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Using 3D Visualisation in the Repair of Intra-articular Fractures

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Abstract

The overall aim of this work in progress is to use visualisation to provide a tool for pre-operative planning of surgery on complex fractures, in particular for intra-articular fractures. Currently, a patient suffering from an intra-articular fracture has a high risk of developing arthritis if the fracture is not restored to an exact anatomical position. The visualisation of bone fractures may provide useful information that could assist the orthopaedic surgeon. The intention is to create a prototype using 2D and 3D visualisation to manipulate bone fragments on screen.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modelling: Curve, surface, solid, and object representations

1. Introduction

Currently there is a high risk of a patient developing arthritis within two years of suffering an intra-articular fracture if the fracture is not restored to an exact anatomical position. This research is looking at using computer visualisation as an aid to help surgeons in the repair of intra-articular fractures with the intention of achieving a repair with the smoothest articulating surfaces possible.

Imaging and visualisation has been used successfully in medicine for many years [DEV99]. X-rays, or radiographs, were the first medical images used for diagnosis. Before such images were developed, medical training in anatomy had to be done on cadavers [CZ07]. X-rays are images which show a cross-section of internal structures, showing dense tissues, such as bone, more clearly than soft tissues, such as muscle. Using X-rays for diagnosis has been developed further by Computed Tomography (CT) which produces a series of cross-section images, often called "slices". These can be processed by a computer to produce a three-dimensional (3D) image which can provide information about skeletal fractures in a non-invasive way, thus removing the need to cut open a patient to discover the severity of the fracture. This could allow surgeons to see images of the fracture on-screen and plan appropriate surgery before actually performing the operation. Figures 1 and 2 illustrate how a series of cross-sectional slices, where an object appears in each slice, can be built up into a 3D solid.

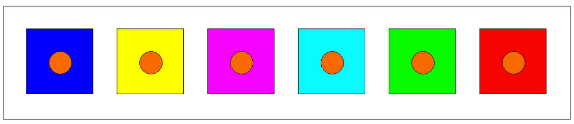

Figure 1: *Series of 2D slices.*

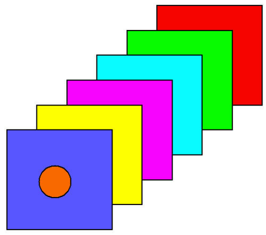

Figure 2: *3D solid created from 2D slices.*

The "Visible Human Project" is an example of a medical application using computer visualisation [BAN02] where a person's whole body has been scanned and visualised. The planning for this project began in 1989 and the first data set was released in November 1994. A male human (after death) was scanned, frozen, scanned again, and then cut into 1871 axial slices at 1mm intervals which were then photographed and digitised. This was the first time that accurate details of some human internal organs were obtained, and it is worth noting that as a result researchers at Columbia University found several errors in anatomy textbooks. Figure 3 shows an example of a photograph and a CT slice from the visible human project.

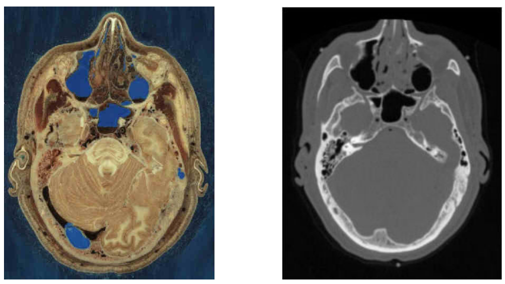

Figure 3: *Images from the Visible Human Project obtained from the United States National Library of Medicine.*

2. Visualisation from CT scans

The CT slices, which consist of grey-scale density values, can be built up into a 3D solid by using an isosurface. This is a three-dimensional surface that represents points of a constant value within a volume of space. One problem here is that the density value must be chosen correctly if only the bone surface is to be displayed. An image which also shows skin, or fat, or muscle, could obscure the bone fracture. Moreover, noise or errors from the scan may be a problem. Figure 4 shows an image from CT data where the layer of fat can also be seen which makes it more difficult to see the bone structure.

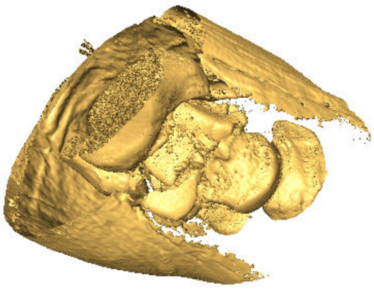

Figure 4: *Image showing both soft tissue and bone. (Image created using AMIRA software of data acquired from Derbyshire Royal Infirmary)*

In the past surgeons would look at a series of CT slices and build up a 3D image by "mind's eye". In fact, according to Gordon Harris [MZ05], when Massachusetts General Hospital started their 3D imaging service in February 1999, some of the staff thought it was an unnecessary "novelty for making pretty pictures" because they had been trained to read the 2D images and assemble in their minds a 3D model, see figure 5.

