SME
BLUE BOOK SERIES
2005

Capturing a Competitive Edge Through Digital Shape Sampling & Processing (DSSP)

Peter Marks
Author

Published by the Society of Manufacturing Engineers

Society of
Manufacturing
Engineers

Society of Manufacturing Engineers • One SME Drive • P.O. Box 930 • Dearborn, Michigan 48121 USA
(313) 271-1500 • FAX (313) 425-3400 • *www.sme.org*

Copyright © 2005
Society of Manufacturing Engineers
This Blue Book may not be reproduced in whole or in part in any form without the express written permission of the Society of Manufacturing Engineers. By publishing this Blue Book, SME neither endorses any product, service or information discussed herein, nor offers any advice. SME specifically disclaims any warranty of reliability or safety of any of the information contained herein.

ISSN 0895-5085
Manufactured in the United States

PUBLISHED BY THE SOCIETY OF MANUFACTURING ENGINEERS

ABOUT THE AUTHOR

Peter Marks is managing director of Design Insight (Santa Cruz, Calif.) and an internationally recognized expert in new product development and the tools to support it. Marks has published three books covering various aspects of product and process development, and has helped his clients create more than $3 billion of new and improved products.

He has a long history of firsts. Marks wrote the first book on managing computer-aided engineering, chaired the first conferences on engineering data management and rapid prototyping, and managed the development team for the first practical NC verification software. In 1994, he authored the SME Blue Book “Process Reengineering and the New Manufacturing Enterprise Wheel,” which describes a framework for process improvement and cross-functional teaming. His eDesign column for CAE magazine was the first linking the Web and new product development. Marks also co-founded the American Product Excellence (APEX) Awards with the Management Roundtable and served as head of the Board of Judges for several years. He sees the topic of this Blue Book, DSSP, as an important tool for competitive design and manufacturing.

The original manuscript on which this Blue Book is based is copyrighted by Peter Marks, Managing Director, Design Insight, 3760 Old Pilkington Road, Santa Cruz, CA 95065. Marks can be reached at *peter@designinsight.com*.

Capturing a Competitive Edge Through Digital Shape Sampling & Processing (DSSP)

The ability to capture the shape of things to come has exponentially improved, driven by advances in scanning software and hardware (*Figure 1*). The technology is now sufficiently mature that many companies can gain a competitive edge in design or manufacturing. This Blue Book is a clarion call to get moving and take advantage of all this technology has to offer.

To put this exponential progress in historical perspective, for centuries it took roughly a minute to make an accurate single point-to-point measurement. For example, think about the time it took to mark off a field, when a "foot" was actually measured one foot at a time.

Consider, later, the first users of the micrometer. Maudslay built the first precision screws and the first micrometer around 1805. In France, Palmer patented a micrometer in 1848. Whitworth sent a precision screw to the 1851 Great Exhibition that was reportedly capable of registering millionths of an inch. In the United States, Brown & Sharpe introduced the "first practical micrometer" for measuring sheet metal in 1868. Again, it took about a minute to retrieve the instrument, carefully apply it and record the results.

While making multiple measurements was somewhat time consuming, this level of measurement technology was good enough and fast enough to help manufacturers create interchangeable parts and begin the industrial revolution.

More recently, point-to-point measurements were partially automated using two-dimensional comparators and three-dimensional coordinate measuring machines (CMMs). Precision screws and scales remained the heart of measurement, but the process was automated. Mechanical touch probes now provide about one point per second speeds for geometry capture. These improvements in point-to-point measurement speeds—one or two orders of magnitude over the past 50 years—helped create the advanced products we use today.

The recent and dramatic change in all this is with various noncontact measurement methods, such as laser scanners, which are capable of cap-

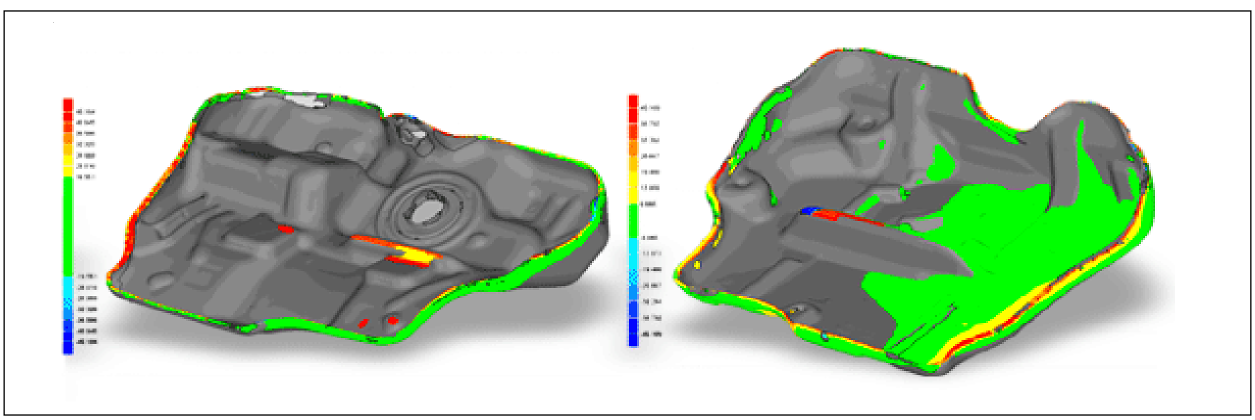

Figure 1. Scanning technology now offers a competitive edge in design, tooling, manufacturing, mass customization, supplier quality assurance and other areas. The example above, a tolerance analysis of an entire blow-molded fuel tank, is from Vitec. Image courtesy of Geomagic (Research Triangle Park, N.C.).

turing up to millions of points per minute. This is four to five orders of magnitude faster than coordinate measuring machines using touch probes. We have seen how exponential increases in computer power have revolutionized society. Exponential increases in geometry capture are poised to revolutionize manufacturing.

The most important change is that it is now realistic to capture the entire shape of tool or part, not just a few critical dimensions. Prior to writing this Blue Book, this author gathered a group of industry experts, who are using the technology for everything from precision plastic molding to jet turbines, for a day of discussion. A main conclusion? We have already seen tasks such as reverse engineering (traditionally, processes such as copy milling) and first-article inspection (formerly using micrometers, height gages and the like) get faster and cheaper. What we are now beginning to see are new applications. Just as using computers to automate tasks such as balancing checkbooks (the old tasks) gave way to e-commerce and online payments, the greatest paybacks for scanning are new applications.

NAMING THE TECHNOLOGY

The three most common terms relating to this technology are reverse engineering, 3-D scanning and computer-aided inspection (CAI). None does it justice.

Reverse engineering has the connotation of capturing geometry solely to make a copy—legal in its intent or otherwise. However, the greatest benefit of scanning technology is to improve a product or its manufacturing process, not just make a copy. Reverse engineering steps backward, often with a poor fidelity copy, or at least lacking the design intent of the original. The potential of this technology is to move forward with product and process improvement, not repeat the past.

Three-dimensional scanning describes some of today's latest data acquisition technology, but misses the applications and also the crucial role of software to turn scanned data into usable forms. In addition, the "scanning" part may eventually give way to alternative technologies, much as today's 2-D display technologies do not all rely on scanning an electron beam across a cathode ray tube. It is the accuracy and exponential increase in speed that are important, not the various contact and noncontact point-location technologies that make it possible.

Finally, while the term CAI represents an important set of applications, the breadth and value of geometry capture goes beyond what most people think of as inspection. CAI describes only a subset of the seven main application areas to be considered here.

Names like reverse engineering and CAI have done little or nothing to help this technology gain the management attention it deserves. Frankly, this author does not have a great name for the technology—one that manufacturing execs would hear and immediately think "we have got to take a closer look at that." One possibility is calling it rapid shape capture. Rapid because it is exponentially faster, shape because higher data acquisition speed goes beyond sampling a few points to capturing entire shapes, and capture because what is really being captured is a magical and elusive quality—the entire shape of real-world objects. Just as there are RISC (reduced instruction set computing) processors for computing, there might even be RASC (rapid shape capture) processors for manufacturing. Rapid shape capture also pairs reasonably well with rapid prototyping.

There is also the notion of sampling. Quality inspectors sample parts through measurement. They sample some measurements on some percentage of their parts to characterize what is happening in manufacturing. The speed of the new technology allows us to sample orders of magnitude more point-to-point measurements and also a higher percentage of parts.

Musicians use the term sampling in a more creative vein. They sample bits of music and reuse it in other compositions. The same process applies to industrial and engineering design. Existing designs or tools can be sampled and incorporated into new work. Indeed, every great design rests on existing design elements augmented with something new.

Both meanings of sampling apply to capturing 3-D geometry. Even when a million points on a surface are captured, it is still a sample among infinite possibilities. The better the fidelity of this sample, the more useful it is for both measurement and reuse in countless design and manufacturing applications.

Sampling is not the whole story, however. The genius of today's technology goes beyond scanning, shape capture, sampling, or whatever you want to call it, to process point cloud data and turn it into usable forms for inspection, reuse in CAD, visualization on the Web and so on. Processing the raw data makes it useful. Mathematicians use the term geometry processing to describe many of the relevant technologies.

The best design, engineering and manufacturing applications are not to steal geometry, but to capture it and create something even more compelling. So, names for this technology might include:

- Shape sampling (scanning, capture, measurement, mainly data acquisition)
- Rapid shape capture (or rapid shape measurement)
- Digital shape sampling
- Digital shape sampling and processing
- Geometry processing
- Automated metrology systems
- Scanned geometry processing

The most accurate term, in this author's opinion, is the somewhat unwieldy digital shape sampling and processing (DSSP). What digital signal processing (DSP) is to audio, DSSP is to 3-D geometry. Both DSP and DSSP take a sample, often a huge and sometimes noisy sample, and clean up the data for higher fidelity. The name is not catchy, but it is reasonably descriptive of this important technology.

The "digital" part is important because of the implications for storing, processing and transforming the data. Moving from paper-based to digital descriptions is key. Over time, as it is taken for granted that design and manufacturing are digital, it might make sense to drop the word and simply talk about shape sampling and processing. Similarly, perhaps the role of software processing will become engrained in everyone's minds and one can simply say shape sampling. But, for now, DSSP seems to be the best description.

OVERVIEW OF DSSP TECHNOLOGY

Seven main application areas (and more than 40 applications) for shape sampling are as follows:

1. Product design—beginning with the customer's context.
2. Process selection and optimization—choosing to win.
3. Manufacturing—moving toward flawless production.
4. Mass customization—the ultimate differentiator.
5. Supply chain qualification—minimizing the risks of a global supply base.
6. Product support—extended life (and profits) from existing products.
7. Scenarios of use—where physical products and digital services intersect.

It should be noted that many points summarized in this Blue Book were drawn from a roundtable discussion among experts in the areas of reverse engineering and computer-aided inspection. Participants included a variety of leading industry practitioners and experts.

DSSP is based on two main technology developments: scanners and other hardware to capture point data, and software to process the data into useful forms.

