Inverse Geometry for Stereolithographic Manufacturing

Don R. Brown Venkatesh Subramanyan
Samuel Drake
Mechanical Engineering and Computer Science Departments

University of Utah
Salt Lake City, Utah

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Abstract

As parts produced by stereolithography form and cure, they warp and shrink to produce parts that are not quite the same as those originally specified. This research attempts to solve the inverse geometry problem, that is, what shape should be specified initially so that the shape produced is the desired one. Assuming that the process is repeatable, we measure the difference between the ideal and actual part dimensions. A finite-element based model is built which mirrors the distortion from the ideal geometry. A "pre-deformed" geometry is then built so that it deforms to the ideal geometry under the conditions imposed on the finite element model. This pre-warped geometry is the geometry we seek.

Introduction

Stereolithography holds considerable promise as a means of quickly producing prototypes of small mechanical parts [1, 2, 3]. However, skilled operators are currently needed to make small adjustments to the geometric model so that the resulting part can meet the specifications [4]. For very complex parts, this warping can be excessive. The photograph in Figure 1 shows an extreme case of a warped part that was specified to have straight edges.

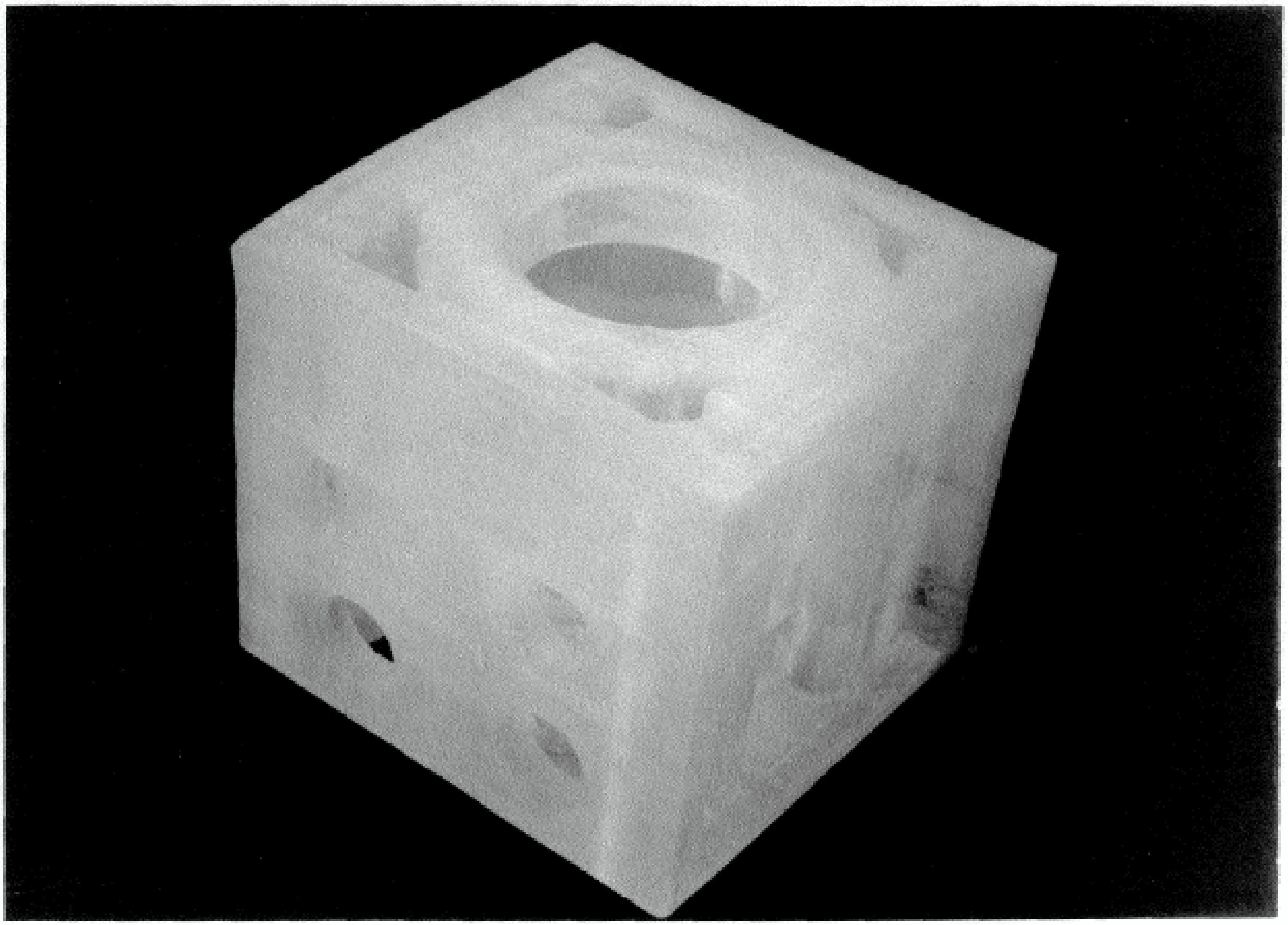


Figure 1: A stereolithography part with warped edges.

