Interchangeable Physical and Electronic Models for Complex 3D Shape Design*

David W. Robinson, Emanuel M. Sachs, David C. Gossard
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

The design of complex 3D geometry is a vital part of engineering practice today. Both physical and computer models are necessary in that design process. Currently, designers use an ad-hoc combination of physical and electronic models. This paper proposes a system, a "design cycle", wherein a designer can manipulate either physical or computer model and can readily translate between the two. The designer uses whichever model is more appropriate to capture the design intent. Physical models are used for subjective design of complex shape. Computer models are used for precise, mathematical shape. Moreover, the information gained in either modeling medium is preserved during translation from one to the other.

The translation from computer to physical is done using Three Dimensional Printing [17], a rapid prototyping technique. A designer can then use hand tools to change the physical model by carving, shaping, and joining additional material. The physical to electronic translation is done by a layered digitizing method [4] and semi-automated software tools are used to create a BRep polygonal solid model. Conventional CAD tools are used to manipulate the electronic model and the cycle can be repeated as necessary.

This system provides a powerful and fluid approach to the design of 3D complex shape. Applications of the design cycle are explained and demonstrated.

*Submitted to the Journal of Research in Engineering Design, July 1998.

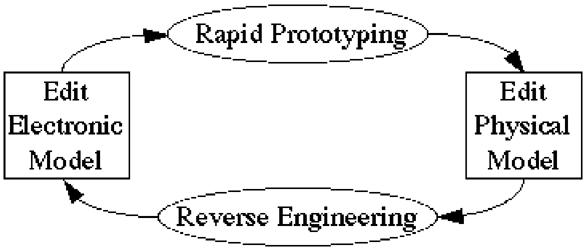

Figure 1: The concept of the shape design cycle. A designer can use either a physical or electronic model and easily translate between the two. This gives increased design flexibility.

1 Introduction

The ability to design parts with complex 3D geometry and to rapidly reduce them to prototypes is a basic necessity in today's marketplace. Functional parts which require complex shape for structural soundness and proper assembly under demands of low weight and material utilization are common. Aesthetics and ergonomics also play an important role in part design. Industrial designers, for example, utilize shape as a key element of product differentiation in almost every product of commercial interest.

In today's practice, the design of complex 3D shape is an ad-hoc mixture of methods involving both physical and electronic models. This mixture of modeling mediums is done using reverse engineering and rapid prototyping. Each medium serves a different need. Physical models are useful for subjective design (i.e. aesthetic or ergonomic design) where the "look" and "feel" is examined and where complex interplay between geometry and assemblies can be visualized. On the other hand, electronic models are well suited to the precise, mathematical specification of shape (holes are round and planes are planer).

Both physical and electronic models are essential tools in the design of 3D geometry. They play complementary roles and neither model is exclusive of the other. Furthermore, both models are required for truly effective 3D shape design. This raises a difficulty in the fact that the information contained in each model is often difficult to transfer to the other medium. Difficulty associated with these transitions decreases the opportunity for design iteration.

This paper examines a system, a "design cycle", that allows a designer to create and manipulate a part as either a physical or electronic model and readily translate between the two mediums [16]. Figure 1 shows the concept of the design cycle.

A brief overview of the current capabilities of reverse engineering and rapid prototyping are discussed. Then, the "design cycle" is demonstrated by using it to design a complex sculptured razor. Details on the design cycle implemention are then explained. Finally, areas for future work are itentified.

2 Current Practice

Even with the problems associated with mixing the two model mediums of electronic and physical models, the practice of using both continues. The reason for this is that to use one method in isolation often eliminates the oportunity to gain valuable design information that only the other medium can capture. For example, in the automobile industry, stylists and engineers insist that the visual cues used by customers to make styling-related decisions can only be perceived in full-scale models [21]. The outer bodies of automobiles are often sculpted in clay. These clay models are then digitized and a mathematical surface is best-fit to the data points. These surfaces are used to create tooling for the outer body panels. Finally, the manufactured panels are compared to the original design intent of the clay model. This process requires both electronic and physical models.

Industrial designers for consumer products likewise make full-scale models from computer or paper designs to help in understanding design problems such as the complex interplay of geometry and assemblies. This becomes especially important at the interface where human and machine interact. These models are used as demonstrations for customers and as a communication tool for manufacturing engineers and machinists. Often these models are made by hand. During the design review process they are physically altered. These alterations are then somehow incorporated in the existing computer model or a new model must be started from scratch.

To assist in the translation process between computer and physical models, two active research fields have emerged: Reverse Engineering and Rapid Prototyping.

2.1 Reverse Engineering

The most direct method for creating a mathematical or electronic model of an object is to take traditional measuring devices such as calipers, make measurements directly on the part, and subsequently record the information on paper or in a computer model. This requires extensive user input. Reverse engineering is the field of research involved with automating the process of creating computer models from physical ones.

In industrial practice today, physical models are digitized by a variety of methods. Coordinate measuring machines (CMM) are the most common approach and they offer high accuracy. Accuracy of 1-10 μm over working envelopes of 1 meter on a side are typical[1]. However, the need to make measurements by a sequence of point contacts dictates that CMM's are slow.

