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FREEFORM FLUIDICS

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Abstract

This work explores the integration of miniaturized fluid power and additive manufacturing. Oak Ridge National Laboratory (ORNL) has been developing an approach to miniaturized fluidic actuation and control that enables high dexterity, low cost and a pathway towards energy efficiency. Previous work focused on mesoscale digital control valves (high pressure, low flow) and the integration of actuation and fluid passages directly with the structure, the primary application being fluid powered robotics. The fundamental challenge was part complexity. ORNL's new additive manufacturing technologies (e-beam, laser and ultrasonic deposition) enables freeform manufacturing using conventional metal alloys with excellent mechanical properties. The combination of these two technologies, miniaturized fluid power and additive manufacturing, can enable a paradigm shift in fluid power, increasing efficiency while simultaneously reducing weight, size, complexity and cost.

This paper focuses on the impact additive manufacturing can have on new forms of fluid power components and systems. We begin with a description of additive manufacturing processes, highlighting the strengths and weaknesses of each technology. Next we describe fundamental results of material characterization to understand the design and mechanical limits of parts made with the e-beam process. A novel design approach is introduced that enables integration of fluid powered actuation with mechanical structure. Finally, we describe a proof-of-principle demonstration: an anthropomorphic (human-like) hydraulically powered hand with integrated power supply and actuation.

Keywords: Additive Manufacturing, Robotics, Fluid Power

1. Introduction

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 and sensors are all fabricated with different processes and then integrated into the final system during the assembly process (see Fig. 1). As a result, systems tend to be larger, heavier, more complex and expensive. Compare this to the human form that is a phenomenal model of mechanical design (see Fig. 2). We have 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.

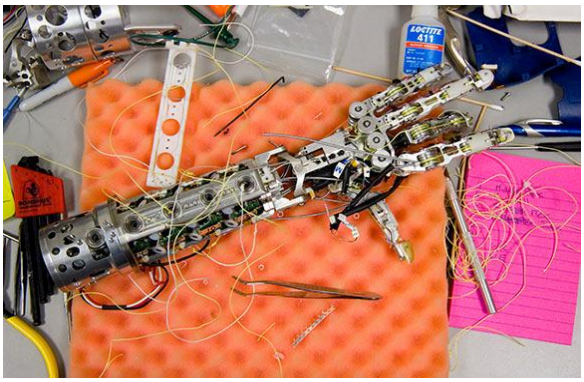

Fig. 1. Currently, components made separately are extremely complex and expensive.

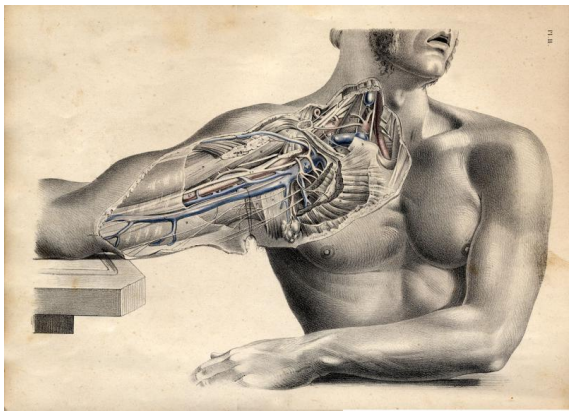

Fig. 2. Cross section of the human form.

2. Additive Manufacturing

Emerging additive manufacturing processes are enabling a fresh new perspective on the design of mechanical systems. Additive manufacturing, like nature, builds structures layer by layer. This approach to manufacturing enables the synthesis of components and systems that have previously been impossible. The first additive processing systems based on stereolithography (3-dimensional printing) were introduced in the late 1980s.[1] Today, there are many different approaches (Stereolithography (SLA),[2] Selective Layer Sintering (SLS),[3] Fused Deposition Modeling (FDM),[4] Solid Ground Curing (SGC)[5] and Laminated Object Manufacturing (LOM)[6] for achieving the same purpose, constructing a part layer by layer. The primary advantage of additive manufacturing is that complexity is cost-free. Unlike traditional machining practices where you begin with a block of material and remove material to create your part, additive manufacturing constructs parts through layer-by-layer deposition of material. Parts can be made with voids and mesh structures, reducing weight, energy and material usage. The earliest systems focused on polymers and plastics. Today, there are numerous metal-based systems.

