Selective Laser Sintering, Birth of an Industry

From left to right: Carl Deckard, Joe Beaman, and Paul Forderhase photographed November 19, 2012. The image in the background is of selective laser sintered miniature University of Texas towers before removal from the powder bed.

AUSTIN, TEXAS—December 7, 2012

By Alex Lou & Carol Grosvenor from interviews with Dr. Carl Deckard, Dr. Joe Beaman, and Dr. Dave Bourell. Special thanks to Tim O'Meara, Paul Forderhase, Dr. Paul McClure, Rick Booth, Matthew Haggerty, Dr. Hans Mark, Ross F. Housholder, and Kent Firestone for additional information.

Note: In this article, ***links in bold type*** *are two-way links between important terms and their respective entries in the appendices or glossary. All other links redirect to external web pages.*

This is the story of the birth of an industry that began here in the 1980s. A mechanical engineering undergraduate, with an idea hatched while working a summer job, asked for the help of a young and hungry assistant professor, who managed to get the project funded. Soon enthusiastic, powerful and hardworking people defended its potential, and with a few strokes of luck, and a lot of just plain hard work, developed a manufacturing technology that spawned the additive manufacturing industry.

If a few things had been different—an early math error not caught, a pending patent not defended, another patent not purchased, a corporate partnership not established, it wouldn't have happened. The ME department, the Regents from The University of Texas at Austin, the Austin Technology Incubator, and National Science Foundation backed the idea from the beginning, and the resulting business became the first student/faculty-owned entrepreneurial enterprise spun out from the university. It served as an initial example of the research-to-corporate link that continues to fuel the American economy.

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Selective laser sintering (SLS) is a modern manufacturing technology that was created in the 1980s at The University of Texas at Austin's Mechanical Engineering Department (UT ME). Originally developed by an undergraduate and later master's and Ph.D. student of the department, SLS has grown to be one of the world's most advanced and promising manufacturing methods in use today. The SLS patents were the highest revenue generating intellectual property of UT Austin for many years and, although the original patents will soon expire, UT has continued to be highly involved with the development of the technology since the beginning.

1. The Early Years: 1981-1986

The story of SLS begins with a UT undergraduate named **Carl Deckard** (LinkedIn profile). Born in 1961 to two parents with Ph.D.'s and having doctors and lawyers for grandparents, Deckard was the product of both a very well educated family and the scientific boom of the Space Race. Although first wanting to be a scientist, after visiting the Henry Ford Museum around age 8 Deckard decided he wanted to be an inventor. When time came for Deckard to choose a college degree program, he chose mechanical engineering because it was, as he describes it, "the closest thing to majoring in inventing."

Dr. Carl Deckard

The summer of 1981, after his freshman year of college, Deckard worked for **TRW Mission**, a machine-shop-based manufacturing facility in Houston that made parts for the oil fields. 3D **computer-aided design (CAD)** was still fairly new and TRW was on the cutting edge by using 3D CAD in programs that controlled machine tools. However, many of the raw parts started out as castings, and the shapes of those castings came from handcrafted casting patterns. During his time at TRW Mission, Deckard saw that there would be a big market for an automated method for creating casting patterns out of CAD models. He spent the next two and a half years thinking about how to develop such a method.

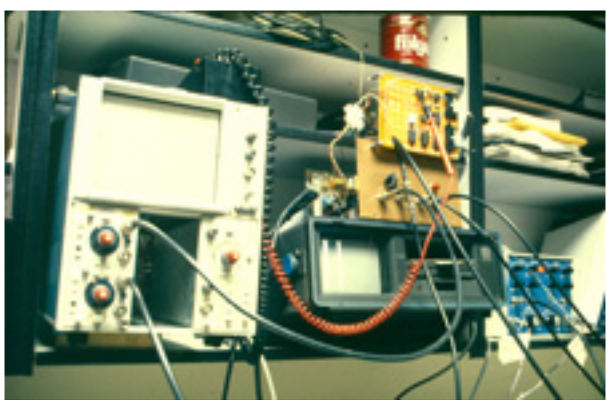
By the end of his senior year in 1984, Deckard had come up with the idea of using a directed energy beam (such as a laser or electron beam) to melt particles of powder together to make a part. Realizing he had more than just another of his previous thought experiments and in need of a graduate school project, Deckard approached one of his professors, **Dr. Joe Beaman**, then a young assistant professor who saw value in the idea. Beaman agreed to work with Deckard on the project and took him in as a master's student later that year.

Dr. Joe Beaman

At the time that Deckard was transitioning into graduate school, the UT ME Department was moving to a new building and had a budget to spend on new equipment. The window of time to request money was closing, so Beaman had Deckard spend his first semester of graduate school specifying the equipment he would need to begin working on his project. Deckard specified a 2-watt laser and a fast scanner and came up with a budget of $30,000, but something seemed wrong. He kept looking over his calculations trying to find an error, but all of his calculations were correct. It wasn't until after submitting his $30,000 budget request that Deckard finally realized he had incorrectly copied a physical constant from one page to the next, off by three orders of magnitude, which led him to think he needed a much smaller laser than he actually did. Fortunately, the correct laser was still within his budget, so Deckard ordered the right one: a 100 watt **YAG laser**.

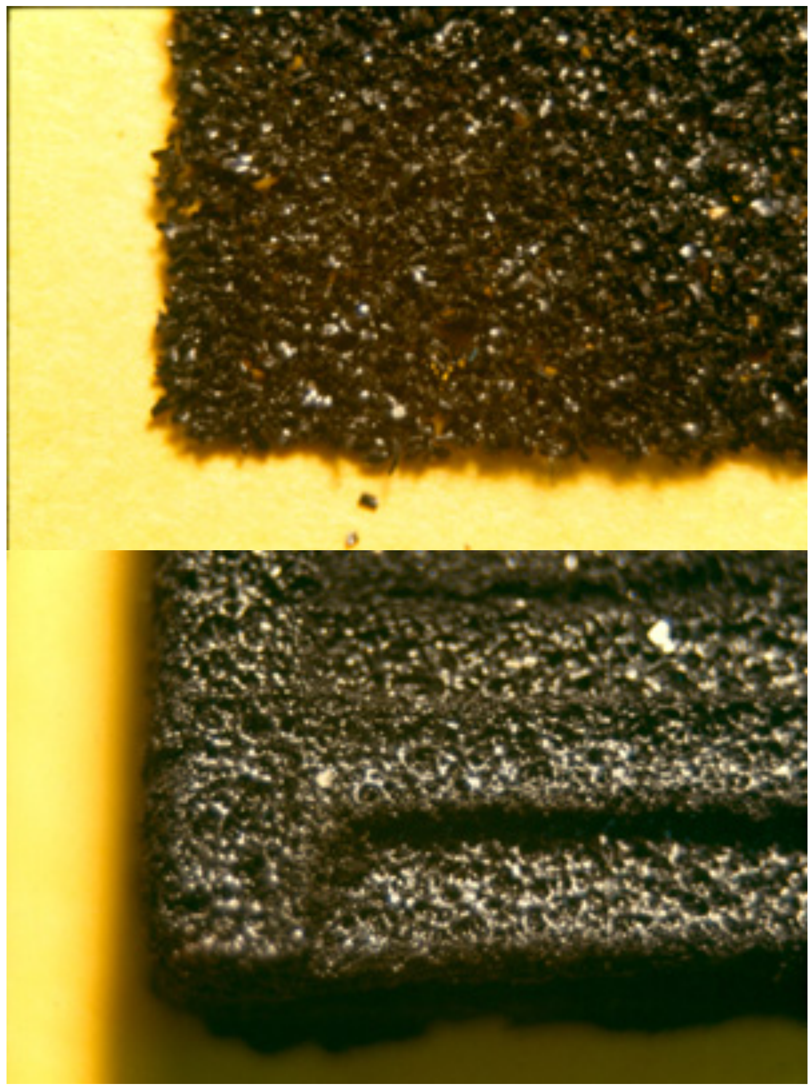
Betsy: An Evolutionary Academic Machine

While waiting for more equipment, Deckard figured out a way to regulate the laser with a computer. He used a **Commodore 64** computer and made a custom board to control it, with all the hand-assembled programming able to fit into 4KB. Once he had established good enough parameters that the parts were strong enough to handle, he brought a part to Beaman who told him to write it up for his master's degree.



Instrumentation for the Betsy machine: an oscilloscope, Deckard's custom board, a Commodore 64, and scanner drivers.

After completing his master's in 1986, Deckard

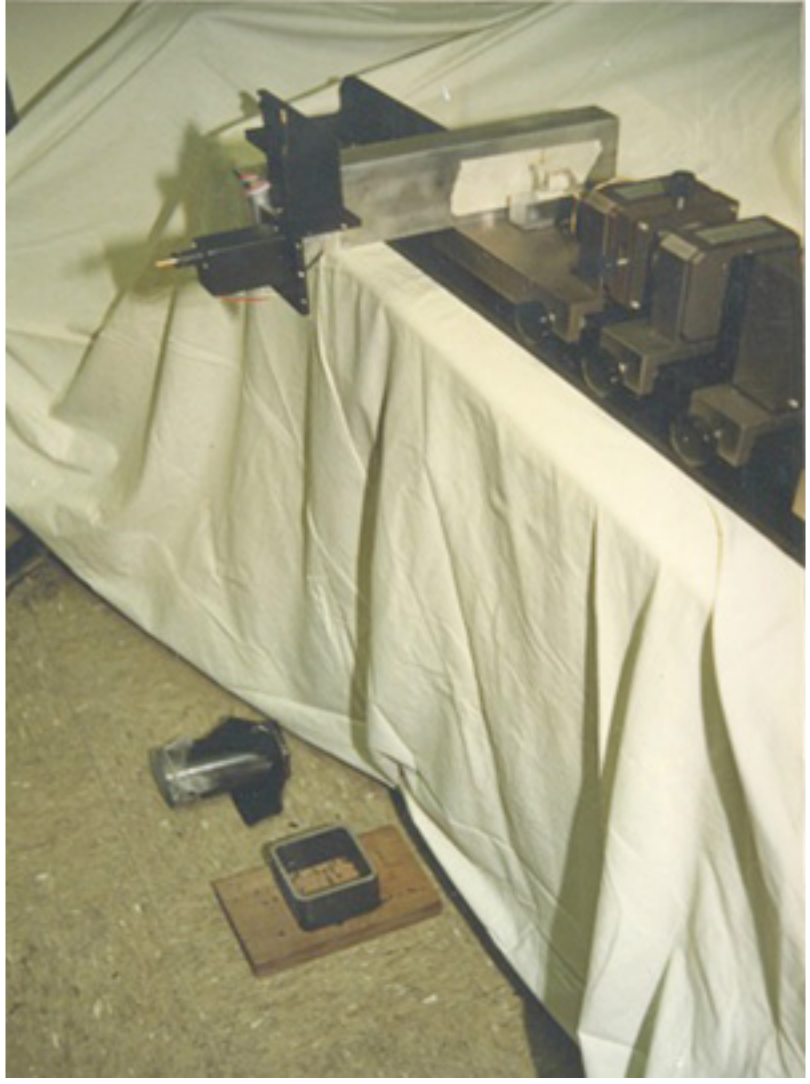


Close ups of the first plastic powder Deckard used in his SLS project before (top) and after (bottom) the sintering process.

From 1986-89, academic and commercial progress were going on concurrently. Deckard was involved in both ventures. From 1990-92, Joe Beaman took a leave of absence from the university to head up of Advanced Development for Nova Automation/DTM.

decided to stay at UT as a Ph.D. student to continue working on the project. He and Dr. Beaman, who was the Principal Investigator (PI), received a $30,000 grant from the **National Science Foundation (NSF)** to advance the technology, building another academic machine nicknamed "**Betsy**." They improved the system by enclosing it in an electrical box and adding a counter-rotating roller for more even powder deposition, which Deckard had previously been controlling by hand using a device similar to a saltshaker. By this point, the parts coming out of Deckard's machine were good enough to use as casting patterns for real parts.

One of the intermediate parts that Deckard created with Betsy once he had begun improving the scan parameters of his machine.



The early stages of the SLS machine that would later be called Betsy. Deckard filled a small box with powder by hand using a device similar to a salt shaker while a computer ran the scanner on the table. The first parts that came out of this machine were just chunks of plastic to demonstrate that the idea had validity, such as the one shown to the left.

