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D 3.1 Soft grippers for archaeology

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Disclaimer

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Abbreviations

WP: Work package

M: Month

UNIPI: Università 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

Executive summary

Deliverable D3.1 is a demonstration deliverable that contains images and videos showcasing the configurations and features of the soft end-effectors developed within AUTOMATA. The document builds upon the discussion introduced in D2.1 (Methodologies, Scenario, and User Requirements) and the system specifications presented in D2.3 (System Specification). It provides a detailed description of the soft end-effector prototypes, focusing on their components and motion control mechanisms, which are designed to handle archaeological objects and position them at various stations for examination by different sensors.

The Deliverable has been developed through the joint effort of the Istituto Italiano di Tecnologia (in particular, the *Soft Robotics for Human Cooperation and Rehabilitation* team and the *Center for Cultural Heritage Technology*) and QBRobotics.

The AUTOMATA robotic cell will employ a single collaborative UR5 robot equipped with a soft end-effector. To identify the most effective design, two types of end-effectors were tested: the SoftHand and the SoftClaw, each explored in multiple versions and customisations, based on the concept of the Pisa/IIT SoftHand and the VSA-Cube, respectively. The next project phase will include further customisations tailored to AUTOMATA's specific requirements and, based on predefined evaluation metrics, the selection of the optimal configuration.

The document is structured as follows:

- *Section 2* describes all the end-effectors under examination, including their hardware, operation, and reconfigurability according to specific requirements;
- *Section 3* presents the setups prepared for the demonstrations;
- *Section 4* is dedicated to demonstrating the use of the soft end-effectors and discussing related considerations.

1. Introduction

The AUTOMATA project focuses on the development and implementation of an autonomous robotic workcell for the documentation, digitisation and analysis of archaeological artefacts, with a specific focus on ceramics and lithics. Within this robotic system, a key requirement for supporting research activities is the safe and effective manipulation of artefacts, achieved by means of adaptive end-effectors equipped with soft-grip technologies and force control. Considering the broad variability of cultural heritage objects, these tools must ensure a high degree of versatility and adaptability to accommodate a wide range of shapes and dimensions.

In this document, we introduce the SoftHand and SoftClaw grippers (Fig. 1), highlighting their reconfigurability in terms of versatility and adaptability. These grippers have been applied to the project's use cases, studied and tested on authentic artefacts provided by UNIPI. The aim is to demonstrate the potential of soft end-effectors and provide a comprehensive overview of their capabilities.

Fig. 1. Left - the SoftHand; Right - the SoftClaw

2. Soft end-effectors for artefacts

The soft end-effectors tested for D3.1 are described below.

2.1 SoftHand

The *SoftHand* (Fig. 2) is an under-actuated gripping device with a single actuator and 19 degrees of freedom. Its operation relies on a motor with a pulley that winds a single tendon. This tendon passes through all the hand's joints, running on idle pulleys at each joint, thereby enabling the closure of the fingers until the motor reaches its reference position.

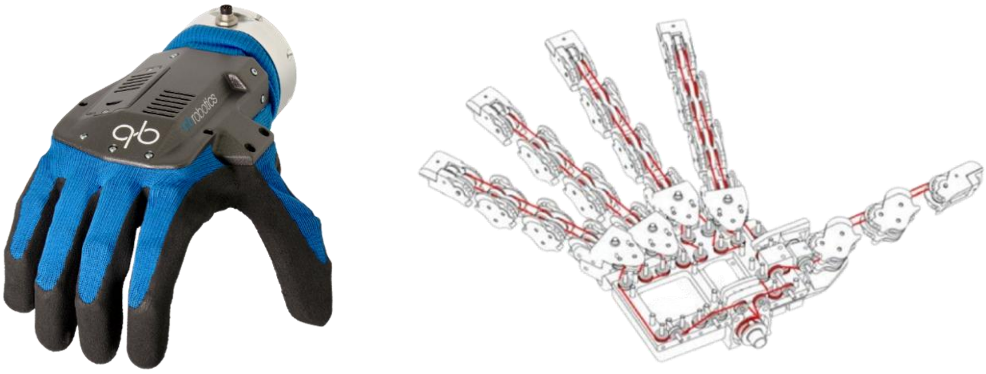

Fig. 2: SoftHand

The hand acts as a large differential mechanism where power flow is transmitted in series to all joints. If some joints are blocked (for instance, by external constraints or by the grasped object), the tendon continues to run on the idle pulleys of those joints, still transmitting power to the other free joints. This design allows the fingers to adapt to the shape of objects, similar to human fingers. The peculiar adaptivity of the *SoftHand* is intrinsic to its mechanical design and is not dependent on complex control strategies.

