Compliant Bi-bellows Actuator with PVDF Force-Shape Sensing
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Abstract—Soft actuators are a key-stone for safe human-robots interaction, but deformation of compliant manipulators complicates their control. We propose using feedback from a deflection sensor consisting of a thin piezoelectric polymer. A Bi-bellows actuator was used as test-bed for demonstrating shape-tracking during free actuation, and also detection of contact with an obstacle. This sensor will enable accurate kinematic control of compliant manipulators and introduce in conjunction force sensing capabilities.

I. INTRODUCTION

Humano-robot interaction (HRI) has drawn much attention from the academic community in the passing decade. A major challenge for HRI is designing robots capable of safe interaction with humans [1]. One solution, impedance control [2], has been adopted by leading organizations such as DLR [3] and many bi-lateral (master and slave) manipulation systems. Another solution is incorporating compliant hardware in the manipulator; perhaps the earliest example is the remote center compliance (RCC) for peg-in-hole tasks, and a few novel grippers also rely on passive compliant components [4, 5].

Active compliant components facilitate fabrication of an entirely soft mechanism via a variety of actuation methods including: pneumatics, hydraulics, cable-driven, electro-active shape memory polymers and electro-conjugate fluids. Fluidic actuation (pneumatic or hydraulic) holds the advantage of a high power volume ratio [6], a valuable trait for miniaturization [7]. Bulky supply lines are a pitfall of fluidic actuation. Nevertheless, novel techniques have been suggested for actuating a few actuators with a single supply line [8-10] or by thermally controlled gas reservoirs [11, 12]. Fluidic actuators span a wide range, HRI representatives include; muscle actuators which are common in exoskeletons [13-15] and humanoid robots [16], limited rotary joints which have been used for rehabilitation [17], traveling-wave generators for colonoscopy [18] and various bending actuators: single degree of freedom (DOF) bellows [19, 20], two or three DOF chambered actuators [21, 22] and triplets of muscle-actuators [23].

Bellows actuators have been utilized for grippers [24, 25], locomotion [26, 27], and active surgical catheters [8]. Minute and highly flexible catheters would probably apply very low force on the tissue during catheter insertion, potentially reducing complications in MIS [28, 29]. Most steerable catheters and endoscopes rely on natural conduits, a bellows catheter on the other hand could theoretically remain compliant while being able of self supporting and retro-flexing; two traits which are vital for certain minimally invasive surgical (MIS) procedures, e.g. [30-32].

A fundamental challenge impeding the use of soft actuators is that tracking the actuation variable (e.g. pressure) is not sufficient for kinematic control, since obstacles and external loads induce significant actuator deformation. In the present work we confront the deformation problem by embedding Polyvinylidene fluoride (PVDF) film sensors onto a soft bending pneumatic actuator, Bi-bellows [20]. PVDF film is a piezoelectric-polymer which has been applied as a sensor in robotic systems for force sensing [33, 34], vibration damping [35], tracking deflection [36] and more. Here we examine PVDF film as a large-range deflection sensor, working at low frequencies (<5Hz). The shape of the bi-bellows actuator and its stress-strain field is influenced by external loads and constraints. If the position of an interaction force is known a priori then geometric sensors (strain, proximity) can be interpreted for force feedback, furthermore using redundant sensors eliminates the need for any prior knowledge on the external loads [37]. Using PVDF readings for force sensing may help reduce tissue perforation during catheter insertion and moreover enable palpitation during MIS [38].

In the following sections we describe the bi-bellows actuator, embedding of the PVDF and actuation trials under different conditions. We show that the PVDF sensor is capable of tracking the actuator’s strain and may be used for detecting contact with an obstacle. This solution is ideal for HRIs being compliant, scalable and having force sensing.

II. BI-BELLOWS ACTUATOR

Bi-bellows consists of a hollow, elongated, compliant body with a non-axisymmetric cut-section; this profile creates a distance between the center of pressure (COP) and the centroid as shown in Fig. 1(a). Increasing internal pressure induces a tensile force \(N\) and a bending moment \(M\) at the centroid (Fig. 1(b)), leading to deflection (see Fig. 1(c)). The large deflection may be parameterized with \(\theta\), the tangent angle to the actuators back-bone. Using this parameterization it was shown in [20] that the actuator resembles an Euler-Bernoulli beam, i.e. curvature is proportional to local bending moment.