The most common form of additive manufacturing is based on FDM (see Fig. 3). This approach uses a polymer filament and extrudes a small bead of plastic and has tremendous market acceptance led by Stratasys.[7] The primary advantage is low capital procurement costs and large-scale systems. There are many material options ranging from softer acrylonitrile butadiene styrene plastics to relatively high strength polymer (Ultem). There are also multiple options for the support material, from break away to soluble. The primary disadvantage is part porosity and z-strength (the layer to layer strength).

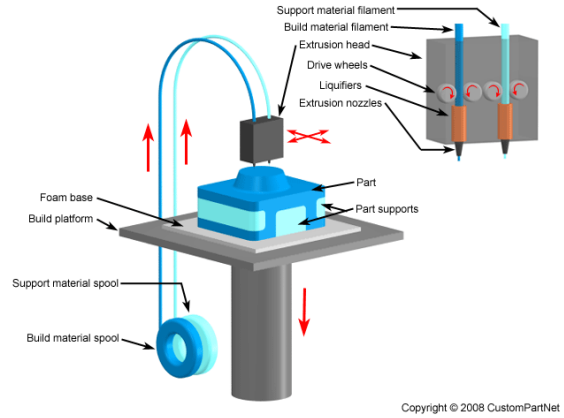

Fig. 3. Fused Deposition Modeling.

Selective laser sintering systems (see Fig. 4) are available for both polymers and metals. The advantage of laser based systems, such as EOS, Rennishaw, and Optomec, is part resolution. Parts can be manufactured that have extremely smooth surface finish and fine resolution, minimizing the need for post process finishing. Many commercial systems use a powder bed to provide mechanical support. A raking system spreads a thin layer of powder over a vertical table. The laser then melts the powder at the part's cross section. The table moves downward and then repeats the process. Unmelted powder, that can be recycled, provides mechanical support. The disadvantages are deposition rates, part sizes and residual stress.

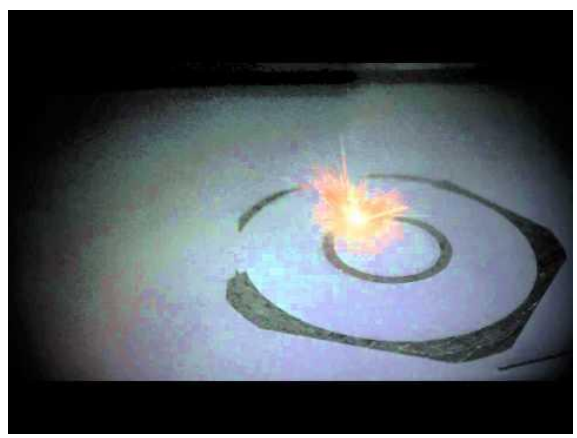

Fig. 4. Selective Laser Sintering.

In a process very similar to selective laser sintering, Electron beam (e-beam, see Fig. 5) melts metal powders. As with the laser sintering powder bed approach, a raking system deposits a thin layer of metal powder over a vertical table. An e-beam is guided over the powder and melts the material at the

part cross section. One of the advantages of the e-beam is the ability to rapidly split the beam and, with a single electron gun, run parallel melt pools simultaneously, significantly increasing deposition rate. In addition, the e-beam system uses the same gun to preheat the powder. The powder bed is maintained at an elevated temperature to reduce residual stresses as the part is being fabricated. The primary disadvantage of e-beam systems is that, unlike the laser system, the support powders are partially sintered. It is still possible to recycle unmelted powder, but it becomes more difficult to remove the material from small passages and cavities. With each of these systems, it is easy to manufacture lightweight mesh structures (see Fig. 6).

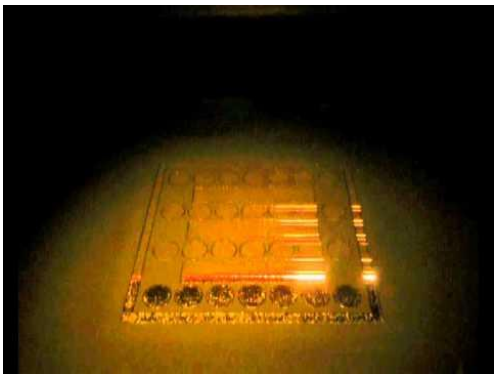

Fig. 5. Electron Beam Melting.

