Challenges for Advanced Applications in Archaeology

What IT can still learn from humanities

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***Abstract*—Computer science frequently considers much of humanities and in particular archaeology "trivial". The "hard challenges" were defined by sciences, such as physics. Yet these "soft" domains have been and are struggling with challenges that still exceed computational capabilities and that cannot be solved with current approaches. On the other hand, climatological models, remote sensing, agent modelling etc. all can benefit from archaeological data and approaches. In this paper we review how current computer science is insufficient to address the challenges posed in an archaeological context.**

Keywords – advanced applications; archaeology; high performance computing; physics; simulation; network analysis; social networks; agent systems; theoretical computer science.

I. INTRODUCTION

Archaeology developed into a complex science only in the last century. It brings together experts from numerous disciplines to preserve and unveil the (human) past. Though archaeology is typically associated with a pen and paper science (Figure 1), it may come as a surprise that it adopts modern technology fast, such as radiocarbon dating and remote sensing [1] [12].

Due to the nature of the field, namely working with (and "in") the past, the need for complex applications and simulations in archaeology is typically not apparent. Yet organisations such as the CAA (short for "Computer Applications and Quantitative Methods in Archaeology") exist since the 1970s, having identified the need for computational power in archaeology early on.

This paper examines some of the challenges arising from archaeology that necessitate complex and state-of-the-art computational methods. Existing approaches are frequently insufficient to address the requirements and challenges posed by this field. The main purpose of this paper is to raise awareness of these issues and elaborate how computer science methodologies could improve further by addressing them. Section 2 thus lists some of these challenges and elaborates why current methodologies are insufficient. The final section will examine how computer science could contribute to and benefit from addressing this field.

Figure 1. Archaeologist mapping the layout of a trench. Source: Wikipedia.

II. THE (HIDDEN) COMPLEXITY OF ARCHAEOLGY

Archaeology is no domain constrained to a single scientific area – as it deals with human behavior over a range of unknown factors, it incorporates aspects of social sciences, evolution theory and neuropsychology, but also of surrounding domains, such as weather and climate. The most important aspect however is that all data must necessarily be incomplete: not only is there scarce archaeological evidence in the first instance, but also such evidence consists only in what humans leave behind – and intentions and beliefs leave no visible trace. Imagine finding a watch somewhere in the street and try to derive what happened from what little evidence there is: did the owner lose it? This is unlikely if the strap is intact. Did the owner throw it away? Is there any sign of damage on the watch? If so, may it stem from being pushed around on the street? Was the wearer male or female? Form alone may indicate taste, not convention and so on.

Multiple factors have to be cross-examined when trying to reconstruct the potential events that led to the watch being on the street. Archaeology does this every day, very much similar to forensic criminology with the added complexity that assumptions about (modern) human thinking cannot be applied.

A. Big Data, Data Mining etc.

The only way to approach the problem consists in gathering as much information – ideally hard evidence – about the situation as possible and then starting to make assumptions over potential relationships, causes and effects. In most cases this means that logical errors have to be eliminated first. The principle of Ockham's razor is equally important for archaeology as any other science, as e.g. the recent find of a Roman coin in Japan demonstrates [2]: an implausible explanation would be that ancient Japan by accident minted a coin that is absolutely identical to Roman coins, not only in shape and depiction, but also in metallurgic configuration. We can already note that comparison of type and metal plays an important role in identifying the coin's origin in the first instance.

Such analysis requires an in-depth knowledge about Roman coinage, which exceeds the capabilities of a single domain expert: metallurgists have to talk with Roman experts on coinage and on trading networks etc. Logical consistency across all these aspects is difficult to assess – for example the implications if some individual Romans may have indeed travelled as far as Japan. The amount of data involved in this analysis is not only vast and completely differently structured across domains, but in most cases only human (i.e. not machine) readable. Most importantly, however, it is incomplete, basing on scarce evidence and conjecture. Testing for logical implications is therefore difficult: not only because the data formalizes little of the logical constraints, but also because it is simply incomplete.