To increase measurement speed and decrease mechanical complexity, a wide range of optical digitizing techniques have come into use [5]. The most common type is based on laser range-finding. A laser spot is projected onto the surface and an image of reflected light is collected off-axis and used to calculate position by triangulation. Such techniques can be employed for the measurement of individual points. Higher speeds can be attained by using these methods to scan along lines [15]. An alternative approach is the projection of structured light (fringes) which can be interpreted using either triangulation or Moiré interferometry. The best accuracy for current optical scanners 0.001 inches over a volume of 18 inches.

Both CMM's and optical methods suffer from severe limitations in that geometry can only be measured from "one view". Neither technique can accommodate overhangs, undercuts or internal features. Even holes present a problem. It is possible to scan multiple views and then fuse them together into one data set but this significantly increases the level of effort required [13]. A solution to the view merging problem is to add another axis to the measuring frame and mount the object on a turntable as is done with some commercial scanners.

Once data points from the surface of the objects have been obtained, a useful CAD model must be created. Given current CAD software technology, creating a electronic model of an object, whether from a set of measured data points or "from scratch", can be a complex, tedious and time-consuming process with an entire set of problems and issues of its own. This is an active area of research. Two methods that generate useful CAD models from unorganized data points are of particular interest to this paper. One is an automatic method that creates a piecewise smooth surface [9, 10, 11] over extremely complex data. The other is a user interactive method which creates a CAD model using shape features defined from the processes used to create the part originally [20].

[1]Data taken from Brown & Sharpe product literature.

2.2 Rapid Prototyping

Over the past several years a family of processes has evolved which have the common element of creating parts directly from a computer model by adding material on a layer by layer basis. These techniques are variously known as Rapid Prototyping, Desk-top Manufacturing, and Solid Freeform Fabrication.

The additive nature of these processes allows them to create a part of virtually any geometry with a minimum of process planning. This geometric flexibility has spawned the use of Rapid Prototyping models for design studies [2]. In such applications, the rapid prototyping model is generally the end product of a design study and is produced to verify a complex CAD model, test the fit of two or more parts, or test the ergonomic "feel" of a part.

The most commercially successful product is stereolithography which is marketed by 3D Systems in Valencia, CA. This method uses a low-power ultraviolet laser beam that traces across a vat of photocurable liquid polymer and thus produces a layer of solidified resin. The vat is lowered incrementally by the height of the next slice, the layer is recoated with resin and another is traced on top of it. This cycle is repeated until the part is completed.

Of relevence to this paper are the desktop 3D printers. These are smaller systems which are less expensive to purchase, install and maintain. They can not compete with the full capabilities of the high end systems but they can be used as a physical counterpart of CAD systems. Similar to a laser printer and a word processing program. These machines are just emerging but have great potential to become an integral part of the "design cycle". The most promising of these machines are one developed by Z Corp in Somerville, MA and another developed by Stratasys, Inc. in Eden Prairie, MN.

2.3 Virtual Reality

Due to its prominence, both in research circles and in the popular press, the topic of virtual reality deserves special mention. One approach to the design of 3D geometry is to provide a virtual counterpart to the physical model using techniques such as 3D input devices, stereoscopic displays, and tactile feedback [18]. However, despite the use of state-of-the-art graphics, stereoscopic displays, etc., there is still a need to provide a fuller range of feedback to the designer.

It might be argued that substantial improvements in input and display technology will and are being made and that through the use of these improved technologies, virtual reality may come of age [19]. However, it is the authors' conviction that physical models are and will remain a vital part of industrial and engineering design. Virtual reality can enhance the capabilities of the electronic model but it will not eliminate the need for a physical one. In the limit, the "feel" of a virtual model can only approach, but not equal that of a physical model.

3 Design Cycle

As briefly mentioned in the introduction, both physical and electronic models are essential tools in the creation process. Recognizing that fact in its relation to the design of complex 3D geometry, an integrated system that can efficiently and economically take advantage of both modeling mediums is needed. In order to do this, not only must a designer be able to use both models but they must be able to translate quickly between them in a systematic method. The "design cycle" (figure 1) provides a powerful and fluid approach to the design of complex 3D geometry.

Being able to use both of these models allows the designer to spend more time actually designing and less time worrying about how to create, explain, and communicate their ideas. All of the good aspects of each modeling medium can be exploited. The physical models will help the designer use their subjective human skill and the electronic models allow the use of the computer's precision. With a cycle in place that maintains information gained in each step of the design, there will be no fear of losing information in model transition. This should give designers more opportunity for design iterations and for working out all the design details to clearly see everything they have imagined and envisioned.

3.1 Research Objective

The main objective of this research is to create a functional shape design cycle as described above and demonstrate possible applications. In so doing, we intend to identify areas for future research as we define the challenges and key problems of the "design cycle".

3.2 Example

One of the main applications of this design cycle is the ability to design parts which have both subjective contours and functional constraints. Many consumer hand held objects fit into this category of having subjective contours as well as geometric and kinematic constraints. Examples

Figure 2: This complex sculptured razor is one example of many that have subjective contours as well as geometric and kinematic constraints.

