provides "focused insight/oversight, specifying to industry—where appropriate—what we need, instead of how to build it," he told the House Committee on Science, Space, and Technology in July testimony. Still, Bolden admitted the agency continues "wrestling with how we do development" with the ISS contracts, which are fixed price. "The risk is that if something goes wrong, how do we get it fixed?" For cargo, at least, the approach appears to be succeeding so far. "The fact is we are months away from having an American capability to take cargo to the ISS," Bolden said.

## Missed deadlines, new goals

Long-duration human travel to destinations beyond low-Earth orbit awaits development of a more advanced spacecraft—a capability that Congress is prodding NASA to provide as quickly as possible. The agency announced last year that it will continue development of the Orion crew vehicle that had been part of President George W. Bush's Constellation program. Lockheed, which had been the prime contractor on the Orion program, will continue to manage what NASA now calls the multipurpose crew vehicle. Some $9 billion has already been spent on the Orion.

Although Congress set a deadline of January 2011 for a decision on an architecture and plan for building the heavy-lift booster, or Space Launch System (SLS), NASA didn't announce its choice until 14 September. Both stages of the rocket will be liquid fueled. The first-stage rocket engines are the same design used for the space shuttle's main engines. The second-stage engine will be the same engine that was going to be used in the Constellation launcher. Both will be openly competed.

The White House Office of Management and Budget had ordered multiple reviews of the plan submitted by NASA months ago. One review, an independent cost estimate by consulting firm Booz Allen Hamilton, offered a qualified endorsement of NASA's figure, saying the agency had made highly optimistic assumptions about its ability to improve the efficiency of the development program. Senator Kay Bailey Hutchison of Texas, the ranking Republican member of the Senate Committee on Commerce, Science, and Transportation, charged that the holdup has resulted in the layoff of thousands of Constellation and shuttle program workers who could have been kept to work on the SLS.

Logsdon, though, says the administration's caution shouldn't come as a surprise, given news reports that the rocket will cost $38 billion over 10 years. Griffin claims that the SLS should cost nothing close to that; the administration's goal, he contends, is to ensure that the heavy-lift launch vehicle that Congress demanded in 2010 is never completed. The White House Office of Science and Technology Policy declined repeated requests for comment.

The Obama administration has set a goal of landing humans on an asteroid in 2025, followed by a trip to Mars in the mid 2030s. The Moon, which Bush had proposed as the destination in 2020, isn't on the Obama administration's itinerary. Bolden told the House Science committee that he doesn't rule out a return to the Moon, or visits to Earth–Moon Lagrange points.

**David Kramer**

# 3D printing breaks out of its mold

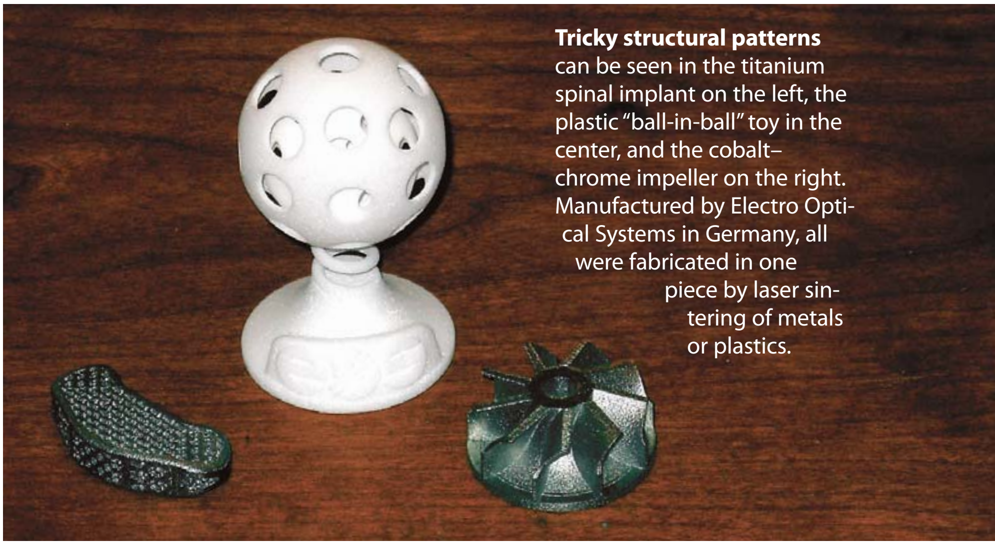
**Medical implants, injection-molding tools, and aircraft custom parts are just a few of the products being manufactured with technology once reserved for prototyping.**

**"I'm a physicist,** and I didn't believe that something manufactured from a powder could be just as strong or almost as strong as something cut from a solid," says Hans Langer, founder and CEO of Electro Optical Systems (EOS) in Krailling, Germany. The company manufactures laser-based systems that take a digital rendering of an object and fabricate a three-dimensional copy layer by layer using raw materials in liquid or powder form. The process, known formally as additive manufacturing and commonly as 3D printing, can fabricate dental crowns up to three times faster than traditional casting methods, says Langer. The company's customers also include aircraft, racecar, and prosthetics manufacturers and other industries that require relatively small batches of custom parts.

