# Rapid Prototyping Benchmark: 3D Printers

by Todd Grimm

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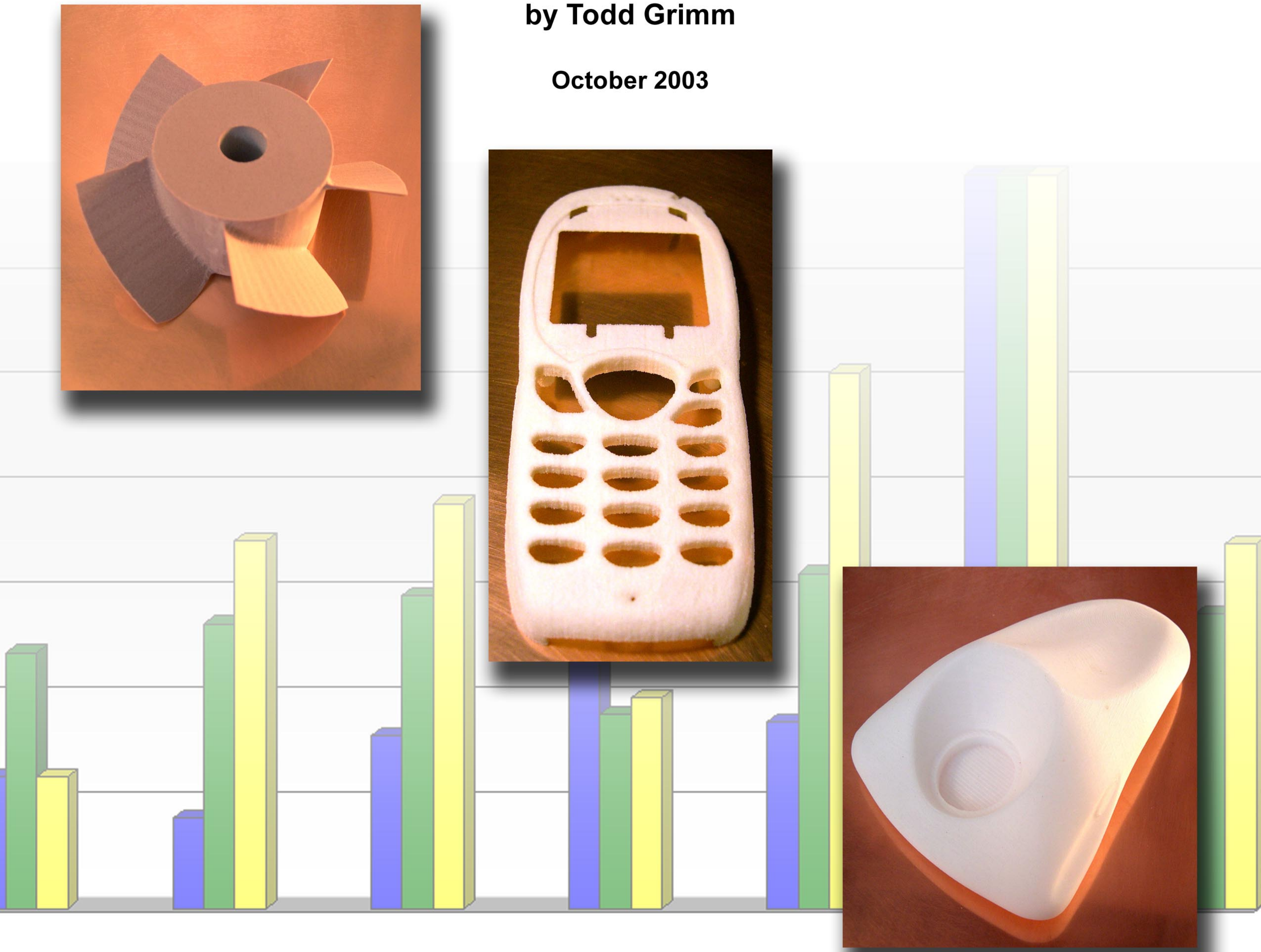

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## I. Overview

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 this benchmark study is to provide a comparison with an in-depth analysis of the technologies and processes.

The fastest growing segment of the rapid prototyping industry is 3D printers. With the increasing interest in these affordable systems, there is a greater need for information that can be used in an evaluation. Therefore, the benchmark study measures the performance of 3D printers. The criteria for inclusion in the benchmark are:

- System price below $100,000
- Office or departmental operating environment
- Small footprint

Additionally, the benchmark includes only those systems that have been commercially available for more than one year.

Two exceptions were introduced into the testing matrix. 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, due to the likelihood of familiarity with the stereolithography process, and the possibility of using that familiarity as a baseline of measurement, 3D Systems' Viper si2 is also included.

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)
- ThermoJet (3D Systems)

In an evaluation 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:

- Time
  - Machine time
  - Total processing time
- Quality
  - Dimensional accuracy
  - Surface finish
- Expense
  - Acquisition expense
  - Annual operational expense
  - Hourly cost of operation
  - Prototype cost

**Testing Procedures**

Testing results from rapid prototyping systems 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, fan and track ball base. The cell phone (*Figure 2*) offers the evaluation of a thin walled, highly detailed, relatively small prototype that represents many injection molded parts. The fan (*Figure 1*) is larger than the cell phone in both size and volume, and the blades have a complex shape. The track ball (*Figure 3*) offers an even larger prototype with large mass —it is solid — and many contoured surfaces.

Users of the technology, not the system manufacturers, produced the prototypes. Each was constructed individually in the test systems 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.

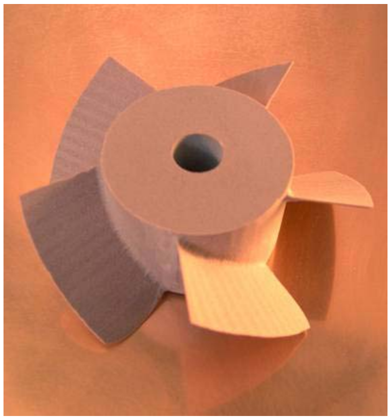


**Figure 1 –** Prototype fan from MDX-650.

**Figure 2** – Prototype cell phone from Z406.

**Figure 3** – Prototype track ball from Dimension.

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.

A complete description of the testing procedures, assumptions and formulas used in the benchmark is available in Appendix D.

## II. System Expense and Throughput

Without benchmark data, many buying decisions are based on system cost and vendor claims of system speed. While these are critical components in an analysis, they do not accurately reflect the true ownership and operational cost or the actual time for prototype production. By capturing all elements of time and cost, this 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.

## Acquisition Expense

The acquisition expense (*Figure 4*) reflects the investment for the system configuration used in the benchmark, including all necessary support equipment. The expenses do not include optional equipment that is at the user's discretion and any costs for facility changes and system installation. While two of the systems may require facility modification (Viper si2 and PatternMaster), the associated cost is highly variable and difficult to quantify, and therefore, it has been omitted. When conducting a system evaluation, the facility modifications specific to the buyer's operation and the associated cost should be determined to quantify the full acquisition and implementation expense.

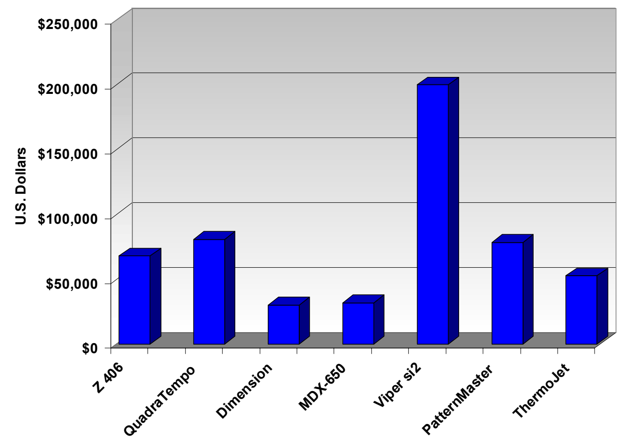



**Figure 4 -** Total expense for purchase of benchmark systems and supporting equipment.

## Annual Operating Expense

To determine annual operating expense (*Figure 5*), 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, acquisition 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. It does not include the variable expenses of labor and material for the production of prototypes. These are captured in the cost of the individual prototypes.

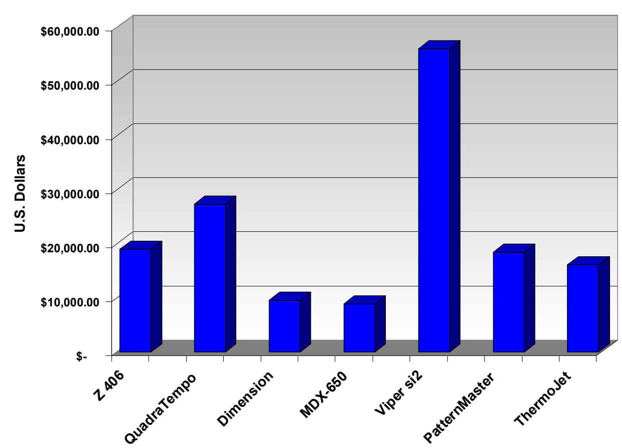



**Figure 5** – Annual operating expense including amortized acquisition cost.

The reported annual expense, and all other measures derived from it, is applicable to only the specific systems used in the benchmark. Therefore, conclusions drawn from the presented data may not apply to other devices offered by the system vendors.

## Hourly Cost

The annual expense, when amortized over anticipated annual prototype throughput, yields a standardized hourly cost for machine operation.

To determine annual prototype throughput and the associated machine hours, build times are calculated for the construction of two "typical" parts. The *X*, *Y*, and *Z* dimensions and part volumes of the test parts are averaged to yield the "typical" part.

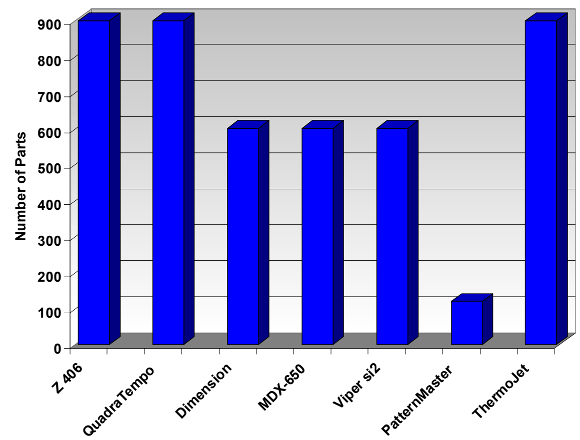



**Figure 6** – Annual throughput of systems based on typical part.

The study assumes that machine runs commonly use 25% to 50% of a system's capacity (*X*–*Y* build envelope). To satisfy this criterion, construction times are calculated for the concurrent building of two "typical" parts. Using the time per run and assuming a single shift operation—nine hours per day, five days a week, and 50 days a year— the maximum number of runs and the daily throughput are determined. Taking into account lost time for repairs, maintenance and scheduling inefficiencies, a utilization rate of 60% is applied to the daily maximum. The resulting annual throughput is show in *Figure 6*.

The annual throughput and the associated build time yields the annual operating hours for the test systems. The hourly rate for machine operation (*Figure 7*) is calculated from the annual operating hours and annual expense (*Figure 5*). For each system, the most significant factors affecting hourly rate are annual throughput, system cost, and maintenance expense. The Viper si2's hourly rate also has a high cost contribution for the purchase of equipment necessary for post-processing of the prototypes.

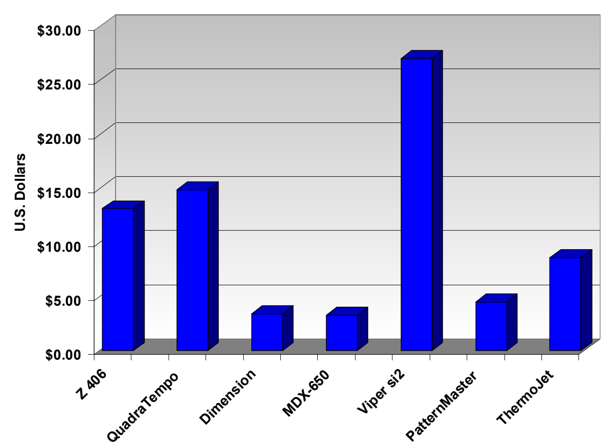



**Figure 7** – Hourly cost for machine operation.

The MDX-650 and Dimension have the lowest hourly rates at $3.26 and $3.40, respectively. The PatternMaster is a close third with a rate of $4.49. At $27.03, the Viper si2 has the highest hourly rate. The ThermoJet, Z406 and QuadraTempo fall in the middle with rates of $8.59, $13.16 and $14.89, respectively.

While it may be tempting to use hourly rate in an evaluation, this is not a viable measure of system performance or operational cost. The calculation of the hourly rate is such that the slower of two systems with equal annual operating expense would have a lower hourly cost. This parameter is determined solely for calculating the production costs of the benchmark parts. The prototype cost is the viable measure in a system evaluation, and this data is presented in the following section.

## III. Prototype Time and Expense

### Averaged Results

Time and expense for rapid prototyping are dependent on many parameters, including the physical size of the part. To show the overall positioning of the seven rapid prototyping technologies, average cost and time for the cell phone, fan and track ball are presented.

<u>Prototype Cost</u>

Using the 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 8*).

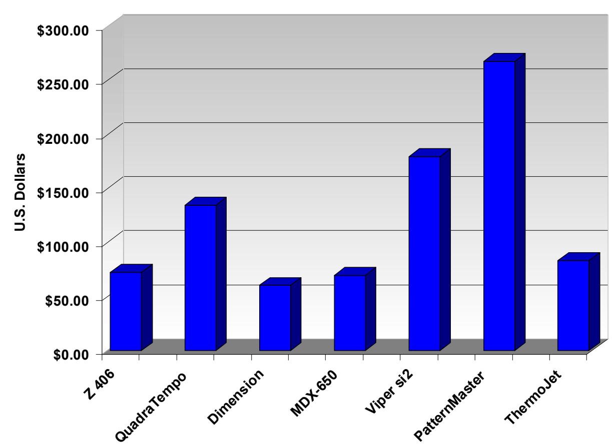



**Figure 8** – Average cost for the three benchmark prototypes.

The average part cost includes labor expense, at a rate of $35.00/hour, 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 and support material, and in the case of the Z406, infiltration materials used in post-processing.

The variance in average prototype cost is substantial, ranging from $60.53 to $267.85. With an annual production of 300 cell phones, fans and track balls, the difference in annual prototyping expense between the lowest and highest cost systems would be $186,588. Excluding the Viper si2 and PatternMaster from the comparison of 3D printing devices, the difference drops to $66,573, which is still significant.

<u>Prototype Time</u>

*Figure 9* shows the average build time for the prototypes. This is an average of the time for building the three test prototypes individually, not the total time for construction of the three parts in a single build. 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.