Point Sampling (Scanning) Hardware

The first development is improved measuring tools, especially noncontact scanning devices, such as laser, white light, light-emitting diode and so on (see *Figure 2*). Scanners now capture thousands or millions of points in the time manual methods might capture a handful of points. Scanners take us beyond measuring a few critical dimensions and hoping these capture what is happening with the geometry to "seeing" the entire geometry at once.

The technology is changing and the industry consolidating so fast that it is futile to outline de-

Figure 2. Laser scanners are often mounted on coordinate measuring machines or, in this case, on articulated arms, such as the Faro ScanArm shown here.

velopments or make vendor comparisons in any great depth. The vendor mentions below will likely be out of date by the time you read this. Some companies will have merged. Several names should appear in multiple categories, while other names will disappear. The hottest new technology may be from some vendor not even listed.

The categories are also in flux. Some segment the technology by application (long-range terrestrial measurements versus short-range micromeasurements), others by methods of operation. Several fundamental physical principles are employed (precise mechanical positioning of probes, triangulation, optical radar, fringe pattern projection and so on).

Many systems combine two or more principles to extend the range, accuracy and capability of their instruments. Thus, *Table 1* should be regarded as just the briefest of introductions to the various sampling technologies. For updated information, several Web sources are noted in the Appendix. Older methods are primarily mechanical but still dominate manufacturing and inspection. Laser and structured light scanners are currently making the greatest strides.

Transformation (Processing) Software

Putting a complete DSSP system together is a bit like CAD in that there are both hardware vendors and software vendors. You will need sophisticated software to take scanned data (typically referred to as a "point cloud") and prepare it for use in various applications. Software from companies such as Geomagic, InnovMetric Software and INUS Technology cleans up the point cloud data, transforms it into usable forms and often automates specific applications. The software generally does not care where the point cloud data comes from—only what processing must be done to make it usable for various design, measurement, manufacturing, inspection and visualization applications (*Figure 3*).

Most scanning hardware vendors provide basic software with their machines—sometimes a scaled-down version from one of the pure software players. Greater levels of functionality and automation are generally required and available from one of the handful of leading software vendors.

Unlike CAD, where hardware and software have stayed distinct, it is likely that some hardware and software vendors will merge in the future. This may or may not prove to be in the user's best interest.The "pro" is likely to be better integration of hardware and software. The "con" is being locked into a single hardware vendor at a time when the scanning technology is rapidly changing.

Scanners acquire many thousands of point measurements, each with an *x,y,z* location in space and sometimes color information or verification of control points through other methods. Each point measurement is subject to a wide variety of measurement errors. While sources of error (contamination on the part, vibration, operator error and so on) are on the same order of magnitude as traditional measurement methods, the sheer volume of point cloud data requires sophisticated algorithms to catch problems, such as minute surface defects, and properly register the entire shape. Until recently, this process could take days; now it is dramatically faster.

As an example of transformations, point cloud data might be converted to an accurate polygonal mesh or a surface representation (typically the non-uniform rational B-splines, or NURBS, used by most CAD systems). Ease of use is an issue in this process. The conversion to NURBS must be easier than remodeling in CAD as well as providing surfaces that can be used directly within CAD.

As an example of an application, a comparison might be made of the "as-designed" CAD model with what was actually produced based on shape-sampled data. A wide variety of process variations (shrinkage, tool wear and so on) might show up in plots provided by the software, along with guidance on how to correct the problem.

Much of the software industry finds itself poised between two important user constituencies. Early adopters of the technology want, and are able to use, a multitude of tweaks and controls. Many might be happy to be the only one in the company smart enough to master the application. While these experts and early adopters are crucial to getting started, more pragmatic buyers insist on sufficient ease of use so that DSSP becomes a tool rather than a career path. Smart buyers will find a middle path that works for their business.

Scanning hardware and software can be combined in many scenarios of use, ranging from reverse engineering to computer-aided inspection.

	Sampling Technology	Pros	Cons	Vendors
M E C H	**Coordinate measuring machines (CMM)** with mechanical touch probes	• Established and widely available technology • Accurate for rigid bodies • Unaffected by optical issues	Slow point-by-point measurement	Hexagon (Brown & Sharpe, DEA, Sheffield, Starrett, Leitz, Johansson), Zeiss, Mitutoyo, LK, Wenzel, IMS and others
M E C H	**Mechanical scanning probes on CMMs**	Faster than touch-trigger probes, as probe tracks along a prescribed path	Much slower than optical scanning methods	Renishaw, Zeiss and other makers of probes
M E C H	**Mechanical probes on articulated arms** (also described as portable CMMs by some vendors)	Relatively affordable. Often handles large volumes and easier to use in a production environment. Capable of reasonable accuracy (.001 to .010 in. [0.00254 to 0.0254 cm]).	Slow	Faro Technologies, Hexagon (Romer/Cimcore), Immersion, Metris (Krypton) Roland
L A S E R	**Laser scanning heads** fitted to either CMM or articulated arms from companies such as Faro and Romer. May also be fitted to robots, machine tools and other devices. The heads lay a laser line down on a surface, somewhat like capturing a loft curve. The positions of points along the line are triangulated using sensors.	Dramatically faster at capturing points on a surface – on the order of a million points per minute. Cost-effective use of existing CMM or arm. Possibilities of combining both touch and scanning to solve measurement problems. Potential accuracy in the same range as articulated arms.	Not suitable for all surfaces, though issues with transparent and highly reflective surfaces are being addressed. As with CMMs, experienced operators are needed. Systems can be somewhat complicated to use. Some safety concerns (eye exposure) in the hands of inexperienced operators.	Faro Technologies, Laser Design, KREON, Metris, NexTec, Perceptron and others
L A S E R	**Mid-range laser scanners**	More camera-like in operation (3-D photography) and potentially easier to use than high-end laser scanners. Millions of points per minute. Some capture color data by combining vision/video for color and laser scanning for point location.	Typically lower accuracy and resolution, although this is not inherent in the configuration, just the price point. Also, less automation for scan registration.	Callidus, Laser Design, Minolta, ShapeGrabber, Steintek

Table 1. Chart of point sampling technologies.

Figure 4, for example, illustrates a computer-aided inspection scenario. Hardware is responsible for the "3-D scanning" block. Software handles the other five functions from "scan processing" through "reporting."

As might be expected, the 3-D scanners and software available a decade ago had many limitations. According to the roundtable experts, older scanning hardware was often prohibitively expensive, slow to acquire points, limited in accuracy and unable to deal with some objects, such as those with shiny or transparent surfaces. In the 1990s, scanning software was often difficult to use, unable to deal with large data sets and limited in

	Sampling Technology	Pros	Cons	Vendors
F R I N G E	**High-end structured light scanners.** These systems typically project a moire fringe pattern on surfaces and capture the result to map-point locations. Some vendors combine other methods, such as photogrammetry.	High accuracy	Often high cost	Breuckmann Gmbh, CogniTens, GOM Gmbh, Steinbichler Optotechnik
V A R I O U S	**Terrestrial**. Long-range scanners using **1) tracking, 2) optical radar, 3) time-of-flight and 4) phase-based** methods of locating points.	Trackers offer good accuracy over very large spaces. Currently used mainly for construction, factory floor layout and similar large-scale applications.	Accuracy is sufficient for some plant layout applications, but not manufacturing accuracies. Multiple scans may be needed to "see" all of an existing	Faro (iQvolution), Leica HDS (Cyra), Riegl, Trimble (MENSI) and many others
V A R I O U S	**Micro** scanners (short range) including **LED trackers, microtrackers, laser profilometers, various microscopic methods and so on**	Suitable for tracking locations in smaller volumes, such as for guided surgical techniques, microassembly work or surface characterization.	Varies by application	
V I S I O N	**Vision systems**, typically stereo vision, to estimate depth	Typically lower cost, often leveraging CCD and other technology from the consumer domain. Excellent for 2-D profile information.	Typically limited accuracy in depth perception	Wide variety; check with sources, such as the Automated Imaging Association
T O M O G R A P H Y	A wide variety of other technologies for capturing point-cloud data exist. **X-ray and computer tomography (CT or CAT scans), magnetic resonance and ultrasound imaging** methods capture internal detail, voids and density changes; typically at moderate-to-low resolution.	Extend the range of point measurements inside objects or beyond a line of sight	Varies by resolution, cost and so on	BIR, Hytec

Table 1 cont'd. Chart of point sampling technologies.

its ability to turn point clouds into usable data. While there are still limitations in both hardware and software, we are now at a point where the costs are low enough, accuracy good enough and throughput compelling enough to improve many design and manufacturing processes.

Software + Scanners = DSSP. Who Needs It?

The makers of scanning hardware and software, while experiencing strong growth from a small base, are still looking for "killer applications." Look at any vendor's Web site and you will find half a dozen relatively modest application areas. These include reverse engineering (making copies of past products when drawings or CAD models are not available), scaling up an artist's model to life size, specialized inspection tasks and creating 3-D images of historically or culturally relevant objects. The few rapidly growing applications, such as fitting patients for medical devices

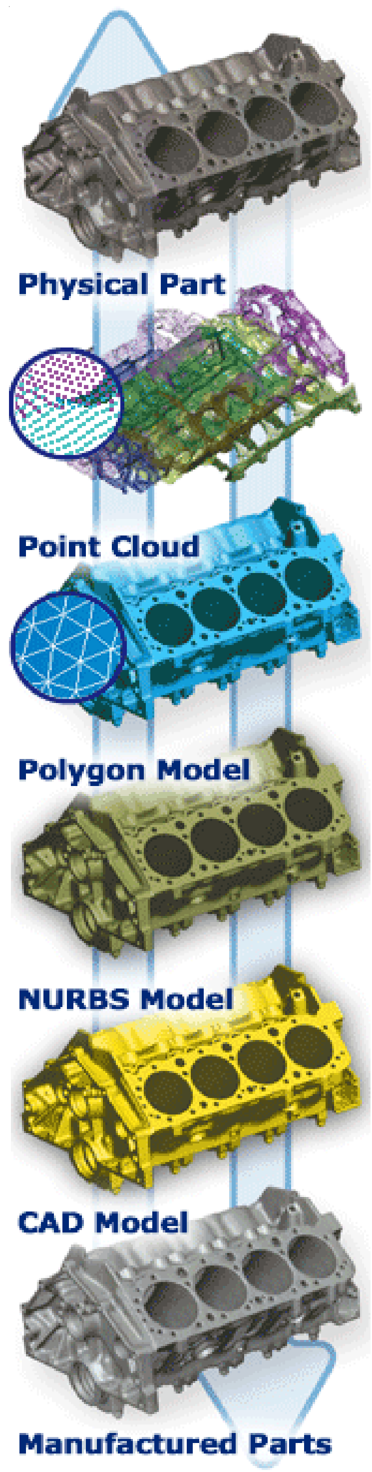

Figure 3. Geometry can be transformed to a wide variety of forms. Image courtesy of Geomagic.

