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Searching the Past in the Future

- Joining Cuneiform Tablet Fragments in Virtual Collections

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Abstract

Joining cuneiform tablet fragments are separated within and between collections worldwide. In previous work of the Virtual Cuneiform Tablet Reconstruction Project [VCTR, 2018], automated joins were achieved for virtual 3D Ur and Uruk fragments held within the same collections. By virtue of this fact, these physical fragments were in close proximity to each other and, therefore, manual verification of each join could be readily achieved. Now, for the first time, a long-distance join is reported between cuneiform tablet fragments separated by 1000 km.

Background

In Philadelphia in 2016 we presented the first computer algorithm for joining virtual cuneiform tablet fragments [Gehlken, 2016]. Virtual joins between fragments from within the same collection were successfully achieved without human interaction, solely on the basis of geometric computations on 3D computer models. At the end of our lecture we thanked the British Museum for its generous help in allowing us to join Ur fragments to improve our algorithm. We also outlined some ambitions for future work including the hope that we would soon be able to make joins between fragments housed in *different* institutions. In 2017, it was the British Museum that helped us again. Curator Jonathan Taylor suggested that we might try to join the fragments of the third tablet of the Old Babylonian copy of the Atrahasis epic [Lambert, 1969] written by the scribe Ipiq-Aya in Sippar around 1635 BC. This third tablet describes the flood and the building of the ark. A potential join between two fragments of this tablet had been debated for some 50 years. The possibility is summarised, as follows, by Irving Finkel:

> *"The crucial episode about the Ark and the Flood occurs in Ipiq-Aya's Tablet III. This tablet is now in two pieces. The larger, known as C_1, might just possibly join C_2 if they could ever be manoeuvred into the same room, but the former is in the British Museum and the latter in the Musée d'Art et d'Histoire in Geneva. One day I will try out the join…"*
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> Finkel, I.L. (2014). *The Ark Before Noah: Decoding the Story of the Flood.*