Statistical analysis is based on the assumption that sufficient sample and reference data exists. In the case of archaeological evidence, only little data exists and reference data is in most cases conjecture, e.g. when comparing ancient structures with modern ones. All data is therefore associated with a high error potential, which is insufficiently formalized, even though network analysis, sample clustering, typology etc. all are based on statistical methods.

The implicit error must therefore be formalized and taken into consideration in analytical methods – and, what is more, its implications discussed: a deviation propagated over multiple implications / relations not only carries forth but increases with all further associated errors.

Approaches. Modern data mining technologies are quintessential for archaeological analysis. Standard methods look for clusters in datasets to identify (potential) relationships – this essentially means that the analysis stays within one ontology. In cross-disciplinary analysis, however, the data belongs to different ontologies and their correlation is not obvious. Such relationships need to be explicitly defined and logically constrained by a metadata set that defines type, period, context, location etc. Notably, any find may be cross-referenced against any other find of same type and from a related period. Take the example of the Roman coin: would it be possible to travel the according distance given the means and conditions at the time? For each according assumption, the associated risk of error needs to be taken into account: how *likely* is such travel given the situation and what does that mean for all other assumptions made so far?

Due to the lacking structure of archaeological data, better data conversion techniques are needed, including natural language processing. As a first step, it would be sufficient to extract key words from the data that classify find types and context, including location, population, time frame etc. This would at least allow that finds and reports can be correlated according to their context – even if such information would be insufficient for (logical) reasoning. Metadata for scientific purposes is constantly being improved, but has not reached this level as yet [10].

To this end, logical relationships need to be encoded – notably, many of them take the form of complex simulations themselves (see below), whereas others can be simple constraints, such as that the context cannot be older than the find. New mechanisms for incomplete reasoning are needed that can perform statistical analysis and assumptions on insufficient data. By associating an error with the number of assumptions violated, Ockham's razor can be used as a qualitative assessment. Regarding our Roman coin in Japan, logical explanations include equally trading networks, individual travelers and chance reproduction. Given the time and circumstances, however, direct travel and trading are highly unlikely, as is chance reproduction. This does not mean that an indirect trading "chain" could not have existed along which route a coin happened to travel as an exotic gift. The likelihood of an individual traveler can be calculated by (a) the complexity and cost of such a travel, (b) the other evidence for exchange, i.e. frequency of similar finds, and (c) relative timing of the contexts, i.e. appearance of other finds in the same context etc.

Potential explanations (assumptions) must be encoded and their logic must be reproducible. As opposed to this, most modern AI focuses on statistical analysis of massive amount of (equally structured) data.

B. Simulating Human Behaviour

Archaeology is about humans: how they lived, what they have done, when and why. However, in an illiterate society, ways of thinking leave no traces and even in literate societies, written evidence should not be confused with facts [1]. The challenge for archaeology therefore consists in relating finds to potential behaviour, intentions and way of thinking. Some of this behaviour is obvious and straight-forward: a ceramic pot indicates that (a) someone was there to leave the pot behind and (b) someone made the pot. However, was the pot used as a domestic item, was it an item of worship, was it just decorative, was it discarded right away? All this cannot be gathered from the pot alone.

As seen (data mining, above), a considerable amount of information has to be cross-linked. What is more, though, is that human behaviour, intentions and beliefs, capabilities and knowledge etc. stand at the middle of the explanation chain and form the basis for any conjecture. As indicated above, this can obviously take different levels:

1. Presence. At the most straight-forward level, the remains are just indicators for human presence and actions, such as that someone must have brought the

find to the location, must have made it etc. Notably, not always is a find clearly of human origin, as e.g. is the case with some Palaeolithic "tools" [3]. This is the level of direct archaeological evidence.