(hearing aids), inspecting turbine blades or verifying plastic molds tend to provide high returns in highly specialized applications.

The real issue is that a "killer application" is rarely doing the same old thing faster, especially if it costs a lot to get started. In addition, traditional applications often have speed limits built into the process. For $250,000, almost anyone can buy a 200 mph car. But few commuters would gain much from the increase in speed, faced with a "commute process" geared to 55 mph.

The speed of point data acquisition has increased exponentially—akin to breaking the sound barrier if one were driving a car. However, the cost of scanning systems that are accurate to typical manufacturing tolerances has only slightly improved, down from $250,000 to maybe half that for high-accuracy scanners. Scanner manufacturers are generally small, specialized companies, not mass producers of precision electro-opto-mechanical equipment. The market has not yet attracted many giants similar to Canon, for instance, with its expertise in mass production of optical devices (lenses and digital cameras) and precision mass-produced mechanisms (printers).

One of today's most affordable scanners, made by Minolta, costs about $30,000 and has accuracy and speed that is acceptable for a subset of applications. The good news is that this is a relatively new and affordable price point. The bad news is that $30,000 is still enough of an entry barrier to encourage many design and manufacturing engineers to keep using the tools and processes they know (and which their organizations are geared to accept) rather than try something new.

SEVEN KEY APPLICATION AREAS

The focus therefore should be less on doing the same old processes a little better and more on doing important new processes. There are now at least seven application areas where many companies can justify investing in DSSP technology. Each brings something new to the traditional methods.

Following is where those killer applications are hiding:

1. Product design—beginning with the customer's context.
2. Process selection and tolerance design—choosing to win.
3. Manufacturing—moving toward flawless net-shape production.

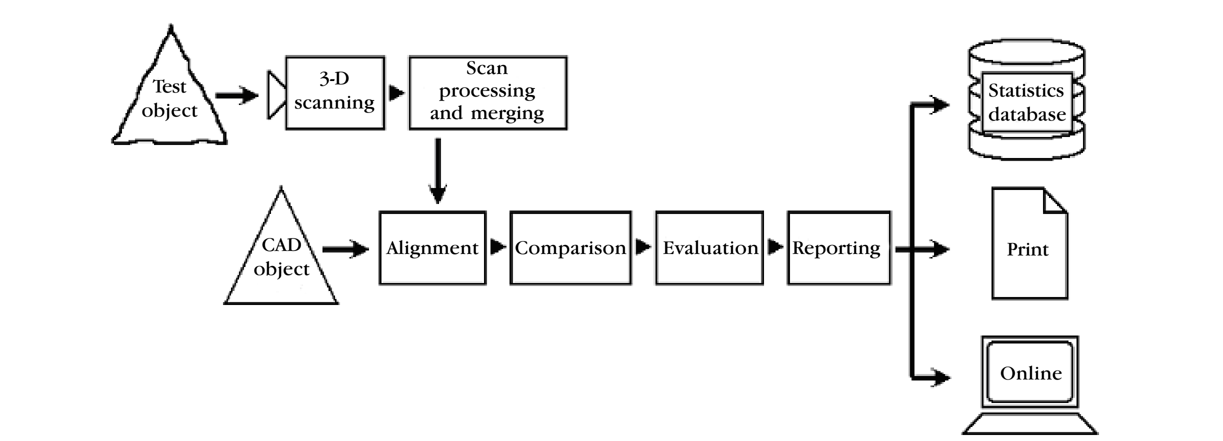

Figure 4. Flow diagram of a computer-aided inspection scenario.

4. Mass customization—the ultimate differentiator.
5. Supply chain qualification—minimizing the risks of a global supply base.
6. Product support—extended life (and profits) from existing products.
7. Scenarios of use—where physical products and digital services intersect.

Product Design—Beginning with the Customer's Context

Design is perhaps 90% knowing what not to change and 10% knowing what to change, as can be seen in *Figure 5*. Successful car companies build multiple vehicles from the same platform. For example, Chrysler's PT Cruiser was 90% a Neon and 10% inspired design. The Apple iPod has basically the same guts (a hard drive and controls) as its competitors and similar manufacturing processes as well (injection molding for the case and so on). Yet, Apple has managed to dominate the market for MP3 players, earn 20% higher prices than same-spec competitors and create an aura of success for all its products. Most CEOs would happily write a multi-million dollar check if it meant their product could be the PT Cruiser or iPod of their industry, with a similar impact on profits and stock price.

What does this have to do with DSSP? It turns out that great products are designed in the customer's context. A large part of the context is visual (iconic and archetypal shapes) and spatial (how the product fits its users and their environment).

Figure 5. Great products are a perfect wedding of customer interests. There's something visually old, to capture favorable associations. There's something visually new, to create excitement. Harley-Davidson is an icon in its industry in part because it understands this balance. This "retro" tank design for a new Harley is based on sampling a customer favorite from the past. Scanned data from the old tank was used as a starting point for the new design. Image courtesy of Advanced Design Concepts (Pewaukee, Wisc.) and Harley-Davidson (Milwaukee).

The technology inside an iPod is much the same as that from competitors, such as iRiver, Samsung and Creative Labs. Apple, however, recognized customer context better than its competitors. To begin with, vision is the sense people use to make first impressions. Apple has captured a design style that appeals to customers across its entire product line, from iMacs to iPods.

Second, Apple recognized that touch and feel are how people make more lasting impressions. The iPod's designers got the package, the feel in a user's hand and user interface better than any competitor.

Apple also recognized that great products fit a social context. The thing most users remember from Apple ads is the shadow images of very cool people dancing connected to their iPods. It is not the spec sheet that sells iPods—the competitors match up well there—it is how users see it fitting their world.

Shape sampling is often the best technology investment a company can make—even if used on a service bureau basis—to capture their customers' context. Want to run a focus group at the earliest stages of development? Scan existing products and rapidly prototype variations on a theme. Want to create a visual identity? Scan design themes that resonate with customers and bring them into new designs. Want to get the user interaction just right? Start by scanning the immediate environment of the product. It may be fit to hand for a consumer product, fit to the space shuttle for a NASA experiment or fit to ear canal for a hearing aid.

Design applications for DSSP include the following:

- Concept testing—using existing products and forms as a starting point.
- Styling and aesthetic design—evoking iconic, archetypical, retro and brand images.
- Ergonomic design—fitting the product to the customer or customers.
- Environmental context—mapping the surrounding environment; the site in architecture and the spatial constraints and opportunities in product design.
- Social context—scanned data, especially realistic 3-D images and 2-D views, are often useful in a variety of communication, advertising, marketing and Web applications.

In addition to these five customer-centered issues, scanning is often more productive in routine tasks, such as:

- Styling innovation—from sculpture and automotive body-in-white design to eyeglass frame design, designers often find it easier to create designs by direct interaction with a physical medium rather than punching entries into a computer. DSSP then creates a digital model for use in downstream applications.
- Capturing 3-D components for use in an assembly model, when models exist for only some of the components (components from other suppliers).
- Capturing geometry for use by various analysis packages (finite element structural, computational fluid dynamics, kinematics and so on)
- Packaging, interference detection and space allocation. Wrap a surface around components or products as a starting point for engineering and package design.
- Communication of design intent. The ability to quickly and seamlessly move from point data to polygonal mesh representations to various surface representations (commonly NURBS or non-uniform rational b-spline) often solves problems in getting data in and out of various systems.
- Product design in many firms is component centric rather than customer centric. Average companies figure what functions their product needs, assemble the necessary components in CAD, package it and push it out to market.

Great companies figure out their customers' context first—increasingly by scanning the alternatives and testing them with customers. What looks just right? What fits in customers' eyes, their hands and their environments? Shape sampling is the ideal tool to capture the visual, spatial, tactile and kinesthetic elements of the customer's context. Shape sampling is also a more productive tool, compared to CAD, for many design, analysis and collaboration tasks.

Process Selection and Tolerance Design—Choosing to Win

There is an old saying, "don't bring a knife to a gun fight." Readers may remember seeing this parodied in a scene from "Raiders of the Lost Ark" where Indiana Jones' handgun beats an enthusiastic sword-wielding bad guy. Sadly, many manufacturers are bringing the equivalent of a knife to a manufacturing competition that can only be won by the best processes.

It turns out that DSSP is an ideal tool to help companies evaluate and optimize various manufacturing processes. This applies especially to net-shape processes (thermoplastic injection molding, thermoset and RIM molding, casting, forging, die stamping and powder metallurgy)—essentially any process where molds or dies and production variables control a complex shape.

Manufacturing now moves wherever customer expectations can be met at minimum cost. To read the business press, the impression is that this is wherever workers are willing to work for the least. However, the real story has as much to do with selecting productive manufacturing processes as the cost of labor. The threat of low-cost producers to manufacturers in North America and Europe has as much to do with investment in modern manufacturing equipment (or lack thereof) as it does with lower wages. Manufacturing "touch" labor for many products is less than 5% of costs. Even if manufacturing labor were free, and moving production abroad had no costs or risks, that 5% is only part of the story. Indeed, China itself is losing millions of low-skill manufacturing jobs as it acquires more productive equipment.

This Blue Book shows how the design applications for DSSP can help companies develop the "iPod" of their market. However, business is often won by building a product that is simply a bit better in areas such as fit and finish, reliability, durability, safety and performance. Consider both the reputation and relative financial performance of Toyota versus GM. Similarly, companies such as Milwaukee, Makita, Bosch and Hitachi have tended to end up with somewhat similar tool designs. Their customer loyalty comes from providing a high-performing, safe and reliable product at a fair price. Dozens of seemingly subtle process choices, cast or molded gears versus cut gears, for example, become the difference between failure and success.

There are at least two ways for companies to lose at manufacturing and one way to win. The first way to lose is to blindly outsource manufacturing in search of a quick profit fix. Quality may slip and orders may be delayed. Soon, generic clones emerge at still lower price points. Customers are not stupid. They soon learn that a commodity product with a brand name slapped on it is not worth a hefty surcharge. Thus the entire business becomes unprofitable, ending perhaps with the brand being sold off.

The second way to lose at manufacturing is to try to stay in the game but starve operations of the investment needed to compete. Typically, if a company owns screw machines to manufacture turned parts, it uses its own screw machines. If a company owns CNC turning centers, it uses its own turning centers. Sometimes the choice of processes does not matter. More commonly, one process beats the other in providing those Toyota-like benefits of quality and reliability. Sticking with the wrong process because that is what we know and own is like bringing a knife to a gun fight.

If a company wants to win at manufacturing, it has to choose the right processes. Only then can it decide to keep them in-house or find a sourcing partner. DSSP is a powerful tool to evaluate alternative processes early on and choose the best. It also provides deep insight into process capability and the optimum trade-off between tight tolerances (performance, reliability, safety) and loose tolerances (lower costs, higher yields).

