A NOVEL SPATIAL MICROCHANNEL FLUIDIC JOINT

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Abstract: This paper presents and discusses a flexible, polymer-based, novel microchannel fluidic joint (MFJ) that is driven by a pressurized working fluid. The MFJ has been designed for being used in biomedical applications in the future. The MFJ actuating system has two degrees of freedom and implements a unique 3-channel design. In this paper, a prototype of the proposed MFJ is presented along with its manufacturing procedure. Measurements related to the MFJ displacements are presented and a simplified fitting exponential equation is proposed to describe the relationship between MFJ deformation and the working fluid pressure. Performance of the proposed device and its potential future applications are discussed.

1 INTRODUCTION

Fluidic actuators are relatively simple systems that can be beneficial for a diverse range of devices. Whereas many actuators require an electric voltage, a magnetic field, or temperature changes to operate, fluidic actuators require only a hydraulic pressure to bend and/or deform.

The earliest design of a fluidic actuator consists of a soft, cylindrical rubber tube containing three chambers that extend parallel to the tube's axis. When a hydraulic pressure is forced through any of the three chambers, the actuator is able to bend in three primary directions (Suzumori, et al., 1991). This design offers a multi-dimensional movement, a property that is not found in all fluidic actuators. However, it requires a number of different components and its long chambers do not allow for an even distribution of force throughout the actuator. An example of a simple, easy-to-manufacture actuator consists of a pneumatically controlled balloon attached to a flexible material; when the balloon expands, the actuator bends in on direction (Kawai, et al., 2001). The trade-off is simplicity of design for a limited range of motion. A final example of a fluidic actuator is a hydraulic suction actuator. This design consists of a metal-reinforced silicon-rubber tube whose bending angle is controlled by hydraulic suction (Muvari, et al., 2003). The metal reinforcements are dispersed evenly along the tube, and the actuator can produce a large bending angle (Muvari, et al., 2003). The complexity of the design and numerous materials assumes a complex manufacturing process. Additionally, the metallic components may not be desirable in all environments, such as the human body.

In this paper, we discuss the design of a spatial MFJ. It is a novel fluidic-powered device that is composed of one single polymer, is easy to manufacture, and can move in 2 dimensions. We first present the structure and desired function of our design and explain the manufacturing process of a spatial MFJ. In order to justify our design conjecture, we perform a series of practical tests and provide experimental verification to our design hypotheses. Finally, we propose several applications in which our device can be integrated.

2 PROPOSED CONCEPT

We present a MFJ that can be implemented as an active catheter or catheter guide. With this design, the user will be able to control the bendable catheter while it is inside the patient. This will facilitate the intubation process by allowing the user to navigate the catheter around obstacles and access the intubation destination more easily.

Active catheters are not a novel concept. One example of an active catheter design incorporates shape memory alloy (SMA) actuators embedded in a mechanism made of silicon, glass, aluminium, and an integrated circuit (Lim, et al., 1996). Other

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designs also consist of SMA actuators and other metallic components (Haga & Esashi, 1998). Although these devices ease the intubation process, their designs are complex and require electronic components and power. The proposed MFJ would provide a simpler and effective alternative to intubation processes.

3 MFJ DESIGN

The special MFJ is bendable and driven by hydraulic (or pneumatic) pressure. The MFJ is made from a deformable polymer embedded with a sub-millimeter-scale channel. The channels, illustrated in Figure 1, have rounded edges and uniform turns that will help to evenly distribute the force throughout the MFJ.

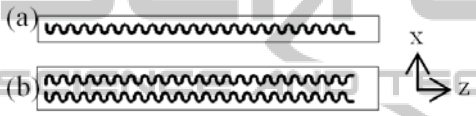

Figure 1: CAD drawing of two designs (a) Single-channel. (b) Double-channel.

The two components shown in Figure 1(a) and (b) are bonded together in the configuration shown in Figure 2.