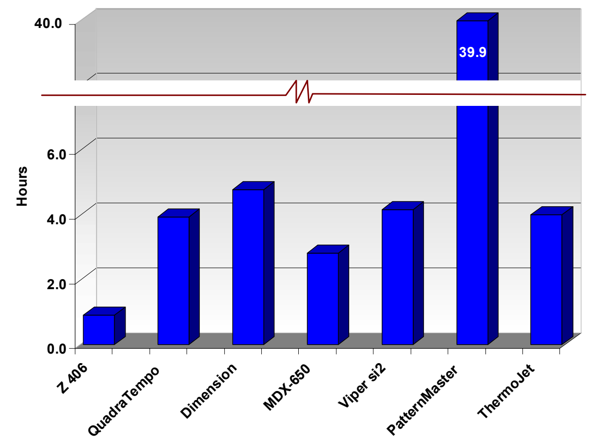



**Figure 9** - Average build time for the three benchmark prototypes.

Build time is often cited as a measure of system performance. While it is a key component in the total delivery time of a prototype, its value in a system evaluation is questionable. When comparing systems, the important time measure is that for the entire process—from the moment that an STL file is opened to the completion of a prototype that is ready for delivery.

As noted previously, the benchmark study does not include the time for benching (sanding and finishing a prototype to user specification) but does include secondary operations necessary for part production. *Figure 10* 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.

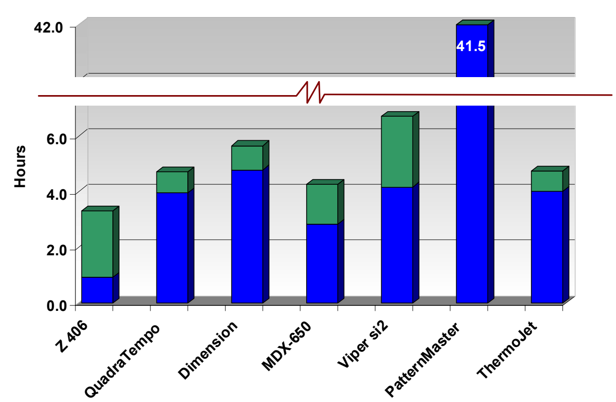



**Figure 10** – Average time for the complete prototyping process.

As seen in *Figure 10*, 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. These systems average 5 to 11 minutes for file and build preparation. Surprisingly, the data preparation (tool path generation) of the subtractive process (MDX-650) was completed in an average of only 52 minutes.

Inexperienced operators will find that the data preparation time for Z406, QuadraTempo, Dimension and ThermoJet will be consistent with that of an experienced operator. These systems offer software preparation tools that limit user-defined parameters and simplify the process. This simplification results in efficient data preparation for the inexperienced user. On the other hand, the MDX-650—while it has a simplified, wizard-driven interface—requires some experience to reach the operational efficiency shown in the benchmark data. Similarly, the Viper si2 and PatternMaster offer numerous user-defined build parameters, which can increase processing time for inexperienced operators.

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. For the Z406, parts remain in the build chamber while they dry. The Z406 also requires the removal of excess powder from the part surface and infiltration of the raw part. On average, this added 2.11 hours to the Z406 process. For the Dimension, support structures are removed from the prototypes, and this added an average of 37.5 minutes. Similarly, the support removal for the QuadraTempo parts added an average of 14.1 minutes.

Like the Dimension and QuadraTempo, the Viper si2 and ThermoJet require support structure removal, but each requires interim processes. With the Viper si2, parts are drained prior to removal from the machine, the part surface is cleaned—usually with a solvent—and the part is cured in a UV oven. Combined with support removal, these steps added an average of 1.83 hours to the Viper si2 process. With the ThermoJet, parts are chilled prior to support removal, and these processes averaged 35.8 minutes.

While the averages for time and cost are good indicators of relative positioning of the seven rapid prototyping systems, they do not illustrate the effect of prototype size, volume and complexity. To understand the impact of these factors, a review of time and cost for each of the three prototypes is necessary. This data is presented in the following section.

Conclusions

From the average time and cost, the limitations of the PatternMaster, as a general-purpose 3D printer for industrial parts, is obvious. The benchmark results support Solidscape's position of the PatternMaster as a concept modeler and pattern generator for small, intricate parts. The speed of the system and cost of the prototypes illustrate that the technology is best suited for parts smaller than the cell phone, such as those found in the jewelry industry.

From the averages, another conclusion is that each of the six remaining systems is competitive in the 3D printer environment. With prototype cost averaging $100.10—ranging from $60.53 to $179.85—each system offers a cost-effective solution for 3D printing applications. Likewise, the total construction time of each system, averaging 4.91 hours—ranging from 3.31 to 6.72 hours— is also fitting of a 3D printer. However, when physical size of the systems and acquisition expenses are considered, the Viper si2 does not meet the criteria of a 3D printer. Instead, it is positioned as an enterprise resource for prototype and pattern production.

The last conclusion drawn from the averages is that the MDX–650 is a competitive solution that offers an alternative to the additive 3D printing technologies. When the definition is expanded to include both additive and subtractive processes, the MDX-650 is a rapid prototyping device.

**Results by Test Part**

Prototype Cost

With the assumptions, criteria and calculations used for average expense, the cost of the cell phone, fan and track ball are determined for each of the rapid prototyping systems. *Figure 11* lists the results.

This chart illustrates the limitations of decisions based on a single prototype or on averaged data. While three systems (Z406, Dimension and MDX-650) are relatively stable across the test parts, the other systems show substantial increase in cost as prototypes get larger. This is the result of the dependence of machine time/cost and material cost on the size and volume of the prototypes.

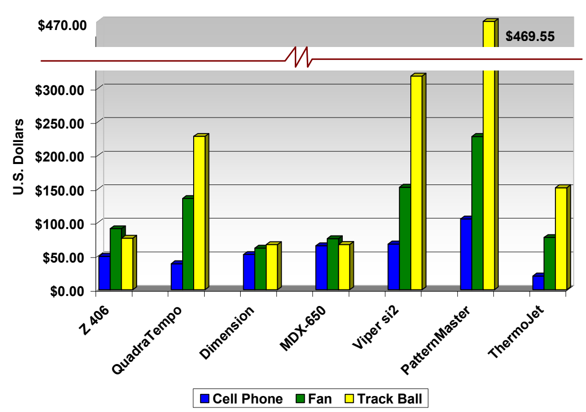



**Figure 11** – Cost of benchmark prototypes.

With higher costs for the fan, when compared to the cell phone and track ball, it is clear that the Z406 and MDX-650 are dependent on parameters beyond prototype size. For both systems, lower cost materials make the prototype expense less dependent on the prototype's volume. In addition, the other key component of expense—machine time—is less sensitive to part size.

Note that the Dimension would have shown a cost trend similar to that of the QuadraTempo and Viper si2 if all parts were built solid. Within the constraints of the benchmark—prototypes suitable for engineering evaluation—the fan and track ball were constructed with the sparse fill build style. With a solid fill, the cost for both parts would be higher.

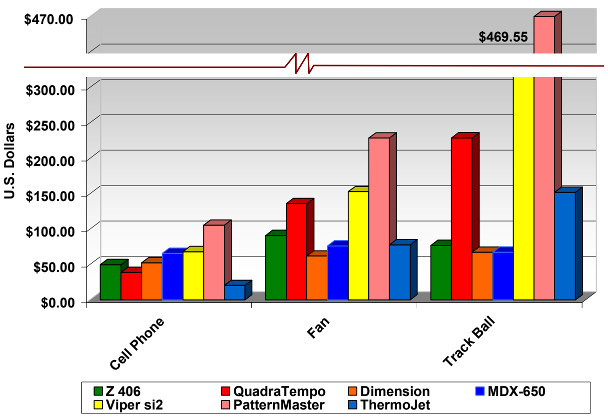



**Figure 12** – Cost of prototypes grouped by part.

*Figure 12* presents the data in *Figure 11* grouped by prototype.  Excluding the PatternMaster, the high and low costs for the cell phone differ by only $47.72. Meanwhile, the cost for the fan has a variance of $90.89, and the track ball has a variance of $251.35.

<u>Prototype Time</u>

In *Figures 13* and *14*, the machine (build) time of the prototypes are shown. As expected, all systems, with the exception of the MDX-650, have an increase in machine time as the size and volume of the

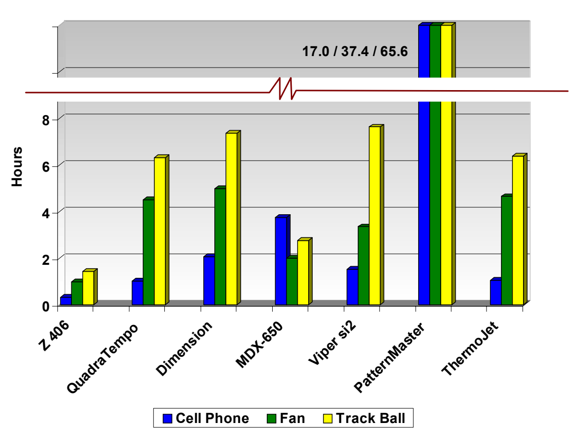



**Figure 13** – Build time for benchmark parts—grouped by technology.

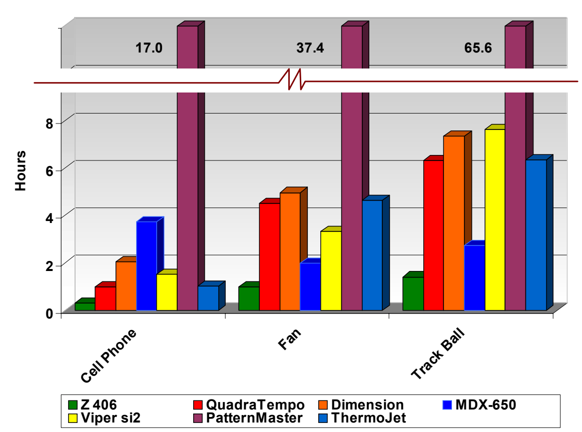



**Figure 14 -** Build time for benchmark parts—grouped by prototype.

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. For the Z406, QuadraTempo and ThermoJet, part volume is not a factor for machine time. Instead, time is a function of the *X*-*Y* footprint. For these three devices, the time to print the prototype is, in part, determined by the number of print passes required to cover the *X*-*Y* profile of each layer.

Unlike the additive systems, the MDX-650 has less sensitivity to prototype size and increased sensitivity to part complexity. For machining, key variables that affect time are the amount of material removed, number of machining passes, number and type of features, and the number of set-ups and tool changes. For the MDX-650 in the benchmark study, the use of the fourth axis rotary table and automatic tool changer (ATC) eliminates set-ups and tool changes. Yet with the second highest time for the cell phone, the influence of part complexity and number of features is evident. In contrast, the MDX-650 is the second fastest system for the bulky, contoured track ball.

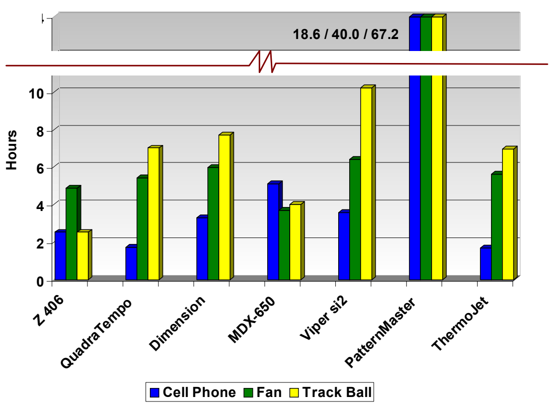



**Figure 15** – Total elapsed time—grouped by technology.

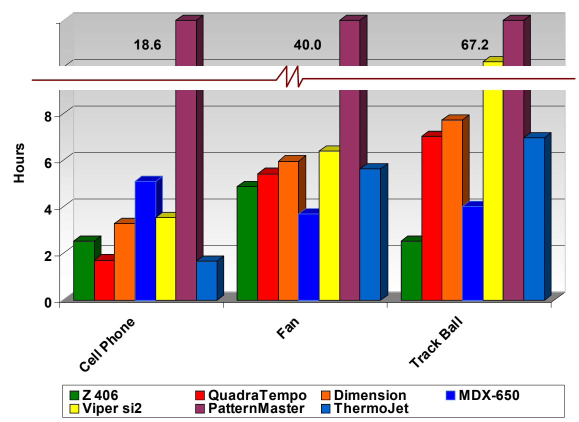



**Figure 16** – Total elapsed time—grouped by prototype.

*Figures 15* and *16* show the total time for prototype development. When combined with the information in *Figures 13* and *14*, the impact of pre- and post-processing of the rapid prototypes is evident. This clearly illustrates that machine time should not be used as a measure in a system evaluation.

From the total processing times, it is apparent that there is not a system that is the fastest or slowest—if the PatternMaster is excluded— for each of the benchmark parts. Instead, the ranking of systems varies with the part size and configuration. Therefore, when evaluating systems, use the total process time for the test part(s) that are most similar to those needed in the company's product development process.

For further detail, see Appendix C for charts of the cumulative process time for each of the individual prototypes.

# IV. Quality

The benchmark study measured two factors of quality, dimensional accuracy and surface 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 majority of the dimensions, four measurements were taken. From this data, an average value and standard deviation were calculated for each inspected feature.

For the three benchmark parts, a total of 22 features were measured.

For surface finish analysis, the parts were measured with a Wyco white light interferometer. The surface finish was determined for the top surface of the fan. To support the surface finish measurements, images from the track ball were taken with a stereo microscope. Due to excessive build times, the fan and track ball were not produced on the PatternMaster, and therefore, no surface finish data is available.

## Averaged Results

As with the time and expense data, quality is also a function of many parameters, including the physical size of the part and build parameters. To show the overall positioning of the seven rapid prototyping technologies, the results for the three test parts are averaged for the presentation of dimensional accuracy.

### Dimensional Accuracy

Averages of the absolute deviations from the nominal dimensions are shown in *Figure 17*. The figure also indicates the standard deviation (σ) for the data sets 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.). The data used to calculate the averages and σ's is presented in Appendix C – *Table 4*.

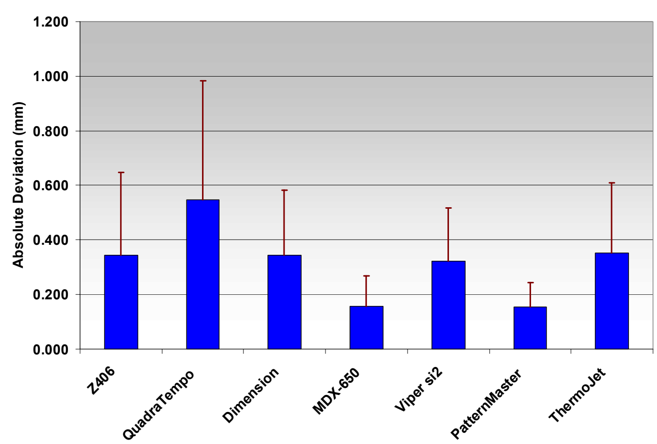



**Figure 17-** Average dimensional accuracy and standard deviation (extended bar).

For the calculation of the average dimensional accuracy data, any values that exceed 3σ are excluded. This testing standard prevents skewing of the results by what could be an anomaly in the part or in measurement of the feature. For each system, there were at least two excluded measurements.

