Rapid Prototyping Benchmark: 3D Printers

Executive Summary

by Todd Grimm

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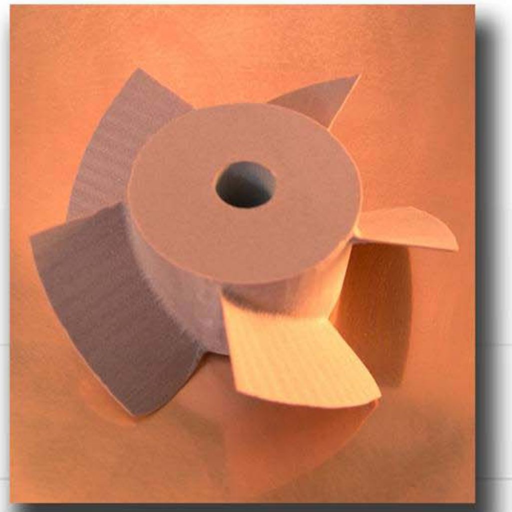

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To purchase the full Rapid Prototyping Benchmark of 3D Printers, visit www.tagrimm.com/benchmark/.

The 55-page benchmark report includes 34 charts, 5 tables and 36 images. The expanded coverage includes additional information on expenses, processing time, dimensional accuracy and surface finish. It also includes results for the individual prototypes, subjective reviews of the prototypes and a detailed description of the test procedures and supporting data.

To review the table of contents, see page 7 of the Executive Summary.

Acknowledgements

This rapid prototyping benchmark required many hours of man and machine time. It also required a thorough documentation process that is well beyond that of any commercial rapid prototyping project. Without the assistance (and patience) of the following companies, the benchmark would not have been possible.

American Precision Prototyping
Tulsa, Oklahoma, USA, www.approto.com
Instant on-line quoting for rapid prototyping services.

Accelerated Technologies
Austin, Texas, USA, www.acceleratedtechnologies.com
Rapid prototyping, rapid tooling and contract manufacturing.

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University of Louisville, Rapid Prototyping Center
Louisville, Kentucky, USA, www.louisville.edu/speed/chemical/research/rapid_prototyping_center.htm
Rapid prototyping services (for consortium members) and research and development for systems and materials.

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Founded by Todd Grimm, a 13-year veteran of the rapid prototyping industry, T. A. Grimm & Associates, Inc. offers consulting services on rapid prototyping and related technologies, including competitive analysis, benchmarking and educational programs. The company also offers outsourced marketing services that include marketing plan development, Web optimization, copywriting and lead generation. Grimm combines his engineering background and technical knowledge with years of sales, management and marketing experience to create and implement strategic and tactical plans. For more information, visit the T. A. Grimm & Associates Web site at http://www.tagrimm.com.

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About Todd Grimm:

Todd Grimm, president of T. A. Grimm & Associates, Inc., has been actively involved in the rapid prototyping industry since 1990. After five years in the CAD industry, Todd began working with rapid prototyping service bureaus and has had responsibility for general management, sales and marketing. He is recognized as an accomplished speaker and author on rapid prototyping.

Todd is the author of "User's Guide to Rapid Prototyping," which will be available in early 2004. He is also a contributing author for McGraw-Hill's "Manufacturing Engineering Handbook." Todd co-authors a rapid prototyping feature in the industry trade publication Time-Compression Technologies.

For the past four years, Todd has served as an advisor for the Society of Manufacturing Engineers' Rapid Prototyping & Manufacturing conference and tradeshow. He is a graduate of Purdue University where he earned a Bachelor of Science degree in Mechanical Engineering.

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Rapid Prototyping Benchmark of 3D Printers

Executive Summary

The rapid prototyping industry is not short on claims of fast processes, low operating costs and tight tolerances. However, beyond vendor supplied data and generalized industry perceptions, there is little information available that offers thorough comparisons of rapid prototyping systems. The purpose of the benchmark study is to provide a comparison with an in-depth analysis of the technologies and processes.

