al., 2023).

The RIS3D consists of a PostgreSQL database, a Node.js web server, and a Unity build as a 3D viewer. To automate the production of RIS3D instances per object, a default RIS3D will be set up once with a minimal database structure and predefined accounts. This RIS3D will then be duplicated and populated by the acquisition device.

This can be done during the acquisition process if a master computer manages all acquisition steps and knows which software generates which data. Alternatively, it can be done at the end, if all acquisition devices store their data in a common location, such as a shared folder.

3D digitisations must be copied into the backdrop geometries folder of the web server in the GLB format (glTF binary file format). These files will be loaded on demand by the user in the 3D viewer. To ensure smooth visualisation, it is recommended to limit meshes to 50 million polygons (this may vary depending on the client's computer hardware), which may require a decimation process. In contrast, point clouds converted into the Potree format have no such limitation.

For data analysis, the web server and database must be running, and data will be inserted via an API provided by the web server. Files such as ENVI will be uploaded to the web server, and all analysis parameters (author, date, location, device, etc.) will be sent as JSON using the HTTP POST protocol.

Once everything is set up in the RIS3D, the database and web server are stopped, and the RIS3D is ready to be shared.

6.6.2 Software coordination and integration

In parallel with hardware implementation, the development of a coherent and modular software architecture is planned to ensure the coordination between all components of the AUTOMATA system. The aim is to support a distributed set of software modules, each managing a specific functionality while ensuring that they operate as part of a unified and synchronised digitisation pipeline. These modules will include: a robotic control module for managing arm movement and object positioning; sensor-specific acquisition modules for hyperspectral imaging, pXRF, and handheld Raman spectroscopy; and an AI-based monitoring module for validating acquisition quality, detecting anomalies, and triggering repeat scans when needed. Additional planned components include a synchronisation manager to align timing across operations and a session scheduler for managing sequencing and task prioritisation.

Several of these software components, such as the metadata aggregator and the data packaging module, will be designed to interface directly with the RIS3D platform. They will ensure that data collected from different sensors is spatially aligned, properly structured, and enriched with contextual metadata before being archived or made available for visualisation and analysis. The overall software framework is intended to support real-time coordination where required while also allowing deferred processing for high-volume or resource-intensive tasks. Its modular design will facilitate debugging and validation during the prototyping phase and will allow for iterative refinement based on system performance and user feedback.

6.7 Object labelling

To identify and track each individual fragment, a protocol with dedicated coding and an organised positioning at the end of the process is needed. The coding must be speaking and has to follow a predetermined structure, which indicates metadata such as family, subfamily and progressive number of the find. This will allow practical tracking and accessibility of the find in the database that will be created, as well as in the destination warehouse. Silkscreens cannot be applied to the surface of the finds; therefore, at the end of the digitisation process, the artefacts must be repositioned in containers provided with compartments identified uniquely and associated with the respective code.

6.8 Cloud integration: storage, access and sharing

The AUTOMATA system integrates a multi-layered data management infrastructure designed to ensure secure storage, efficient access, and long-term sharing of high-volume digitisation outputs. Given the complexity and heterogeneity of the data, ranging from 3D geometries to analytical measurements, cloud integration plays a crucial role in supporting the system's automation, scalability, and FAIR data principles. During the development and acquisition phases, project partners are responsible for the safe handling and backup of data. Local backups on physical hard disks are regularly performed to mitigate the risk of data loss. All data generated during the digitisation workflow are temporarily stored and indexed through the RIS3D platform, which integrates 3D geometry, spatial metadata, and analytical results within a unified interface.

Technically, 3D data are stored in formats such as OBJ, PLY, STL, and GLB, with point clouds and mesh models generated by structured light scanners, photogrammetry, or LiDAR systems. Spectral and analytical data are stored in standard formats: CSV, HDR, TIFF for hyperspectral imaging, TXT and DPT for Raman spectroscopy, and CSV, XLS, and TXT for pXRF outputs. Each dataset is associated with structured metadata and stored in PostgreSQL and JSON formats within the RIS3D environment. JSON structures allow for flexibility in describing artefact attributes, spatial coordinates, measurement conditions, and acquisition parameters. A key aspect of RIS3D is the use of a relative coordinate system during acquisition, which is later aligned with the full 3D model. This allows for accurate georeferencing of all analytical points (e.g. pXRF and handheld Raman spots, HSI areas) within the digital model. Spatial consistency is maintained through the use of transformation matrices and, when necessary, fiducial markers or calibration routines.

Once data reach a final validated state, they are archived with the Archaeology Data Service (ADS), which ensures long-term preservation and accessibility. ADS assigns persistent identifiers (DOIs), uses qualified Dublin Core metadata, and ensures compliance with the CoreTrustSeal certification. Data deposited with ADS are retrievable via HTTPS, and large datasets can be made available through services like the University of York DropOff platform. Archived resources are indexed in ArchSearch, the ARIADNE Portal, and Europeana, enhancing discoverability. The ADS supports all file formats used by AUTOMATA and provides detailed guidelines on technical metadata and file structure. Licensing for archived datasets typically follows Creative Commons Attribution (CC BY 4.0), supporting reuse while ensuring appropriate credit. The integration of cloud-based storage with certified digital archiving and a unified relational data infrastructure ensures that AUTOMATA outputs are interoperable, secure, and accessible to a wide range of stakeholders, including archaeologists, heritage professionals, and researchers, now and in the future.

7 Conclusions

The AUTOMATA system is being developed as a modular, scalable and technically advanced platform for the digitisation of archaeological artefacts, integrating robotics, artificial intelligence, multi-sensor data acquisition, and cloud-based data management into a cohesive workflow. This deliverable outlines the architectural framework and technical roadmap that will guide the implementation and testing of the system in the upcoming phases. It provides the conceptual and functional specifications for the robotic workcell, the adaptive gripping solutions, and the acquisition infrastructure, with particular attention to the safe handling of delicate materials and the efficient coordination of the digitisation workflow.

