

CUSTOM, INTEGRATED, PNEUMATIC, ROTARY ACTUATOR FOR AN ACTIVE ANKLE-FOOT ORTHOSIS

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ABSTRACT

End-use objects produced via additive manufacturing (AM) are on the rise and new applications in the fluid power industry are emerging. Recently, a custom, pneumatic, rotary actuator was designed and additively manufactured for integration into an active ankle-foot orthosis that is being developed in the National Science Foundation's Center for Compact and Efficient Fluid Power. All necessary plumbing, between the valves and vanes, is integrated into the additively-manufactured housing of the actuator; and, the silicone translating seals were vacuum-transfer molded using additively-manufactured molds and inserts. This non-conventional actuator has more theoretical torque, and weighs less, than the off-the-shelf component that it replaced. Further development will reduce seal leakage, and optimize designs for additional mass reduction. Results-to-date are presented, in addition to several other examples of the growing use of AM in the fluid-power industry.

1. INTRODUCTION

Purpose

Applications of AM are expanding each year in a multitude of industries due to increased AM awareness (through education), process and material improvements, and system cost reductions. The fluid power (FP) industry has used AM for NPD for well over a decade, creating prototype systems for form, fit, function and production. Now, end-use AM components and systems are becoming a reality and this research project demonstrates mass reductions and flexible reconfiguration options enabled by AM. The challenges faced on this project were to produce a reduced-mass rotary actuator for an Active-Ankle-Foot-Orthosis (AAFO) within a tight timeline with increased torque compared to the state-of-the-art off-the-shelf actuators available. This project also served to fulfill a masters capstone design thesis for the completion of MSE-ME. This paper has been prepared to share this example of AM technologies being leveraged directly and indirectly to solve a real-world problem in the FP industry.

Scope

The approach to solving this problem was initially to create a model using National Instruments LabView software to aid in establishment of a "working window" for size and performance of the actuator. Next, an actuator was designed based on existing off-the-shelf actuators with the added degrees of design freedom offered by AM fabrication. And finally, the design was refined using several FEA packages to further reduce mass and increase housing stiffness. A combination of AM-based fabrication and conventional machining was used for this time-critical project. Other possible solutions were considered to generate the needed torque including mechanically-linked cylinders, motors, and a yet-to-be-disclosed fluid power actuator.

Within the time constraints the “lower-risk” AM-based rotary actuator was chosen. The most critical considerations in choosing the path for this actuator included time, mass, torque and size. The timeframe was short at less than 25 weeks and the mass needed to be less than one kilogram for the entire AAFO. The torque target was 6-10 N-m and the size needed to be reasonable, with a profile and compactness improvement over the current design.

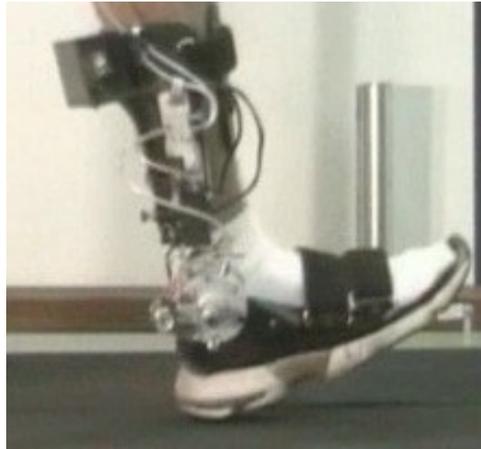


Figure 1. Prototype 1 Active-Ankle-Foot-Orthosis (AAFO), UIUC.