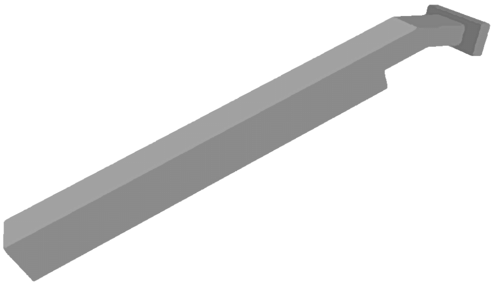

Figure 3: Razor blocked out in a CAD system. The construction time was only a few minutes.

include hand-held and electric razors (figure 2), a car door handle, a screwdriver, a computer mouse, and a telephone handset. There are many more.

As a demonstration of the design cycle's functionality, a new complex sculptured razor handle is created. The important part of the demonstration is not the finished razor. The important part is the design process and recognizing the contribution the design cycle makes to the design of complex 3D shapes by allowing interchangeable physical and electronic models. In each step, the designer uses the model that can best capture design intent.

The demonstration begins in the computer where the rough shape of the razor is quickly blocked out into a CAD model. This took approximately 10 minutes. Figure 3 shows the razor in its blocked out form with only the major features included. The CAD model is used to produce several physical models by 3D printing (Figure 4). This gives the designer plenty of parts to work with and the freedom to think and design freely. An industrial designer drew rough sketches of possible concepts to help visualize some of his ideas. He then carved three different razors from the 3D printed ones. He did not necessarily follow his original sketches. The sketches were used

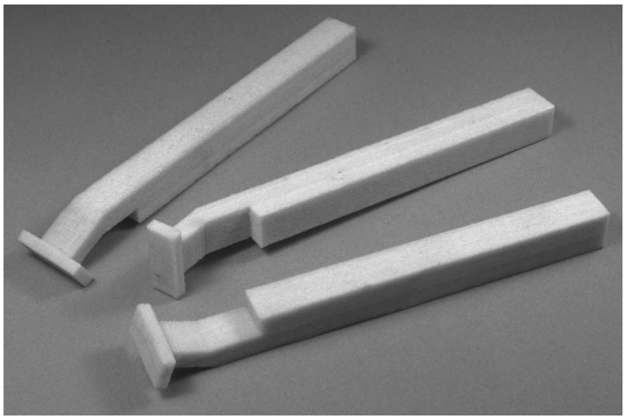

Figure 4: Three razors created by 3D printing and wax infiltration from the blocked out CAD model.

Figure 5: One of the razors carved by a designer. Starting from the rapid prototyped model, he used simple hand tools to create the complex shape.

Figure 6: The razor is scanned and reconstructed into a BRep solid model.

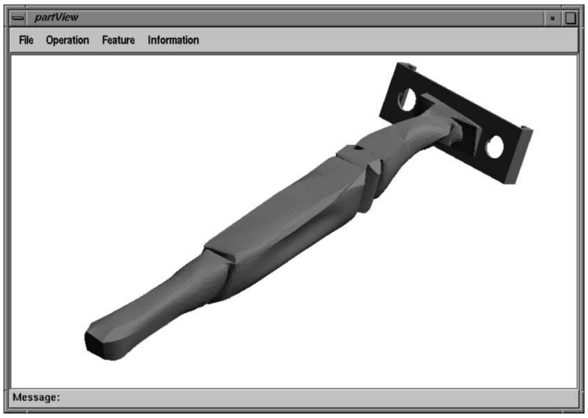

Figure 7: The complex sculptured razor CAD model is unioned with a standard head.

simply as idea starters. One of the parts is shown in Figure 5. He used a simple carving knife and each razor took just under 1 hour to finish. The designer decided on one of the models that he liked and digitized it.

A polygonal BRep CAD model is created from digitized data and is shown in Figure 6. A razor head which was previously designed is added to the body, an initial design for the razor is completed. Figure 7 shows this union. Further iterations on this design can be completed as needed.

In the demonstration of the design cycle just shown, the designer uses the model, physical or electronic, which can best implement a design idea. The complex surface of the body is made

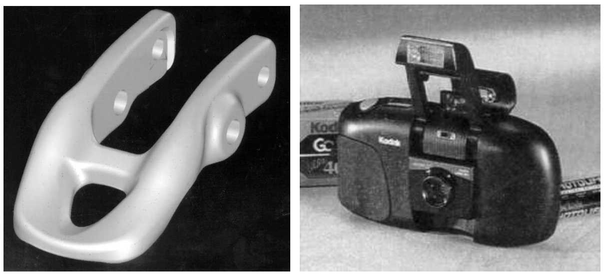

Figure 8: Further example of how the design cycle could be useful: ski binding component (left) and camera assembly (right).

with the physical model and the head is completely designed in the computer and both are combined into one model. This design is created quickly and efficiently. This gives the designer more time to design rather than spending time on figuring out how to design.

3.3 Other Examples

Figure 8 shows shows two more examples of how the design cycle could be used. One is of a complex part on a ski binding and the other is a camera assembly. The ski binding part can be modified in the design cycle similarly to the razor example just demonstrated. The camera assembly is an example of where two or more parts mate to form a continuous subjective contour. Other commonplace examples of this are walkmans, cellular phones, and camcorders.

For the design of the camera, the freeform shell can be formed and carved as a physical model. This gives the designer the best opportunity to work with the style and ergonomics considerations without worrying about the kinematic and assembly constraints for the flash, film hatch, and other buttons. The shell can then be scanned. The other doors and buttons can be easily created as a CAD model. The kinematics can also be created in CAD. This way, the assembly is still guaranteed to be flush when the pieces are put together.