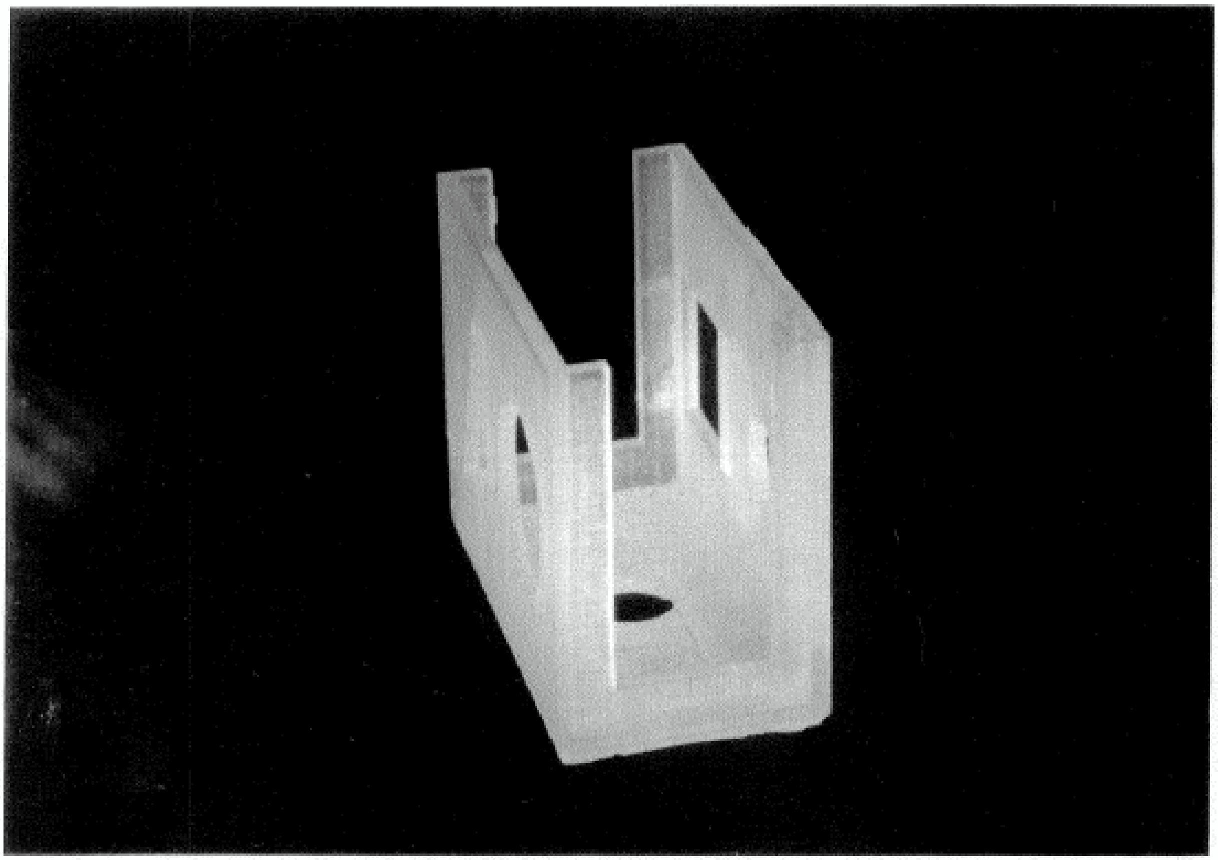


Figure 2: A part produced by stereolithography.

Our experience has been that the warping of most models is much less severe than the part in Figure 1 but still significant enough to warrant attention. Part deformations can be corrected by constructing appropriate temporary support structures, but such practice reduces the attractiveness of this method because it requires experienced artisans. The goal of this research is to build in computational corrections that automatically adjust the geometry in the appropriate fashion. The feasibility of any such method depends heavily on the repeatability of the process.