There are several important notes regarding the data in *Figure 17*. First, the Z406, QuadraTempo and PatternMaster results do not include complete data sets. Due to warpage of the cell phone produced on the Z406 and QuadraTempo, six center-to-center dimensions were excluded. The PatternMaster does not include data for the fan and track ball since the parts were not constructed. Second, after construction of the ThermoJet parts, it was discovered that a change in the build material yielded inaccurate shrinkage compensation factors in the *X*- axis. Since suppliers were not allowed to rebuild any prototypes, the incorrect material shrinkage compensation is reflected in the data. However, there was not a consistent variance in the *X*-axis of the parts, so the data is reasonably accurate.

Based on past testing, the tolerance values for QuadraTempo seem unreasonably high. Typically, tolerances equivalent to the Viper si2 are expected. The inaccuracy shown may be the result of warpage or dimensional change that occurred during the time lapse between part construction and dimensional inspection. Another possibility is that incorrect shrinkage compensation values were used when constructing the test parts.

The issues of warpage and shrinkage compensation with the QuadraTempo illustrate 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. For example, several of the systems offer a robust set of user-defined build parameters. To improve accuracy (and surface finish) from systems like the Viper si2, MDX-650 or PatternMaster, construction parameters could be modified. However, in most instances, improving on the output quality would result in increased time and expense.

To expand on the data in *Figure 17*, *Figure 18* 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.).

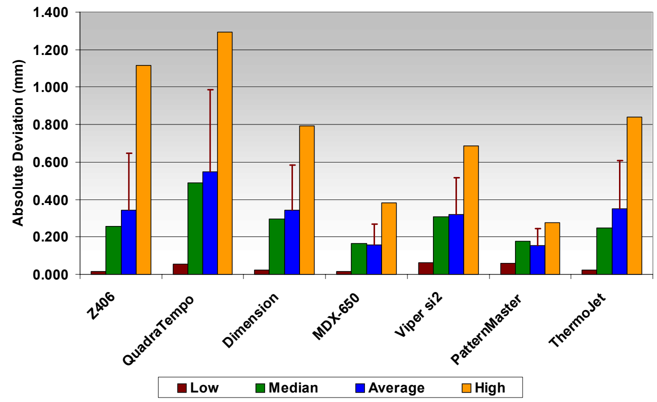



**Figure 18** – High, low, median and average dimensional accuracy.

An alternative presentation of dimensional accuracy is shown in *Figures 19* to *25*. In these charts, the *Y*-axis lists the percentage of dimensions that have a deviation below the specified tolerance (*X*-axis of chart). Note that this data is not subject to the exclusion of values that exceed 3σ.

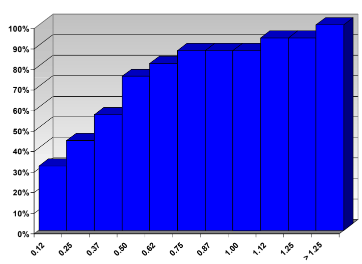


**Figure 19** - Z406

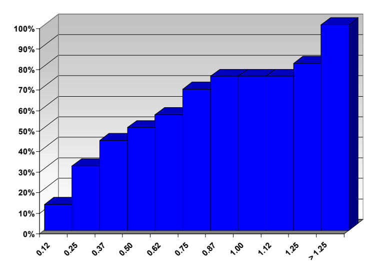


**Figure 20** - QuadraTempo

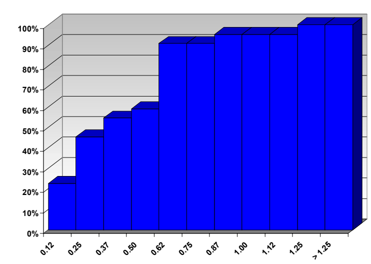


**Figure 21** - Dimension

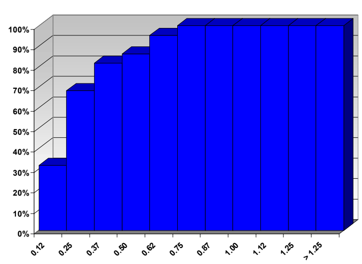


**Figure 22** – MDX-650

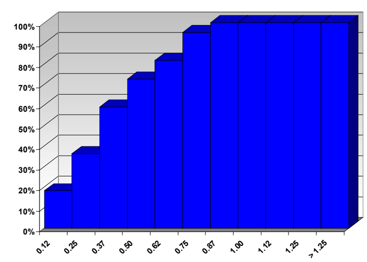


**Figure 23** – Viper si2

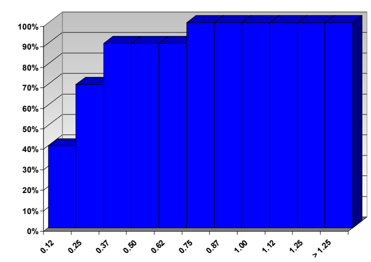


**Figure 24** - PatternMaster

**Figures 19 – 25**: Cumulative charts listing the percentage of the 22 individual dimensions that are equal to or less than the dimensional deviation listed on the *X*-axis of the charts. The scale ranges from 0.12 to 1.25 mm (0.005 to 0.050 in.) in 0.125 mm (0.005 in.) increments.

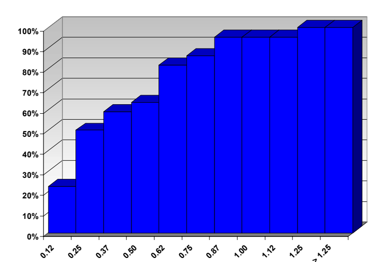


**Figure 25** - ThermoJet

Conclusion

Vendor claims of ± 0.13 mm (± 0.005 in) are not realistic for all features on all parts. Somehow, the accuracy claim of ± 0.13 mm became a standard upon which to measure rapid prototyping systems. 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.).

**Results by Test Part**

Dimensional Accuracy

As with cost and time, the averages for dimensional accuracy are reasonable indicators of general expectations. However, each prototype is likely to vary, sometimes significantly, from the averages. To illustrate the variance, the following charts list the average dimensional deviation for each prototype. Unlike the overall averages (*Figure 17*), the individual results do not exclude values that exceed 3σ.

*Figure 26* shows the average deviation for 10 features on the cell phone. As with the previous charts, it also shows the standard deviation. Surprisingly, only one system, the Dimension, had tighter tolerances than those of the overall average (including 3σ deviations). The general consensus in the rapid prototyping industry is that dimensional accuracy declines as the size of the dimensions increase. Accordingly, many vendors often cite their tolerances on a millimeter-per-millimeter (inch-per-inch) basis. However, the results for the cell phone, which has only one dimension that exceeds 50 mm (2 in.), are counter to this belief.

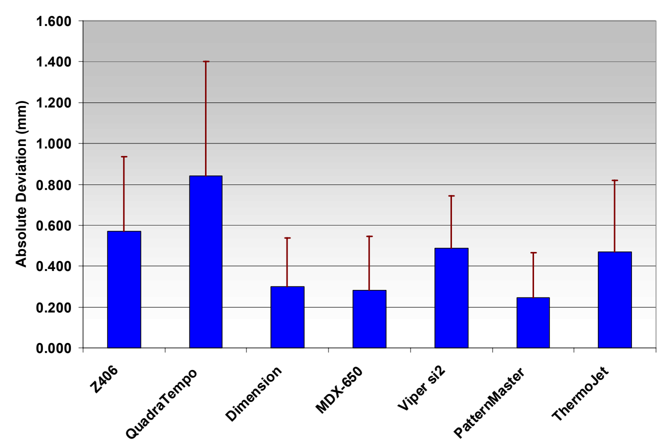



**Figure 26** – Average dimensional accuracy for the cell phone benchmark test part.

For the cell phone, the most accurate parts were from the PatternMaster [± 0.46 mm (± 0.016 in.)], Dimension [± 0.54 mm (± 0.020 in.)] and MDX-650 [± 0.54 mm (± 0.022 in.)].

*Figure 27* shows the average deviation for five features on the fan. While the Dimension is one of the top three for the cell phone, for the fan it has the loosest tolerance. For this part, the MDX-650 has the tightest tolerance [± 0.25 mm (± 0.010 in.)]. Across the board, the dimensional accuracies for the fan were better than those in the overall averages and those for the track ball. All systems offer a ± 1σ tolerance range between ± 0.25 and 0.57 mm (± 0.010 and 0.022 in.).

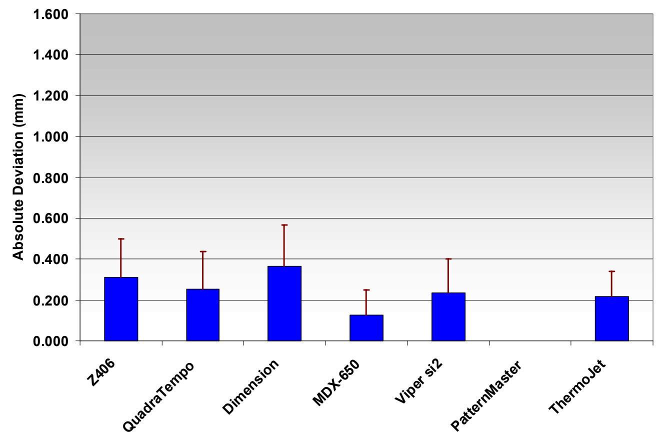



**Figure 27** - Average dimensional accuracy for the fan benchmark test part.

*Figure 28* shows the average deviation for seven features on the track ball. When compared to the cell phone and fan data, it is evident that there is little consistency in dimensional accuracy across the different benchmark parts. For this prototype the 1σ tolerance ranges between ± 0.43 and 1.14 mm (±0.017 and 0.045 in.). The Viper si2 had the best dimensional tolerance with ± 0.43 mm (± 0.017 in.).

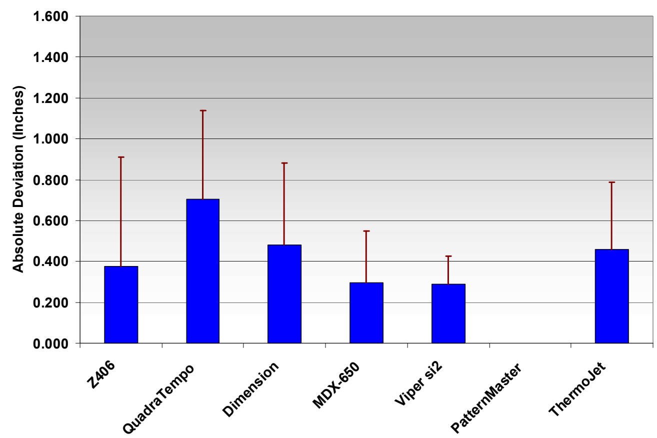



**Figure 28** - Average dimensional accuracy for the track ball benchmark test part.

## Surface Finish

A visual representation of the surface finish produced by each technology is show in *Figure 29*. Using a stereo microscope at 10 X magnification, the surface finish on the side wall of the track ball is captured. Since the track ball was not constructed with the PatternMaster, no surface finish image is shown.

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. Since the texture of the Z406 part is not evident in the edge view, an inset photo of the surface finish is included.

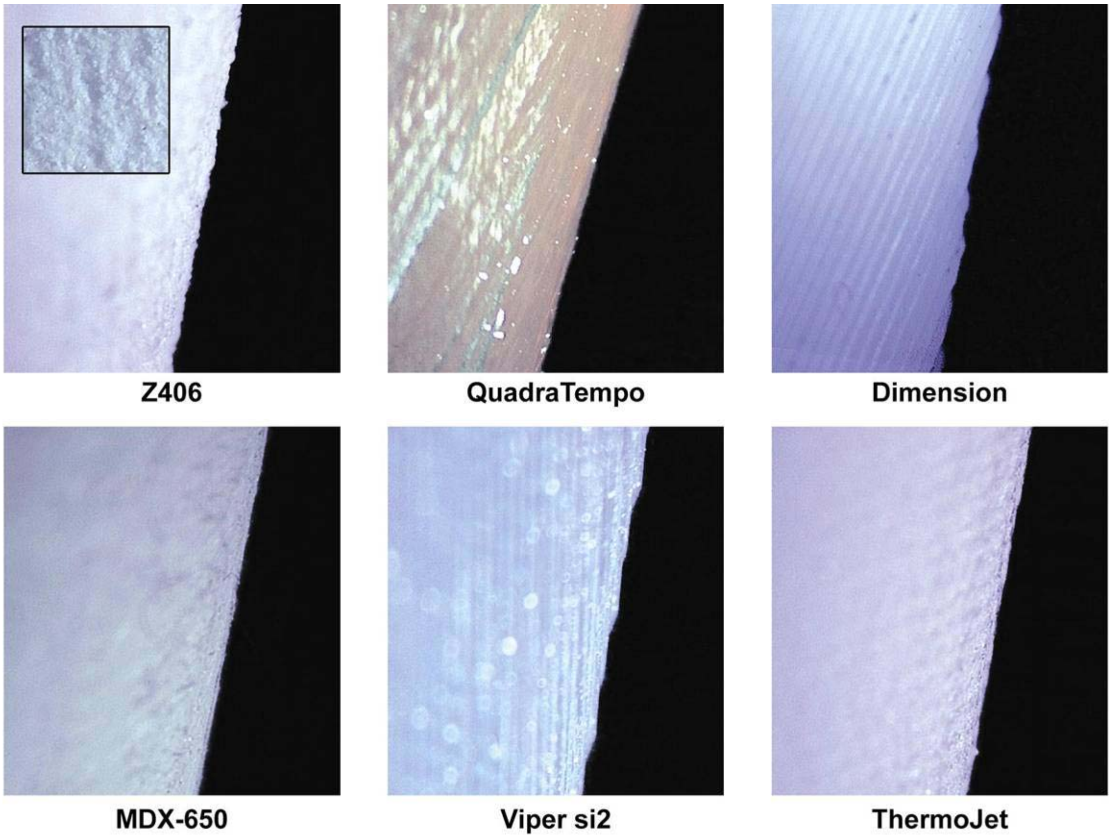



**Figure 29** – Surface finish images from the track ball. Images captured with a stereo microscope at 10 X magnification.

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. On unsupported surfaces, both of these technologies deliver a smooth surface finish. As expected, the 3-axis machining process of the MDX-650 delivered a smooth, stair step free, surface finish.

Using a white light interferometer, surface roughness data was measured on the fan. These measurements were taken on the top surface of the hub, which is a flat. The resulting data offers a best case for each of the additive technologies.

The surface roughness, expressed as $R_a$, is shown in *Figure 30*. $R_a$ is the average deviation of the surface profile in the sample area. This means that $R_a$ is the average of all of the peaks and valleys in the surface profile. As seen in the chart, the upfacing surface of the parts from the Viper si2 and QuadraTempo have a mirror-like surface with $R_a$ values of 0.30 and 0.49 µm (11.8 and 19.3 µin), respectively. The roughest finish is on the Z406—12.63 µm (487.2 µin)—which is followed by the Dimension with 7.01 µm (275.98 µin). The MDX-650 and the ThermoJet had surface finishes of 2.14 and 1.68 µm (84.25 and 66.14 µin), respectively.