PROCESS SELECTION

Each manufacturing process has its own potential for shrinkage, warping, springback, deflection and other dimensional uncertainties. Depending on the process, factors such as casting or molding shrinkage must be determined. As any manufacturing engineer knows, the actual part geometry does not precisely mirror the die, mold or CNC geometry. Metal bent to 90° may spring back to something less. Parts machined to 0.0001 accuracy may distort as they cool or are unclamped. A bracket might be cast, welded, molded, stamped or machined.

The structural booms for backhoes made by Case (which invented the backhoe) were traditionally high-strength castings. Caterpillar, which entered the market and gained significant share later, chose welded structures. The initial selection (casting versus welding) was more a matter of using what was familiar to engineers and their companies, not a carefully planned strategy. But the ease of welding up shapes that promised greater reach in backhoe booms ended up as a differentiator for Caterpillar. The point is that each choice of materials and processes has cost, performance and dimensional capability trade-offs. Selecting the best combination of price, performance and quality contributes to higher sales and profits.

Many companies still rely on rules of thumb and tradition to select processes—we choose what we know. Today, companies need to know what to choose. This usually means using experience and analytical tools to narrow the choice of processes, and then doing actual prototype tooling and manufacturing experiments to make the final choice.

Shape sampling is the ideal tool to verify dimensional quality and capability at this stage. Molds or dies can be scanned and compared to CAD geometry. Finished parts can be scanned and compared to nominal geometry. Where fit is an issue, the mating parts can be scanned. In almost every case where complex net shapes are involved, DSSP is ideal to compare alternative processes. Even if production will be outsourced, a process selection group within the prime company should decide what processes are acceptable and also set tolerances.

Every company faces process selection issues, for example, the materials and processes used for laptop shells. The "best" process a decade ago may not be the best process in light of new manufacturing options, improved materials or changing customer requirements. So, the question is, who is making these decisions in your company? Purchasing? Engineering? Or experts who actually take time—and have the DSSP tools—to understand the trade-offs?

Tolerance Design

Once a process has been selected, tolerances need to be established. Product design starts with an idealized vision, where a nominal geometric representation represents each part in an assembly. In such a world, the 2 × 4 lumber used to build houses is always in 2 × 4 in. (5.1 × 10.2 cm) sections, always straight and never flawed. In the real world, the oldest houses have lumber that is more or less 2 in. (5.1 cm) thick, those a few decades older are likely to be about 1.63 in. (4.14 cm) thick, while the newest versions are about 1.5 in. (3.81 cm) thick. Flaws and variations are common.

Engineering is not complete until real-world process variation is accounted for. Because of cost, as much variation as possible is accommodated. For reasons of performance, quality and safety, the limits of acceptability must clearly be specified.

Designers are typically given the responsibility for tolerance selection, yet they frequently lack the motivation, time, training and support to do the job properly. Some end up "sprinkling" their drawings with arbitrarily selected tolerances. When problems arise downstream, reconciling issues of tolerances that are too tight or too loose falls into a formal or informal process of negotiation between engineering, tooling, inspection and manufacturing. This process gets even more complicated when parts of the job are outsourced to another organization, as is common today. Tolerance design is a misunderstood discipline in modern manufacturing. A majority of companies do not pay enough attention. A few get too wrapped up in arcane details of geometric dimensioning and tolerancing. Not enough companies consider tolerances as their customers might: how does one get highly reliable products at the lowest possible cost?

Significant differences in cost and performance hang in the balance. One of the roundtable experts noted that getting tolerance design right early in the process can save tens of thousands in tooling costs and also avoid the potential for catastrophic failures. A combination of analytical tools (tolerance stack-up analysis) and experimental methods (prototype production and testing) is commonly employed. DSSP to capture as-built geometry helps set tolerances that are just right—tight enough to ensure performance without a penny wasted to meet tolerances that provide no value.

DSSP, of both tools and prototype parts, offers a more complete picture (all the dimensions, not just a few) and faster experimentation than is possible with traditional methods. Smart manufacturers design experiments to test various combinations of materials and processing variables to find the optimums. Even if these experiments are conducted with suppliers, companies should probably perform independent shape sampling.

If a company is planning to compete in manufacturing, it needs to have the tools to close the loop from design to process and tolerance selection. If a company is planning to outsource manufacturing, it needs to have enough manufacturing expertise to select the right processes—and have suppliers capable of optimizing yield and throughput.

MANUFACTURING—MOVING TOWARD FLAWLESS NET-SHAPE PRODUCTION

So, a great product design has been created, designed in the customer's context and brought to market quickly using the most productive tools. An ideal manufacturing process has been selected and the right tolerances assigned, saving a few percent on bids while assuring customers of quality.

We are hardly out of the woods, though. There may be hundreds of product variations, wide swings in demand, new products coming down the line, supplier quality problems, shortages, equipment failures, labor issues and more. Production can start out great in the morning and degenerate to chaos by noon.

Many scanning vendors see computer-aided inspection (CAI) as the next big application for DSSP technologies. Put scanners at the end of every manufacturing process and instantly detect when processes veer out of control. As the cost of noncontact methods decreases, the technology will (they say) displace more and more traditional gaging methods. It is an attractive vision for scanner companies because it means selling dozens or more scanners into every large manufacturing facility. It may also be the wrong approach.

Consider this analogy: companies once built huge automatic storage and retrieval systems to improve inventory management. Many of these companies eventually decided that the solution was not automating the handling of inventory but to get rid of the inventory itself. In the same way, we are likely to move from automating the detection of bad parts to getting rid of processes that make bad parts. DSSP is a powerful ally in this quest, with immediate application in eight of the following areas:

1. Tooling inspection
2. First-article inspection
3. Continued process optimization
4. In-process inspection
5. Off-line inspection and soft gaging
6. Detailed coordinate verification
7. Tool wear monitoring and retooling
8. Troubleshooting

Many net-shape processes (molding, casting, stamping, CNC machining and so on) go part way toward the objective of processes that do not make bad parts. If the tool is right and the process controlled, the incidence of defects is commonly low, which leads to the first production application for DSSP, tooling inspection.

Scanner-Based Tooling Inspection

Tooling is commonly outsourced. Even if tooling is built in-house, there is still the issue of conformance. Assume we have selected the ideal process, determined tolerances and accounted for every bit of shrinkage, springback and manufacturing variation in the tool designs. Now, we must assure that the tools (as built) match the tool design.

This is comparatively simple for things like one-dimensional gages and fairly complicated for complex shapes with tight requirements. Tooling inspection, increasingly through shape sampling and processing methods, is required. In those cases where precise control of tolerances is critical, companies (including most of those who participated in the roundtable) typically buy and check tooling at two stages. First, they check prototype tooling to verify and refine the process. Second, they check production tooling before beginning quantity production.

The old approach was to try out the tool and check the parts. If the parts were bad, then figure out why. If the parts were good, then we would not bother to ask if the tool designs and the actual tools as built were in sync.

The new approach is to scan the tooling first. Problems are immediately identified and specific instructions for rework can be given. In addition, we know that our tooling designs and tooling are in sync, preventing problems downstream and also making it easier to get replacement tooling or move production to alternative suppliers in the future.

First-Article Inspection

One benefit of many net-shape and numerically controlled processes is that if the first part is good, then the sources of subsequent variation, such as mold/die wear or tool breakage, are easier to track. Modern manufacturing increasingly relies on first-article inspection, followed by process controls in a few key areas. Especially for net-shape processes (molding, casting, forming, stamping and so on) and multiaxis machining (complex surfaces), scanning or a combination of scanning and traditional coordinate measurement of critical features is often the best technology for first-article inspection.

One point made by our expert panel is that the part designer (or company management, for that matter) rarely understands that the cost of first-article inspection may be on the order of $50,000 per tool because this cost is built into the tooling cost. To put it another way, the justification for investing in DSSP is often hiding in tooling costs.

Continued Process Optimization

As noted earlier, carefully designed experiments to select processes and set tolerances should be done prior to full production. Subsequently, there are usually additional gains in yield to be had through tuning processes in the actual production environment. If production goes down, very rapid "experiments" are required to find and correct the problem. If production could be better, then slight incremental changes when production is running are the norm. In either case, having the ability to quickly sample entire part geometries at the plant location is a big plus in many industries.

In-Process Inspection

The ideal is a process that cannot make bad parts. Second best is capturing defects in real time and immediately correcting the process.

At present, in-process inspection has generally been limited to such things as probing tapped holes, vision capture of 2-D profiles and the like. Three-dimensional scanning has been too expensive for universal application. The exceptions are in such areas as turbine blade manufacturing and remanufacturing, where the shapes are complex, the entire geometry matters and quality is essential. As scanning hardware costs decrease, additional applications will prove cost effective.

Off-Line Inspection and Soft Gaging

A sampling of parts is commonly selected to assure that a manufacturing process has not drifted out of control. For simple parts, with a few critical dimensions to be checked, hard gages are commonly employed. The cost of hard gages skyrockets as gaging requirements become more complex and different products (requiring new gages) are introduced. Industry is seeing increased demand for "soft gages" where a single piece of equipment (such as an articulated arm with a scanner) can be quickly programmed to gage different parts. The payback can be very quick. Soft gages are sometimes justified with the replacement of a single hard gage. Any reuse of the scanning hardware and software beyond that is almost pure profit because the only additional cost is reprogramming. Companies such as Faro and Perceptron were cited by the roundtable experts as two examples of scanning vendors in this area. There are many others.

Detailed Coordinate Verification

For complex parts and assemblies, with many critical dimensions, samples are commonly taken into an environmentally controlled lab for detailed verification. Decades ago, this work was laboriously completed with height gages on granite surface plates, optical comparators and the like. It is still done this way in many smaller facilities. More recently, coordinate measuring machines have displaced purely manual measurement methods. Scanning methods are now poised to take this a step further.

Scanners are ideal for quick characterization of an entire complex geometry. Coordinate measuring machines still have the edge in comfort level ("we have already ISO-certified this process using CMMs…") and for measuring a few critical dimensions at tight tolerances. A hybrid approach is often ideal. Scanning is used as a first step, and then a CMM is used for problem areas revealed by scanning or critical dimensions required by contract. In response to this, CMM vendors are producing machines with interchangeable touch probes (traditional CMM) and noncontact scanners. Perceptron, Metris, Laser Design, Kreon and NexTec were cited as examples of suppliers who retrofit a scanner head to a CMM.

Tool Wear Monitoring and Retooling

Net-shape processes, such as casting, molding and stamping, eliminate some sources of variability. If the first article is right, the next thousand articles are more likely to be right—at least compared to handcrafting. Tool wear is, however, one of the common sources of process capability degradation. Given that some net-shape tools (auto body stamping dies) cost hundreds of thousands of dollars, there is significant work going on to predict tool wear, increase tool life, monitor tools and speed the process of rework or replacement. Shape sampling and processing technology is the ideal adjunct to any effort to understand tool wear, experiment to achieve longer life, monitor wear and specify and verify rework (*Figure 6*).

A company may have gone through years of process design, perhaps trial and error, to arrive at a set of working jigs, fixtures, molds, dies and other tools. Today, that experience may be lost or undocumented, but the company still needs to retool the process. Perhaps the old tools are worn?

