**Additively Manufactured Flexible Fluidic Actuators For Precision Control in Surgical Applications**

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## Abstract

Previously, the Milwaukee School of Engineering (MSOE) demonstrated a dexterous tele-operational robotic system where actuators, joints, and linkages were fabricated simultaneously using Selective Laser Sintered Nylon 12. Primary motivation for this research was to conceive novel fluid power actuators that were inherently safe, compact, and Magnetic Resonance Imaging (MRI) compatible for surgery and rehabilitation. Although the concept of fabricating MRI compatible fluid power devices was demonstrated, further proof of precision control was needed. The design and implementation of additively manufactured flexible fluidic actuators (AMFFA) for precision control, best practices, and the comparison of these actuators with other actuation technologies are presented.

## Introduction

### *Purpose*

Project 2G, "Robotic Surgery and Rehabilitation via Compact, Integrated Systems" is focused on the research and development of compact surgical and rehabilitation devices for use inside the confines of MRI equipment. Expanding the use of fluid power in medical applications is primary technological motivation for this work. It provides an efficient way to implement compact precise control in harsh environments such as the strong magnetic fields associated with MRI machines while also tapping into existing pneumatic power readily available in hospital infrastructure [1]. While MRI-compatible pneumatically powered actuators and robotic systems are seldom commercially available, those available aren't inherently safe. The use of additive manufacturing (AM) technologies in fluid power and robotics has continued to illustrate significant technological benefits that typically yield greater performance through reductions in mass, size, and energy consumption. Using AM also has introduced the realization of simultaneous manufacturing, the process of fabricating systems as a single entity opposed to traditional methods that assemble separate components after they're produced. Simultaneous manufacturing allows for actuators, mechanical structures, mechanisms, and sensors to be fabricated at the same time, producing a framework similar to what's often illustrated in nature. For robotic engineers, the ability to seamlessly manufacture robotic systems paralleling the fabrication of biological systems provides a tool to develop robots that are fundamentally what's desired to be mirror images or extensions of ourselves. The purpose of this research is to blend the ideology behind the ability to use additive manufacturing to simultaneously manufacture robotic systems and technological need to develop inherently safe and compact robotic systems for MR-image guided surgical interventions. This endeavor presents technical challenges in the use of AM, discusses modeling strategies for precision control, and most importantly presents the inherent safety in the design of an additively manufactured flexible fluidic actuator (FFA) for surgical applications.

*Scope*

Research and technical artifacts from MSOE's involvement with the National Science Foundation's Engineering Research Center for Compact and Efficient Fluid Power are presented herein. The scope encompasses similar research conducted by other research institutions and MSOE and medical motivation for the current work is presented. The paradigm of simultaneous manufacturing design in development of FFAs, technical challenges in simultaneous manufacturing, modeling strategies, development results and motivation for future investigations in addition to breakthrough applications are discussed.

*Background*

Research by Delaurentis, Mavroidis, and Won demonstrated the feasibility of using AM for simultaneously fabricating mechanisms using selective laser sintering (SLS) and stereolithography (SLA) [2-6]. However, only some electromagnetic actuators could be embedded during fabrication by pausing the fabrication process mid-build and is feasible only with SLA and fused deposition modeling (FDM). Festo Inc. and members of the Fraunhofer Institute for Manufacturing Engineering and Automation realized the ability to manufacture FFAs using SLS for manipulation and grasping on fluid-powered robots, as the bionic handling assistant depicts in Figure 1[7-12].

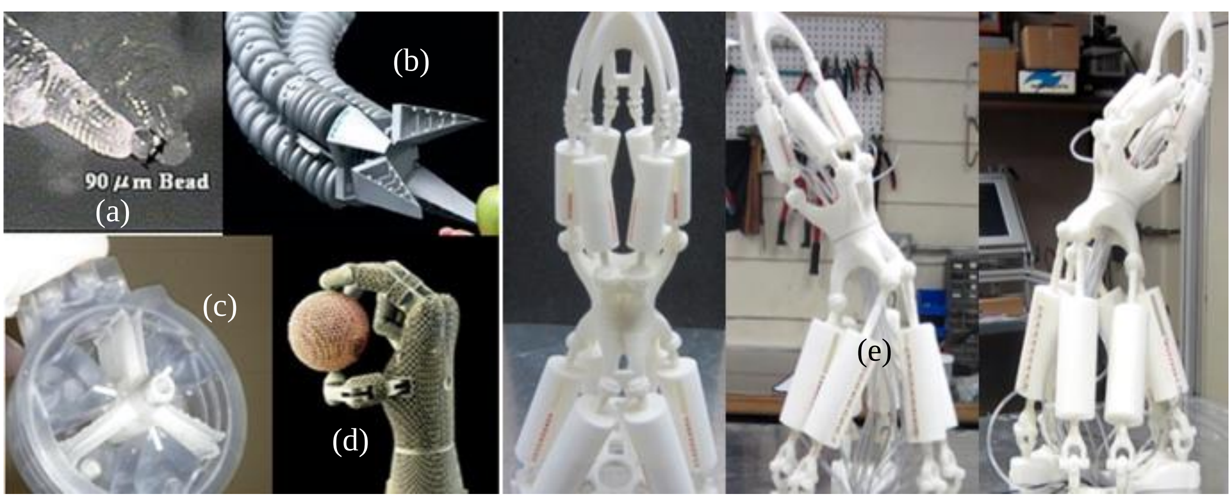



**Figure 1: Myriad of additively manufactured fluid power robots and actuators: a) SLA micro-gripper b) Bionic Handling Assistant c) MSOE's SLA rotary actuator d) Oak Ridge's titanium mesh hydraulic arm e) MSOE's simultaneously manufactured multi-level parallel manipulator.**

