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Bending angle prediction and control of soft pneumatic actuators with embedded flex sensors – A data-driven approach☆

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ABSTRACT

In this paper, a purely data-driven modelling approach is presented for predicting and controlling the free bending angle response of a typical soft pneumatic actuator (SPA), embedded with a resistive flex sensor. An experimental setup was constructed to test the SPA at different input pressure values and orientations, while recording the resulting feedback from the embedded flex sensor and on-board pressure sensor. A calibrated high speed camera captures image frames during the actuation, which are then analysed using an image processing program to calculate the actual bending angle and synchronise it with the recorded sensory feedback. Empirical models were derived based on the generated experimental data using two common data-driven modelling techniques; regression analysis and artificial neural networks. Both techniques were validated using a new dataset at untrained operating conditions to evaluate their prediction accuracy. Furthermore, the derived empirical model was used as part of a closed-loop PID controller to estimate and control the bending angle of the tested SPA based on the real-time sensory feedback generated. The tuned PID controller allowed the bending SPA to accurately follow stepped and sinusoidal reference signals, even in the presence of pressure leaks in the pneumatic supply. This work demonstrates how purely data-driven models can be effectively used in controlling the bending of SPAs under different operating conditions, avoiding the need for complex analytical modelling and material characterisation. Ultimately, the aim is to create more controllable soft grippers based on such SPAs with embedded sensing capabilities, to be used in applications requiring both a 'soft touch' as well as a more controllable object manipulation.

1. Introduction

Soft pneumatic actuators (SPAs) with internal fluidic channels (commonly referred to as PneuNets) are made of highly stretchable elastomer materials, which deform upon the pressurisation of the internal channels to create a predefined motion [1]. The response of this type of actuators is governed by its morphology, which is defined by the geometry of the internal fluidic channels and the properties of the materials used in fabrication. Inserting a flexible but inextensible strain limiting layer, in the form of a paper or fabric, at the base of the SPA prevents it from elongating and forces it to generate a bending motion that is analogous to that of a human finger. Hence, this class of bending actuators is being adopted as compliant soft gripper fingers, which are able to passively conform to objects of complex geometries and adapt to dimensional variations and location uncertainty [2,3]. In addition, the soft nature of the elastomer materials used to create these soft gripper fingers, allows grasping of delicate objects safely without damaging their surface [4].

On the other hand, the complex deformation exhibited by the nonlinear elastomer materials, commonly used to create the SPA based fingers, are difficult to model and control accurately [5]. Some examples of recent work addressing the modelling and characterisation of bending SPAs include; an experimental characterisation of the geometry of bending and rotary SPAs [6,7], finite element analysis (FEA) of cylindrical SPAs for surgical applications [8], theoretical modelling of a soft snake robot based on the bending SPAs [9], and a detailed analytical and finite element modelling of a single chamber fibre-reinforced bending SPA [10]. One of the main challenges associated with the analytical and FEA modelling approaches is the need for accurate material models and relevant material coefficients, which can accurately describe the nonlinear behaviour of the hyperelastic materials used. This becomes even more complex when SPAs are made of combinations of different materials, or when equipped with external reinforcements or embedded components. Furthermore, there is some uncertainty in the manual process commonly followed in fabricating SPAs due to human error. This could result in variations in the geometry or material

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properties of fabricated SPA samples, which would influence their bending response. Therefore, it would be interesting to investigate a simpler approach for predicting and controlling bending SPAs, based on experimental data that implicitly accounts for the effects of uncontrollable variations in the morphology.

The main contribution of this paper is in the proposition of a purely data-driven modelling approach that utilises feedback from inexpensive commercially available sensors, to derive empirical models that can be used for predicting and controlling the free bending response of soft actuators. This data-driven modelling approach was initially introduced in our previous work [11], and is further extended here by utilising the derived empirical models for controlling the free bending response of SPAs based on real-time sensory feedback. Recent relevant work demonstrated how the free bending angle can be accurately controlled using a feed-forward controller, which relies on detailed analytical models describing the physical behaviour of fiber-reinforced bending actuators specifically [10]. Yet, the data-driven approach presented here is not constrained to a specific actuator morphology or input actuation pressure, since it is entirely based on the generated experimental data. Thus, this approach not only avoids the need for deriving precise physical and material models that could be difficult to achieve in some cases, but also the experimental data generated from real tests implicitly accounts for variations that are otherwise difficult to model mathematically. The primary requirement of this approach however, is to generate sufficient experimental data that describes the behaviour of the modelled SPA under different operating conditions, so that the derived models can be further generalised to new untrained scenarios. Hence, equipping SPAs with reliable sensing capabilities becomes essential to generate the required sensory feedback.

