By LONNIE J. LOVE, BRADLEY RICHARDSON, RANDALL LIND, RYAN DEHOFF, BILL PETER, LARRY LOWE and CRAIG BLUE

Oak Ridge National Laboratory, Automation, Robotics and Manufacturing Group, P.O. Box 2008, M.S. 6305, Oak Ridge, TN 37831*

FREEFORM *FLUIDICS*

** This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-000R22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.*

The basic mechanical design and fabrication of fluid powered systems has changed little since the start of the industrial revolution. Mechanical structure, actuators (motors), electronics, energy storage, thermal management, sensors and controls are all fabricated with different processes and then integrated into the final system during the assembly process (see **Figure 1**). Compare this to nature (see **Figure 2**). The human form has a lightweight but strong skeletal structure seamlessly integrated with muscles, tendons and nerves. Veins and arteries are integrated into the body delivering energy to all parts of the body while simultaneously exposing our blood to tremendous amounts of surface area for thermal management. All of this is covered with a pliable and durable skin that protects all of our internal organs from the environment. We have this wonderful model for mechanical design but have never come close to replicating it—until now.

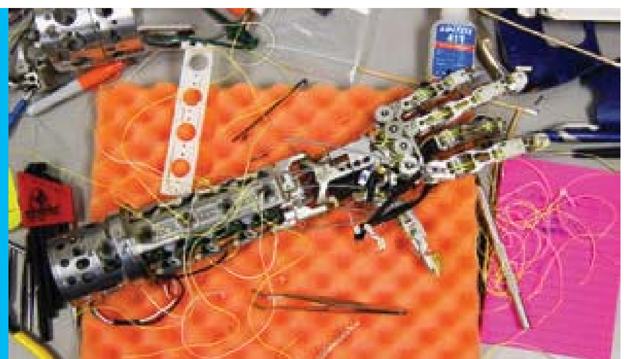

FIGURE 1 Currently, components made separately are extremely complex and expensive.

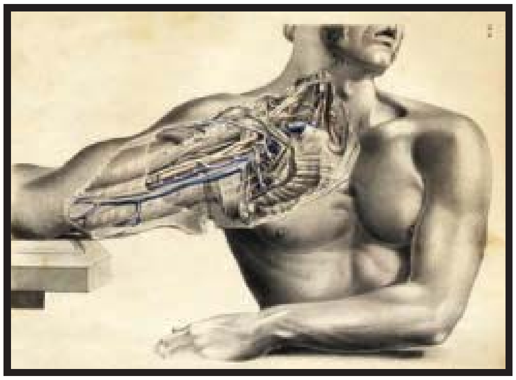

FIGURE 2 Cross-section of the human form.

Emerging additive manufacturing processes are enabling a fresh new perspective on the design of mechanical systems. Unlike traditional machining practices, where material is removed to create a part, additive manufacturing constructs parts through layer-by-layer deposition of material. Parts can be manufactured with voids and mesh structures, reducing weight, manufacturing energy, material usage and subsequently cost. This approach to manufacturing enables the design and fabrication of components and systems that have previously been impossible.

FIGURE 3 Cross-section of the test manifold.

Today, fluid powered devices are manufactured using conventional fabrication practices. Pumps are cast and machined, fluid passages in manifolds are drilled, cross-drilled and plugged, pistons are turned on lathes, reinforced rubber hoses pass fluid across joints. Historically, new manufacturing methods introduce new solutions to old problems. Additive manufacturing enables a revolutionary, not evolutionary, approach to the design and fabrication of fluid powered devices that far exceeds the state-of-the-art in terms of performance, strength, reliability and cost. Freeform fluidics is defined as the merging of fluid power and additive manufacturing. It is defined as freeform due to the fact that many prior manufacturing constraints are removed. The additive process enables integrated structure, actuation,