2. Capabilities. At an intermediate level of complexity, human capabilities must be taken into consideration. This defines whether it was e.g. possible to reach a location, build a structure etc. How humans reached the American continent is one unsolved question on this level. At this level we talk about the assumptions that can be substantiated by archaeological evidence (existence of boats), but not fully proven.
3. Belief and Intention. At the most complex level we need to argue over belief and actions that are behind the evidence. It is a frequent cliché that archaeologists classify any evidence without clear functionality as "ritualistic". Indeed, it is difficult to assess the intention of an object that has no comparison in modern context. At this level, all "evidence" is pure conjecture and may change on basis of new theories.

Whereas knowledge at level 1 and partially at level 2 falls clearly into big data management, i.e. cross-checking facts, most of level 2 and in particular level 3 are conjecture and base on logical possibilities alone. Aspects such as movement of peoples require that the behaviour is simulated and the likelihood assessed on basis of this simulation.

Approaches. Human behaviour can be simulated in many different ways. Standard approaches consist in agent based simulations, which model multiple entities and their interactions on a simplified level [4]. There is a considerable amount of criticism of these models, as they must naturally be incomplete and error prone – it is currently not even possible to appropriately simulate how a crowd walks on a street, let alone how a whole settlement would behave [5].

Human behaviour is complex and cannot be easily abstracted, so a major question relates to which human aspects have to be modelled in the first instance and how. Much can be learned from social network interactions, but care must be taken when applying modern contexts to ancient circumstances, as behaviour and mindset are in constant flux [1].

Statistical analyses can reduce the computational effort, even though they have a high error margin. They can help to eliminate *unlikely* situations, such as for the Roman "tourist" in Japan which would necessitate the according means of travel, communication etc. [6] suggest an analysis basing on throwing angles and strengths to assess the layout of shell middens. This is a highly simplified human behaviour model but already allows for some degree of feasibility assessment.

C. Simulating Climate

Climate is constantly changing – not only due to human interference, but also due to the earth's rotation and movement, leading to glacial and hot periods. The implication of such weather changes is obvious and can already be observed today: different plants grow in different climatic zones, animals (and certainly humans) move to different areas, clothing changes etc. In times before Air Conditioning, this hit doubly strong and will have caused (and prevented) massive movement and settlement patterns, following game or reacting to environmental pressure.

Climate completely changes the face of the earth, from rising (and sinking) sea levels to landscapes covered in ice sheets or turned into steppes. These changes leave their marks and are sometimes directly measurable, such as in tree growth (dendrochronology) or remains of marine life in the dessert, respectively vice versa [1] [12].

In the archaeological context climate is only of interest insofar as it influences humans [7]. As such, it is only a contributing factor to Simulating Human Behaviour (see section II.B) and can serve equally as an explanation, as well as an obstacle. For example, the movement of Homo Sapiens to the American continent is frequently explained by the possibility of a connection between North America and Siberia (the Bering land bridge) [8]. This land bridge could have existed due to a massive amount of water being locked in ice, thus causing the sea-level to sink considerably. Similarly, the movement of hominins into central Europe from Africa may have been made possible by fluctuations (inter-pluvial arid periods) in the temperature of the Sahara [9].

Climate conditions apparently play a role in any discussion about behaviour influenced by weather, such as clothing, foodstuff etc. Therefore, modelling the weather and in particular the climatic changes over history is a relevant aspect of the argumentation chain related to Simulating Human Behaviour (see section II.B).

Approaches. It is well-known that weather simulation belongs to the most difficult tasks in advanced applications [11]. While meteorological simulations try to accurately predict local, minute changes in the weather, climate models can be more coarse-grained, identifying patterns of general weather trends over longer periods of time. However, already the overall climatic changes in the glacial and interglacial periods are difficult to predict and not all factors are known. Such models base more on observed factors, such as glacial movements and encapsulated CO^2, than on calculations [12].