Prior research on Project 2G at MSOE synthesized simultaneous manufacturing and FFAs, introducing the capability to simultaneously manufacture fluid power robotic systems. Most recently, the Automation Manufacturing and Robotics (ARM) group at Oak Ridge National Laboratory and MSOE outline guidelines for use in the design of additively manufactured fluidically integrated robot systems and components for electron beam melting and polymer SLS processes, respectively [13,14]. Engineered fluid power robot components and devices have illustrated reductions in weight up to 80% and also up approximately 90% reduction in volume [13,14]. Yet, the most limiting technical barrier on smaller sizes is removal of unsintered and lightly sintered powder around and inside fabricated components [13,14]. This is due in part to the residual energy dissipated into the powder surrounding parts in the powder bed ultimately causing powder degradation [15,16]. Fluidic channels and internal recessed geometries out of direct line of sight make it difficult for powder removal and is sometimes the leading cause of an unacceptable design as Figure 2 illustrates for an embedded universal joint. Knowing distinct limitations in design that are highly repeatable are needed for the design of MRI-compatible actuators and robotic systems.

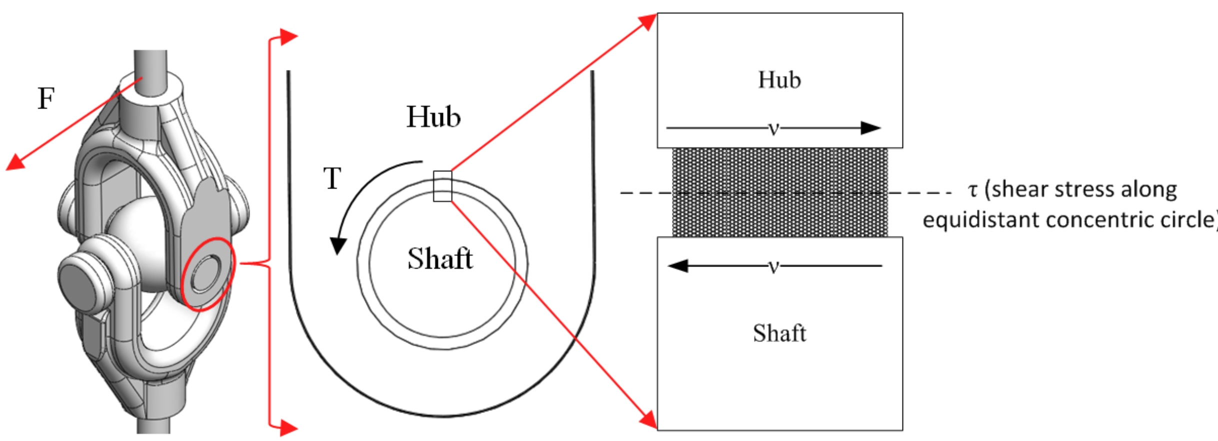



**Figure 2: Embedded universal joint depicting required force to shear unsintered powder.**

Project 2G's primary focus for MRI guided interventions is hypothermal ablation for treatment of epilepsy. Epilepsy is known to effect approximately 50 million people worldwide, 40% of which are unresponsive to medication [17]. In addition, 7 – 17% of those diagnosed with epilepsy experience sudden death [17]. Of the 2 million Americans diagnosed, 50% remain untreated and surgical procedures have only illustrated a 70% success rate [18-20]. The use of MRI guidance allows for precise minimally invasive procedures to be executed by using imaging as feedback for closed loop position and temperature control [1]. Present MRI-compatible actuators are pneumatically powered 2-way piston cylinders fabricated with MRI-compatible materials. However, 2-way piston cylinders aren't inherently safe for image guided interventions and surgical procedures. If a pressurized pneumatic supply or return line were to disconnect, a valve circuit were to short and fully open, the cylinder could fully retract or actuate the entire stroke length. This presents an immediate danger to uses in clinical trials and is unacceptable. Clinical needs and technical deficiencies illustrate a strong need for inherently safe actuation devices operable in MRI environments.

This research discusses the use of additive manufacturing to simultaneously manufacture inherently safe devices using flexible fluidic actuators for image guided interventions and surgical procedures, current and previously proposed system models for FFAs, actuator performance, recommended approaches, and potential applications. The culmination of previous work as well as clinical and technical needs fully support the motivation for this applied research.

## Additively Manufactured Flexible Fluidic Actuators

### *Design and Approach Paradigm*

Use of additively manufactured FFAs allow for simultaneous fabrication of pneumatically powered robotic systems and devices. As previously proposed, the class of actuator allows for freeform fabrication around or through specific geometries allowing for effective power transmission and reducing the overall system size. For designing a device that drives a hypodermic needle or an ablator tip for MRI-guided interventions, the design process illustrated in Figure 3 was used from prior work and implemented. It helps convey the overall ideology behind simultaneous manufacturing and that consolidation of multiple components can lead to more compact systems.