Ultrasonic additive manufacturing uses a combination of additive and subtractive techniques enabling precise machining of intricate components and channels while simultaneously merging dissimilar materials (see Fig. 7). This low temperature process enables incorporation of sensitive materials such as sensors, wires and fiber optics (see Fig. 8) directly into the structure. However, this technology is still in the research and development phase.

Fig. 6. Engine part with lattice structure.

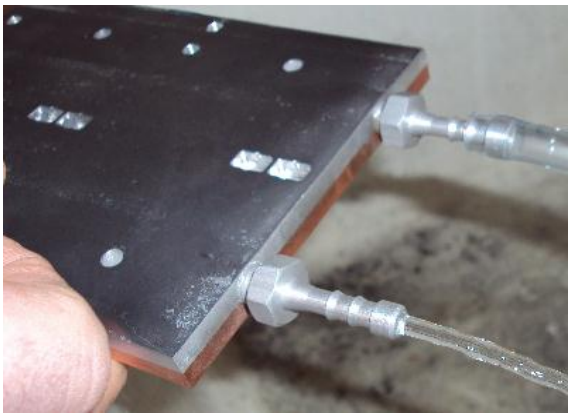

Fig. 7. Ultrasonic fusion of dissimilar material.

Fig. 8. Integration of structure and fiber optics.

The objective of this work is to explore the integration of mesofluidics with additive manufacturing, designing mechanical systems that integrate hydraulic actuation, power and control with the mechanical structure *during* the fabrication process. Each of these methodologies can have an impact on fluid powered systems. Polymer-based systems have the strength suitable for pneumatics. It is possible to directly manufacture custom pistons or incorporate pneumatics directly into a structure. Laser systems have merit in both manufacturing of parts as well as adding surface treatments to increase hardness. Ultrasonic systems, while the least mature of the technologies, hold great promise in terms of integrating electronics with the structure. The majority of the work presently underway at ORNL is focusing on e-beam systems.

ORNL, motivated by breakthroughs in previous Defense Advanced Research Projects Agency (DARPA) programs (Titanium and Revolutionizing Prosthetics), has developed unique capabilities that, when blended, enable a revolutionary new approach to the design and fabrication of fluid powered systems. Mesofluidics, developed under DARPA's Revolutionizing Prosthetics Program[8] and the Office

integrated systems. The power and stress levels of the hydraulic systems are approximately an order of magnitude greater than human muscles, enabling strength and packaging superior to nature. Today, mesofluidic devices are manufactured using conventional fabrication practices. The integration of the actuations with the structure has the advantage of compactness, ease of assembly and maintenance with increased reliability. The penalty has been the complexity and cost of fabrication of the parts.

With respect to fluid power, 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. We describe the merging of fluid power and additive manufacturing as freeform fluidics. It is defined as freeform due to the fact that prior manufacturing constraints are removed. What makes freeform fluidics unique is the ability to integrate structure, actuation, power, sensing, 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.

3. Mechanical Testing

One of the primary issues regarding parts manufacturing using the additive manufacturing process is the mechanical properties. Table 1 lists the results of tensile mechanical tests of parts manufacturing in various positions and configurations within the build volume using the Arcam e-beam system. The 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.

3.1 Minimum Wall Thickness

Prior results show that components manufacturing with the e-beam system exhibit wrought material properties. The next set of experiments explored the porosity of the components. Parts are fabricated by fusing fine powder. 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 Figs. 9 and 10). 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 41.4 MPa. All components held pressure. However, one test specimen (0.38 mm wall thickness) had a slow weeping from the end. Figures 5 and 6 show the FEA model and actual components. Therefore, ***future designs should ensure a minimum wall thickness of 0.51 mm to avoid porosity.***

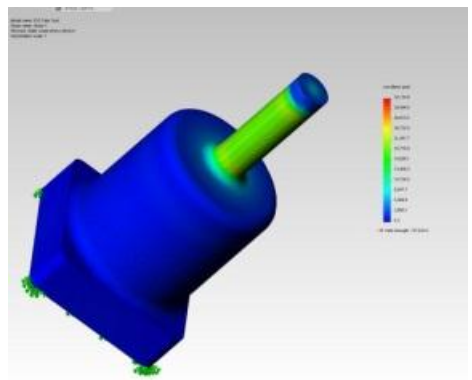

Fig. 9. Tube test specimen.

Fig. 10. Test specimens.