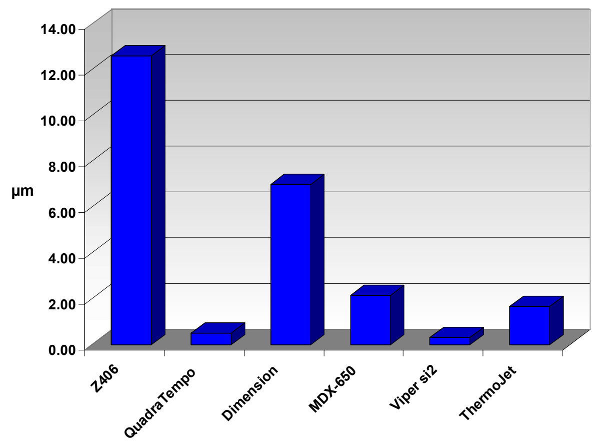



**Figure 30** – Finish measurements for top surface of the fan. $R_a$ Values reported in microns (µm).

Since $R_a$ is an average, is does not tell the whole story on surface roughness. In fact, two surface profiles, as shown in *Figure 31*, can have different characteristics while having the same $R_a$ value. For an improved description of the benchmark parts' surface roughness, $R_t$ is needed. This measurement provides the maximum deviation from the deepest valley to the tallest peak.

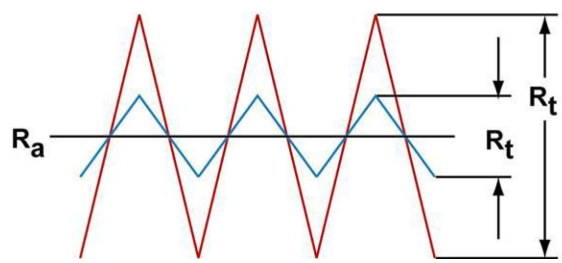



**Figure 31**- Surface profiles with equal $R_a$ (average) values and different $R_t$ values (peak to valley).

In *Figure 32*, the lower portion of the bar shows the $R_a$ value from *Figure 30*, and the total of the lower and upper portion of the bar shows the $R_t$ value. The values for Z406, Dimension and MDX-650 are indicative of irregular surfaces. The Z406, as shown in *Figure 32*, has a rough, porous surface finish, which is illustrate by its high $R_t$ value. The Dimension's $R_t$ value reflects the paths of the extrusions process. On the Dimension part surfaces, the furrows between adjacent extrusion paths create a ribbing effect. With the use of medium density modeling board, the MDX-650 has a moderately high $R_t$; however, the surface feels smooth.

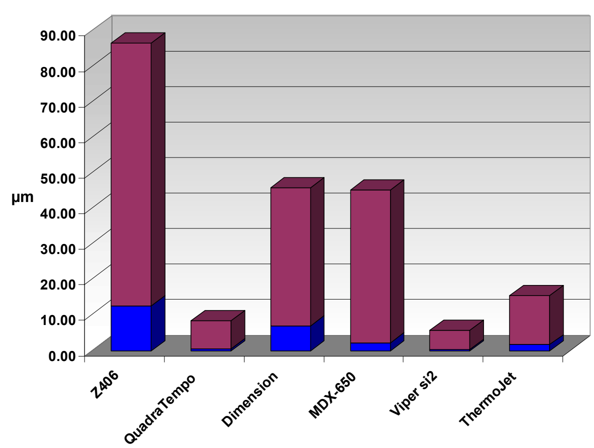



**Figure 32 –** $R_t$ results for top surface of the fan. Values shown in microns (µm).

The MDX-650 $R_t$ results introduce other limitations in measuring and using surface roughness data on prototype parts. For the MDX-650, the distance between the peaks of the surface roughness profile is small. Therefore, in spite of its $R_t$ value, the surface feels almost as smooth as those from the QuadraTempo, Viper si2 and PatternMaster. However, peak-to-peak measurement is not a standard surface testing parameter.

In general, surface roughness testing devices are intended for use on parts (or tools) that have a consistent finish across the entire part. This is not true of many prototype parts. Measuring a surface profile in a 1.2 mm (0.05 in.) area, the measurement devices are unable to capture the variances that may occur on a prototype's surface.  Therefore, defects such as waviness, texture and lay are not reflected in the surface measurement data. For example, on both the QuadraTempo and ThermoJet parts, there was some streaking caused by the print head, a surface defect not shown in the measurement data.

For the additive systems, the finish of a downfacing surface is often different from the upfacing surface and side walls. The Viper si2 and QuadraTempo do not have the mirror-like finish of the top surface on the downfacing surfaces. Instead, they deliver $R_a$ values that range from 4.3 to 5.5 µm (170 to 215 µin). For the ThermoJet, the downfacing surface approaches a roughness similar to that of the Z406. In contrast, the MDX-650's surface finish is consistent across all surfaces.

Combining the data from the stereo microscope and interferometer with visual inspection, the overall surface finishes—with consideration of all surfaces— from the tested technologies range from poor to excellent. The MDX-650 and PatternMaster offer good to excellent finishes. 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.

In Appendix C, images from the white light interferometer are shown in *Figures 62* to *67*.

## V. 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.

To capture five decision-making parameters that are difficult to quantify, the index also includes a subjective ranking of ease of use, reliability, feature detail, material properties and part benching. Ease of use is a consideration of the front-end preparation and back-end part cleaning. Reliability includes consideration of system stability and the confidence that a build will produce a good part. Feature detail measures the minimum size and crispness of small part features. Material properties consider the breadth of materials available and the durability/strength of those materials. While benching is quantifiable, the benchmark study did not evaluate the part finishing. Therefore, for the index, benching is a subjective measure that considers both time and effort.

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 are shown in *Figures 33* to *36*. The parameters and the weighting factors are listed in *Table 1*.

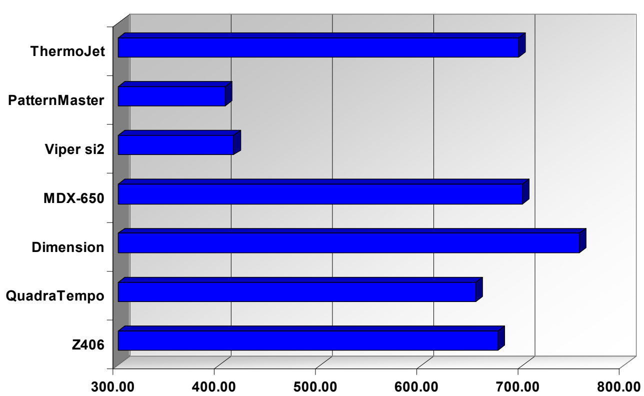



**Figure 33** – Concept modeling index.

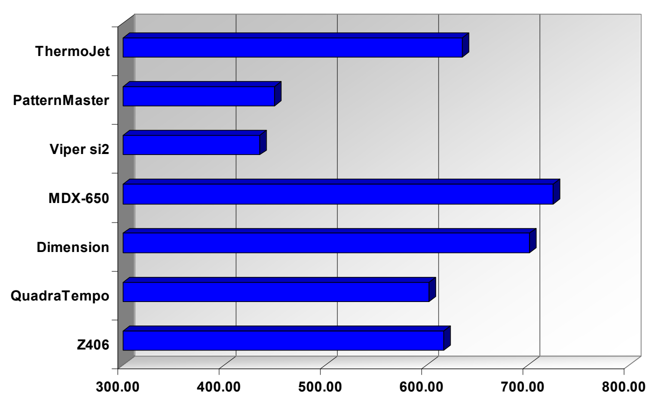



**Figure 34** – Form and fit modeling index.

*Figures 33* and *34* offer the most accurate ranking of the seven systems. Since the benchmark criteria defined the application as engineering tools for concept, form & fit review, prototypes were constructed with build parameters suited to the these applications. If the testing criteria were modified to include functional analysis and/or patterns, the build parameters may have been modified to fit the application, which would improve the accuracy of the rankings in *Figures 35* and *36* (functional models and patterns). However, this data is still usable for general positioning of the seven technologies.

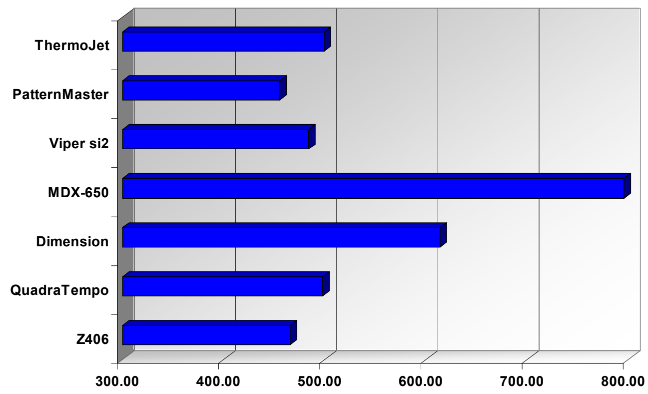



**Figure 35** – Functional analysis index.

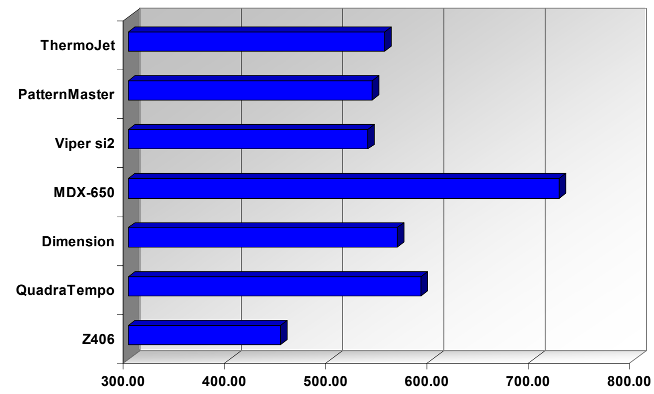



**Figure 36** – Pattern generation index.

When reviewing the Rapid Prototyping Index, consider three points. First, the high cost of the Viper si2 is a primary source of the low rankings. If measured against high-end systems outside of the 3D printer category, the systems ranking could improve. Second, the low cost of the Dimension and MDX-650 has an influence on the relative positioning of each system. For example, the Dimension is not commonly used as a pattern generation device, yet its ranking is relatively strong for this application because of the value placed on system expense. Third, the QuadraTempo rank across all applications is lower than anticipated due to the poor results in dimensional accuracy.

| Parameter | Weighting Factor | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Concept | | Form/Fit | | Function | | Patterns | |
| **Cost** | **30** | | **30** | | **20** | | **20** | |
| **Part Cost** | | 10 | | 12 | | 8 | | 8 |
| **Acquisition Expense** | | 10 | | 9 | | 6 | | 6 |
| **Annual Expense** | | 10 | | 9 | | 6 | | 6 |
| **Time** | **30** | | **25** | | **20** | | **20** | |
| **Prep/post time** | | 12 | | 8 | | 5 | | 5 |
| **Machine Time** | | 10 | | 8 | | 5 | | 5 |
| **Throughput** | | 8 | | 6 | | 4 | | 4 |
| **Benching *** | | 0 | | 3 | | 6 | | 6 |
| **Quality** | **10** | | **20** | | **45** | | **45** | |
| **Tolerance** | | 2 | | 7 | | 9 | | 10 |
| **Surface Finish** | | 3 | | 6 | | 8 | | 15 |
| **Feature Detail *** | | 3 | | 4 | | 8 | | 15 |
| **Material Properties *** | | 2 | | 3 | | 20 | | 5 |
| **Operation** | **30** | | **25** | | **15** | | **15** | |
| **Ease of Use *** | | 15 | | 12 | | 5 | | 5 |
| **Reliability *** | | 15 | | 13 | | 10 | | 10 |
| * Subjective measures | | | | | | | | |

**Table 1** – Rapid Prototyping Index weighting factors.

## VI. 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. And while the PatternMaster literally prints in 3D, it does not satisfy the time requirements when applied to parts typical in industrial applications. The other systems are fitting of a 3D printer classification, even the MDX-650, which is not a printer at all.

As the Rapid Prototyping Index shows, the advantages of each of the systems are dependent on the application. Therefore, when evaluating rapid prototyping technologies, it is imperative that the process begins with a clear definition of the intended applications for the prototypes. It is also important to identify the type of parts that will be prototyped. As seen in the time, cost and dimensional accuracy data, results will vary with the size and geometric definition of the prototype.

While the goal of the benchmark is the thorough and accurate evaluation of the technologies, it is impossible to measure these systems under all scenarios. There are a vast number of combinations of build parameters, prototyping materials, part definitions and operating conditions. Testing all scenarios 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.

## Appendix A – System Overview and Benchmark Build Parameters

### Z406 (Z Corporation):

The Z406 uses ink jet technology to print rapid prototypes from powdered material. As the print head passes over the powder bed, it deposits binder to solidify a layer of the part. After each layer is complete, a fresh layer of powder is deposited, and the process is repeated.

For the benchmark, the following were used:

- zp102 plaster material
- zb52 binder
- zr12 infiltrant (cyanoacrylate)
- 0.10 mm (0.004 in.) layers
- Monochrome mode

### QuadraTempo (Objet Geometries):

Like the Z406, the QuadraTempo uses an ink jet process. However, it deposits droplets of photocurable materials that are solidified with UV light. As the print head passes over the build area, it deposits both model and support material. On the front and rear of the print head assembly are UV lamps that solidify the material immediately after deposition.

For the benchmark, the following were used:

- M-510T-Y photopolymer resin
- 0.02 mm (0.0008 in.) layers
- Glossy mode

### Dimension (Stratasys):

The Dimension uses the fused deposition modeling process of Stratasys, Inc. A thin filament of thermoplastic material passes through a liquefier. In a semi-molten state, the material is extruded to produce the prototype. Dimension uses two materials, one for the break away supports and one for the prototype.

For the benchmark, the following were used:

- ABS material
- 0.25 mm (0.010 in.) layers
- Fill type:
    - Cell phone: dense fill
    - Fan and track ball: sparse fill

**MDX-650 (Roland DG):**

MDX-650 is a three-axis milling machine. Unlike the additive rapid prototyping systems, the MDX-650 is a subtractive process—material is removed with a cutting tool. With three-axis motion of the cutter, the process is not performed as a layer-by-layer operation, and as a result, there is no layering effect.

For the benchmark, the following were used:

- Materials:
    - Cell phone and fan: medium density modeling board
    - Track ball: low density modeling board
- Fourth axis rotary table
- Automatic tool changer (ATC)
- Fan
    - 6.4 mm (0.25 in.) end mill, 3.2 mm (0.125 in.) ball end mill
    - Six operations (passes): four roughing and two finishing
- Cell phone
    - 3.2 mm (0.125 in.) ball end mill, 1.6 mm (0.062 in.) ball end mill
    - Six operations: two roughing and four finishing
- Track ball
    - 3.2 mm (0.125 in.) end mill
    - Four operations : two roughing and two finishing

**Viper si2 (3D Systems):**

The Viper si2 is a stereolithography system. A UV laser draws the cross section of the prototype on the surface of a vat of liquid, photocurable polymer. The UV energy solidifies the polymer to create solid geometry. After a layer is complete, the part dips into the vat, and a fresh layer of liquid resin recoats the part surface.

For the benchmark, the following were used:

- DSM Somos Watershed photopolymer
- 0.15 mm (0.006 in.) layers
- Standard mode: 0.25 mm (0.010 in.) beam diameter
- Exact/ACES build style

**PatternMaster (Solidscape):**

PatternMaster uses an ink jet process, but unlike the Z406 or QuadraTempo, a single nozzle deposits the wax-like thermoplastic material. The system uses two materials, a soluble support material and the model material. Each material is deposited through a dedicated nozzle. At predetermined intervals, the surface of the build is milled with a fly cutter to ensure a flat plane for subsequent layers.