The *SoftHand* consists of five main subsystems, as illustrated in Figure 3:

- **Fingers:** This is the active part responsible for grasping, adapting to the shape of objects, and squeezing them against the palm.
- **Palm:** This is the passive part against which the fingers squeeze objects. It houses all other subsystems on its back.
- **Motor Unit:** This is the driver that actuates the closure of the fingers.
- **SoftHand Board:** This commands the driver, enabling the SoftHand to open and close. It also manages power and logic flow.
- **Compliant Wrist Interface:** This provides a certain degree of flexibility between the hand and the electromechanical robot arm interface.

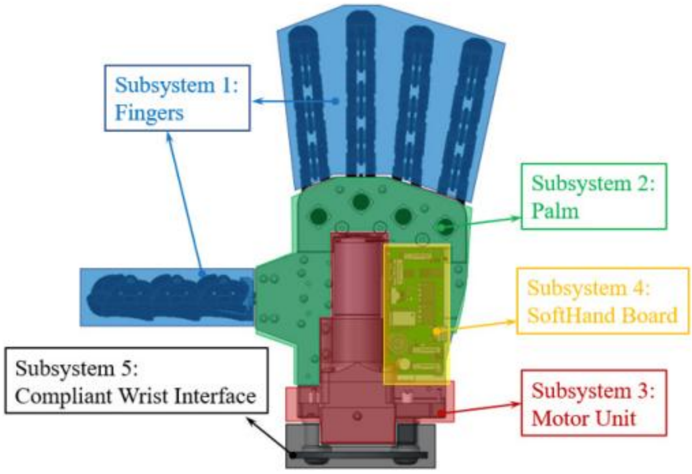

Fig. 3: Five subsystems of the SoftHand

The *SoftHand* has four identical fingers and a thumb. Each finger is composed of four phalanges: a proximal phalanx that allows adduction and abduction movement, a first and a second middle phalanx, and finally, a distal phalanx. Each phalanx is connected to the others by means of two rubber beams and can roll on top of each other, engaging on their toothed profile (Fig. 4 - Left). The rubber beams allow the phalanges to return to their straight configuration once their initial position has been perturbed (for example, by a commanded closure, an impact, or a disarticulation). Each phalanx has two rails that allow the tendon to move back and forth throughout the finger, winding around an idler pulley at the distal phalanx.

The palm of the hand is the element that connects all the subsystems. On the palm lies the routing of the tendon from the motor through all the fingers and then back to the motor. The tendon runs through idler pulleys suitably arranged over the palm, which deflect and redirect the tendon towards the fingers, realising the under-actuation mechanism.