3.2 Mesh Structures

With additive manufacturing, 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 structure fabricated using additive

manufacturing. Meshed tensile test specimens were manufactured using the e-beam system in a

variety of configurations. Figures 11 and 12 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 13 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 analysis of the mesh shows that the actual peak stress in the material, given the load of 13.8 MPa (e.g., a similar load condition as in Fig. 14), was 963.9 MPa, close to the bulk yield stress of the solid test specimens.

Table 1. Caption Here

Plate Information	Thermal Treatment	Sample Number	Yield Strength MPa	Ultimate Strength MPa	Elongation %
Old Build Version **Flat build**	750°C 1.5 hr	1	994.9	1043.9	15.0
		2	1024.6	1077.0	14.0
		3	1018.4	1065.9	13.7
		Average	**1012.8**	**1062.5**	**14.2**
Tensile specimens were cut from the plate parallel to the flat surface.	750°C 1.5 hr + 1000°C 1 hr + 750°C 1.5 hr	1	908.7	930.8	7.3
		2	932.9	959.1	9.7
		3	897.0	914.3	8.7
		Average	**912.9**	**934.9**	**8.6**
Specimens were tested perpendicular to the columnar grains.	750°C 1.5hr. + 1200°C 1 hr + 750°C 1.5 hr	1	906.0	932.9	4.7
		2	917.7	937.7	7.3
		3	861.8	864.6	3.7
		Average	**894.9**	**911.5**	**5.2**
	Tensile Specimen Orientation to Columnar Grains				
Build Date 5-7-11 Version 3.2.36 **Vertical build**	Segment 4: As-Built - Perpendicular	1	1024.6	1065.9	12.0
		2	999.7	1045.2	12.7
		3	977.0	1014.9	11.7
		Average	**1000.4**	**1041.8**	**12.1**
	Segment 5: As-Built - Parallel	1	1009.4	1043.2	13.0
		2	1037.7	1074.9	14.3
		3	1048.0	1089.4	15.7
		Average	**1031.4**	**1069.4**	**14.3**
	Segment 3: 750°C 1.5 hr - Perpendicular	1	985.3	1031.4	11.3
		2	1012.8	1057.7	10.0
		3	1004.6	1050.8	11.7
		Average	**1001.1**	**1046.6**	**11.0**
	Segment 6: 750°C 1.5 hr - Parallel	1	947.9	1012.2	10.0
		2	985.3	1028.0	17.7
		3	1005.9	1037.0	5.4
		Average	**988.7**	**1025.9**	**11.0**
	Grade 5 Specification		827.4	896.3	10

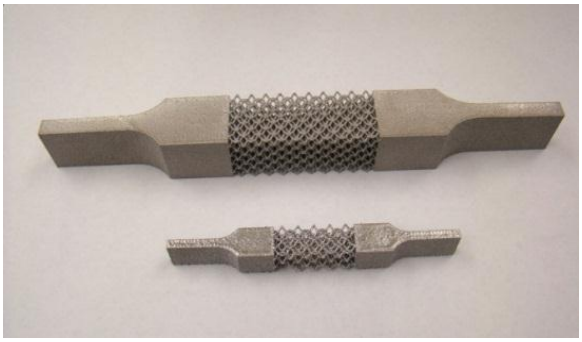

Fig. 11. Meshed tensile member.

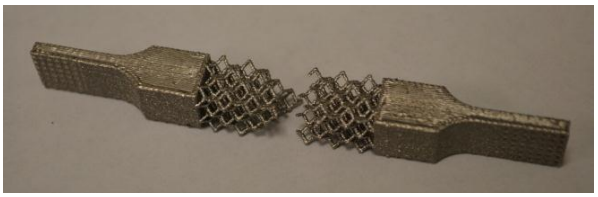

Fig. 12. Failure mode.

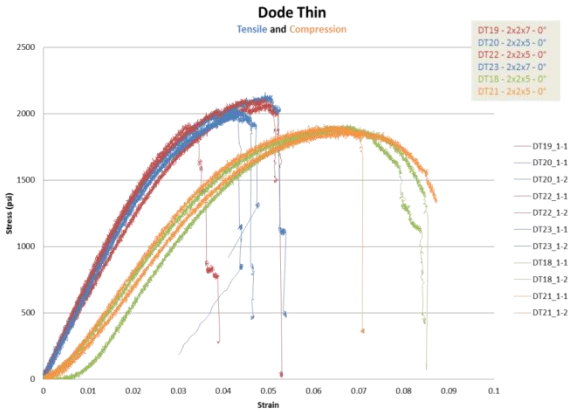

Fig. 13. Stress-strain of mesh structures.

