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Rapid Prototyping Using 3D Systems (Stereolithography), DTM (Selective Laser Sintering) and Cubital (Mask Plotting) Systems

by

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I. Introduction

Rapid prototyping is a process which takes advantage of many technologies and procedures. Some very old and traditional, yet effective in there own right, and some on the leading edge of technology. This paper will address Sikorsky Aircraft's involvement in United Technologies Express Prototyping Consortium and it's utilization of an emerging technology, 3D printing, in it's Rapid prototyping program.

II. Background

United Technologies is a 20 Billion dollar-a-year Corporation and is comprised of many Divisions. Sikorsky Aircraft is only one of the many divisions of UTC. Sikorsky Aircraft is the largest helicopter producer in the world. It's current business base is derived 60% from the US government and 40 % from other Government and commercial customers. Sikorsky Aircraft employs approximately 12,000 people with yearly revenues of approximately $2.1 billion. Significant Engineering, Test and Manufacturing facilities exist in Connecticut and Florida. UTC's business base spans the globe, where each of it's divisions are universally acknowledged as leaders in their respective industries. The most prominent divisions are listed in **Table 1** along with their area of specialty.

United Technologies Corporation announced the formation of the Express Prototyping Consortium (EPC) in early 1991. All of the major UTC divisions eagerly participated in the EPC. The EPC was established to investigate alternate methods to the traditional model, tooling and prototype fabrication processes already in service within the UTC divisions. The objective of Senior Management was to accelerate the development cycle, thereby reducing the time to production. The ultimate objective was to make UTC a stronger competitor by reducing the time and cost of introducing new products to market.

Table I

DIVISION	BUSINESS
Sikorsky Aircraft	Helicopters
Pratt & Whitney	Turbine Engines
Carrier	Heating and Ventilating
OTIS	Elevators
Hamilton Standard	Control Systems
Norden Systems	Radar Systems
UT Automotive	Wiring harnesses

Pratt and Whitney, having the most experience in rapid prototyping, was selected as lead Division of the EPC. P&W established an area on it's factory floor and staffed the organization with Manufacturing Engineers and support Technicians. After several pilot meetings, the EPC executive body decided to pursue 3D Systems Stereolithography process to launch it's pilot program. Figure 1 shows a picture of the Facility and equipment.

Figure 1 - EPC Facility

III. Conventional Prototyping Methods

Within UTC, the most typical prototyping methods and procedures included, but were not limited to, manual drawings, clay, paper and wood carvings with extensive hand work and multiple iterations. At best, a thought was transferred to paper and a (Computer Aided Design) CAD database for (Numerical Control) N/C Programming. The bottom line often involved high cost and long lead times. Figure 2 shows a photograph of an early Comanche clay model. Figure **3** shows a photograph of a later version of the Comanche design fabricated using 3D Systems Stereolithography process.

Figure 2 - Early Clay Comanche Model

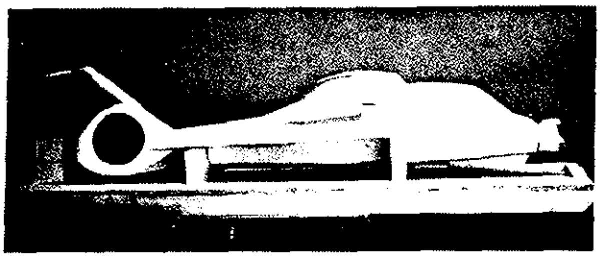

Figure 3 - Stereolithography Comanche Model

IV. 3-D Printing: An emerging Technology

Printing provides a good two-dimensional analogy to the three-dimensional Solid Freeform Fabrication. Lettering or drawing by hand is analogous to manual manufacturing. Offset printing is analogous to conventional automated manufacturing. One method of printing that has no conventional manufacturing analog is dot matrix or laser printing. This printing method can produce any two-dimensional pattern on paper directly from a computer representation with resolution, determined by the number of dots per unit area, being the only restriction. Dot matrix and laser printing cannot compete with offset printing for large numbers of copies, but are practical and cost effective for small numbers of originals, or master copies. Larger numbers of copies can be made cost effectively by using dot matrix and laser printing as inputs to other processes such as photocopying.

