# Towards a Complementary Design & Control Strategy for Linearized Pneumatically Powered Soft Robots

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***Abstract*— The control of pneumatically driven soft robots has great promise, but also great challenges as the robot's compliance and non-linear nature confound classical control processes. A soft robot design strategy that is complementary to control, and in particular MIMO state-space control, is proposed. By simplifying the mechanical structure such that it is an independent linear dynamical system, it affords a linearization (e.g., via a Jacobian) over a greater span of the control space between the pneumatic inputs and output pose.**

**By using a complementary process that compensates for the mechanical non-linearity in subsequent pressure regulation and control stages a novel silicone-based soft robot was designed without rigid components separating segments in the robot. This is illustrated and experimentally validated for a 12-input, 2-output (planar targeting) robot that is able to quickly adapt to variations (such as those from supply pressure and mechanical creep) so as to trace a rectangular paths. The results (over 15 trials) show a repeatability and reliability in the robot's movements. While the mean path traveled had variance to a desired path, the shape is followed consistently on average with bounded deviations. This suggests that this design strategy supports soft robot applications where deviations may then be compensated for though multiple sequences using probabilistic approaches. This together could allow for soft robots to have precision movements and compliance.**

## I. INTRODUCTION

Flexible and compliant robots, often classified as "soft robots," are coming into the fore [1]–[4]. Soft robots allow for greater manipulation as they are not restricted by rigid links (see also Fig. 1). However, this also means there is a greater level of variation associated with their forward model and actual movements. The current soft robot designs explored in the research of this project all contained rigid linking elements within the body of the soft robot which is not particularly ideal for placement / pointing tasks [5].

Soft robots offer a reduced risk in injury over rigid robots, partly due to their soft material and its ability to shape to the environment; however, that same property means that the robot's motions are now no longer independent of neighboring elements nor the loadings placed on the robot.

However, through a complementary consideration of the mechanics, (pneumatic) actuation and the control, it is asserted that the mechanics may be locally simplified in independent neighborhoods such that a linearization may provide sufficient prediction for local control of the system [6]–[8]. This may be seen as a hardware invocation of the Linearization Theorem [9]. In particular, material choices and manufacturing processes can be tailored such that the non-linearities introduced by the latter can help compensate for non-linear stiffness and viscoelastic effects of the former. This "complementary" systems approach extends throughout the design process and ties together the soft robot design approach and its assembly/construction of the overall soft robot system including actuation selection and implementation of any necessary hardware or electrical subsystems and the development of control to experimentally test the repeatability of the robots movements [10].

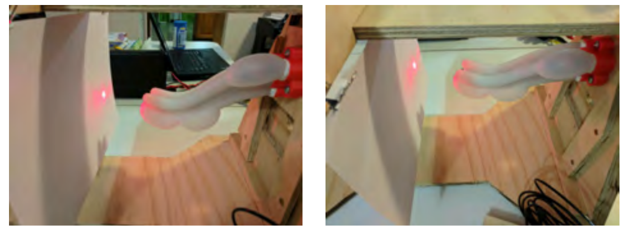

Fig. 1: Soft robot with no rigid sections designed using a complementary approach that eases subsequent tip trajectory tracking.

## II. BACKGROUND

### A. Soft Robotics Hardware

There are two distinct forms of actuation for soft robots: (1) embedded tension cables or shape memory alloys to bend segments of the robot; or (2) fluid actuation (pneumatic or hydraulic) [2]. For example, a soft robot arm developed in [11] is manipulated using 12 embedded cables in the main structure. Notably, this work also suggested that friction was the largest source of tracking errors.

An alternative to is a silicon robot, such as the STIFF-FLOP robot [7]. The design includes three pneumatically controlled soft chambers made from Ecoflex® 00-50 silicone rubber, a rigid structure in the center whose stiffness can be altered and an outer shell to contain the different elements of the structure. It also consists of four separate soft segments made from Ecoflex® 00-30 silicone rubber that use a stiffer material as a connecting piece. The segments are inflated with air using fluidic drive cylinders. Within each segment there are four separate hollow chambers, radially spaced 90 degrees apart. The width of the robot tapers towards the tip as less tubing is required and to reduce stiffness.