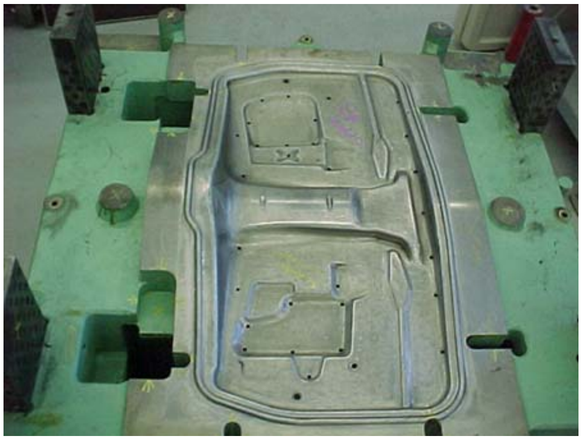

Figure 6. DSSP is an ideal tool to track both initial quality and wear in molds and dies. Mustang (automotive) stamping die example provided courtesy of Detail Technologies (Wyoming, Mich.), which uses scanning in a variety of applications.

Perhaps production is expanding? Maybe production is moving to another location or different equipment? Characterizing the existing tooling through DSSP is typically the starting point for capturing past knowledge and procuring new tooling.

Troubleshooting

The better a company does at failure proofing its processes, the less time it will spend troubleshooting. Still, dimensional problems commonly arise in once-capable processes. Changes in suppliers, material composition, tooling wear and the like can throw a process out of control. Think of this as unplanned experimentation. The investigation usually goes first to quality control. If the problem is not obvious, companies without adequate manufacturing engineering resources often spend hours, days, even weeks, trying to troubleshoot the problem. Scanning hardware, along with sophisticated geometry processing software, can commonly cut the time it takes to find a solution. It should also be noted that some DSSP technologies are suitable for deformation and vibration analysis.

MASS CUSTOMIZATION—THE ULTIMATE DIFFERENTIATOR

What happens when we blend differentiated design, select the best process and never make a bad product? The answer might be "mass customization."

To date, mass customization has had mixed success. The ideal is a perfect blend of products produced to meet individual needs (craft production, hand tailoring), with the lower costs and quality benefits of mass production. Some early attempts at this, as with Panasonic in custom-fit bicycles and Levi in custom-fit jeans, were not successes, while other areas—medical devices (hearing aids, dental implants and so on) and several other applications—are rapidly growing.

Designing products to fit individual needs can be a clear product differentiator. One element of this is fit to body form. Scanning is the ideal way to acquire the human form because no touch or deformation is involved. The process is quick and accurate, and the benefits fairly obvious.

In an ideal world, it would be possible to "scan" the emotional preferences of customers, but that is another story involving the instrumentation of emotional responses and out of the scope of this Blue Book. What is known about emotional responses is that simply asking customers what they want often results in receiving wrong or incomplete answers. "Show and respond" works better. Testing new product ideas by using scanned artifacts as a starting point for derivative designs is the most practical and accurate means of understanding buyers' emotional preferences regarding visual, tactile and kinesthetic form.

Success with mass customization is a matter of cost versus customer benefit. There are at least three competing strategies to make products that fit different people. One is a one-size-fits-all approach, including foam ear plugs that fit most any ear canal, chairs with multiple degrees of adjustment and socks that stretch.

Another long-standing strategy is to divide the population into a continuum of sizes, such as shoe and sweater sizes. We have little cars, medium cars, large cars and so on with a wide variety of equipment.

Many products employ elements of both of these strategies. For instance, Herman Miller Aeron chairs come in three sizes, plus a myriad of adjustments. Clothes come in standard sizes, but often add a bit of spandex to expand a size or two.

The last strategy is to tailor each product to the customer—mass customization (*Figure 7*). It offers one compelling benefit—exactly what the customer wants or needs at the time of scanning. There are also two hurdles to widespread adop-

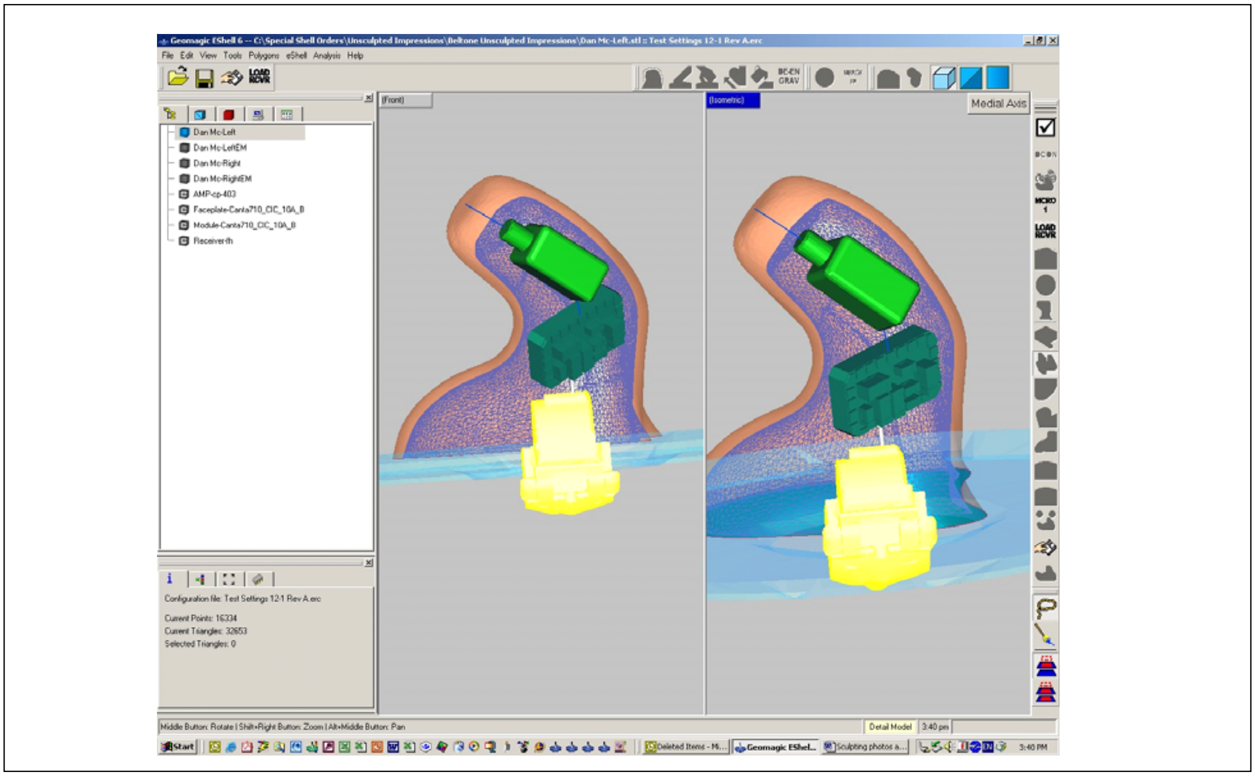

Figure 7. Here is one example of DSSP for mass customization. Hearing aids are now fitted to patients by scanning the ear canal. The process is fast, affordable and provides a better fit. Image courtesy of GN ReSound (Bloomington, Minn.)..

tion compared to the other two alternatives: higher costs and somewhat delayed gratification depending on the speed of the manufacturing process. It can be expected that initial hardware costs will decline, throughput will increase (lowering costs per item) and the manufacturing process will become more like eyewear store LensCrafters—customized products within an hour or two.

Mass customization applications include medical prostheses, sports equipment, safety equipment, hand tools—most anything that benefits from fitting an individual's body. Medical applications are already moving toward "killer app status." High-end sports and safety equipment may be next. In the former case, prosthetics are fit to restore people to normal capability. In the latter case, we fit equipment to give people superior capabilities. As an interesting side note, research into market-leading products shows that the fit-to-hand of a product (such as Good Grips® household tools) is often a key factor in success. In the future, one can expect mass customization of hand grips and other body-fitting elements.

Boutique mass-customization applications are also gaining a foothold where customers want to capture personally meaningful shapes, such as likenesses of their children, pets or a family heirloom. Some examples are already available at your local shopping mall in the form of subsurface laser engraving. Who knows, perhaps the family album of the future will be filled with viewable 2-D images and manufacturable 3-D data sets.

There are additional applications where scanning shapes is faster and cheaper than attempting to model them. As an example, several companies make architectural light poles in a variety of historical styles. Think of towns trying to restore a former gaslight district to electrical power while retaining the old-town look. The pole bases, formerly made from elaborate patterns in cast iron, may now be aluminum castings. Manufacturers are often asked to replicate an old pattern or to create a new and unique pattern from an artist's mockup. When the old pattern exists, it is far easier to scan than model it. Even when designing from scratch, it is usually easier to carve a design and scan it than try to model every curving detail in CAD.

Certainly there is hype surrounding mass customization. Just slapping on the description "mass customized" does not make a product an instant success compared to one-size-fits-all and choose-your-size-and-style alternatives. However, scanning some elements of the design at the front end followed by digital-model-based manufacturing is an increasingly profitable and customer-satisfying alternative.

SUPPLY CHAIN QUALIFICATION — MINIMIZING THE RISKS OF A GLOBAL SUPPLY BASE

Manufacturers used to think vertical integration was the key to success. Companies made key components, held themselves responsible for subassemblies and concentrated manufacturing in large industrial campuses. Today, manufacturing is being outsourced or at least globally dispersed to subsidiaries. The focus has shifted to supply chain management, primarily at a bill of material level: "We need 5,000 of part 839820 at 11 cents each—on the double."

DSSP is a tool to help ensure quality, quantify manufacturing knowledge and, even better, protect intellectual property in an increasingly complex global manufacturing environment. The attraction of moving manufacturing from a high-cost location (say, in North America) to a low-cost location is beginning to face several pragmatic realities. Even companies with well-documented designs and processes learn that some key knowledge has not been documented when they move production.

Start-up facilities almost always suffer problems until they relearn this manufacturing knowledge. This author has seen companies in the automotive and computer industries suffer this twice—first in moving manufacturing to Mexico and later in moving to China. One roundtable expert participant noted a case where manufacturing was moved from Europe to the United States with the same initial quality and productivity issues. Regardless of where manufacturing moves, there is always something undocumented and a learning curve.

Giving purchasing full reign to send work to the lowest bidder is risky in at least three ways. First, quality is likely to suffer initially (and sometimes for years). Second, we can expect outright clones of the design or a more subtle transfer of expertise that allows others to make copies. Third, an extended supply chain adds risks of delays and interruptions. We can buy every enterprise resource planning, supply chain management and collaboration tool in the world, but if there is a shipping strike, a plant disaster or just someone else who commands a higher priority from the supplier, then customers will see delays.

