Towards a Robotic Intervention for On-Land Archaeological Fieldwork in Prehistoric Sites

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Abstract. Archaeological activities lead to ancient artifacts discoveries and vestiges. Some excavation operations are both difficult and repetitive: industry 4.0 concepts such as artificial intelligence (AI) and advanced robotics are exploited in the production manufacturing processes to increase performance and could help automate some stages of excavation. This paper deals with the integration of these concepts in the archaeological domain to address specific and tedious tasks. Indeed, archaeological sites are mostly difficult to access places such as open sites and caves, thus making excavation even more challenging, hence the need for robots. The Archaeological Cobotic Explorer (A.C.E.), presented in this paper is a robot that could work alongside humans during archeological surveys. It would be a precise and untiring workforce, capable of locating and retrieving artifacts underground. This project aims to describe the appropriate industry 4.0 concepts that could be exploited in this particular domain and to create a machine, (A.C.E.), built with commercially available materials or replaceable 3D-printed pieces, capable of automating specific stages of the excavation process. Advanced computer aided design and functional prototypes were built and are presented in this paper.

Keywords: Artificial intelligence · Visual recognition · Advanced Robotics · Archaeological excavation · Mechanical engineering

1 Introduction

Archaeology is confronted to various complexities such as the geographical location of vestiges, the random nature of discoveries, temperature or humidity levels in a region, the problem of sediment evacuation or the traceability of the discovered items. Despite tedious and time-consuming tasks, archaeology is mainly conducted by humans: ergonomic concepts could aid archaeologists in their work. Industry 4.0 concepts and sustainability aspects contribute to a company's digital transformation by introducing new technologies in its manufacturing processes to eliminate non-added values and optimizing added values. In an industrial context, those concepts have proven their efficiency when it comes to flexibilizing the capacities on a production line. For instance,

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collaborative robots ("cobots") are designed to assist humans and work with them [1]. They are equipped with detection mechanisms, pressure sensors and cameras for security purposes, and they automate strenuous or non-value-added tasks. To sum up, while traditional robotics' reliability lies in redundancy, repetitiveness and predictability [2], new technologies already used in industrial contexts can help take a step and automate more complex tasks that require higher flexibility in the peculiar fieldwork of archaeologists.

This paper focuses on the exploitation of new technologies such as artificial intelligence, advanced robotics, big data analytics, internet of things and 3D printing to elaborate the adapted concepts to create a specific robot designed to assist archeologists in their repetitive tasks. It aims to address the operational difficulties archaeologists encounter by prototyping ways of bypassing them with automated systems, especially by assisting surveys in difficult to access areas and during excavations. The autonomous nature of this robot would make it capable of operating at night in case of long excavations, thus making it an additional workforce that could potentially perform twice as long as a human. Also, it would not be prone to human error: it should record every action with great precision, a crucial asset since archaeology is a destructive activity.

Following a literature review, the main concepts and designs of the robot will be presented. Discussions on future developments will be outlined, along with artificial intelligence tools that could be implemented in the robot to fulfill the various tasks.

2 Literature Review

Artificial intelligence, machine learning and remotely controlled autonomous rovers have an increasing impact on archaeological research. Current applications focus on issues in landscape archaeology, as well as aerial and underwater vehicles, equipped for on-land and underwater remote sensing, or 3D and Lidar-based scanning of monuments and settlement sites. Some can also analyze sunken settlement structures and shipwrecks. Yet, there are no archaeological research projects that automate excavations of prehistoric sites so far. Although archeological robots for on land archaeological surveys do not exist yet, similar machines have already been built for other environments and purposes and have brought inspiration for the concept presented in this paper: ROVINA [3] is capable of investigating hidden chambers, passages and sanctuaries of monuments such as the Egyptian pyramids or the catacombs of Rome. Excavating machines were also built to operate on construction sites [4] and adapt to any work condition. What makes the Archaeological Cobotic Explorer (A.C.E.) unique are the possible whereabouts of its application and the use archeologists will have for it.