The benchmark study measures the performance of 3D printers, rapid prototyping systems that offer affordability and ease of use. Two exceptions are introduced into the benchmark. First, with the claims of subtractive rapid prototyping (SRP) and a price point that makes it competitive to 3D printers, Roland DG's MDX–650 CNC machine tool is included. Second, with the popularity of the stereolithography process, 3D Systems' Viper si2 is included to serve as a baseline of measurement.

The resulting list of benchmarked systems is: Z406 (Z Corporation), QuadraTempo (Objet Geometries), Dimension (Stratasys), MDX–650 (Roland DG), Viper si2 (3D Systems), PatternMaster (Solidscape) and ThermoJet (3D Systems).

In a review of rapid prototyping systems, there are three key considerations—time, expense and quality. To assist in a 3D printer evaluation, this benchmark supplies the following data:

<u>Time</u>
- Machine time
- Total processing time

<u>Quality</u>
- Dimensional accuracy
- Surface finish

<u>Expense</u>
- Annual operating expense
- Prototype cost

These performance measures are dependent on the prototype that is produced. Prototype parameters such as size, volume, and level of detail can influence production time, cost and quality. Previous benchmark studies have used a single part in the analysis, which make the results applicable only to prototypes of similar size and geometry.

To provide data that is relevant to a wide array of parts, this benchmark analyzes three distinctly different prototypes: cell phone housing (*Figure 2*), fan (*Figure 1*) and track ball base (*Figure 3*). The cell phone offers the evaluation of a thin walled, highly detailed, relatively small prototype that represents many injection molded parts.

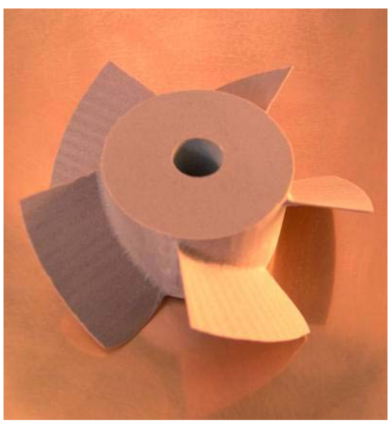

Figure 1 – Prototype fan from MDX-650.

Figure 2 –Prototype cell phone from Z406.

Figure 3 – Prototype track ball from Dimension.

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Users of the technology, not the system manufacturers, produced the prototypes. Each was constructed with parameters suited to concept, form and fit applications. During the process, all elements of time and cost were measured—from opening the STL file to the time that the prototype was ready for shipment. In doing so, the most important aspect of time, total process time, is documented.

To eliminate the variable of post processing (part finishing) and to facilitate surface measurement studies of raw prototypes, benching of the parts was not permitted. However, all secondary operations necessary for the completion of the test parts were performed. These operations included cleaning, curing, support removal and part infiltration.

Benchmark Results – Cost and Time

Without benchmark data, many buying decisions are based on system cost and vendor claims of system speed and accuracy. Often, these claims do not accurately reflect the true ownership and operational costs or the actual time for prototype production. By capturing all elements of time and cost and measuring deliverable tolerance, the benchmark data offers an accurate depiction of acquisition expense, annual expense, hourly cost and prototype cost. It also offers an accurate measure of the total time to produce a prototype.

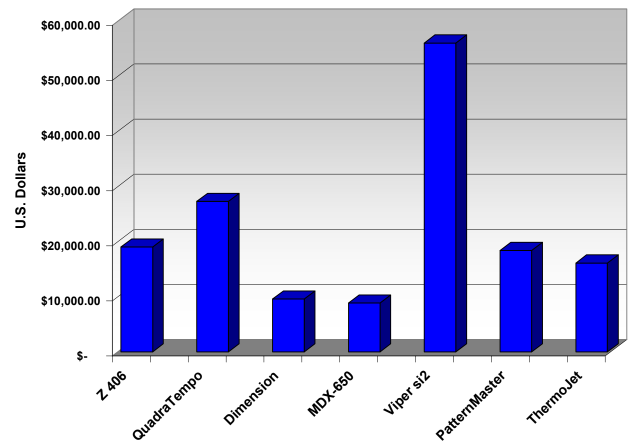

Figure 4 - Annual operating expense including amortized acquisition cost.