Fig. 1. Bi-bellows actuation principle. (a) Cut section: The centroid is removed from the COP. (b) Side view: The actuation pressure yields an equivalent tensile force \(N\) and bending moment \(M\) induced by the actuation pressure. (c) Deflection: The actuator deflects as an Euler-Bernoulli beam.
The actuators were fabricated with a 3D rapid-prototyper (Objet Connex500). The 3D printer uses tiny droplets of resin to create a slice of the CAD model, cures this slice with UV light and then prints the next slice on top. Several types of resin can be used with various elastic moduli; the actuator’s body has a Young modulus (E) of ~0.45MPa while the inlet and hoops are harder, E~3.5MPa (Values of Young moduli through the courtesy of Objet). A support material which can be removed later on fills up empty spaces during the process. The bi-bellows’ external diameter is 10mm and it length, L, is 120mm (active length 104mm). The internal cavity is Ø7mm and the cut-section second moment is ~1000 mm$^4$. For a thin-walled cylindrical pressure-vessel the circumferential stress is twice the longitude stress i.e. the tendency for swelling is significant. Rigid hoops were embedded into the actuator in order to maintain a constant profile and enhance its motion. The hoops’ cut-section is Ø1mm, and they are spaced along the bellows at a 4 mm distance between centers. The resulting actuator is highly flexible; showing large deflection angles at low pressures with only slight swelling, e.g. the actuation pressure in Fig. 1(c) is only 1.6atm.

The actuators were anchored at the rigid inlet and an Intersema MS5407 pressure sensor monitored the actuation pressure. The actuation pressure was determined by a LabVIEW implemented PI controller, as explained in our reconnaissance [20].

### III. PIEZOELECTRIC SENSOR

Strips 120mm long, 4mm wide and 52µm thick of PVDF film were embedded into the actuators as shown in Fig. 2.

The PVDF tensile-stiffness (E=2-4GPa) is approximately twenty folds higher than that of the body of the bi-bellows which serves to augment bending, while the film’s resistance to bending is practically non-existent. We show the common annotation for PVDF film in Fig. 3. The voltage measured in direction 3 (V) is responsive to stress/strain in direction 1, bending round direction 2 and compression forces in direction 3 i.e. the PVDF signal is expected to be proportional to a combination of its own deflection, strain at the plane it is attached to and perpendicular contact forces.

The PVDF voltage was read with a follow-amp circuit, schematically provided in Fig. 4. The capacitive PVDF sensor was connected in parallel to a capacitor several orders of magnitude greater in order to lower the high-pass frequency beneath the working range, i.e. <0.1Hz. PVDF readings were post-treated by removing the initial offset.

### IV. VISUAL TRACKING

The sensor’s output was compared against geometric features of the actuator which were visually collected and served as a ground-truth for the actuator’s shape. Fifteen visual tracers, 1.5mm in diameter and 0.5mm thick, were equally spaced along each side of the actuator. Images of the actuator were taken with a webcam and the tracers were identified in post-process.
A cubic spline was generated through the tracer-centers in each frame, serving as a geodesic for strain estimation and yielding an analytic expression for the actuator’s curvature. Visual tracking of a single sinusoidal cycle is demonstrated in Fig. 5.

V. RESULTS

Two trials of free motion were conducted with different deflection ranges of the tip (β), 0°-90° and 0°-180°. The actuation pressure P was a 0.5Hz biased sinus reaching 0.06 MPa (0.6 bar) and 0.1 MPa (1 bar) i.e. a sine wave with a 0.03/0.05 MPa amplitude and a 0.03/0.05 MPa bias, correspondingly. The results of the 90° trial are shown in Fig. 6. The actuation-pressure set-point and the reading from the pressure sensor are displayed in the top axis. In the central axis we show the tip angle (β) and the actuator length. We can see that β follows the actuation pressure, roughly linearly as reported previously [20]. Comparing to previous work we notice that the PVDF film reduces strain and enhances bending. On the bottom axis we see that the PVDF follows the actuator’s strain, accompanied with what seems to be significant noise.