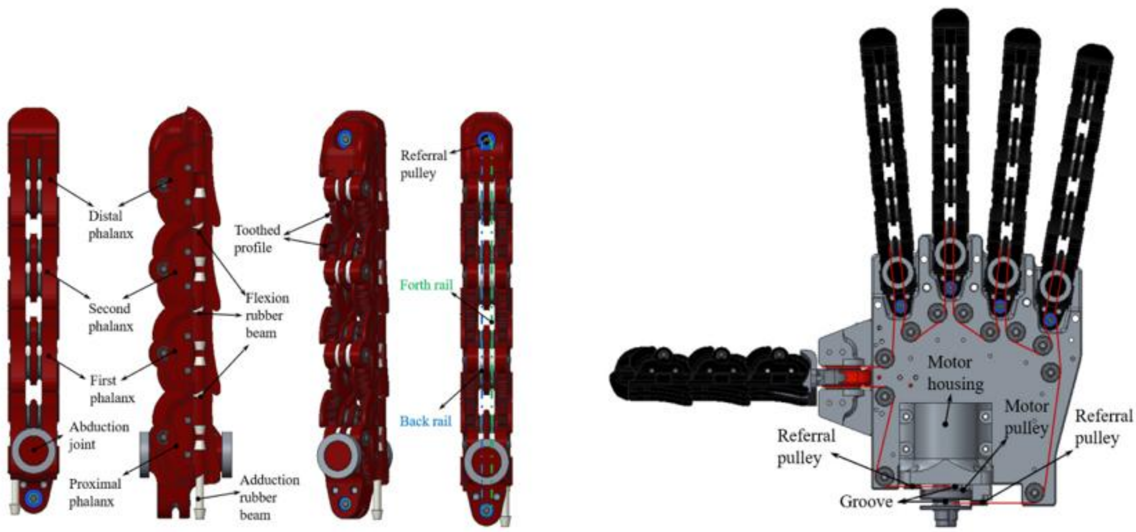

Fig. 4: Left - detailed illustration of the finger geometrical features and the main elements. Right - the tendon routing on the palm.

The hand is controlled by the SoftHand board. It drives the motor to reach the input position reference command and reads the signal from a rotary magnetic encoder, closing the loop control. A second auxiliary encoder makes the angular position readings absolute despite several motor turns. This ensures a one-to-one correspondence between the motor's angular position and the hand's configuration, preventing misinterpretations of feedback. The SoftHand board processes the readings from the two encoders and retrieves the actual hand configuration. Additionally, it manages power flow from the external power supply to the hand's motor.

The *SoftHand* is attached to the base plate through 4 dampers, which provide a compliant connection between the hand and the wrist. The SoftHand base is then fixed to the adapter plate of the electromechanical robot arm interface.

2.1.1 Reconfigurability

The SoftHand can be reconfigured in terms of actuations and size (Fig. 5).

2.1.1.1 Addition of synergy - SoftHand2

The evolution of SoftHand is SoftHand2. The transmission system by a single tendon, the kinematic movements of joints, and the layout of fingers are the same as in the original SoftHand, which was used as a starting point. In the successor model, SoftHand2, the friction of the transmission system and the introduction of a second motor enable the hand to achieve several finger postures by exploiting the combination of movements of the two driving pulleys (see Fig. 5). With this design, we have added a second synergy of the human hand. We can generate multiple postures as a combination of the first and the second synergy (Della Santina et al., 2015; Della Santina et al., 2018). This robotic hand can manipulate objects without changing the wrist orientation, perform a precise grasp and apply localised contact forces. The new skills, especially the more precise “pinch grasp”, allow for better grasping of small objects such as lithics (Fig. 1). The ability to grasp larger objects has been preserved.

Fig. 5: SoftHand2: left - transmission system with two motors; right - the two synergies of the hand are shown

2.1.1.2 Size Reconfigurability

The technology behind the SoftHand can also be scaled to different hardware sizes (Fig. 6), allowing the end-effector to be adapted for grasping both larger and smaller objects. By adjusting its dimensions, either in a scaled-down or enlarged version, the SoftHand can be optimised to handle a broader range of object sizes. An example of this approach is the SoftHand Mini (on the right of Fig. 6), a smaller prototype specifically conceived for grasping smaller objects and used as one of the end-effectors for the demonstrator.

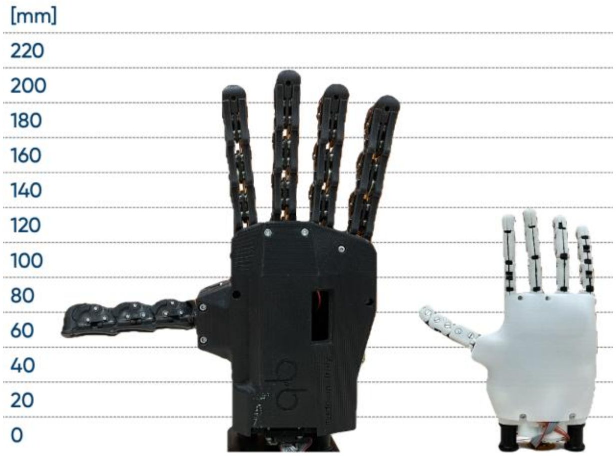

Fig. 6: Left - SoftHand. Right - SoftHand mini.