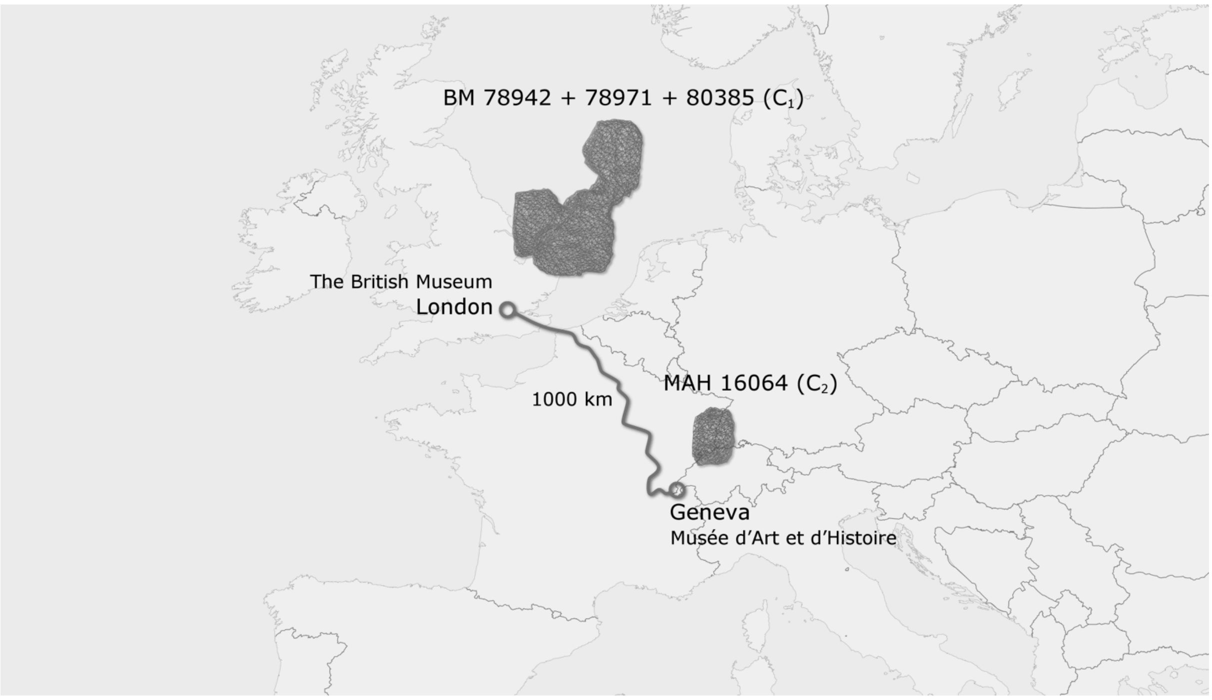

Figure 1 – The separated C_1 and C_2 tablet fragments

The problem behind manoeuvring the tablets into the same room is illustrated in Figure 1; physically attempting to match these fragments is not feasible given their separation of 1000 km. This is not an isolated case. Other examples of potential matches have even larger separations, with fragments separated between various parts of Europe, Iraq and the USA.

Although a physical matching attempt was out of the question, a virtual match using digitised versions of the fragments was conceivable. Two photogrammetric acquisition systems belonging to members of the Virtual Cuneiform Tablet Reconstruction Project [VCTR, 2018] were used to acquire 3D models of the fragments. Tim Collins travelled to London to acquire fragment C_1 (BM 78942 + 78971 + 80385) whilst Erlend Gehlken travelled to Geneva to acquire images of fragment C_2 (MAH 16064).

Acquisition of the Fragments

The first stage in making a virtual join is to acquire 3D computer models of the fragments to be joined. As part of the Virtual Cuneiform Tablet Reconstruction Project, a low-cost, portable acquisition system based on photogrammetric processing was previously developed. The system consists of a camera and turntable synchronised to a laptop computer and software that automatically captures sequences of 36 photographs at ten-degree rotational intervals. This system and methodology has been used extensively on fragments from the Ur collection held at the British Museum, as reported at the 2016 Rencontre Assyriologique Internationale [Gehlken, 2016].

i) Acquiring the Geneva Fragment:

MAH 16064 is a similar form-factor to some of the Ur tablets previously acquired, and we were able to use the existing acquisition system without modification, following the standard procedure. This involves, sequences of photographs being taken for obverse and reverse sides plus two or more edge-on orientations. Due to the size and geometry of MAH 16064, the edge-on poses were difficult to achieve. However, with the assistance from museum staff, edge-on poses were successfully acquired using foam blocks for stability.

(i) (ii)

Figure 2 – Acquisitions at (i) The British Museum, London and (ii) Musée d'Art et d'Histoire, Geneva

ii) Acquiring the London Fragment:

The C_1 fragment (already a composite of three joined pieces: BM 78942 + 78971 + 80385) was considerably larger than any tablet we had previously attempted to acquire, however, there were no fundamental problems in applying the same photogrammetric processing techniques.

Photogrammetry works at any scale and has found applications in modelling tiny objects, with dimensions of the order of microns, captured using electron microscopy, all the way up to large-scale applications such as terrain mapping and the acquisition of buildings and monuments with dimensions of the order of tens of metres. The only potential problem in our acquisition of the C_1 fragment was that the resolution and precision of the process scales with the size of the object. We had previously reported a 50-micron precision for small tablets approximately 25 mm wide. The C_1 tablet, being approximately ten times larger, meant we expected a precision of the order of 500 microns (half a millimetre). A more significant problem was the size and weight of the tablet, as well as its fragility (as a composite of several fragments glued together). The large fragment size required the creation of a new and larger calibration plate, approximately four times the size of the original, for the turntable. The fragility of the composite fragment meant that edge-on poses could not be attempted.

Automated Joining

With appropriate interfaces [Woolley, 2017], it is possible to attempt manual joining of fragments by manipulating their virtual models, however, without supporting tools, it can be very difficult and exceptionally time-consuming even for quite small numbers of fragments. For example, as shown in Figure 3, even when candidate joining 3D surfaces are aligned over each other, it can be difficult to assess exactly where they may connect. Automated joining has the advantage that it can compute optimal matching orientations and also yield statistics indicating the goodness-of-fit.