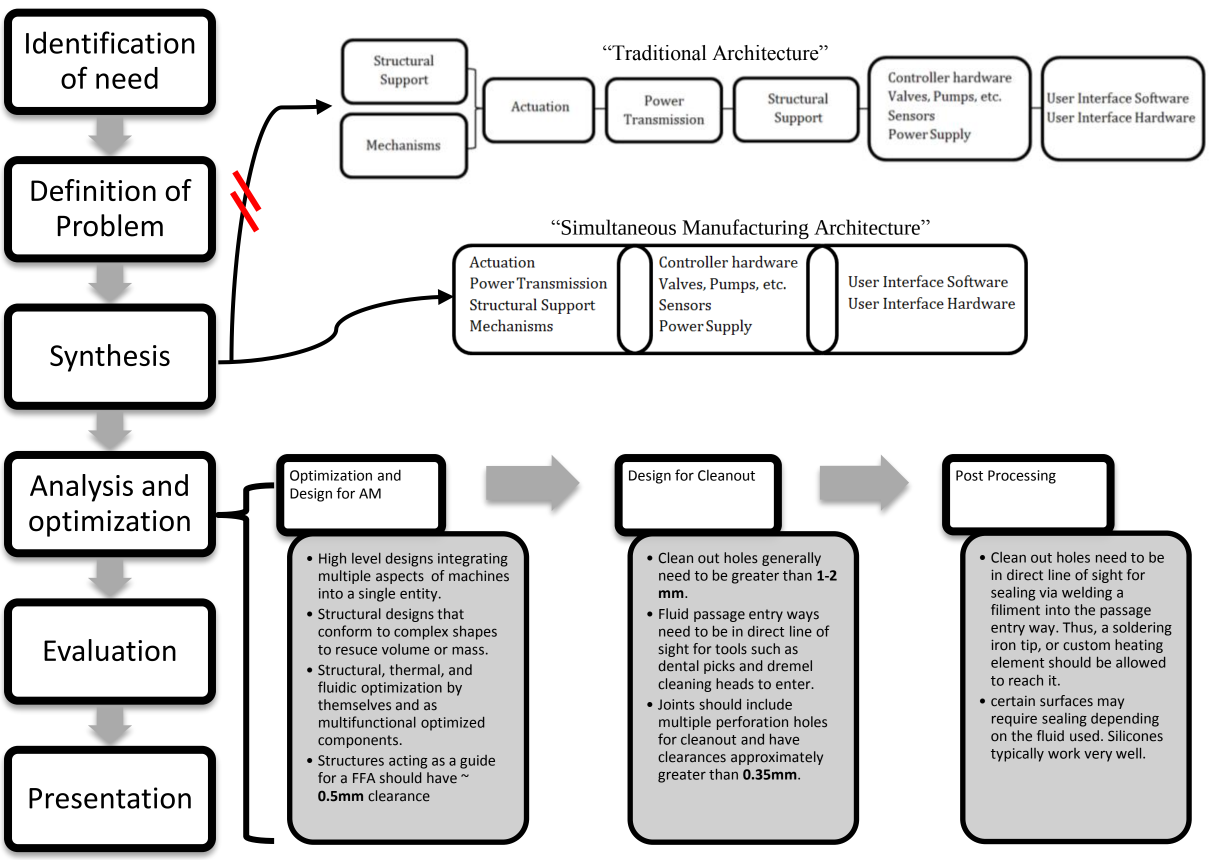


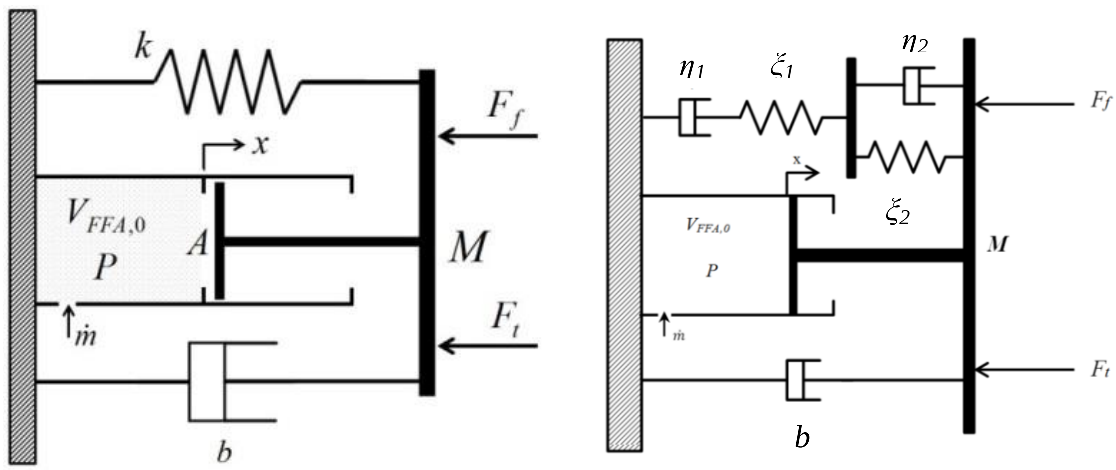

**Figure 3: Simultaneous manufacturing architecture and design outlines [21].**

Using the design process and guidelines specifically aimed at generating fluid powered robotic devices actuated with FFAs, devices that are extremely compact can be developed.

Following these guidelines can produce repeatable results that are inherently more compact than conventionally manufactured counterparts because of sub-system & component integration that is part of the overall changing framework in robotic system and device design.