2. Nova Automation: 1986-1989

With the SLS process showing improvement, it was time to pair up with a private corporation to continue improving the technology. In October 1986, **Dr. Paul F. McClure** (LinkedIn profile), then an Assistant Dean of Engineering and occasional adjunct professor, and **Harold Blair**, an Austin business owner, approached Deckard about commercializing the technology. The UT research team formed the first SLS company named **Nova Automation** after Blair's existing company, **Nova Graphics Intl. Corp.** Although Deckard originally estimated that they would only need $75,000 to start their company, Beaman doubled the number to $150,000, and McClure doubled the number again to $300,000. UT agreed with that figure and licensed Nova Automation to commercially develop SLS under the condition that they raise $300,000 by the end of 1988.

'Revolutionary'

Machine makes 3-D objects from drawings

By Kathleen Sullivan
American-Statesman Staff

Wedged into the corner of an unused photo lab at the University of Texas is an ungainly machine that can transform a computer drawing into a three-dimensional model at the touch of a button.

Sometime next year, the machine, which was developed by a UT graduate student, will make its way out of the lab and into the commercial arena. It will leave with the blessing of the UT Board of Regents, which Thursday gave an Austin company exclusive licensing rights to the "revolutionary" new technology embodied in the machine.

The licensing pact paves the way for the first transfer of technology from the University of Texas at Austin to a commercial venture.

The company that won the right to market the invention is Nova Automation Corp., whose principal shareholders are an Austin consulting engineer and Nova Graphics International Corp., an Austin-based computer graphics software firm.

The agreement represents a "hard fought" victory for UT's fledgling Center for Technology Development and Transfer, said Meg Wilson, coordinator of the center, which was given life during the last Texas Legislature and got

See Inventor, A11

Staff photo by Ralph Barrera

Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

A 1987 news clipping from the Austin American-Statesman newspaper describing Nova Automation and their "revolutionary" new technology. Pictured are Carl Deckard (left) and Joe Beaman (right).

1986- 1989, Academic and Commercial Activities

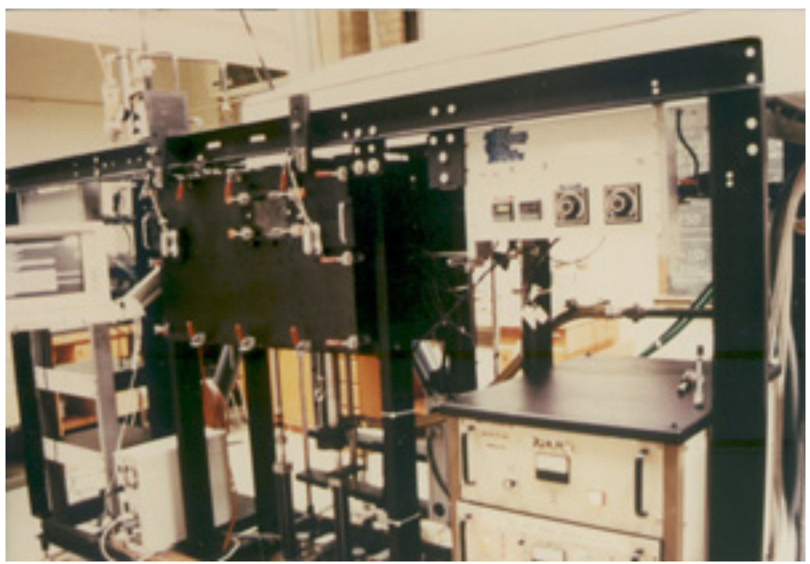
Academic Timeline	Commercial Timeline
May 1986, Deckard receives master's	End of 1986, Deckard meets Blair and McClure and form Nova Automation
October 1986, Deckard filed first patent	End of 1987, License is signed
1987, Deckard develops Betsy machine and shows it to potential investors	End of 1988, sets up financial arrangement with Goodrich
December 1988, Deckard completes his Ph.D. using the Betsy machine	First part of 1989, UT gives them a 3-month extension to secure funding
1989, Deckard, now a post-doc, works with Paul Forderhase to design, complete, use and test Bambi	February 27, 1989, Nova Automation becomes DTM. DTM designs and builds Mod A and Mod B.

Godzilla: The Machine That Was Never Built

Going into 1987 with their license signed, Nova Automation began trying to raise money for their new business. Meanwhile on campus, Deckard and **Paul Forderhase**, another graduate student of Joe Beaman, were designing a second machine which later earned the nickname "**Godzilla**" for its design. In order to meet the decided temperature and pressure requirements, which in hindsight were too much for its time, Godzilla would have been much too big, heavy and expensive to economically produce — it would have taken $50,000 and over 6 months just to build the pressure vessel alone. Godzilla was never built, and the design team went back to the drawing board. Deckard instead used the Betsy machine to generate the data for his Ph.D., which he received in December 1988.

Bambi: The Second Academic Machine

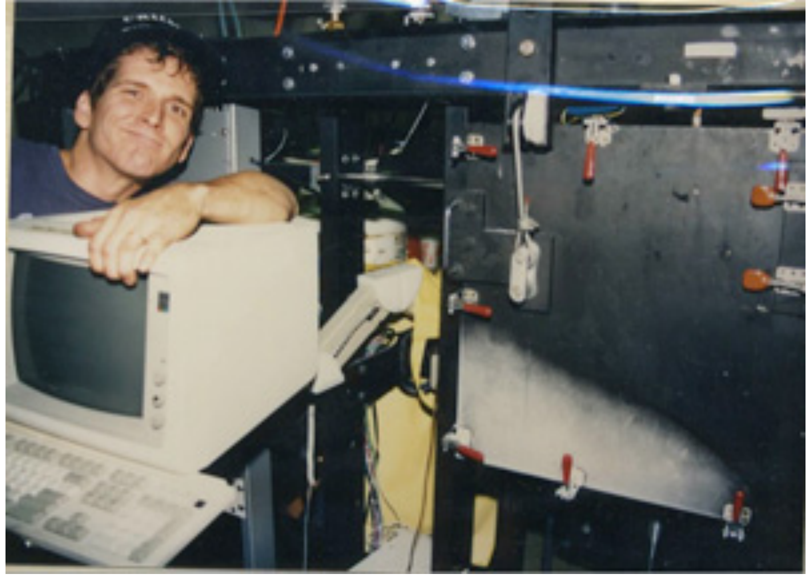
After abandoning the Godzilla design, the UT team decided to ease up on their requirements and spent the rest of 1987 designing a third machine named "**Bambi**," a reference to the short film titled Bambi Meets Godzilla. 1988 was spent building the machine itself, which was designed and supervised by Forderhase with integrated CAD software (nicknamed "Stanley CAD") written by **Stanley Ogrydziak**, a graduate student under the supervision of **Dr. Rich Crawford**.



Another UT ME professor, **Dave Bourell**, got involved at this time because of his knowledge of laser technology and materials science. Although not an expert in laser technology at the time, he had recently done a project for **International Business Machines Corp. (IBM)** involving lasers in their packaging effort and was already well versed in materials science. While Bourell worked with the metals and general materials, UT Chemical Engineering professor **Joel Barlow** was working in polymer synthesis at the time. Although never employed directly at Nova Automation, Bourell or Barlow were both consulted by Nova Automation and their expertise used in further developing SLS.

Bambi stayed in service at UT for many years as a research and production machine while Nova Automation worked on improving the technology for commercial use.

A collection of plastic parts built with the Bambi machine, except for the far left part which was built with Betsy.



The Bambi machine and lead designer Paul Forderhase.

3. Ups and Downs for Nova Automation/DTM: 1988-1997

Nova Automation first looked into an investment from **E. I. du Pont de Nemours and Co. (DuPont)**, now the world's third largest chemical company, but the negotiator drove too hard a bargain for a deal to be made. They also spoke to **General Motors Corp. (GM)** and **Bill Masters**, owner of **Perception Systems, Inc.** (later **BPM Technology**, the driving company behind another additive manufacturing process called ballistic particle manufacturing) but neither of the deals went through. McClure did most of the fund-raising and traveled to Wall Street to look for more potential investors, but Nova Automation still couldn't find a partner company and the time on their fund-raising deadline was running out.

By the end of 1988, Nova Automation had formulated a tentative funding arrangement with chemicals and aerospace manufacturing giant **Goodrich Corp.** but required more time past the deadline to finalize the deal. Nova Automation obtained a three-month extension from UT, and in early 1989 they had finally gotten an investment. Around the same time, McClure became President of the company and it was renamed **DTM Corp.**, a reference to the term Desk Top Manufacturing (a term being used by the media at the time to describe the CAD-manufacturing process, analogous to the term "desktop printing" for 2D printing). McClure explained the name originally had another meaning, "Deckard, Texas, and McClure." They liked the fact that the name could mean two different things, but it never was officially an acronym for either phrase.

Dave Bonner, Vice President of Research at Goodrich at the time, was both a UT Distinguished Alumnus and on UT's Chemical Engineering Visiting Committee. His father, **Z.D. Bonner**, was both a professor and Chair of UT's Chemical Engineering Department. Although the Bonner family already had strong ties to UT which helped negotiate a deal, it was actually through Deckard that Goodrich got involved with Nova Automation. Deckard's friend **Rick Edwards** had sold a computer to his own father-in-law, who worked with Dave Bonner and had a contract from Goodrich to look for new technologies to invest in. Edwards introduced his father-in-law to Deckard, and after that the two companies became interested in a partnership.

Goodrich was generally a good match, but DTM still faced serious challenges. Beaman was still teaching at the time, and they had to run a startup with the constraints of a large company.

Rick Booth worked at DTM as a chemist during the early years of the company. He later moved to Advanced Laser Materials and currently serves as vice-president. Photographed August 6, 2012 at the Solid Freeform Fabrication Symposium, Austin, Texas.

DTM grew to a large number of employees and engineers in years following Autofact '89. Others involved in DTM were **Rick Booth**, a chemist who now serves as Vice President of Advanced Laser Materials, and **Kent Firestone**, a former project manager at DTM and now Operations Manager for Solid Concepts in Austin.

Other Contributions

In 1989, **George Kozmesky**, Dean of the College of Business Administration (now the McCombs School of Business) and founder of Teledyne and IC^2, had established the **Austin Technology Incubator (ATI)** with an association to the university. DTM was one of two original members of the incubator, which has since helped over 200 companies raise over $750M dollars. This gave them a higher profile and access to business leadership.

DTM's placard from the Austin Technology Incubator.

McClure credits **Hans Mark** (then Chancellor of UT System and also an Aerospace Engineering professor) with promoting and supporting their fledgling business to UT System, thus allowing UT System to make the substantial commitment to protecting the intellectual property. He acknowledges former UT System attorney **Dudley Dobie** for making a crucial early decision to fight for Deckard's original patent when another patent for layered object manufacturing threatened Deckard's.

Paul McClure was instrumental in securing the initial contact with Dave Bonner, which led to DTM's connection to Goodrich and $6M in funding. DTM was the first student/faculty-owned entrepreneurial spin-off from the university, as a law allowing this had been enacted only one year earlier by the state legislature. While working at the Dean's office in the College of Engineering, McClure had heard about the NSF's Small Business Innovation Research (SBIR) Program. He wrote the grant proposal and secured the first $50,000 that allowed them to start their company. **Ritchie Coryell**, a Program Manager at NSF and one of the pioneers who created the SBIR program, took a personal interest in DTM and visited with Paul McClure and the start-up team in Austin. The grant was to be followed up later by a second $250,000 grant, but it was specifically for small businesses. By the time the second grant was to be awarded, DTM had become a subsidiary of Goodrich and could not accept it. DTM was held up as a model by both the university and NSF as how

McClure recalls that Dr. Mark would often come visit the graduate students working in the lab to check on their progress—not a common practice for a busy university chancellor.

Mod A, Mod B and the 125s: The First Commercial Machines

Once DTM had secured funding from Goodrich, they began designing their first commercial, off-campus product line. The first two of these machines were called **Mod A** and **Mod B**, and the rest were called **125s**. Only four 125 machines were built.

The design team for Mod A, the first of the 125 machines, was led by machinist **Jerry P.** of **GEMCITY Engineering and Manufacturing** in Dayton, Ohio. Jerry was not an engineer, but was a very talented machinist and designer who did all of his work by hand with a pencil and paper. **Tim O'Meara** served as sales executive for GEMCITY on the project, **Jim Darrah** wrote the software for the 125s, and **Dave Cutherell**, another graduate student of Beaman's, worked with Deckard and Beaman as lead engineer.

Given the rushed production of the Mod A, DTM didn't have time to make any parts with the new machine in time for Autofact. However, they were able bring some aluminum parts (shown above) for display at the trade show. These parts were made from casting patterns produced by Bambi, the previous SLS machine. The photograph is from DTM's booth at Autofact '89.

