Multiplexed Single-Pump Actuation of Soft Robotic Systems for Patient-Conforming Radiotherapy Devices

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MEDICAL PHYSICS COMMUNITY · INSPIRATION · INNOVATION · IMPACT
2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

ABSTRACT

This work presents a low-cost, multiplexer-style control system enabling a single 100 mL pump to independently actuate up to 25 fluid channels in soft robotic devices for radiation therapy.

Designed for open-loop, volume-controlled filling, the system addressed a 4×6 cuboidal soft robot array, achieving clinically relevant surface deformations, including arches, twists, domes, and shells, on the order of seconds to minutes. A normally-closed architecture ensures isolated channels without continuous power draw.

This scalable, inexpensive platform establishes a practical foundation for multi-channel soft robotic bolus and immobilization systems in clinical radiotherapy workflows.

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INTRODUCTION

This work sought to develop an inexpensive control system for fluid-actuated soft robotic applications in radiation therapy, including customizable boluses and immobilization devices.

This system aims to provide control over multiple fluid lines with a single pump, potentially expanding the functionality and versatility of soft robotics in clinical settings.

METHODS AND MATERIALS

1. A multiplexer-style (Figure 1) control system was designed and prototyped, enabling the control of up to 25 distinct fluid lines from a single 100 mL pump. For this study, 24 fill lines and 1 pump line was utilized. Fluid lines were controlled with cams mounted on servo motors that opened or closed an entire row or column of the grid (cf. Figure 4).

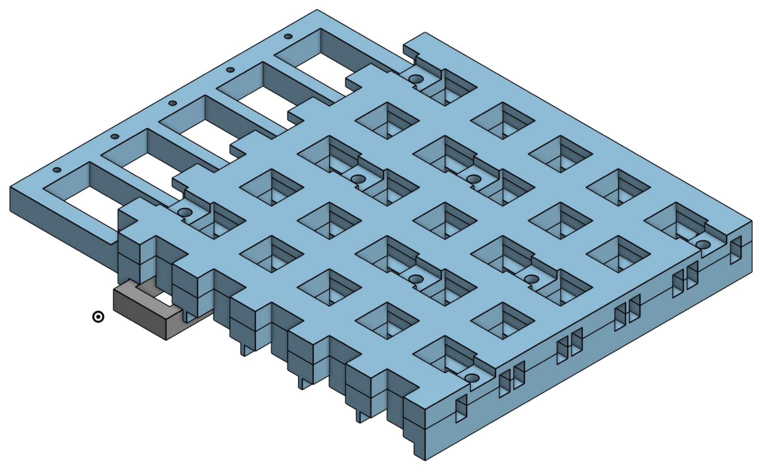

Figure 1. CAD model of multiplexer main body. The cam closure mechanism is indicated by ⊙.

2. This system was tested using a compressed air pump driver with a geared motor to actuate a 4x6 cuboidal array soft robot (8cm x 12 cm; cf. Figure 2).

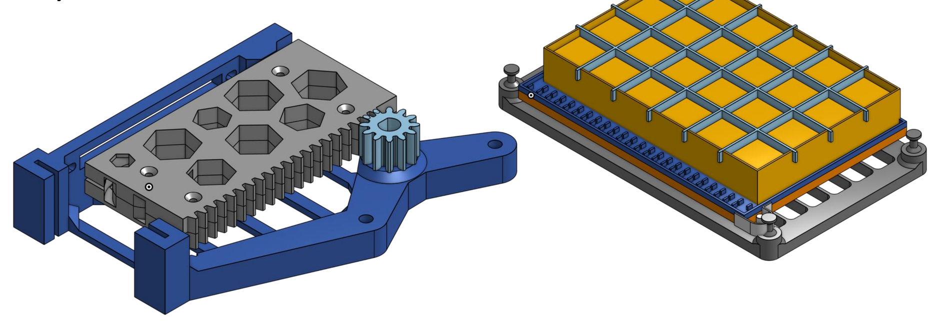

Figure 2. CAD models of pump driver mechanism and mold for cuboidal array soft robot.

3. Each cube in the system was individually controllable (i.e., addressable) for open-loop, volume-controlled filling, allowing manipulation of the planar surface below the cubes (Figure 3).