The results of the 180° trial are shown in Fig. 7, notice the surprising behavior; while the tip’s angle β adheres to the actuation pressure the strain does not (middle axis). Beyond a 90° tip-angle (denoted by dotted lines) the tracers’ fiber stops contracting and starts to stretch back to its original length. A possible reason for this phenomenon might be the exaggerated swelling which increases the external diameter and reduces wall thickness, encouraging elongation over bending. However this point is beyond our scope of interest. The PVDF response resembles this double-humped behavior of this geometric strain feature, as depicted in Fig. 7, bottom axis. We examine the PVDF response-loop in Fig. 8 the double-humped profile is reflected in the U-shaped response on the left. The PVDF response to length is shown on the right – while the PVDF signal shows a higher correlation to the length than to the pressure but the relation is nonlinear beyond the critical tip-angle of β=90°.

In the limited working range (<90°) the PVDF response was close to linear with both strain and actuation-pressure P but in the larger working range (<180°) PVDF responded non-linearly to strain and showed no correlation to P or the deflection angle β (which followed P). This information is summarized in TABLE I by examining the correlation (ρ) of the signal with the actuator length (L) and actuation pressure (P) during a single cycle.

After investigating free-motion we proceeded to consider restricted motion. In Fig. 9 we display how the actuator was obstructed during actuation and in Fig. 10 we show the tip’s angle (β) vs. the PVDF signal (top axis) and vs. the pressure reading (P, bottom axis). The actuator was activated freely and then an outer obstacle was introduced, preventing bending. After a couple of free cycles an internal obstacle

![Fig. 6. Actuation trial of a free actuator bent up to 90°. Top – pressure set-point (SP, dashed blue) vs. the actual pressure measured (P, solid red). Middle – features extracted by visual tracking; actuator length (L, dashed blue), and tip angle (β, solid green). Bottom – PVDF reading (PVDF, solid red) vs. the actuator length (L, dashed blue).](image)

![Fig. 7. Actuation trial of a free actuator bent up to 180°. Top – pressure set-point (SP, dashed blue) vs. the actual pressure measured (P, solid red). Middle – features extracted by visual tracking; actuator length (L, dashed blue), and tip angle (β, solid green). Bottom – PVDF reading (PVDF, solid red) vs. the actuator length (L, dashed blue).](image)

![Fig. 8. PVDF response at large deflection angles (90°-β<180°). Left – the backbone length (solid line, blue squares) and PVDF (dashed line, black triangles) change in a non-linear fashion as actuation pressure is increased and β is pushed beyond 90°. Right – beyond the critical β angle the PVDF-Length relationship becomes highly non-linear.](image)
was presented, restraining flexion. Again the PVDF followed the free motion (showed in opposite polarity) but contact with an obstacle stimulated a sharp response. The pressure sensor remained indifferent to the kinematic constraint.

VI. DISCUSSION

Control of flexible actuators requires overcoming a fundamental difficulty; the significant influence of external forces and constraints on the actuator’s shape. We demonstrated that the PVDF signal is generated by a geometric feature (strain), independently of the pressure reading. The PVDF response corresponds to strain reasonably well in the $0^\circ$-$90^\circ$ range but displayed a non-linear response beyond the $90^\circ$ limit. We will try to improve this problem by distributing several short sensors along the actuator instead of a single long strip. This is reminiscent of works on a sensitized end effector which is able of estimating the magnitude, location and shape of external forces acting on it [37].

Operating at low frequencies, the PVDF signal suffers from poor SNR and drift - other circuits might be more suitable than the follow-amp. For example, a low-frequency charge-amplifier, which acts as a band-pass (BP) differentiator and might also solve problems such as current-leakage during long periods of constant actuation. Overall we conclude that the proposed sensor is able to monitor the shape of single-DOF bending actuators without inhibiting their operation. Further work is necessary in order to interpret the strain reading into shape.

Data fusion of the PVDF with the pressure sensor enables estimation of the location of the actuator tip and will be used for external force estimation and closed loop control. Full data integration requires an accurate kinematic-model of the actuator, a non-linear problem which might be difficult to solve in real time. It might be possible to circumvent this hurdle using redundant PVDF-sensors, i.e. the pressure sensor will monitor the actuation-variable and the PVDF sensors will give shape/force feedback independently.

Combining several bi-bellow actuators will enable to build stiffness varying hyper redundant robots for various HRI applications. We suggest several applications in Fig. 11 such as a self supporting ablation catheter with shape tracking capabilities, a compliant endoscope accessory for stereoscopic vision and a force controlled gripper for home-care robots.

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