Repeatability

The part shown in Figure 2 was produced by stereolithography. In comparing the desired geometry with the corresponding part, the upper edges of the walls are displaced toward each other by an average of 0.025 inches from where they were specified.
Fortunately, the error is quite consistent. The fact that manual iterative adjustment of input data can result in improved parts for stereolithography suggests that the process is repeatable [4]. Experiments bear this out. Figure 3 shows the mean distance between walls for 30 different versions of the part shown in Figure 2. The standard deviation is 0.006 inches. The fact that the process is quite repeatable leads us to

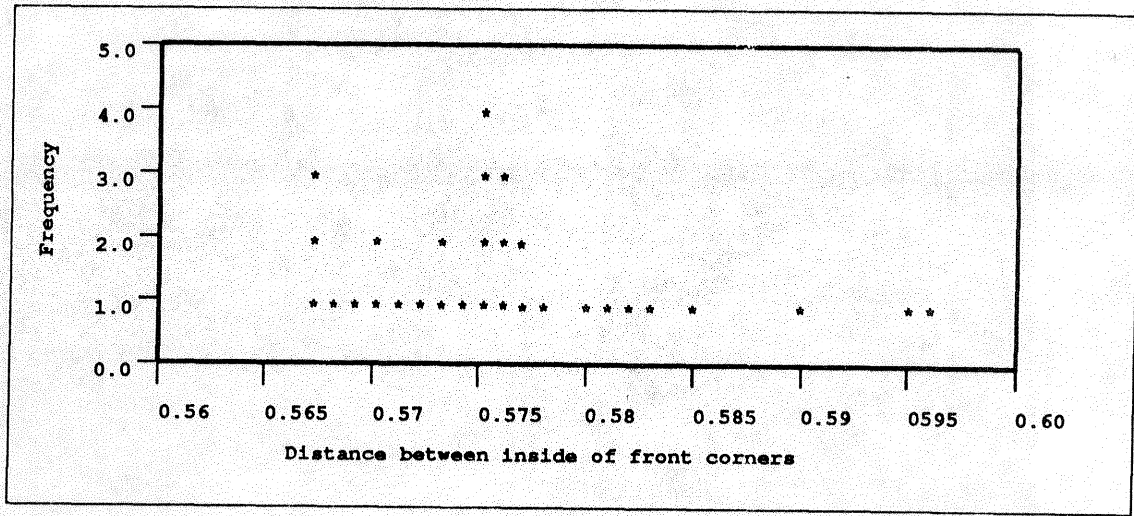


Figure 3: The distribution of the distances between the upper edges of walls for 30 different parts. The value was specified to be 0.600 inches.

believe that there is room to improve part accuracy.

Approach

Figure 4 depicts our approach to the problem. The desired geometry is input to the stereolithography process. The resulting geometry is distorted. We then try to find a process that is similar to stereolithography in that it produces the same distortions. This similar process should be invertable, that is, it should be capable of taking an output and producing an input that would generate that output. The resulting input is the inverse geometry that we seek. When the inverse geometry is input to the stereolithography process, the result should be the desired geometry in physical form.

Discovering a Similar Process

At the heart of the inverse geometry problem is the discovery of a process that produces shape distortions that are the same as those produced by stereolithography. Our main candidate is force-based distortion which is simulated using finite-element analysis. Force-based distortion is based on the notion that the disfigurements are caused by the molecular bonding forces inherent in photo-polymerization. If we can discover a set of forces whose resultant is equivalent to the resultant forces produced by the molecular bonding then we have found a similar process. We may be able to reproduce the gross effects of the molecular forces using an appropriate finite element