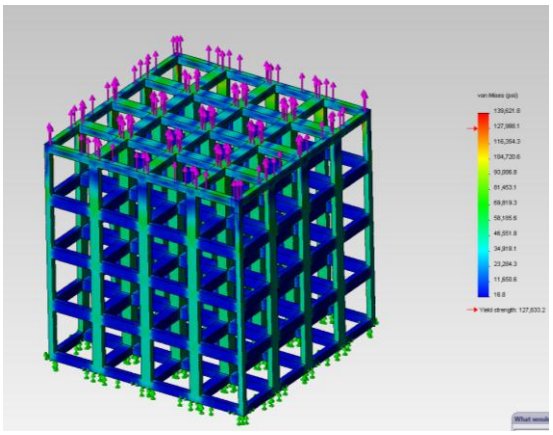

Fig. 14. FEA of mesh.

The impact of blending hydraulic components and mesh structures within the same component is illustrated in Figs. 15 and 16 that show the palm of a robotic hand. The solid palm weighs approximately 857 grams whereas the meshed hand weighs 188 grams (approximately 80% reduction in weight).

Fig. 15. Solid palm weighing 857 grams.

Fig. 16. Meshed palm weighing 178 grams.

3.3 Material Removal

Additive manufacturing requires the use of a support structure when building parts that have overhangs. For powder bed systems, material that is not melted serves as the support. When the part is

complete, the supporting material is removed. One of the primary issues is surface finish. Figures 17–19 shows a manifold that has 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 (Fig. 20) 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. Figures 18 and 21 shows that moderate abrasives removed all unsintered particles but left a slightly rough surface finish. Figure 18 and Fig. 22 show 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.

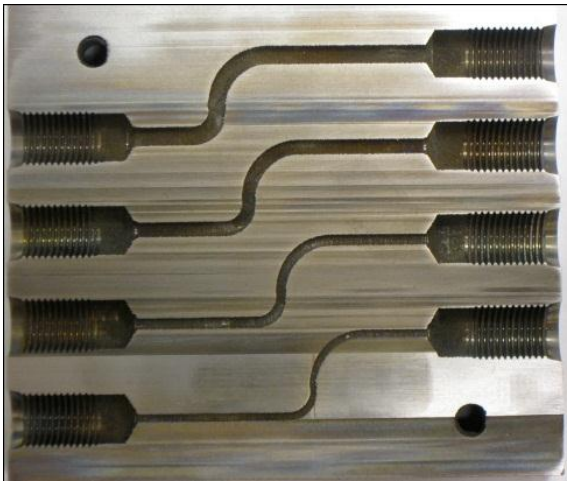

Fig. 17. No finishing.

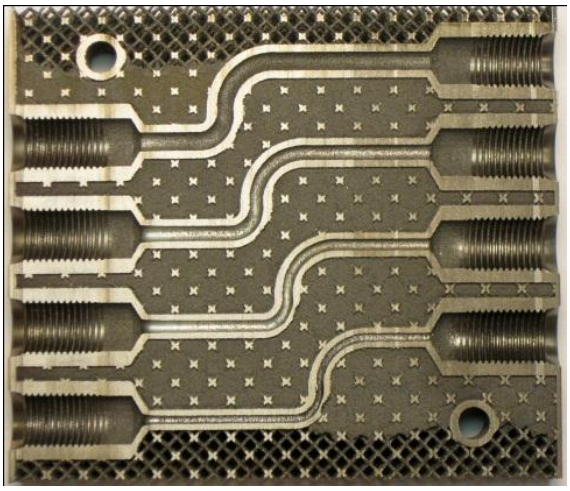

Figure 18: Moderate finishing

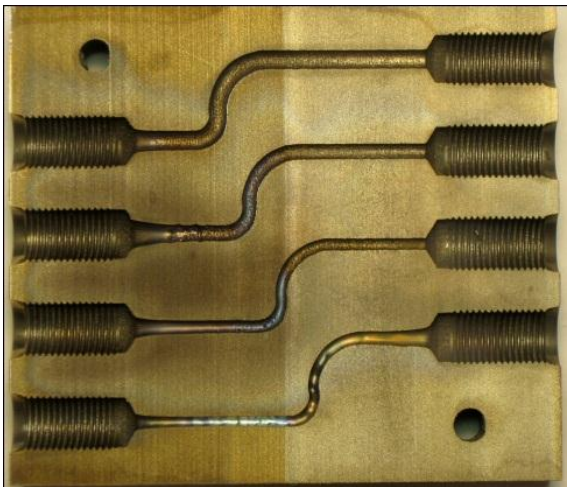

Fig. 19. Aggressive finishing.