Stereolithography, Selective Laser Sintering, Masked Printing and other processes not covered here, are the manufacturing analog to dot matrix or laser printing. These processes produce three-dimensional solid objects directly from a computer representation with resolution, determined by the number of volume elements ("voxels") per unit volume, being the only restriction. These processes are practical and cost effective for small numbers of arbitrarily-shaped originals, such as models, prototypes and patterns. Larger numbers of parts can be manufactured by conventional shape transfer processes such as investment *casting*.

Primary application of these processes will be in three main areas: model-making by product designers, batch manufacturing of specialized objects, and production of molds and patterns required for large-scale production runs. Designer's at Sikorsky Aircraft use these processes to build prototypes, visualization models and casting patterns themselves, in a few minutes or hours, depending on size, instead of waiting days, weeks or months for specialty shops to fabricate such one-of-a-kind parts.

The initial focus of the Express Prototyping Consortium was primarily on 3D Systems' Stereolithography. A process which utilizes and coordinates advanced technologies in 3 primary areas to produce 3D plastic prototype objects without drawings or tooling. Advanced polymer chemistry, lasers and computer science were all pushed to the limits within the constraints of cost and complexity. 3D Systems would be unable to market a product which was too expensive or so complex it's reliability wouldn't allow the successful completion of the process.

V. Stereolithography

Stereolithography technology starts with a 10" (25.4cm) or 20" (50.8cm) cubed vat of photo sensitive liquid resin. A unique property of this resin is to harden when exposed to ultraviolet light. An argon laser is used to generate a pencil point beam of ultraviolet light. A sophisticated software package slices the solid computer model *into thin cross sections as illustrated in* Figure 4 (depths range from .002" (.0051cm) to .020" (.0508cm)). The cross sectional information is used to drive a laser beam positioner. Where ever the laser beam contacts the resin surface an outline is hardened. The bed, which is suspended in the resin, and has a starting position at the surface, is lowered anywhere from .002" (.0051cm) to .020" (.0508cm) and another cross section is outlined on the surface. The laser penetrates far enough through the surface of the resin to bond each layer to the previous layers. This process is repeated until the full depth of the object is defined. Once the process is completed, the elevator bed is raised and the excess resin is allowed to drain off. The object is removed from the bed and placed in an ultraviolet light chamber to

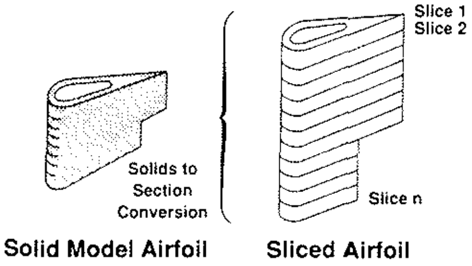

Figure 4 - Geometry slices

be thoroughly hardened. Once hardened, the part is structurally stable, but somewhat brittle. Recent advances in polymer technology have overcome this problem. The part can be sanded, buffed and painted to meet whatever surface finish requirements have been established. Figure 5 illustrates the process.

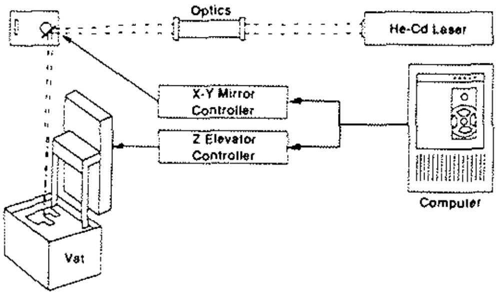

Figure 5 - Stereolithography Process

VI. Selective Laser Sintering (SLS)

Selective laser sintering is similar to Stereolithography in many respects. SLS utilizes a heat fusible powdered material as it's media as opposed to a liquid resin. The term "sintering" refers to the process by which particulates are melded into a solid mass by means of externally applied energy. Figure 6 illustrates this process.