2.1 Explorers and Excavators

Backhoes [5] are the most common excavators. They can even be used for underwater excavation. Underwater archaeological sites cannot be easily accessed by humans due to the increasing pressure that arises as the seafloor is deeper in the high seas. Instead, specific machines are designed to dive and fetch the items with robotic arms. Whereas the ARROWS project [6] consisted in creating a subaquatic vehicle meant to reduce the cost of archaeological research, Remora 2000, a small submarine capable of carrying two passengers and diving 610 m below the surface, is used to explore deep underwater grounds, for up to ten hours. Europe prepared the ExoMars mission in 2022 in order to investigate possible life forms of the past on Mars, and built its own rover, Rosalind Franklin, to carry it out [7]. National Aeronautics and Space Administration have already designed machines capable of exploring foreign planets: the Curiosity Rover [8] and its more recent cousin, Perseverance. Since (A.C.E.) does not have to move on horizontal surfaces, the very same mechanism would be useless. However, since it needs to dive in trenches, similar mechanisms can be implemented when it comes to controlling position within the trench. Bio-inspiration is the process of developing machines by analyzing animal species such as insects and bugs [9]. Spider-like movement could meet the requirements of this robot: six to eight legs would enable precise movements and specific contortions for instance. However, simpler solutions exist to control positioning, not to mention that this kind of mechanism would hardly allow fully retractable designs for the legs. The French company Aspirloc, specialized in civil-engineering, has designed a vacuum-excavator specifically designed to fit into pipes and evacuate rubble and other debris with its vacuum. Movements within the pipes are made easier by its crawlers. Similar maintenance robots also exist for other applications [10]. (A.C.E.) will exploit advantages of these mechanisms.

2.2 New Technologies

Artificial intelligence will be implemented to the machine in the fieldwork process to automate object recognition. In industrial contexts, applications for computer vision are common and now benefit from a heavy scientific background that can be transposed to archaeology: the use of deep learning and especially convolution neural networks (CNN) has become a standard method [11]. Since on-field discoveries may not match with known data, a database can be created to initiate a supervised training process of a deep learning model, and exploited to compare to already encountered situations, which will improve precision and reliability [12]: such a database will be implemented to (A.C.E.). During the training process, active learning [13] with archaeologists can help reach high classification performance quicker. Additionally, semantic segmentation with attention maps [14, 15] can both improve the model's performance and make it more understandable by highlighting specific areas on the images the model focuses on to make predictions: since artificial intelligence knowledge is hardly in an archaeologist's area of expertise, fathomable models [16] can be essential to ensure usability and the smooth training of the system. The database should mainly include photos of common artifacts, which will be provided by archaeologists. For instance, Artificial Neural Networks (ANN) [17] could be used to classify artifacts according to their chemical composition. During the excavation fieldwork, chemical tests are hardly easy to run. Thus, a deep learning method based on a sample of labeled images could generate a simple classification prior to further analysis. Unsupervised Data Augmentation (UDA) [18] can help improve performances with limited training samples by artificially filling up the database. Similarly, self-supervised learning (SSL) techniques such as contrastive learning [19] can improve a model's performance despite having few labeled data points. Collaborative robotics (Cobotics) are usually implemented in industrial contexts for it allows the automation of repetitive tasks while still being able to benefit from human adaptability with the use of Robot Operating System tool for the programming [20]. Thus, a production process can be flexibilized, making it easier to adapt to continuously varying demands. A lean automation approach [21] shows that an implementation of Roozenburg's engineering design cycle [22] to cobotic applications is possible. In the context of archaeological research, since what the fieldwork produces cannot be accurately predicted, human adaptability becomes a strong asset in the process: designing a machine capable of operating alongside archaeologists in critical parts of the process makes it possible to handle the variability of the fieldwork results.