2.2 SoftClaw

Starting from the VSA-Cube, a Variable Stiffness Actuator, the *SoftClaw* (Fig. 7) was conceived as a compact, lightweight, and versatile variable stiffness gripper. It features two fingers: a mobile finger driven by the qbMove Advanced's shaft, enabling soft movement for grasping delicate objects and stronger grasps by increasing stiffness, and a fixed finger directly connected to the frame.

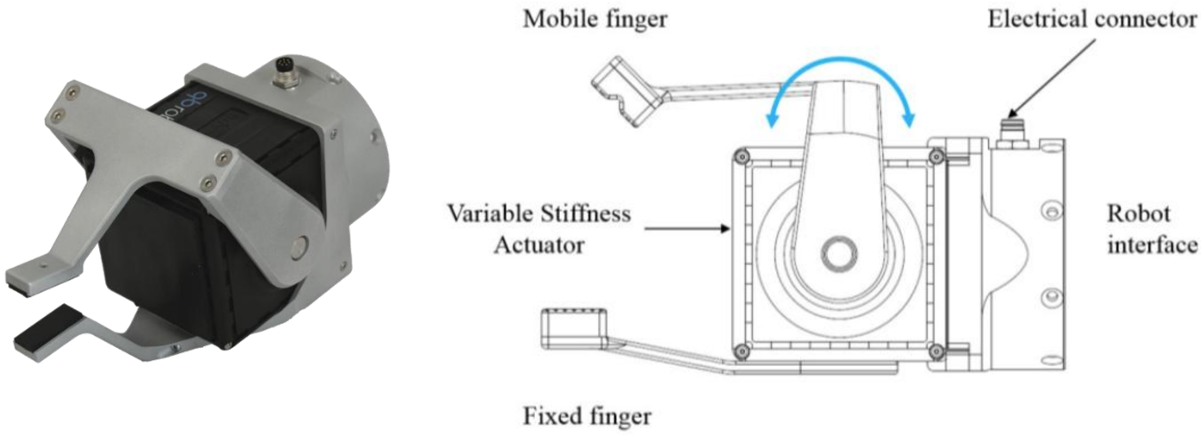

Fig. 7: SoftClaw

While it does not offer all the functionalities of a five-fingered hand, the *SoftClaw* is effective for precise pick-and-place tasks. This gripper's design incorporates variable stiffness systems, which are developed to overcome the limitations of conventionally actuated robots in terms of safety in human-robot interaction and operation in unstructured environments. These systems function as a non-linear transmission, converting input torques and velocities from prime movers into four output variables for the shaft: torque, velocity, stiffness, and stiffness velocity. The basic characteristics of the *SoftClaw* are detailed in Table 1.

Data	value	[unit]
$Force_{min}$	0.5	$[N]$
$Force_{max}$	64.0	$[N]$
k_{min}	0.07	$[N/mm]$
k_{max}	11.5	$[N/mm]$
$Closingtime$	0.5	$[s]$
$Dimensions$	81x90x165	$[mm]$
$Weight$	0.78	$[kg]$

Table 1: SoftClaw main data. Force values are evaluated by tests with a load cell mounted on the fixed finger, grasping objects of different dimensions. K indicates the stiffness of the pad's centre, tangent to the closing trajectory and evaluated from the torsional stiffness of qbmove Advanced.

A low-level controller has been implemented on-board. It controls motor positions θ_1 and θ_2 (Fig. 8) according to the reference inputs: the preset stiffness and the equilibrium position of the output shaft. When the two pulleys rotate in opposite directions, the nonlinear springs become loaded. This results in a change of their working point and thus in a different stiffness. Since the two transmission systems have the same characteristics, this movement does not change the output shaft equilibrium position in the absence of an external load. Conversely, pulley rotations in the same direction move the output shaft equilibrium with no load. The gripper is able to grasp objects of considerably disparate nature, exploiting the intrinsic mechanical intelligence of its variable stiffness system, without using any type of sensors on the contact surfaces or specific algorithms to control the motors. These aspects make it a versatile, light, economical and easy-to-use device.