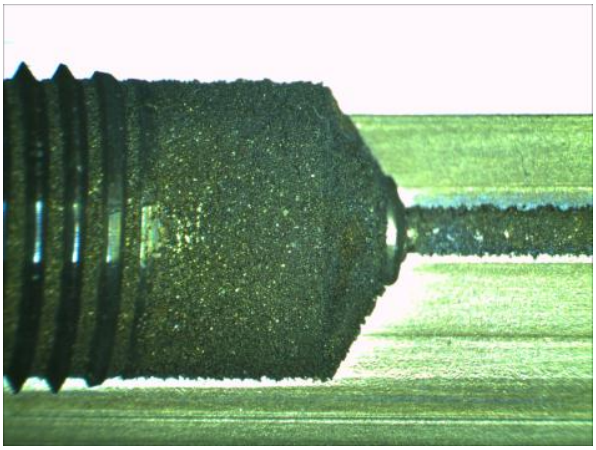

Fig. 20. No finishing (close-up).

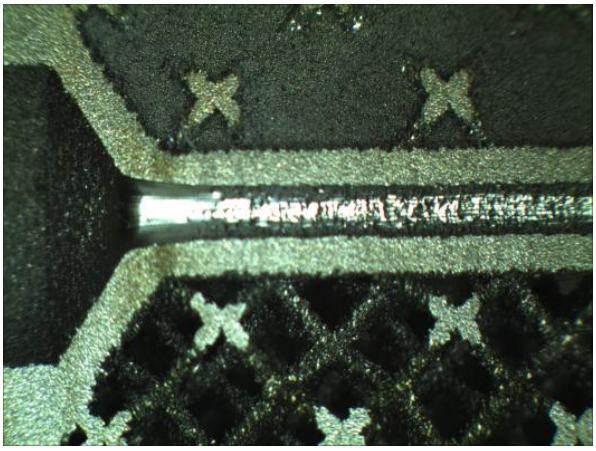

Fig. 21. Moderate finishing (close-up).

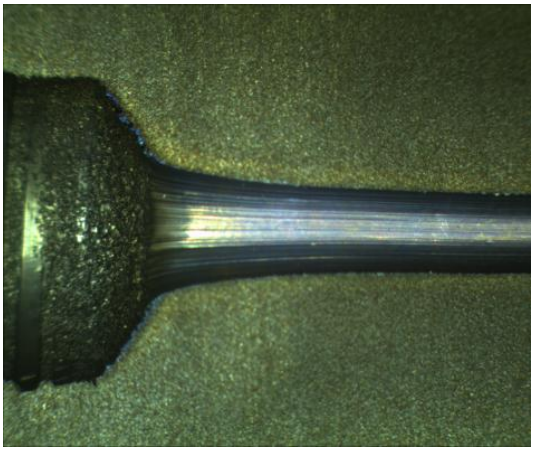

Fig. 22. Aggressive finishing (close-up).

3.4 Mechanical Design

Once we understand the manufacturing constraints, we can begin to explore the design and fabrication of fluid powered systems. ORNL is developing a 3-degree-of-freedom robotic arm, shown in Fig. 11. The system uses cams with antagonistic linear actuators to provide rotary motions. The piston bores are integrated into the structure to eliminate hose routing and ease assembly. For transverse motion, involute cams transform the linear motion of the pistons to rotary motion of the joints. For collinear joints (wrist roll, humeral rotate), barrel cams transform the linear motion of the actuators to the rotary motion of the joints. Each joint is powered by a pair of antagonistic pistons. 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. Joint force/torque feedback can be accomplished by measuring the cylinder pressure or stress on the pistons. Since the piston bores are fixed and are a part of the structure, the wires are stationary. 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.

This approach to hydraulic robot design was developed by ORNL. 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 Figs. 21–25, fluid passages can be routed through the structure without the need of cross drilled holes or plugs. Furthermore, the fluid passages can be curved and even expand or contract as needed (see Fig. 24). 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. In addition, 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.