Since the technology was first developed in 1987, 3D printers have been at work prototyping objects in design labs at technology companies and in fabrication labs at research universities. But now the technology is increasingly moving into the commercial manufacturing sector. "The application of 3D printing to direct-part production is probably the most significant change I've seen in [the additive manufacturing] industry," says Terry Wohlers, founder and president of Wohlers

Associates, a consulting firm based in Fort Collins, Colorado, that has been tracking the technology since its commercialization.

ELLIOT PLOTKIN



**Tricky structural patterns** can be seen in the titanium spinal implant on the left, the plastic “ball-in-ball” toy in the center, and the cobalt–chrome impeller on the right. Manufactured by Electro Optical Systems in Germany, all were fabricated in one piece by laser sintering of metals or plastics.

## Copy, print, implant

The concept of 3D printing can be traced back to the 1950s, when computers were first connected to milling machines, says Neil Gershenfeld, director of MIT’s Center for Bits and Atoms. Gershenfeld pioneered the concept of fab labs—small-scale factories stocked with 3D printers and other computer-controlled fabrication tools (see the report about fab labs in PHYSICS TODAY, March 2002, page 27). Where 3D printers and other additive manufacturing technologies shine, says Gershenfeld, is in their ability to reconstruct complex digital designs.

Although various 3D printing technologies exist, they all operate under similar principles: Computer-aided design (CAD) software is used to slice a digital object into layers as thin as 10 microns; the 2D pattern of each layer is transmitted to the 3D printer, which extrudes, sprays, or spreads raw material onto a flat, horizontal platform; the material is cured, laser-sintered, fused, or bound by UV light, lasers, or electron beams. The process repeats until the object is fully formed.

Most industrial 3D printers can fabricate objects as large as a typical kitchen sink or as small as a pinhead. Some advanced CAD software allows scientists and engineers to optimize such structural properties as strength-to-mass and surface-to-volume ratios. And in the past 10 years, advances in 3D printing technology have expanded the range of usable raw materials beyond plastics to glass, ceramics, and metal.

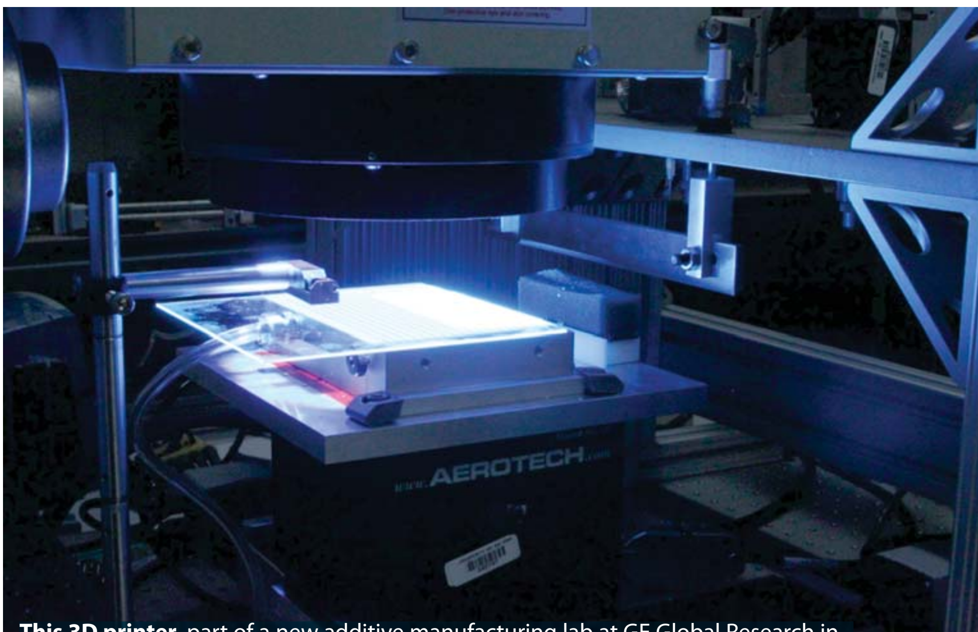
Langer says that metal processing with laser sintering has been advanced by use of fiber lasers, which he says “offer an intense, high-quality beam that can be easily focused.” Scientists at EOS are collaborating with academic researchers on a process called micro-laser-sintering, which can print features in layers as thin as 1 micron. “We are now melting and changing the crystal structure of some metals, such as stainless steel,” says Langer. “Laser sintering is no longer just a geometry effect. Now it’s also a materials effect.”

## Curbing waste

Aerospace and medical products, such as patient-specific surgical instruments and drill guides, are among the fastest-growing segments of EOS’s customer base, says Andrew Snow, sales director of the company’s North American division. Also growing in popularity are 3D-printed medical implants, which contain complex lattice structures that support the implant’s integration with surrounding tissue. Snow adds that the need for the Food and Drug Administration’s approval has prevented the US from keeping pace with Europe, where such implants have been sold for more than four years now. Just this year, the FDA granted its first approval for the sale of a 3D-printed medical implant—a titanium hip.