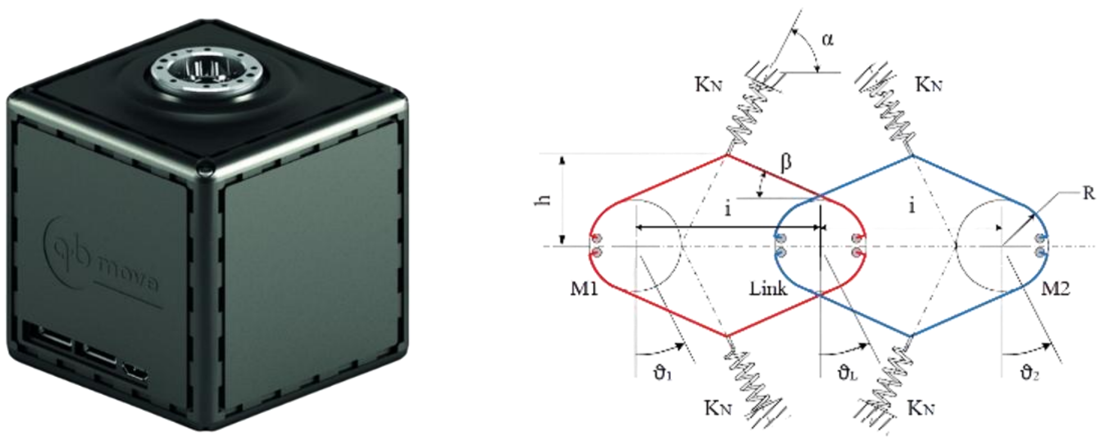

Fig. 8: The variable stiffness mechanism that permits the implementation of human-like behaviours. The geometrical disposition of linear springs and tendons implements the non-linear characteristic of the agonistic-antagonist mechanism in the qbMove. The three circles indicate the two motors and the output shaft in the middle.

The two motors offer control over two distinct behaviours:

- ***Position***: This mode functions similarly to a traditional gripper, allowing users to control both position and stiffness. The position parameter adjusts the movable finger's angular position, while the stiffness parameter regulates its elasticity. Higher stiffness values result in a firmer grip, whereas lower values enable softer grasps.
- ***Deflection***: This mode allows users to regulate the gripper's force during a grasp. The movable arm closes completely towards the fixed part for any commanded value. Small values are suitable for grasping fragile and lightweight objects, while higher values can be used for heavier and more rigid objects (Fig. 9).

Fig. 9: SoftClaw with deflection control: soft grasp on the left and strong grasp (high deflection reference) on the right side.

In the first modality, the user directly controls the finger position and the grasp stiffness according to the nonlinear behaviour of the VS system. In this way, a precise grasp and pre-grasp can be obtained, setting the stiffness according to the object's fragility. However, to obtain the grasp with desired stiffness, the object's dimensions must be known first. On the other hand, in deflection control, we can set the maximum deflection between the link position θ_L and the equilibrium position $(\theta_1+\theta_2)/2$, which enables us to fully close the finger. In this way, we can set the maximum force applied to the object, regardless of its size. The deflection control is the most appropriate modality for the AUTOMATA use cases, due to the variety of shapes and dimensions of electronic devices.

2.2.2 Reconfigurability

The SoftClaw allows for the convenient replacement and customisation of its two fingers/tools (Fig. 10-11). This provides the opportunity to test an infinite number of custom finger shape combinations in order to identify the optimal configuration for the AUTOMATA project and the grasping of archaeological artefacts.

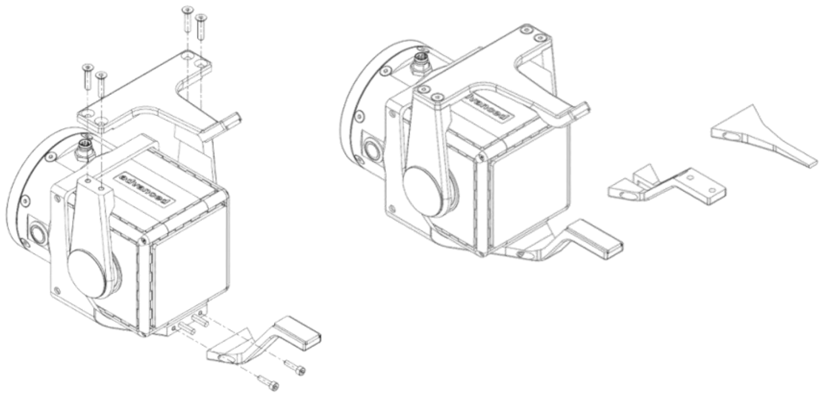

Fig. 10: SoftClaw fingers substitution system.