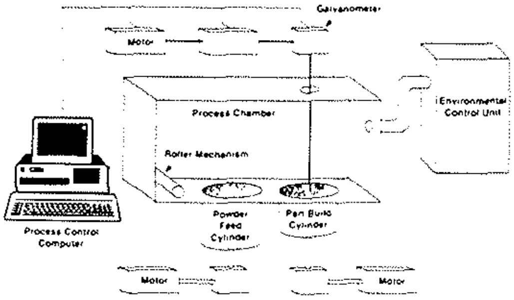

Figure 6 - Selective Laser Sintering Process

A bed is suspended at the top of 12" diameter, 15" high hollow cylinder. The bed is coated with a thin layer of heat fuseable powder. The SLS process also utilizes a sophisticated software package to slice solid computer models into thin cross sections. Each cross section is traced onto the bed with a 20 watt carbon dioxide laser. The tracing causes the outline to harden in place. The bed is lowered .002" (.0051cm) to .020" (.0508cm) depending upon resolution and accuracy requirements. Additional powder is applied over the hardened layer and the process is repeated until the object is formed. At the end of the process a solid cylinder of powder is removed from the form. The unhardened powder is removed with a brush and/or compressed air. The part is sanded and buffed to the desired surface finish and painted. Figure 7 shows a Comanche 1/6th scale rotor blade made by DTM for Sikorsky Aircraft using the SLS process.

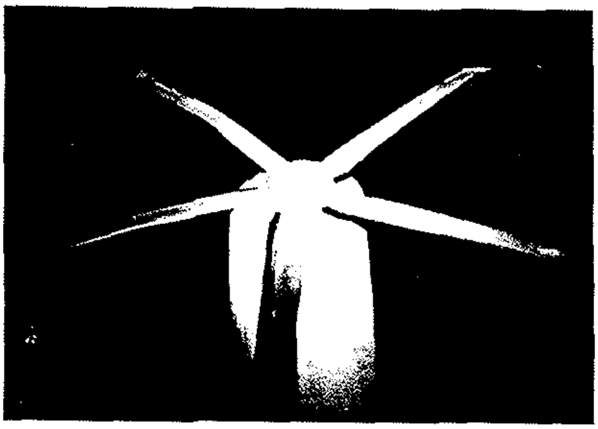

Figure 7 - Comanche 1/6th scale rotor

The SLS process has an advantage over Stereolithography in that virtually any material which softens and has decreased viscosity upon heating can potentially be used as an input material. Use of investment casting waxes to produce parts for lost wax casting, use of polymer coated ceramics and direct use of metal powders further extend the range of materials from which prototype parts can be made. The down side is the potential power requirements required for high metallic content materials. Current technology allows for an extensive variety of powdered input materials to be used, including ABS plastic, PVC, nylon, polycarbonate and investment casting wax.

VII. Masked Printing

The masked printing process as implemented by Cubital LTD. is also similar to the stereolithography process in that it utilizes light-sensitive liquid resin which is hardened and bonded layer by layer. The exception here is that the masked printing process hardens an entire layer all at once. The masked printing process prints a mask on clear glass. The mask is then precisely positioned over a resin coated bed. A high intensity mercury vapor light is exposed for 5 seconds through the optical mask. Unhardened resin is suctioned off. Cavities and voids are then filled with liquid wax. Once the liquid wax solidifies, the entire surface is then machined flat. The bed lowers and a new layer of liquid resin is applied and the process repeats itself until the object is completely formed. At the completion of the process the wax is removed with hot water. The Cubital equipment supports a 14" (35.56cm) x 20" (50.8cm) x 20" (50.8cm) volume. Figure 8 illustrates the masked printing process as implemented by Cubital, Inc.