The design cycle is useful for complex parts and assemblies. It can be used original design or as a tool for redesign. The design cycle may also be helpful in communication. For example, it could be used to incorporate modification suggestions that come from the shop floor. It bypasses the interpretation of the suggestions that is often required because these suggestions can be scanned into the model directly.

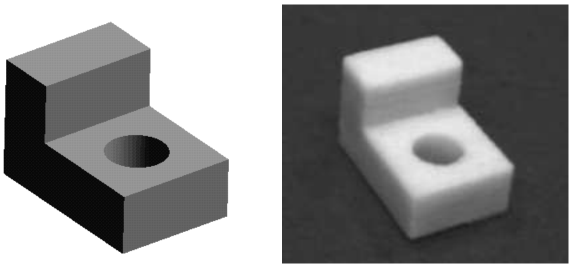

Figure 9: A computer and physical model of the simple block used as a test piece in the implementation of the design cycle.

4 Design Cycle Implementation

The shape design cycle is a continuous design method which can be entered at any point. However, in order to explain all the elements of the cycle, the description begins as a computer model. This model is translated to a physical model using rapid prototyping. In each step of the design cycle, a block with a cut and a hole is used as a test piece. A computer and physical model are shown in figure 9.[2]

4.1 Rapid Prototyping

This work utilizes a manufacturing technique called Three Dimensional Printing (3DP) which was invented and developed at MIT [17]. Like many other rapid prototyping methods, Three Dimensional Printing creates parts by a layered manufacturing process. The information in each layer is obtained by applying a slicing algorithm to the computer model of the part. A physical two-dimensional layer is created by adding a layer of powder to the top of a piston and cylinder containing a powder bed and the part being fabricated. The new powder layer is selectively joined where the part is to be formed by "ink-jet" printing a binder material. The piston, powder bed and part are lowered and a new layer of powder is spread out and selectively joined. The layering process is repeated until the part is completely printed. The unbound powder is removed, leaving the fabricated part. The sequence of operation for 3D Printing is demonstrated in Figure 10.

3DP is one of the most flexible of all the rapid prototyping techniques. The process can create parts of any geometry. The support gained from the powder bed means that overhangs,

[2]Some of the finer details of the design cycle's implementation have been eliminated for space considerations. For a more complete description and analysis of the implementation's different components, please refer to [16].

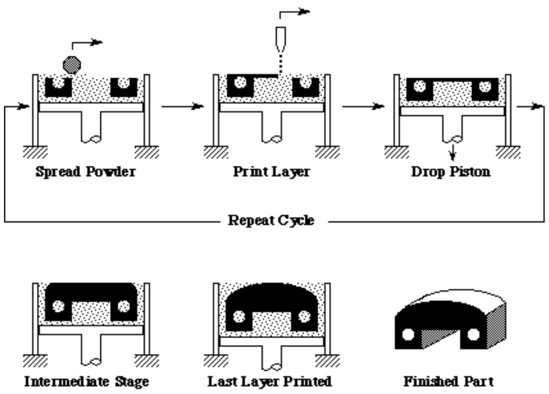

Figure 10: Sequence of Operations for Three Dimensional Printing.

undercuts and internal geometry can be created. Many other processes need to build support structures along with the part to create this difficult geometry [1]. Upon completion, these support structures must be removed.

The material used in the design cycle is also very important. Model makers currently use materials like bass wood, clay, RenShape^{TM}, and polyurethane dense foam for creating model by hand. The material's properties are patterned to be similar to the industrial design modeling materials. The requirements for the prototyping material are as follows.

- Must be able to carve, sand, machine, join and manipulate the material by hand. These are properties taken from the different currently available prototyping materials.
- Due to the rough handling environment the material must be stable.
- Must be inexpensive. Since the model may be built several times, it is important to keep the costs to a minimum.
- Non-toxic. It will be used in an office environment.

3DP has great material flexibility because it can form any material which can be obtained as a powder - which is about any material. As a first pass at finding a suitable modeling material however, experiments were constrained to modifying current successful material systems (powder, binder, and infiltrant). These systems include ceramics, metals, polymers, and glass. Each of these uses a different binder in the 3DP process.

Experiments varied material, powder size, powder geometry, and infiltrant (mostly different waxes). Twenty-five material combinations were tested against the requirements specified above. The results of the testing showed that a composite material of bees wax and soda-lime glass powder would work in the design cycle. The glass powder is used in 3D printing with an acrylic binder called acrysol. When the printing is complete, bees wax is infiltrated into the part.

The infiltration is a simple task and can be accomplished either by immersing the part in molten wax or by letting the wax wick through the perosity in the printed part. A direct method of printing wax into powder has also been demonstrated [3].

The physical model shown in figure 9 was made by 3D printing. Spherical soda-lime glass in the 55-69 μm range was used as the powder and acrysol as the binder. The part was infiltrated by immersing it in molten bees wax.

4.2 Physical Model

The designer can now use the part as a visual tool or can modify it as a method of making changes to the model. The material can be manipulated by carving, sanding, machining, and joining. Typical hand tools are used to make the modifications.