*Modeling of Additively Manufactured Flexible Fluidic Actuators*

Prior research using FFAs used a dynamical model that was linear in nature. However, nonlinear models were proposed by Slightam and Gervasi to properly describe the visco-elastic behavior of the polymer membranes [22]. These two representations are depicted in Figure 4 part a) and part b), respectively.




a) b)

**Figure 4: Tradition linearized model vs. previously proposed visco-elastic model.**

The use of a spring-mass-damper (SMD) model implies a straightforward approach because of its common use in controls, but requires use of nonlinear sliding mode control (SMC) to account for nonlinear characteristics as previously demonstrated [23]. A visco-elastic model was developed to accurately describe the physics of the dynamic system and determine whether or not it is better than the SMD model. One of the primary tradeoffs to consider is the time invested in system design and characterization, which is discussed in the results of implementing a new AM FFA.

## Performance Comparison

The use of bellows as actuation is not relatively new. However, recent implementation and new developments have arisen from needs for complaint actuators in human-machine interaction. It is because of this need for compliance that fluidically actuated bellows or FFAs have illustrated a strong reemergence. Qualitatively, FFAs are compliant when powered by hydraulic fluid and more so with compressed air but little known work has illustrate how recent developments of FFAs compare with other actuation technologies [23]. This comparison is an essential part in high level robotic system design and helps select the most suitable means of actuation for a particular actuation, while providing insight into other applications beyond the scope of current surgical and rehabilitation applications.

Typically, strain, stress, specific power, bandwidth, and stiffness, and often efficiency are traits for comparing actuation technologies to one another [24]. Figure 5 depicts a generalized form of an actuator that helps define these traits for comparison.

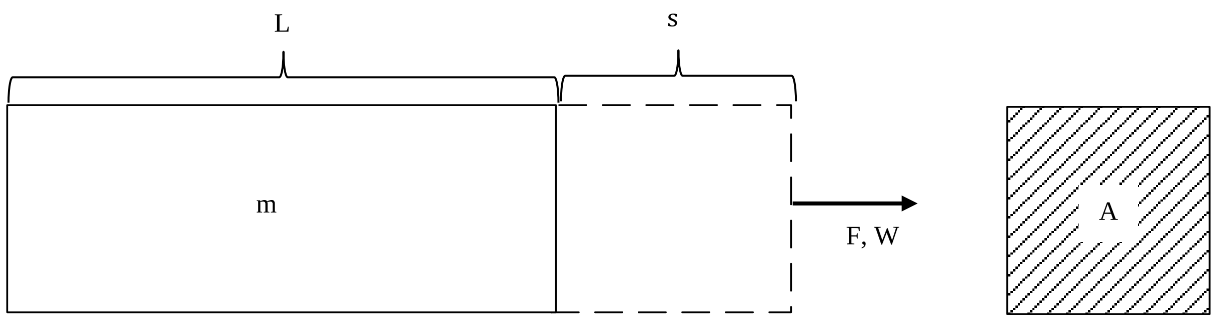



**Figure 5: Free body diagram of a general actuating element.**

Where s is the actuator stroke length and L the actuator's overall length, F, is the produced force from the actuator, A, the cross-sectional area of the actuator, W, is the work out from the actuator, m, is the mass, and k is the actuator stiffness.

The strain of an actuator is defined by the actuation stroke length per the total actuator length as Eq. (1) depicts.

$$\varepsilon = \frac{s}{L} \tag{1}$$

Stress of an actuator can be characterized by the produced force per cross sectional area, defined by Eq. (2).

$$\sigma = \frac{F}{A} \tag{2}$$

Specific power can be determined from the mechanical work produced from the actuator per its total mass as Eq. (3) describes.

$$\rho_W = \frac{W}{m} \tag{3}$$

Bandwidth, also referred to as the response of a diaphragm, is defined by Eq. (4).

$$f = \frac{10.21}{2\pi a^2}\left[\frac{gD}{hw}\right]^{1/2} \tag{4}$$

Where $g$ is the gravitational constant, $D$ is the flexural rigidity, and $w$ is the specific weight of the material, where these material constraints affecting the diaphragm responses are more thoroughly described by Giovanni [25]. However, one of the limiting factors for response is the fluid power system and is on average approximately 50Hz. Since diaphragm responses are typically greater than this, it's suffice to use this approximation for the bandwidth.

Lastly, the stiffness or load holding capabilities of an actuator can be determined by its stiffness per unit length.

$$K = \frac{k}{L} \quad (5)$$

Efficiency is regarded to be an important parameter for actuator performance comparison as well. It has been declared that the efficiency of FFAs is greater than those of their piston-cylinder counterparts [26]. However, this claim may be fallacious without proper validation as FFAs are also subjected to energy losses in the fluid, losses from stored strain energy, friction, and is also dependent on the work out of the actuator, that is dependent on the output force. The control system of FFAs is also a contributing factor to the overall efficiency. Use of high speed digital solenoid valves allows efficient discrete control of air in and out of the actuator. Otherwise, a less efficient approach is pressurization via backpressure in the FFA caused by restricted flow on the exhaust passage from an orifice.

This speculation and criticism provides motivation for validating these claims and conducting non-dimensional performance analysis on AM FFAs to improve the understanding of the entire spectrum of capabilities. However, validating claims or speculations of high efficiencies of FFAs are not included because of the technical depth is beyond the scope of this technical paper.

## Results

As a result of using the ideology of simultaneous manufacturing and guidelines outlined in Figure 3 and the clinical need to develop and inherently MRI-compatible device, the linear stepper motor for needle actuation depicted in Figure 6 was developed.