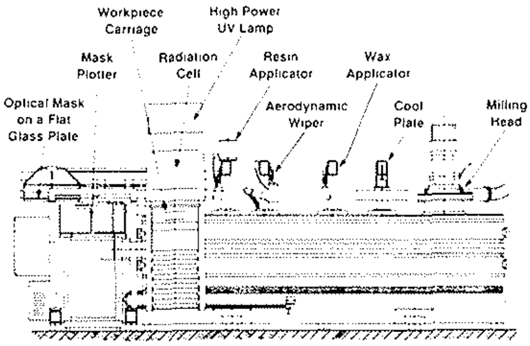

Figure 8 - Masked Printing Process

VIII. UTC / EPC Facilities and staff

The EPC was housed within 2000 square feet of a modern environmentally controlled manufacturing facility meeting all of the requirements established to initiate this activity. This facility contained 3 - 10" (25.4cm) 3D Systems Stereolithography machines, 1 - 20" (50.8cm) 3D Systems Stereolithography machines, and an assortment of Ultrasonic cleaners and Ultraviolet chambers for part hardening and curing. The EPC maintained agreements with Cubital and DTM for access to there facilities, capabilities and expertise.

The EPC was staffed with 5 full time employees and several part time employees. Three Manufacturing engineers were on staff to help the UTC divisions design prototype parts, convert file formats and to develop new techniques for using the Rapid Prototyping technology. Two full-time technicians were on staff to support the engineering staff, run translation code, run the 3D Systems equipment and provide final finishing and painting services.

The EPC was guided by a Steering committee comprised of representatives from each UTC division. The Committee would meet quarterly to discuss EPC utilization, past quarters performance and anticipations for the next quarter. Committee members would bring recommendations forward from each UTC division to improve technology or services.

IX. Sikorsky Aircraft's participation

Sikorsky Aircraft's management was quick to see the advantages of participation in the Express Prototyping Consortium. A plan had to be implemented to maximize the return on investment of membership in the EPC. Several initial objectives were established to take full advantage of this corporate asset. They were 1) make all levels of management and potential users aware of this capability, 2) make it easy and convenient to use, 3) determine just how far this technology could be utilized to accelerate ideas to market, and to additionally determine 4) accuracy limitations, 5) speed limitations and ultimately 6) should Sikorsky fund and implement an in-house capability?

In my role as EPC task manager for Sikorsky Aircraft, I set out to meet these objectives and answer some of these questions. There were several layers of management which were reluctant to allow participation of their designers in this process. Although impressed with the prototypes displayed, they were reluctant to introduce a change in culture into their environment. To overcome this, a vigorous education process was required. All management and Engineers involved with modelling and design were subjected to an indoctrination. Once educated on the capability and the limitations of the system and the process, the utilization of the EPC sky-rocketed.

To make the process easy, all of the suppliers of CAD packages utilized at Sikorsky were called upon to provide file translators from their format to an acceptable Stereolithography format. Were they did not exist, they were written in-house. Also, as Sikorsky is some 40 miles away from the Pratt and Whitney facility, an existing network link was utilized to transfer data files instantly to the EPC computer system via e-mail. Essentially, with the file translators in place and the ability to instantly transfer files from a desk top computer, most if not all obstacles for using the EPC were removed. The system was easy to use and fast.

X. EPC - 2 Year Utilization Statistics

During the two year period, May 1988 through May 1990, there are several significant statistics which deserve mention. 1) Over 100 unique parts were fabricated, 2) Over 300 parts were fabricated overall, 3) Average process time per part - 14 hrs, 4) Average turnaround time per part - 15 days, 5) Average cost per process hour - $27, 6) Average cost per part - $380, 7) Process utilized by every major engineering and manufacturing function,

8) over 40 Engineers and Designers were trained in the modeling and network skills required to fabricate a part using Stereolithography.

Utilization steadily increased over the 2 year period to the point of full capacity of the Consortium. The only statistic not fully quantified is what the utilization would have been if Sikorsky's standard modeling procedure required the use of solids in all modelling. Engineers and Designers were initially reluctant to make the additional investment in time to model in full 3D solids for all applications. This resulted in a burden to convert old files into the required structure. If Sikorsky's database had been entirely in 3D solids, the EPC surely would have experienced an immediate overload.