The material behaves much like hard soap for subtractive operations. Since most of the structural strength of the material comes from the wax, no appreciable damage is done to a cutting blade during modification. Material can easily be added to the part as well. In fact, nicks and small holes can simply be smoothed away by rubbing them with your hand. For display purposes, the material can also be painted.

The material is not ideal and many improvements can be made. However, an informal survey of model makers, part designers, and industrial engineers, most all had a favorable impression and said that they could work with the material.

4.3 Digitizing

After a designer has modified the model to a desirable form, it can be digitized and made into a CAD model once again. This work utilizes a digitization method accomplished by decomposing the part layer-by-layer, "deconstruction" [4]. The sequence of operation for deconstruction is shown in Figure 11.

First, the physical model is embedded in a block of material which acts as a physical support

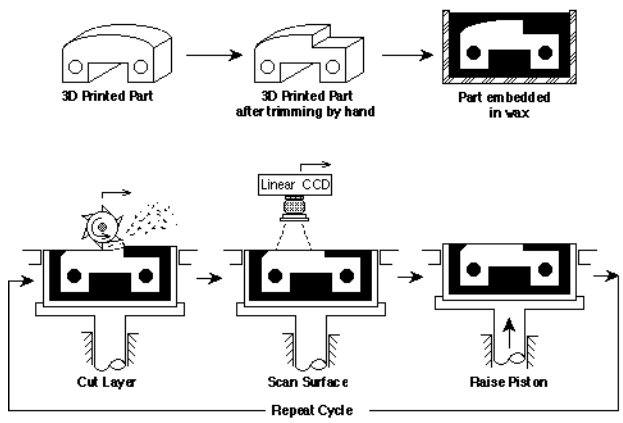

Figure 11: Sequence of Operations for destructively digitizing an object.

and provides optical contrast to the model. A thin layer of this block of material is milled off. After each layer is removed, an optical scanner captures an image of that layer. The part is located based on the optical contrast between the part and the support material. Milling and scanning are repeated until the entire part is imaged.

This approach has several key benefits. First, since the part is decomposed on a layer-by-layer basis and since it is held in place by a support material, any geometry can be imaged. The full set of data is obtained from one "set-up" with no need to fuse the data from multiple views. Further, the data is delivered in a Cartesian coordinate system, permitting easy analysis.

The single disadvantage of this approach is that it is destructive. The part will only exist as an electronic model after deconstruction. However, should a need arise where the physical model is required, it can always be printed from the electronic model.

Finding the right embedding material is a balancing act between its properties and that of the prototyping material. The following are the required characteristics of the embedding material.

- Lower melting temperature than the prototyping material. This helps the object maintain its geometry during embedding.

- Does not crack during milling. Cracks and chips show up in the scans as lines and speckles and are difficult to filter out digitally.

- Small change in specific volume from liquid to solid. This insures that the embedding material completely encases the object and does not leave holes or depressions.

Figure 12: Six slices taken from digitizing the test block. These slices show the transition from the boss into the lower part of the block.

- Low viscosity so that it will fill all cavities.
- High visual contrast from prototyping material for better clarity in scanning.
- Opaque so that embedded features remain hidden until cut.
- Fast solidification time.
- Inexpensive.

Ten material combinations ranging from waxes to polyester resins and epoxy were tried with varying levels of success. The experiments demonstrate that the recommended embedding material for use right now is paraffin with a carbon black dispersion. The exact formula for the compound is 20-1-1 by weight: paraffin, carbon black, and stearine. Stearine is a common candle making additive which makes the wax harder and opaque.

As described above and shown in Figure 11, the part is embedded in wax and imaged layer by layer. Unlike 3D printing, the scanning process is not currently automated. The scanning is accomplished by hand using a milling machine and a desktop scanner. The process of imaging each layer of the part is a repeatable process. However, small variations (rotation or translation) in the images do occur. Therefore, during the setup process, holes are drilled perpendicular to the cutting plane in the embedding material and filled with white wax. These registration marks help to digitally place all the pictures (slices) of the part into alignment. Six scans taken from digitizing the test block are shown in figure 12. This sequence of pictures shows the transition onto the middle flat. As can easily be seen the block is not exactly perpendicular to the cutting plane. But as will be shown it is not important.

4.4 Computer Model

After the realignment of the images corresponding to each layer is complete, the data now represents an accurate discrete digital pointwise data set of the original physical model. This representation, called a voxel model (combination of volume and pixel), is receiving much attention in the medical fields as a visualization tool for radiologists. It has also been looked at as a CAD tool for mechanical design [6, 8, 14]. The information required to drive a rapid prototyping machine is in essence a binary voxel set for where material should and should not be over the entire work volume. For many reasons, a voxel model fits the criteria for a valid CAD model and therefore must be mentioned here.

One might conclude that in this design cycle there is no need to change existing information to any other file format besides a voxel. Voxel models can easily accommodate Boolean operations, are good at file-to-file comparisons, interference checking, offsetting, and eliminate many of the problems with surface models such as overlapping surfaces. Unfortunately, voxel models require an immense amount of memory and high CPU speed in order to work with the model interactively. This is difficult especially if the model has very fine resolution because the file size goes up by resolution cubed. While novel methods of improving these limitations are currently being developed [8, 14] the machines needed to run such models are still expensive and beyond the scope of this design cycle's target. Voxel models may improve but right now a different type of CAD model is necessary.