Background

The Center for Compact and Efficient Fluid Power (CCEFP) is a National Science Foundation (NSF) Engineering Research Center (ERC) based at the University of Minnesota. The CCEFP is a collaborative network of researchers, professors and industry partners working to advance the field of fluid power technology. One of the Center’s design platforms, designated Test Bed 6 (TB6), embodies research and design at the 10-to- 100-Watt-system range and is currently the lowest-powered test bed of the Center. TB6 currently features the study of Active Ankle Foot Orthosis (AAFO) technology. These are braces that help people who have lost mobility in their ankle(s) by providing force to assist toe-up and toe-down motion. Under the support of the Center for Compact and Efficient Fluid Power (CCEFP) the UIUC had constructed an AAFO using an off-the-shelf rotary actuator and the unit, shown in Figure 1, was functioning as intended with a few limiting factors including size, mass, and torque. The rotary actuator provided more rotation than needed, 90 degrees. The specifications for the replacement actuator were as follows:

- Mass less than 1 kg for entire AAFO
- Rotation of greater than 25 degrees
- Size and profile smaller than prototype I
- Torque target of 6-10 Nm
- Operating pressure of 0.35MPa

Efforts on prototype II began during mid-summer of 2009. Clinical testing of the AAFO was scheduled to begin in late 2009 and the timely replacement of the “bulkier” configuration was considered time-critical. To achieve the goal of upgrading the prototype I AAFO to meet the specifications conventional actuator fabrication techniques were not able to provide the addition of a “third” blade in the small actuator package needed to achieve the torque at the lower



Figure 2. Fluid Power Actuators Grown Directly using Additive Manufacturing (2a-Wisner-2004, 2b-Zientarski-2009, 2c-Kang-2004).

pressure and reduced mass. To address these design constraints AM was identified as the key enabling technology to deliver the actuator in the desired time-frame to meet specifications.

The theory and knowledge-base informing the FP side of the project relied on basic fluid mechanics theory. The AM side of this project drew from a general understanding of the capabilities and limitations of AM obtained from experts and literature as well as suppliers and material property data-sheets. A number of projects leveraging AM for fluid power components and systems have been performed at the MSOE Rapid Prototyping Center including several by former REU students. The first related project was titled, “Direct Manufacturing of Fluid Flow Devices in a Single Build” by Wisner (shown in Figure 2a) and a more recent project titled, “Additive Manufacturing of Fully Functional Fluid Power Components,” by Zientarski (Figure 2b). There are many examples of AM being used to create desirable FP actuator movement through the use of additive technologies including the micro-fluidic actuator shown in Figure 2c. This project leveraged the capability of AM to grow complex internal structure combined with the tight-tolerance capability of traditional material removal methods, specifically CNC milling and turning.

Actuator Design

The design goal was to reduce the number of individual components, and the size of the actuator, in order to reduce both mass and potential leak sites. The pneumatic diagram shown in Figure 3 illustrates the sub-system functions to meet the specifications for the AAFO. The grey shaded region includes those components integrated into the custom fluid-power system. The power source is regulated externally to provide two separate pressure levels, allowing for the generation of different torque outputs in either direction of rotation. Actuation is controlled by two, solenoid, directional-control valves; and, the pressure in the actuator is released to atmosphere through an adjustable flow-control valve and silencer. This setup provides more control over rate-of-motion and exhaust noise.

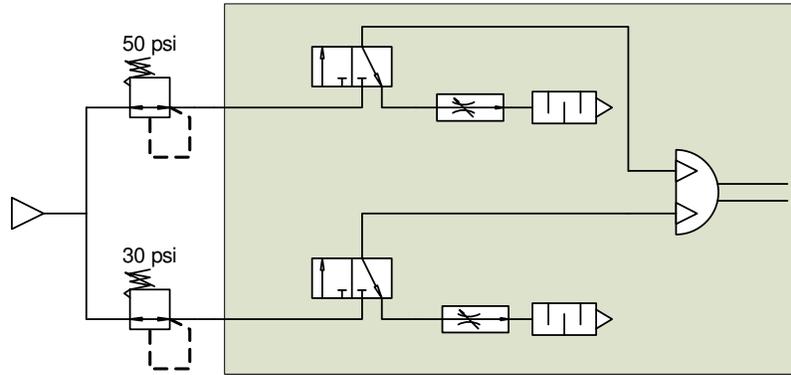


Figure 3: Pnuematic Diagram of Prototype System

One of the most outstanding features of this actuator is the use of blind, internal passages to connect different control volumes. Actuators with two rotor blades are quite common and typical methods of connecting the chambers use conventional machining operations, e.g. a hole drilled tangentially through the center shaft. Adding a third blade complicated the typical two-

blade form, necessitating an alternate approach. As shown in Figure 4, the red sections needed to be connected and supplied the same pressure -- likewise for the blue sections.