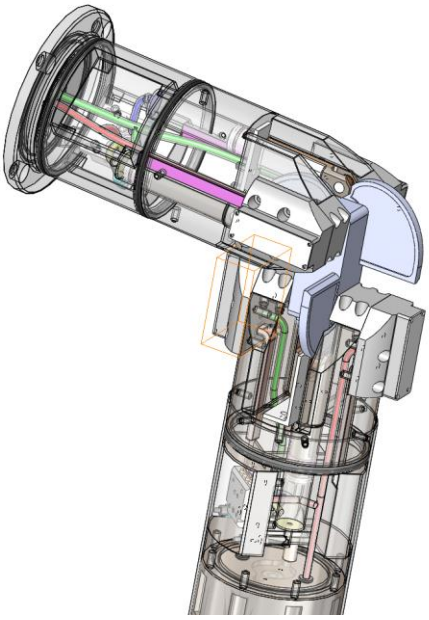

Fig. 23. Transparent view of a hydraulic arm.

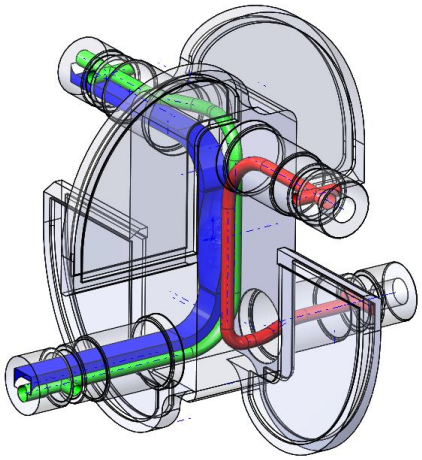

Fig. 24. Two axis involute cam with supply (red), return (green) and wire harness (blue).

3.5 Hydraulic Hand

As a proof-of-principle, a single-degree-of-freedom hydraulic hand was designed, fabricated and tested. Figure 25 shows a transparent view of the hand. An electric motor is housed in the palm of the hand and serves are 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 pistons at the base of the hand. One master piston forces the fingers to contract while the other causes the fingers to expand. Figure 26 shows the final product, an operational hydraulic hand based on merging hydraulics and additive manufacturing.

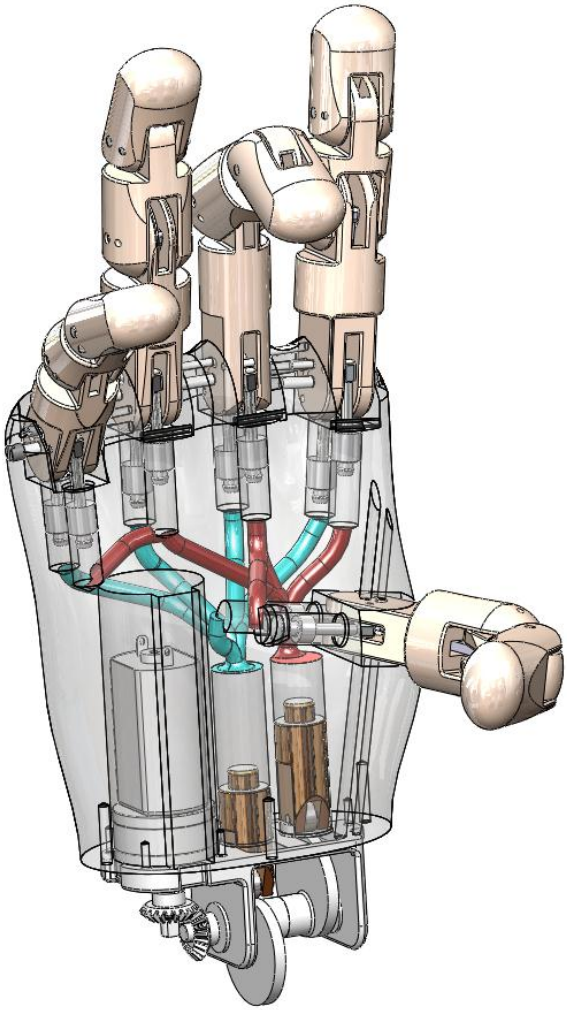

Fig. 25. Transparent view of a hydraulic hand.

Fig. 26. Hydraulic hand.

4. Conclusion

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.

Acknowledgements

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