With work beginning in mid-1989, the Mod A was designed and built in a rush to be finished in time for the **Autofact** annual trade show in Detroit later that year. Although the rush and inadequate testing caused the machine to break down, the machine was completed and shipped in time for Autofact '89 and lasted until the last hour of the three-day trade show. The demonstration was a success, and soon after the first commercial sale was made to **Frank Zanner**, Principle Scientist at **Sandia National Laboratories**. **Clinton L. Atwood**, the project leader at Sandia working with the machine, used it primarily for a process known as **investment casting** where a wax model is used to create a cast for making metal parts.

1990, a Development Period

John Murchison took over as CEO and President of DTM in 1990 and maintained his position until the company was sold in 2001. Having previously held executive positions for the Pratt Group, Celanese, and Thyssen Bornimisa, Murchison was a seasoned manager and had experience working globally. 1990 was also the year DTM received their second round of funding from Goodrich and spent time acquiring more intellectual property materials, including a patent on laser sintering materials that became a foundation piece for the technology and has since been referenced in 160 patents to date.

During this period, DTM developed another machine called **Beta**. The design turned out to be overly complex and not the correct machine for the market at the time, and only a handful of the machines were ever sold.

Ross Housholder

When DTM was first started, there were so many possible patent categories to search that it wasn't until 1992 that DTM discovered US patent #4247508: Molding Process, a similar concept filed in 1979 by **Ross Housholder**

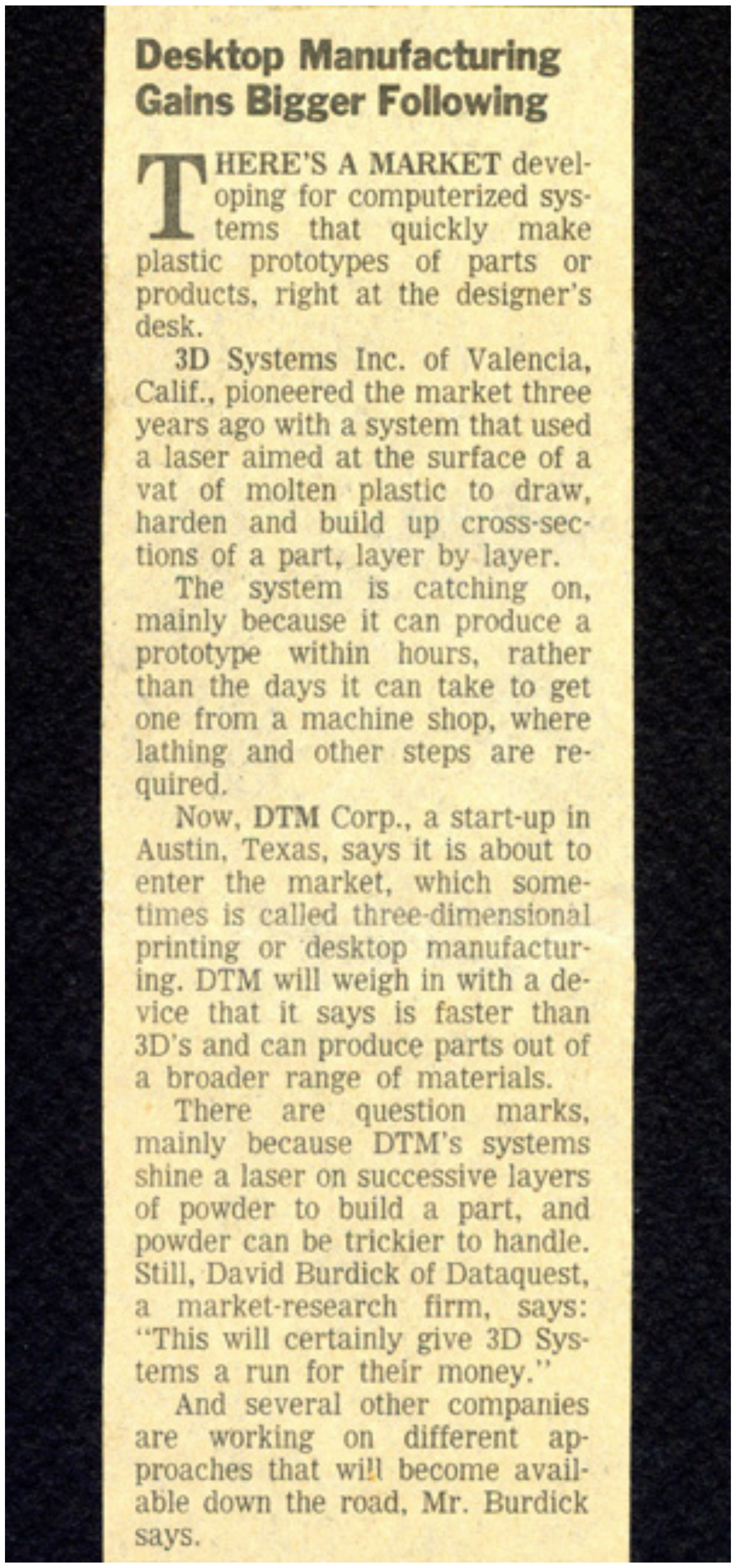
Ross "Frank" Housholder, circa 1981.

Housholder got the idea of building objects in layers from watching sand and washes as he drove to and from work while living in Las Vegas, Nevada in 1970. His idea involved pouring sand and cement into a square matrix, one layer at a time, and then solidifying the cement with water. He thought of using a laser to accomplish the task prior to filing his patent, but without having access to such equipment Housholder was unable to test and develop the idea.

The patent, filed in 1979 and granted in 1981, was issued to **Hico**

a small investment in a start-up venture could grow into a successful larger business. McClure remains proud of DTM's success as a technology innovator and the financial benefits bestowed on the many people involved with the company, the university and Central Texas.

Paul Forderhase while working for DTM in 1990, with two of the 125s. Only four of these machines were built, and none were sold commercially. Photo courtesy of Kent Firestone, Solid Concepts, Austin.



Desktop Manufacturing Gains Bigger Following

THERE'S A MARKET developing for computerized systems that quickly make plastic prototypes of parts or products, right at the designer's desk.

3D Systems Inc. of Valencia, Calif., pioneered the market three years ago with a system that used a laser aimed at the surface of a vat of molten plastic to draw, harden and build up cross-sections of a part, layer by layer.

The system is catching on, mainly because it can produce a prototype within hours, rather than the days it can take to get one from a machine shop, where lathing and other steps are required.

Now, DTM Corp., a start-up in Austin, Texas, says it is about to enter the market, which sometimes is called three-dimensional printing or desktop manufacturing. DTM will weigh in with a device that it says is faster than 3D's and can produce parts out of a broader range of materials.

There are question marks, mainly because DTM's systems shine a laser on successive layers of powder to build a part, and powder can be trickier to handle. Still, David Burdick of Dataquest, a market-research firm, says: "This will certainly give 3D Systems a run for their money."

And several other companies are working on different approaches that will become available down the road, Mr. Burdick says.

A clipping from the Wall Street Journal discussing DTM and the expanding market for SLS technology in 1989.

Western Products Co., a company jointly owned by Housholder and his brother. In 1981, Housholder was hired by Saudi ARAMCO and had to move to Saudi Arabia, preventing him from fulfilling his interest in developing the technology. In 1991, while living in Saudi Arabia, Housholder read a magazine article about advances in additive manufacturing technology that included a list of contact information for all of the companies mentioned in the article. Housholder, realizing that some of the companies may be interested in acquiring his patent, informed his brother about the story so that he could contact some potential buyers of the patent.

Murchison, the President of DTM at the time, negotiated the deal with Hico Western Products for the rights to the patent, which was crucial to DTM's survival in the marketplace. Today, the Housholder patent has been cited over 260 times and was the most important of the related patents.

The Beta machine, built in 1992 by DTM. Photo courtesy of Kent Firestone, Solid Concepts, Austin.

The SinterStation

1992 was also the year that DTM brought in an outside design firm, **Product Genesis**, to come up with a design for its next line of SLS machines beginning with the **SinterStation 2000**. These were the first modern production machines, featuring a 13" diameter cylindrical build area and a robust design – so robust, even, that one was accidentally dropped off of a forklift and was still salvageable.

Three models of the SinterStation followed the 2000:

- SinterStation 2500: Featuring a square 13x13" fabrication area (rather than the previous cylindrical fabrication area).
- SinterStation 2500+: A cost-reduced machine with fewer options and a square 13x13" fabrication area.
- SinterStation Pro (released by 3D Systems; see below): Featuring a square 24x24" fabrication area.

Inside the SinterStation 2000.

The SinterStation 2000.

In the summer of 1993, Deckard left DTM to take a position as an assistant professor at **Clemson University** in Clemson, South Carolina. By the time he left Clemson in December 1996, he had graduated four SLS students. After later returning to Austin he began learning more about materials science, leading him to his current work in producing additional materials for additive manufacturing.

4. Sold, and Sold Again: 1997-Present

Goodrich had invested in DTM for the expected material sales revenue, but at that point the industry was in its infancy and sales weren't high enough to merit their continued involvement. In 1999, Goodrich sold their majority share of DTM to **ProActive Finance**, a group of private investors who owned the company for two years. In 2001, ProActive Finance sold the company to **3D Systems, Inc.**, inventors of a competing technology called **stereolithography**. 3D Systems was and remains the industry leader in additive manufacturing, and obtaining rights to SLS technology was important to their success.

Before acquiring DTM in 2001, 3D Systems was the biggest competitor of DTM and SLS technology. Now owning both technologies, 3D Systems currently controls the largest share of the additive manufacturing market worldwide. Their main US competitor **Stratasys, Inc.**, inventors of **fused deposition modeling**, has more unit sales and a larger installed base, but a smaller market than 3D Systems' technologies. The biggest foreign competitor, German manufacturer **EOS GmbH**, sold its stereolithography business to 3D Systems in 1997. EOS continues to make SLS machines and is now focused on **selective laser melting**, a similar technology that focuses on making metal parts. This process was originally developed by **Suman Das**, a former graduate student of Beaman's and now a Professor of Mechanical Engineering at the **Georgia Institute of Technology**. 3D Systems continues to sell SLS and stereolithography machines and remains the industry's revenue leader.

DTM's Director of Sales **Dennis Medler** continued working in sales after the company was acquired by 3D Systems. An excellent salesman, Medler is remembered as having loved the saying, "Perception is more important than reality." Beaman describes him as a workhorse – on the road all the time. Although it was actually Beaman who sold the first SLS machine to Sandia National Labs, he had never realized how hard it was to be in sales until his involvement in DTM. Medler eventually advanced to the position of Vice President within 3D Systems.

5. Terminology

Additive Manufacturing (AM)
Synonyms: **3D Printing, Solid Freeform Fabrication**
Refers to any manufacturing process where parts are built up from raw material (generally powders, liquids, or molten solids) rather than cut out of a stock material such as a block of

Suman Das

Suman Das conducted research on laser sintering of metals for his M.S. and Ph.D. degrees under the supervision of Joe Beaman from 1990-1998. Under DARPA, ONR, and AFRL sponsorships, he designed and wood or metal. Additive manufacturing is sometimes called "3D printing," although that term first referred to **a specific technology** and today still generally refers to the lower end of the industry (non-production parts, such as prototypes). The abbreviation "3DP" applies only when referring to the specific technology.

Rapid Prototyping (RP)
Synonyms: **Direct Digital Manufacturing (DDM), Desktop Manufacturing**
Refers to any manufacturing process that uses CAD data to produce a part. Although the older term "rapid prototyping" is still widely used today, the industry is moving toward using "direct digital manufacturing" as these methods become more and more often employed for production-level manufacturing rather than just prototyping. Inversely to how "3D printing" refers to the lower end of the industry, "direct digital manufacturing" typically refers to the higher end of the industry (tools and end-use parts). "Rapid prototyping" can also refer to other CAD-controlled manufacturing process like machining but, for practical purposes, "RP" and "DDM" can be used interchangeably.