One design path would have been to attempt drilling three holes in the center shaft that met in the center at one location and three more holes at a parallel location along the shaft. This method would have the top two chambers pictured in Figure 4 supplied by the manifold and the other two chambers would be connected through the top chamber.

The preferred design utilizes the unique capabilities of AM to create channels that could only be generated via an additive process. There is no line-of-sight for a tool to create these circumferential channels that connect all of the chambers to their respective valves, and allow for more uniform pressurization. Figure 4 shows these channels colored to match the control volumes (blue channels are hidden behind red).

Shown in Figure 5 are the design revisions of the actuator. Clearly visible is the reduction in mass and component integration of the design. Revision 4 was the final design. Threaded brass inserts were placed with epoxy into the housing in several areas where fasteners required significant torque.

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Actuator Construction

As mainstream as stereolithography (SLA) has become, there are limitations to the dimensional tolerances that can be achieved. Some of the features of the actuator required tight tolerances. For this reason, these areas had material (machine stock) added to them so that they could be machined to tolerance after the part was grown. The areas colored red in the Figure 6 were machined to improve the surface finish and tolerance of those surfaces as they are critical to operation of the actuator.

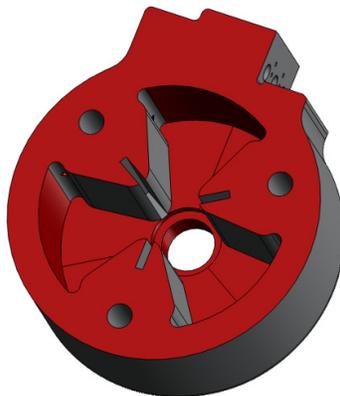


Figure 6: Machined Areas of AM Housing Component

The seal located between the actuator housing and the back plate was created using a laser cutting system. The laser cut out a the seal, shown in Figure 7, from a sheet of Buna-N 70A durometer rubber.



Figure 7: Seal Between Back Plate to Actuator Housing

This method of making seals was found to work well for static seals where the faces cut by the laser are not critical for sealing. Using only the as-manufactured top and bottom faces of a rubber gasket sheet provided an adequate seal between the back plate and the actuator housing.

The most challenging part of this design and construction was the fabrication of the dynamic seals that reside in grooves on the three rotor blades (Figure 8) and in the actuator housing resulting in a moving seal on the rotor shaft. Their function is to form a seal between the rotor blade (or shaft) and the housing surfaces to maintain a pressure differential as needed to generate torque output while at the same time providing a sliding seal within the housing. The challenge, then, is that the seals must: be rigid enough to resist deformation at maximum operating pressure; slide with minimal friction across the sealing surfaces; and, conform to any imperfections.

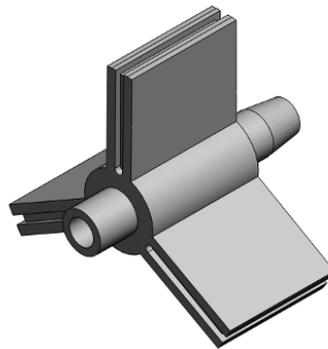


Figure 8: Three-bladed Rotor and Shaft.