The CAD model representation that this research achieves is a commonly used file type called a boundary representation or BRep solid model. A BRep solid model is a closed surface model which means that each surface knows its neighbor and it is possible to traverse over the boundary of the entire object. However, some steps must be taken to go from the Voxel model to the BRep.

A 3D edge detection algorithm is implemented to find points which on the boundary of the voxel model. Simple 2D edge detection on each slice of the model cannot capture features which are parallel to the cutting plane. If the block shown in figure 9 is cut and scanned parallel to the top surface, then the top, middle flat, and bottom surfaces would be missed using a 2D edge detection algorithm (figure 13). On those surfaces there is in sufficient point density to construct a solid model.

The 3D edge detection employed here is done by a method we call erosion. The voxel model is allowed to erode away a mono layer of surface voxels. This new model is then subtracted from the original and the result is a set of 3D points which represent the surface of the part. A simple 2D example of erosion is shown in figure 14.

This 3D edge detection algorithm is used on the test block. The same six layers of the digitization pictured in figure 12 are shown in figure 15 after the erosion and set subtraction have

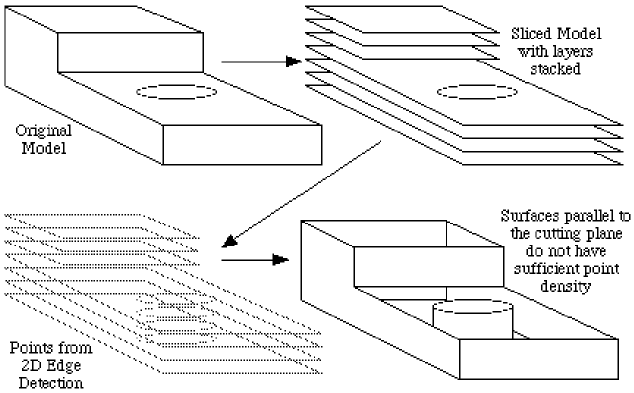

Figure 13: By simply applying 2D edge detection to each slice of the voxel model, the features parallel to the cutting plane will be missed in the solid model reconstruction.

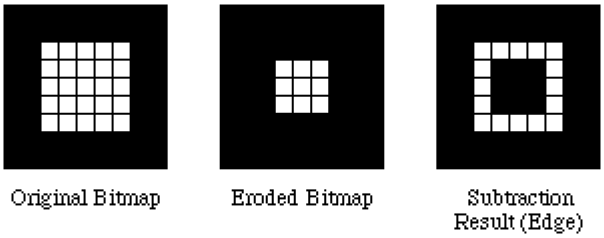

Figure 14: A 2D example of erosion. A monolayer of pixels is eroded away from the original model. This new model is then subtracted from the original and the result is a set of points which represent the surface of the part. This 2D example of erosion is applied in 3D for the scanned model.

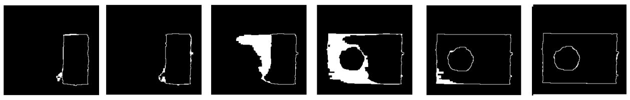

Figure 15: 3D edge detection results. The points on the surface perpendicular to the cutting plane are preserved. This allows a complete solid model reconstruction.

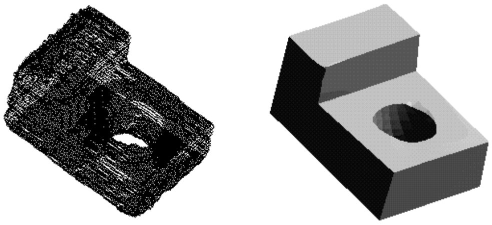

Figure 16: Raw Data Points to a BRep CAD Model

been completed. As can be seen, the points on the middle flat surface are preserved.

With a fully dense set of data points which describe the boundary of the object, a BRep CAD model can be formed. A group at the University of Washington worked on the problem of creating surface models from unorganized data points [9, 10, 11]. The algorithm goes through three steps. Step one determines the topological type of the surface and produces a rough estimate of its geometry. This is done using a contouring algorithm (a modified version of the marching cubes algorithm [12]). The inputs to this step are the raw point data and the minimum surface spacing. Step two takes the output from step one and defines an energy function on the surface mesh. This function models the competition between a concise representation and fidelity to the data. The function is minimized using mesh transformations that locally modify the mesh connectivity. Step three places a piecewise smooth surface over the optimized mesh of step two. The University of Washington surface is based on subdivision (i.e. dividing the mesh into smaller and smaller triangles.) At some threshold value the subdividing stops. Most rapid prototyping techniques use a polygonal model (STL file format) as input to the system. Therefore, this level of detail in the model is sufficient. Figure 16 shows the results of reconstructing a block using these algorithms.

One more step must be taken in order to demonstrate common CAD operations on the model. This is done using a solid modeling library from Purdue University's CADlab called TWIN.

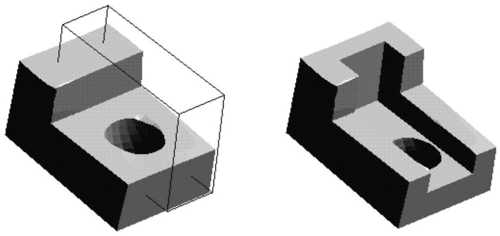

Figure 17: Set subtraction of a reconstructed block.