Sintering vs. Melting

The term "sintering" refers to a process by which objects are created from powders using the mechanism of atomic diffusion. Although atomic diffusion occurs in any material above absolute zero, the process occurs much faster at higher temperatures which is why sintering involves heating a powder. Sintering is different from melting in that the materials never reach a liquid phase during the sintering process. Although this distinction is important from a scientific standpoint, SLS works with both sintering and melting; what really determines which term is applicable is the material being used. Earlier machines used **acrylonitrile butadiene styrene (ABS)**, which is an **amorphous solid**. Technically speaking, amorphous solids do not actually melt; by strict definition, melting involves a phase transition from a solid to a liquid state. Amorphous solids, although classified as solids, are actually supercooled viscous liquids and therefore already in a liquid state. Unlike **crystalline and semi-crystalline materials** that have a discrete melting/freezing temperature, amorphous solids instead become continuously less solid and more molten or liquid-like as they are heated, eventually achieving physical properties that scientists have deemed to be sufficient for the material to be considered a liquid. This point is known as the **glass transition temperature**.

Since the first SLS machines were only used with ABS, the term "sintering" was used as it was most technically accurate — the original SLS patent cited previous research papers that had all used the term "sintering" in reference to ABS. However, when SLS began using crystalline and semi-crystalline materials such as nylon and metal that *do* melt during the SLS process, the name "selective laser sintering" was already well established and stuck despite having become a misnomer. Now, the term "SLS" refers to any use of a directed energy beam to selectively sinter *or* melt certain areas of a powder bed in order to build an object in layers. The original patents filed by UT covers both sintering and melting technologies.

6. Direction of the Industry

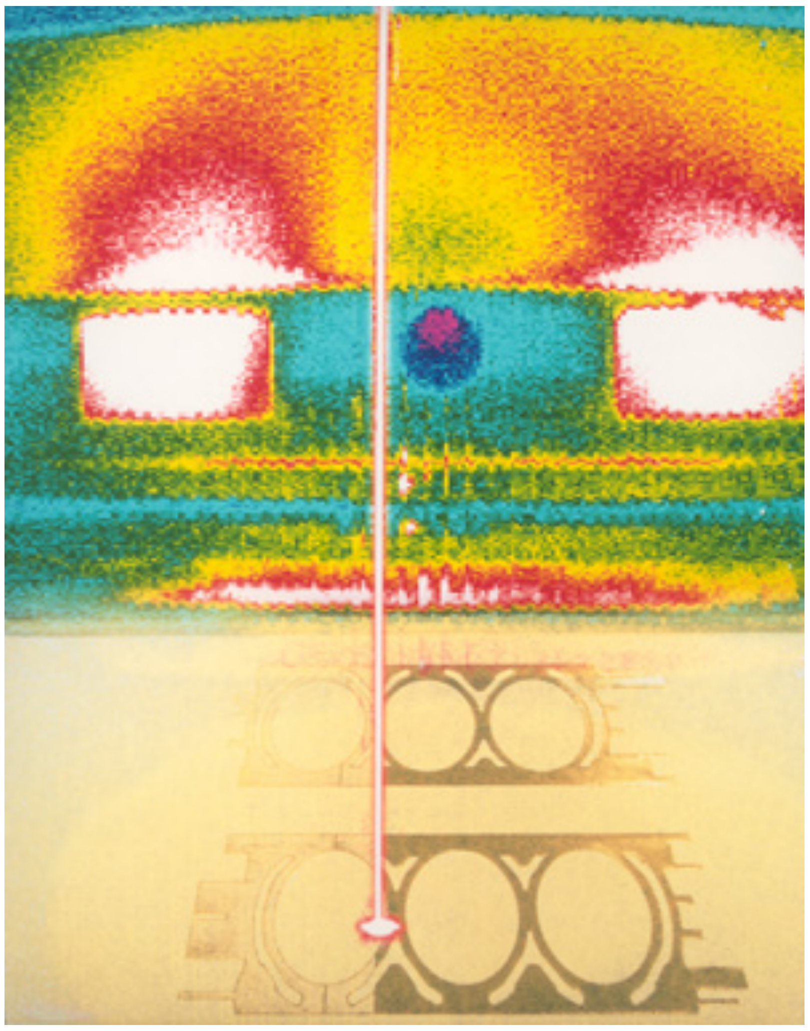
History of the Additive Manufacturing Industry

In the early days of additive manufacturing, the term "manufacturing" actually wasn't accurate at all. Companies interested in SLS and the other additive technologies developing at the time were not interested in using them for manufacturing production parts, but rather as a way to make "look and feel" prototypes or to streamline the process of casting, an intermediate step in certain manufacturing processes (as was Deckard's original goal for SLS).

Although many terms for the technology arose around the births of different additive manufacturing techniques, one of the more popular ones was "desktop manufacturing," for which DTM was named. Toward the late 1980s and early 1990s, the term "desktop manufacturing" started being replaced with "rapid prototyping" (RP) because most of the companies involved, primarily in the automotive industry, were interested in using the technology strictly for prototyping. The parts being made weren't yet strong enough to be used in production parts, nor was it an economical option compared to traditional methods, but they still had the enormous advantage of being created from a CAD model that could be stored and altered on a computer.

Before the time of RP, many manufacturers made both prototypes and real parts with investment casting, injection molding, or other similar methods, all of which require a cast or mold. Making the cast or mold required a casting pattern, which had to be made out of wood, wax, or ceramic by a skilled craftsman working from a 2D picture. Not only was this process time consuming, it was also very expensive. Molds can cost thousands of dollars to make, so prototypes and new models had to be very carefully designed; minor tweaks were rarely worth

built two additive manufacturing machines and co-invented two laser-based additive manufacturing processes to manufacture high performance aerospace components in titanium, nickel-base superalloys, and superalloy cermets. One collaborative project with Lockheed Martin led to a prototype machine and a short run production process for making the guidance section housing base in titanium alloy (Ti-6Al-4V) for the AIM-9 Sidewinder missile. A second collaborative project with Rolls-Royce led to a new technique for making nickel superalloy cermet abrasive tips for aircraft engine turbine blades, resulting in more than a 66% cost savings over the conventional production technique.



the price and mistakes were very costly.

With RP, these issues are largely mitigated. CAD models are easy to modify and one machine can get through a product's prototyping phase in a quick, cost-effective manner. Companies like **Dyson Ltd.** have since used SLS to design extremely successful and popular products by being able to go through dozens of prototype iterations in order to perfect their design.

Before long, using RP just for prototyping was not enough for manufacturers. After seeing what additive manufacturing can do, along with the improvement of materials and parameters used to make parts, various industries have adopted additive manufacturing as a way to build real parts, not just prototypes. While the term "rapid prototyping" is still used, the industry is now moving toward the term "direct digital manufacturing" for SLS and other high-end technologies that more commonly produce end-use parts than prototypes.

The Industry Today

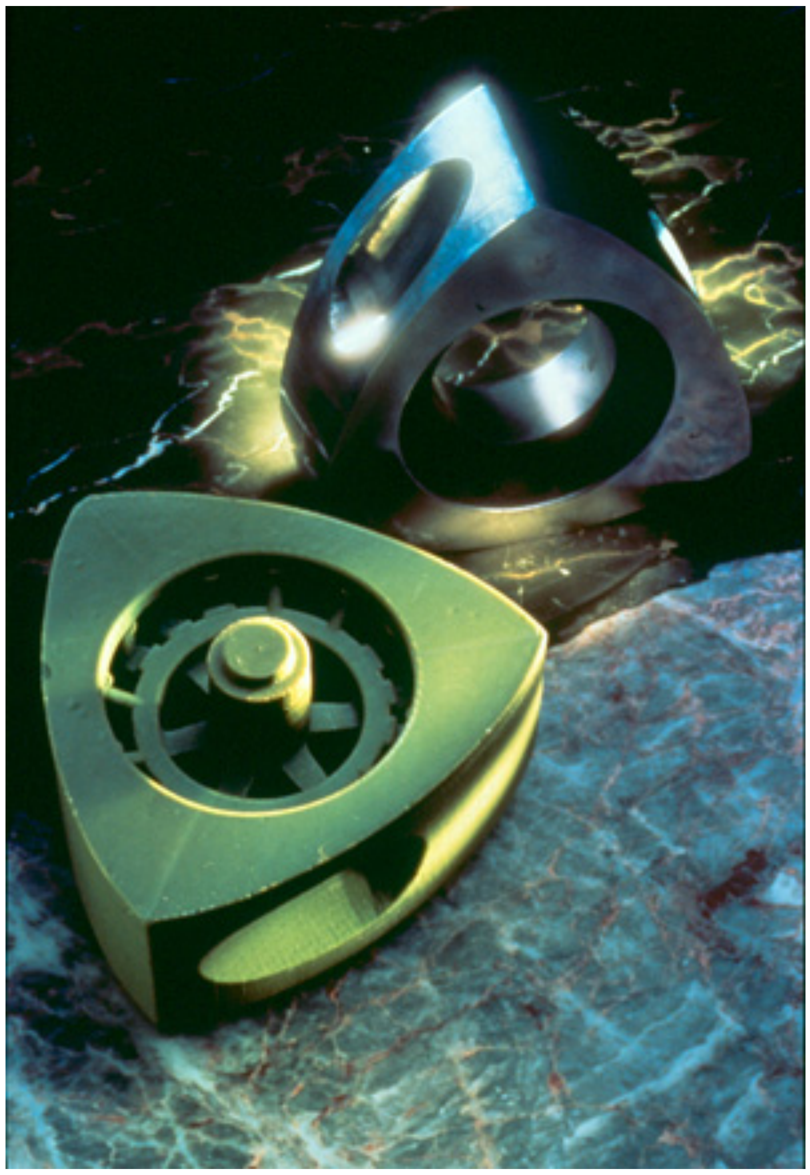
Courtney Shell, a graduate student in Dr. Rick Neptune's Neuromuscular Biomechanics Lab, pulls an SLS prosthetic part she designed from the powder bed of a SinterStation 2000.

Although SLS is sometimes used to fill standard manufacturing orders, it has found a niche in certain applications where other methods are particularly lacking. One of the biggest issues remaining with traditional manufacturing processes is the use of molds. Since the vast majority of plastic and even many metal products are made in enormous quantities, investing in a mold that will produce many thousands of parts is usually the cheapest and most efficient way to manufacture a product. However, there are still many high-value, low-production parts for which the use of molds presents a myriad of problems. One of the best examples of this is in the aerospace industry, which is why today aerospace manufacturers are one of the biggest markets for additive manufacturing technologies. Unlike parts for cars, electronics, or other products made in bulk quantities, airplanes are made in very limited quantities and stay in service for decades. Millions of parts go into building a commercial airplane and, when they break, the process of transporting, setting up, storing, and inventorying a different mold every time a replacement part is needed is a time-consuming hassle. Furthermore, molds can corrode over time and need to be carefully stored and maintained, and all parts verified for consistency with the original design after production. With SLS, one computer can do the job of hundreds of molds and eliminate all the costs associated with transportation, storage, and corrosion. All the data needed to produce parts can be stored in one place and lasts virtually indefinitely.

Another niche in which SLS and other types of DDM are gaining momentum is in **mass customization**. Certain products like hearing aids, dental retainers and prosthetics require that every unit be custom-made to match the body of the specific end user, and DDM has made mass customization a cost-effective and efficient option for various industries. For example, researchers in the Neuromuscular Biomechanics Lab of UT ME professor **Dr. Rick Neptune** use SLS to create custom-fit prostheses for US veterans to match the user's body, disability, gait and level of activity. A student at London's Royal College of Art has also recently used SLS to design a customized

An infrared image of the inside of a SinterStation machine in action, used to build the part seen below.

SLS was originally intended by Deckard as a way to make wax models for a casting process known as investment casting or lost-wax casting (see the glossary entry for "investment casting"). The part made of green wax (left) can be used as a casting pattern to make an identical part out of aluminum (right) or other metal. The off-white part (center) is made of polycarbonate and is not involved in the investment casting process.



Wax (left) and cast aluminum (right) parts demonstrating SLS's capability of investment casting, as well as its usefulness in creating complex shapes that are difficult to machine or create casting patterns for. The above part is a rotor for a Wankel engine, a compact yet powerful pistonless engine used in some sports cars, motorcycles, jet skis, chain saws, and other applications where a compact engine is desirable.

running shoe.

Kelly Alexander's Archimedes screw.

Finally, one of the most unique advantages of additive manufacturing technologies is their ability to create complex geometrical shapes that would be impossible to do with any other method of manufacturing. In the case of complex shapes, **subtractive manufacturing** methods often run into the problem of **tool clearance**, the amount of space required for a tool to reach the cutting area of a part. Tool clearance is usually overcome through **joining** (i.e., the use of nails, screws, adhesives, welding, etc. to couple multiple parts), but joining creates structural weaknesses and is not always possible depending on the application, especially when manufacturing small or delicate parts. Other methods including **molding** and **casting** exist, but for certain objects of complex shapes, such as **Kelly Alexander**'s Archimedes screw, it can be difficult or impossible to create a mold for or to remove the object from one. For such complex objects, additive manufacturing is simply the only manufacturing option available with today's technology.