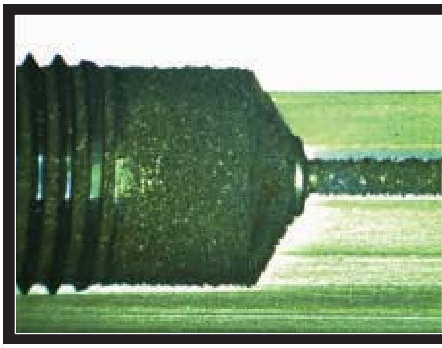


FIGURE 4 **No finishing (close-up), and FIGURE 5 Aggressive finishing (close-up).**

fluid passages, thermal management and control within a single fabrication process. The designer is not limited to straight, fixed geometry fluid passages. Fluid can be routed efficiently through the structure without the need for cross-drilled holes or plugs. Fluid passages can be optimized for heat dissipation and minimized head loss. Material that is not under stress can be removed or replaced with lattice or shell structures for weight reduction. The following sections cover preliminary work exploring the impact, and design considerations, made possible for fluid powered systems based on additive processes.

FIGURE 6 **Test specimens.**

One of the primary issues regarding parts manufactured using the additive manufacturing process is their mechanical properties. The following analysis focuses on one process: the electron beam (e-beam) melting process with powder bed support provided by Arcam. For mechanical strength, tensile coupons were manufactured in various positions and configurations within the build volume. Results show that components made with Ti-6-4 powders have a minimum yield stress (894.9 MPa) and ultimate strength (911.5 MPa) that exceeds Grade 5 specifications. The Arcam system uses a powder bed that has an elevated temperature. Therefore, the part exhibits very little residual stress during the manufacturing process. This leads to improved mechanical strength but induces challenges in powder removal.

For powder bed systems, material that is not melted serves as mechanical support for overhanging features. When the part is complete, the supporting material is removed by blasting the part with the same powder used for the additive process. This enables the un-melted material to be recovered and reused. One of the primary issues is powder removal and surface finish. For external surfaces where surface finish is critical (e.g., bearing surfaces, piston bores…), the addition of a sacrificial layer of material, approximately 1 mm thick is adequate, can be removed with conventional machining leaving a polished surface. Internal passages are more complicated. If the un-melted powder is not sintered during the manufacturing process, the material can be easily removed from internal passageways by simply shaking the part. However, the lower temperature of the powder bed leads to temperature gradients in the part during the melting process that manifests itself as residual stress in the part. By keeping the powder bed at a high temperature and lightly sintering the powder, residual stress is reduced and it is possible to manufacture very complex parts with large aspect ratios (exceeding 40:1). The penalty is difficulty in removing the powder from internal passageways. For the majority of the lightly sintered material in internal passages that are not easily accessible, it is best to have gradual transitions (5 mm or greater bend radius) and diameters greater than 1.5 mm. A braided wire in a Dremel tool can easily agitate the powder removing all lightly sintered material. The more challenging problem is the

FIGURE 8 **Meshed tensile member.**

FIGURE 9 **Failure mode.**

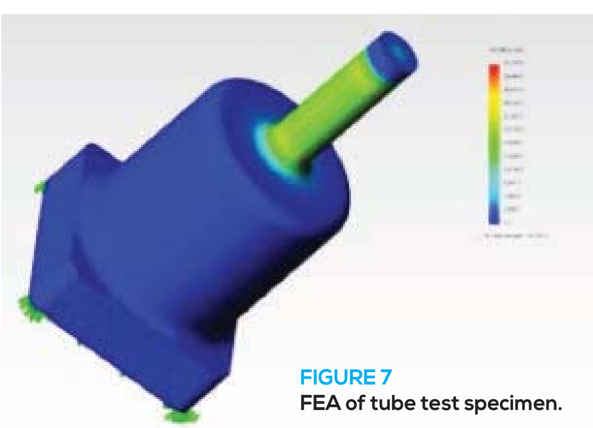

FIGURE 7
FEA of tube test specimen.