Cost

To determine annual operating expense (*Figure 4*), the acquisition expense is combined with ongoing expenses such as annual maintenance contracts, labor and replacement parts for routine service, consumables and material disposal. For this calculation, the system cost and supporting equipment expenses are amortized (straight line) over seven years. Note that annual operating expense includes fixed expenses and the variable expenses associated with a single shift operation.

Using an hourly machine rate, time for production, material cost and labor expense, a prototype cost is calculated for each test part. From this data, the average is calculated (*Figure 5*).

The average part cost includes labor expense for all operations that require operator attendance or intervention. The processes for which labor was collected include data preparation, machine preparation, machine operation, part removal and part post-processing. Material costs for the prototypes include the expense of model, support and infiltration materials.

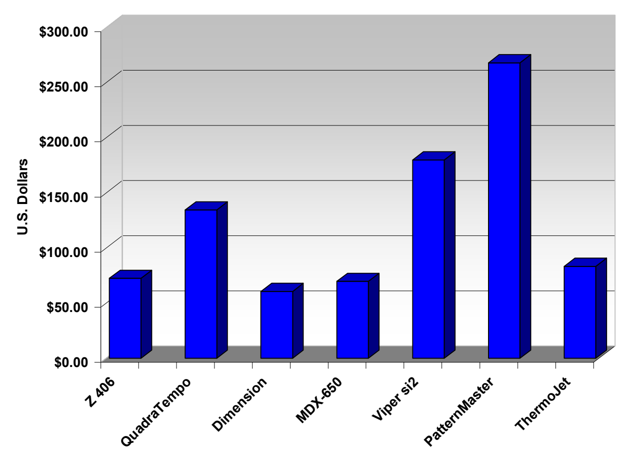

Figure 5 – Average cost for the three benchmark prototypes.

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Time

Figure 6 shows the average build time for the prototypes. This build time measure includes only the time that the systems required for the construction of the prototype. It does not include time for data preparation, machine set-up, and post-build operations.

Figure 7 shows the average time for the total prototyping process. In this chart, the lower portion of the bar reflects machine time and the upper portion reflects all other processes.

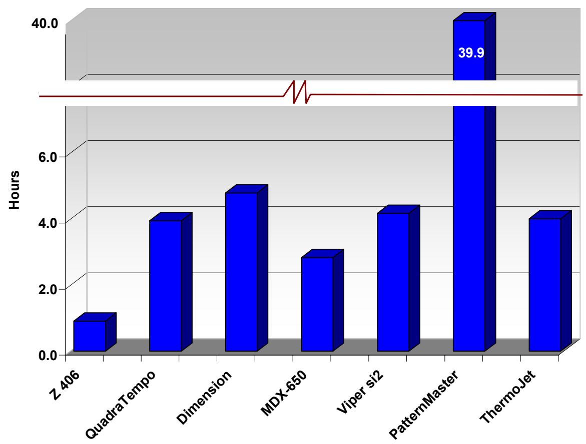

Figure 6 - Average build time for the three benchmark prototypes.