XI. Case Studies

There are 5 of the over 100 parts fabricated reviewed in this case study. They are 1) UH60 1/10th scale model, 2) Comanche 1/6th scale model, 3) Comanche 1/10th scale rotor head, 4) Comanche 1/3rd scale engine inlet model, and 5) UH60 full scale Heater Duct.

1) The UH60 1/10th scale model was assembled from 18 individually fabricated pieces. Total cost of this model, including EPC process time, assembly cost and finishing costs, was approximately $16,000. Typical models of this quality have cost on the order of $28,000. Figure 9 illustrates the UH60 model at 1/10th and 1/32nd scale. Both were fabricated from the same CAD file. The primary purpose of these models was to confirm Outer Mold Line (OML) quality and to fabricate a scale model for testing.

Figure 9 - 1/10th and 1/32nd UH60 Models

2) The Comanche 1/6th scale model was assembled from 12 individually fabricated pieces. The total cost of this model, including process, assembly and finishing, was approximately $30,000. This compares to an estimate of $30,000 for a conventionally fabricated model. The EPC models were completed in less than 10 days, with another week to ten days to complete assembly and application of a thin layer of fiber glass to provide additional strength. Figure 10 shows an exploded view of the components used to assemble the Comanche model. Figure 11 shows the completed Comanche model being tested.

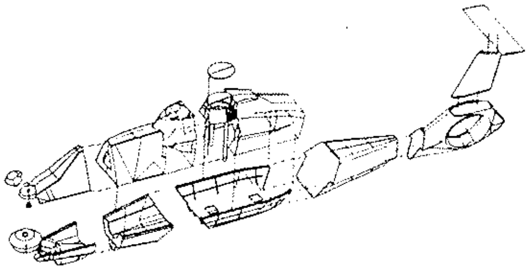

Figure 10- Comanche Component Assembly

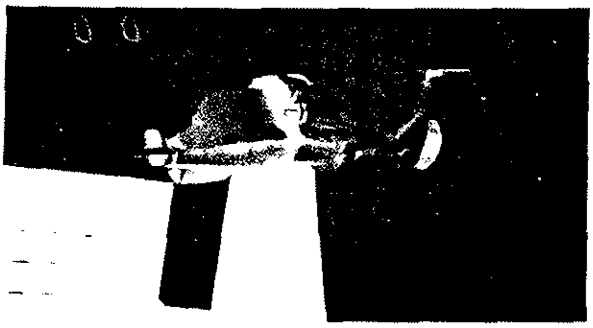

Figure 11 - Completed 1/6th Scale Comanche Model

3) The Comanche 1/10th scale rotor head model was fabricated in less than 8 hours at a cost of $216. This model was used primarily for fit, form and function evaluations, management and customer reviews. As a result of this model, geometric changes were made to the final design which would not have been incorporated if it weren't for the Stereolithography model. Figure 12 shows the completed Comanche rotor hub pieces.

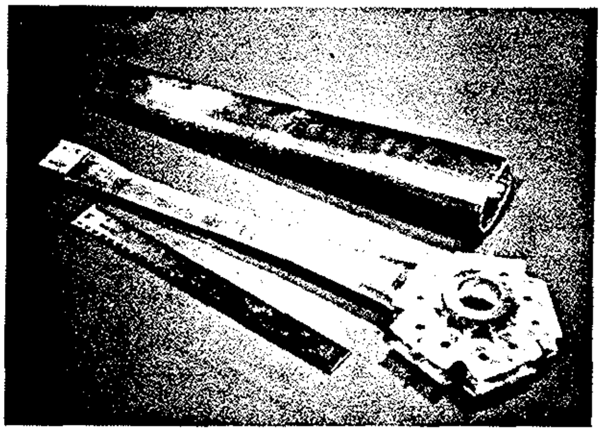

Figure 12 - Comanche rotor hub pieces

4) The Comanche 1/3rd scale engine inlet model was fabricated for geometric evaluation and for some flow testing. The part, even though extremely complicated geometrically, was fabricated in less than 20 hours at a cost of $540. Manufacturing estimates were in the thousands of dollars and months to fabricate a one of a kind prototype. Figure 13 shows the prototype 1/3rd scale inlet duct.