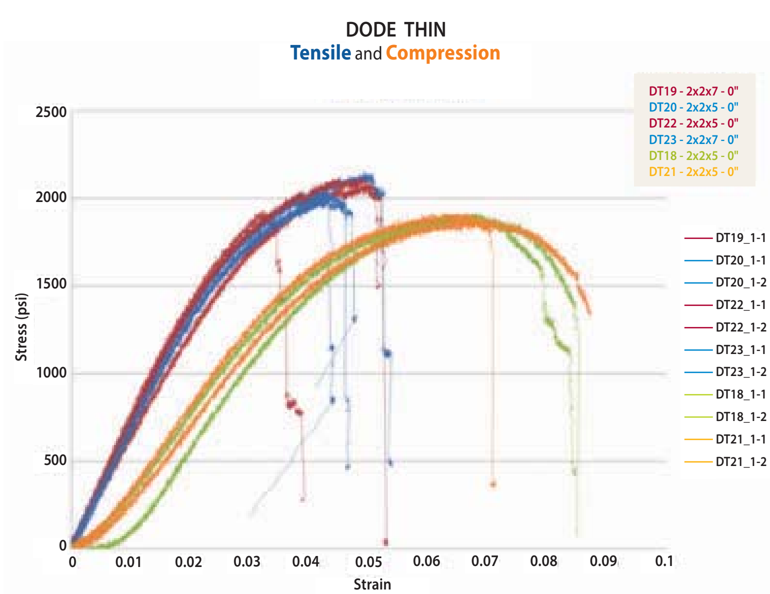

FIGURE 10 **Stress-strain of mesh structures.**

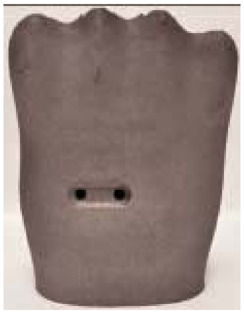

FIGURE 11 Solid palm weighing 857 grams.

FIGURE 12 Meshed palm weighing 178 grams.

residual powder that is lightly sintered onto the walls of the fluid passages. **Figure 3** shows a cross section of a set of manifolds with internal tube structures that were manufactured with S shaped fluid passages of varying diameters (1.6 mm, 2.4 mm, 3.2 mm and 3.8 mm). A close-up of the unfinished fluid passage (**Figure 4**) shows a rough surface finish. Preliminary experiments indicated that, during high-pressure tests, small particulates that were not firmly melted into the part would break loose. To resolve this problem, tests were conducted by pumping abrasive slurry through the passages. **Figure 5** shows that a more aggressive treatment (high pressures and larger particles) resulted in a smooth finish. Therefore, fluid powered systems should use some form of pumped abrasive slurry to ensure all loosely bonded particles are removed prior to operation.

FIGURE 14 Additive Manufactured involute joint.

One advantage of the additive process is that parts can be manufactured with integrated tube structures for conducting high and low pressure fluid between the supply, valves, and actuators. If the final product is porous, a fluid powered system will not be able to hold pressure and will be prone to leaks. The objective of the wall thickness study was to establish design guidelines for minimum wall thickness and wall strength for tubes for high-pressure fluid. Four separate test specimens were designed and fabricated (**see Figure 6**). Tests were validated with finite element analysis (FEA) shown in **Figure 7**. The components each had an inner diameter of 1.6 mm with different wall thicknesses (0.38 mm, 0.51 mm, 0.76 mm, 1.02 mm). The components were connected to a static hydraulic pressure source. Pressure was increased to 42 MPa. All components held pressure except one test specimen (0.38 mm wall thickness) that exhibited a slow weeping from the end. Therefore, future designs should ensure a minimum wall thickness of 0.51 mm to avoid porosity.