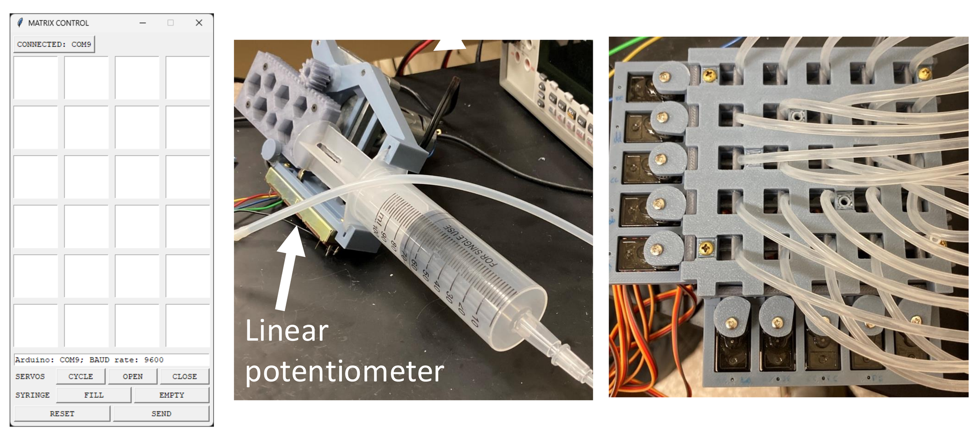

Figure 3. A user interface built in Python translated cube geometry to an Arduino Mega, which controlled pump actuation and servo motion.

5. A linear potentiometer provided a signal correlated to volume filling (Figure 3).

6. Motions of arching, twisting, and bending were explored through various actuation sequences.

RESULTS

- The system successfully managed 25 independent fluid lines (24 fill plus 1 for inlet/outlet; cf. Figure 4).
- Individual cubes filled on the order of seconds for simple actuations and minutes for multi-channel shapes.
- Complex surfaces such as twist (Figure 5), dome (Figure 6), arch (Figure 7), and half dome (Figure 8) were achieved, demonstrating the system's ability to handle complex degrees of freedom, to either conform to patient surfaces or respond to specific commands.
- Volume filling accuracy was limited by the linear potentiometer used for geared motor feedback.