The initial attempts to create the dynamic seals were made using the same laser-cutting technique used for the housing-to-back-plate seal. It was desired to use a low-durometer rubber for these seals so they would be more likely to conform to the surfaces. The laser cutter could cut shore 70A rubber; but it would simply melt rubber with shore hardness less than 50A. No usable seals could be made out of the lower durometer rubber using the available laser cutter system. The shore 70A rubber was used for many attempts to make dynamic seals. Due to the width of the laser beam, there is a degree of inaccuracy in converting the CAD file to a seal; this is also affected by the precision of the linear stages and focus of the laser beam. The laser cut creates an irregular finish on the cut faces that resulted in leakage.

Several sets of seals were made with varying widths. The goal was to find the proper thickness of seal that would create the optimal tradeoff between sealing and friction. On one occasion, when testing these seals the actuator did move, albeit with very little torque. This was an encouraging moment; however, on the following day, the lubricant used in the actuator had been absorbed by the rubber causing it to swell. The actuator essentially locked up.

A superior method of forming these insert seals was later used, again leveraging additive manufacturing. A single-cavity silicone-transfer-mold was constructed from tool steel, and included a receptacle for an AM mold insert that contained the geometry of the seals, as well as the mold gating. Figure 9 shows the mold design, with the top portion rendered transparent. Tool steel was chosen because it was readily available in plates, and was already ground and lapped to an appropriate surface finish for the mold. Steel is also durable enough to withstand the frequent tightening and loosening of the bolts that hold the mold halves together. The AM mold insert (shown to the lower right in Figure 9) was thin, at 1.6 mm (1/16 in), to allow rapid build-times, therefore, multiple iterations could be made if necessary to adjust size and design to achieve a functional seal. A very low (shore10A) durometer silicone was cast to produce a set of low durometer seals.

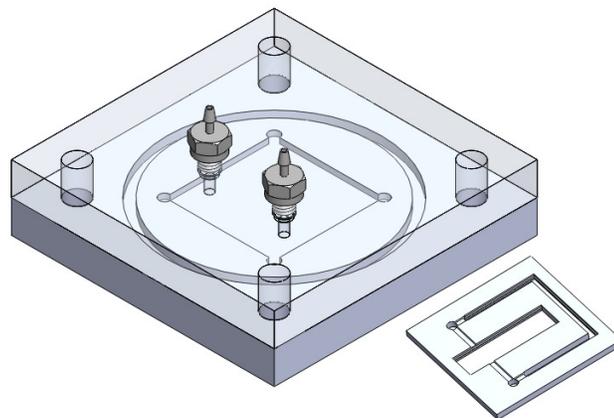


Figure 9: Steel Transfer Mold and AM Mold Insert

Over-Molded Seals

Additionally, considerations were made for over-molding the blades of the actuator rotor with an elastomer. The lower shear loading at the blade tip, relative to the root, afforded a radial,

tapered reduction in blade cross-sectional area, thereby increasing the area available for an elastomeric seal. Once again employing additive manufacturing, a silicone-transfer mold was fabricated using the Watershed™ resin, as was a prototype of the proposed rotor geometry (Figure 10). The transparency of this material, achieved with moderate sanding and buffing, allowed for inspection of the silicone flow; so that, trapped air, and any other potential defects, could be addressed before the material cured.

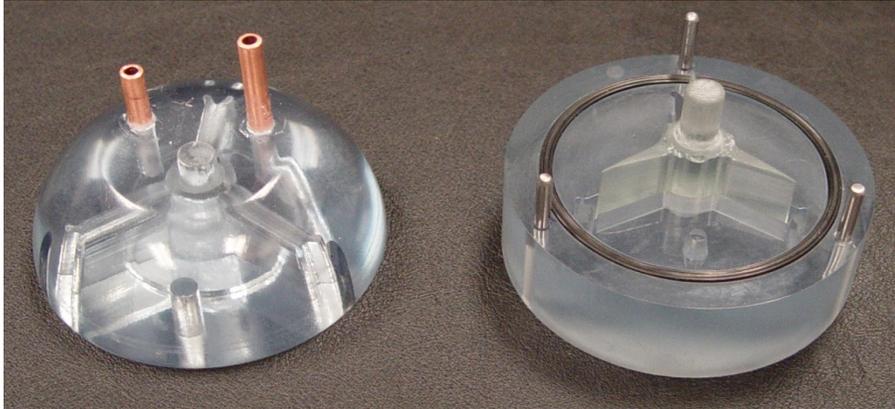


Figure 10: Vacuum-transfer Mold for Overmolding the Blades of the Actuator Rotor with an Elastomeric-seal Geometry.