Despite these risks, outsourcing is here to stay. Fortunately, DSSP is a powerful tool to manage the risks of a globally dispersed supply chain. First, it is the best and fastest assurance that parts are being built to spec when complex shapes are involved. Second, geometry processing software can act as a sort of universal translator for geometry, more clearly communicating design intent. Third, DSSP substitutes hard numbers for rules of thumb. It captures manufacturing knowledge in a way that reduces the risk of outsourcing. Fourth, creative applications of the technology may help protect intellectual property rather than facilitate theft, as in the case of reverse engineering.

Supplier Quality Management

Customers typically require either sampling or 100% inspection of outgoing parts from suppliers. Many should also require that inspection be done by DSSP—capturing all the points defining a shape and not just a few selected dimensions.

Scanning is often the fastest and best method to assure conformance with a 3-D digital model. It is especially suited to net-shape processes, such as injection-molded or cast parts. Conventional inspection methods, which sample relatively few points, rarely reveal subtle deviations. In some cases, such as turbine blades, performance and even safety may be at risk. In other cases, such as plastic snap-fit housings for cell phones, it turns out to be fairly difficult to create and maintain a perfect mate.

So, why is scanning not as popular a tool as, say, SAP or Oracle for enterprise resource planning? Paradoxically, scanning can be "too good." The roundtable experts noted that some suppliers avoid scanning because it commonly reveals "problems" (in quotes because the problems may or may not be functional issues) that had not been revealed in older methods of inspection. Over time, we can expect suppliers and their customers to work out the kinks. In my opinion, it is better to have an inspection tool that is too good—and open up the tolerances—than a tool that is too blind and misses defects.

Incoming inspection has the same quality assurance objective as outgoing inspection, but is performed by the buyer or user. The decision of whether to require outgoing or incoming inspection and at what sampling level, speaks to issues of trust and competence in supplier relationships. Some industries are pushing inspection requirements out to their suppliers. Others are pushing most requirements out to suppliers but still sampling incoming items. In many cases, both outgoing inspection (from the supplier) and incoming inspection (by the assembler or user) are required. Still, others are ignoring the issues, hoping to save costs, but ending up disappointed. The dramatic rise in outsourcing to low-labor-cost suppliers is now putting all this in flux. Regardless of whether DSSP is performed by the supplier, the customer or both, it is often the best tool to assure quality.

Clear Communication Between Manufacturing Partners

The communication of design intent between manufacturing companies has long been an issue. In 1979, CAD vendors and users made a first attempt at standardization using the Initial Graphics Exchange Specification (IGES). A quarter century later, proprietary CAD formats are still a problem. At this year's Conference on the Future of Engineering Software (COFES), attendees from Boeing noted that the annual cost of data exchange problems for end users probably exceeds the market capitalization of all major CAD companies.

DSSP technologies do not eliminate the obligation of CAD companies to become more "open," but in many cases the ability to convert geometry to polygonal meshes (even somewhat clumsy .STL files) is a viable workaround. In other cases, scanning the actual part geometry, creating a 3-D model and comparing it with the design intent of the original CAD model is the solution. In many other cases, DSSP is the most direct way to communicate what is out of spec and needs to be changed.

Having fast, accurate and flexible processing software to convert from point cloud data to any required format proves extremely useful in doing what "CAD standards" and "collaboration software" have failed to do.

Manufacturing Knowledge Capture

It has already been noted that almost inevitably something is not documented (and gets messed up for awhile—in moving production from one location to another. Commonly, the 2-D print says one thing, the 3-D CAD another, the tool is slightly different and the final workaround is undocumented. Today's global outsourcing model is based on moving production frequently, so the potential for problems is obvious.

DSSP provides a tool to carefully document what is really happening and to get processes under full dimensional control. Even better, companies with processes optimized and under control might even feel less inclined to move manufacturing to other locations.

Protection of Intellectual Property

If scanning vendors had an NRA (national reverse engineering association), their slogan might be "scanners don't steal, people do." Certainly, scanning has helped enable design theft in some cases. What used to be a problem for a few products, such as Rolex watches, now includes most fashion items, Nike shoes, Makita® power tools, Honda motorcycles and even car designs in a recent GM case.

However, the technology can also work to protect intellectual property for those who take time to address the issues. Rather than outsource a complete product, one emerging best practice is to break the product down into subassemblies, farm the work out to different suppliers and perform assembly closer to the customer. That way, no single supplier has access to the entire design. There can be additional synergies when some element of the final product is mass customized. To make up a hypothetical original NRA example, the receiver of a rifle might come from one supplier, a variety of barrels might come from other suppliers and a custom grip might be shape sampled and fabricated for customers wanting the ultimate product. In this kind of scenario, the OEM retains both the customer relationship and greater control of the supply chain.

We may even see scanning used as a tool to help prosecute IP theft. As newly industrializing countries develop their own design and engineering capabilities, they are moving from giving lip service to patent and copyright protection to real enforcement. With software theft, companies look for bits of unchanged code. With design theft, this author would not be surprised to see scanned comparisons and deviation maps of the original and infringed products admitted as evidence at trial. Innovative purchasing managers and lawyers might even write supplier contracts with penalties for any infringed products, shifting some of the responsibility for IP protection to suppliers. DSSP would be a tool to enforce those contracts.

If the product design has not changed in decades, there is customer demand and the product can be built and shipped in cargo container lots—then clones are almost inevitable. Milwaukee Electric Tools, the former U.S. maker of power tools, became a target of low-cost clones selling at about one-fifth the price (*Figure 8*). The Milwaukee® tool designs, while proven, had remained relatively unchanged for decades. There was not enough "worth more" in the better bearings, motors and switches of the original compared to the clone for many customers. So, it should not have been a surprise that Milwaukee (along with AEG) was acquired by TTI, a Hong Kong based supplier. Hopefully, the new owners will manage the balance between differentiation and cost-competitive operations needed in a clone-prone industry.

The ultimate protection against design theft is to simultaneously present a moving target while continually improving quality and lowering costs. DSSP provides companies with a tool to capture their own heritage, refresh the design and stay ahead of the pirates.

Figure 8. Many companies are battling low-cost clones. This Milwaukee Electric Tools (Brookfield, Wisc.) right-angle drill and its near-clone (upper picture) are an example.

PRODUCT SUPPORT—EXTENDED LIFE (AND PROFITS) FROM EXISTING PRODUCTS

A quiet revolution is under way in product support. Companies and entrepreneurs that understand it can profit.

As recently as 15 or 20 years ago, there were a large number of repair shops for small appliances, TVs, typewriters and computers. More recently, products have been designed to be thrown away rather than repaired. That trend is now reversing in a surprisingly large number of product categories.

Makers of expensive commercial equipment, such as machine tools, construction equipment and farm tractors, have always paid attention to sales and support of used equipment. Companies like Caterpillar and Deere knew that their best customers would buy the most productive new equipment every few years—but only if they could get a good price for their used equipment. They also knew that a day's downtime during construction or a harvest meant big losses for their customers. So these businesses worked hard at offering legendary support and managed their own used equipment markets. Interestingly, companies such as Caterpillar have also come out of the recent recession in good financial shape.

Several things have changed to make a longer view to customer satisfaction relevant for other product categories. Among these changes:

- Recognition of the life cycle costs of product disposal (environmental contamination, dump sites that are full).
- Countries mandating end-of-life recycling programs.
- Nostalgia for the "good old days" in many product categories—from Airstream™ trailers to cars, sturdy U.S.-made power tools, KitchenAid® mixers and classic Bell telephones.
- The Web and services such as eBay® are making it possible to track down parts and accessories for most anything from classic cars to Barbie® dolls.
- Less disposable income in recent recessions and moderate growth prospects in the years ahead.
- Less satisfaction with products that become obsolete in a few years and crowd attics, closets, basements and garages because the dump does not want them.
- A possible move toward "voluntary simplicity" and less materialism, as witnessed in several recent best-selling books.
- A "do-it-yourself" ethic in everything from home remodeling to custom cars and motor-

cycles, as witnessed by many of cable TV's most-watched shows.

- Higher profits in services. From small to large businesses (IBM Global Services or General Electric in aircraft engines), the old "give the razor away at cost and sell the blades" model is being updated with services being the "blade."

Both consumers and businesses are becoming more conscious of what items they intend to buy and throw away, and those items, typically ones that matter more to them, they hope to maintain for many years to come. There are still profits in disposable categories, such as consumer electronics and BIC® pens. However, many disposable items have become commodities with low margins and low customer loyalty. The profits are increasingly used to support the products that customers care about over a complete cycle of use. There are several ways that DSSP enters this picture, as follows:

Spare Parts and Service Items

There are literally hundreds, perhaps thousands, of product categories where customers want spare parts and service items, patents and copyrights have expired and original engineering models or tooling no longer exist.

In some cases, entrepreneurs are starting up small businesses and watching them grow to $10 million or so in size. In other cases, the OEM recognizes the profit potential in its own installed base. One privately held manufacturer of commercial food processing equipment earns 60% of its profits from spare parts. Thus, companies with loyal customers and many units in the field might consider investing in scanning before another seat of CAD.

The availability of low-cost sources for casting, molding and other processes is a boon. Decide which parts are worth a run of a few hundred or thousand, scan one, possibly improve the design, send the job out for bid, use the Web as the channel and earn the gratitude and money of a loyal cadre of customers.

Modern Upgrades

In many cases there is nothing wrong with the basic structure of a product (think homes, machine tools, old tractors, BMWs, Porsches and so on). Rather, it is something more mundane as the controls, electronics or cup holders that need an update. Scanning technology is the ideal tool to capture the available space and design an upgrade.

Design of Entirely New Products, Built Around a Life Cycle Support Model

Given the trends above, it should not be a surprise that many best-selling cars evoke something from the past. This Blue Book has already discussed the role of scanning in capturing iconic forms and updating them for maximum customer appeal.

The next step might be to figure out what components of a vehicle are likely to remain state of the art and which are likely to require updates. To use one example, the BMW 5 Series car ("E39" body) from the mid-1990s to 2003 is considered a classic by many owners. Today, the ride and handling are still top-notch. But many electronic items that are just a few years old, such as integrated cell phones that cost thousands of dollars or cassette and CD players made obsolete by MP3 players, are a source of frustration for owners. The latest generation of BMW vehicles, with an even greater integration of electronics, are at an even greater risk of becoming problematic over the years.

Perhaps stable and proven design elements (mostly mechanical) should have clean interfaces to the more rapidly changing and at-risk (mostly electronic) elements. Owners of classically designed cars, for example, would likely be delighted to pay $995 for plug-ins of updated electronic systems. Auto companies might even open up their architecture to third parties, many of which are already thriving in audio and performance-tuning aftermarkets. This same principle of designing products for upgrades throughout their life cycle applies to everything from high-tech appliances to personal electronics and smart homes.

Smart companies will increasingly create and profit from their own aftermarkets. DSSP will be as important as CAD in such an environment.

CAPTURING THE USER'S ENVIRONMENT

The environment most designers and engineers work in is a computer screen. The environment where the product will be used is rarely captured "on screen."