*This research was partly supported by the Australian Research Council Biomechanics Meets Robotics Project (DP160100714) and the School of Information Technology and Electrical Engineering. This workshop short paper is based on work completed as part of thesis, "One Soft Robot: A Pneumatically Controlled Soft Robot for Minimally Invasive Surgery"

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### B. Soft Robotics Control

Due to the high level of compliance with soft robots, controlling their movement is complex [12]. A continuous function may be required to model the shape of the robot so that it can continuously update to capture the robot as it adapts to the environment [2]. However, it is possible to design such a systems with redundancy, and thus the controller need not be as exact as the robots conform to their environment as a subsequent controller element may compensate. Low level control of fluid actuated soft robots usually involves the use of sensors, such as pressure sensors or strain gauges to know the volume of fluid. Open loop control using valves to control fluid flow is one of the most common control methods used by fluid actuated soft robots [3], [8], [13]. The soft fluidic elastomer manipulator [14], uses simulation iteration as the method of control. The geometry of the soft robot as it deforms was characterised using circumferential and longitudinal stresses and strains.

The kinematic equation of a segment is developed using the assumption that it deforms with constant curvature and that the hollow channels in each segment are cylindrical [6]. To this an N-segment kinematics chain is then used to cascade together the transformation of the soft robot design as rigid components separate segments, meaning the deformations of each segment can be treated separately. An issue with this is that such methods are limited as the design they are deriving control for has segments separated by rigid components. This separation simplifies control of the robot, when compared to a completely soft robot with no rigid components, because the segments can be treated separately. One of the major goals is to develop a completely soft robot, meaning it would not be separated by rigid sections. Therefore, these current control methods are not suitable as they will not work as precisely with a completely soft robot.

From testing [6], [14], it is noted that the model works most accurately with larger bend angles and at higher pressures. Thus, if the chambers can be "small" such that they are asked to execute significant control, the overall control method is less complex and can be linearized (for example using a Jacobian) [15]. This is explored further in the following section.

## III. COMPLEMENTARY DESIGN

While individual aspects of a soft robot design might be non-linear, and hence complicated to control, when cascaded together they may compensate for effects complementary manner. We focus on two key aspects of the robot's design and show how they interact.

### A. Mechanical Design for Multiple Chambers

Forming multiple chambers by adhering them in series would result in rigidizing intermediate sections, points of failure, and non-linearities. Thus, procedure to create multiple air pockets was designed using a sacrificial fluid/emulsion that was removed after initial curing but before operation. If such a material was not added then the chambers would merge and turn into a single volume. After testing against various mixtures of emulsions including an extensive catalog of sugar/corn/rice flour starches, it was found that Dr. Oetker Ready to Roll Icing was able to be **(1)** shaped easily; **(2)** stick to a supporting post(s) in the middle of the mould yet allow silicone to mould completely around it; **(3)** hold its shape during curing; and **(4)** dissolve in water. This is illustrated in Fig. 2.

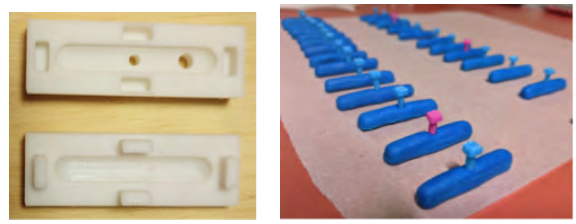

Fig. 2: Moulds (*left*) and sacrificial chambers from them (*right*) to support multiple air pockets in a single casting).

Having multiple hollow chambers within each segment would simplify control for moving in a two-dimensional space as each would correspond to a specific forward, backward, left or right movement to reach a coordinate. However, while the control may become more complex, to achieve two-dimensional movement four hollow chambers is unnecessary and the required movement can possibly be achieved with three hollow chambers radially spaced 120 degrees apart. The permanent-pattern mould consists of three 3D printed components: the two main pieces that fit together allow the soft silicone robot to easily be removed without damage and the third base piece ensures the silicone, when poured, does not leak out the bottom of the mould.