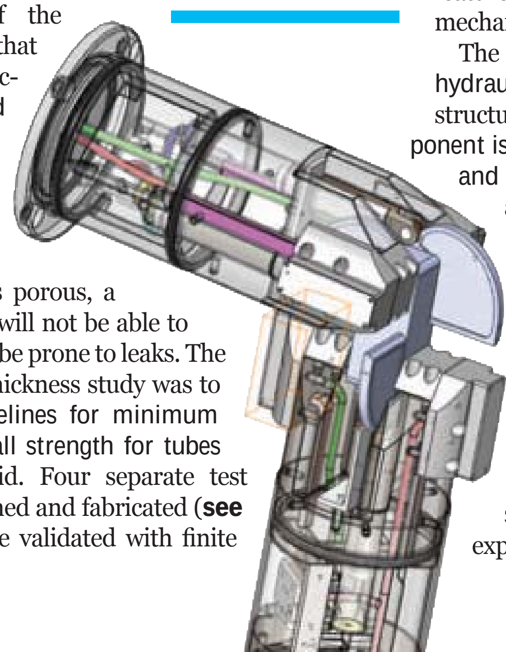

FIGURE 13 Transparent view of a hydraulic arm.

With additive manufacturing, part complexity is free. By minimizing weight, less material is used which reduces fabrication energy, build time and cost. A fundamental question is the mechanical integrity of mesh structures fabricated using additive manufacturing. Meshed tensile test specimens were manufactured using the e beam system in a variety of configurations. **Figures 8** and **9** show the tensile specimens before and after testing. The mesh consisted of a 0.51 mm diameter wire. Failure occurred along the anticipated mesh structure. **Figure 10** shows the stress-strain curve under both tension and compression. Failure of the mesh occurs at approximately 13.8 MPa. The stress-strain curve is based on the tensile cross section, not actual material cross section in the mesh. An FEA of the mesh shows that the actual peak stress in the material, given the load of 13.8 MPa, was 963.9 MPa, close to the bulk yield stress of the solid test specimens. Therefore, mesh structures with greater than 0.5 mm diameter features exhibit wrought-like mechanical properties.

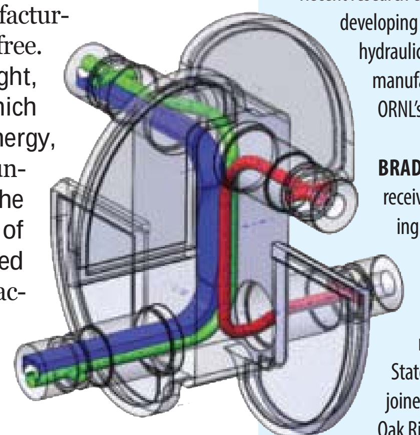

FIGURE 15 Two-axis involute cam with supply (red), return (green) and wire harness (blue).

The impact of blending hydraulic components and mesh structures within the same component is illustrated in **Figures 11** and **12** that show the palm of a fluid powered robotic hand. The solid palm weighs approximately 857 grams whereas the meshed hand weighs 188 grams (approximately 80% reduction in weight).

Once we understand the manufacturing constraints, we can begin to explore the design and fabri-

ABOUT THE AUTHORS

LONNIE LOVE, Ph.D., is the group leader of Oak Ridge National Laboratory's Automation, Robotics and Manufacturing Group. He has over 15 years of experience in the design and control of complex robotic and hydraulic systems. His primary expertise is in the areas of hydraulics, additive manufacturing, force-controlled systems, human strength amplification, high payload robotics and nanomaterials. Recent research efforts have focused on developing new lightweight low-cost hydraulic systems through additive manufacturing. Dr. Love was ORNL's 2009 Inventor of the year.

BRADLEY S. RICHARDSON received his B.S. in engineering science and mechanics from the University of Tennessee in 1979, an M.S. in engineering mechanics from the Ohio State University in 1980. He joined the research staff at the Oak Ridge National Laboratory in 1985 and has served as the principal investigator for numerous research projects. These include mobile manipulation and real-time control systems. He has been involved in multiple research projects dealing with remotely and autonomously operated vehicles and material handling systems and has implemented real-time control systems for a variety of systems.