Losing track of the user's environment is among the top causes of failed products. Here are two examples: automotive production machinery that meets capability requirements but will not fit the intended assembly line, and computer servers with great features that would not fit through the doors of their intended customers. Problems in fitting the existing environment are not the exception in some industries—they are the norm. For example, commercial air conditioners now require more space to do the same amount of cooling because higher efficiencies are demanded from less-efficient but more environmentally friendly refrigerants. Something has to give, and it is usually increasing the size of the heat exchanger. If the old unit was a tight fit, the new unit may require a (mass) customized heat exchanger.

For a wide variety of products, the first step in design is mapping the user's environment. Architects start with a site plan. Kitchen remodelers start with dimensions. Tailors start with measurements. When this step is skipped, problems arise and opportunities are lost. We are probably just a few years away from total product and service offerings (beyond today's medical prostheses) where the first step is to always to scan the product environment. This can already be seen with terrestrial scanners at many construction jobs. DSSP is already good enough, though still a bit too expensive and packaged too clumsily for convenient field use, to make this the standard approach for everything from landscape design to custom furniture design.

Forensic Engineering

At the time of this writing, CBS's "CSI" (Crime Scene Investigators) is Nielsen's top-rated TV show. "CSI Miami" is fourth. Apparently, people just love figuring out why things went bad—and who to blame. DSSP is becoming a major player in this arena and is being used increasingly to document and reproduce crime scenes. Perhaps the ultimate end-of-life issue in product support is figuring out what went wrong (and who to blame) for product failures.

Scanning is also employed to sample the geometry of failed parts, make comparisons and the like. The case was made earlier in the Tolerance Design section that pre-production analysis of the design and process was the way to avoid problems later. So, the forensic applications for scanning become a bit like "if you don't pay to avoid failures, you can always watch lawyers use the technology to have you pay later."

There are many other applications where capturing shape can become part of a profitable business model, from marketing through customer support. Many of these applications are important enough to have their own category.

SCENARIOS OF USE WHERE PHYSICAL PRODUCTS AND DIGITAL SERVICES INTERSECT

We are entering an age where Web logs are replacing diaries, where video games and digitally produced movies are among the fastest-growing forms of play and entertainment and physical libraries are moving to the Web.

The first place many people turn for information is the Web. Physical stores are giving way to online stores, such as *Amazon.com* and *Cars/Furniture/Etc.com*. The market values of companies such as Google™ and Yahoo!®, which do not produce any products, are now substantially greater than companies such as General Motors. Rather than mail catalogs or provide missing copies of user manuals, many companies make them available online. Attendance at local user groups and some associations is declining, despite a real need for human contact, while some online forums are growing. Training and product support are increasingly online.

Sharp executives are now asking themselves what parts of today's product design, building, selling, buying, owning, using and supporting cycle can and should go digital.

How much of our personal and professional lives can be captured and conducted digitally? One way to get at this is to ask what parts of our personal or professional lives might survive if, say, a fire wiped out everything we physically owned, except the backups. Can a life or a business be backed up? It turns out the digitization of our lives has gone quite a bit beyond having good records for insurance replacement purposes. Today, we are using mostly text documents, databases and 2-D pictures and representations as the dominant ways of capturing personal and business interactions.

Where does DSSP fit in all this? Richer media, such as dimensionally measurable 3-D shapes, are gradually replacing lesser-quality media as costs decline and bandwidth increases. It is a bit like how color TV displaced black-and-white TV. At first, it is not economically feasible. Then, skeptics ask who needs color, who needs 3-D? Then, most everyone wants it. The same is happening with 3-D in games, online furniture stores, user manuals and more.

Nine areas where digital services with 3-D content are displacing physically based business processes:

1. Online customer and market research versus traditional focus groups.
2. Virtual meetings versus travel, occasionally augmented with 3-D visualizations. As an example, physicians are already performing remote diagnostics from visualizations.
3. A whole new class of "you-are-here" applications where users locate their precise positions within a mapped or scanned or modeled space. We are using GPS and maps for the big picture. Tools such as image-guided surgery (using an LED scanner in the case of the Boulder Innovation Group) are handling near space. The you-are-here principle applies to everything from oil exploration to service instructions for copier repair folks.
4. Online training—often augmented with 3-D models.
5. Digital product models and tooling coupled with just-in-time manufacturing to replace physical inventory.
6. Games with life forms, such as avatars, are scanned and adapted from models or real people.
7. Virtual reality systems for immersive walk-throughs, training and so on.
8. Before and after assessments from forensics to reconstructive surgery, to 3-D images showing what that next haircut or suit will look like.
9. Digital documentation, service support and troubleshooting made better by including interactive 3-D models.

To sum this up, we have covered more than 40 distinct applications for DSSP in seven main areas. One hundred years ago, photography might have been described as "2-D shape sampling." The cameras did the "2-D shape sampling" and the darkroom and subsequent printing and other applications did the "processing." During that time period, cameras were expensive. Photography was only fast in comparison to life-like painting. But, the technology quickly became the basis for new methods of printing, movies, X-ray recording and even semiconductor fabrication. Photography and all those applications are now going digital. DSSP takes photography into three dimensions, adds the ability to know (measure) precisely where every point is and also turns the digital model into forms usable in a variety of manufacturing and business applications.

RELATIONSHIP OF DSSP TO CAD

Computer-aided design (CAD) and computer-aided manufacturing (CAM) dominate engineering software investment decisions in many companies. This Blue Book makes the case that DSSP will increasingly become an equal partner in design, engineering and manufacturing. If CAD is important to you, chances are DSSP should be, too.

There is little question that scanning, reverse engineering and computer-aided inspection technologies have grown up in the shadow of CAD. Computer-aided design technology matured earlier. It was easier, computationally, to deal with parametrically defined surfaces than millions of unruly points in space.

Emerging DSSP applications have been trying to go along for the ride ever since. We hear about scanning as an alternative when CAD is not convenient, about converting point data to NURBS surfaces because that is what most CAD systems use, about driving CNC systems through the same protocols used by CAD and so on.

The case can be made that DSSP may eventually surpass its older brother, CAD. At the least, CAD and DSSP tools are complementary—each gains power when used in combination with the other.

Technology typically makes its greatest advance when it has dual methods of solving problems. Physics has wave and particle theory. Mechanical engineers solve dynamic problems in the time and frequency domains. Electronics work in analog and digital domains. Psychologists talk about thinking with the "left brain" and the "right brain." Management, though not quite a science, tries to solve problems from both top-down and bottom-up.

Dual representations are powerful. Problems that are difficult to solve when approached in one domain are often easy to solve in the other.

It turns out that some product development and manufacturing problems can best solved by simulation with computer models. Others are best solved by experimenting and capturing real results. Thus, a combination of the two approaches—in this case 3-D modeling and 3-D measurement—is more powerful than either alone. CAD deals with "to be," while DSSP captures "as is." With the appropriate processing software, we can move almost effortlessly back and forth between these two domains, using each where it works best.

The term "point domain" will be suggested here to include methods of measurement (including scanning) that start by locating points in space, and the term "surface domain" includes descriptions that build a model from lines, surfaces and stitched-together solids (*Figure 9*). Measurement devices and scanners start in the point domain. Here, we capture a sufficient (often large) number of points to characterize a shape. Conversely, most CAD systems work in the surface domain, mathematically describing bounding surfaces. Parallel developments in these two domains can be seen in *Table 2*.

The great advances with CAD came when we went from automating 2-D vector plots and 3-D wireframe design to 3-D surface modeling and 3-D solids. Now, even mid-range CAD systems are capable of rapidly modeling entire products, including fairly sophisticated shapes.

Digital sampling and processing in the "point domain" has undergone a similar evolution, though currently a step behind the adoption curve compared to CAD. For centuries, right through to the mid-1900s, the dominant means of inspection was a visual look combined with point-to-point measurement of selected dimensions using rulers, micrometers, height gages and similar measuring instruments. Coordinate measuring machines automated point-by-point measurements in 3-D space, which is about the equivalent of 3-D wireframe modeling on the

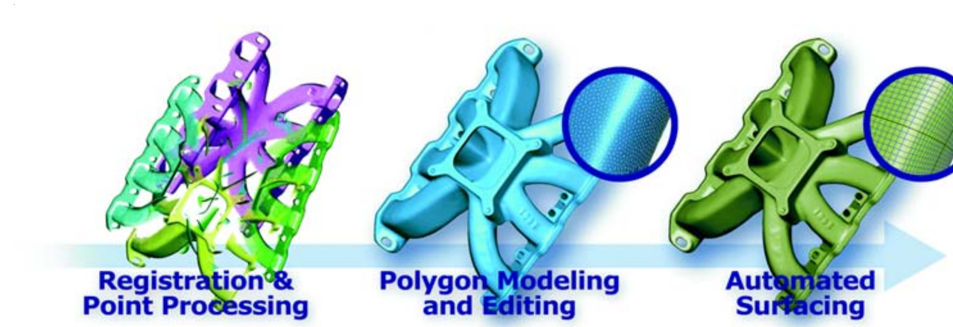

Figure 9. Processing software allows us to move seamlessly between the "point domain" and the "surface domain." Part of the art of design, engineering and manufacturing is knowing when to solve a problem through measurement (the point domain) and when to solve it through modeling.

Capturing shapes in the "point domain" (slow and incomplete to rapid and extensive point measurements)	Capturing shapes in the "surface domain" (crude-to-sophisticated geometric modeling)
Fingers, feet and forearms to measure	Paintings on cave walls
Build the pyramids square	Design the pyramids on papyrus
Early measurement standards	Plane geometry and the Greeks
Surveying	Perspective drawing
Precision ruling engines	Early photography
Surface plates and height gages	Mechanical drawing
Coordinate measuring machines	Analog plotters
2-D pixel-based vision systems	2-D CAD
Computer-automated CMM	3-D wireframe CAD
3-D scanners...	3-D surface-based CAD
	3-D solid modeling
	3-D able to handle complex assemblies

Table 2. Parallel developments in point domain and surface domain.

CAD side. Optical scanners are now able to “look” at an entire object and capture the precise locations of millions of points. DSSP technology is about where 3-D CAD was a decade ago. It is still expensive and not entirely user friendly, but it is good enough for a significant competitive advantage in the right hands (*Figure 10*).

DIGITAL MANUFACTURING CYCLE

The need to have DSSP as a complement to CAD is evidenced by a basic fact: practically zero percent of the known universe is presently modeled in 3-D CAD. Perhaps about one percent of our built world has valid 3-D CAD models, with a higher percent in the industrialized world. DSSP is for the other 99%, especially when we want to understand the interaction of freshly created geometry with the people, past products, emotional responses and boundary conditions of the world around it. Given its state of development and potential, it seems obvious that many companies are under-investing in DSSP.

COMMON-SENSE CRITERIA FOR SELECTION AND IMPLEMENTATION

Our experts were bullish on the new scanning technologies. They noted that the bad experiences of just a few years ago (shiny parts that would not scan, accuracy less than needed, millions of points that choked the software) had increasingly become success stories with the latest scanners and software. That said, they were also mindful of remaining limitations and cost barriers. For example, there are still relatively few economies of scale for hardware vendors, especially at the high end.