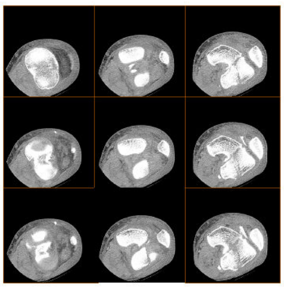

Figure 5: *Series of 2D CT slices of data acquired from Derbyshire Royal Infirmary.*

Therefore it may take surgeons some time to become experienced enough to use successfully a 3D image that can be viewed from different positions. To help alleviate this problem it may prove useful to combine 2D and 3D views, for example as Cohen and Brodlie [CB04] suggest in their focus and content approach.

The data from the CT slices can create a 3D image, but it would simply be shades of grey because the data values are only grey-scale values. It may be easier to understand a coloured 3D image, so directional lighting and false colour can be added to the image as illustrated in figure 6.

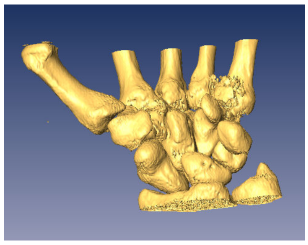

Figure 6: *Image from CT data of part of a hand. (Image created using AMIRA software of data acquired from Derbyshire Royal Infirmary)*

It may also be useful to consider stylised rendering, for example, non-photorealistic rendering, to improve the understanding of the bone images [LYC07]. This technique could improve illustrations of medical images, in particular in this research because the stylised rendering may be able to emphasise certain features relevant to the diagnosis and therefore the repair of the fracture.

3. Identification of bone fragments

The next step in the process, once the 3D image has been created, is to identify the bone fragments. Segmentation of the image should identify the bone fragments, and colour can be added to help the surgeon see all the fragments from the fracture. The process of segmentation could be done manually by the surgeon but this research aims to be able to perform segmentation automatically. To do this we would need to know the density values for bone in the data from the CT scan. It may prove necessary for some manual intervention to finely tune the threshold for the density values used. The segmentation should allow us to pick out just the bone from the whole data set.

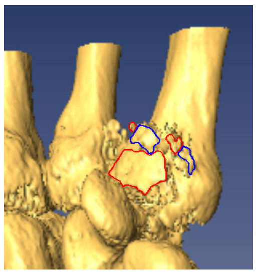

Figure 6: *Visualisation with extra colour added to show segmentation of some bone fragments (image created using AMIRA software of data acquired from Derbyshire Royal Infirmary).*

4. Manipulation of bone fragments

Once the bone fragments have been identified the surgeon needs to be able to reposition the fragments to obtain the smoothest possible surfaces. While the surgeon is attempting to find the best fit of the bone fragments it may help to have more than one view of the fracture visible at the same time. Showing the three different 2D views of the fracture (axial – horizontal cut away view as seen from above, coronal – vertical cut away view as seen from the front, and sagittal – vertical view cut away view as seen from the left side) may prove useful, but updating continuously as a fragment is manipulated would be essential.

Another complication in the manipulation of the bone fragments is that the fragments must not be allowed to overlap; therefore a collision detection routine must be incorporated into the programming. It may be useful to use a hierarchy of bounding shapes, as suggested by Silver and Gagvani [SG00], to speed up collision detection. The hierarchy of bounding shapes could be spheres which are created around the objects in ever decreasing circles. When a collision between outer bounding shapes is detected then the next tighter fit boundary is tested. The process is repeated until either no collision is detected, or the object itself is reached.

5. Review of Object Matching

One of the aims of this research is to investigate whether the computer can analyse the position of the fragments and suggest a better match of fragments if one can be found. Therefore, once the surgeon considers that the best possible fit has been made by manipulating the fragments on screen, the computer needs to analyse the smoothness of the resulting surface of the fracture. If the fragment is not a perfect fit the best possible fit needs to be found automatically.

One method which may be useful in this work is the Iterative Closest Point (ICP) algorithm [BM92]. Once the closest point between two objects is found, the algorithm looks for matching features on each object, calculates the transformation which would map one feature onto the other, and then applies the transformation to move one of the objects closer to the other. The process is repeated until acceptable convergence of the two objects is achieved.