The paper proceeds with a review on relevant work addressing the modelling and control of bending SPAs aided by different techniques for embedding sensory feedback. This is followed by a summary of a common fabrication process that can be followed to create typical bending SPAs, while embedding a flex sensor inside. Afterwards, in Section 4, the platform involving the use of pneumatic control board and a high-speed imaging system is presented, explaining how the SPAs are actuated under different operating conditions to collect the required experimental data. In Section 5, the data-driven modelling of the relation between the acquired sensory feedback and the bending angle measured using the vision system is derived using regression analysis and neural networks. The results obtained using both techniques are presented, comparing their prediction accuracy when tested with a new dataset acquired at untrained operating conditions. Moreover, in Section 6, the derived empirical model is utilised as part of a closed-loop PID controller to control the bending of the SPA to a desired target value. Finally, the paper ends with some conclusions regarding the outcomes of the proposed data-driven approach, highlighting the planned future work.

2. Review on sensor enabled control of SPAs

Despite the fact that the passive compliance of SPA based soft fingers is desired for adapting to sources of variations and uncertainties without the need for expensive sensing and complex control, it also has the drawback of limiting their application to simple pick and place tasks that do not require controlled manipulation and feedback about the grasp quality. The absence of active sensing also means that the orientation of a grasped object with respect to the soft gripper would be unknown, since the grasp was achieved passively. Hence, accurate object positioning would be difficult to achieve, which is required in applications such as assembly tasks for example. Thus, equipping SPA based soft fingers with some level of sensing capabilities that do not hinder their desired softness and compliance would result in more controllable SPAs with enhanced functionality and wider application involving more complex manipulation tasks.

The primary controllable input parameter that can be varied during the actuation of soft actuators is the pressure of the pneumatic supply, which in turn controls the input pneumatic flow rate. The internal pressure response can be easily measured using common pressure sensors connected to the pneumatic supply tubes, and can be used to control the bending of a SPA if the model relating the input pressure to the bending angle response is known in advance. This has been demonstrated for a soft fibre-reinforced actuator, which used an angle filter to estimate the bending angle based on the pressure measurements and a PID controller to meet the target bending angle [10]. The main challenge in sensing however is to directly measure the bending motion of SPAs as they curve towards their base, without actually hindering this passive behaviour. Hence, a flexible sensor is required that can be embedded at the base layer of an SPA, where extension is restricted by the constraint layer, to provide a measurable change in a physical parameter that can be directly related to the witnessed bending motion. This is one of several applications motivating research over the past few years into developing new concepts for flexible and stretchable sensors, which can be integrated with soft bodies in general [12]. The main soft sensing techniques that could be smoothly integrated with soft gripper fingers specifically for measuring and controlling their bending angle can be classified into three main approaches as follows:

(1) The first approach is adding different forms of carbon content into an elastomer material, in order to make it conductive and hence becoming a soft sensing element that changes in resistance when strained. This type of conductive elastomer sensor has been incorporated with a two-fingered soft gripper design that is actuated using linear displacements [13], to detect grasped objects and recognise their different sizes using an adaptive neuro-fuzzy controller [14]. The main challenge with conductive elastomer sensors is the difficulty in producing sensors with consistent electrical properties, since repeated deformation may affect the distribution of carbon particles within the elastomer material. Also, stable electrical connections are difficult to achieve and may be a source of additional fluctuations in the sensory readings. Yet, the process of fabricating conductive elastomer sensors is potentially scalable through a customised 3D printing process of carbon grease inside a silicone elastomer reservoir [15].

(2) A popular soft sensing approach now is achieved by filling patterns of micro-channels imprinted within an elastomer body with a conductive liquid metal (EGaIn). Different physical parameters can be measured depending on the geometry and pattern of the conductive channels [16]. Previous work demonstrated the use of this sensing approach to measure parameters such as: Multi-axis forces [17], strain [18], curvature [19], and pressure [20]. The concept was integrated with a SPA based gripper to achieve accurate position and force control using feed-forward models in conjunction with a PID controller [21]. It was also used to control the bending of soft beams actuated by an antagonistic pair of SMAs [22], and was integrated with a soft gripper to detect the presence of an object while grasping [23]. However, the process of creating the embedded micro-channels and injecting conductive liquid metal is still a manual multi-stage process that is not easily repeatable. In addition, the conductive EGaIn material is quite expensive, though usually needed only in small quantities. The strain feedback from this approach was reported to be mostly linear and highly repeatable, but suffered from some hysteresis at higher strain rates as the EGaIn material is allowed to refill the micro-channels [18].

(3) An alternative soft sensing approach is achieved by simply embedding commercial resistive flex sensors within the strain limiting layer of bending SPAs. The flex sensors are made of thin films that can easily bend and change in resistance upon bending [24]. This has been adopted with SPA based gripper fingers for haptic identification, by clustering the Readings from the embedded flex sensors so that a trained algorithm can identify the grasped objects