Particular attention is given to the synchronisation of motion control, data acquisition, and sensor calibration, ensuring that high-resolution 3D models and analytical data (from HSI, pXRF, and handheld Raman spectroscopy) are generated efficiently, accurately, and in a traceable manner. The system is designed to operate in parallel, with three rotating supports enabling continuous throughput. This architectural choice will be tested and validated in the prototyping phase. The platform's flexibility relies on a compact, portable and environmentally resilient design, supporting deployment in laboratory, warehouses and museum settings. It is intended to support a range of digitisation scenarios (from rapid baseline scans to more detailed, multi-modal acquisition workflow), adapting to different artefact types and needs.

On the software side, AUTOMATA is expected to integrate a coordinated suite of modules for sensor control, data acquisition, AI-assisted processing, and real-time quality monitoring. These components will be developed to manage hardware synchronisation, trigger acquisition routines, and streamline post-processing operations through automated pipelines. The RIS3D platform will serve as the digital backbone for integrating geometric and analytical data, maintaining spatial coherence and enabling interactive exploration of enriched models.

The integration of AI-driven tools is planned to support calibration, acquisition guidance, digitisation time reduction and post-processing optimisation while preserving data quality. Particular focus will be placed on real-time responsiveness and on the ability to adapt system parameters dynamically based on artefact characteristics. Case-based testing, carried out on selected ceramic and lithic assemblages, serves as a foundation for testing the integration of analytical tools and validating the complete automation of the digitisation workflow. These practical studies are instrumental for refining the design parameters and ensuring that the prototype aligns with both the research requirements and operational conditions defined by the consortium and will be further expanded and formalised during the next phase to support a systematic evaluation of the system's performance under real-world conditions. This deliverable lays the groundwork for the upcoming prototyping phases and supports the iterative optimisation of AUTOMATA's core system components.

Looking to the future, the evolution of the AUTOMATA system could integrate with emerging technologies, including augmented reality and data provenance and traceability frameworks (e.g. blockchain technologies), to further enrich the experience of preserving and sharing cultural heritage. This potential integration promises to transform the way we interact with artefacts, making their history and significance even more accessible to a global audience.

References

Ahmad, J., Dassie, F., Frascella, S., Cannella, F., Marchello, G., & Traviglia, A. (2025). DARS: A dual-arm robotic system for autonomous 3D artefact scanning. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. (Manuscript submitted for publication).

Ahmad, J., Frascella, S., Dassie, F., Lahoud, M. G., Marchello, G., Cannella, F., & Traviglia, A. (2024). AAPOE: Automated artifacts position and orientation estimation in cultural heritage. *Proceedings of the 20th International Conference on Mechatronic, Embedded Systems and Applications (MESA 2024)*. https://doi.org/10.1109/MESA61532.2024.10704902

Dutailly, B., Portais, J. C., & Granier, X. (2023). RIS3D: A referenced information system in 3D. *ACM Journal on Computing and Cultural Heritage, 15*(4), 1–20.

Frahm, E. (2024). Protocols, pitfalls, and publishing for pXRF analyses: From “know how” to “best practices.” *Journal of Archaeological Science: Reports, 60*, 104831. https://doi.org/10.1016/j.jasrep.2024.104831

Galantucci, L. M., Guerra, M. G., & Lavecchia, F. (2018). Photogrammetry applied to small and micro-scaled objects: A review. In J. Ni, V. Majstorovic, & D. Djurdjanovic (Eds.), *Proceedings of the 3rd International Conference on the Industry 4.0 Model for Advanced Manufacturing (AMP 2018)*. Springer, Cham. https://doi.org/10.1007/978-3-319-89563-5_4

Grosman, L., Muller, A., Dag, I., Goldgeier, H., Harush, O., Herzlinger, G., Nebenhaus, K., Valletta, F., Yashuv, T., & Dick, N. (2022). Artifact3-D: New software for accurate, objective and efficient 3D analysis and documentation of archaeological artifacts. *PLoS ONE, 17*(6), e0268401. https://doi.org/10.1371/journal.pone.0268401

Muller, A., Barsky, D., Sala-Ramos, R., Sharon, G., Titton, S., Vergès, J. M., & Grosman, L. (2023). The limestone spheroids of ‘Ubeidiya: Intentional imposition of symmetric geometry by early hominins? *Royal Society Open Science, 10*(2), 230671. https://doi.org/10.1098/rsos.230671

Pamart, A., Abergel, V., Flammin, A., Morineau, C., Paitier, H., et al. (2019). *Apport critique sur les matériels et logiciels 3D. Les recommandations du Consortium 3D SHS*. HAL. https://hal.archives-ouvertes.fr/hal-02159453

Richardson, E., Grosman, L., Smilansky, U., & Werman, M. (2014). Extracting scar and ridge features from 3D-scanned lithic artifacts. In G. Earl, T. Sly, D. Wheatley, et al. (Eds.), *Archaeology in the digital era: Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton, 26–29 March 2012* (pp. 83–92). Amsterdam University Press.

Valletta, F., Dag, I., & Grosman, L. (2021). Identifying local learning communities during the Terminal Palaeolithic in the Southern Levant: Multi-scale 3-D analysis of flint cores. *Journal of Computer Applications in Archaeology, 4*(1), 145–168. https://doi.org/10.5334/jcaa.74

Yashuv, T., & Grosman, L. (2024). 12,000-year-old spindle whorls and the innovation of wheeled rotational technologies. *PLOS ONE, 19*(11), e0312007. https://doi.org/10.1371/journal.pone.0312007