Other work in this area has been done by archaeologists who have found reconstructing 3D objects automatically has become more important in the last few years due mainly to the increased use of shape acquisition devices in field archaeology. The main problem of archaeological reconstruction is that the original colour and texture of the fragments have been lost. This relates closely to the reconstruction of bone fractures because fragments visualised from CT scans have no colour. The process of finding the best fit by trying to fit the pieces together like a jigsaw puzzle has been tried by archaeologists trying to reconstruct broken pottery fragments [PKT01 and PK03]. The broken pottery fragments were scanned and then the faces of each piece of pottery were analysed to try to find possible matching pieces. This example was actually quite successful because about 90% of the objects were correctly matched. The 10% not correctly reconstructed included objects where surfaces were similar and the matching errors were so small it was not possible to match the fragments correctly (for some objects, humans couldn't either).

Automatic re-assembling of broken 3D solids has also been presented by Huang et al [HFG*06] who developed a matching algorithm using only the geometric information from the broken surfaces. This method classifies all the surfaces as either original faces or fracture faces before attempting re-assembly.

Other work that may contribute to this research are attempts to solve 2D jigsaw puzzles automatically. Many jigsaw puzzle solving algorithms have been developed, but most have considerable restrictions on the size and type of jigsaw which can be solved successfully. However, there is one novel algorithm in particular developed by Goldberg et al [GMB04], which can solve more difficult jigsaws than could have been solved before, dealing with puzzles of up to 200 pieces and solving those with pieces that border more than four neighbours. The algorithm uses a feature-based method, searching first of all for indents on each piece, secondly straight sides, and finally outdents, or tabs, on each piece. To check whether two pieces match, the distance between the edges of two possible matching pieces is measured, as illustrated in figure 8.

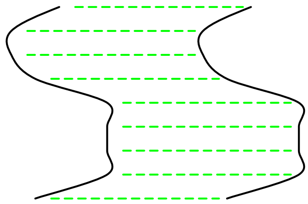

Figure 8: *Measuring the distance between jigsaw pieces.*

6. Progress so far

So far this work in progress has moved in several directions. Real CT data has been obtained from Derbyshire Royal Infirmary. Single 2D slices can be viewed, and current programming is attempting to detect the edges of the bone using the Rotating Squares method [MAP00] which is based on the Marching Squares algorithm developed by Lorensen and Cline [LC87]. The initial program did not detect the edges of the 2D image very well as can be seen in figure 9. The slightly different pixel values caused too many edges to be found. The results so far suggest that some thresholding of the density values may also be necessary before the bone surface can be detected accurately.

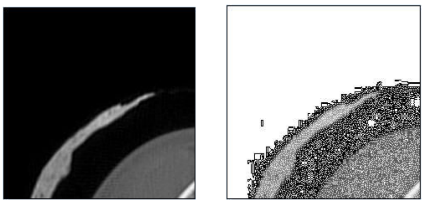

Figure 9: *A CT slice (left), edges detected (right)*

To cater for independent manipulation of the fragments, i.e. rotation and transformation, simple shapes have been created to use as test data and some manipulation of these objects has been achieved. Figure 10 shows screen shots from the program which allows the "L" shaped object to be rotated through any angle and moved any direction and any distance to fit against the diamond shaped object. The grid background was used simply to aid the calculations for checking the movement of the objects.

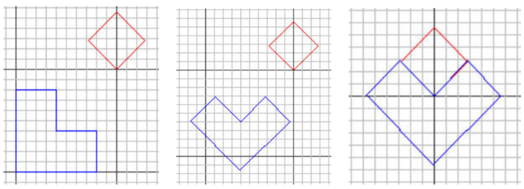

Figure 10: *Screen shots from manipulation program*

Some analysis of the edges of the objects has been done and a visualisation of the distance between the edges of the objects and some surrounding border shape can be displayed. Here it is simply the distance displayed as the height in a box graph below the object. Mlejnek et al [MVG04] have used a similar idea of visualising unfolded objects to aid calculation of the thickness of articular cartilage. Figures 11 and 12 show screen shots from the surface analysis program when a circle is used for measuring the distances. The surface of the diamond shape object is analysed and the result displayed on screen. It was clear that the results would differ according to the position of the centre of the circle so a different approach is needed to give consistent analysis results.