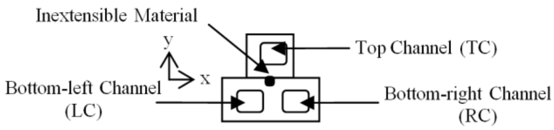

Figure 2: Arrangement of single-channel (top) and double-channel (bottom) components.

In order for the MFJ to bend in the x-y plane, a relatively inextensible material must be placed in the centre of the MFJ. This material should have a much higher Young's Modulus than the deformable polymer. The black circle in Figure 2 represents the inextensible material, placed along the z-axis in between the channels of the double-channel component. When a hydraulic pressure is introduced to a channel, it will exert force on all four walls of the channel. This idea is illustrated in Figure 3, which shows a cross-sectional view of an MFJ channel. When a fluid exerts force in the z-axis, the difference in elasticity between the two materials will cause the MFJ to bend toward the inextensible material. The force exerted in the y-axis will cause the top and bottom walls of the channel to swell slightly; this may cause the MFJ to break if thehydraulic pressure is too high.

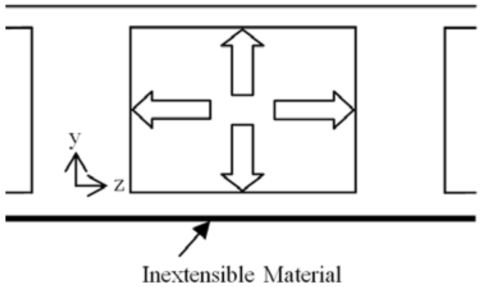

Figure 3: Force exerted on the walls of a channel.

Figure 4 shows an example of a MFJ bending up to 40 degrees when subjected to an internal pressure of less than 20 psi.

Figure 4: Deformation of a 40mm long MFJ, larger than 40 degrees.

The channel configuration of the spatial MFJ enables movement in 2 dimensions. Activation of the top channel causes the MFJ to bend downwards, activation of the bottom-right channel causes the MFJ to bend to the left, simultaneous activation of the bottom-left and top channels causes the MFJ to bend to the right, and activation of both bottom channels causes the MFJ to bend upward. The motions described above are illustrated in Figure 5. Note that the MFJ can also bend diagonally in all directions by activating different combinations of channels.

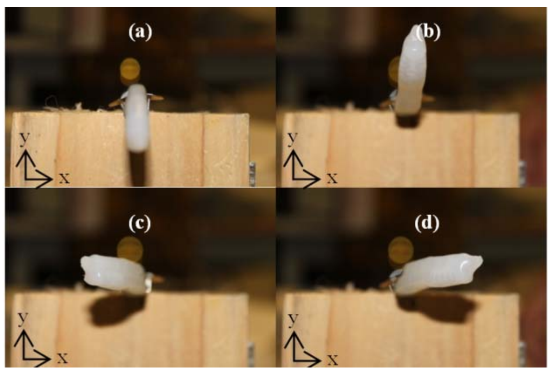

Figure 5: Bending of a special MFJ prototype. (a) Activation of the top channel. (b) Activation of both

bottom channels. (c) Activation of the bottom-right channel. (d). Simultaneous activation of the bottom-left and top channels.

4 MANUFACTURING

Firstly, two different molds with specific shapes and channel designs are required to make a spatial MFJ. Figure 1(a) is a sketch of the single-channel mold, consisting of a single meandering channel and an outer rectangular frame. Figure 1(b) is a sketch of the double-channel mold, which is twice the width of the first and consists of 2 meandering channels and an outer rectangular frame.

The molds are sketched on AutoCAD and are 40 millimeters (mm) long, 3 or 6mm wide, and have a 0.3mm channel width. The sketches serve as templates that are etched onto a piece of Poly(methyl methacrylate) (PMMA) with a CO_2, 50-Watt, X-660 Universal laser engraver at 80% power and 15% speed. To facilitate mass production, multiple molds can be etched onto one piece of PMMA, as seen in Figure 6. PMMA was chosen as a suitable material mainly because the polymer does not adhere to it. Therefore, after the polymer has been poured onto the mold and cured, it can easily be removed. It was also chosen over other materials because of its cheap cost and its high glass transition temperature, which prevents the material from excessive warping. The MFJ molds shown in Figure 6 have the same channel dimensions as stated previously. Notice how there is a single piece of thread running between the channels of the double-channel mold. This thread serves as the inextensible material of the spatial MFJ. out of TC-5005 polymer (manufactured by BJB Enterprises, Inc.).