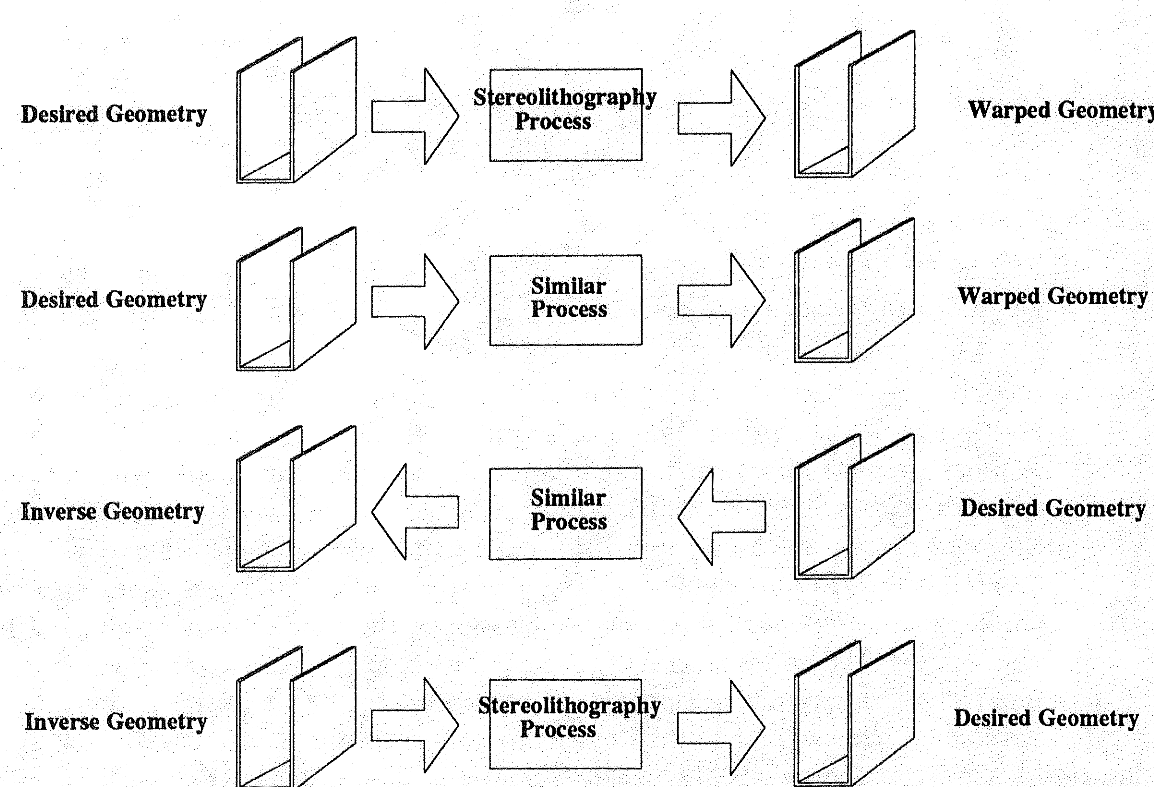
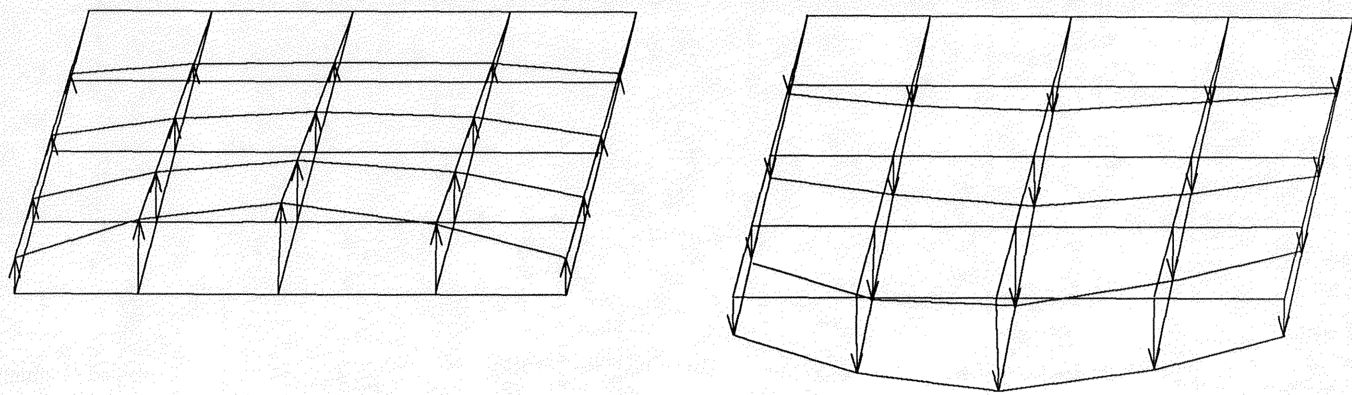


Figure 4: The four main steps in the inverse geometry problem.



a. **b.**

Figure 5: Force-based distortion. The forces in "a." are applied to the original geometry in the opposite direction.

model. Once the forces that produce that distortion are known, they are reversed and applied to the original data as Figure 5 depicts.

A finite-element approach to force-based distortion is illustrated with a sample part. Figure 6 shows the part we wish to create.

Suppose that it was found by measurement that the walls of this part are inclined by 0.025 inches. A finite element model was created that had a similar cross section. A similar displacement of 0.025 inches was given the model to find out what forces are necessary at the nodes to create that displacement. Figure 7 shows the finite element model and the resulting stresses. Opposite forces of the same magnitude are then applied to the original finite element model to produce an outwardly warped model as shown in Figure 5. A geometric model is then created that with the same cross sectional shape as shown in Figure 7. This becomes the inverse geometry that will be used to create the new part.