Results and Discussion

Through mass- and size-reducing design, the custom actuator is significantly smaller, lighter and more compact than the original prototype. It is difficult to give a direct comparison of the first prototype actuator to the new prototype actuator because the new actuator incorporates many components in its assembly. However, Table 1 shows the contrast in mass, along with the performance specifications of the prototype I actuator alone to the custom actuator.

Table 1: Revision Comparison

	Prototype I	Custom Actuator
Components	SMC Rotary Vane Actuator CRB2BW40-90D-DIM00653 (alone, no valves/lines/etc.)	Rotary Vane Actuator, two directional control valves, two flow control valves, orthotic strut brace, electronics board
Mass	390 g	372 g
Torque	5 N-m at 0.35 MPa	4 N-m at 0.35 MPa
Rotation Angle	90°	55°

Figure 11a and 11b illustrate the SMC actuator and custom actuator (with the additional components listed in Table 1 installed, *less the electronics board*).

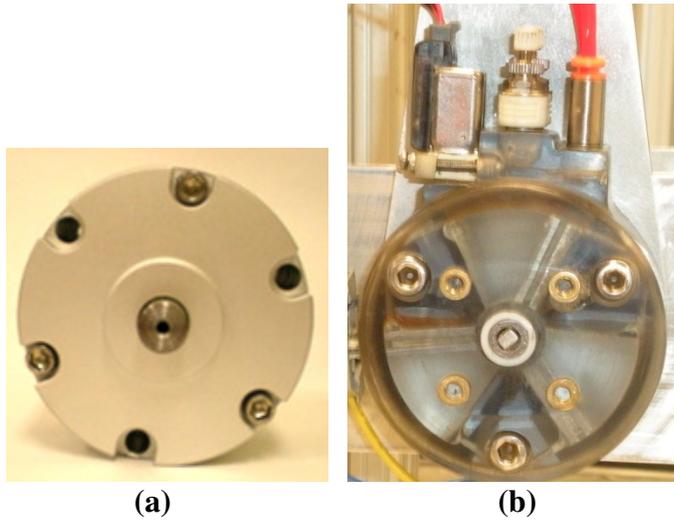
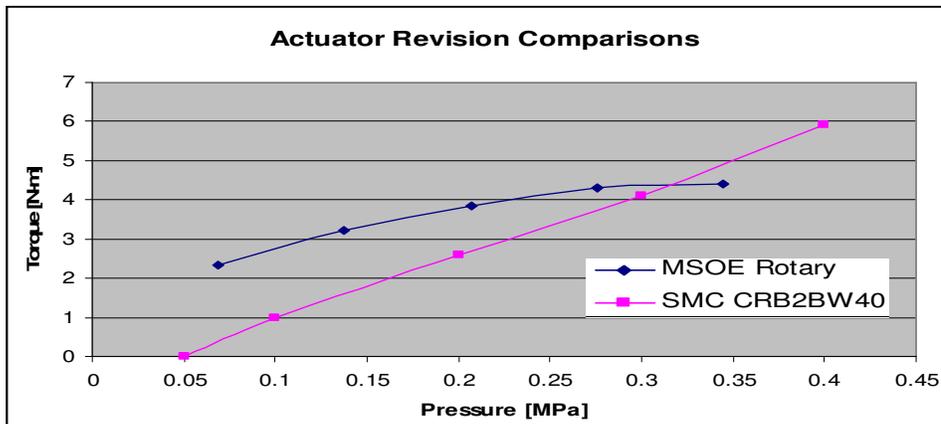