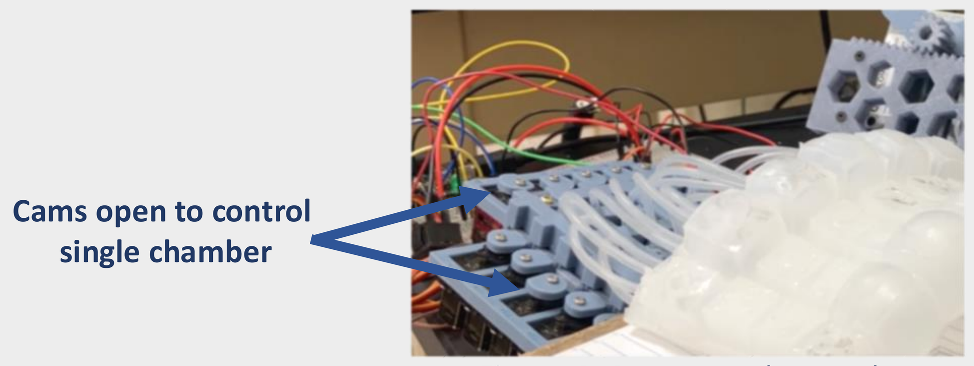

Figure 4. Cam control example

Figure 5. Surface twist example

Figure 6. Surface dome example

Figure 7. Surface arch example

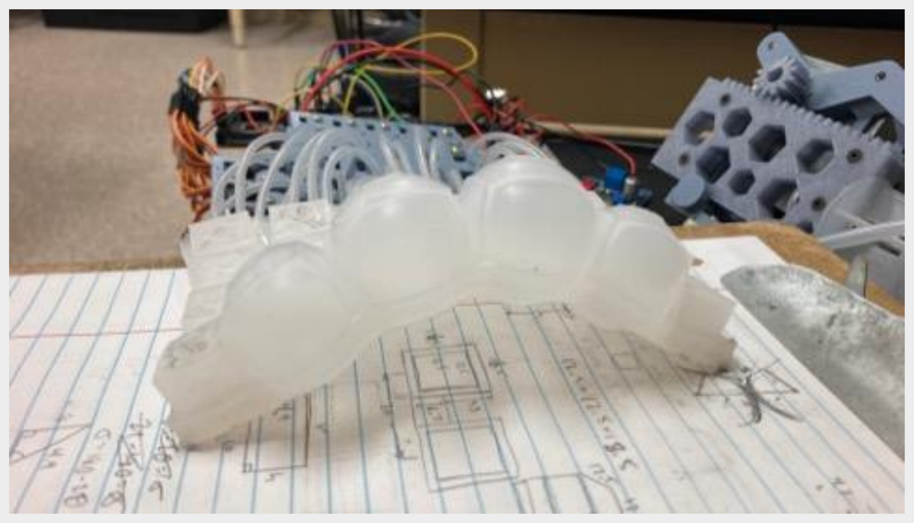

Figure 8. Surface half dome example

DISCUSSION

- This work establishes a low-cost and scalable control architecture geared towards clinical applications.
- Being normally closed, all outputs remain closed and are held closed without the need for additional supply power. Opening the row and column corresponding to the desired index position opens only that location, while all others remain sealed (Figure 4).
- Any robotic system (or multiple independent systems) of less than 24 lines can be controlled with the pump. Twists (Fig 5), domes (Fig 6), arches (Fig 7), and half domes (Fig 8) were demonstrated as a first pass at clinically relevant geometries.
- The multiplexed control reduces complexity compared to a multi-pump systems yet enables a high degree of freedom for soft robotic actuation with any fluid serviceable by a conventional 100 mL syringe.
- The speed of actuation is a limitation. The actuation sequence shown in the Figure 9 panel took about 30 seconds to complete.
- This inexpensive and flexible system introduces research clinicians to a platform for soft robotics in radiation therapy.

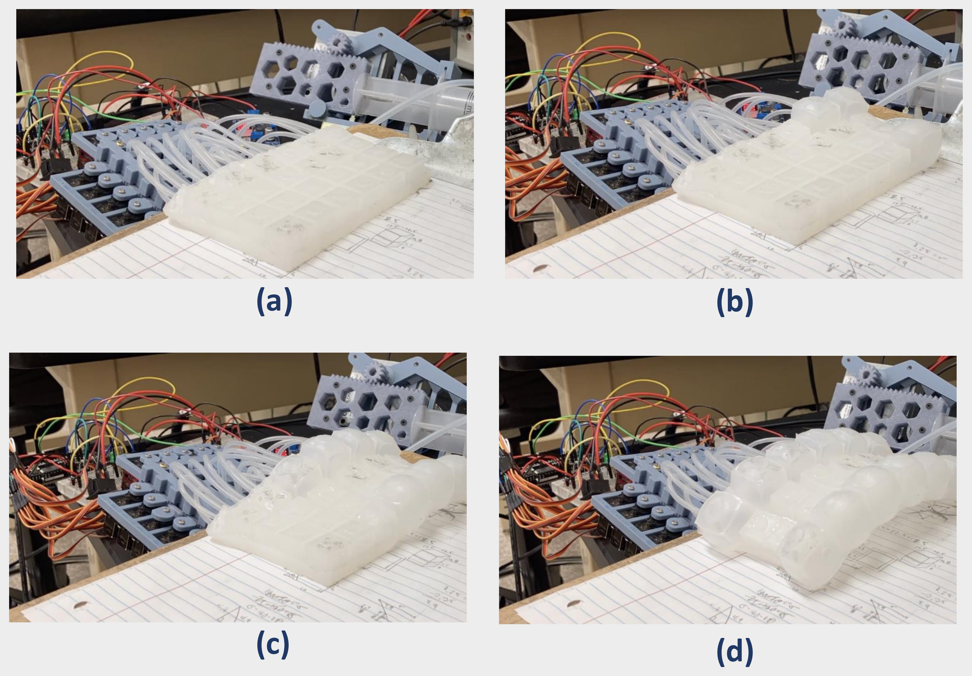

Figure 9. Sample actuation sequence, requiring about 2 seconds per chamber.

CONCLUSIONS

- We demonstrated the ability to prototype a low-cost, multiplexed control system capable of actuating 25 fluid channels in soft robotic devices using a single pump.
- The design enables complex deformations needed for patient conforming surfaces in radiation therapy yet keeps hardware complexity and cost at a minimum.
- Future work will focus on integration into clinically relevant soft robotic boluses and immobilization prototypes.

REFERENCES

1. B. Mosadegh et al., "Pneumatic Networks for Soft Robotics that Actuate Rapidly," Advanced Functional Materials, vol. 24, no. 15, pp. 2163–2170, Apr. 2014, doi: 10.1002/adfm.201303288.
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