The polygonal surface model is converted to a BRep solid model in the TWIN file format. In order to more easily utilize the library's functions, an interactive CAD system was built on top of TWIN. This CAD system perform basic manipulations of the electronic model. A simple Boolean operation done on the reconstructed block is seen in Figure 17. This model can be easily exported to a 3D printing machine after all modifications have been completed.

All of the components of the design cycle have been explained and demonstrated. The cycle can now be repeated as necessary.

5 Future Work

Even though a working design cycle now exists and different applications can be explored, it is still in a fundamental state and many improvements and additions should be made to both software and hardware. Along with specific tasks that must be completed, ideas for further application can also be explored.

5.1 CAD: Shape Features

A major task will be to develop software methods to enable the user to identify and modify "shape features", e.g. planes, holes , pockets, bosses, etc. Such shape features play an important role in efficient editing during CAD model creation and modification because they describe a model in a higher level language which is closer to the way that the designer thinks about it. Shape features also play an important role in down-stream manufacturing applications that use the CAD model. Free-form surfaces must also be easily be identified and a mathematical description should be automatically generated.

Software tools can be envisioned which enable the user to designate distinct regions of the model, apply constraints to that region (e.g. planar, cylindrical, etc.) and have the model adjust to those constraints. Work similar to this has been done previously [7, 20].

For the design cycle, extracting shape features from the reconstructed CAD model poses a particularly difficult task. Since a designer is modifying the physical model by hand, the intent of the designer may be different than the physical model created for prismatic shapes. For example if the designer intends to make two surfaces perpendicular, but actually carves them to be acute or obtuse, the reconstructed CAD model will have off-perpendicular surfaces. In this case the designer could edit the surfaces to be perpendicular. Creating CAD models which capture the designers intent from digitized data is an interesting avenue for future research.

Often physical and electronic models have a plane of symmetry. If such a model is carved by a designer, it may not actually be symmetric because humans have difficulty making perfectly symmetric objects. However, it is conceivable that the designer could define a plane of symmetry in the reconstructed computer model. The two halves of the object could then be adjusted to best fit the data points while maintaining the symmetry requirement. This is an example of capturing design intent rather than simply recreating a model from raw data.

5.2 CAD: Cycle Remembering

Finding shape features as described in the previous section might be semi-automated if the reconstructed CAD model had a method of comparing itself with the original CAD model that was used to create the physical prototype. In other words, only the changes made to the physical model would be registered and modified and the rest of the model would revert back to the original CAD model. This would hopefully create a more simple CAD model as well as reduce time needed to extract shape features.

There are two problems that must be confronted in order to remember cycle iterations. First is the problem of aligning the new model to the old. Depending on how much the physical model is modified this problem could be as simple as having the user define three common points if there are not significant changes. If the digitized model is significantly different from the original one, then the solution may not be so easy. Regardless of the solution to this problem it will need user interaction and will be difficult to automate.

The other problem is to identify which parts have been modified. A possible solution to this is to create offsetting surfaces within a tolerance of the original model and build a "similarity envelope" where the two models can be compared and the differences can be identified. Unfortunately, offsetting surfaces of an object is well known as a difficult problem. However, one such solution is to take advantage of the fact that the raw data of the digitized object comes as a voxel representation. A "similarity envelope" can be created by simultaneously eroding and dilating the model several voxel layers thick. Set subracting the eroded model from the dilated model yields a discrete "similarity envelope."

5.3 Concept Modeling 3D Printer

A concept modeler based on the 3D printing process is currently being marketed. It does not use wax a binder but infiltrates the 3D printed parts with wax to help with handling strength. Even with the postprocessing, this 3D printer is by far the fastest rapid prototyping machine available. It would be good to start incorporating state-of-the-art advances into the design cycle.

5.4 Automated Digitizer

Along with building a wax printer, the digitizing process could also be automated. This will help in reducing the translation time between physical and computer model. As a prototype digitizing system, a handheld digital scanner could be mounted onto a CNC milling machine and connected to a PC in order to collect the data. However, this is only a small step above the hand milling and scanning done thus far. Since the digitizing process is repetitive and simple, a new machine that can mill and scan could also be designed and built. A machine similar to this has been built by CGI of Minneapolis, MN.

The only feasible scanning method for very complex parts currently is the one presented in this paper. Nevertheless, other nondestructive methods should be explored. One method that may hold promise is ultrasonic scanning.

5.5 Export for Manufacture

One point that was never formally addressed was that a finished design must leave the cycle and be manufactured in the final material either as a single piece or in mass production. The design cycle is a process for designing geometry. Since there is only one material used for the prototyping in this research, it is not an actual manufacturing method. Making sure that the designed part could be manufactured is very important and must considered in future work on the design cycle.

6 Conclusion

This paper describes a complete functional "design cycle" where a designer has the ability to manipulate either electronic or physical models and can easily translate between the two. This allows the designer to work with whichever model can best capture the design intent. The physical model is useful for subjective design (aesthetic or ergonomic). Here the "look" and "feel" can be examined. The electronic model is useful for precise, mathematical specification of shape (corners are square, holes are round).