For the benchmark, the following were used:

- 0.05 mm (0.002 in.) layers
- ProtoBuild material (proprietary thermoplastic wax)
- Open cell build style, medium fast

**ThermoJet (3D Systems):**

ThermoJet is a blend of the QuadraTempo and PatternMaster processes. Like the QuadraTempo, an ink jet print head with multiple nozzles deposits the build material. Like the PatternMaster, the material is a wax-like thermoplastic.

For the benchmark, the following were used:

- TJ-88 material
- 0.04 mm (0.0015 in.) layers
- Standard build style

# Appendix B – Observations from Benchmark Parts

## General Observations

One of the primary goals of rapid prototyping is to find the flaws in a design before it is too late. One of the primary benefits of rapid prototyping is quick, clear and concise communication. If the benchmark study was a live prototyping project, the fan would have delivered the primary benefit and satisfied the primary goal.

After building the fan in the Z406, the first of the tested systems to build the part, it was discovered that the blades were poorly suited for a plastic part design. It was a poor candidate for the benchmark analysis. Soon after this discovery, three more suppliers came to the same conclusion.

The five blades of the fan have a thickness of only 0.76 mm (0.030 in.), and this thickness does not increase where the blades attach to the hub. This design is ill-suited for rapid prototyping as well as manufacturing. With the exception of metals, or possibly a few engineered thermoplastics, there would be no chance that the blades could be produced with reasonable results.

When reviewing the candidates for the benchmark study, the files were opened in a STL viewer. They were visually inspected for overall design and complexity of the features. Additionally, the extents (overall dimensions) and volume were calculated. In the case of the fan, everything looked good. The part had challenging geometry, and its size was reasonable. With the view zoomed in to fill the monitor, a quick, visual review of the blades was performed. For a few moments, measurement of the blades was considered. However, since it looked good on the screen, the part was accepted without further analysis.

With the rapid prototypes of the fan, it was obvious that the blades were too thin. What the computer monitor could not communicate, the rapid prototypes quickly, clearly and concisely conveyed to anyone that held the part. This is the benefit expected of rapid prototyping. Had this been a live design project, rapid prototyping would have satisfied the primary goal of error detection. The moment that the fan prototype was produced, any design engineer would have immediately started the revision process to create a part that could be made at a reasonable cost with acceptable quality.

If the facts of the blades where known, the fan would not have been included in the benchmark study. However, it turned out to be a challenging part that helped to illustrate the strengths and weaknesses of each technology. Surprisingly, two systems were able to produce acceptable results. These are documented in the following observations of the prototype parts from each benchmark system.

## System and Prototype Observations

### 1. Z406

The benchmark parts had a rough surface finish on all sides. The surfaces have a textured quality somewhat like 100 –150 grit sandpaper. On the downfacing surface, there was some evidence of streaking in the direction of the print head. Combining the 0.10 mm (0.004 in.) layer thickness and the surface texture, stair stepping was not evident.

While small features were replicated, they lacked crispness in their details.

Prior to infiltration, the benchmark parts were fragile and weak. Additionally, the surface powder continued to slough off during routine handling. After infiltration with cyanoacrylate, the parts had reasonable strength and durability. While suitable for concept and form/fit models, the infiltrated parts would not be suitable for most functional testing.

a. Cell phone

Prior to infiltration, the cell phone was fragile. When removing excess powder after the build, care and caution were required. In one area, the thin slots on the underside of the cell phone, the excess powder was allowed to remain for fear that the walls would be broken during the removal process. When infiltrated, this excess powder was captured, and the prototype's slots were partially filled (*Figure 37*).

**Figure 37** – The slots on the left and right sides are partially filled with excess powder.

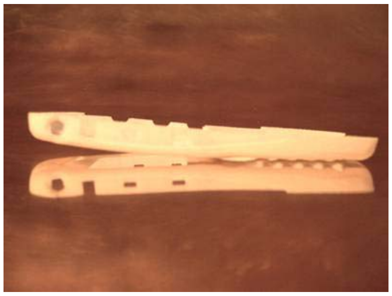


**Figure 38** – Warpage of the cell phone is evident on the left side of image.

After infiltration, the part had a slight deformation (*Figure 38*). This is most likely due to the application and drying of the cyanoacrylate on one side of the part prior to infiltrating the opposite side. The warpage of the part prevented dimensional analysis of the center-to-center dimensions on the underside.

The prototype would be acceptable for early concept modeling and form/fit analysis.

b. Fan

During removal from the machine's powder bed, three of the blades detached from the hub. Even with extreme care and caution, the blades could not be saved (*Figure 39*). After infiltration, the two remaining blades remained rigidly attached, but they were still fragile.

Due to the fan blade design, this prototype would be unacceptable for any application.

**Figure 39** – Three of the fan blades detached during removal from the system.

c. Track ball

The prototype is suitable for concept and form/fit applications.

## 2. QuadraTempo

With ultra-thin layers [0.02 mm (0.0008 in.)], the upfacing surfaces of all prototypes were extremely smooth and glossy. These surfaces had the appearance of a sanded and polished prototype with the application of a clear coat. However, the downfacing surfaces and side walls had a waxy/gummy feel and a matte-like appearance. In addition, downfacing surfaces showed evidence of the print head pattern, which further degraded surface finish.

Features were well defined and crisp. Even for shallow curvatures, stair stepping was not detectable. However, on the downfacing surfaces and side walls, details and crispness of features were obscured by the support material residue.

The benchmark parts were rigid but somewhat brittle. With these material properties, the prototypes would be suitable for concept, form/fit models and patterns.

a. Cell phone

The advantages of the high resolution (thin layers and small droplet size) of the technology were apparent in this benchmark part. All details were crisp and well defined, including both small positive and negative geometry. In addition, the slight rise around the keypad area showed little evidence of stair stepping (*Figure 40*).

The limitation of material properties was immediately evident. During removal of the support material, the wall of one mounting boss broke easily when an X-Acto knife was inserted. Additionally, in the time lag between part construction and dimensional inspection, the part deformed. The warpage of the part prevented center-to-center dimensional inspection of the features on the underside of the part (*Figure 41*).

**Figure 40** – The thin layers of the process offer smooth surfaces, even on the shallow arc of the key pad area.

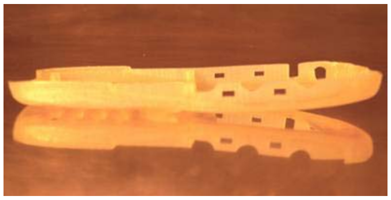


**Figure 41** – Warpage of the cell phone is evident on the right side of image.

The prototype would be suitable for concept, form/fit models and for patterns, if deformation was controlled.

b. Fan

While all the blades survived, several were damaged when the part was removed from the build platform. The damaged blades had broken and chipped edges on the bottom area. The blades also distorted. Each had significant warpage and curl (*Figure 42*).

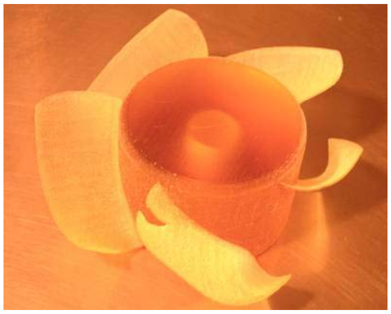


**Figure 42** – Curled and damaged blades.

Over time, the blades lost their rigidity and became soft and pliable. This is most likely the result of moisture absorption —typical of many photopolymers.

Due to the fan blade design, this prototype would be unacceptable for any application.

c. Track ball

The upfacing surfaces of the benchmark part were extremely smooth and glossy. The appearance was consistent with a model that is sanded, polished and lacquered *(Figure 43)*. But these operations were not performed. However, this is in contrast to the matte texture and tacky feel of the downfacing surfaces and side walls.

**Figure 43** – The smooth and glossy surface has the appearance of a polished surface.

The prototype would be suitable for concept, form/fit models and for patterns.

**3. Dimension**

The Dimension uses the fused deposition modeling process, which extrudes a filament of thermoplastic. The path of the extrusion is detectable, even on flat surfaces, in the form of slight ridges or grooves. Additionally, the process uses 0.25 mm (0.010 in.) layers that created noticeable stair stepping. Overall, the surfaces of the parts were rough.

With the break away supports, there was some difficulty in removing the excess material from small features. In a few areas, small amounts of support material remained on the prototypes.

The ABS material used in the process yielded strong and rigid prototypes that are suitable for functional testing. Additionally, the prototypes would be suitable for concept and form/fit models.

a. Cell phone

Stair stepping was evident on all surfaces of the part and was most notable around the gradual contour of the keypad area. In addition, the crisscross pattern of the extrusion path was visible on the upper and lower surfaces.

Small features lacked crispness of detail, and the small through-holes for the speaker and microphone were partially filled. In addition, the thin walls that surround the key appeared to be thicker than the nominal dimensions. Finally, in some areas where the extrusion was wider than the path that it had to follow, there were voids in the part surface (*Figure 44*).

**Figure 44** – Stair stepping and voids around small details.

With the ABS material, the prototype was strong, tough and rigid.

The prototype would be suitable for concept, form/fit and functional testing models.

b. Fan

Dimension was one of the three systems that successfully built the fan with all blades intact. However, there was some minor damage done to the lower surface when the support material was removed (*Figure 45*). With greater care, this could have been avoided. The material properties gave the blades strength and rigidity.

The hub of the fan was built with the sparse fill option. Therefore, it did not have the mass of the intended design.

The prototype would be suitable for concept, form/fit and functional testing models.

**Figure 45** – With the exception of chipping during support removal, this fan was one of only two that would be suitable for prototyping applications.

c. Track ball

Like the hub of the fan, the track ball prototype was built with the sparse fill option.

While stair stepping was apparent, the overall quality of the prototype was good (*Figure 46*). In fact, the layer striations where less noticeable than anticipated. This could be due to the low contrast of the white ABS material.

**Figure 46** – While stair stepping is evident, it is less noticeable than expected.

**4. MDX-650**

Surface finish for the prototype parts was variable, ranging from good to excellent. However, unlike the additive systems, the surface finish is user-definable. Material selection and tool path definition are the key parameters that define the surface smoothness. Some modeling materials, such as low-density foams, will produce a rough, porous finish, while others, such as high-density modeling board, can produce a smooth finish. The other variable is the tool path used for the milling operation. Multiple finishing passes with small tool step-overs deliver smooth finishes. When finish is not important, less time can be invested in the finish cuts.

The other factor that contributes to the smooth surface finish is the 3-axis milling operation, which eliminates the stair stepping effect common with additive systems. Small features are produced accurately with crisp detail.

With the wide array of machineable materials, the prototypes can be applied to concept, form/fit, function and pattern-making applications.

a. Cell phone

Machined from medium density modeling board, the cell phone had a good surface finish and good strength/durability. All features, with the exception of the small holes for the speaker and microphone, were produced with sharp edges and crisp detail (*Figure 47*). The through holes for the speaker and microphone—approximately 0.25 to .035 mm (0.010 to 0.015 in)—were not machined into the prototype.

**Figure 47** – Smooth surfaces and sharp detail from the MDX-650.

As an engineering review model, the supplier of the test part elected to omit additional machining passes for some of the detail on the underside of the part. This left excess material around the walls of the key pad holes and in the side wall slots.

The prototype would be suitable for concept, form/fit and functional testing models.

b. Fan

MDX-650 was one of the three systems that successfully built the fan with all blades intact. With the material properties of the medium-density modeling board, the blades where durable and strong (*Figure 48*).

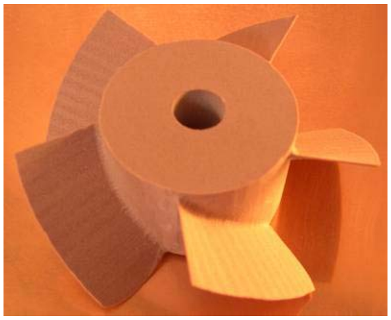


**Figure 48** – One of two fan prototypes suitable for prototyping applications.

The surface of the blades was somewhat rough, but this could have been remedied with an additional machining pass. The supplier elected not to perform this operation in light of the benchmark procedures that prevented construction of multiple parts. Concerned that another machining pass could damage the blades, they were left with some surface roughness.

The prototype would be suitable for concept and form/fit models.

c. Track ball

This prototype had excellent feature detail, and the contours of the part were smooth. When machined from light-density modeling board, a porous material, the surfaces where similar to that of the Z406 (*Figure 49*). However, when machined from Delrin, all surfaces and all contours were smooth (*Figure 50*).

**Figure 49** – Although there is no stair stepping, the light-density modeling board has a slight texture.

**Figure 50** – The surface of the Delrin part is smooth and free of texture.

The prototype would be suitable for concept, form/fit, function and pattern applications.

## 5. Viper si2

The surface finish of the benchmark parts was dependent on orientation of the feature. Flat, upfacing surfaces were extremely smooth and transparent. Downfacing surfaces had an opaque appearance with surface mars resulting from support removal. Side walls were rough due to stair stepping. For contoured surface, stair stepping was readily apparent. If lower layer thicknesses were used—Viper si2 can go down to 0.05 mm (0.002 in.)—stair stepping would have been minimized at the expense of additional machine time.

All features were sharply defined with crisp bounding edges.

With the DSM Somos Watershed material, the prototypes were both rigid and durable. However, it should be noted that material properties would vary when using other stereolithography resins.

The benchmark parts would be suitable for concept, form/fit models, patterns, and some functional testing prototypes.

a. Cell phone

Stair stepping was readily apparent on the external surfaces. With the shallow curvature of the face and the selected layer thickness, the stair steps were obvious to both the eye and the hand (*Figure 51*).

**Figure 51** – Stair stepping is apparent on the shallow curve of the key pad area.

The material properties yield a rigid prototype with some flexibility (due to the thin wall sections). The prototype has the necessary durability for routine handling and light functional testing.

The prototype would be suitable for concept, form/fit models, light functional testing, and with additional benching, for patterns.

b. Fan

All of the blades survived the construction and cleaning process. However, on the top edge of each there was delamination of layers and some missing areas (*Figure 52*). This is believed to be a result of the support structures used on the blade surfaces. If allowed to rebuild the prototype with supports that went all the way to the top, it is likely that they would have built correctly. However, due to the thin wall section, the blades had a pliable nature that would not have been appropriate for many applications.

**Figure 52** – Due to a support structure problem, the top edge of the fan blades curled and separated.

Due to the fan blade design, this prototype would be unacceptable for any application.

c. Track ball

With the contoured nature of the part, stair stepping was obvious (*Figure 53*).

The prototype would be suitable for concept, form/fit models, light functional testing, and with additional benching, for patterns.

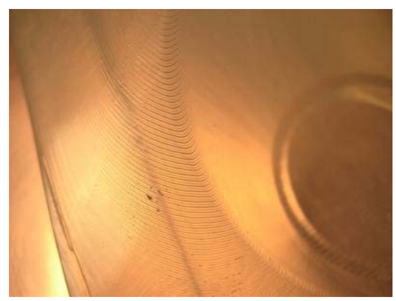


**Figure 53** – Although top surfaces are smooth, contoured areas are stair stepped.

## 6. PatternMaster

The surface finish of the benchmark part (cell phone only) was exceptional. The fine resolution and thin layers of the construction process were readily apparent. However, due to calibration problems, some of the surface did have a checked surface. The PatternMaster is extremely sensitive to calibration of the material flow, and in the case of the benchmark part, mis-calibration resulted in too little material to fill the surface of the “open cells” of the selected build style. With proper calibration, this problem would be eliminated.