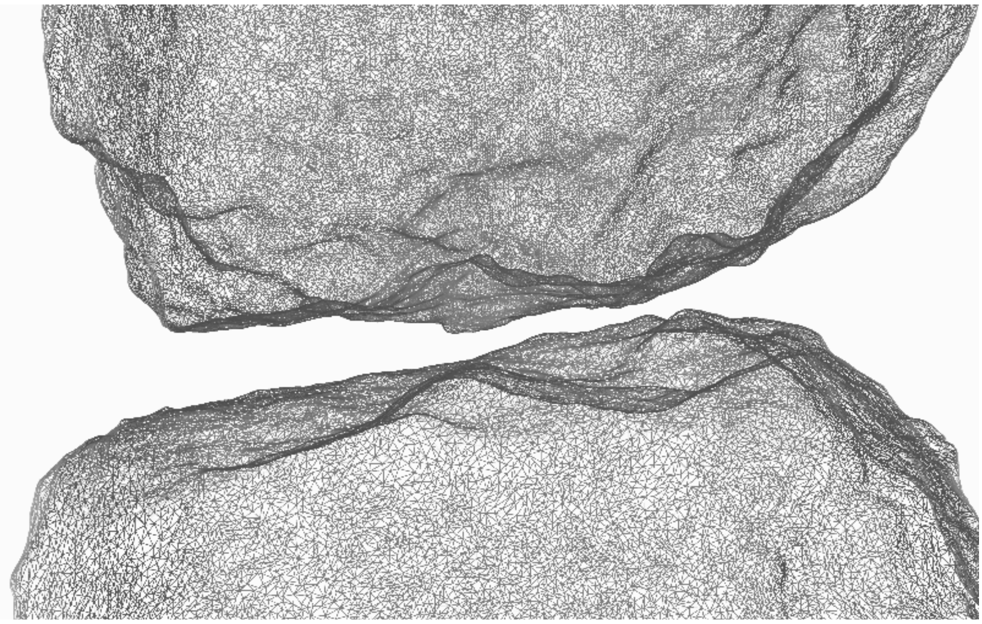

Figure 3 – A 3D mesh view of the joining edges of C_1 and C_2

The first stage of automated joining is to determine the minimum volume oriented bounding box of each fragment – this is equivalent to looking for the smallest possible cardboard box that the fragments will fit into. In many cases, the inscribed faces of the fragments will approximately line up with the faces of the box. Apart from slight rotations, which are to be expected (because the fragments are not perfectly rectangular), C_1 and C_2 aligned nicely in this way in their bounding boxes. The six sides of each box can, optionally, be annotated as text, tablet-edge, or broken edge and the orientation of the text noted. For example, looking at MAH 16064 (see fig. 2 (ii)), it is obvious that the obverse and reverse surfaces are text, the left-hand edge is a tablet-edge and the remaining edges are breaks that require testing for joins. This annotation is not essential but helps to eliminate joining attempts for impossible combinations. During the matching process, each feasible pair of box-sides is tested for a possible match using an iterative optimisation algorithm that aims to find the translations (i.e., movements) and set of rotations (i.e., 3D orientation) that results in the closest fit between fragments. The best result from these matching attempts is saved and presented as the result.