RANDALL LIND is a mechanical engineer specializing in robotics and automation. He received an M.S. in mechanical engineering from the University of Tennessee and a B.S. in engineering from the University of Illinois. Since joining the staff of ORNL in 1987, he has led the mechanical development and design of a variety of systems including: two high payload omnidirectional vehicles, a multi-ton payload hydraulic ship motion simulator platform, a neutron imaging system, an automated surgical tool loader, hydraulic and electric robot systems, solar trackers, hydraulic pumps and valve systems and numerous sensors.

RYAN DEHOFF, Ph.D, is Technical Lead for Metal Additive Manufacturing at Oak Ridge National Laboratory and is facilitating the development of additive manufacturing of components, utilizing various techniques including electron beam melting, laser metal deposition and ultrasonic additive manufacturing. He is developing processing techniques and exploring new materials via additive manufacturing to improve energy efficiency during component production, decrease material waste, and improve material performance. Dr. Dehoff won two R&D 100

cation of fluid powered systems. Oak Ridge National Laboratory is developing a 7-degree-of-freedom robotic arm for the Office of Naval Research. The system uses cams with antagonistic linear actuators to provide rotary motions. Involute cams are used for transverse motion (i.e., shoulder, elbow and wrist pitch), barrel cams for collinear motion (i.e., wrist roll). For the involute cam, the transmission ratio (relationship between force and torque) is constant throughout the range of motion and the range of motion can exceed 180 degrees. The piston bores are integrated into the structure to eliminate hose routing and ease assembly. Joint force/torque feedback can be accomplished by measuring the cylinder pressure or stress on the pistons. The most significant advantage is that the fluid is routed through the structure, eliminating the need for hoses. Rotary unions pass the fluid from joint to joint. Supply and return lines are designed into the structure to route the fluid to valve ports. The ports for the cylinders are likewise routed through the structure from the valve to the actuators. The disadvantage was part complexity. However, with the introduction of additive manufacturing, the cost of this complexity is removed. Furthermore, this manufacturing process opens up new possibilities. As shown in **Figures 13** through **16**, fluid passages can be routed through the structure without the need for cross drilled holes or plugs. In addition, the fluid passages can be curved and even expand or contract as needed. The length of the passage is no longer restricted to straight-line holes so it is possible to reduce the fluid length. Weight can be reduced by replacing solid material with a lightweight mesh or shell. The paradigm shift is that the lighter structure takes less material and less energy to fabricate, therefore taking less time and lower cost. The lower structural weight also reduces the embedded energy required for moving the part. The impact this manufacturing process can have on the design of fluid powered systems is enormous.

FIGURE 16 Additive manufactured hydraulic power unit with motor, pump and accumulators.

As a proof-of-principle, a single-degree-of-freedom hydraulic hand was designed, fabricated and tested. **Figure 17** shows a transparent view of the hand. An electric motor is housed in the palm of the hand and serves as the primary power source. It drives a pair of cams that are 180° out of phase. The cams drive a pair of master pistons that are hydraulically coupled to slave pistons at the base of the fingers. One master piston forces the fingers to contract while the other causes the fingers to expand. **Figure 18** shows the final product, an operational hydraulic hand based on merging hydraulics and additive manufacturing.

This paper introduces the concept of blending fluid power with mechanical structure through additive manufacturing. The specific advantages are reduced weight, potential for lower cost, and reduced part counts. The results verified the present limits of manufacturing, validating mechanical properties and operational tolerances. Future work will focus on expanding integration to include wiring, sensing and integration of electronics. ■