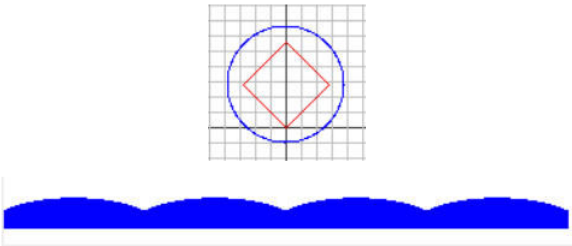

Figure 11: *Screen shots from surface analysis*

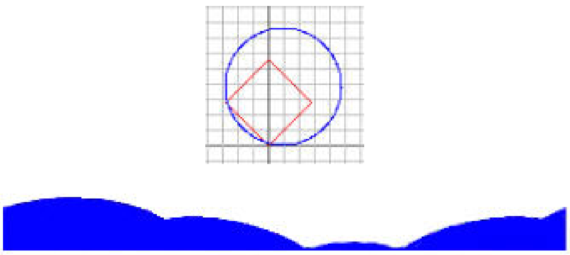

Figure 12: *Screen shots from surface analysis*

However, work with this method of analysing the surfaces indicated that calculating the distance from the object to a surrounding rectangle would produce the more consistent measurements needed here. Figure 13 shows screen shots of the surface analysis of the diamond measuring the distances from the vertical sides of a surrounding square.

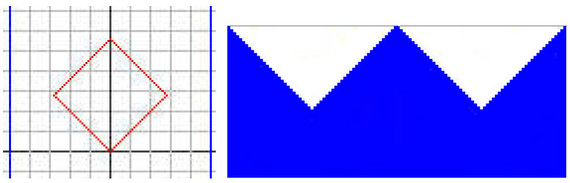

Figure 13: S*urface analysis using a surrounding square*

Similar analysis of the "L" shaped object gave the results shown in figure 14, and the object rotated in figure 15.

Figure 14: *Surface analysis before rotation*

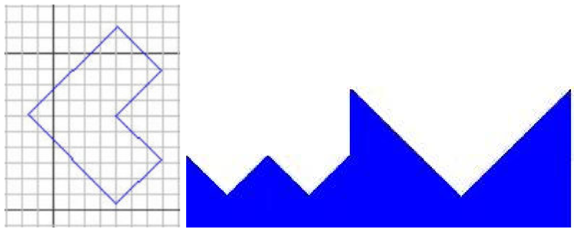

Figure 15: *Surface analysis after rotation*

At this point it was decided to use more realistic shapes for attempting the match. It was also decided to ignore all smooth surfaces, once the surfaces had been analysed, because a smooth surface would not be likely to be a broken surface. Two jagged shaped objects were then created for more realistic testing purposes, see figure 16.

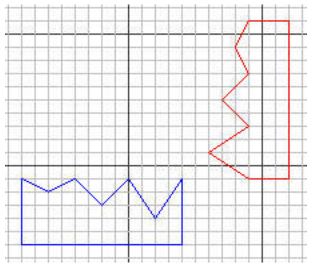

Figure 16: *Two jagged shaped objects*

Analysis of the jagged surface of the red object (upper right) provided the visualisation shown in figure 17, and analysis of the jagged surface of the blue object (lower left) is shown in figure 18.

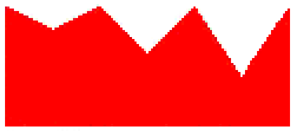

Figure 17: *Analysis of red object*

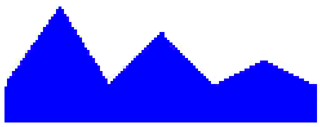

Figure 18: *Analysis of blue object*

The program was then able to match the results and move the two objects together as shown in figure 19.

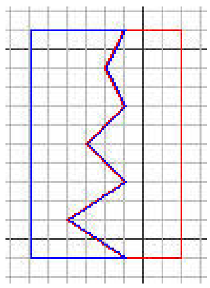

Figure 19: *Objects correctly matched and repositioned*

7. Further work

Further work includes extending the 2D processing to deal with 3D objects. The same method used to analyse the 2D surface will be adapted to work in a similar manner in 3D. Rotating the objects when working in 3D is expected to be more complicated because there will be many more possible positions when attempting to fit the broken surfaces back together, and there may be issues in finding a suitable combination of views of the fragments to allow the user to interact easily with the system.

Once the process is working on suitable 3D test data, then data from CT scans will be used. The resulting prototype will be evaluated by expects in this medical field who will look at images from both test data, and some samples of anonymous real data, to compare the images of the fractures before manipulation of the bone fragments with the images of the fractures after manipulation.

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