Cost Function Computation

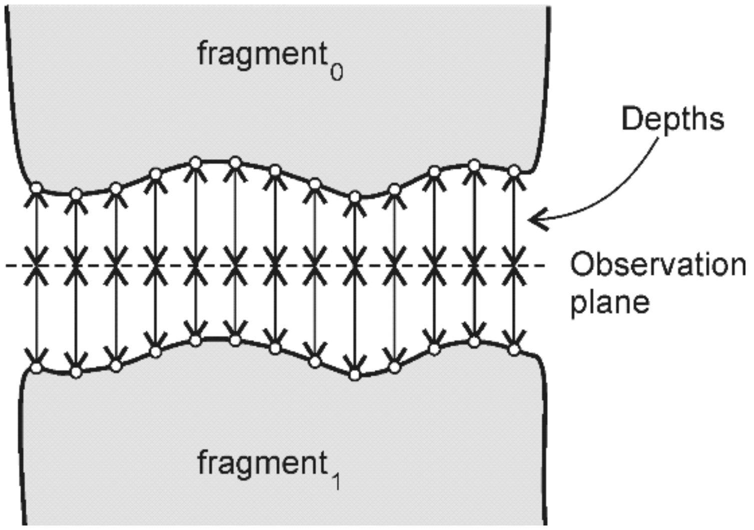

Figure 4 – Depths as calculated between candidate surfaces

The iterative optimisation process requires a measure of the goodness-of-fit for a potential join (a 'cost function'). The optimisation algorithm iteratively adjusts fragment translations and rotations to optimise the goodness-of-fit. We assess goodness-of-fit by calculating the distances, or depths, between pairs of opposing points on the two fragment surfaces as illustrated in this cross-sectional example shown in Figure 4. If all of the depths are equal then the fragments will join perfectly when brought together. Calculating the depths is computationally expensive but can be efficiently achieved using the 3D Graphical Processing Units (GPUs) now used in modern graphically-capable computers and mobile devices. Depth-map calculation is an essential part of the 3D rendering pipeline – it is needed to work out which parts of an object we can see (because they are nearest to us) and which parts do not require drawing because they are hidden by other parts of the object. Depth-maps of the fragment edges can be formed by taking the fragments one at a time, virtually viewing them end-on and extracting the depth information. If the depths from a pair of depth-maps are summed the distances shown in the illustration are calculated.

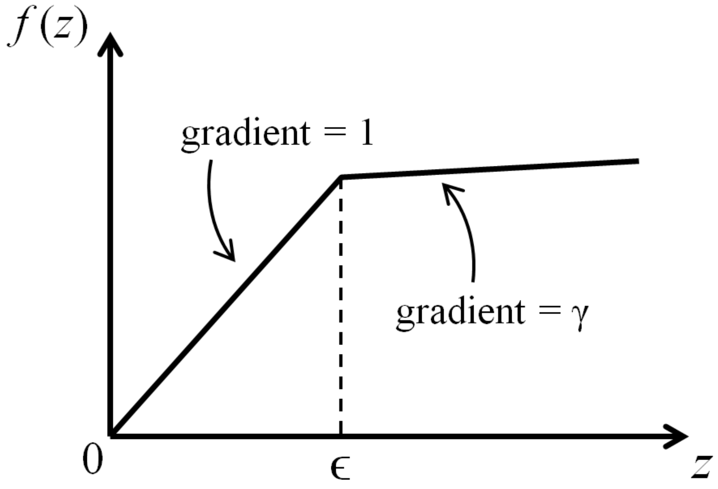

Figure 5 – The piece-wise linear cost function, *f(z)*, used by the optimisation algorithm.

The optimisation algorithm requires a single goodness-of-fit figure to assess a potential join. The simplest way of calculating this metric would be to simply sum all the surface-to-surface depths illustrated in Figure 4. This works very well for “perfect” breaks, but not so well where there is significant erosion or where the join is incomplete because of a missing fragment. We have found that applying a piecewise-linear cost function to each depth, z, as shown in Figure 5, addresses such cases well. Each depth that is less than a predetermined threshold, ε, (we use 2mm) is considered part of a potentially joining surface and the algorithm will attempt to find orientations that minimise these depths. Beyond this threshold, the cost function increases at a much lesser rate, thereby reducing the focus given to these depths which, therefore, have correspondingly less influence on the optimisation. The result is that non-matching pairs of points do not deteriorate (twist) the orientation out of the actual correct positioning. This method was first described by our team in 2014 [Collins, 2014] and was demonstrated using scans of tablets from the Eanna archive from Uruk. It has also been demonstrated using tablets from Ur [Gehlken, 2016].