2.3 Organizational Concepts

This section discusses the methods and tools that could be used to manage the project and ensure its success by using an efficient process. Lean manufacturing is a methodology destined to reduce waste in manufacturing processes [23]. It focuses on value-added activities and reduces non-value-added ones [24]. It is effective when it comes to company performance improvements, and its concepts can be transposed to project management. Lean thinking has been developed to use the same approach in other areas [25] such as product development. Design thinking is an innovative, human-centered approach used to develop new designs, products or services, and a toolbox meant to assist product development [26]. An approach based on five steps (Empathize, Define, Ideate, Prototype and Test) has been developed by the Stanford Design School [27]. As it is an iterative process that constantly focuses on user expectations, this methodology is adapted to (A.C.E.)'s development and would ensure its mechanical development. Although, as previously mentioned, the development and exploitation of this robot require new technologies and the development of an adapted software to manage both human and robot information in this collaborative system. Some other useful tools could be the Agile methods [28]: they promise to deliver consistent business value to adapt and improve the product as well as the work process both incrementally and empirically. They are used in various areas such as agile business models, enterprise agility, organizational agility, agile manufacturing, agile supply chains, and agile software development [29]. One of the most important agile methods is Scrum. Scrum is a framework meant to address complex adaptive problems while productively delivering creative products of the highest possible value [30]. Product development is described as an iterative cyclic process with continuous validation during the process [31]. Then, requirements are continuously integrated. Indeed, as explained in reference [32], the use of agile methods such as Scrum in the development of physical products is advantageous: it improves communication, responsiveness, flexibility, transparency and increased commitment/motivation.

These methods and tools will be combined to define the methodology that will be used to develop (A.C.E.) and manage the project.

3 Concepts and Methods

3.1 Global Approach

The methodology presented below is the one used in the project. It is the result of a combination between lean design, design thinking and the agile method Scrum (Fig. 1).

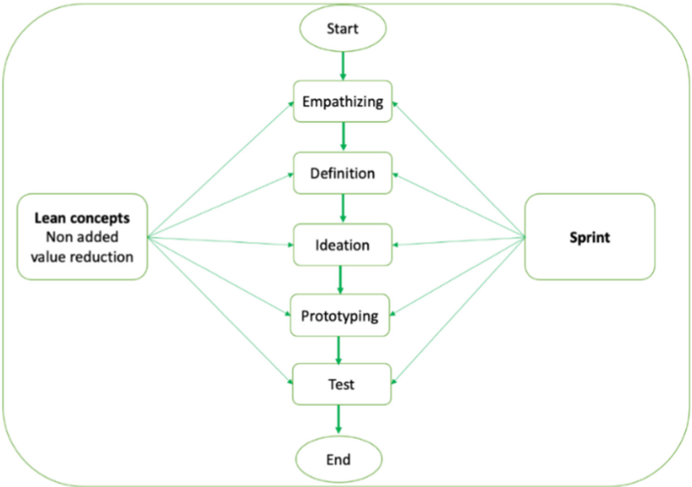

Fig. 1. Agile Lean design thinking Methodology

Starting the project from scratch meant innovative solutions had to be brought up, for it is a one-of-a-kind machine with specific requirements. Given the variety of tasks it has to achieve, it seemed much more simple to build two separate contraptions: the first one, referred to as the Explorer, is exclusively designed to go down trenches, dig and collect the items, and the other, referred to as the processing unit due to its functions, is meant to clean, bag and label with QR codes, thus preparing the found objects for further laboratory analysis. The main reason for this dual design is practicality: it reduces the weight of the Explorer by having it perform a lesser number of tasks, and cutting down the quantity of moving parts is crucial for a functioning, redundant design.

This chapter aims to describe the process that has been applied to imagine solutions regarding the overall mechanism: first, emphasis is placed on the Explorer and the ways of handling its movements within the trench with maximum precision by considering environmental constraints, followed by a description of the processing unit, especially the sieving mechanism and how it manipulates archaeological artifacts.

