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# Anatomy Education using Rapid Prototyping

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**Abstract**

*Rapid Prototyping is a technique which is rapidly gaining interest amongst the medical community for many different purposes. In this paper we present a novel tool that uses rapidly prototyped models to serve as an interaction device for the teaching of anatomy. The user interacts with volume data of real human organs in an Augmented Reality environment delivered via a Head-Mounted Display. We include a description of how all of the key parts of the system operate and describe their integration. Our hypothesis is that this approach provides an effective and compelling alternative to cadaver based anatomy education.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality I.3.6 [Computer Graphics]: Interaction Techniques H.5.2 [User Interfaces]: Interaction Styles

## 1. Introduction

We have previously reported on the potential application of computer graphics technologies for anatomy education [TJL06]. In particular we have described a mixed reality anatomy teaching tool in which a student manipulates the on-screen position and orientation of a volume rendering of segmented anatomy using a plastic model of the organ to be observed. One drawback of this approach, however, is that the plastic model has a fixed topology and it often does not reflect the variation found in patient specific volume rendered data sets. At the same time, we have noted that the accessibility of Rapid Prototyping (RP) technologies has been increasing, particularly with the launch of several bureau services that will produce RP models at a reasonable cost. A logical step has therefore been to integrate RP models into our anatomy teaching tool. The gold standard for anatomy education remains the dissection of a cadaver and this provides a student with an excellent spatial understanding. However, as ethical and financial issues make access to cadavers less and less common, we hypothesise that new technologies such as RP and augmented reality can provide a viable alternative.

This paper begins by summarising existing uses of RP in medical applications. Whereas there are many medical uses reported in the literature, few examples can be found of RP being used specifically to improve anatomy education. This is due to the high cost that has traditionally been required to invest in RP hardware. We are now able to address this apparent gap in the market. Section three describes the integration of RP models into our mixed reality teaching tool. We also report on the advantages of using video eyewear, and improved functionality such as support for virtual resection. The paper ends with a summary of current results and a discussion of the usefulness of the system.

## 2. Background

Rapid Prototyping (RP) is the practice of taking 3D virtual models (usually an *stl* file, a stereolithography file format for CAD software) and creating a physical equivalent. Typically rapid prototyping machines construct models layer by layer, which are then attached to each other by a process such as gluing, or fusion using a laser. The models tend to be made from a plastic material, although some machines may use paper, cardboard or a metal. RP has been referred to as Automated Fabrication [OY99]. An Automated Fabrication system has been described by Burns [Bur93] as one in which:

1. The process should take in raw material in some shapeless form such as blocks, sheets or a fluid, and produce solid objects with a definite shape.
2. The process must do this without a significant amount of human interaction.
3. The process must produce shapes with some degree of

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three-dimensional complexity. This criterion eliminates the forming of simple tubes or rods by extrusion and cutting or drilling of simple holes in sheet material.
4. The process must not involve the manufacture of new tools for each different shape to be generated (part specific tooling). This criterion eliminates all types of moulding and casting, EDM (Electrical Discharge Machining) die sinking and copy milling.
5. Each item produced must be a single object not an assembly of component parts thus eliminating joining operations such as gluing, welding and riveting.

RP is now becoming more affordable as hardware costs fall and because companies such as Inition (`http://www.3dmodelprinting.com`, and Ambler (`http://www.expressprototyping.com`) provide a bureau service so that the purchase of specialised equipment is no longer necessary.

Rapidly prototyped models can be produced to faithfully reproduce anatomy segmented from CT and other medical data and can even use pumps to circulate fluid, mimicking blood flow and permitting contrast media injections, with realistic guidance using through-transmission of light or real fluoroscopy. Webb [Web00] and Gibson et al. [GCC*06] provide useful surveys of most current uses of RP to assist medical applications. In particular, they identify oral and maxillofacial surgery, orthopaedic applications, forensics, prosthesis development and tissue engineering. A brief overview of some of these areas is given below.

Elastrat (`http://www.elastrat.com`) produce in vitro models of the human vascular system with the aim of training surgeons. The models produced allow a surgeon to rehearse patient specific tasks prior to an operation. Another system that uses rapid prototyping is described in [CHB*98]. This system allows a surgeon to rehearse the insertion of stent-grafts, a procedure which can be difficult to perform without accurate data due to differences between human anatomy and that of animals which have traditionally been used for the training of this procedure, and because the pressure caused by the flow of blood in the arteries can be difficult to predict. Such complex RP models remain expensive, however, and if used for procedures training, will eventually be destroyed by multiple needle punctures. They also lack a facility to easily alter anatomy and pathology.