Summary

We have found that stereolithography often does not yield parts that the same shape was specified. Operators skilled in the art of stereolithography can correct these distortions but there exists no proven and codified method for doing so. This research

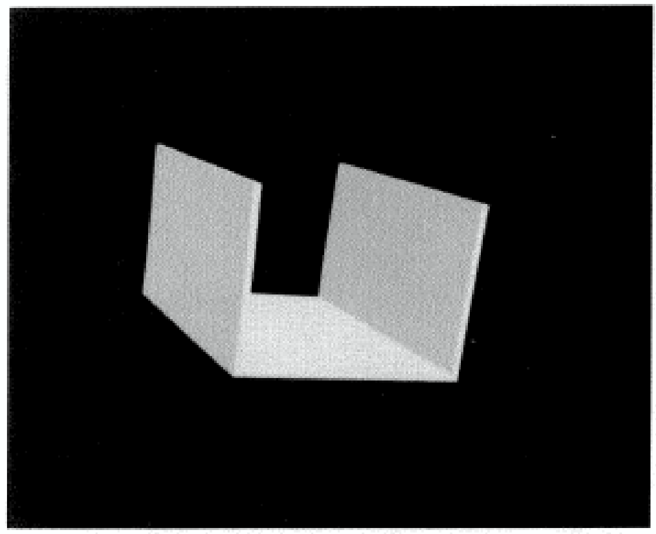


Figure 6: An Alpha_1 model of the part we wish to create.

aims at discovering such a method.
Although the inaccuracies associated with stereolithography are usually not large when comparing with those obtained with other forming processes, there is room for improvement. Rapid prototyping processes have an advantage of having flexible inputs and therefore iterations are possible without modifying hard tooling.
Since stereolithography is quite repeatable, it is theoretically possible to improve the accuracy of the process. If a computational process can produce the same distortions to geometric data that stereolithography produces in real parts, then it may be possible to achieve the theoretical limits to part accuracy. We are investigating finite element modelling as a candidate for such a process.

References

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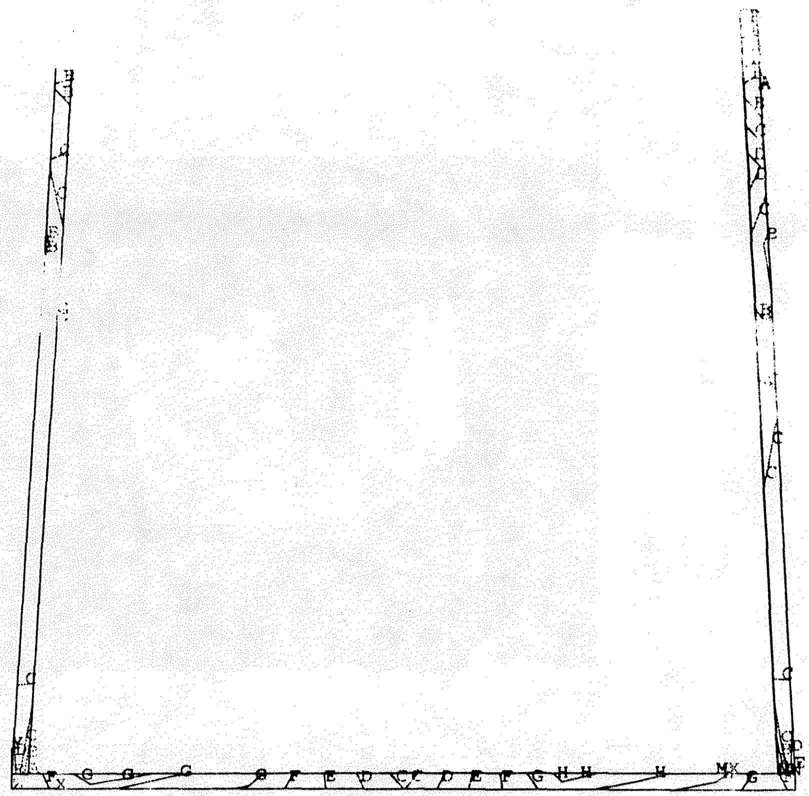

Figure 7: A finite element model of the distorted part.

[4] F. Prioleau. Beyond prototypes: Using stereolithography for production-quality parts. In *National Conference on Rapid Prototyping*, pages 145–147, June 1990.