3.2 The Excavation Robot Concepts

The excavation robot has been defined as a human aided system integrating all the concepts necessary to the creation, design, and elaboration phases. The design includes an Explorer, the conceptualization of a processing unit, the use of new technologies such as artificial intelligence or 3D printing and the elaboration of torque and gear systems. (A.C.E.)'s AI is handled through a Raspberry device for it offers the necessary features for this robot. This intelligent system uses deep learning to detect and recognize finds. A module meant to contain all the data required to increase the quality of the detection system is being designed. The Explorer handles motors, cameras and images by sending collected data to a specific file. Several versions of the machine have been imagined inspired by existing machines such as the Gargantua robot moving along the Z axis [33]. Due to its rather small size (approximately fourty centimeters high and thirty centimeters wide), the Explorer can go down trenches thanks to a hoist that remains at ground level. As for lateral movements, it is divided in two separate rotating parts: the upper one containing four telescopic arms designed to handle position within the trench, and the lower part containing both digging mechanisms. The first would gradually dig the trench whereas the second would retrieve the items with a specific clamp that has not been designed yet. Once collected, they would be taken to the surface by the hoist and passed on to the processing unit. The hoist itself could be designed based on 3D-printer mechanisms to ensure precision, meant to remain at the surface, guiding the Explorer at all times [34]. As the main concern was space, one of the very first ideas was to include telescopic arms to the Explorer [35]. Pressure against the walls would have been applied using a spring, one per arm, each of them fixed within the arm itself. However, asperities on the walls had to be taken into account to ensure fluent movement: four wheels with suspensions [36] would be created by placing springs between the wheels and the upper plate. The solution actually being developed is described as follows (see Fig. 2).

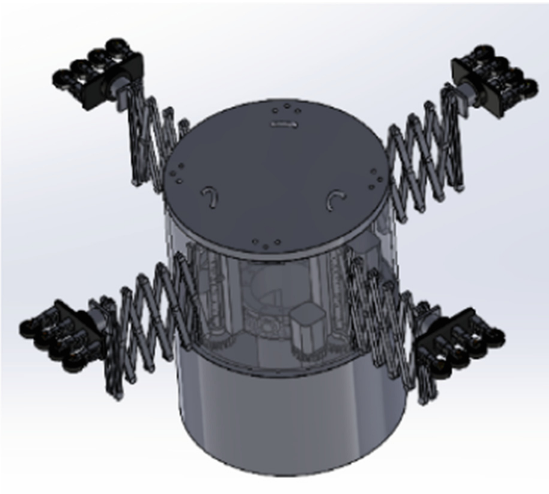

Fig. 2. Explorer overview

The one issue with bone-like arms was the vertical movement of the wheels as the arms deploy and retract. This can easily be overcome by attaching the bone structure to a slide at the very end of the arms: the arms could deploy naturally, without causing the wheels to move vertically at all for they would be fixed to the slide. Also, fully deployed arms could possibly be impossible to retract: an ascender could be fixed to the threaded rod, and step motors programmed to stop at that precise point to prevent both impossible movements and overheating. A circuit mainly composed of logic gates and limit sensors, such as the one further below, could be wired to the motors to kill power when the arms are fully deployed. The processing unit (Fig. 3) is a one meter long and fifty centimeters wide contraption divided in three separate modules, each designed to fulfill a specific task: sieving [37], cleaning, and bagging/stamping the artifacts one at a time. Special attention has to be paid to ensure item handling without damaging them at all [38]. The processing unit will be powered by a rechargeable battery: voltage will be reduced through voltage dividers.