The manufacture of prostheses and implants is another growing use of RP (e.g. `http://home.att.net/~castleisland/med_lks.htm`). Such applications allow for custom made parts to be constructed, ensuring that a replacement is well suited to the patient, whereas in the past a replacement joint, such as a hip, would be selected from a range of parts of standard sizes, and therefore may not be an optimal solution for the patient. ProtoCAM (`http://www.protocam.com/html/medical.html`), is a company that also specialises in RP for medical applications. Among the products they offer are rapidly prototyped prostheses, or anatomical models for treatment planning, in addition to tools used for medical procedures.

The Rapid Prototyping Centre (RPC) at the Milwaukee School of Engineering (`http://www.rpc.msoe.edu/medical.php`) uses Rapid Prototyping in a similar way, however they also outline the use of RP in education by making models for school children to learn from, as a way to reproduce ancient artifacts, and also to reproduce bone structures for forensic investigations where the original might only be available for a short time.

There are few other uses of RP reported for anatomical education, however. Our contribution is to address this apparent gap and to integrate RP models with the Bangor mixed reality anatomy education tool. This work is partly inspired by the work described in [GSSO05] which uses an RP model as an interface to an augmented reality environment to enhance a molecule models' semantic content and show dynamic properties.

## 3. Methods and Tools

This section provides an overview of how our earlier system described in [TJL06], has now improved the educational experience by integrating RP models and other new functionality. The core APIs used are the ARToolkit (`http://www.hitl.washington.edu/artoolkit`), an optical tracking system, and The Visualization Toolkit (VTK) (`http://www.vtk.org`) which is a versatile software toolkit for rendering many different data types. The mixed reality environment has been designed so that the software supports different technology components and allows them to be interchanged easily.

### 3.1. Segmenting Data

The teaching tool can start with any medical data set so that a large variety of anatomical models are supported, and variations between people can be explored. We acquired an anonymised CT data set of an abdomen for testing purposes, containing the liver, the kidneys, and a portion of the stomach, as well as a section of the spine and the rib cage. The first step is to segment the anatomy of interest from this data set.

Currently, we are using a segmentation tool called ITK-Snap (`http://www.itk-snap.org`) [YPH*06], a free software package built using the Insight Toolkit (ITK), available from `http://www.itk.org`. ITK provides many classes which are designed to allow for rapid development of software that can segment and register data. ITKSnap is a GUI based program which enables the user to use manual segmentation, or automatic segmentation using an extremely tunable region growing algorithm; regions are grown from one or more spheres placed by the user within the volume and their growth is controlled by a variety of weighted forces

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that can be adjusted by the user. To segment our abdomen dataset we used the automatic option to create our initial segmentation data, which was subsequently manually modified to correct for the inaccuracies caused at tissue boundaries.

Once the segmentation step is complete the individual organs can be extracted and stored in separate voxel data set files. These are converted into the VTK file format using Eric Vidholm's raw to vtk conversion utility `http://www.cb.uu.se/~eric/vtk/`. Using VTK, we can then display a volume rendering of the anatomy models in real time providing the usual transfer function support to set colour and opacity values.

**Figure 1:** *The mannequin liver model*

### 3.2. Creating a RP Model

Previously we used a plastic model from an anatomy mannequin 1 as the user interface device for the software. This model is typically not a good match to the actual patient specific anatomy. The new system therefore replaces the mannequin model with an RP model. Using the segmented liver data as an example, a multi-stage process is required to produce an stl file that is an acceptable format for processing by an RP bureau service. The first step in this process is to create an iso-surface of the volume data, (Figure 2, top), and save the result as a VTK polygon data file. The resolution of the CT data is usually not high enough to produce a smooth isosurface - in particular the larger interslice distance is a problem. We therefore apply a smoothing filter to the polygon data, producing the result shown in Figure 2 (middle).

The main difficulty is in the selection of appropriate parameter values to control the smoothing algorithm. The two parameters used are the number of iterations to be carried out, and the relaxation factor. The latter controls the maximum displacement of any vertex in a single iteration and can prevent large ridges appearing in the resulting surface. The parameter values that were chosen were decided on by a trial and error process.