Figure 13 - Prototype 1/3rd scale inlet duct

5) The UH60 full scale Heater Duct was fabricated to evaluate fit on the aircraft. Geometry file integrity was verified and component fit and function was determined prior to commitment of production tooling. Several interferences were determined and minor redesign was completed prior to the production run. This duct required 80 hours of process time at a cost of $2,200. The EPC provided a 25 day turn-around. Figure 14 shows the completed Heater Duct.

Figure 14 - Full scale UH60 Heater Duct

XII. The future of Rapid Prototyping Technology

The first generation of Rapid prototyping products focused on desk side modeling for visualization purposes, prototyping and rough tooling. Accuracy and surface finish limitations constrained utilization. As the process matures and technology is infused into systems, utilization will expand to high accuracy prototypes and tooling. Next generation implementation of the process will allow for direct metal and ceramic part fabrication through the use of Hi-Temperature Laser Sintering and metal powders. Direct metal and ceramic shells are projected as production type capabilities by the end of the decade. Figure 15 illustrates the time lines and projected technology advances.

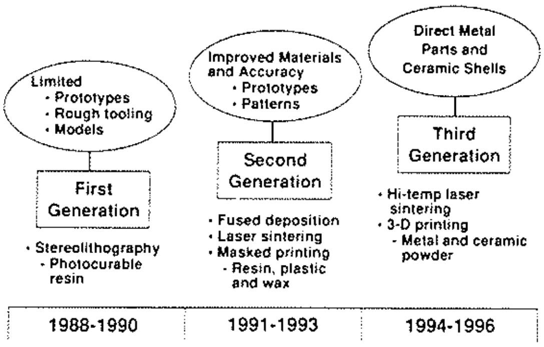

Figure 15 - Rapid Prototyping Technology Trends

XIII. Lessons Learned

The Express Prototyping Consortium was a great investment for Sikorsky Aircraft. Many very complicated parts were fabricated directly from designer's CAD files at a very low cost. Also, some significant geometry issues were identified in many of these parts.

Sikorsky Aircraft's utilization of the EPC would have been an order of magnitude greater if 1) the Technology had been able to provide larger part capacity. One of the biggest "gripes" of the users was that the process required too many sub pieces for an assembly. This particular shortcoming seemed to be less of an issue with other UTC divisions, due to the size of their components. They were in a position to make full size parts, whereas Sikorsky components were typically so large that many pieces were required to assemble one component. The limit of pieces per component, for a large model similar to the Comanche and the UH60 models is 10-12, before it begins to require more time to assemble and finish than would be required by other fabricating processes, and 2) the engineering procedures of the time would have required all CAD work be performed in solids, as opposed to wire frame, surfaces or faces.

Parts of great mass, due to thick areas of resin tend to have a proportional distortion in the curing cycle. Shrinkage can be accounted for in the design phase. Accuracies of .001" have been attained, greater accuracy can be obtained through modeling/fabrication iteration.

Sikorsky's experience concludes that Stereolithography and similar processes can not always replace conventional prototyping techniques, due to accuracy requirements and material properties. This process, may not replace the conventional techniques, but can more often than not, supplement the fabrication of models and prototypes.

Sikorsky continues to support and utilize the Express Prototype Consortium, and at this time has not opted to purchase a system for dedicated use. The Capital investment of $450,000 for process equipment alone, and the investment in facilities, training and resources and personnel exceeds the benefit obtained through our current membership in the EPC. As utilization increases, Sikorsky Aircraft may in fact decide to purchase a prototyping machine.