Benefits

The following 10 criteria distinguish applications with high paybacks for DSSP—a “yes” to two or more of these should suggest taking a closer look:

1. Product design and style is a significant part of the customer’s buying decision.

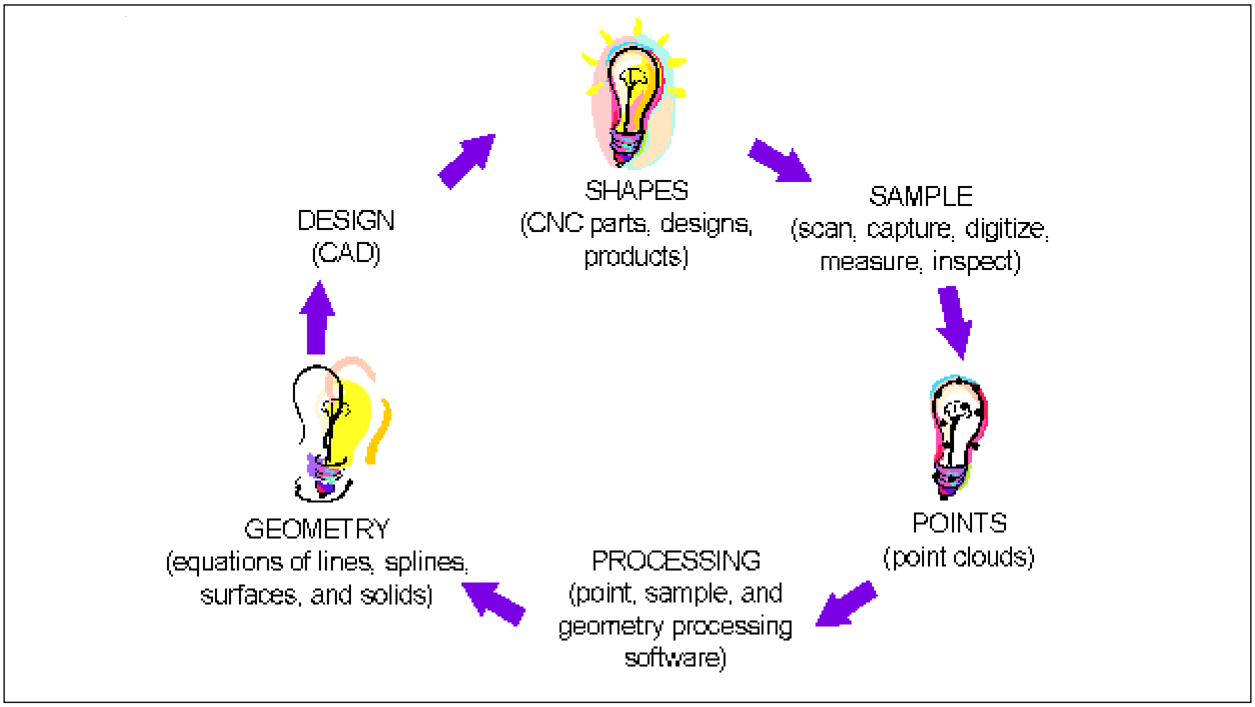

Figure 10. The greatest value of CAD and DSSP come when the technologies are used in closed-loop processes, using the methods of geometry representation for the problems they solve best.

2. The product has complex geometry or surfaces, a few simple measurements are not enough to characterize the component. Turbine blades, circuit breaker housings and the like are examples.
3. Non-rigid materials need to be inspected. Touching the part (or person) to make a measurement will alter the shape to be sampled.
4. There are differences between "as-designed" and "as-built" geometry due to the manufacturing process. Accounting for shrinkage, distortion, springback and so on typically requires at least two (prototype and production) tooling cycles.
5. There are significant risks, ranging from customer acceptance through efficiency and safety, if out-of-tolerance parts or products get into the field. It is not enough to control a handful of critical dimensions.
6. Product performance is affected by the shape. This includes anything from the physics of fluid flow to the aesthetics of car body design (*Figure 11*).
7. Separation of design and manufacturing functions requires clear communication of design intent and manufacturing compliance. This can be between functions within a company or between links in a long chain of OEM and supplier relationships.
8. There is an opportunity to differentiate the product by customizing the shape to the customer's needs and manufacturing it in a reasonably speedy and cost-effective digitally driven process.
9. There is an opportunity to earn higher profits from service parts and upgrades, where the original geometry has not been 100% captured in 3-D CAD.
10. One or more business processes that currently rely on physical media, sales calls, classrooms, inventory, repair calls and so on could be replaced by digital variants.

Getting Started

Following are seven thoughts on getting started:

1. Start with a clear business objective in mind, perhaps from one of the seven main application areas discussed here. Is the objective to design great products? If the "make or buy" decision is to "make," what will it take to optimize our manufacturing process? If the decision is to "buy," how will we hold our suppliers to the needed standard of quality while protecting our designs?
2. Have informal conversations with the executive or executives who will ultimately be responsible for approving any investment later on. Explain the potential, but also the uncertainties, with this technology. Get their take on the business priorities and promise to get back with a good analysis of the situation. Make this a shared venture.
3. Consider testing your ideas with a service bureau that has experience with your application. This gives a better shot at getting good results the first time and leverages their experience. It also helps sort out the many choices in hardware and software should you decide to bring the technology inside later. A good service bureau will continue to be valuable even if you later decide to bring the technology inside.
4. Resist the normal temptation to buy a scanner first and consider software later, unless you have a trivial application where a turnkey offering is affordable and proven. Check references. Starting an acquisition process with software vendors rather than scanner vendors has six advantages, as follows:
   - It is easier to narrow the field to a top two or three. There are a few top-tier software vendors compared to dozens of competent hardware vendors.
   - The bottleneck in most digital shape sampling processes is typically software to make sense of the point cloud data, not the speed of acquisition.
   - A software vendor with experience in your application area is likely to be an expert and neutral source on the pros and cons of various scanners. They do not have a vested interest in what hardware you buy, only that it works.
   - The investment in standard software helps you make better use of the $30-$300,000 or so that might be invested in scanning hardware.
   - If your application requires customization to solve difficult problems or to scale up a process, most of the work will be on the software side.
   - Working with a software-only vendor makes it easier to move to a better scanning technology at a time when the hardware is rapidly changing. You want to focus the investment

Figure 11. The ProDrive Ferrari team uses DSSP and CFD (computational fluid dynamics) to optimize aerodynamics. Image courtesy of 3D Scanners (London).

on a better process, not the hardware du jour. The best processes for converting point clouds to usable forms are likely to be relatively stable compared to the best hardware technology to capture those points.

After you have gained experience, acquire productive scanning hardware. Realize that the technology is moving quickly. You want either a killer application (and there are several) or a productive application that will keep the equipment busy. You may want to strike up an arrangement with a service bureau. Some companies have even invested in the equivalent of time shares. You may also want to talk to other functions in your company. The same DSSP hardware and software can often be used by several groups. Over time, the cost of scanning equipment will come down. Until then, you want to maximize the use of equipment that may quickly become obsolete. The good news is that very rapid return on investment and a true competitive edge is possible. Focus on the upside, while maximizing use of the hardware.

Engage your people in a quest to better serve customers and improve your business. Invest in education. Be creative in developing better processes and overcoming resistance to change.

If a significant investment is contemplated, consider involving one of your company's finance officers early in your investigation to help shepherd your team through the justification process. You might also want to visit *Amazon.com* and get a copy of this author's book, "Aligning Technology for Best Business Results." The basic suggestions for the selection, justification and implementation of design and manufacturing technologies still hold.

CAPTURING A COMPETITIVE EDGE

DSSP technologies are a double-edged sword. Cutting one way, they have made it easier to capture the geometry of a product and create a clone or derivative design.

Cutting the other way, these technologies give companies a powerful tool to differentiate their products, optimize their manufacturing processes, streamline supplier relations and create new and more profitable business processes. This Blue Book lists more than 40 applications for DSSP. One or more of these may be worth millions to your customers and your company.

As an aside, several of the expert roundtable participants for this Blue Book asked that specific details of their DSSP applications not be shared. The successes, however, speak for themselves: circuit breakers, for example, that meet the highest standards of reliability for just a little more than a clone; or turbine blades whose value proposition includes "too complicated for anyone to blindly reverse engineer" and "so much more fuel efficient and reliable you'd be crazy to choose anything else."

Companies that want to thrive need to be great at design or manufacturing and preferably both. Increasingly, that means paying attention to the applications for DSSP in competitive manufacturing.

ACKNOWLEDGMENTS

This is an interesting field, with interesting people—several of whom contributed to this Blue Book. The author would like to thank the participants of the day-long discussion of DSSP technology and manufacturing and inspection applications—very sharp folks. They included John Jarvela and Nalin Patel of Product Development Technologies, Charles Furr of Howmet Castings and Rus Emerick and Randy Siebels of Square D/Schneider Electric. Todd Grimm of T.A. Grimm & Associates was instrumental in both suggesting this Blue Book and providing a thorough and insightful review. Vendor discussions at the CMSC 2004 conference and exhibit helped fill in my sampling technologies chart. Thanks to Ping Fu of Geomagic who provided a wide range of real-world application examples and is pioneering the field of DSSP. Numerous others provided ideas along the way. Michael Raphael of Direct Dimensions, for example, had ideas for DSSP applications beyond even the seven key areas noted here. Industry experts Marty Schuster, Eyal Mizrahi, Marc Bisson and Peter Champ were generous with their time in phone interviews. Thank you, all.

APPENDIX:
ADDITIONAL RESOURCES

- **Society of Manufacturing Engineers**
  www.sme.org/cgi-bin/communities.pl?/communities/techgroups/capture/capture_hp.htm&&&SME&

- **3D Scanners Report**
  www.geomagic.com/support/resources/3scannersA.pdf

- **Wohlers Associates (strong on rapid prototyping, some DSSP links)**
  www.wohlersassociates.com/3D-Digitizing-and-Reverse-Engineering.html

- **Tenlinks.com**
  www.tenlinks.com/Technology/Computers/HARDWARE/INPUT/3D_DIGIT.HTM

- **Dmitri Papadopoulos' Links**
  http://dpo.club.fr/numerisation3d/index.html

- **Simple 3D**
  www.simple3d.com

- **Computer Graphics World**
  http://cgw.pennnet.com/Articles/article_Display.cfm?Section=Archives&Subsection=Display&ARTICLE_ID=74764&KEYWORD=3d%20scanners

- **3-D Photography Web Sites**
  www.stat.washington.edu/wxs/3D-photography-websites.htm

- **Castle Island Reverse Engineering Directory**
  http://home.att.net/~castleisland/scn3_lks.htm#led

- **Jerry Isdale's VR Links (an older scanner-related link list)**
  http://vr.isdale.com/