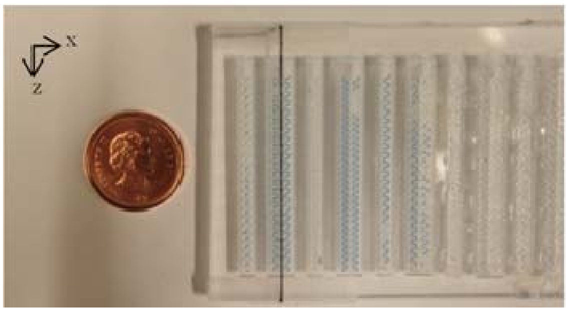

Figure 6: Spatial MFJ Molds.

The polymer is prepared by mixing 10 parts A with 1 part B in a beaker and placing it in an ultrasonic cleaner for 3 minutes to ensure a thorough and even mixture. This process will cause bubbles to form within the mixture. In order to remove these bubbles, the polymer is poured onto a mold and placed in a vacuum chamber for approximately 60 minutes to de-gas. It is important to place the polymer on the mold before de-gassing it because TC-5005 has a work-life of only 45 minutes. The polymer is set aside to cure for at least 18 hours.

Once the polymer has cured, it is removed from the molds, resulting in a single-channel component and a double-channel component. The back of each component is sealed with a thin layer of TC-5005 so that there is no leakage when fluid is introduced to the system. Once the components are sealed, they are glued together in the formation shown in Figure 2.

The resulting system consists of 1 single-channel and 1 double-channel component. 3 pieces of wire skin are inserted into each of the 3 channels to facilitate the injection of fluid into the channels. Wire skin is chosen because TC-5005 adheres to this material, creating a good seal and preventing leakage. To finalize the design, the system is dipped in TC-5005 polymer, resulting in a single spatial MFJ with rounded edges.

5 MFJ TESTING

To analyze and characterize the MFJ, a test to correlate the driving pressure and actuation displacement is designed. The tip of a MFJ is attached to a laser and then hung from the root with the laser pointing down towards a grid paper. A graphical illustration of the experimental setup is shown in Figure 7.

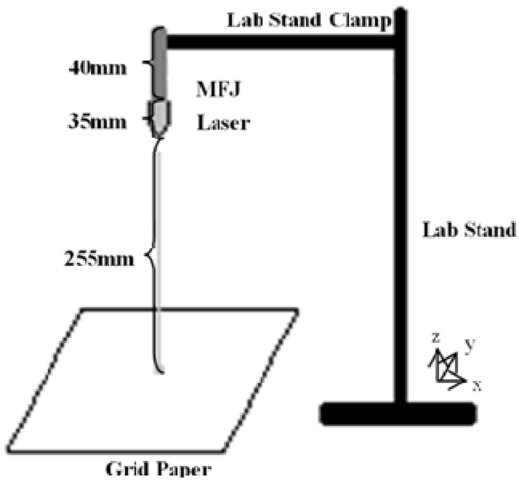

Figure 7: Illustration of Experimental Setup.

Figure 8 illustrates how a MFJ is attached to a laser pointer at the tip and attached to a PMMA backing at the root then secured to a lab stand. Note that the mass of the laser head is 1.96g while the mass of the MFJ itself is 2.26g.