Nonetheless, different models are under development (e.g. [13]) and particularly try to provide more local and fine-grained climatic conditions, so as to assess the size and distribution of ice sheets, but also just to predict shorelines, climatic zones etc. Such models can be validated partially against archaeobotanical finds, i.e. seeds that have been preserved under anaerobic conditions.

D. Physics

Physics pervade all human life for obvious reasons and thus are relevant for interpreting any (archaeological) find – for example, when arguing why and how a find ended in a specific position. Complex physic simulations can (and do) contribute to various aspects in archaeology, of which only a few examples will be listed here:

Humans having been killed violently and / or moved after death will end up in certain positions and orientation. For example skeletons in the Tollense valley have been moved by water slides and thus ended up in a collective heap [14]. Knowing the shape of the land, the flow of water and intensity of rainfall allows reconstructing where the bodies originated from, and (to a degree) their original positions. As the process is irreversible, this is not entirely possible – but the order of skeletons already indicates how they must have been flooded down the hill. Notably, the state of decomposition makes a major difference with this respect.

Related to this, wounds in the body (skeleton) give an indicator for strength and direction of a blow or of the projectile. Arrowheads embedded in bones tell something about the position of the opponents relative to each other, but also about how the weapon was used and the force that the respective weapon can transmit. Obviously, human factors have to be taken into consideration, such as whether the force could be created by muscle strength (spear) or whether additional means would have been needed (bow). Given e.g. the Tollense layout, a reconstruction of the event can thus be attempted.

Other aspects related to physics simulation are e.g. how structures or burial mounds collapse and organic material decomposes over time. Just as in the Tollense case, the layout of the original structure can never be reconstructed from the final collapsed heap. Nonetheless, the shape and layout of the elements in the heap allow reasoning over the possible original structures. By comparing these with existing, similar structures (see section II.E), reasonable assumptions about the original layout can be made, as well as about the factors that led to the final distribution.

Human intervention is a factor in both scenarios. In the first case, humans define in particular the strength and way of usage. In the second case, they (may!) define the causes for collapse and potential rearrangement of the final structure, e.g. if stones were removed or shifted to make space for other structures.

Approaches. Rigid body physics belong to the oldest forms of computational simulations and in principle can already be employed in the fashion suggested – however, only for performing the "forward" calculation, i.e. from a given structure to the collapsed heap. Inverting this process is not possible, though, and thus the likelihood that a structure will lead to the observed distribution is highly unlikely.

New methods are needed that essentially invert physics, i.e. to reconstruct the original layout from the final distribution by taking different influencing factors into consideration. These include human intervention, which so far is still most difficult to model. Essentially, such a model would generate a likelihood assessment that a recorded heap relates to a specific structure, given the conditions specific to the context of the find.

E. *Matching*

By nature, most archaeological finds are in fragments: destroyed, decomposed, collapsed etc. Next to the general layout of the finds, the actual material and shape of the fragments themselves provide indicators for their relationship. Consider the various forms of pottery that can be found in archaeology: shape, material and texture, respectively decoration are good indicators as to whether two sherds may have belonged to the same object. This also applies to (human) bones, larger sculptures etc.

Generally, parts are missing, scattered all over the place, or even archived in a completely different city / country due to different excavation processes, movement after excavation etc. Furthermore, due to the vast amount of similar fragments, identification of corresponding parts is close to impossible.

Figure 2. Matching sherds on basis of profile information [15].

In itself, this is a considerable big data process where multiple factors need to be compared and cross-correlated to identify potential matches. These in turn will have to be matched in shape and against types of objects. Ideally, the fragments touch and thus have a common breakage area. Though this may sound like "just" a fitting task, one needs to consider (a) the amount and size of fits and (b) that natural processes change the breakage area by smoothing and reducing it etc., so that no perfect fit can be achieved anymore. Such processes will have to be taken into consideration when asserting whether two fragments match [16].