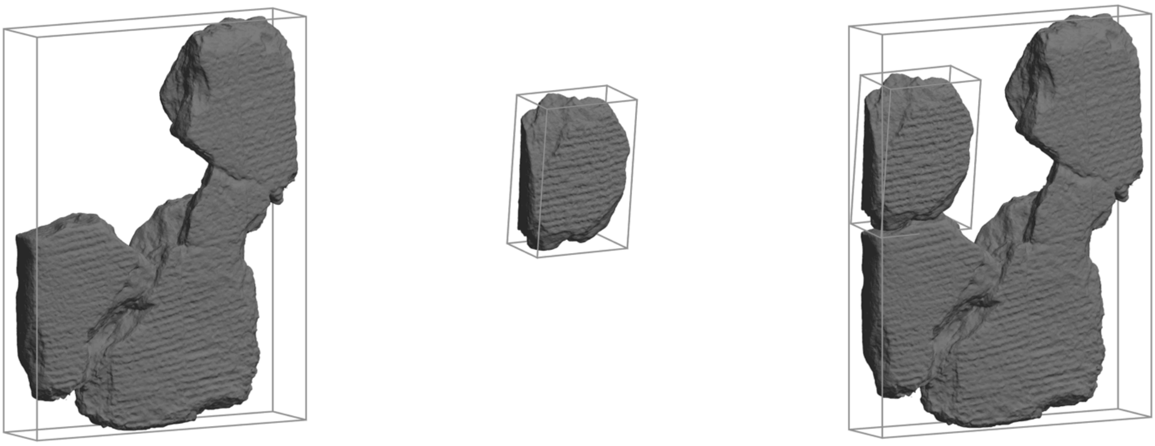

Figure 6 – 3D images of the individual fragments (left and centre) and the virtual join (right).

Figure 6 shows the result of the virtual automated matching algorithm. The fragments, along with their bounding boxes, are shown individually and, on the right, together in the pose determined by minimisation of the cost function. The rotation required can be seen by comparing the bounding box orientations. The match appears good with the tablet edge and the inscribed surfaces lining up well. What is not clear from this view is the quality of the actual join. This can be assessed from the depth maps.

Examination of the Join

Figure 7(i) shows the depth map of the upper edge of the left-hand portion of tablet C_1 (the BM 80385 part of the overall composite). Figure 7(ii) shows the lower edge of C_2 (MAH 16064) viewed from below but mirrored so it can be more easily compared with Figure 7(i). Ideally, one would be a ‘negative image’ of the other. It is certainly possible to see complementary features in the two depth maps, a valley in C_1 corresponds to a matching ridge in C_2, but to rigorously test the overall goodness-of-fit, we need to examine the sum of the two depth maps.