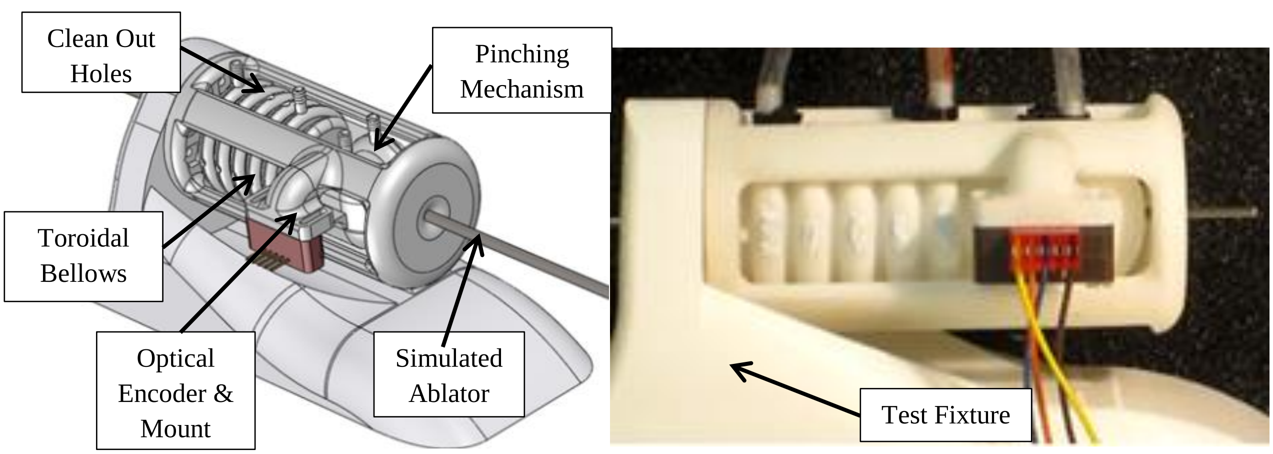



**Figure 6: MRI-compatible linear stepper motor for needle insertion.**

The inherent safety of the actuator is through its discrete sequential stepping design. For example, in the event of a system malfunction as previously discussed the actuation or retraction of the needle would be limited to the discrete step size. In addition, sub-step control is possible for precise needle placement between discrete step lengths. The actuator implemented a US-Digital EM1 transmissive optical encoder module with 500 lines per inch.

Using SMC, precision control was achieved. Steady state error of 25 microns was illustrated during multiple tests such as the one depicted in Figure 7. Only 15 microns of precision could feasibly be achieved because of the digital encoder used.

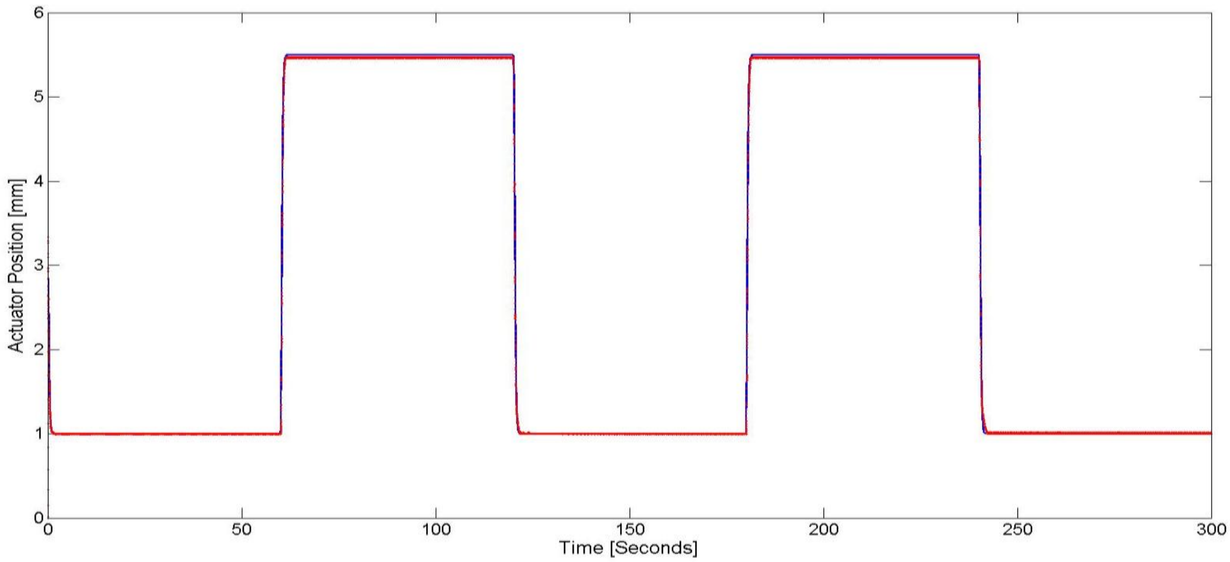



**Figure 7: SMC Results.**

The performance of the actuator followed theoretical predictions of stiffness and near linear behavior on initial actuation as Figure 8 depicts. This also allowed for the hysteretic damping to be determined experimentally.