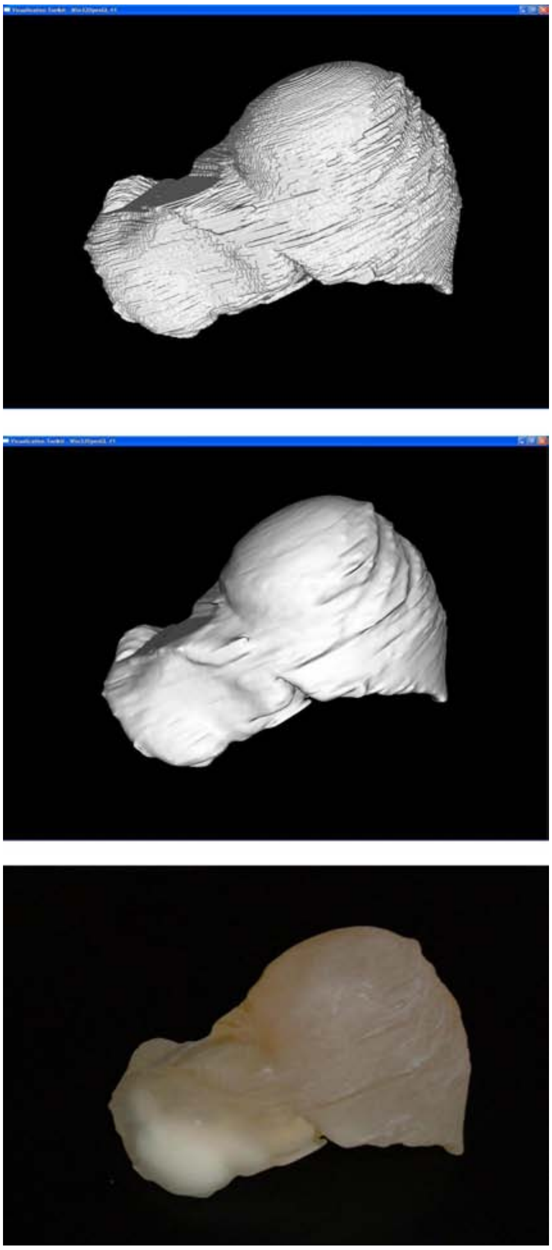

**Figure 2:** *The various stages of model development. The top image shows the original iso-surface, the middle image shows the smoothed and polygon reduced surface and the bottom image shows the finished RP model.*

The output from the smoothing algorithm was then passed into a decimator to reduce the polygonal complexity. The result can then be output as a stl file and sent to an RP bureau service. The physical model is made using an InVision 3D printer and is constructed from a strong, versatile plastic material. The RP model shown in 2 (bottom) cost £200 to

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fabricate, but this price is expected to fall as the RP market develops.

### 3.3. Tracking

Our mixed reality environment requires anatomy models to be tracked. As the user manipulates a model in their hands, the volume rendered version is set to the same orientation. One tracking solution is to use the ARToolkit and to make use of the computer vision algorithms implemented in this software. To do this each anatomy model is therefore assigned a unique ARToolkit pattern, which is attached to its surface. The corresponding volume data for the anatomy models is loaded into memory at program startup for quick access when a new pattern becomes visible. In order to display the correct volume data the tracking component of the program passes an enumerated value to the rendering component; if the correct volume is already displayed then nothing is done otherwise the input to the volume mapper in the VTK pipeline is changed so that the correct volume is rendered. The main problem with the ARToolkit, however, is that the pattern can often become obscured and cannot be tracked correctly.

As an alternative to the ARToolkit computer vision tracking we have also made use of magnetic tracking, in particular a flock of Ascension Technologies miniBIRDs. The setup (Figure 3) consists of two miniBIRD 800 units, each with a sensor attached, and a transmitter attached to the master unit. The master unit is attached to a standard desktop PC using an RS232 interface. A sensor is then attached to the RP model by fitting it snuggly into a small hole drilled into the surface. The miniBIRD system was chosen because it is a full 6 degrees-of-freedom system and therefore allows a much greater range of motion than an optical tracking system. This system is much less suseptible to noise than Ascension's previous products, and therefore no smoothing of the tracking data is required.