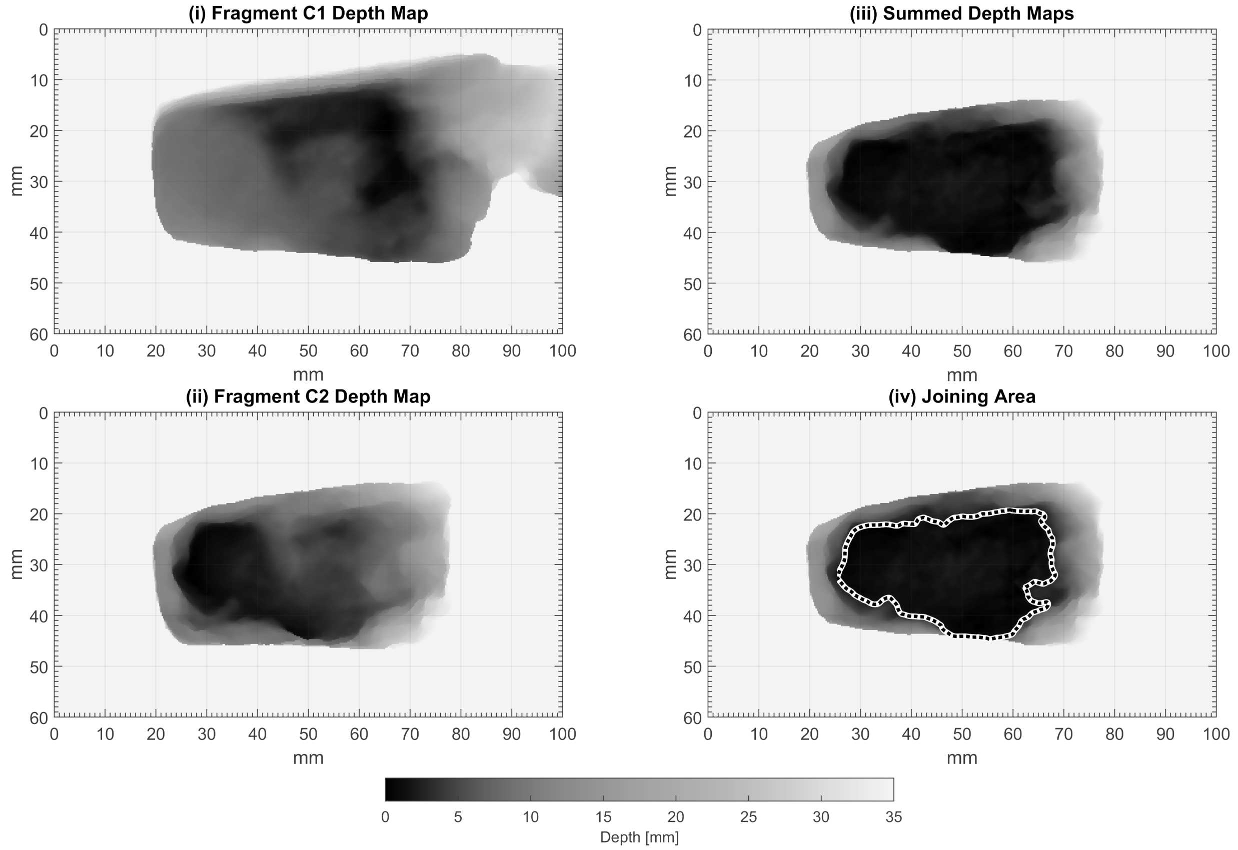

Figure 7 – (i) and (ii), Depth maps of the two joining surfaces, (iii) the summation of the depth maps showing the distance between the virtual surfaces, (iv) the joining area (defined by the contour where the summed depths fall below 2mm).

The summed depth map, Figure 7(iii), has had the minimum summed value subtracted (equivalent to bringing the two fragments into contact). Black areas on the summed map correspond to zero depth and indicate perfect joining. Areas appearing in lighter grey tones are virtual separations of several millimetres but these only appear at the outer edges of the join and are caused by the erosion clearly visible on the fragment surfaces. Within the joining surface, illustrated by the contour in figure 7(iv), the depth match between the surfaces is very good across the entire middle region. The evidence of these results confirms that the tablet fragments do, indeed, join.

Following the first announcement of these results at the 2017 Marburg Rencontre Assyriologique Internationale, the computational detail of the method has been published within the technical virtual community of researchers [Collins 2017a; b] and also disseminated more widely for public engagement [Woolley, 2018].

Conclusions and Further Work

Tablets C_1 and C_2 have now been proven to join despite the physical fragments remaining separated by 1000 km throughout the whole process. We previously demonstrated that virtual cuneiform tablet reconstruction can be used to automatically find joins within a collection. We have now shown that there need be no geographical limitations and joins can be found between collections in different parts of the world. In this case, the technique was used to demonstrate a match that was already suspected. We hope, in the future, to also demonstrate previously undiscovered joins. Administrative archives, parts of which are held in different museums, could never otherwise be joined. Even if 3D printing is used to enable fragment analogues to be collocated, the joining task is intractable for human reconstructors to achieve manually. Unlike humans, computation is available 24hrs per day with high precision and accuracy. Now that this process has been fully automated, only the 3D models would be required and then whole archives could be virtually reassembled.

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