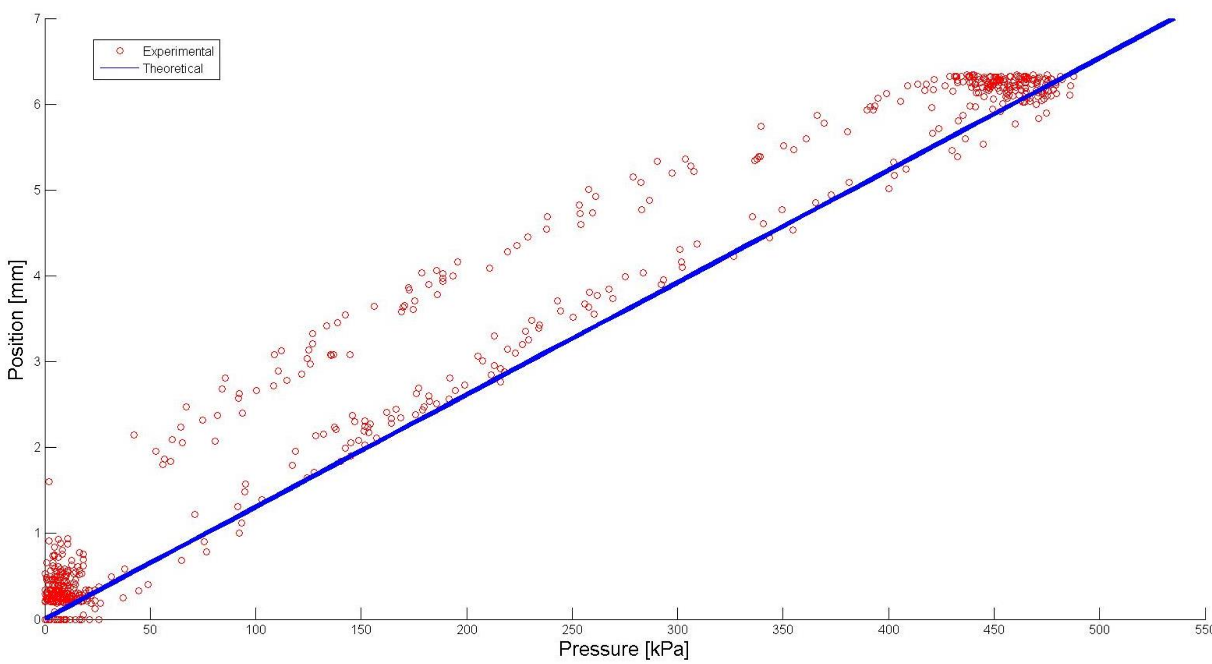



**Figure 8: Toroidal FFA position as a function of internal pressure.**

As expected, the actuator exhibited visco-elastic behavior that the controller was able to compensate. This is especially apparent in Figure 9 and 10 that illustrate the exponential decay and growth of pressure needed to achieve the desired motion in Figure 7 and the modulus behavior, respectively.