In most cases, no 3d models are available, let alone provide sufficient details to attempt a match in the first instance. As the number of available models increases, so does the complexity to match all the available finds – but even just within a single excavation, the effort is considerable.

Approaches. Various approaches exist for automated shape matching, but they mostly assume that the fragments show near-perfect fits (Figure 2). Fewer approaches consider additional factors, such as general shape and continuation of patterns or pigments, which in both cases require additional knowledge about shapes and types of objects in the period and region. It is already helpful to use continuation aspects both for the overall shape and for the basic principles of the pattern, as discontinuity is comparatively rare.

As opposed to this, matches of the actual breakage surface must be similar, not identical. This means that fragments can be placed basing on continuation aspects of shape and breakage area: as distance between the sherds increases, the breakage surface will have been subject to other processes and thus similarity in the surfaces becomes increasingly irrelevant – up to the point where intermediate pieces are lacking (the distance at which this is the case is influenced by the type of material).

F. *Geophysics*

Remote sensing is relevant for archaeology as it is generally non-intrusive and thus non-destructive [18]. It can provide essential information as to whether an excavation is justified in the first instance. Most remote sensing technologies base on the principle that differences in density or conductivity of the material can be measured up to a certain distance (Figure 3).

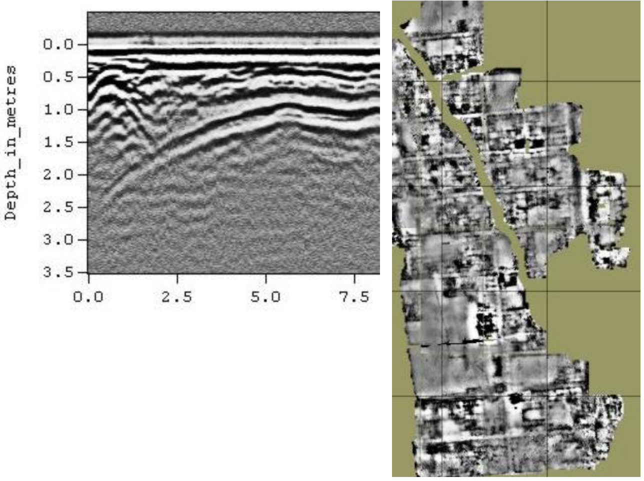

Figure 3. Ground Penetrating Radar (left) and map resulting from a resistance survey (right). Source: Wikipedia.

The resulting data is not meaningful on its own and only predicts a change in material within the ground. It does (currently) not allow any conjecture about the material, let alone about the structure itself. Even larger area scans can only indicate whether a regular structure (building) may be present at all.

Producing a visual depiction from the raw data takes considerable computational power – however, even more important is the assessment of the data against known structures and comparison of material distribution in surrounding ground (i.e. geological properties of the area). With such knowledge, the interpretation of the geophysical data could be improved considerably.

Approaches. The task is comparable to big data mining. Next to the obvious shape information, however, material properties of the objects / structures play an important role as they influence the details in the remote sensing data. As of now, most remote sensing data focus on larger structures, mostly due to the coarse granularity of the data in the first instance.

As with any human (or in fact animal) artefacts, non-regarding all past and present standardisation efforts, individual structures will differ from each, already just because of taste. In addition to this, local circumstances, as well as the differences in collapse and deterioration will lead to strong individual deviations.

These factors make direct data comparison, as is typically the case in other data mining tasks, difficult. Instead, the data must be considered indicative, in the sense that certain properties are correct rather than the whole structure – this includes an indirect match with the possible material properties, and a comparison to the rough layout. Layouts must be represented as key features with *likely* positioning, because, as noted, the individual layout will differ considerably. The likelihood of the layout may thereby be linked to the physics simulations discussed above.

G. *3d images*

3d scanning is a growing field of interest in general, but also more and more archaeologists are making use of photogrammetry to document the excavation [17]. There is a high risk here that this is considered sufficient documentation, though it cannot replace profile drawings or good maps, but we shall not follow this discussion in this paper.