### 3.4. Display Paradigms

Our software supports two display paradigms; the first paradigm supported uses a standard monitor, and the second uses a Head-Mounted display (HMD). The standard monitor version of the software is developed from our earlier work, in which the real and virtual views were displayed in two side-by-side windows in which the position and orientation of the volume rendering was controlled by moving the mannequin organ. Feedback from our anatomy colleagues at Bangor indicated that this was acceptable. However to take full advantage of an augmented reality paradigm, we need to combine real and virtual scenes more effectively [Azu97].

To render both the live video feed and the volume rendered anatomy in the same window, rather than in two side-by-side windows, real time registration of the two scenes is the main requirement. We found that when the ARToolkit pattern was at the centre of the screen the VTK rendering was co-incident, however as the pattern moved the rendering moved at a different rate. The effect of this was reduced by altering the view angle of the VTK camera being used, such that the parameters of the virtual camera were close to identical to those of the real camera being used to provide the live video feed.

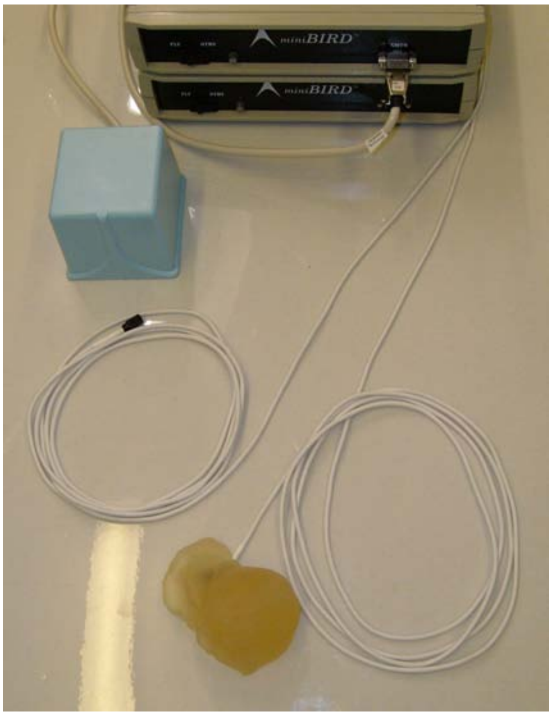

**Figure 3:** *The flock of miniBIRDs attached to the RP model*

To render our scene conveniently for the user we use a HMD. The HMD that we use is an Icuiti DV920, which is a relatively inexpensive HMD, which consists of a spectacle type head mounting and contains two LCD screens. Each screen has a resolution of 640x480, and also an independent focus control. The DV920 uses page flipping to display the separate images to each eye; it supports a refresh rate of 60Hz and displays alternate refresh cycles to each eye, so that the screen for each eye is updated thirty times per second.

To align the real and virtual worlds successfully in the display, the HMD was tracked using our flock of birds. One of the sensors from our flock was attached to the HMD, which made the system a little more awkward for the user as the addition of a second cable greatly reduced the users' range of motion.

To support the HMD the existing software had to be modified so that VTK would render one viewpoint for each display. VTK does not explicitly support a display of the type that we were using, however as VTK supports Crystal Eyes stereo glasses, another page flipping stereo technology, we were able to enable support for Crystal Eyes and view our scene in 3D through the HMD without having to make any further changes.

### 3.5. Slab Rendering

Slab rendering describes the practice of rendering a slice of an arbitrary thickness of a volume. This functionality allows the student to more effectively explore the anatomy data. To implement slab rendering we extended the clipping plane support already provided, and added a second clpping plane at an arbitrary distance, such that the normals of the two planes were pointing in opposite directions and away from each other.

### 3.6. Virtual Resection

We have carried out much experimentation on virtual resection to provide a virtual realisation of cadaver dissection where a portion of an organ, such as the liver is removed.

The first challenge in implementing virtual resection was to find a way in which the cut-away data could be removed from the users view. This is currently achieved by accessing the raw data and setting the values of the voxels within the resection area to zero. Currently the resection area is hard-coded as a pair of tetrahedrons, used as an approximation to a sphere; the resection tool is represented on screen as a sphere (Figure 4 botttom).

We maintain a data structure that records the centre of the cut away regions and the normal to the tools cutting direction (which isn't necessary for a sphere, however if we were to introduce a resection tool of any other shape, then the orientation of the tool becomes more important). This allows us to include an undo function in the software so that any mistakes could be corrected without the user having to restart their session.