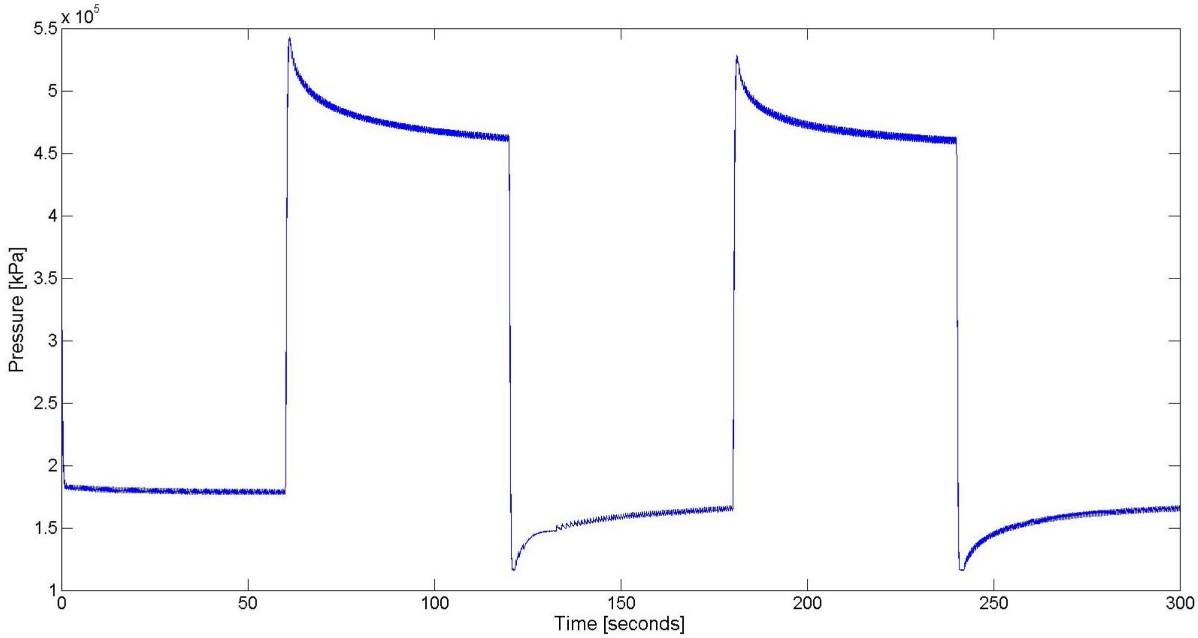



**Figure 9: Pressure applied to FFA in SMC trial.**

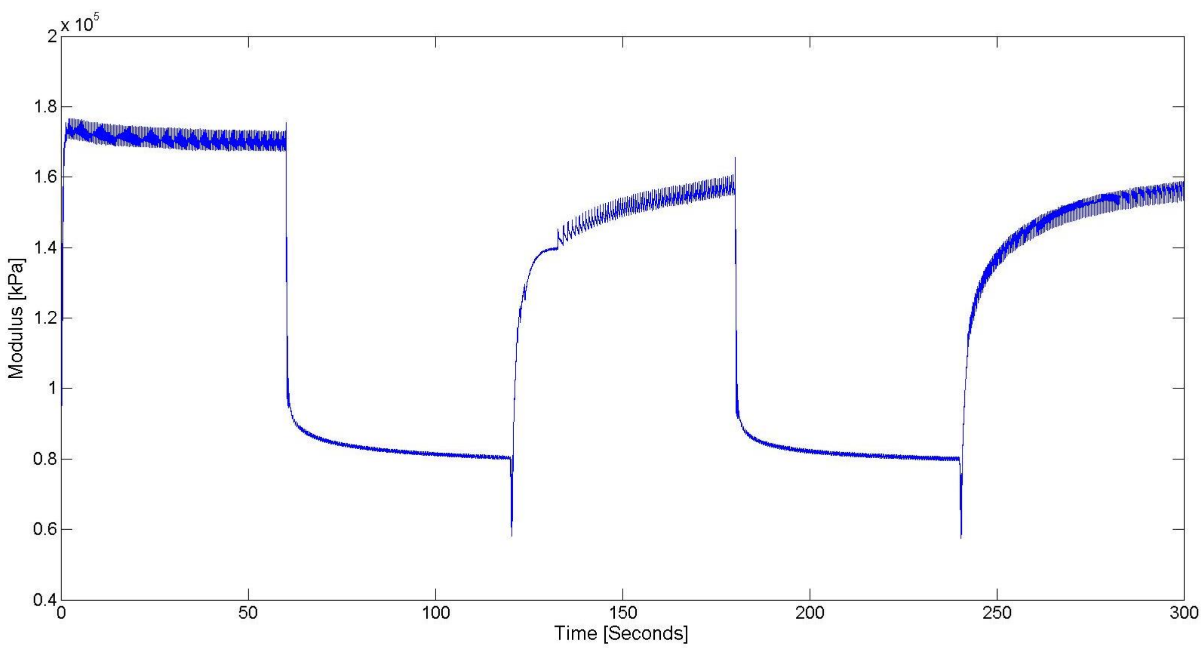



**Figure 10: Approximate Modulus of FFA during SMC trial.**

From experimental data using the SMC the visco-elastic model was once again tested and the results are depicted in Figure 11. However, it was only conducted for one actuation cycle as the visco-elastic model is time dependent and employing a real-time system model that integrates the Boltzmann's superposition principal is beyond the scope of this work [27].

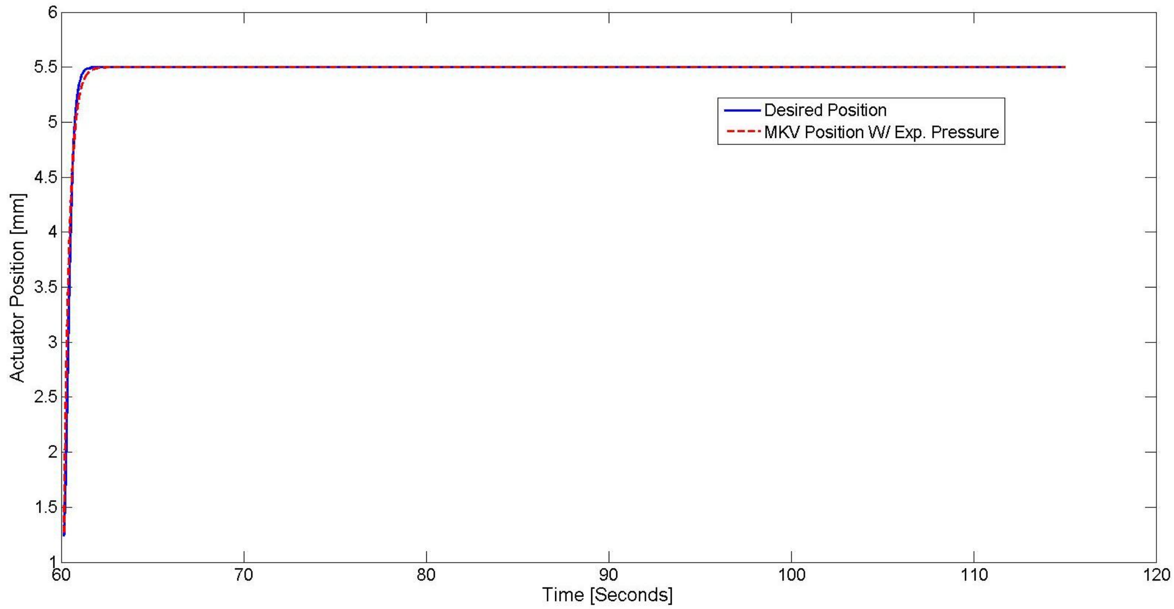



**Figure 11: Visco-elastic dynamic model results.**

Given the actuator parameters, the performance was also characterized. The pneumatically powered toroidal FFA was compared to other actuation technologies in Table 1.