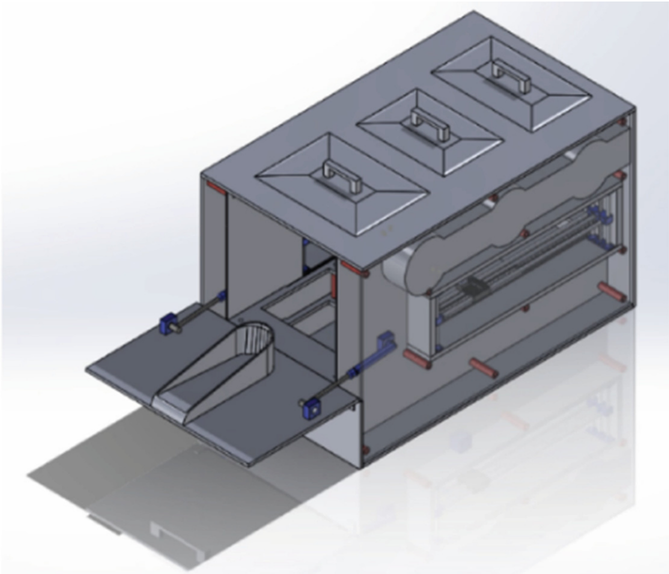

Fig. 3. Processing unit overview

Cleaning the items involves separating earth from precious materials: this is accomplished by the sieving module and its grid. The design of the bagging system resembles a knife plastic welder combined with a folding mechanism and rolls that will stretch the plastic before folding it. 3D-printing as an industry 4.0 concept has been used to develop the prototype. 3D-printing offers many solutions [39] to the various problems encountered during the designing process: innovative mechanisms can be built and implemented to the machine. So far, PLA plastic filament was used for it is a quite cheap material, which makes it suitable for multiple prototyping and testing: although building such a machine is expensive, additive fabrication can help cut down costs over time. Furthermore, most of these pieces can be robust enough to withstand the efforts applied to them if sufficiently filled while printing. Also, the motors used for this robot have so far been sized to hold a heavier load than that which is actually applied to them. The system meant to manipulate the artifacts that has been implemented to the device consisted in two robotic arms, located on each side of the processing unit. These arms are able to deploy and retract according to the size of the items, protected by both the foam [40] fixed to the arms and the force sensor located on the plates since they are the first "hard" parts in contact with the items. These sensors evaluate the force applied to the items, thus ensuring it does not exceed a certain value. Foam also adds mechanical friction which helps prevent the object from gliding and falling.

4 Experimental Results

Theoretical results obtained through calculus and computer simulation validate the concepts and formalisms developed above, and design analysis [41]. So far, the focus was placed on the sieving module and the foam arms along with their mobility mechanism: functional prototypes have been built, and although the final version of the robot should include metal pieces when possible to increase resistance and durability, 3D-printing brought surprisingly good results. The sieving mechanism has been developed with computer simulations to predict the linear speed of the grid, actuated by a slider-crank mechanism (Fig. 5, a) to generate translation. A rack-and-pinion mechanism (Fig. 5, b) lifts it for the arms to grab the artifact. Their movements have to be slow enough not to hurt the artifacts: this could either be handled with a rotary encoder, a visual sensor [42], or with a simple mechanism, using a photoresistor and a laser beam on either side of the rack, pierced with three or four holes. To get the items to turn and change their angular position, they first have to be lifted above ground level. Many systems could have been used to get the arms to move vertically, a belt or a chain for instance, yet a threaded rod attached to a step motor (Figs. 4 and 5 c, d and e) seemed to be the most appropriate solution for that case for precision reasons. The overall mechanism must be approximately one meter long to make sure the arms can seize the items on the three different modules.

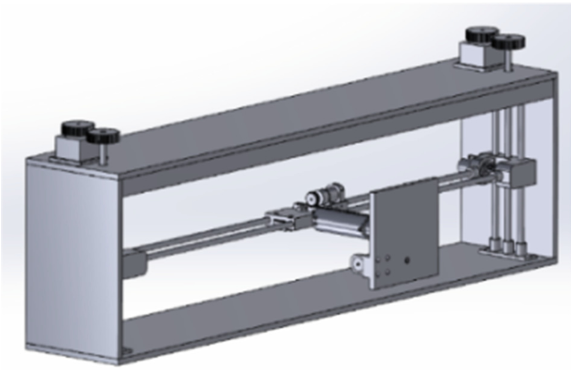

Fig. 4. Grabbing archaeological items: foam arms movement mechanism

Since for the most part, the items (A.C.E.) will manipulate are extremely fragile, an overheating protection system is being implemented, to protect both the engines and the artifacts by shutting power down according to the force applied.