Dr. Rick Neptune holding a custom prosthetic foot made using SLS.

The Industry Tomorrow

In the past, SLS has been used to replace parts designed with traditional manufacturing methods, but there has recently been a push to use additive methods as a primary form of manufacturing rather than just for part replacement. Many in the industry believe that future designs will more fully utilize the technology as materials improve and engineers begin to be more aware of the complex geometries that SLS is capable of building. For example, aerospace manufacturer **Boeing** plans to incorporate more SLS-manufactured parts in their future designs.

Currently, SLS is constrained by a limited number of available powdered polymers. Since plastics companies already sell materials "by the truckload," there hasn't been enough of an installed base of SLS machines to get polymer companies interested in research and development. While this is starting to change as SLS becomes a more popular manufacturing method, other initiatives are working to address the problem in the meantime. Carl Deckard and associate **Jim Mikulak**, have founded a new startup, **Structured Polymers, LLC**, focused on improving the number and quality of polymers available for SLS. Others such as EOS in Germany and **Arcam AB** in Sweden are working to make technological extensions of SLS more effective. EOS's technology (selective laser melting) and Arcam's technology (**electron beam melting**) both focus on producing metal parts, although EOS also makes machines that can use **polyether ether ketone (PEEK)**, an expensive but high-quality thermoplastic used in demanding applications.

The Wohlers Report

Terry Wohlers is a consultant who has made his career around writing industry reports for additive manufacturing. His company, **Wohlers Associates, Inc.**, publishes an annual report detailing significant events, technical information, and predictions for the future of the industry. Back issues of his reports are available online and current issues are available by subscription. In 2010, Wohlers estimated that the worldwide market for SLS was $67M. That number is expected to grow rapidly if the industry can get the attention of polymer companies.

7. The Solid Freeform Fabrication Symposium

In 1989, the year that SLS was introduced to the market at the Autofact trade show, a number of companies including **Ford Motor Co.**, Pratt & Whitney, and United Technologies Corp. (UTC) became interested in the technology. Beaman, Bourell, Crawford, and a fourth UT professor, **Harris Marcus**, decided they should hold a meeting for industry representatives to come together and exchange ideas, so later that year they hosted a one-and-a-half day event with 20 attendees and seven presentations. The professors felt it was an interesting, informative, and successful meeting that was well received.

The group decided to have a larger meeting of interested parties, so in August of 1990 they held a similar but larger event. At the time additive manufacturing was commonly called "solid freeform fabrication," so they named the event the **Solid Freeform Fabrication Symposium**. The meeting has continued ever since.

The Solid Freeform Fabrication Symposium has become unique in the world of technical conferences as it is truly a high-level, academic meeting. It mostly attracts industry researchers and academics and, although industrial networking occurs, the commercial aspects of a trade show are not organized into the conference. It is the longest running research meeting in the field and is well respected; they receive positive reviews in technical journals and it is the most often recommended research meeting in additive manufacturing.

Harris Marcus did most of the organization for the first meeting and continued to organize the event until 1994 when he left the department. In 1995, Bourell took over the job of chairing the event and has done so ever since.

Professor Harris Marcus at the Solid Freeform Fabrication Symposium, June 2012. Marcus was the original organizer of the conference.

Dave Bourell, UT, and the Industry

Bourell has been a primary figure within the additive manufacturing industry in growing the community

FAME Awards

In 2007, Bourell met with about 25 other industry experts who decided to give an annual set of awards for recognition in additive manufacturing: one for a junior researcher who has demonstrated potential, and the other for senior researcher. Bourell coined the name "**Freeform and Additive Manufacturing Excellence (FAME) Award**," and the accolade has been awarded at every the Solid Freeform Fabrication Symposium since 2009. The first year of the award, UT ME's **Carolyn Seepersad** won the junior award, and in the third year Bourell received the senior award. These awards are still new, but the conference hopes they will become known as an award with significant stature in the additive manufacturing community. Bourell's goal for the award is for it to become something that transcends the meeting: a pinnacle award for additive manufacturing development that just happens to be given at the symposium. Although organized by UT ME, the awards are determined by a committee not affiliated with the university.

8. The Roadmap to Additive Manufacturing

Before the Solid Freeform Fabrication Symposium in 2008, the **Office of Naval Research (ONR)** asked Bourell to gather additive manufacturing leaders together to discuss the future of additive manufacturing. In August of that year, Bourell arranged a meeting of several colleagues to discuss a special workshop for ONR to fund. Bourell, **Ming Leu** of **Missouri University of Science and Technology**, and **David Rosen** of the Georgia Institute of Technology were to lead the workshop.

In December 2008, Bourell and Leu met in Washington, D.C. and asked NSF Division Program Director **George Hazelrigg** to help fund the workshops. They received additional funding from ONR and held a two-day workshop in March 2009. With enough funding to bring 65 people to Washington, D.C. for the meeting, the attendees produced a 50-page document with 50 pages of additional appendixes titled "**The Roadmap to Additive Manufacturing**." The document was designed both to help researchers know how to apply for funding and to inform funding agencies on specific areas with high development potential.

9. Researchers at UT ME Working in Additive Manufacturing

Beaman was Director of the **Laboratory for Freeform Fabrication** until he became the UT ME Department Chair in 2001. **Dr. Kris Wood** took over as Director until 2007, and the lab has since been directed by Bourell. Ten faculty are currently working in the lab: David Bourell, Kris Wood, Carolyn Seepersad, Rick Neptune, Joe Beaman, Rich Crawford, **Harovel Wheat**, **Janet Ellzey**, **Desiderio Kovar**, and **Ashish Deshpande**. **Listed beside Appendix C** are graduate students who have worked in the Laboratory for Freeform Fabrication and the titles of their respective dissertations.

10. SLS Companies Born Out of UT and DTM

- **Harvest Technologies**, *a service bureau in Belton, Texas owned by* ***David K. Leigh*** *and his father,* ***David E. Leigh****.*

  David K. Leigh graduated from UT ME and began working for DTM, assisting on the SinterStation design and becoming familiar with additive manufacturing technology. He later left to work with his father's company, Harvest Technologies, which was then still a machine shop. However, with David K. Leigh's experience in additive manufacturing, Harvest Technologies expanded to include various prototyping and manufacturing services including SLS. David K. Leigh serves as President of Harvest Technologies and has returned to UT to earn his Ph.D. with Bourell serving as his advisor. Both Leigh's are Distinguished Alumni of the Mechanical Engineering Department.

- **Advanced Laser Materials, LLC (ALM)**, *a materials provider started by* ***Scott Evans*** *and* ***Donnie Vanelli****, financed by* ***Bruce Thorton*** *and a research grant won by Dave Bourell and Joe Beaman in 2004.*

  In 2004, Beaman and Bourell won a research contract with a local company called **Cryco Quartz, Inc.** The company was making chip carriers out of quartz, which are used in the manufacturing of computer chips and boards and are expensive to produce due to their complex geometry. Cryco Quartz was looking for an additive manufacturing for the quartz chip carriers, but an employee suggested that they instead look into **silicon carbide**, a ceramic material used in applications requiring high hardness and endurance such as automobile brakes and clutches, ceramic plates in bulletproof vests, and

internationally, and of UT ME faculty has been the most involved with the research sector. He meets with researchers from around the world and is heavily involved in networking for the industry, UT ME, and the Solid Freeform Fabrication Symposium. Thanks in part to the conference, SLS machines are now being built and supplied in many countries around the world. He believes his work is both good for the university and has brought related industries to Texas. UT has managed to stay on the forefront of the technology partially because of the Solid Freeform Fabrication Symposium.

Professor David Bourell photographed in his office at The University of Texas at Austin, March 9, 2011.

nuclear fuel coatings.

Beaman and Bourell partnered with the employee to explore the idea. Bourell received grant funding from the State of Texas Technology and Development and Transfer Grant to start a new company, but the grant had to be dollar-for-dollar matched by an investor and the partner couldn't match the funding. Bourell nearly had to refund the grant money, but UT ME professor **Steve Nichols** was sponsoring an entrepreneurial competition at the time, and silicon carbide project was entered into the competition. Although it didn't win, the idea came in second place. Two Ph.D. students, Scott Evans and Donnie Vanelli, showed the project to an **angel investor** named Bruce Thorton, who was one of the judges of the competition. Thorton was quite interested in the technology and agreed to match the funding from the state grant to start a company. Vanelli became President of the new company, first called **Advanced Laser Composites, LLC (ALC)**.

ALC determined there wasn't enough of a market for silicon carbide, so they shifted to developing special niche materials and later became a boutique materials supplier for laser sintering. They have since changed their name to Advanced Laser Materials (ALM) and now market more general materials for laser sintering. ALM is now located in Temple, Texas and Vanelli remains President. Thorton became chairman of ALM and the third cofounder, Evans, now works for Correlated Magnetics Research in Austin, Texas.

Harvest Technologies and UT ME both currently buy their materials from ALM. In 2009, ALM formed a strategic partnership with EOS, the German market leader of SLM.

- **Structured Polymers, LLC**, *a startup focused on making more polymers available for SLS machines.*

  As of May 2012, Carl Deckard has been involved in a new startup company called Structured Polymers. His partner in the new venture, Jim Mikulak, is also a Ph.D. graduate of UT ME. Selective laser sintering can make use of many different polymers, but these materials must be available in powder form. There are currently 33,000 available polymers, but most are only offered in pellets and not powders. Structured Polymers is developing a process to extrude polymer pellets into a thread and then chop them into a fine powder, making them usable in SLS machines.

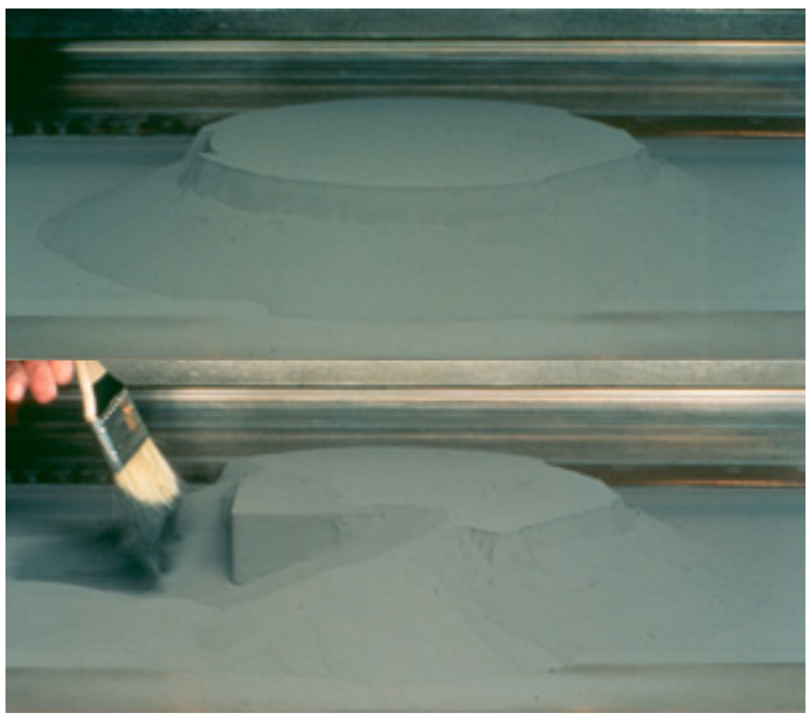
- **Integra Services**, *a support and service provider for a variety of additive manufacturing machines located in Round Rock, Texas.*

  Integra was formed in 2002 by former DTM employees and offers alternative support services for SLS, SLA, and SLM machines. The company has strong ties to Harvest Technologies, and David K. Leigh is acquainted with many of their employees.

Appendix A: Hierarchy of Modern Additive Manufacturing Technologies (From High- to Low-End)

- **Selective laser sintering (SLS)**, *a powder-based technology invented at UT in 1986 by Carl Deckard and further developed by DTM.*

  SLS uses a directed energy beam to sinter or melt powdered material and is the most widely used for manufacturing real parts and tools, offering the widest selection of materials. Two newer technologies, listed below, are both extensions of SLS. More info.