Generating 3d models from pictures taken in the open field is still time consuming and error prone, where missing pictures can only be identified after generation of the point cloud, which can take days in itself. Since the excavation will have progressed by then, this can lead to considerable problems. Better methods are needed to assess quality and potential gaps right at the time of taking the pictures, and the process in general needs to become more flexible – both requires new algorithmic approaches that are highly related to performance optimisation in general.

One should also not ignore the fact that 3d scanning generates massive amount of data (i.e. the 3d points) that so far cannot be easily processed. Identifying an object in 3d space, i.e. which points belong to each other to form an artefact of its own, is still basically impossible. Similar challenges exist in 2d image analysis, where major progress has been made. So far most approaches simply generate a mesh of the whole scan, thus not allowing to (re)move individual objects, let alone perform an analysis on this level.

Since the advent of LIDAR scanning [18], processing of 3d images becomes an important factor for detecting hidden and obscured structures, very similar to identifying hidden structures in geophysical data (see section II.F).

Approaches. So far, most approaches rely on methods from 2d image processing, such as similarity of colour, identification of key features and of their relationship etc., but application in 3d is still very limited – not alone because the size of data is considerably larger (at least from n^2 to n^3).

Google and Microsoft already try to incorporate scans and 3d data from multiple (social) sources, but the sheer amount and computational complexity is still an unsolved challenge. Ideally, however, multiple sources are integrated in scanning, but notably, these will all have to be calibrated individually and the data then has to be cross-correlated first.

Some attempts also try to make use of additional data, such as arising from the accelerometer to pre-assess the quality and usability of the images, but there is no general good solution as yet and the amount of data will only increase.

H. *Others*

Additional aspects include simulation of decomposition of organic material, such as wood and flesh, but also of inorganic material, i.e. rusting of metal etc. Similar to the collapse of structures, reproduction of the original shape or even just identifying conjoining pieces is a challenge in itself.

Reconstruction in general relies on reference material, which typically only indicates general layout, not concrete shape (such as in the typology of vases). Identifying the appropriate structures from fragments is still basically unsolved given the complexity of the domain.

Many more challenges such as this exist.

III. CONCLUSIONS

The list of issues presented in this paper is far from exhaustive but already demonstrates the shortcoming of current computer science methodologies with respect to the needs of archaeology. Specifically, by addressing these challenges and incorporating knowledge from archaeology, the following improvements could be achieved:

- improved geological modelling: archaeology has knowledge about more short-term processes, such as soil deposition and collapse that can be exploited for engineering, city planning etc.;
- better human and agent models: anthropology and archaeology have information about human movement that is not reflected in simulation, thus leading to unrealistic movement and agency models;
- prospecting can benefit from prediction models and material knowledge gained from excavations;
- data mining and big data do not address complexities raised by such interdisciplinary fields as archaeology, which develops such methods for 100 years now;
- statistical analysis is an important field in archaeology and needs to be applied differently for network analysis, clustering etc. The feedback is rarely incorporated (see e.g. [20]);
- structure from motion is constantly being improved through landscape archaeology and field surveys [17] – new more robust methods and better object recognition are still being researched;
- most simulations model time forward from a given situation– in archaeology, time needs to be modelled backwards, i.e. leading from effect to cause which in turn improves simulation performance and analysis capabilities [6];
- dealing with incomplete data by adding assumption models: archaeology is using methods for this on a daily basis, yet big data still struggles with it;
- both fields need better methods to capture the probability and likelihood of complex data to be correct and to identify logical and improbable errors;
- reasoning needs to improve beyond stochastic data mapping and in particular needs to include the probability that two actions are related. Artificial Intelligence concepts from the 90ies already approach such issues on a limited scale.

Not only can computer science improve archaeology further, but also knowledge from archaeology can help advance computer science capabilities in particular for application in any human-centric simulation or modelling.

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