Aircraft and racecar manufacturers have been among the early adopters of 3D printing, with which engineers can digitally optimize density and other structural properties to manufacture customized, lightweight components such as impellers, fuel-injection nozzles, and door hinges. “Weight equates to cost in our industry,” says Chris Wilkinson, an executive responsible for engineering development at Spirit AeroSystems in Wichita, Kansas. The company designed and manufactured a portion of the fuselage for the 787 Dreamliner, Boeing’s new carbon fiber–composite commercial airplane. Additive methods help reduce waste associated with traditional subtractive manufacturing techniques, which can leave up to 90% of expensive raw materials, such as titanium, on the floor. Wilkinson says that 3D printing “also addresses the need for rapid translation

GE GLOBAL RESEARCH




**This 3D printer**, part of a new additive manufacturing lab at GE Global Research in Niskayuna, New York, uses UV light to cure successive layers of ceramic slurry. Within several minutes, it can fabricate the intricate piezoelectric structures in an ultrasound transducer, orders of magnitude faster than can be done via traditional subtractive manufacturing techniques.

of engineering to manufactured parts."

David Bolognino, director of General Motors' design fabrication operations, says that additive manufacturing tools in the company's design labs are used to produce automotive parts for preproduction models of the Chevrolet Volt, GM's first all-electric vehicle. The technology "allows us to do very quick iterations of complicated parts and systems with supreme accuracy to reduce product development time and expense," says Bolognino, who recalls seeing his father go from hand-chiseling wooden prototypes to becoming an early advocate of and a supervisor in GM's rapid prototype lab. Bolognino says traditional tooling methods are still required for car manufacturers like GM to meet their mass-production needs: "At the end of the day, we have to be careful not to make parts that can't be tooled in other ways," he says.

## Made in space

Manufacturing in zero gravity is the latest venture for 3D printers. In July the entrepreneurs at Made in Space, a Silicon Valley startup, successfully demonstrated the 3D printing of a plastic adjustable wrench during a NASA parabolic airplane flight. Jason Dunn, the company's chief technology officer, says they still have much to learn about the fluid dynamics of the process in space. Once those problems are solved, Dunn says that a space-bound vehicle would be lugging less weight because its cargo could be built in space using up to 30% less raw material. On Earth, satellites and other space equipment are made artificially heavy to withstand extreme liftoff vibrations. Dunn and his business partners are currently preparing their customized 3D printer for performance test flights funded by NASA's Commercial Reusable Suborbital Research program aboard manned spaceflights expected to start next year (see the report about the NASA program in PHYSICS TODAY, October 2010, page 28).

Revenues from additive manufacturing technologies grew by 24.1% in 2010, according to the latest *Wohlers Report*, an annual state-of-the-industry publication by Wohlers Associates. The report highlights the "explosive growth of low-cost personal 3D printers," which are primarily sold to individuals, small businesses, and academic institutions. The personal systems start at around $1000 and are used for materials science research, basic prototyping, and teaching; industrial machines can cost more than $1 million. "I'm thrilled by how many universities, community colleges, even high schools, are buying the technology," says Wohlers.

"Kids are empowered to learn math and science when they can use a 3D printer to design an iPod holder for their bike," says Hod Lipson, a mechanical engineer at Cornell University's computational synthesis laboratory. He and his team use 3D printers to fabricate tiny, bio-inspired, battery-powered flying robots, dubbed ornithopters, which mimic the aerodynamic properties of hovering birds and insects. "Just a few years ago, 3D printing was an expensive technology that only large design firms could afford," says Lipson. "Now [it is] like pencil and paper in the modern robotics lab. If we need a component, we can print it within minutes."

## Clay versus Lego

Lipson and Gershenfeld say that 3D printing is just the start of the digital fabrication revolution. They are collaborating on the development of programmable materials, which Gershenfeld describes as "coded construction." Their aim is to mimic the efficiency of molecular biological processes by applying computational error-correction techniques. "The difference between bulk raw materials and digital materials is like the difference between playing with clay and playing with Lego blocks," Gershenfeld says. Lipson adds that the ability to assemble materials with such precision could lead to robots and machines that "respond to external stimuli in a much more sophisticated way."

**Jermey N. A. Matthews**

# Electron microscope gets x-ray vision

A new electron microscope makes possible direct imaging and identification of individual atoms via x rays. Anticipated applications of the Austrian scanning transmission electron microscope (ASTEM) include analyzing material interfaces and impurities in semiconductor devices, and studying nanoplasmonics. With improved sample preparation methods the instrument could eventually be used to study biomaterials, says Ferdinand Hofer, director of the Austrian Center for Electron Microscopy and Nanoanalysis in Graz, where ASTEM was inaugurated on 22 June.

The electron microscope's resolution of 70 pm (a picometer is $10^{-12}$ meters) is not the world's best; that distinction goes to a 50-pm-resolution instrument at the National Center for Electron Mi-