  - **Selective laser melting (SLM)** is essentially the same process as SLS, but refers to the use of metal powder rather than polymers (see SLS Materials: Terminology). SLM machines are specialized for use with metals and produce finished, fully dense parts in one step, unlike the metal parts made with SLS machines which must be **infiltrated** (see right). The current market leader in SLM technology is the German company EOS. More info.
  - **Electron beam melting (EBM)** is similar to SLM in that it uses metallic powders to make fully homogenous metal parts, but EBM uses an electron beam rather than a laser and builds parts in a vacuum, which allows the use of highly

oxygen-reactive metals (usually titanium, a common aerospace material). EBM was invented by the Swedish corporation Arcam. More info.

- **Stereolithography (SLA)**, *a liquid-photopolymer-based technology developed by* ***Charles Hull*** *of 3D Systems in 1984.*

  SLA uses photopolymers, which are liquid polymers that harden when exposed to certain frequencies of light. Built in successive layers as with SLS, SLA parts are durable but not quite as strong as SLS parts. Due to the nature of the technology, stereolithography is limited to a relatively small set of materials available for use and is generally thought to have already reached the peak of its capabilities. Since the unused raw materials are liquid, SLA also requires that parts include temporary support structures for any overhanging portions during builds, a disadvantage that SLS and 3DP overcome simply by retaining loose raw material until the build is finished. However, 3D Systems now owns both the SLS and 3D printing technologies in addition to SLA, making it the holder of the largest share of the additive manufacturing market worldwide. More info.

- **Fused deposition modeling (FDM)**, *an extrusion-based technology developed by* ***Scott Crump*** *of Stratasys in 1988.*

  FDM uses a thick filament of polymer or metal that is forced through a heated nozzle, which melts the polymer like a hot glue gun. It makes the part by moving the table or nozzle to deposit the material selectively in a molten form, building the part up one layer at a time. Like SLA, FDM requires support structures for parts with overhangs. While fused deposition modeling advertises that it can create end-use parts, the technology only offers amorphous materials and parts are significantly more fragile than those of other technologies. As a result, fused deposition modeling is primarily used for making precise and durable prototypes. More info.

- **3D printing (3DP)**, *a powder-and-binder-based technology patented in 1993 by* ***Ely Sachs*** *and* ***Mike Cima*** *of the* ***Massachusetts Institute of Technology (MIT)*** *and sold in 1995 to* ***Z Corp.****, which was recently acquired by 3D Systems in January 2012.*

  3DP uses a powder bed method like SLS, but instead of sintering or melting the powder a binder (glue) is injected into the powder using an inkjet-like printing head. The powder-binder mix cannot achieve the same material properties found in objects formed out of a single material, placing this technology on the low-end of the additive manufacturing spectrum. **Solid Concepts**, a large DDM service bureau in Valencia, California, describes Z Corp. printers on their website as "ideal for users looking for a cost-effective 3D printing solution for projects not requiring high accuracy or durability." Although "3D printing" originally referred specifically to this technology, the term is now also used as a synonym for additive manufacturing in general. More info.

Appendix B: SLS Machines Before 3D Systems Acquisition in Chronological Order

- **Betsy** (1984-1986) - The first-generation SLS machine that served as a prototype machine for proving the viability of the SLS process. Designed and built by Carl Deckard.
- **Godzilla** (1987) - The SLS machine design that followed Betsy and preceded Bambi but was never actually built. The Godzilla design tried to do too much for its time and would have been too big and expensive to build. Designed by DTM.
- **Bambi** (1987-1989) - The second-generation SLS machine, designed by DTM, that served as a research and production machine.
- **Mod A** (1989) - The first of the third-generation (125-series) SLS machines. The design was originally intended to be modular, but DTM chose not to pursue that feature. The Mod A was the machine DTM presented at the Autofact '89 trade show.
- **Mod B** (1989) - the second of the third-generation (125-series) SLS machines. Like the Mod A, the design was originally intended to be modular, but DTM chose not to pursue that feature.

A metal part is made using the SLS process. First, an SLS

- **125** (1989) - The third-generation SLS machine, hurriedly designed by DTM and GEMCITY for debut at the Autofact '89 trade show. The 125 line was the first commercial SLS machine and, despite the design rush and lack of safety features, made good parts and was generally a successful design. The first two machines were called Mod A and Mod B.
- **Beta** (1990) - The SLS machine designed by DTM that followed the 125 and preceded the SinterStation, but was never built. The Beta had so many safety and engineering requirements set forth by the design team that the final design was neither practical nor usable enough to go to market.
- **SinterStation** (1992-ownership by 3D Systems) - The robustly built fourth-generation of SLS machines designed by Product Genesis and DTM. This design was commercially successful and included four models: the SinterStation 2000, the SinterStation 2500, the SinterStation 2500+, and the SinterStation Pro.

machine is run using a powdered mixture of metal and binder to create a "green part". Next, the part is placed into a furnace where the binder will be burned out. Simultaneously, bronze bars placed adjacent to the part will melt and be wicked into the part, "infiltrating" the empty spaces left by the burnt-out binder. In the past, Dave Bourell has conducted research on the infiltration process.

Appendix C: Important People in Alphabetical Order

- **Kelly Alexander** - Former undergraduate student of Joe Beaman who designed and built the one-piece Archimedes screw pictured above using the SLS process. More info.
- **Clint Atwood** - Project leader at Sandia National Laboratories, the first organization to purchase a commercial SLS machine. Atwood primarily used the machine for investment casting.
- **Joel Barlow** – UT chemical engineering professor who did polymer synthesis work for the Bambi machine and helped organize the Solid Freeform Fabrication Symposium. He worked in the Lab for Freeform Fabrication until his retirement in 2002.
- **Joe Beaman** - UT ME professor who mentored Carl Deckard during his invention of SLS and years as a graduate student. Beaman was also highly involved in the formation and management of DTM (formerly Nova Automation) and helped organize the Solid Freeform Fabrication Symposium. Beaman served as the UT ME Department Chair from 2001-2011 and Director of the Lab for Freeform Fabrication prior to that. Beaman worked in tandem with Dave Bourell to gain grant funding to establish UT's partnership with Cryco Quartz. Beaman continues to work as a professor at UT and is conducting research on how to use polyether ether ketone with SLS machines. More info.
- **Harold Blair** - One of the original founders of DTM, which was first named Nova Automation after Blair's older company, Nova Graphics. Blair worked with Paul McClure as Nova Automation's first executive team, but left the company a year after it was founded.
- **Dave Bonner** - UT Distinguished Alumnus and former UT Chemical Engineering Visiting Committee member who was Vice President of Research at Goodrich at the time the company had its partnership with DTM. Dave Bonner is the son of Z. D. Bonner. More info.
- **Z.D. Bonner** - Former Professor and Chair of the UT Chemical Engineering Department and father of Dave Bonner. More info.
- **Rick Booth** - Former chemist at DTM in the early years. Currently Vice President of Advanced Laser Materials, in Temple, Texas. Booth was interviewed and photographed for this story at the 2012 Solid Freeform Fabrication Symposium.
- **David Bourell** - UT ME professor who was consulted during the designing of the Bambi machine for his knowledge of laser technology and materials science. Bourell assisted DTM again in 1990 by helping write patents related to SLS. Bourell's greatest involvement with SLS has been in leading the Solid Freeform Fabrication Symposium to expand the technology internationally and maintain UT's position as a leader of innovation in the industry. Bourell has also served as Director of the Lab for Freeform Fabrication since 2007 and earned grants for partnerships with both Cryco Quartz and Advanced Laser Materials (formerly Advanced Laser Composites). More info.
- **Mike Cima** - One of the two professors at MIT who invented 3D printing technology, which was later sold to Z Corp. Cima is still at MIT.
- **Ritchie Coryell** - Program Manager at NSF who took a personal interest in DTM and helped get the company off the ground. Coryell helped create the NSF's Small Business Innovation Research (SBIR) Program that gave DTM a $50,000 grant.
- **Rich Crawford** - UT ME who does work in the Laboratory for Freeform

Graduate Students and Post-Doctoral Scholars of the Laboratory for Freeform Fabrication

Student	Theses, Dissertations, and Current Employment
Mukesh Agarwala	• Synthesis, SLS and Post Processing of Metal and Ceramic Composites (Ph.D., 1994)
Seokyoung Ahn	• Modeling, Estimation, and Control of Electroslag Remelting Process (Ph.D., 2005) • Pusan National University (Associate Professor)
Kaushik Alayavalli	• Design, Fabrication and Testing of Graphite Bipolar Plates for Direct Methanol Fuel Cells by Indirect Laser Sintering (Ph.D., 2011) • Applied Materials
Stacia Barrow	• An Initial Assessment of Infiltration Material Selection for Selective Laser Sintered Preforms (M.S., 2004)
Shweta Bhandari	• Binder Optimization for Manufacturing of Silicon Carbide Preforms (M.S., 2004)
David Bunnell	• Fundamentals of SLS (Ph.D., 1995)
Patrick "PJ" Casey	• Real-Time Estimation of MIG Welding Weld Bead Width using an IR Camera (M.S., 2009) • Osterhout Design Group
Ana Maria Castaño Ibarra	• Direct Selective Laser Sintering of a Bronze-Ni System (1996)
Kumaran Murugesan Chakravarthy	• Laser Sintering for High Electrical Conduction Applications (Ph.D., 2012)
Ssu-Wei Chen	• Fabrication of PEM Fuel Cell Bipolar Plate by Indirect SLS (Ph.D., 2006) • Tokyo Electron Limited (TEL-FSI)
Uichung Cho	• Novel Empirical Similarity Method for Rapid Product Testing and Development (1999)
Greg Danyo	• Direct Laser Fabrication of a Ceramic Composite Abrasive Turbine Blade Tip (1998)
Suman Das	• Direct SLS of High Performance Metals - Machine Design, Process Development and Process Control (Ph.D., 1998) • Georgia Institute of Technology

Fabrication and whose graduate student wrote the software for the Bambi machine.

- **Scott Crump** - Cofounder of Stratasys and inventor of fused deposition modeling.
- **Dave Cutherell** - Former graduate student of Joe Beaman who served as lead engineer for the Mod A machine that later became the 125 design. Cutherell now owns an outdoors equipment company, Gossamer Gear. More info.
- **Jim Darrah** - Software engineer who wrote the software for the Mod A machine that later became the 125 design. Darrah now works at Advanced Communications Concepts, Inc., a computer and network security firm in Austin, Texas.
- **Suman Das** - A former graduate student of Joe Beaman who did research on selective laser melting and is now a professor at Georgia Institute of Technology. His research has led to the development of two laser-based additive manufacturing processes for high-performance aerospace parts, as well as collaborative projects with Lockheed Martin and Rolls-Royce. More info.
- **Carl Deckard** - UT ME graduate and inventor of SLS technology. Deckard began his work on developing SLS during the late years of his undergraduate career and stayed at UT as a master's and Ph.D. student to continue working on the technology. Deckard was a cofounder of DTM (formerly Nova Automation) and received the largest royalty stream from the original SLS patents, being the inventor of the process. Deckard designed and built the first SLS machine, Betsy, on his own and remained an integral member of the design teams of later machines. Deckard left DTM to teach at Clemson University for three years and is now co-owner of Structured Polymers, a SLS materials developer in Austin, Texas. More info.
- **Dudley Dobie** - A UT attorney who successfully fought for the Deckard patent, while it ws still pending, fending off a threatening patent for a similar technology for layered object manufacturing.
- **Rick Edwards** - Friend of Carl Deckard who introduced him to Dave Bonner, Vice President of Research at Goodrich.
- **Scott Evans** - UT ME Ph.D. graduate and cofounder of Advanced Laser Materials (formerly Advanced Laser Composites). Evans now works for Correlated Magnetics Research in Austin, Texas. More info.
- **Kent Firestone** - Manager of Process Development at DTM for four years and the project manager for the Vanguard HS system. He is currently the Director of Operations for Solid Concepts's Austin facility where he is focused on production applications with the SLS technology. Firestone provided information on PEEK and SLM for this story and supplied photos of the 125 and Beta machines.
- **Paul Forderhase** - Lead designer and supervisor of the Bambi machine now working at Applied Materials in Austin, Texas. More info.
- **George Hazelrigg** - NSF Division Program Director who provided funding for the Roadmap to Additive Manufacturing workshops. More info.
- **Ross Housholder** - Holder of an additive manufacturing patent that was bought by DTM in 1992.
- **Charles Hull** - Cofounder of 3D Systems and inventor of stereolithography.
- **George Kozmetsky** - An extremely influential Austin business man, educator and philanthropist who served as Dean of the Business School (now McCombs School of Business), was a co-founder and former Executive Vice President of Teledyne, Inc., and founded both the Austin Technology Incubator and IC^2, a technology research institute affiliated with the university. More info.
- **David E. Leigh** - UT ME Distinguished Alumnus and owner of Harvest Technologies, a rapid prototyping service bureau in Belton, Texas. Father of David K. Leigh. More info.
- **David K. Leigh** - UT ME Distinguished Alumnus who worked at DTM and later went to work for his father, David E. Leigh, at Harvest Technologies. Currently a UT ME Ph.D. student under David Bourell.
- **Ming Leu** - Professor at Missouri University of Science and Technology who worked with David Bourell to organize the Roadmap to Additive Manufacturing collaboration. Leu and Bourell met with George Hazelrigg and secured funding for a two-day, 65-person conference in Washington, D.C., which provided the ideas set forth in the Roadmap document. More