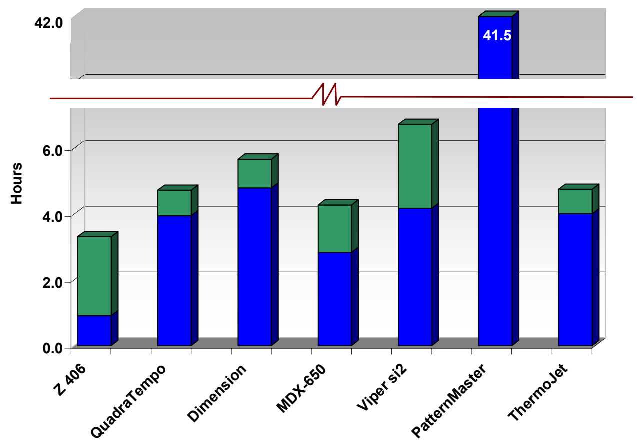

Figure 7 – Average time for the complete prototyping process.

As seen in *Figure 7*, the impact of pre- and post-build operations has varying degrees of effect on the systems' total processing time. For data processing, all additive systems required minimal time and labor. Surprisingly, the data preparation (tool path generation) of the subtractive process (MDX-650) was completed in an average of only 52 minutes.

For all system but the MDX-650, additional time was required to prepare the prototypes after build completion. This yields the most dramatic difference between build time and total process time.

As expected, all systems, with the exception of the MDX-650, have an increase in machine time as the size and volume of the prototypes increase. To varying degrees, these systems' build times are defined by layer thickness, volume of material in the part, and the height of the part in its build orientation. Unlike the additive systems, the MDX-650 has less sensitivity to prototype size and increased sensitivity to part complexity.

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Benchmark Results – Accuracy and Finish

University of Louisville's Rapid Prototyping Center performed all testing for the benchmark study. Using a CMM and other measurement devices, each prototype was inspected for dimensional accuracy. For the three benchmark parts, 22 features were measured. For surface finish analysis, the parts were measured with a Wyco white light interferometer. To support the surface finish measurements, images were taken with a stereo microscope.

Dimensional Accuracy

Averages of the absolute deviations from the nominal dimensions are shown in *Figure 8*. The figure also indicates the standard deviation (σ) for the measurements with the error bar that extends above the average value. Since a range of -1σ to +1σ represents 68% of a populations of values, the data in this chart offers tolerance information that could be reasonably expected on user parts. For example, output from a Z406 is likely to have an average tolerance of ± 0.34 mm (0.013 in.) with an anticipated range of -0.63 to +0.63 mm (-0.025 to + 0.025 in.).

There were issues of warpage and shrinkage compensation with three of the systems. This illustrates a key consideration when reviewing the dimensional accuracy of each system. The deliverable tolerance is subject to many variables, including materials, system calibration, construction parameters, part geometry, operator training, environmental conditions and elapsed time. A change to any one of these variables could result in improved (or perhaps worse) results.

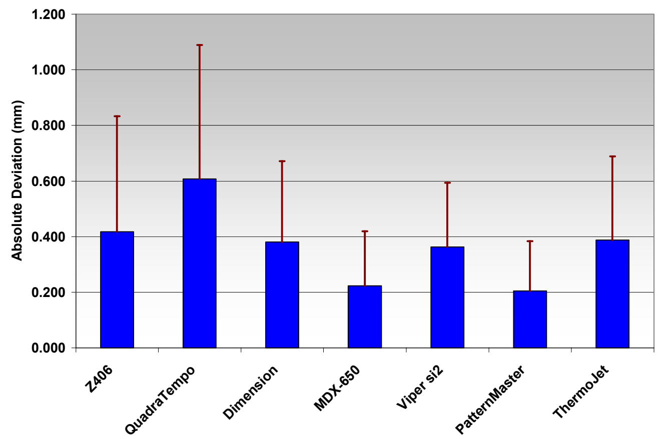

Figure 8 - Average dimensional accuracy and standard deviation (extended bar).

To expand on the data in *Figure* 8, *Figure* 9 adds the minimum, maximum and median values for dimensional accuracy. With the side-by-side comparison of these values, a wide variance in dimensional accuracy is apparent. While each system is capable of delivering at least one dimension between 0.01 and 0.06 mm (0.000 and 0.002 in.), the maximum deviations increase to 0.27 to 1.29 mm (0.015 to 0.044 in.).