The current challenge for virtual resection is registration. In its current state the portion of an organ being removed is not in the same place as the resection tool. This problem is being experienced because VTK's co-ordinate system is oriented and scaled differently to that of the Flock of Birds, therefore we must find a calibration technique which provides us with homogeneous matrices that can convert between the two co-ordinate systems. This is a one-time calibration step if a sensor is attached securely to the RP model and another to the HMD.

**Figure 4:** *Showing the anatomy overlaid on the video image (top), and the resection tool in action (bottom)*

## 4. Results, Conclusions and Future Work

### 4.1. Results

Our early results for the system are promising. Apart from a few small registration issues the system functions as we intended. Performance is approaching what is normally considered acceptable for a real-time system, with the software operating on a mid-range PC with an Nvidia GeForce 8800 GTX graphics card at over 10 frames per second with small volumes, and with future hardware developments, real-time should soon be realisable.

The frame rate performance of the latest ARToolkit version of the software is greatly improved over that reported previously, mainly due to changing the volume mapper in our VTK pipeline from a Ray Cast Mapper to a 2D texture based mapper, which moved the workload towards the GPU from the CPU. Using the unsegmented abdomen CT data set subsampled at 256x256x123 voxels, we achieved a frame rate of 3fps, and a frame rate of 10fps when the data set is sub sampled at 123x123x61 voxels. For our segmented liver model (measuring 287x235x209 voxels) the performance was about 1.5fps. We also used an alternative test system that had an Nvidia Quadro graphics card. Our latest magnetic tracked software was run on this alternative system in conjnction with the HMD, we achieved similar performance

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with a peak frame rate of about 6fps when the whole volume was within the view frustum.

One issue with the system is that the HMD, despite its relative lack of weight, becomes uncomfortable to wear for extended periods for most users. This was partly because of the spectacle type mounting, and also partly because if the cable was allowed to hang loose it would pull one side of the HMD down, causing the two screens to be in awkward viewing positions.

### 4.2. Conclusions

We have presented a novel tool that uses RP techniques to produce tactile physical models that can be used as an intuitive interface for anatomy education. The tool uses off-the-shelf components to create a Virtual Reality environment with which the user can interact with a minimum of learning effort.

Our system uses a pair of Ascension miniBIRD magnetic trackers to determine the position and orientation of our RP model, and an Icuiti DV920 page flipped head mounted display to give output to the user.

We have used several free software tools to process our existing volume data such that it was suitable to be input into an RP printer. We first segmented our data to isolate the organs that we required, we then create a surface, save it in an stl file, a standard format for 3D surfaces, and send this file off to a bureau service. The resulting RP model becomes the user interface for the software.

We used our previous work as our starting point, and enhanced several of it's features to improve our mixed reality teaching tool. The system has been designed in collaboration with an anatomy lecturer to provide a more intuitive learning process than that gleaned from traditional computer based learning materials. Taking advantage of the latest 3D computer graphics components and RP technology, together with functionality such as virtual resections, does appear to provide a compelling alternative to cadaver based anatomy education. Using RP enables patient specific models to be generated and so provides relatively easy access to cases with unusual anatomy. This is in contrast the fixed anatomy models that are a major disadvantage of mannequins.

### 4.3. Future Work

One addition that we intend to make to our system is to add in an InterSense IS-1200 VisTracker. This tracker contains both a small camera for optical tracking, and an inertial tracker capable of measuring at an angular rate of 1000° per second. We intend to mount this tracker centrally on the top of our HMD so that the user can be tracked. It should then be possible to take the captured image from the tracker to provide the user with a real world view required for an Augmented Reality system.

One interesting avenue for experimentation would be to increase the stereo separation within our Augmented Reality environment to see if the zooming increases the accuracy of the tool, particularly when carrying out virtual resections. This can be achieved by using a pair of HMD-mounted cameras with a variable separation to give a real-word point-of-view to each eye, and a change to the VTK software to create a corresponding stereo separation in the virtual world.

Another way of improving our system would be to canvas the opinions of and gain constructive feedback both from the teachers that would use such a system for educating students, and of course the students themselves. We are currently designing a set of user studies with consultancy from Bangor's School of Psychology. Results will be reported in a future paper. Initially, we will will focus on user acceptability and the extent to which the system aids in training.

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