	(Professor)
Michael Deng	• Parametric Analysis for the SLS Process (1992)
Vikram Devaraj	
Dan Devereux	• Design and Development of a Technique for Measuring Radiaive Properties of Dielectric Powders (1993)
Tim Diller	• Thermal Characterization of Powder-Based SLS of Nylon 12 (Postdoc, 2011) • Enthought, Inc.
Alan Dutson	• Functional Prototyping Through Advanced Similitude Techniques (Ph.D., 2002) • Brigham Young University - Idaho
Brett Engel	• Preprocessing of Ti-6Al-4V Powder for Applications in SLS/Hot Isostatic Pressing (M.S., 1998)
Scott Evans	• Rapid Manufacturing of Silicon Carbide Composites (Ph.D., 2005) • Correlated Magnetics Research
Nick Fey	• The Influence of Increasing Steady-State Walking Speed on Muscle Activity in Below-Knee Amputees (M.S., 2008) • The Influence of Prosthetic Foot Design and Walking Speed on Below-Knee Amputee Gait Mechanics (Ph.D., 2011) • Center for Bionic Medicine, Rehabilitation Institute of Chicago
Abishek Goel	• Electromechanical Deposition of Metal Ions in Porous Laser Sintered Inter-Metallic and Ceramic Preforms (M.S., 2010)
Sundararaman Gopalan	• Direct Selective Laser Sintering of Cordierite Powder (M.S., 1998)
Allison Hall	• Individual Plantar Flexor Compensation During Walking with a Passive Dynamic Ankle-Foot Orthosis: A Simulation Study (M.S., 2007) • Understanding Changes in Post-Stroke Walking Ability Through Simulation and Experimental Analyses (Ph.D., 2010) • University of Florida (Postdoc)
Nicole Harlan	• Development of Direct Laser Sintering Process for the Production of a Metal-Ceramic Composite (M.S., 1996) • Titanium Processing Using Selective Laser Sintering (Ph.D., 1999)
Paul Haase	• SLS of Metal Powders (M.S., 1989)
Jerry Jackson	• Design of a Breakout System for SLS Parts Created by the Academic Test Bed (1990)
Larry Jepson	• Multiple Material SLS (2002)
Gerard Johnson	• Molding of Silicon/Silicon Carbide Pressureless Infiltration Process
Liar Cashed	• Sandia National Laboratories
Carey King	
	• Synthesis, Sintering, and Elevated

info.

- **Harris Marcus** - UT ME professor who was the driving force behind the establishment of the Solid Freeform Fabrication Symposium. Marcus developed selective area laser deposition (SALD), a gas-driven additive manufacturing technology that was never commercialized. More info.
- **Hans Mark** - UT Aerospace professor who served as Chancellor of UT System during the early days of DTM. Mark promoted DTM and was able to secure funding from the Board of Regents for the new venture. More info.
- **Bill Masters** - Owner of Perception Systems/BPM Technology, a company whose additive manufacturing technology was unsuccessful. Bill Masters currently owns Perception Kayaks, a large, high-end kayak manufacturer, as well as Evolution Kayaks.
- **Paul McClure** - One of the original two executives of Nova Automation who later became President and CEO when the company became DTM. McClure has a Ph.D. in Mechanical Engineering, although he did not provide engineering services at DTM. When DTM was formed, McClure was serving in a development role for the College of Engineering as Assistant Dean. McClure was instrumental in lining up the funding and partnership with Goodrich, as well a $50,000 grant from NSF for Small Business Innovation Research (SMIR) and working with the University Board of Regents to support DTM initially. McClure served as President and CEO of DTM until 1990 when he left to join a venture capital firm, **Columbine Ventures**, and to provide management consulting to other companies. He is currently CEO of a nano-manufacturing company in Austin, Texas named Xidex Corporation. More info.
- **Dennis Medler** - DTM's Director of Sales who also worked in sales at 3D Systems around and after their acquisition of DTM. Medler eventually advanced to the position of Vice President within 3D Systems.
- **Jim Mikulak** - Ph.D. graduate of UT ME and co-owner of Structured Polymers, a SLS materials developer in Austin, Texas. More info.
- **John Murchison** - President and CEO of DTM from 1990 to 2001 who made the crucial purchase of Ross Housholder's patent in 1992.
- **Rick Neptune** - is a professor in the Mechanical Engineering Department. His research work in musculoskeletal and sport biomechanics and neuromotor control of human movement makes use of additive manufacturing in the design and production of custom prosthetics for wounded veterans. More info.
- **Steve Nichols** - UT ME professor who organized an entrepreneurial competition which allowed graduate students Scott Evans and Donnie Vanelli to find an investor, Bruce Thorton, to start Advanced Laser Materials (formerly Advanced Laser Composites). More info.
- **Tim O'Meara** - Vice President of Sales at GEMCITY during the designing and building of the Mod A machine. O'Meara is still at GEMCITY.
- **Jerry P.** - A talented machinist and designer at GEMCITY who led the design team for the Mod A machine.
- **David Rosen** - Professor at the Georgia Institute of Technology worked with David Bourell to organize the Roadmap to Additive Manufacturing collaboration. Rosen, Leu and Bourell organized a two-day, 65-person conference in Washington, D.C., which provided the ideas set forth in the Roadmap document. More info.
- **Ely Sachs** - One of the two professors at MIT who invented 3D printing technology, which was later sold to Z Corp. Sachs is now running a solar business, 1366 Technologies.
- **Carolyn Seepersad** - UT ME professor who works with SLS in the Lab for Freeform Fabrication and won the first Junior FAME Award. More info.
- **Stanley Ogrydziak** - Former graduate student of Joe Beaman who wrote the "Stanley CAD" software for the Bambi machine.
- **Bruce Thorton** - An angel investor who provided the funds to start Advanced Laser Materials (formerly Advanced Laser Composites) and now serves as Chairman of the company.
- **Terry Wohlers** - Owner of Wohlers Associated, Inc. which publishes an annual additive manufacturing industry analysis.
- **Kristin Wood** - A professor in the Mechanical Engineering Department, served as Director of the Laboratory for Freeform Manufacturing from 2000 until 2007. Dave Bourell became the Director after Wood. Ten faculty are currently working in the lab: More info.

Jaffa Coo	Temperature Deformation Behavior of Noncrystalline Alumina and Alumina-Zirconia Composite (Ph.D., 1996)
Joanna La Rocco	• Thermal Imaging of a SLS Part Bed Surface (M.S., 2010) • Air Liquide
David Leigh	• (M.S., 2011)
Larry Melvin	• An Electrostatic Sieve Feed System Applied to the SLS Process (1994)
John Montgomery	• Investigation and Design of an Actively Actuated Lower-Limb Prosthetic Socket (M.S., 2009) • International Biomedical
Nathan Moore	• The Design and Fabrication of a High Temperature Vacuum Workstation for SLS Research (1995)
Christian Nelson	
Ryan Newcomb	
Nachiket Patwardhan	
Gopalkrishna Prabhu	• Supersolidus Liquid Phase Selective Laser Sintering of Pre-Alloyed Bronze Powder (M.S., 1993) • Synthesis, Sintering Characteristics and Elevated Temperature Deformation Behavior of Nanocrystalline Zirconia and Zirconia-Alumina Nanocomposites (Ph.D., 1996)
Srikanth Raghunathan	• (Ph.D., 1991)
Jorge Ramos	• Surface Modification of Ceramic and Metallic Alloy Substrates by Laser Raster-Scanning (2003) • Universidad Católica de Chile
Rodrigo Ruizpalacios	• Laser Direct-Write of Optical Components Prepared Using the Sol-Gel Process (2004)
Samuel Sih	• The Thermal Properties of Polymer Powders (M.S., 1991) • The Thermal and Optical Properties of Powders in SLS (Ph.D., 1996) • Walla Walla University (Associate Professor)
Tim Silverman	• National Renewable Energy Laboratory
Brian South	• Energy Storage and Return Prosthetic Foot Fabrication Using SLS (M.S., 2008) • UT's McDonald Observatory
Rameshwar Sreenivasan	• Sustainability and Thermal Aspects of Polymer Based Laser Sintering (M.S., 2010) • Caterpillar India Pvt. Ltd.
Brooke Stevinson	• Support Free Infiltration of SLS Silicon Carbide Preforms (2006)
Paramasivan Subramanian	• SLS of Alumina (1995)
Martin Sun	• (1991)

- **Donnie Vanelli** - UT ME Ph.D. graduate and cofounder of Advanced Laser Materials (formerly Advanced Laser Composites). Vanelli has served as President since the formation of the company.
- **Frank Zanner** - Manager at Sandia National Laboratories who bought the first SLS machine shortly after the Autofact '89 trade show.

Appendix D: Important Organizations in Alphabetical Order

- **3D Systems, Inc.** - A rapid prototyping developer that invented stereolithography and later bought DTM and now control the largest share of the additive manufacturing market. More info.
- **Advanced Laser Materials, LLC** (**ALM**, formerly **Advanced Laser Composites, LLC**) - A materials provider in Temple, Texas born out of the idea of creating a silicon carbide powder for SLS machines. More info.
- **Arcam AB** - A Swedish corporation that invented electron beam melting and continues to make machines for that technology. More info.
- **Boeing Company** - An aerospace and defense corporation and the world's largest manufacturer of aircraft. More info.
- **BPM Technology** (formerly **Perception Systems, Inc.**) - A rapid prototyping developer that attempted to market ballistic particle manufacturing technology but was unsuccessful. BPM closed its doors in 1998, but owner Bill Masters is still successful as the owner of Perception Kayaks, now one of the largest kayak manufacturers in the world, as well as a smaller company, Evolution Kayaks.
- **Clemson University** - A university in Clemson, South Carolina where Carl Deckard went to teach after leaving DTM. More info.
- **Cryco Quartz, Inc.** (division of **TOSOH Quartz, Inc.**) - A computer chip manufacturer in Austin, Texas that contracted work to Joe Beaman and Dave Bourell to develop a silicon carbide powder that could be used in SLS machines. The contract gave birth to Advanced Laser Materials (formerly Advanced Laser Composites). More info.
- **DTM Corp.** (formerly **Nova Automation**) - A company founded by Carl Deckard, Joe Beaman, Paul McClure, and Harold Blair to commercialize the SLS process. The company changed its name from Nova Automation when Blair left shortly into the endeavor, and McClure served as President from then until 1990 when the position was taken over by John Murchison. Under McClure, DTM partnered with Goodrich (formerly BFGoodrich and B.F. Goodrich Co.) and designed several machines including Godzilla, Bambi, and the Mod A/ModB/125. During Murchison's time as President, the company designed the Beta and SinterStation machines and was sold by Goodrich to private investors. Murchison's service as President ended in 2001 when DTM was sold to 3D Systems.
- **Dyson Ltd.** - A British technology company that designs and manufactures high-end vacuum cleaners, hand dryers, bladeless fans, and heaters. Dyson is one of the most successful SLS users and were able to develop superior products through numerous prototype iterations made possible by SLS. More info.
- **EOS GmbH** - A Germany company that originally produced both SLS and stereolithography machines but sold its stereolithography business to 3D Systems as part of a patent war settlement between the two companies. EOS now focuses on machines that use SLS with metal powder, also known as selective laser melting (SLM), and is the world leader in SLM technology. More info.
- **Ford Motor Co.** - An automotive manufacturer present at the Autofact '89 trade show, and one of the first companies interested in SLS. Founder Henry Ford also founded the Henry Ford Museum in Dearborn, Michigan, that served as Carl Deckard's childhood inspiration to become an inventor. More info.
- **General Motors Co.** (**GM**, formerly **General Motors Corp.**) - An automotive corporation that was one of the potential investors DTM spoke with when searching for funding. More info.
- **Georgia Institute of Technology** (**Georgia Tech**) - A university in Atlanta, Georgia where David Rosen and Suman Das are professors. More info.
- **GEMCITY** - An engineering and manufacturing bureau in Dayton, Ohio that designed and built the Mod A, Mod B, and 125 machines—the first commercial SLS machines that were presented at the Autofact '89 trade