Features were well defined and crisp. Even for shallow curvatures, stair stepping was barely detectable (*Figure 54*).

**Figure 54** – Smooth surfaces and crisp details from the PatternMaster.

While the material is a thermoplastic with wax-like properties, the benchmark parts were surprisingly durable and resistant to warpage and softening from exposure to heat. With caution, the prototype would survive routine handling in a concept and form/fit evaluation.

The ideal application for this technology would be pattern generation.

a. Cell phone
   Reference previous comments.

b. Fan
   N/A. Prototype was not constructed.

c. Track ball
   N/A. Prototype was not constructed.

**7. ThermoJet**

Layer thickness and process resolution combined to yield prototypes with smooth surfaces and crisp details. However, on the downfacing, supported surface, there was a rougher, textured finish. The material properties of the wax-like thermoplastic yielded prototypes that were easily damaged. As expected, the prototypes had a waxy feel to them and soft surfaces that were easily marred.

The benchmark parts were fragile. With these material properties, the prototypes would be suitable for concept models and patterns. Depending on the part design, they also may be suitable for form/fit models.

a. Cell phone

The side walls and underside (the upfacing surface in the build orientation) were extremely smooth (*Figure 55*). However, the top surface had a rough, textured quality.

The small features of the part were crisp and highly detailed.

The prototype was fragile. The properties of the wax-like material made the prototype brittle.

**Figure 55** – The upfacing surface of the cell phone is smooth and highly detailed.

b. Fan

The ThermoJet was one of the three systems to successfully build the fan with the blades intact. However, they were extremely fragile (*Figures 56 and 57*). With a small amount of force, each was broken.

Due to material properties and the blade design, this prototype would be unacceptable for any application.

**Figure 56** – Although the fan built successfully, the wax-like material was too fragile for routine handling.

**Figure 57** – In contrast to the smooth upfacing surfaces, the downfacing surfaces are rough.

c. Track ball

The contours of the mouse were extremely smooth on the upfacing surfaces and side walls (*Figure 58*). However, the downfacing surfaces were rough and textured.

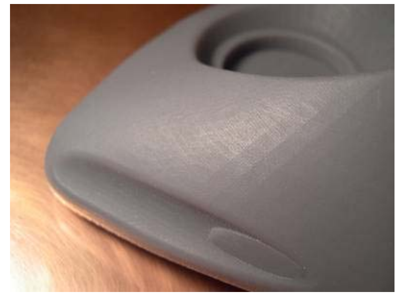


**Figure 58** –Smooth surfaces on the contours of the upfacing side of the prototype.

With the mass of the track ball, the material properties limitations would have little impact on this prototype. Therefore, it would be suitable for concept, form/fit models and for patterns.

## Appendix C – Supplementary Charts, Tables and Diagrams

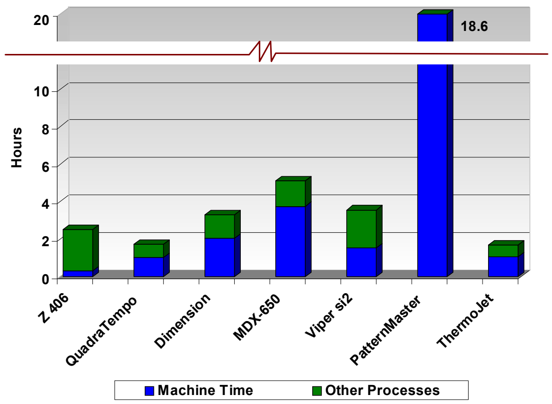



**Figure 59** – Cell phone.

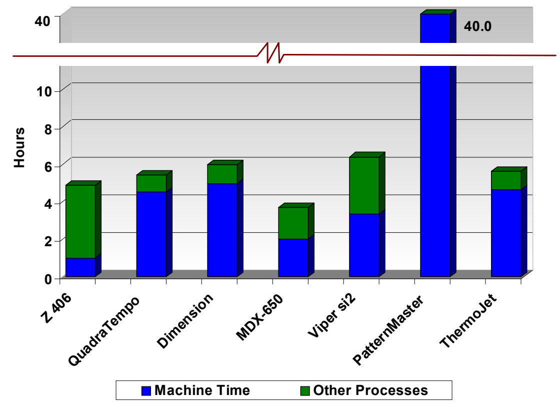



**Figure 60** – Fan.

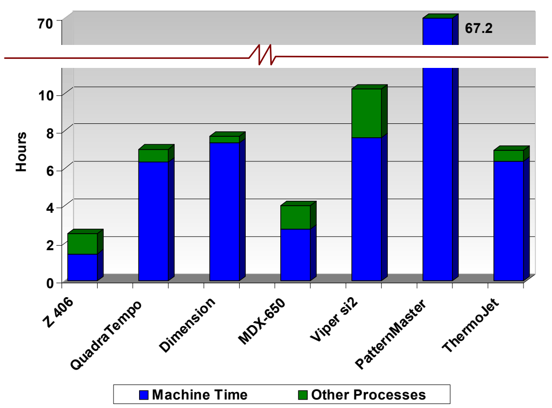



**Figure 61** – Track ball.

**Figures 59 - 61**: Total process time for individual benchmark parts. The lower section of bar represents machine time, and the upper area represents the time for pre- and post-build operations.

| | Cell Phone | | Fan | | Track Ball | |
|---|---|---|---|---|---|---|
| | COGS | Labor | COGS | Labor | COGS | Labor |
| **Z406** | | | | | | |
| Data Preparation | | $2.91 | | $2.91 | | $2.91 |
| Part Construction | | $11.69 | | $14.60 | | $8.75 |
| Materials | $0.33 | | $3.50 | | $16.03 | |
| Build Time | $23.91 | | $52.59 | | $25.33 | |
| Post Processing | $0.76 | $10.19 | $3.97 | $13.41 | $14.58 | $9.31 |
| Sub-total | $25.00 | $24.78 | $60.06 | $30.91 | $55.94 | $20.97 |
| **Total** | **$49.78** | | **$90.96** | | **$76.91** | |
| **QuadraTempo** | | | | | | |
| Data Preparation | | $2.91 | | $2.91 | | $2.91 |
| Part Construction | | $3.61 | | $3.61 | | $3.61 |
| Materials | $6.90 | | $44.60 | | $117.90 | |
| Build Time | $19.58 | | $71.73 | | $98.53 | |
| Post Processing | | $5.81 | | $13.13 | | $5.81 |
| Sub-total | $26.48 | $12.32 | $116.33 | $19.64 | $216.43 | $12.32 |
| **Total** | **$38.80** | | **$135.96** | | **$228.75** | |
| **Dimension** | | | | | | |
| Data Preparation | | $2.91 | | $2.91 | | $2.91 |
| Part Construction | | $2.91 | | $2.91 | | $2.91 |
| Materials | $4.37 | | $12.66 | | $31.79 | |
| Build Time | $7.25 | | $17.18 | | $25.27 | |
| Post Processing | | $35.00 | | $26.25 | | $4.38 |
| Sub-total | $11.62 | $40.81 | $29.84 | $32.06 | $57.06 | $10.19 |
| **Total** | **$52.43** | | **$61.90** | | **$67.25** | |
| **MDX-650** | | | | | | |
| Data Preparation | | $25.66 | | $25.55 | | $22.75 |
| Part Construction | | $10.50 | | $10.50 | | $10.50 |
| Materials | $12.00 | | $16.07 | | $19.99 | |
| Build Time | $12.23 | | $6.52 | | $8.97 | |
| Post Processing | | $5.25 | | $17.50 | | $5.25 |
| Sub-total | $24.23 | $41.41 | $22.59 | $53.55 | $28.96 | $38.50 |
| **Total** | **$65.63** | | **$76.14** | | **$67.46** | |
| **Viper si2** | | | | | | |
| Data Preparation | | $2.35 | | $1.75 | | $5.25 |
| Part Construction | | $2.91 | | $2.91 | | $2.91 |
| Materials | $2.14 | | $19.57 | | $85.69 | |
| Build Time | $54.95 | | $104.07 | | $219.75 | |
| Post Processing | | $5.81 | | $24.50 | | $5.01 |
| Sub-total | $57.09 | $11.06 | $123.64 | $29.16 | $305.44 | $13.16 |
| **Total** | **$68.15** | | **$152.79** | | **$318.60** | |
| **PatternMaster** | | | | | | |
| Data Preparation | | $6.41 | | $6.41 | | $6.41 |
| Part Construction | | $16.91 | | $16.91 | | $16.91 |
| Materials | $5.87 | | $37.36 | | $151.70 | |
| Build Time | $76.37 | | $167.79 | | $294.54 | |
| Post Processing | | $0.00 | | $0.00 | | $0.00 |
| Sub-total | $82.24 | $23.31 | $205.15 | $23.31 | $446.24 | $23.31 |
| **Total** | **$105.55** | | **$228.46** | | **$469.55** | |
| **ThermoJet** | | | | | | |
| Data Preparation | | $5.25 | | $5.25 | | $5.25 |
| Part Construction | | $0.00 | | $0.00 | | $0.00 |
| Materials | $2.28 | | $16.41 | | $88.41 | |
| Build Time | $7.65 | | $38.66 | | $53.09 | |
| Post Processing | | $5.25 | | $17.50 | | $5.25 |
| Sub-total | $9.93 | $10.50 | $55.07 | $22.75 | $141.50 | $10.50 |
| **Total** | **$20.43** | | **$77.82** | | **$152.00** | |

**Table 2** – Cost of prototypes in U.S. dollars.

| | Cell Phone | | Fan | | Track Ball | |
|---|---|---|---|---|---|---|
| | Auto | Manual | Auto | Manual | Auto | Manual |
| **Z406** | | | | | | |
| Data Preparation | | 0.08 | | 0.08 | | 0.08 |
| Part Construction | | | | | | |
| Machine Time | 0.32 | | 1.00 | | 1.43 | |
| Pre & Post Build | 1.50 | 0.34 | 3.00 | 0.42 | 0.50 | 0.25 |
| Post Processing | | 0.29 | | 0.38 | | 0.27 |
| Sub-total | 1.82 | 0.71 | 4.00 | 0.88 | 1.93 | 0..60 |
| **Total** | **2.53** | | **4.88** | | **2.53** | |
| **QuadraTempo** | | | | | | |
| Data Preparation | 0.05 | .08 | 0.05 | 0.08 | 0.05 | 0.08 |
| Part Construction | | | | | | |
| Machine Time | 1.02 | | 4.52 | | 6.32 | |
| Pre & Post Build | 0.30 | 0.10 | 0.30 | 0.10 | 0.30 | 0.10 |
| Post Processing | | 0.17 | | 0.38 | | 0.17 |
| Sub-total | 1.37 | 0.35 | 4.87 | 0.56 | 6.67 | 0.35 |
| **Total** | **1.72** | | **5.43** | | **7.02** | |
| **Dimension** | | | | | | |
| Data Preparation | | 0.08 | | 0.08 | | 0.08 |
| Part Construction | | | | | | |
| Machine Time | 2.05 | | 4.97 | | 7.35 | |
| Pre & Post Build | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Post Processing | | 1.00 | | 0.75 | | 0.13 |
| Sub-total | 2.13 | 1.16 | 5.05 | 0.91 | 7.43 | 0.29 |
| **Total** | **3.29** | | **5.96** | | **7.72** | |
| **MDX-650** | | | | | | |
| Data Preparation | 0.17 | 0.73 | 0.17 | 0.73 | 0.17 | 0.65 |
| Part Construction | | | | | | |
| Machine Time | 3.75 | | 2.00 | | 2.75 | |
| Pre & Post Build | | 0.30 | | 0.30 | | 0.30 |
| Post Processing | | 0.15 | | 0.50 | | 0.15 |
| Sub-total | 3.92 | 1.18 | 2.17 | 1.53 | 2.92 | 1.10 |
| **Total** | **5.10** | | **3.70** | | **4.02** | |
| **Viper si2** | | | | | | |
| Data Preparation | 0.05 | 0.07 | 0.05 | 0.05 | 0.05 | 0.15 |
| Part Construction | | | | | | |
| Machine Time | 1.53 | | 3.35 | | 7.63 | |
| Pre & Post Build | 0.50 | 0.08 | 0.50 | 0.08 | 0.50 | 0.08 |
| Post Processing | 1.16 | 0.17 | 1.66 | 0.70 | 1.66 | 0.14 |
| Sub-total | 3.24 | 0.32 | 5.56 | 0.83 | 9.84 | 0.37 |
| **Total** | **3.56** | | **6.39** | | **10.21** | |
| **PatternMaster** | | | | | | |
| Data Preparation | 0.05 | 0.13 | 0.05 | 0.13 | 0.05 | 0.13 |
| Part Construction | | | | | | |
| Machine Time | 17.01 | | 37.37 | | 65.60 | |
| Pre & Post Build | | 0.48 | | 0.48 | | 0.48 |
| Post Processing | 0.95 | | 0.95 | | 0.95 | |
| Sub-total | 18.01 | 0.61 | 38.37 | 0.61 | 66.60 | 0.61 |
| **Total** | **18.62** | | **38.98** | | **67.21** | |
| **ThermoJet** | | | | | | |
| Data Preparation | | 0.15 | | 0.15 | | 0.15 |
| Part Construction | | | | | | |
| Machine Time | 1.04 | | 4.65 | | 6.33 | |
| Pre & Post Build | | | | | | |
| Post Processing | 0.33 | 0.15 | 0.33 | 0.50 | 0.33 | 0.15 |
| Sub-total | 1.37 | 0.30 | 4.98 | 0.65 | 6.66 | 0.30 |
| **Total** | **1.67** | | **5.63** | | **6.96** | |