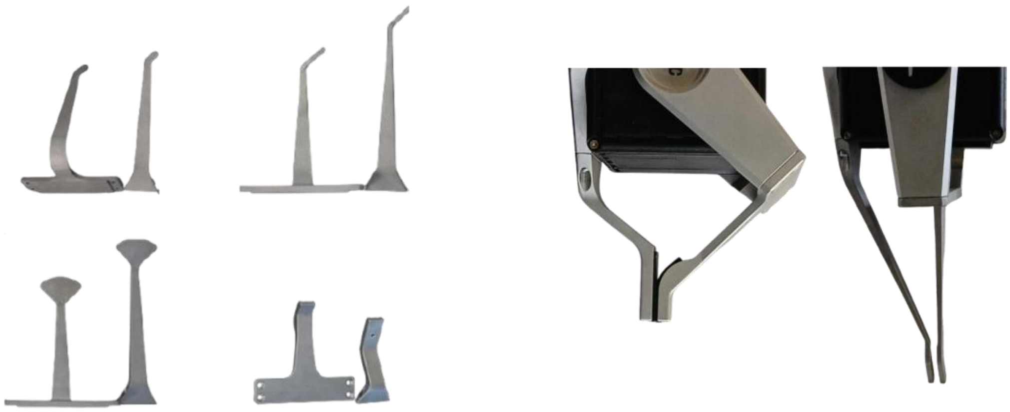

Fig. 11: Examples of different types of fingers.

3. System setup

Three experiments were set up as part of D3.1. Several combinations of hardware (robotic arms and soft end-effectors) were used in different operational modes, such as teleoperation, independent grasping, or manual grasping. The following ceramic and lithic fragments were employed in the experiments, as shown in Fig. 12.

Artefacts	Width (Min-Max)	Thickness (Min-Max)
Ceramics	3 - 10 cm	0.5 - 2 cm
Lithics	1.5 - 5 cm	0.7 - 2 cm

Table 1: Minimum and Maximum Dimensions of Artefacts

(a)

(b)

(c)

Fig. 12: Ceramic (a-b) and lithic (c) fragments provided by UNIPI for the experiments.

3.1 Setup 1 - SoftHand2

- Soft end-effector → SoftHand2;
- Robotic arm → Franka Panda;

In Setup 1 (Fig. 13), teleoperation was employed to grasp the artefact and assess feasibility. Given that the SoftHand2 can perform both power grasps for larger objects and pinch grasps for smaller ones with greater precision, teleoperation was chosen to carefully explore optimal hand poses around the artefacts. This approach also supports future work on trajectory planning and robotic manipulation within the robotic cell.

Fig. 13: Setup 1.

3.2 Setup 2 - SoftHand Mini

- Soft end-effector → SoftHand Mini;
- Robotic arm → None, manually handled.

In Setup 2 (Fig. 14), the SoftHand Mini was manually operated to evaluate both how to grasp the artefacts and what the optimal hand pose should be on the ceramics and lithics. Since the device is still under development and robotic interfaces are not yet available, manual use was necessary. Moreover, due to its reduced dimensions, some adaptations are required.

Fig. 14: Setup 2.

3.3 Setup 3 - SoftClaw

- Soft end-effector → SoftClaw + standard tools/customized tools;
- Robotic arm → UR5.

In Setup 3 (Fig.15), the SoftClaw was initially used with the standard tool as fingers and later also with a customised, more elongated tool to observe the differences.