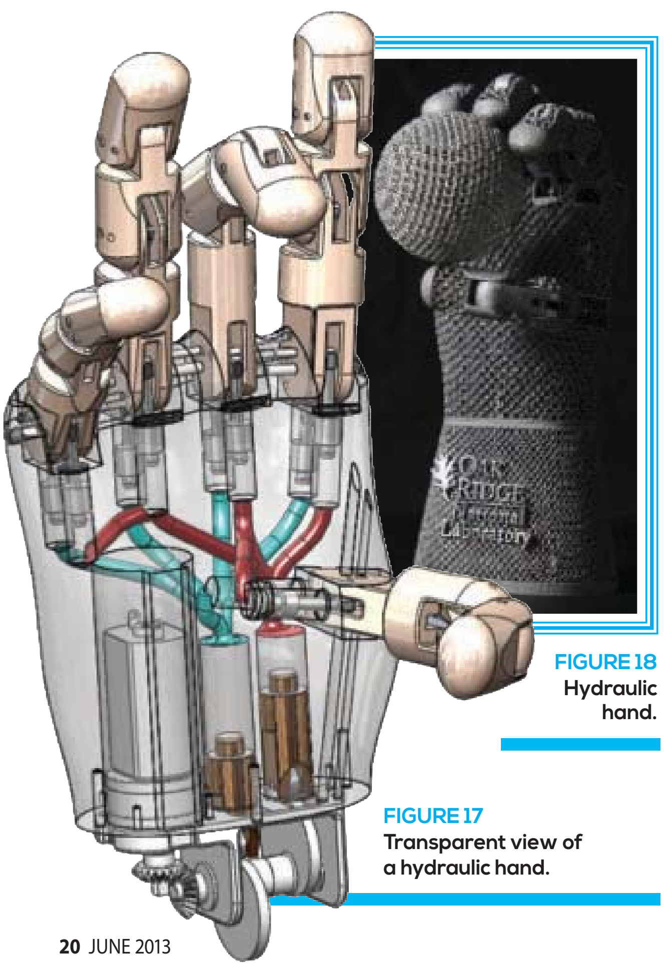

FIGURE 18 Hydraulic hand.

FIGURE 17 Transparent view of a hydraulic hand.

ABOUT THE AUTHORS

awards in 2012 for NanoSHIELD Coating and Low-Cost, Lightweight Robotic Hand Based on Additive Manufacturing.

WILLIAM PETER, Associate Division Director of the Materials Behavior and Processing for Materials Science and Technology Division at ORNL has been the principal investigator for over 20 R&D projects including research in powder metallurgy, nanocrystalline materials, additive manufacturing, and lightweight alloys. He has investigated the laser fusing of wear resistant coatings, and the consolidation of titanium powders for 8 years. In 2012, Dr. Peter was awarded three R&D 100 Magazine awards, including additive manufacturing of robotics, development of a roll mill technology, and the development of laser-fused NanoSHIELD coatings.

LARRY LOWE has worked for over two years as a technician specialist with Additive Manufacturing at Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF). He is working with ORNL's researchers to develop new processes for laser and electron beam engineered net shaping of alloys and polymer-based additive manufacturing components. He currently operates the ARCAM, STRATASYS, SOLIDICA and POM units at the MDF. Larry was on two winning R&D 100 teams in 2012 for NanoSHIELD Coatings and Lightweight Robotic Hand Based on Additive Manufacturing from Oak Ridge National Laboratory.

CRAIG BLUE is Director of the Manufacturing Demonstration Facility and the Advanced Manufacturing Office at Oak Ridge National Laboratory and has led development of ORNL's Advanced Manufacturing Initiative, bringing together a team of scientists and engineers to gain nationwide recognition for leadership in manufacturing technologies including Low-Cost Carbon Fiber and Additive Manufacturing. He holds a Ph.D. in materials science from the University of Cincinnati. He is an ASM Fellow and has received numerous honors including ten R&D 100 Awards, and the UT Battelle Distinguished Engineer. He has over 90 open literature publications, 15 patents, and over 80 technical presentations.

ACKNOWLEDGEMENTS

This work was partially funded by ORNL Seed Money Project number 05958, the Office of Naval Research Project number N0001412IP20002, the U.S. Department of Energy's Advanced Manufacturing Office and the Defense Applied Research Program Agency Project number 1868-V404-11.