The dimensional accuracy data shows that vendor claims of ± 0.13 mm (± 0.005 in) are not realistic for all features on all parts. Having evaluated seven systems and measured 19 separate prototypes, it is apparent that this level of accuracy is unreasonable to expect in a general-purpose prototyping environment. Without changing build parameters or using part finishing to improve prototype accuracy, a realistic expectation of 3D printers would be ± 0.25 to 0.75 mm (± 0.010 to 0.030 in.).

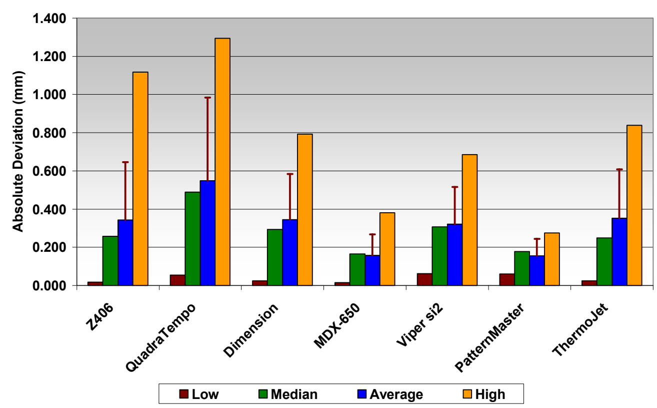

Figure 9 - High, low, median and average dimensional accuracy.

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Surface Finish

A visual representation of the surface finish produced by each technology is show in *Figure 10*. Using a stereo microscope at 10 X magnification, the surface finish on the side wall of the track ball was captured.

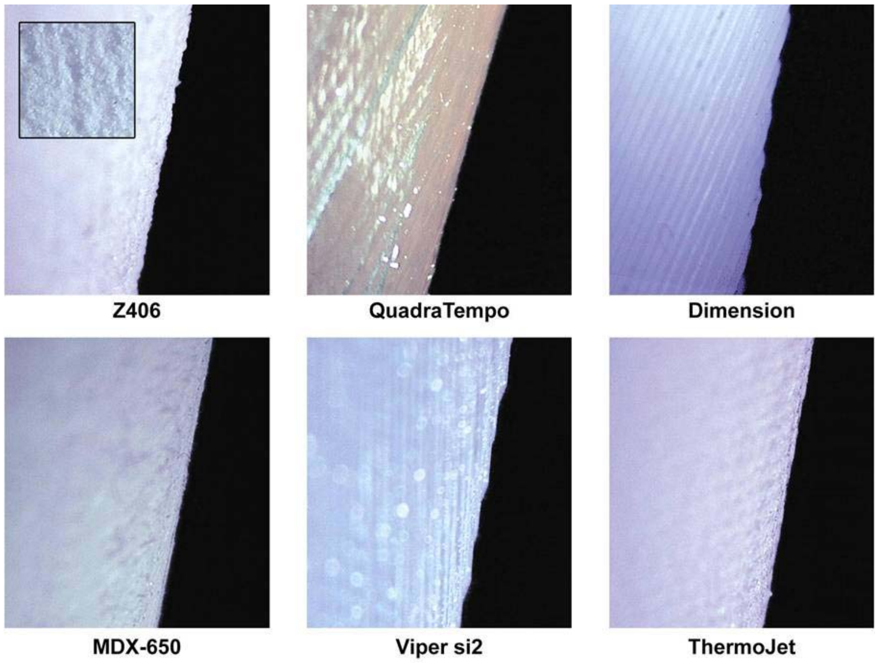

Figure 10 – Surface finish images from the track ball. Images captured with a stereo microscope at 10 X magnification.