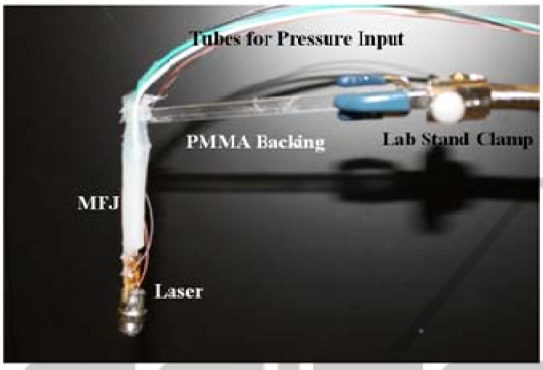

Figure 8: MFJ Attached to a Laser Pointer and Secured onto a Lab Stand Clamp.

Figure 9 illustrates how the laser is projected onto a millimeter resolution grid paper for determining the actuation displacement of the MFJ. The reference and orientation of the MFJ in Figure 9 corresponds to the reference frame shown in Figure 2. The origin of the measurement reference frame is defined as the point indicated by the laser projection while all channels are not pressurized. The top channel (TC), bottom-left channel (LC) and bottom-right channel (RC), shown in Figure 2, were independently and simultaneously pressured during the tests.

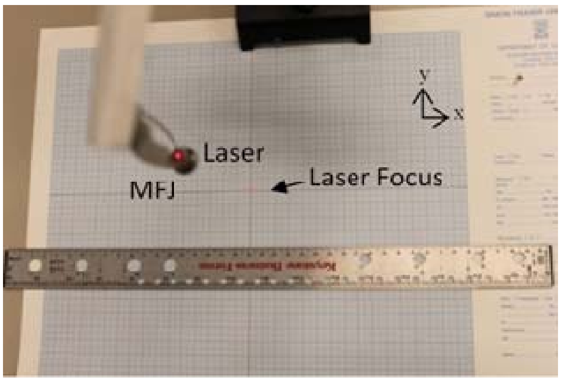

Figure 9: Laser Focused on a Millimeter Resolution Grid Paper.

To measure the driving pressure to the MFJ, two pressure gauges are used in the experiment: a WIKA standard bourdon tube series -30 to +30 psig pressure gauge and an Omega PX209 pressure gauge. During the experiment, only one or two of the channels RC, LC and TC are pressurized and monitored with a pressure gauge. The pressure is manually induced with Becton-Dickinson 10mL plastic disposable syringes. At each set of pressures tested, an x and y displacement read from the grid paper is recorded along with the driving pressures.

Figure 10 Figure 12 illustrates the pressure VS actuated distance while pressurizing only one channel.

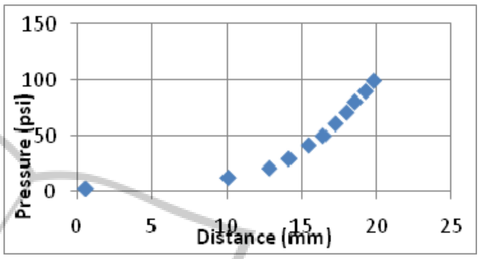

Figure 10: TC Pressure VS Distance from Origin while RC and LC are not pressurized.

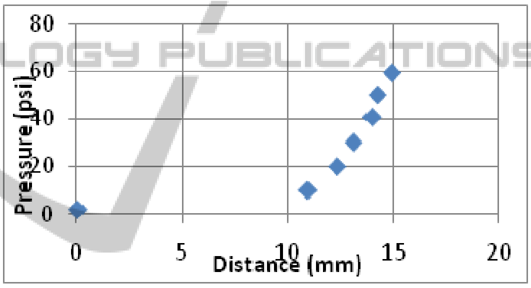

Figure 11: RC Pressure VS Distance from Origin while TC and LC are not pressurized.

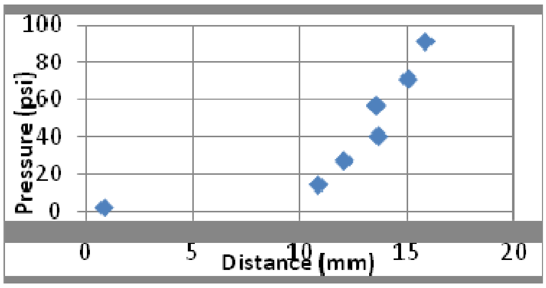

Figure 12: LC Pressure VS Distance from Origin while TC and RC are not pressurized.