Srikanth Tadepalli	• Modeling and Optimization of Manufacturing Through Solid Freeform Fabrication (M.S., 2003) • Advances in Empirical Similitude Method (Ph.D., 2009) • General Electric
William Thissell	• Processing and Control of Selective Area Laser Deposition from Methane and Hydrogen (1994)
James Tobin	• Rapid Manufacture of Prototype Injection Molds Using the SLS Process (M.S., 1994) • GE Power & Water
James Tompkins	• Computer Control of Laser Intensity for Selective Area Laser Deposition (1992)
Neal Vail	• Preparation and Characterization of Microencapsulated, Finely Divided Ceramic Materials for SLS (Ph.D., 1994) • NK Vail and Associates, LLC (President)
Phani Vallabhajosyula	• SLS and Post-Processing of Fully Ferrous Components (Ph.D., 2011) • Intel Corp.
Meagan Vaughan	• Design and Analysis of a Volume Adjustable Transtibial Prosthetic Socket for Pediatric Amputees in Developing Countries (M.S., 2009) • UT ME Ph.D. Student
Ravi Venkataramani	• Advanced Machine Control for SLS (1999)
Jessica Ventura	• (M.S., 2008) • Experimental Analysis and Computational Simulation of Unilateral Transtibial Amputee Walking (Ph.D., 2010) • The effects of prosthetic ankle dorsiflexion and energy return on below-knee amputee leg loading (2011) • The effect of prosthetic ankle energy storage and return properties on muscle activity in below-knee amputee walking (2011) • Gordon College (Assistant Professor)
Hongyun Wang	• (Ph.D., 1999)
Doug Watson	• Process Optimization of SLS Through the Use of Design Rules and Constraints (1999)
Wendy Weiss	• The Formation of Intermetallics by Selective Laser Sintering (M.S., 1991)
Martin Wohlert	• Production of Metal Matrix Composites by Selective Laser Sintering and Metal Infiltration (M.S., 1997) • Hot Isostatic Pressing of Direct Selective Laser Sintered Metal Components (Ph.D., 2000) • Applied Materials
Jeff Worrell	• A Mixed Mode Thermal/Fluids Model for Improvements in SLS Part Quality, Modeling Design, and Process Design (1999)
Yong-Qui Wu	• Design and Experiments on High Temperature Work Station Intended for Academic Research of SLS (1992)

show. More info.

- **Goodrich Corp.** (formerly **BFGoodrich** and **B.F. Goodrich Co.**) - A large aerospace manufacturing company that was DTM's first investor and parent organization. Although their name is widely associated with a tire brand name, Goodrich sold their tire business and rights to the name "B.F. Goodrich" to Michelin in 1988 and now focuses on aerospace manufacturing. More info.
- **Harvest Technologies** - A rapid prototyping service bureau in Belton, Texas owned by UT ME Distinguished Alumni David E. Leigh and David K. Leigh. More info.
- **Hico Western Products Co.** - A company jointly owned by Ross Housholder and his brother that owned one of the first additive manufacturing patents.
- **E. I. du Pont de Nemours and Co.** (**DuPont**)- A large chemical company that was almost DTM's first investor, but initially drove too hard a bargain and didn't loosen their terms until after DTM's deal with Goodrich was already made. More info.
- **International Business Machines Corp.** (**IBM**) - A multinational computer technology corporation that Dave Bourell worked on a project with, earning him early experience in laser use when lasers were still a new technology. More info.
- **Integra Services** - A support and service provider for a variety of additive manufacturing machines located in Round Rock, Texas. More info.
- **Massachusetts Institute of Technology** (**MIT**) - A university in Cambridge, Massachusetts where 3D printing was invented, although the technology wasn't commercialized until it was purchased by Z Corp. More info.
- **Missouri University of Science and Technology** (**MST**) - A university in Rolla, Missouri where Ming Leu is a professor. More info.
- **National Science Foundation** (**NSF**) - A United States government funded agency that supports basic research and education in non-medical fields of science and engineering. NSF, along with the Office of Naval Research, provided funding for the workshops that produced the Roadmap to Additive Manufacturing. More info.
- **Nova Graphics Intl. Corp.** - A computer graphics company owned by Harold Blair, one of the founders of DTM. DTM was originally named Nova Automation after Blair's older company, Nova Graphics, but changed its name when Blair left the project.
- **Office of Naval Research** (**ONR**) - An office within the United States Department of the Navy that organizes and promotes science and technology programs. ONR, along with NSF, provided funding for the workshops that produced the Roadmap to Additive Manufacturing. More info.
- **ProActive Finance** - A financial services and investment firm that bought DTM from Goodrich in More info.
- **Product Genesis** (also **ProGen, Inc.**) - A design firm that DTM contracted to develop the SinterStation SLS machine. More info.
- **Sandia National Laboratories** - A pair of United States Department of Energy National Laboratories that purchased the first commercial SLS machine shortly after the Autofact '89 trade show. More info.
- **Solid Concepts, Inc.** - A large RP/DDM service bureau in Valencia, California that provides various manufacturing services, including all four of the major additive manufacturing categories (laser sintering, SLA, FDM, and 3D printing). More info.
- **Stratasys, Inc.** - A rapid prototyping developer that invented fused deposition modeling, one of the major additive manufacturing methods still used. Stratasys has the largest installed base of any additive manufacturing company, although 3D Systems generates more revenue. More info.
- **Structured Polymers, LLC** - A new startup founded by Carl Deckard and Jim Mikulak to develop more SLS powders out of extruded polymers.
- **TRW Mission** (division of **TRW, Inc.**, acquired by **Northrop Grumman Corp.**) - An iron-based machine shop in Houston, Texas where Carl Deckard worked during the first summer of his undergraduate career. Working at TRW gave Deckard the idea of developing a CAD-based machine to make casting patterns. More info.
- **The University of Texas at Austin** (**UT**) - A university in Austin, Texas where SLS was invented. Carl Deckard, Joe Beaman, Dave Bourell, Joel

Mengqi "Maggie" Yuan	• Thermal Conductivity of Polyamide Powder (M.S., 2011) • UT ME (Ph.D. Student)

Barlow, Harris Marcus, Paul McClure, Paul Forderhase, Stanley Ogrydziak, Dave Bonner, Z.D. Bonner, Dave Cutherell, Rick Neptune, Arumugam Manthiram, Kelly Alexander, Jim Mikulak, Carolyn Seepersad, Kris Wood, Rich Crawford, Harovel Wheat, Janet Ellzey, Desi Kovar, Ashish Deshpande, Steve Nichols, David E. Leigh, and David K. Leigh have all been faculty members and/or students at UT and involved with SLS technology. More info.

- **Wohlers Associates, Inc.** - A consulting firm owned by Terry Wohlers that provides technical and marketing advice regarding the additive manufacturing industry. More info.
- **Z Corp.** - The company that commercialized the 3D printing technology developed at MIT. Z Corp. was acquired by 3D Systems in January, 2012.

Glossary of Terms

- **Acrylonitrile butadiene styrene** (**ABS**) - A class of common thermoplastics that are amorphous solids. ABS plastics have been used in many additive manufacturing machines, including SLS and fused deposition modeling. More info.
- **Amorphous solid** - A class of solids that, unlike crystalline solids, have no true melting point; rather than transitioning discretely from a solid to liquid, amorphous solids get continuously more soft or molten as they are heated. Common amorphous solids include glass, rubber and many plastics. See **crystalline solid**. More info.
- **Angel investor** - An affluent individual who provides capital for a business startup, often for recreational or philanthropic purposes but also largely for financial gain. Unlike a venture capitalist whose profession is to manage the money of others for investment purposes, an angel investor uses his/her own finances for investments. More info.
- **Autofact** - An annual trade show that took place in Detroit, Michigan the year of 1989. SLS made its first market appearance with the Mod A machine at Autofact '89.
- **Casting** - A manufacturing process for creating metal parts that involves creating a "casting pattern" that has the same shape and dimensions of the desired object, but is made out of a different material such as wood or wax. The casting pattern is then used to create a mold, the casting pattern removed, and molten metal poured into the mold which cools and forms the product. The product is then removed either by separating or destroying the mold, depending on the method used. Casting is very similar to molding, although casting processes are almost always used for making metal parts. See **molding**. More info.
- **Commodore 64** - An 8-bit home computer introduced in 1982 that remains the best-selling single personal computer of all time. Carl Deckard used one of these computers to control the scanner and laser of the Betsy machine. More info.
- **Computer-aided design** (**CAD**) - The use of computer models to assist in the creation, modification, analysis, or optimization of a design. More info.
- **Crystalline solid** - A class of solids whose atoms or molecules are arranged in an orderly, repeating pattern. Unlike amorphous solids, crystalline solids exhibit discrete phase changes between solid, liquid, and gaseous phases, although materials may also be semi-crystalline or polycrystalline. See **amorphous solid**. More info.
- **Freeform and Additive Manufacturing Excellence Award** (**FAME Award**) - A recognition granted annually at the Solid Freeform Fabrication Symposium to individuals who have been key to advancing the additive manufacturing industry. There are two versions of the award for young and seasoned researchers. More info.
- **Glass transition temperature** - The temperature above which an amorphous solid's properties meet one of several conventions to be considered a liquid rather than a solid. Such conventions include constant cooling rate and viscosity threshold, among others. More info.
- **Infiltration** - A process involved in creating metal parts using SLS machines. First, a "green part" is created using a mixture of metal powder and a binder. The binder is then burned, leaving some empty space that makes the part weak. Infiltration is the step of filling those spaces with more metal to make the part fully dense. This process is ideal for parts that need to be made out of multiple materials.

- **Investment casting** - A casting process in which a casting pattern is made out of wax or another material that can be melted or burnt out of the mold once it has been created. Creating wax casting patterns for investment casting was the first use intended by SLS. See **casting**. More info.
- **Joining** - A set of manufacturing processes that involves combining multiple parts together to form larger objects. Joining is usually used in conjunction with other manufacturing methods. Examples include welding, taping, gluing, soldering, stitching, and fastening with nails or screws. More info.
- **Laboratory for Freeform Fabrication** - A laboratory in the Department of Mechanical Engineering established in 1988 after Deckard's invention of selective laser sintering. The lab is part of the Advanced Manufacturing Center and has several commercial Sinterstation machines and research machines used by faculty and students of the Mechanical Engineering department. More info.
- **Mass customization** - The process of manufacturing a product for which the design specifications are matched to the end user for every unit produced. Examples include dental retainers matched to the user's teeth and jaw, or the prosthetics designed in Dr. Rick Neptune's lab customized for the user's gait, disability, level of activity and physique.
- **Molding** - A manufacturing process in which a liquid or pliable material is inserted into a mold that contains a negative of the object to be created. Although molding is very similar to casting, molding processes always use reusable molds rather than expendable molds and are used with a much wider variety of materials including plastic, glass, metal, and ceramic. More info.
- **Polyether ether ketone** (**PEEK**) - A high-end thermoplastic used in demanding applications for its extreme heat, impact, and corrosion resistance. Examples of applications include aerospace parts, bearings, pistons, pumps, and valves. More info.
- **Roadmap to Additive Manufacturing** - A document written in 2009 designed to help researchers in the field of additive manufacturing know how to apply for funding, and to give direction for research projects and ideas. More info.
- **Silicon carbide** - A ceramic material used in applications requiring high hardness and endurance, such as automobile breaks and clutches, ceramic plates in bulletproof vests, and nuclear fuel particle coatings. Silicon carbide can be sintered, and was developed into an SLS powder by Advanced Laser Materials (formerly Advanced Laser Composites). More info.
- **Solid Freeform Fabrication Symposium** - A high-credentialed annual research meeting for the field of additive manufacturing hosted by UT ME.
- **Subtractive manufacturing** - A set of manufacturing processes that involve cutting away at stock material such as blocks of wood, marble, or metal until the desired object is formed. Examples include machining, sculpting, carving, drilling and sanding. More info.
- **Tool clearance** - A limitation, primarily in subtractive manufacturing, where there must be enough space or clearance within a stock material or part for tools to reach the cutting or manipulation area.
- **YAG laser** - A laser that uses the synthetic crystal yttrium aluminum garnet (YAG) to increase the power of light emitted by the device. This is the laser Deckard used in his prototype machine, Betsy. More info.