The effects of stair stepping are evident for both the Viper si2 and Dimension. Constructed with 0.15 and 0.25 mm (0.006 and 0.010 in.) layers, respectively, the surfaces from both technologies are rough and layered. Although the Z406 part was built with 0.10 mm (0.004 in.) layers, which should show stair stepping, the layered effect is not evident. Instead, the Z406 part has a rough, textured surface that hides the stair stepping on the part.

While the QuadraTempo and ThermoJet also construct parts in a layered fashion, stair stepping is not detectable since each uses thin layers—0.02 mm (0.0008 in.) and 0.04 mm (0.0015 in.), respectively. As expected, the 3-axis machining process of the MDX-650 delivered a smooth, stair step free, surface finish.

Combining the data from the stereo microscope and Wyco white light interferometer with visual inspection, the overall surface finishes—with consideration of all surfaces— from the tested technologies ranges from poor to excellent. The MDX-650 and PatternMaster offer good to excellent finish. The QuadraTempo, Viper si2 and ThermoJet offer acceptable to good finishes. The Dimension offers an acceptable finish, and the Z406 offers a poor to acceptable finish.

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Rapid Prototyping Index

The Rapid Prototyping Index is a weighted ranking of performance measures for each system in the benchmark study. Compiled from the averaged data for time, cost and quality, the index normalizes the results to a one to ten scale, where 10 is the best. For the weighting factors, 100 points are allotted to the 13 decision-making criteria. The total score is the sum of the normalized results times the weighting factors.

Since the importance of the measured variables differs from one application to the next, the index ranks the systems in the following categories: concept models, form & fit models, functional models and patterns. For each category, the weighting factors are adjusted to reflect common user demands for the application. The results for concept modeling is shown in *Figure 11*.

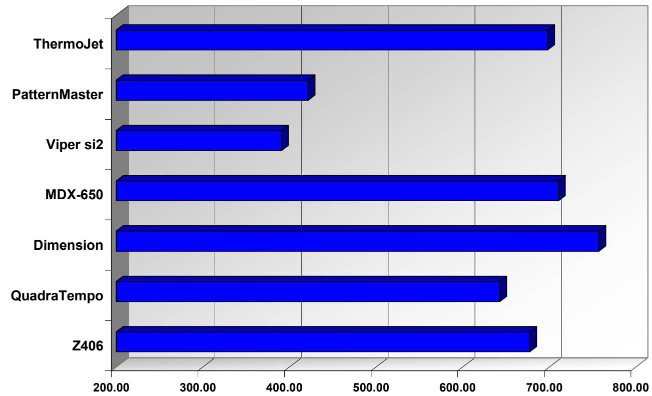

Figure 11 – Concept modeling index.

Conclusion

3D printers are expected to be fast, easy to use, and cost-effective rapid prototyping devices that deliver reasonable quality for concept modeling and engineering analysis. Five of the tested systems satisfy these requirements. With its cost and operational demands, the Viper si2 is not a 3D printer. While the PatternMaster fits many of the characteristics of a 3D printer, it does not satisfy the time requirements when applied to parts typical in industrial applications. The remaining systems are well suited for 3D printer applications, even the MDX-650, which is not a printer at all.

There are a vast number of combinations of build parameters, prototyping materials, part definitions and operating conditions. Testing of all scenarios in the benchmark study is impractical and unreasonable. Therefore, the results presented in the benchmark are best suited for the relative positioning of the rapid prototyping systems when similar parts are constructed with similar build parameters.

When evaluating systems, use this benchmark data as an initial selection guide. Then define the application and the types of parts used in the product development process. Evaluate the systems with the operational and output requirements that are important to the success of the prototyping effort. Finally, add the evaluation of two important criteria that were not reviewed in the benchmark, material properties and finishing time.

With clearly defined goals and a thorough evaluation, the selection of the best rapid prototyping system for a user's unique needs and operational considerations is possible.

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