**Table 1: Actuation technology comparison [11, 28, 29].**

| Actuator Type | Strain [%] | Stress [MPa] | Power Density [W/kg] | Bandwidth [Hz] | Stiffness [MPa] |
|---|---|---|---|---|---|
| Muscle | 20 | 0.35 | 50 | 30 | 20 |
| Electromagnetic | 50 | 0.035 | 200 | 30 | 0.1 |
| Pneumatic | 50 | 0.69 | 200 | 50 | 0.1 |
| **Pneumatic FFA** | **16.8** | **0.37** | **73.45** | **50** | **1.79** |
| Piezoelectric | 0.2 | 110 | 0.1 | kHz | 400 |
| Magnetostrictive | 6 | 9 | 5 | kHz | 29 |
| EAP | 380 | 3 | 35 | 10 | 1 |
| SMA | 8 | 200 | 6 | 1 | 8.30E+04 |
| Hydraulic | 70 | 20.8 | 2000 | 50 | 1380 |

This gives insight into potential applications outside of MRI compatible surgery and rehabilitation in addition to an initial technological assessment of the device. The device can be used in a modular fashion and eventually replace the original 5 degree of freedom cannula robot as conceptualized in Figure 12. The original implemented 5 degree of freedom cannula robot used a volume of approximately 2592 cubic inches (42,475 cubic cm), while it is projected that a modular 5 degree of freedom robot using FFAs could occupy a volume of 260 cubic inches

(4,261 cubic cm). Thus resulting in a projected volume reduction by as much as 90% using the methodologies applied to develop the device.

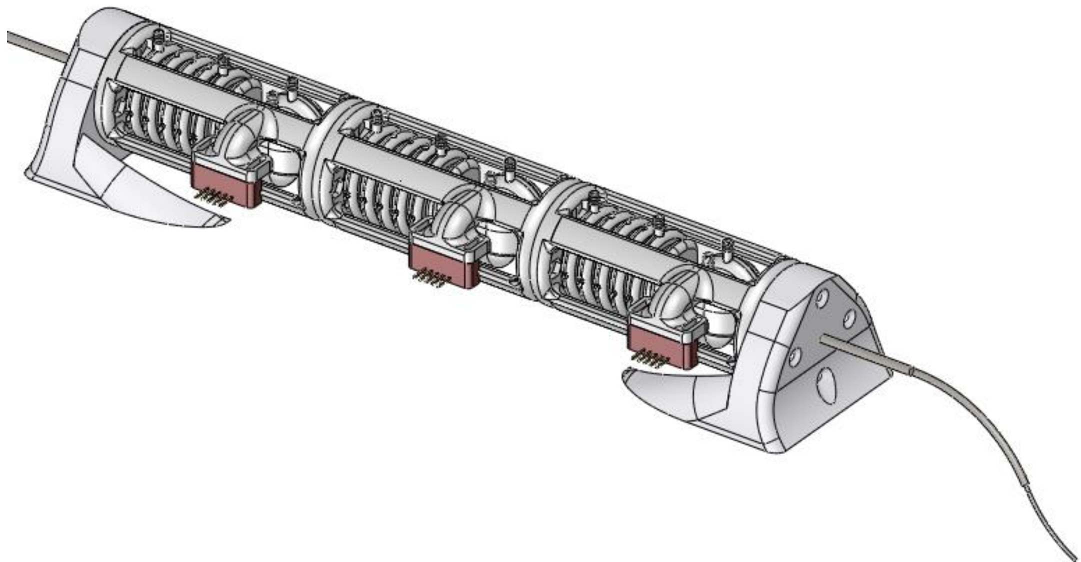


**Figure 12: Conceptual modular 5 DOF cannula robot.**

## Potential applications

Based on the empirical results of implementing the ideology of designing devices and systems with FFAs, other potential applications outside of MRI-compatible surgery can be identified. The precision demonstrated that medical applications outside of the one discussed herein can achieve, such as full surgery rather than interventions, in addition to rehabilitation. The similarities between human muscle and the actuator performance characteristics illustrate that rehabilitation devices such as orthoses and even prostheses could potentially be applicable, as FFAs have been used for in the past, although not with AM. Branching out into other medical applications may provide for mass customization with orthoses.

## Conclusions

Use of the paradigm to simultaneously manufacture devices with integrated fluidic actuators and implementation of SMC has produced a device that is inherently safe because of its discrete motion, compact, and precise. While models used with the SMC don't describe the true nature of Nylon 12 FFAs, it's a more practical and efficient approach when considering the overall design and implementation process. Several steps in experimentation can be skipped that are needed to determine the visco-elastic constants in the MKV model, reducing the time to implement the device. Furthermore, the use of the MKV model has yet to illustrate precision greater than a robust SMC that demonstrates precision consistently near that of the resolution of the position sensors used.

Initial assessments show that the performance of pneumatic FFAs can be similar to the traits of human muscle. While past conjectures have stated that efficiency can be greater than that of piston cylinder counterparts, qualitative discussion of FFAs suggest that efficiencies could be lower than originally claimed. This analysis gives insight to how such devices should be properly designed in the future, to maximize both efficiency and work out of systems. It also identifies that such devices aren't as promising as once thought, but still practical for many applications requiring compact devices that are also customizable.

## Acknowledgements

Special thanks are given to David B. Comber at Vanderbilt University for outstanding performance in collaboration with MSOE for his help in guiding the mechanical design as well as performing the SMC design. Thanks are also given to the National Science Foundation's Engineering Research Center of Compact and Efficient Fluid Power for their continued support and funding of this work.

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