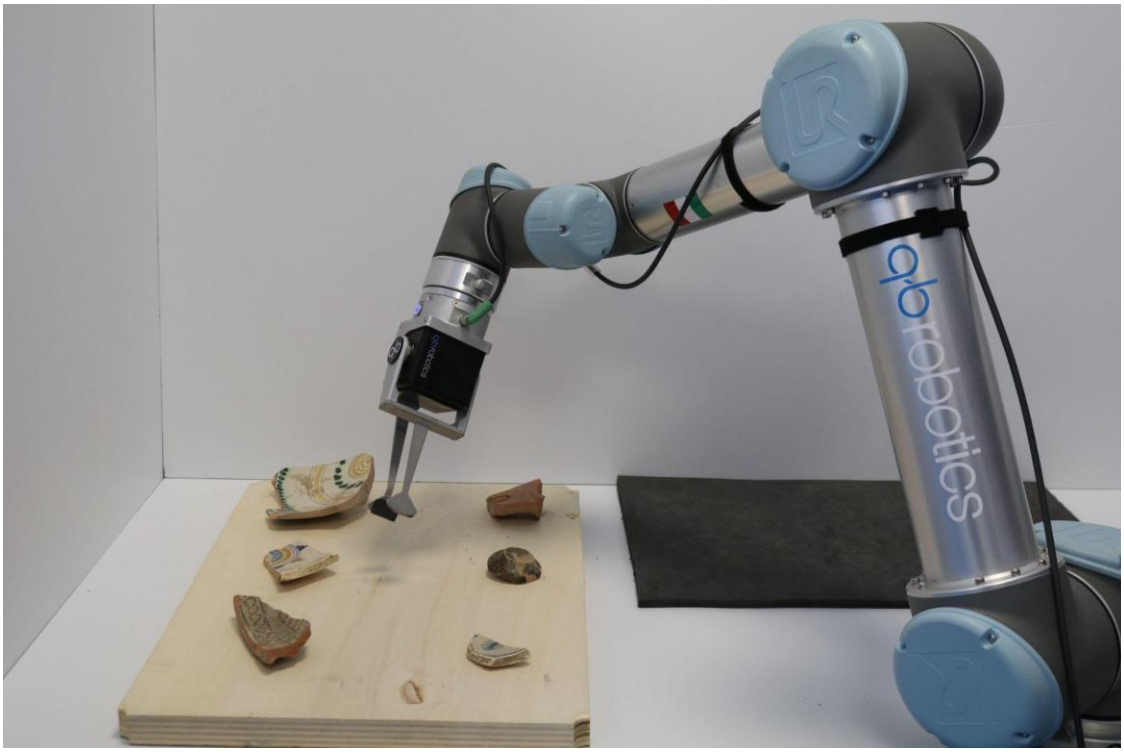

Fig.15: Setup 3.

Fig.16: Left - Standard fingers; Right - Custom fingers.

4. Demonstrator

The experiments carried out using the three setups, with the various combinations of end-effectors and robots, are shown in the attached video (https://youtu.be/3KhxxmlkuTY).

4.1 Setup 1 - SoftHand2

Overall, we observed that the SoftHand2 can reliably grasp large artefacts with a solid grip. For small to medium-sized items, the hand succeeds in grasping about 90% of the time; however, the position and orientation of these objects often change once lifted, as both the hand and the artefact adapt to each other, leading to rotations or flips. Thinner objects, such as small flat lithics, remain particularly challenging. Potential improvements could involve implementing grasping strategies, though this would increase computational cost and processing time.

4.2 Setup 2 - SoftHand Mini

The experience showed performance comparable to that of the SoftHand2. Large objects, especially those reaching the maximum width along both axes as reported in Table 1, are challenging to grasp, or are effectively impossible to grasp due to physiological constraints (Fig.17). Similar to the SoftHand2, artefacts often shift orientation once grasped. Overall, the potential for improvement in this scenario is limited.

Fig.17: SoftHand Mini with the maximum-sized object

4.3 Setup 3 - SoftClaw

The SoftClaw, featuring a body composed of a variable stiffness cube, can softly grasp artefacts of all sizes within the limits defined by the Consortium. Once a sample is grasped, it reliably maintains its position, which is crucial for accurate tracking and placement in the robotic cell for sensor analysis at precise points of interest. Experiments with the standard tool showed positive results, with limited failures observed. Customised fingers, with longer lengths, wider openings and customised geometry, further improve grasping performance, especially for smaller objects near the lower size limit, and enable better handling of artefacts. The main challenges remain with extremely thin artefacts, which are not always successfully grasped even with the customised tool. At the planning level, control is straightforward, and future improvements will focus on further refining the tool design to increase grasping success with thin artefacts, such as lithics.

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