From the x and y displacement data gathered while pressurizing individual channels and by assuming that the three channels have independent behaviors, exponential function curve fitting is performed. By superimposing the effects of pressurizing the three channels, we are able to correlate the motion of the MFJ with the driving pressures (using MATLAB Curve Fitting Toolbox) as presented in the following equations:

$$X = a_1 e^{b_1 P_1} + a_3 e^{b_3 P_2} + a_5 e^{b_5 P_3} \quad (1)$$
$$Y = a_2 e^{b_2 P_1} + a_4 e^{b_4 P_2} + a_6 e^{b_6 P_3} \quad (2)$$

where P1, P2 and P3 are the driving pressures respectively within TC, RC and LC in psi respectively, and the values or the coefficients a_1-a_6 and b_1-b_6 are summarized in Table 1.

Table 1: Coefficients used in Equations (1) and (2).

a_1	1.171	b_1	0.0278
a_2	-1.533	b_2	0.2112
a_3	0.3247	b_3	0.3313
a_4	0.1843	b_4	0.3724
a_5	-0.1334	b_5	0.4113
a_6	0.002285	b_6	0.5300

To visualize the fitting function we have devised, Figure 13-Figure 15 illustrate surface mesh generated with Equation (1) and (2) plotted against actual data points gathered while activating sets of two channels and keeping one channel passive . The normalized root mean square error (NRMSE) for the surface plots are 4.3% in Figure 13, 6.7% in Figure 14, and 12.1% in Figure 15.

The data presented in Figure 13-Figure 15 shows that our mathematical model is able to approximate the movement of the MFJ. However the high NRMSE suggests that the actuations contributed by the three channels are not completely independent of each other.

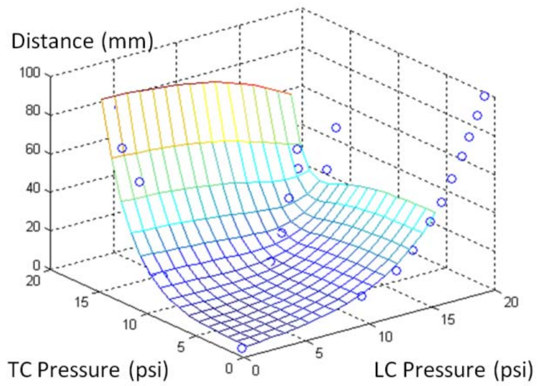

Figure 13: TC and LC Pressure VS Displacement. Interpolated Mesh plotted against data collected.

To further illustrate both the experimental and modeled behavior of the MFJ, Figure 16 plots the data points projected by the laser pointer onto the xy-plane. The RSME for these data points are 5.7% in the x-direction and 3.8% in the y-direction.

We are able to approximate the behavior of the MFJ, but have also noticed that the actuations contributed by the three channels do have some

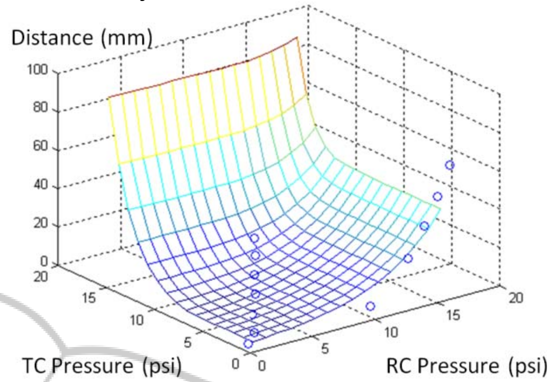

Figure 14: TC and RC Pressure VS Displacement. Interpolated Mesh plotted against data collected.