### B. Control Linearization

Various control methods have been researched for soft robots; however, for fluid actuated robots, they generally have rigid components separating segments in the robot. Therefore, none of the control methods can be directly implemented for a soft robot design, such as the one shown above, that does not have these rigid components.

Given that the soft robot is a Multiple-Input-Multiple-Output (MIMO) system, a Proportional-Integral-Derivative (PID) controller can not be used alone. A Model Predictive Control (MPC) approach could be employed, but its fidelity comes modeling the system with fidelity. As noted before, the system could be modelled with masses and springs to determine the kinematics, however, identifying the stiffness of the elastic material of the soft robot is difficult, especially its properties change over time and with the environment. Here the advantage of a complementary approach is to help reduce higher-order nonlinearities to the extent that a local linear approximation may be employed and thus allow for linearized state-space feedback control (as per Eq. 1).

$$\mathbf{u} = -\mathbf{K}\mathbf{x} = -\begin{bmatrix} K_1 & \dots & K_N \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} \qquad (1)$$

Here **u** describes the change in Pulse Width Modulation (PWM) duty cycle for each air pocket within the robot, **x** would be the desired change in velocity of the tip of the robot and **K** would be a Jacobian or gain matrix that relates these two terms. The **u** term would then be added onto the current **u** term to update the system velocity as required. As the motion of the robot in the prototype is limited to two-dimensions, the **x** matrix is $2 \times 1$. Therefore, direct system identification is limited because for the inverse (or identification) case, the highest rank the **K** matrix could have is 2, which means that during identification not every air pocket needs be inflated for each movement. Also, practically, certain PWM duty cycle values (i.e., less than 0.2 or greater than 0.8) are not effective due to their rapid changes. A low value would not be "on" long enough to allow the air pocket to expand and a too high value would not be "off" long enough to be any different from a 100% duty cycle.

## IV. EXPERIMENTAL EVALUATION & RESULTS

A testing frame consisting of the robot structure mounted horizontally and facing a planar target was constructed (see also Fig. 3). To track the tip location, a laser-diode was installed in the center of the robot. This is targeted at a translucent screen behind which a camera (Logitech C930e) is placed. An automatic spot tracking program tracked the tip based on the laser-diode intensity and resulting corner features in the image.

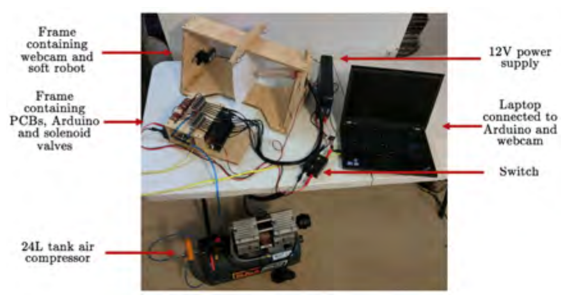


Fig. 3: Assembled soft robot testing system

### A. Linearity Testing

With this apparatus in place, the first set of experiments tested the linearity of the complementary soft robot system. The orientation the soft robot was mounted at meant that four of the air pockets (connected to pins D2, D5, D8 and D11) were able to offer vertical motion as they are the air pockets on the underneath side of the soft robot. As shown in Figs. 4 and 5, the position motion output is approximately linear for small air pocket expansions.

### B. Trajectory Tracking

Based on the linearity testing and system identification, the next step was to assess overall trajectory tracking performance. A procedure in which the robot was commanded to follow a rectangle was repeated over 15 trials starting at different random locations along the rectangular trajectory so as to assess the reliability and repeatability of the soft robot

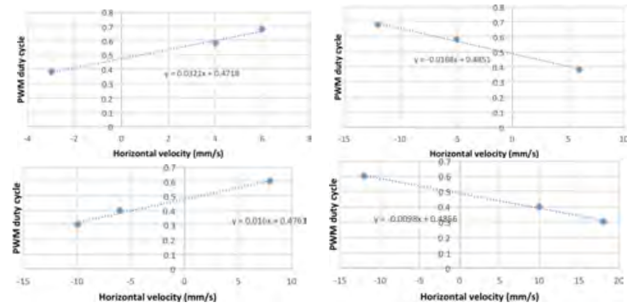


Fig. 4: Horizontal velocity scaling values (the first 4 of the 12 valves are shown for brevity, the remaining 8 are similar)