**Table 3** – Prototype construction times listed in hours.

| | Nominal | Z406 | Dimension | MDX-650 | Quadra-Tempo | Viper si2 | Pattern-Master | ThermoJet |
|---|---|---|---|---|---|---|---|---|
| **Fan** | | | | | | | | |
| **A** | 13.74 | 0.45 | 0.16 | 0.17 | 0.19 | 0.08 | | 0.14 |
| **B** | 51.49 | 0.04 | 0.29 | 0.07 | 0.26 | 0.25 | | 0.06 |
| **C** | 34.32 | 0.36 | 0.61 | 0.32 | 0.06 | 0.47 | | 0.25 |
| **D** | 25.76 | 0.20 | 0.55 | 0.04 | 0.21 | 0.08 | | 0.28 |
| **E** | 51.49 | 0.50 | 0.21 | 0.03 | 0.56 | 0.30 | | 0.37 |
| **Track Ball** | | | | | | | | |
| **A** | 114.67 | 0.02 | 0.14 | 0.01 | 0.63 | 0.32 | | 0.47 |
| **B** | 177.80 | 0.12 | 1.16 | 0.17 | 1.24 | 0.32 | | 0.84 |
| **C** | 47.09 | 0.10 | 0.02 | 0.25 | 0.20 | 0.48 | | 0.65 |
| **D** | 161.46 | 1.53 | 0.79 | 0.17 | 1.29 | 0.06 | | 0.84 |
| **E** | 79.46 | 0.53 | 0.21 | 0.61 | 0.80 | 0.40 | | 0.08 |
| **F** | 31.75 | 0.07 | 0.42 | 0.69 | 0.49 | 0.18 | | 0.22 |
| **G** | 5.66 | 0.26 | 0.62 | 0.17 | 0.28 | 0.26 | | 0.11 |
| **Cell Phone** | | | | | | | | |
| **A** | 122.36 | 0.74 | 0.62 | 0.02 | 1.27 | 0.16 | 0.27 | 1.14 |
| **B** | 33.88 | 0.20 | 0.11 | 0.60 | 0.06 | 0.37 | 0.06 | 0.19 |
| **C** | 33.92 | 0.46 | 0.35 | 0.20 | 0.71 | 0.55 | 0.65 | 0.52 |
| **D** | 47.75 | | | | | | | |
| **E** | 10.23 | 1.12 | 0.56 | 0.02 | 1.49 | 0.62 | 0.22 | 0.60 |
| **F** | 52.20 | | 0.61 | 0.30 | | 0.10 | 0.18 | 0.58 |
| **G** | 52.20 | | 0.53 | 0.25 | | 0.15 | 0.20 | 0.61 |
| **H** | 14.95 | | 0.04 | 0.16 | | 0.60 | 0.06 | 0.09 |
| **I** | 14.95 | | 0.09 | 0.11 | | 0.72 | 0.07 | 0.24 |
| **J** | 17.40 | | 0.08 | 0.38 | | 0.69 | 0.25 | 0.03 |
| **K** | 17.40 | | 0.23 | 0.15 | | 0.84 | 0.08 | 0.23 |
| | | | | | | | | |
| **Average** | | 0.42 | 0.38 | 0.22 | 0.61 | 0.36 | 0.21 | 0.39 |
| **σ** | | 0.42 | 0.29 | 0.20 | 0.48 | 0.23 | 0.18 | 0.30 |
| **With 3 σ constraint** | | | | | | | | |
| **Average** | | 0.34 | 0.34 | 0.16 | 0.55 | 0.32 | 0.16 | 0.35 |
| **σ** | | 0.30 | 0.24 | 0.11 | 0.44 | 0.20 | 0.09 | 0.26 |

**Table 4 –** Dimensional accuracy results in millimeters**.** Absolute deviation from the nominal dimension is listed for each feature. The labels for each feature (left-hand column) correspond to the labels used in the dimensioned drawings in *Figures 68* to *70*. This table also lists the average dimensional deviation and standard deviation for all data and for the data that excludes values that exceed 3σ. Note that dimension "D" of the cell phone has been excluded. This measurement yielded inconsistent data, and since it was difficult to acquire, it was eliminated from the study.

| | Z406 | Quadra-Tempo | Dimension | MDX-650 | Viper si2 | Pattern-Master | ThermoJet |
|---|---|---|---|---|---|---|---|
| **$R_a$** | 12.63 | 0.49 | 7.01 | 2.14 | 0.30 | N/A | 1.68 |
| | | | | | | | |
| **$R_t$** | 86.64 | 8.41 | 45.81 | 45.15 | 5.78 | N/A | 15.45 |
| | | | | | | | |
| **$R_q$** | 15.21 | 0.64 | 8.86 | 3.01 | 0.39 | N/A | 2.10 |
| | | | | | | | |
| **$R_z$** | 76.57 | 7.90 | 41.63 | 39.20 | 3.90 | N/A | 13.79 |
| | | | | | | | |
| All dimensions in µm | | | | | | | |
| **$R_a$**: arithmetic mean deviation of assessed profile | | | **$R_t$**: total height of profile (lowest valley to tallest peak) | | | | |
| **$R_q$**: root mean square deviation (RMS) | | | **$R_z$**: Average max height | | | | |

**Table 5** – Surface finish data from white light interferometer. All measurements taken from the top (smoothest) surface of the fan. Values listed in microns (µm).

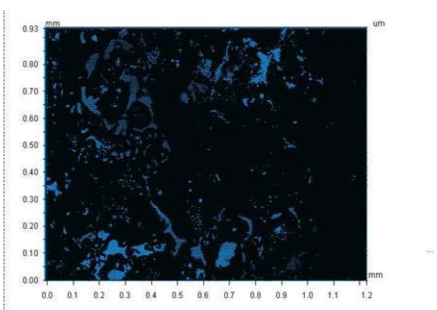



**Figure 62** – Z406

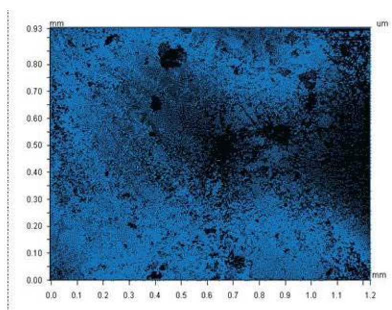



**Figure 63** - QuadraTempo

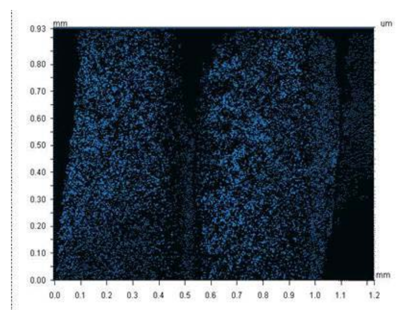



**Figure 64** – Dimension

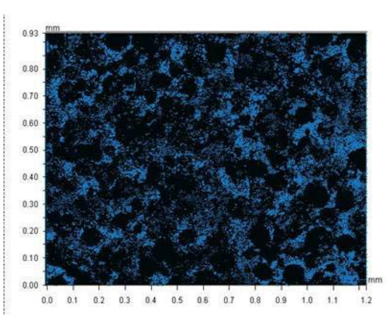



**Figure 65** – MDX-650

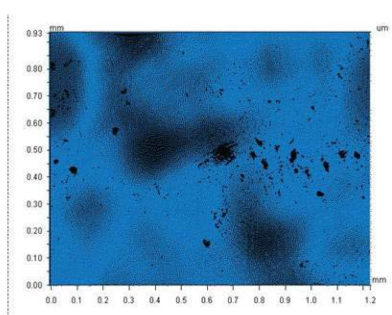



**Figure 66** – Viper si2

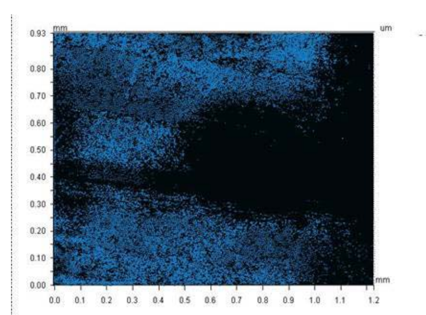
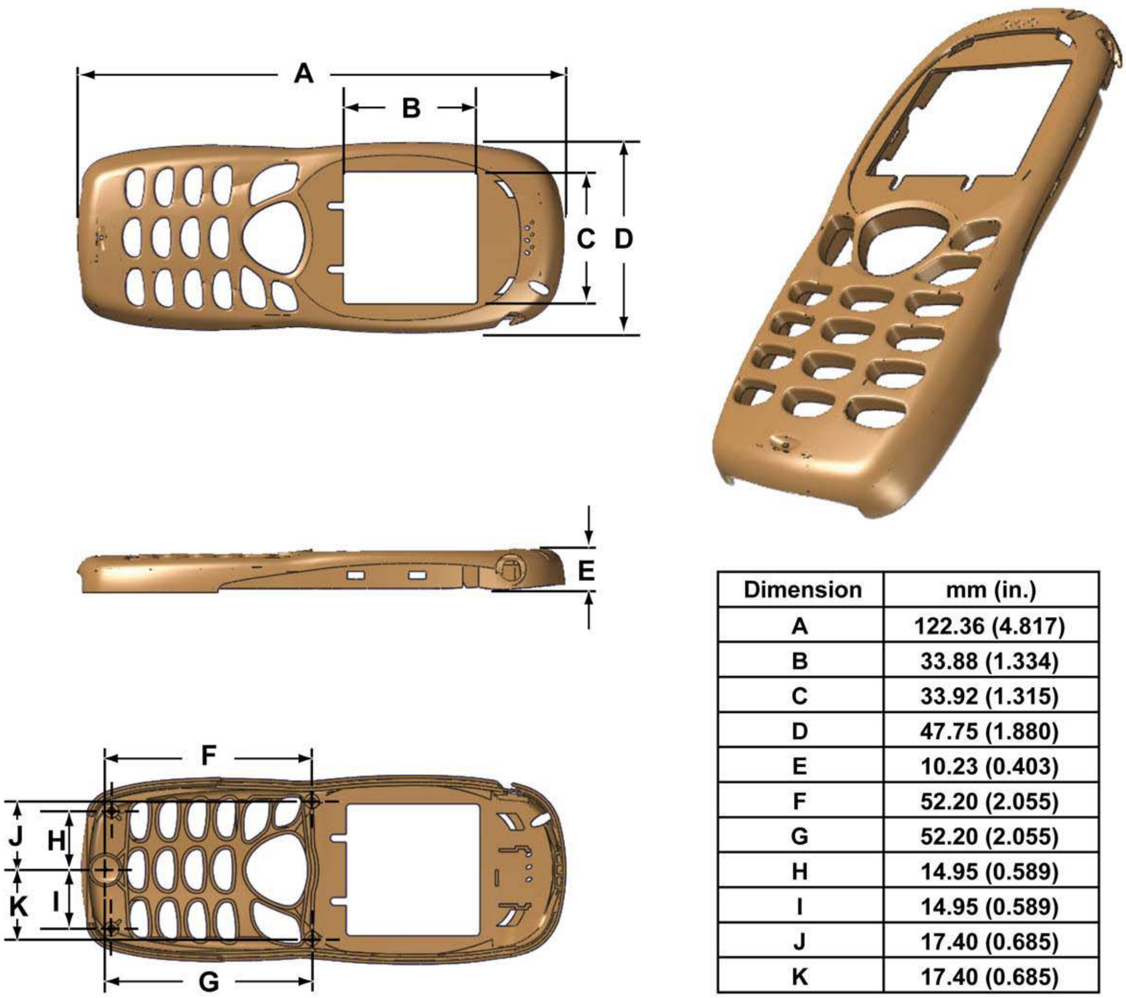