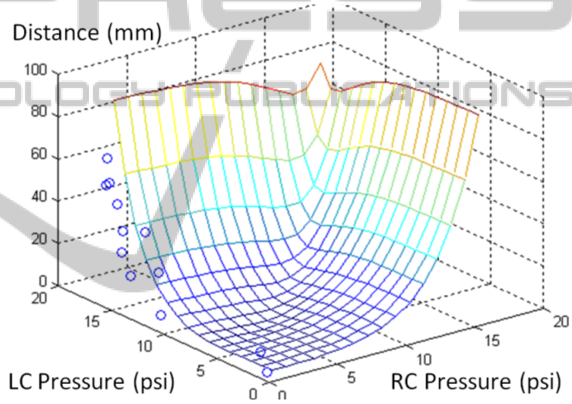

Figure 15: LC and RC Pressure VS Displacement. Interpolated Mesh plotted against data collected.

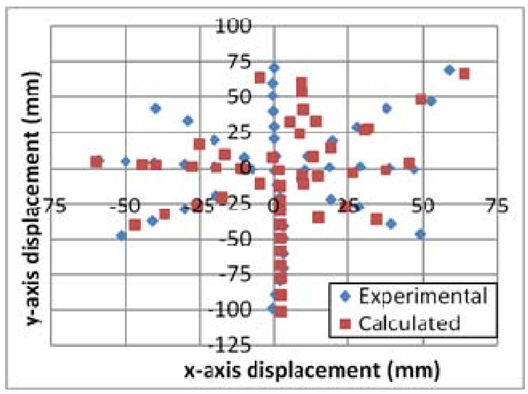

Figure 16: Projection of MFJ Movement onto xy-plane.

dependency on each other. Inducing a driving pressure into a channel will cause the stiffness and other parameters of the system to change in a nonsymmetrical fashion. Therefore, the linear independence of each channel that was assumed during the derivation of equations 1 and 2 does not necessarily hold true. The average NRMSE for our experimental data is approximately 7.7% for the 3-dimensional surfaces, and 4.7% for the 2-dimensional plot.

6 DISCUSSION AND FUTURE WORK

The spatial MFJ's wide range of motion that was proposed in the design concept is indeed supported by experimental analysis. The projection of the MFJ's movement spans all 4 quadrants of the x-y plane. Furthermore, relatively large displacements (greater than 40 degrees as seen in Figure 4) can be achieved by applying no more than 20psi of fluidic pressure.

This wide range of motion, along with its lightweight, non-metallic parts and non-electric or magnetic stimulation make the spatial MFJ a desirable device to insert into the human body. Therefore, it may be useful for biomedical applications based on its performance and composition. Some characteristics of the MFJ are summarized in Table 2.

Table 2: Summary of MFJ Characteristics.

Dimension	$40mm \times 6mm \times 7mm$
Mass	2.26g
Max rotation	> 40 deg
Max pressure required	21.5 psi

The pressure in the channels can be controlled with syringes and syringe pumps, which help to control the pressure input. Using equations 1 and 2, the user can know approximately what pressures must be input into each channel in order to achieve a desired position. This system may be useful in intubation processes such as laryngoscopy, endoscopy, or colonoscopy, in which a destination can be viewed with a camera, and appropriate pressures can be input into the system so that the MFJ can reach the desired destination.

7 CONCLUSIONS

In this paper, we presented the design of the MFJ, which potentially provides solutions to the shortcomings of previous fluidic and pneumatic actuators. The MFJ displays large multi-dimensional movements (rotations greater than 40 deg), is lightweight (about 2g), compact in size (about 1.7 cm^3), and has a predictable pressure-displacement behavior. We have developed a simplified mathematical model, which approximates the relationship between the pressure in the three MFJ channels and the MFJ displacements; error between model prediction and experimental data is about 7.7%. Such an error could potentially be dramatically reduced if the effect of each channel to the other channels could be taken into account. It should be noted that by scaling the fabrication mold up or down, the dimension of the MFJ could be easily altered for different applications. The device presented in this paper is made of a polymer-based material and implements a unique channel design. The manufacturing process is very simple, contains few components, and allows for mass production. These properties make the spatial MFJ potentially useful in bio-mechatronic applications.

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