Figure 11: Revision One and Revision Two Actuators

Graph 1 illustrates the performance of the SMC actuator compared to the new actuator. Notable here is the drop-off in torque as pressure increases to 0.35 MPa. the drop-off in torque is attributed to friction and internal leakage of the dynamic seals. Improvements in sealing were achieved during this stage of the project but an effort to optimize the geometry and durometer of the dynamic seals to achieve the theoretical 7 N-m was not carried out. Despite these challenges, the actuator has successfully demonstrated the use of AM to create a functional fluid power component. It has been tested up to 3,000 cycles. After more refinement of the seals, this actuator will be tested more extensively and the dynamics of the system will be identified to be used in developing the control system for the AAFO. Shown in Figure 12 is the orthosis with the actuator integrated into the unit.



Graph 1: Revision One and Revision Two Actuators



Figure 12. Assembled AAFO with integrated Actuator.

Figure 13 shows the result of the first over-molded seal trial, using Polydimethyl-siloxane (PDMS). While the fit of the assembly was good, changes in the performance requirements of this actuator have prevented us from testing the functionality of the over-molded seals. The next generation must provide more torque, and, therefore, must handle higher pressures to remain compact.

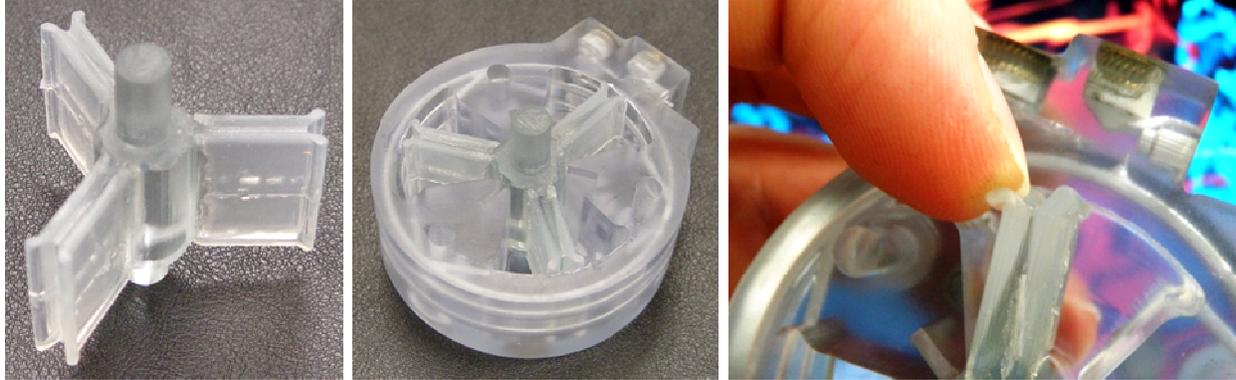


Figure 13: Over-molded silicone seals on the actuator rotor (left) and the fit into the housing (center). The tapered blade within can be seen in contrast to the silicone, being flexed (right).

The torque requirements of this compact actuator necessitate the use of high-strength materials, e.g. steel, for the rotor's shaft and blade roots. Future prototypes may integrate the two materials. Ultimately, as additive technologies progress, such multi-material (metal and elastomer) rotors might be fabricated in one process.

Conclusions

It has been demonstrated that additive manufacturing is useful for creating functional fluid power components and tooling for creating seals for said components. AM has made a tremendous impact in changing the methods used to produce many custom personal products.

For this application, plumbing and multiple components were integrated into a single housing. AM potential has yet to be fully utilized in many engineered components. Through the use of AM, the disparity between an ideal design and a feasibly manufactured component can be reduced.

Future Work

Consideration of higher pressure actuators has begun and future actuator operating pressures may increase to greater than 500psi and air may be replaced with hydraulic fluid.

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