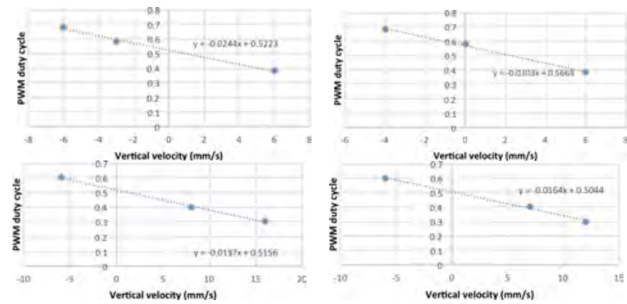


Fig. 5: Vertical velocity scaling values (for the same the 4 of the 12 valves shown in Fig. 4)

complementary approach. The results of this are shown in Figs. 6 and 7.

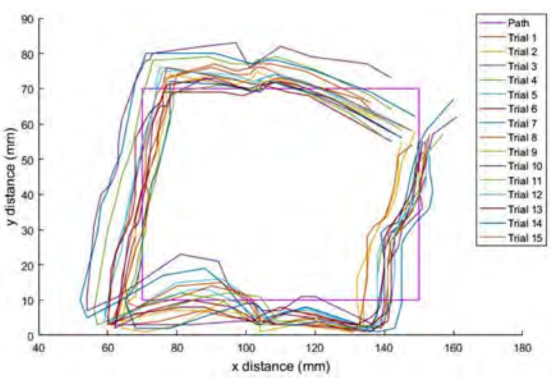


Fig. 6: Open-loop soft robot path tracking

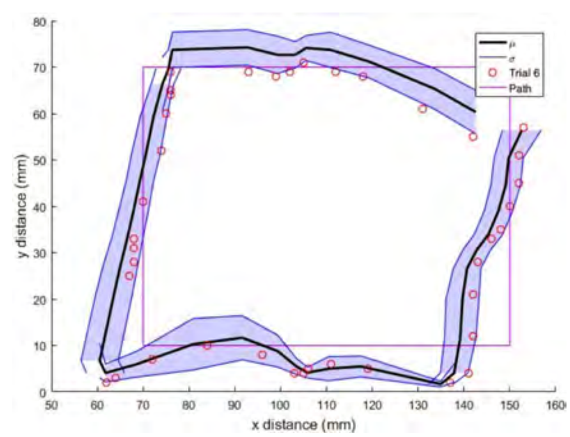


Fig. 7: Soft robot overall tracking
(path mean [*solid black*] and standard deviation [*shaded*])

## V. ANALYSIS & CONCLUSIONS

From the graph in Fig. 7, it can be seen that by comparing the mean path (black) to the set path (pink), the general shape of the set path was followed. The variance plotted in the graph shows a high level of repeatability in the results. Therefore, the uncertainty associated with the soft robots movement is reduced. The results vary by up to 15mm at certain positions in the two-dimensional path, however they generally repeatedly have this error. Therefore, the soft robots position along the path is fairly reliably known, even if at certain points it does not follow the path with great precision, because it is consistently following its own path. The range of movement of the soft robot throughout the fifteen trials was found to be quite large. From Figure 52 it can be seen that the soft robot has the ability to bend certain sections in different ways from one another. This is an important feature as during surgery, obstacles need to be curved around readily. This also greatly extends the soft robots manoeuvrability as it will be able to get through certain restricted openings by curving sections of itself. There are many possible reasons that the soft robot did not precisely follow the set path, such as imperfections in the soft robot due to manufacturing errors. Due to limitations in manufacturing, the air pockets are most likely slightly out of line with one another, resulting in different wall thickness surrounding each air pocket. The control method presented attempts to handle this with the scaling numbers in the Jacobians. The most likely reason that the soft robots movements were not precise is that the control method is not accurate enough to handle the movement of a soft robot. For surgical purposes, the control method would need to be improved. For this project though, the results answer the question initially posed in Section 1. Since the results show a very high level of repeatability and therefore reliability, it can be concluded that a completely soft robot has the capability of being developed to have the precision in movements that rigid robots have.

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