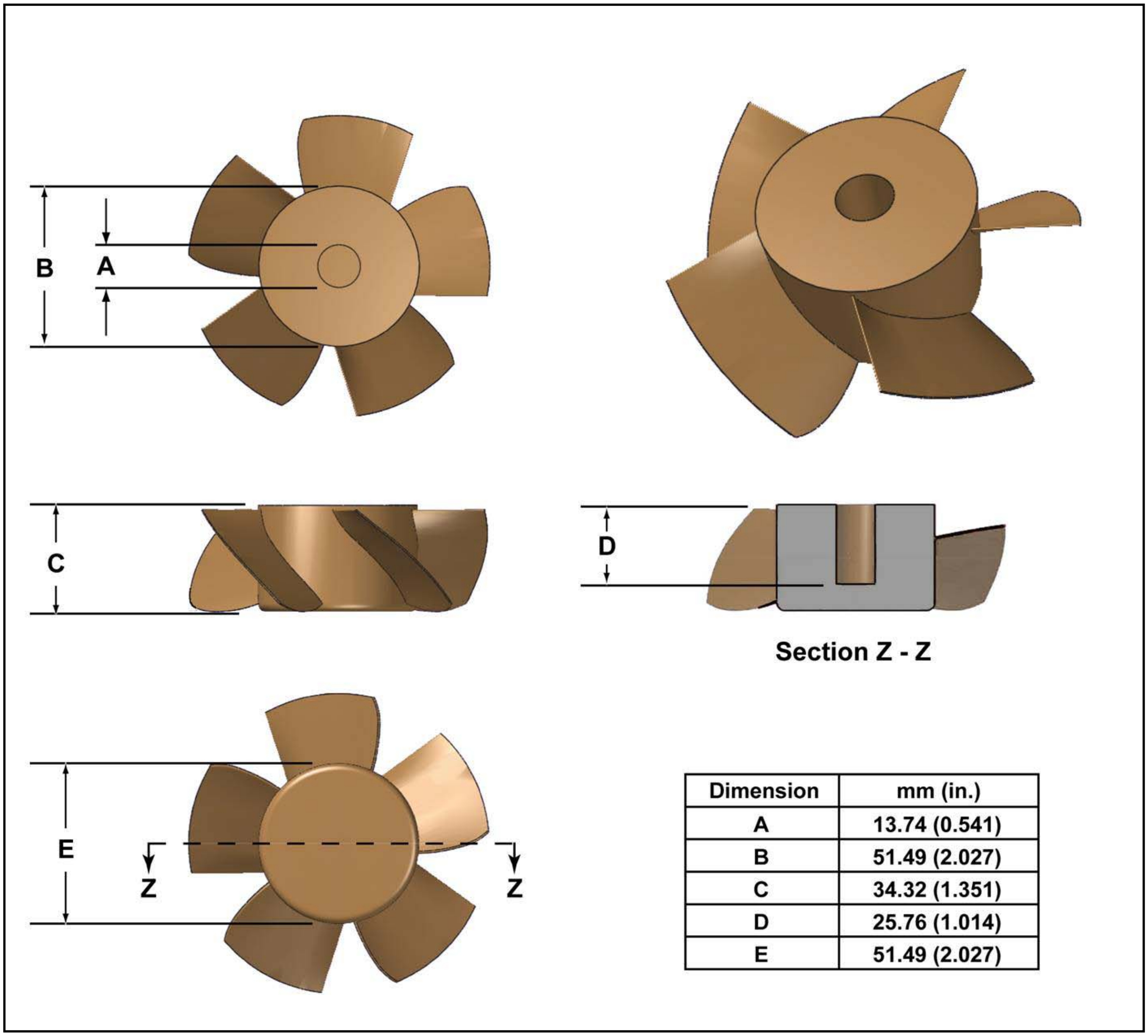

**Figure 67** – ThermoJet

**Figures 62 - 67:** Images from white light interferometer showing characteristics of the top surface of the fan.



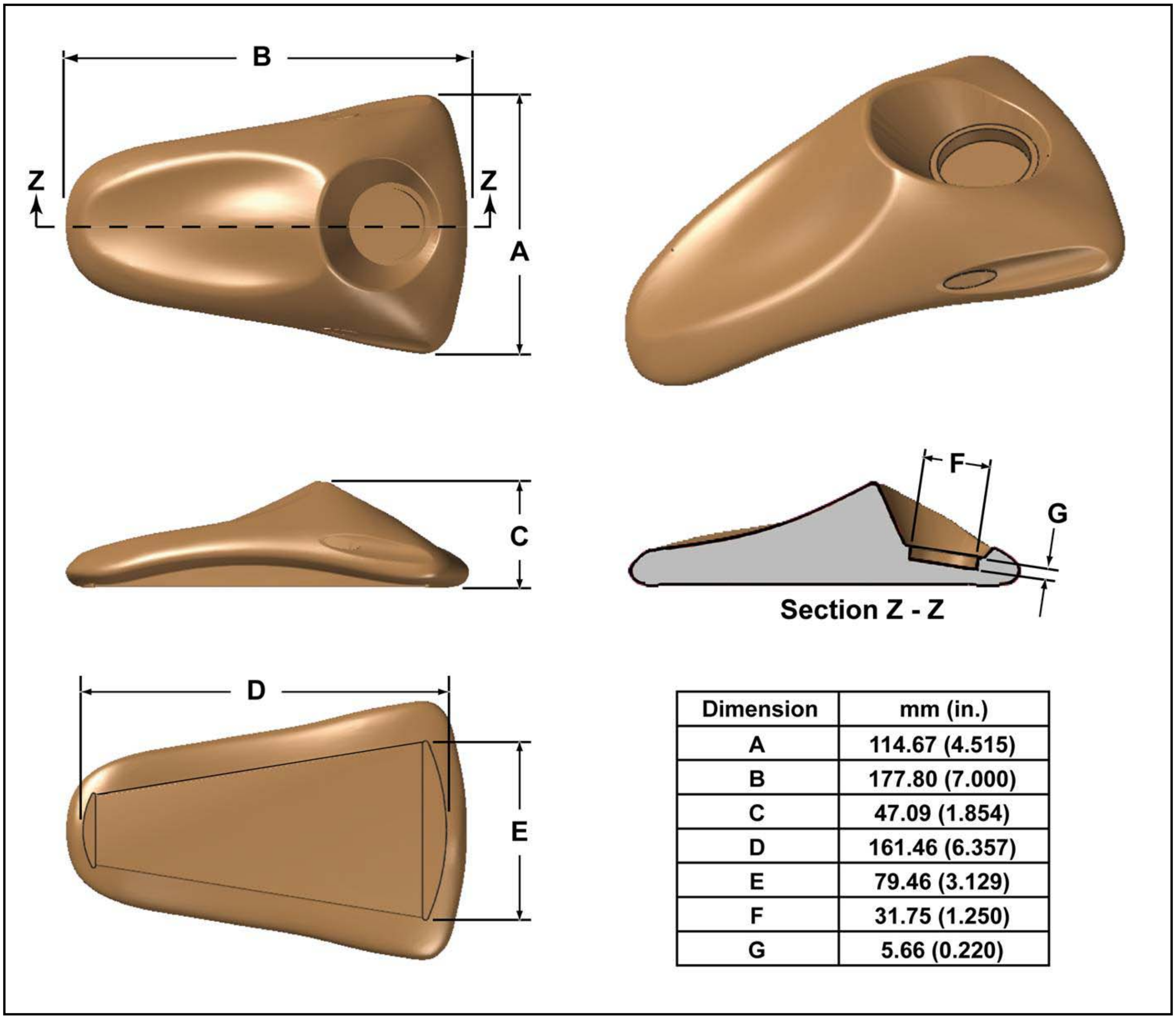

| Dimension | mm (in.) |
|---|---|
| A | 122.36 (4.817) |
| B | 33.88 (1.334) |
| C | 33.92 (1.315) |
| D | 47.75 (1.880) |
| E | 10.23 (0.403) |
| F | 52.20 (2.055) |
| G | 52.20 (2.055) |
| H | 14.95 (0.589) |
| I | 14.95 (0.589) |
| J | 17.40 (0.685) |
| K | 17.40 (0.685) |

**Figure 68** – Dimensioned drawing of the cell phone.




| Dimension | mm (in.) |
|---|---|
| A | 13.74 (0.541) |
| B | 51.49 (2.027) |
| C | 34.32 (1.351) |
| D | 25.76 (1.014) |
| E | 51.49 (2.027) |

**Figure 69** – Dimensioned drawing of the fan.




| Dimension | mm (in.) |
|---|---|
| A | 114.67 (4.515) |
| B | 177.80 (7.000) |
| C | 47.09 (1.854) |
| D | 161.46 (6.357) |
| E | 79.46 (3.129) |
| F | 31.75 (1.250) |
| G | 5.66 (0.220) |

**Figure 70** – Dimensioned drawing of the track ball.

## Appendix D– Procedures, Formulas and Assumptions

### Testing Procedures

The benchmark parts were constructed independent of the OEM for each technology. In each case, the test parts were produced by an organization that is an owner/operator of the technology where the equipment is used for commercial purposes. Each testing partner was allowed only one opportunity to construct the test parts. Under no circumstances were multiple runs allowed. This test procedure was used to eliminate the presentation of best-case data and to accurately reflect a real world environment were prototype production is not an iterative process.

Wherever possible, the production of the prototypes was supervised by Todd Grimm. This measure was taken to ensure that the testing procedures were observed.

All expense and time calculations were based on the construction of a single prototype in each machine run. Concurrent building of the three test parts, while feasible in each technology, is not reported in this study. This test procedure allows the benchmark to report the time and expense for each test part when constructed independent of any other parts.

To reflect the wide array of prototypes produced and to illustrate the impact of size, volume, and level of detail on time, cost and quality, this benchmark used three prototype parts. While previous benchmark studies have used a single part in the analysis, the results are appropriate to only prototypes of similar size and geometry. To provide usable data that is applicable to a wide variety of prototypes, the benchmark analyzes three distinctly different prototypes in the evaluation: cell phone housing, fan and track ball base. The cell phone offers the evaluation of a thin walled, highly detailed, relatively small prototype that represents many injection molded parts. The fan offers a prototype with more size and volume with a complex shape. The track ball offers a larger prototype with a large volume and many contoured surfaces.

Participants in the benchmark study were asked to use construction parameters and materials commonly applied to prototypes for engineering review (form and fit analysis).

To reflect the total process time for prototype construction, the study documents all processes from the initial preparation of the STL file to the cleaning and preparation of the deliverable prototype. However, the benchmark excludes any finishing of the prototype that could be used to improve visual appeal, surface finish and accuracy. With the elimination of benching, the variables of user procedures and quality standards are removed. Additionally, omission of benching facilitates the measurement of surface roughness on “as-constructed” prototypes, not “as finished.” The post-processing work that is included covers only those operations that are mandatory for prototype production. These include support removal, powder removal, washing/cleaning and infiltration.

Participants were informed that the STL files had been verified and repaired. So, the time study omits the process of analyzing and repairing corrupt files.

Throughout the prototype process, all actions, and the tools required, were documented, and time was listed as either manual or automated. Manual operations are those that require employee action or supervision. Automated processes are those that are unattended and demand no time on the part of an employee. For automated processes of less than 10 minutes, the time is considered manual since the operator would be unlikely to perform other duties in this period.

The prototyping process was broken down to three main operations: data preparation, part construction and post-processing. The operations include the following procedures:

- Data preparation
    - Part orientation
    - Support generation
    - Build parameter application
    - Slice generation
    - * Tool path generation for the MDX-650
- Part construction
    - Machine set-up
    - Machine warm-up
    - Part fabrication
    - Post–build operations
        - Draining
        - Cool-down
        - Part drying
- Post–processing
    - Part cleaning
    - Support removal
    - Infiltration

The calculation of operational expense and prototype cost includes all equipment, software, supplies and labor required for the systems as used in the benchmark test. Discretionary or optional equipment that is predicated on a user's process and method of operation was excluded. A key element of cost that was not included in the expense calculations is facility modification. Some of the tested systems require specific operating conditions that are not commonly available in a user's facility. While these expenses may be significant, the associated costs are dependent on factors unique to the user's current facility set-up, local building codes and local construction costs.

Items that were included in the cost calculation are as follows:

- Rapid prototyping system
  - Including system accessories
- Computers and software
- Supporting equipment
  - Pre– and post–processing
- Service/maintenance contracts
- Hand tools
- Consumables
  - Replacement parts
  - Solvents and chemicals
- Waste disposal
- Routine maintenance

For those actions that require labor, a rate of $35.00/hour USD was applied. This hourly cost to the employer represents an employee salary of approximately $36,000 to $40,000.

**Dimensional and Surface Finish Inspection**

The benchmark parts were inspected for dimensional accuracy and surface roughness by the Rapid Prototyping Center of the University of Louisville. The university's lab houses rapid prototyping equipment, CNC mills, injection molding presses and metrology testing equipment. The lab, widely known in the rapid prototyping industry, conducts work for members of its consortium and performs research and development for rapid prototyping processes and materials.

To replicate a real world environment where a prototype may have a useful life of several weeks, all dimensional inspection was conducted between three and four weeks after prototype production. This delay allowed the impact of environmental factors and dimensional instability to be illustrated. Prior to and during the inspection, all prototypes were stored in an office environment where temperature and humidity are maintained at comfortable levels.

Dimensional Inspection

The impeller and cell phone were measured using a CMM. The track ball housing, due to its contours, was fixtured and measured with calipers. For most dimensions, four measurements were taken. From these four measurements, an average and standard deviation (σ) were determined. For those measurements that exceeded 2σ, the value was dropped, and the average and standard deviation were recalculated. Using the average dimensional value for each measured feature, an absolute deviation from the nominal dimension was calculated. For the center-to-center measurements on the cell phone, only one measurement was taken for each feature.

The summary data presents an average deviation and σ that are calculated from the individual deviations for all features across all parts. To illustrate the wide variance in dimensional accuracy, all values less than 3σ, were included. Values that exceeded 3σ where omitted from the summary data to prevent skewing of the results from an anomaly in the part or from the measurement of the feature.

The dimensions evaluated in this benchmark are documented in Appendix C, *Figures 46, 47 and 48*. In these figures, the nominal dimensions and the associated reference labels are listed in the table.

Notes:

The averaged data for the Z406, QuadraTempo and PatternMaster does not include a complete data set. For the Z406 and QuadraTempo, the center-to-center dimensions on the cell phone housing where not reported. This is due to deformation of the cell phone prototypes. With warpage of the prototype, valid dimensional data was not available. Due to extremely long build times for the fan and track ball, these prototypes were not constructed on the PatternMaster. Therefore, the dimensional data for this system represents only that from the cell phone.

Dimension “D” on the cell phone was excluded from the benchmark results. For all prototypes, the dimensional accuracy of “D” was inconsistent with the balance of the measurement data. Upon further inspection, it was determined that the difficulty in measuring this feature led to erratic results.

Surface Finish

The challenges of measuring the surface finish were discovered. Many surface roughness devices are design to capture surface finish in a small sample area. These assume that the surface characteristics of the small sample are consistent across the entire part. This is not true with rapid prototypes. Additionally, the devices are often intended to measure the hard, reflective surfaces of metal parts, another characteristic not common to rapid prototypes.

The initial testing plan was to use a diamond tip profilometer to capture surface finish on the top, side and bottom of the benchmark parts. However, the softness of the prototyping materials allowed the diamond tip to dig into the part surface.

The testing was ultimately performed with a Wyco white light interferometer. Although this device is often used to capture surface roughness in a small sample area (just several μm across the sample), the sampling area was enlarged to collect reasonable measurements. However, the sample is still too small to detect and measure surface variances such as lay, skew and wave. The other challenge was capturing data on the test parts made in white materials—specifically those from the Z406 and Dimension. The final test results were gathered only for the top surface of the fan. While this data reflects a best case for each technology, the results are appropriate for part evaluation.

To extend the surface finish analysis, a stereo microscope was used to capture an image at 10X magnification. The images are taken from the side wall of the track ball.

**Formulas and Assumptions**

Hourly rate/throughput

1. Machine utilization
    a. Single shift operation
        i. Nine hours (including lunch and breaks)
        ii. Five day work week
        iii. 50 work weeks per year
        iv. No operations on off-hours, holidays or weekends
    b. 60% utilization rate
        i. Allowing for maintenance, downtime, scheduling gaps

2. Annual expense
    a. Purchase expense (all required equipment) amortized (straight line) over seven years
        i. Total expense includes all mandatory items to perform work as executed in the benchmark
            1. Includes initial material supply when a minimum quantity is required for machine operation
                a. E.G. initial vat fill of photopolymer for Viper si2
        ii. Items required for secondary operations (finishing, sanding, etc.) are not included in the total expense. These are assumed to be variable and driven by user preference
    b. Yearly expenses
        i. Total expense includes maintenance agreements, user maintenance, consumables and waste disposal
    c. Annual expense = amortized purchase expense + yearly expense
3. Throughput and operating hours
    a. "Typical part" used in calculation of total operating hours and throughput
        i. Assume that the averages of the cell phone, fan and track ball represent a typical part in terms of:
            1. Time
            2. Size
                a. 86.4 x 132.1 x 30.5 mm (3.4 x 5.2 x 1.2 in.)
            3. Volume
                a. 132.7 $cm^3$ (8.1 $in^3$)
        ii. Assume that typical build would use 25% to 50% of the build envelope
            1. For the test systems, this yields two of the "typical part" for each "typical build"
                a. Using "typical part," calculate time to build two of these in one machine run
                    i. Resulting footprint is 172.7 x 132.1 x 30.5 mm (6.8 X 5.2 X 1.2 in.)
                    ii. Resulting volume is 265.4 $cm^3$ (16.1 $in^3$.)

- b. Maximum operating hours (daily)
  - i. Calculate time for "typical build"
  - ii. Determine number of runs that can be started in a given work day
    1. Divide 9 hour day by average build time
    2. Allow 5% overage (approx ½ hour)
       - a. Assumes that an operator would stay ½ hour to increase productivity with one additional run
    3. Round up to whole number
- c. Annual operating hours
  - i. Multiply total daily builds by average build time
    1. Including any machine prep or post–build operations that consume machine time
  - ii. Multiply result by 250 (5 work days, 50 weeks/year)
  - iii. Multiply result by 60% utilization rate
- d. Annual throughput
  - i. Multiply total daily builds by 2
    1. Two "typical parts" per build

4. Cost/hour
   - a. Divide annual expense (2.c) by annual operating hours (3.c)
5. Labor rate
   - a. A labor rate (cost) of $35.00/hour USD is applied to all manual processes
     - i. Assumes annual salary of $35,000
     - ii. Assumes cost to employer is twice the hourly pay rate
       1. Covering employer tax, healthcare, vacation and other contribution
       2. Allowance for additional costs of the employee, such as supplies, workspace and supporting equipment

## Appendix E – 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.

Fisher Design
Cincinnati, Ohio, USA, www.fisherdesign.com
Industrial design, brand identity and package design, interactive communications, and marketing support.

Precision CAD/CAM Service, Inc.
Hunt Valley, Maryland, USA, www.cadcam4u.com
Value added reseller of CAD and CAM software and rapid prototyping systems.

Squid, Inc.
Venice, California, USA, www.squid.cc
Rapid prototyping, rubber molding and design services.

Stafford Jewelers
Dayton, Ohio, USA, www.3djewelers.com
Custom jewelry design and manufacturing with rapid prototyping.

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.

**Benchmark report available at www.tagrimm.com**

To purchase additional copies of this Rapid Prototyping Benchmark of 3D Printers, visit www.tagrimm.com/benchmark/.

**About T. A. Grimm & Associates, Inc.:**

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 or contact the company at 3028 Beth Ct., Edgewood, KY 41017. Tel: (859) 331-5340, Email: tgrimm@tagrimm.com.

**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.