An optocoupler isolates the mechanical part of the design from the circuit, thus ensuring protection should mechanical problems occur. The signal is processed through logic gates, enabling or disabling the motor through transistors according to switch states and Raspberry inputs. These transistors activate the relays that control the motor's rotation direction. The force sensor is handled by the Raspberry and only alters its inputs.

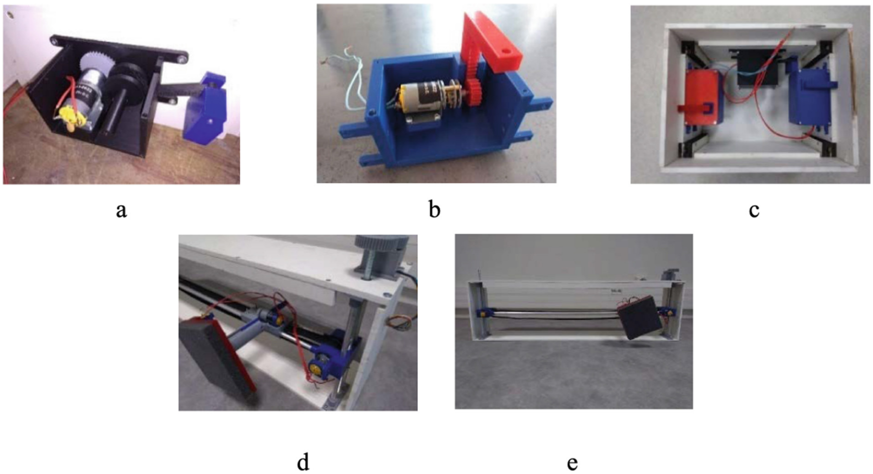

Fig. 5. Processing unit: sieving module (a: slider-crank mechanism. b: rack-and-pinion mechanism. c: overview) and foam arm mechanism (d, e) prototypes

5 Conclusion and Outlook

This project aims to automate several stages of archaeological excavations in order to relieve archaeologists in their daily activities. Those stages include reconnaissance, digging and cleaning. The Archaeological Cobotic Explorer (A.C.E.), ensures secure movements in an archaeological environment, from excavation to preparation for laboratory analysis. Its Explorer scans trenches, digs and retrieves items buried underground, before taking them back to the surface to the processing unit, which prepares them for laboratory analysis. The device is also capable of sorting artifacts by referring to its own database which will be updated over time. Since radars capable of detecting items underground are hardly affordable, (A.C.E.) will dig about five millimeters at a time to avoid damaging the artifacts and will use computer vision to classify them. So far, prototypes of the processing unit, especially its robotic grippers and the sieving module, have been built. The arms are designed to securely manipulate fragile pieces, using foam at low speed, and reasonably close to ground level. Security measures have also been designed to avoid engine overheating. Even though the main ideas for each part of the design have been found and chosen, the exact systems for digging, retrieving items, moving the Explorer both vertically and horizontally, the transmission of the artifacts between the Explorer and the processing unit, cleaning, bagging and QR code labeling have not yet been fully designed and prototyped.

Future work should focus on improving the already-existing design of the arms, designing the digging mechanism and prototyping the rest before testing. Further development to address the issue of classifying artifacts in a supervised learning approach with limited labeled data samples will implement a deep learning algorithm. In particular, data augmentation methods together with active learning should be used to ensure an acceptable generalization performance. Additionally, the use of convolution neural networks with attention maps should initiate the design of an explainable artificial intelligence to address usability issues for the archaeologists. (A.C.E.)'s AI will be implemented along with its databases, as well as the QR code generation system, the human-machine interfaces, and potential 3D imagery for position recording of the artifacts. Handling the agents in the information system should be done with open-source tools such as Robot Operating System (ROS).

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