As a demonstration of the design cycle, the first iteration in the design of a complex sculptured razor handle is shown. Other applications for the design cycle are also explained. The razor demonstration was accomplished through a preliminary functional design cycle.

The translation from computer to physical model for the design cycle is done using three dimensional printing. The material used in the rapid prototyping is a composite of soda-lime glass and bees wax. This prototyping material is similar to typical industrial design modeling materials. It can be carved, sanded, machined, and joined. It is also stable in a rough handling environment.

The physical model can be translated to an electronic one using a layer-by-layer destructive digitizing technique. The digitized data is then used to automatically generate a CAD model. A custom interactive CAD system is used to manipulate the electronic model with simple boolean operations. This last step completes the design cycle and it can be repeated as necessary. Key areas for future research have also been identified which would dramatically improve the quality of the design cycle.

In this paper, there are two levels of research. First is a global system view of the design cycle and its capabilities. Second is the work done on the individual parts of the entire system. While much effort was put into the second goal, the global concept of the design cycle is much more important. The individual elements of the system can be modified and improved as the state-of-the-art in the respective fields continues to advance. This progress will only enhance the capability of the global goal which is to design with physical and electronic models interchangeably in a systematic and fluid manner. There is still much work to be done to make the design cycle a fully integrated and seamless design system. With further improvements in method and mechanics, the design cycle can become a powerful new design tool.

Acknowledgements

This work was supported by the National Science Foundation, Grant DMI-9414793.

References

[1] S. Allen and D. Dutta. Determination and evaluation of support structures in layered manufacturing. *Journal of Design and Manufacturing*, 5:153–162, 1995.

[2] D. Aubin. A case study in rapid prototyping. *Proceedings of Solid Freeform Fabrication Conference*. Austin, TX, August 3-5, 1992.

[3] C. T. Becher. Adaptation of the three dimensional printing process to a drop-on-demand mode. Master's thesis, Technischen Hochschule Aachen/Massachusetts Institute of Technology, May 1996. No. 169789.

[4] Ben-Ezra, Pomerantz, Sava, Hasharon, Shamir, and Raanana. Method and apparatus for volumetric digitization of 3-dimensional objects. *United States Patent*, (#5,139,338). Issued August 18, 1992.

[5] P. J. Besl. Active optical range imaging sensors. *Machine Vision and Applications*, 1(2):127–152, 1988.

[6] V. Chandru and S. Manohar. Volume modelling for emerging manufacturing technologies. *Sadhana Academy Proceedings in Engineering Sciences*, 22(2):199–216, 1997.

[7] H. de St. Germain, S. Stark, W. Thompson, and T. Henderson. Constraint optimization and feature-based model construction for reverse engineering. *Proceedings of the ARPA Image Understanding Workshop*, 1997.

[8] J. Guo, B. Guo, and J. Menon. Sweep and minkowski operations as solid modeling plug-ins. *IBM Research Report*, 1997.

[9] H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, and W. Stuetzle. Surface reconstruction from unorganized points. *Computer Graphics, SIGGRAPH'92*, 26, 1992.

[10] H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, and W. Stuetzle. Mesh optimization. *Computer Graphics, SIGGRAPH'93*, 27, 1993.

[11] H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, and W. Stuetzle. Piecewise smooth surface reconstruction. *Computer Graphics, SIGGRAPH'94*, 28, 1994.

[12] W. E. Lorensen and H. E. Cline. Marching cubes: A high resolution 3d surface construction algorithm. *Computer Graphics, SIGGRAPH'87*, 21(4), 1987.

[13] R. Massen. Bridging the gap between optical 3d digitizers and cad/cam. *Intelligent Manufacturing Systems International Conference on Rapid Product Development*, 1994. Stuttgart, Germany, January 31 to February 2, 1994.

[14] J. Menon. Collaborative visualization and modeling. *Shape Modeling International '97*, 1997. March 3-6, 1997, Aizu-Wakamatsu, Fukushima, Japan.

[15] M. Rioux. Laser rangefinders based on synchronized scanning. *Applied Optics*, 23:3837–3844, 1985. March 3-6, 1997, Aizu-Wakamatsu, Fukushima, Japan.

[16] D. W. Robinson. Integration of rapid prototyping and reverse engineering for complex 3d shape design. Master's thesis, Massachusetts Institute of Technology, May 1996.

[17] E. Sachs, J. Haggerty, M. Cima, and P. Williams. Three dimensional printing techniques. *United States Patent*, (#5,204,055). Issued April 20, 1993.

[18] K. Salisbury and et. al. Haptic rendering: Programming touch interaction with virtual objects. *ACM Symposium on Interactive 3D Graphics*, 1995. Monterey, CA, Apr. 9-12.

[19] S. L. Springer and R. Gadh. State-of-the-art virtual reality hardware for computer-aided design. *Journal of Intelligent Manufacturing*, 7(6):457–465, 1996.

[20] W. B. Thompson, J. C. Owen, and H. J. de St. Germain. Feature-based reverse engineering of mechanical parts. 1995. University of Utah Dept. of Computer Science Tech. Report #UUCS-95-010.

[21] M. Tovey. Computer-aided vehicle styling. *Computer-Aided Design*, 21:172–181, 1989.