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A unified system identification approach for a class of pneumatically-driven soft actuators

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HIGHLIGHTS

- A unified system identification approach is proposed.
- The approach is used to identify the nonlinear pressure–shape dynamic relation.
- The used auxiliary kinematic setting can be implemented by gyroscopic sensors.

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ABSTRACT

The class of Pneumatically-driven Low-pressure Soft Actuators (PLSA) is a popular choice potentially used in the surgical robotic applications. One fundamental problem lying in the PLSA research is the lack of a generally validated model for the complex nonlinear dynamic behaviours. In this paper, a unified identification approach for the general PLSAs is proposed. It is a parameter-independent way directly used to identify the dynamical relation between the actuating pressures and the principal degrees of freedom of a PLSA, the bending and the steering. The approach is based on a modified auxiliary kinematic setting and a newly developed identification model structure, named DIO–PWL–OBF. Following the concluded identification procedure, the implementations for the single chamber bending and the double chamber bending and steering are demonstrated separately. The results show that the proposed approach can accurately capture the nonlinear pressure–shape dynamical relation. The approach is also efficient in real-time applications. It can be further used to improve the current control design for the PLSAs in robotic applications.

1. Introduction

In the fields of surgery and therapy, soft robotic instruments begin to draw researchers' attention in the past 20 years [1,2]. Compared with traditional rigid ones, the soft robots can potentially give a more viable solution when the operation is taken in human bodies. The inherent compliance offers human friendly interaction; the kinematic redundancy provides the manoeuvre competency in highly unstructured in-body organ environments. One promising choice is the class of Pneumatically-driven Low-pressure Soft Actuators (PLSA). They are compactly designed in small sizes and safely operated at low pressures. An immediately foreseeable application is endoscopes [3]. It can overperform the current rigid endoscopes by giving the doctors increased adroitness meanwhile reducing damage on the patients. Fig. 1 shows three typical PLSA examples. In this paper, we specifically use the term PLSA to distinguish it from the Pneumatic Muscle Actuators (PMA) like in [4]. The latter commonly have much larger sizes and higher operation pressures. But both the PLSAs and the PMAs are in the class of the pneumatically-driven soft continuum robots, and they share many similar properties.

For the general pneumatic soft continuum robots, the kinematic modelling is still the backbone in the state-of-the-art control designs [6–10], which is based on a purely geometrical description of the actuators' shapes. Completely validated dynamic modelling for a single section of the pneumatic soft robot arms is lagging behind. The potential applicability is therefore restricted. The modelling has been analytically studied in [11,12]. The Lagrange formation under the constant curvature condition was used to derive the dynamic relation between the individual chamber lengths and the

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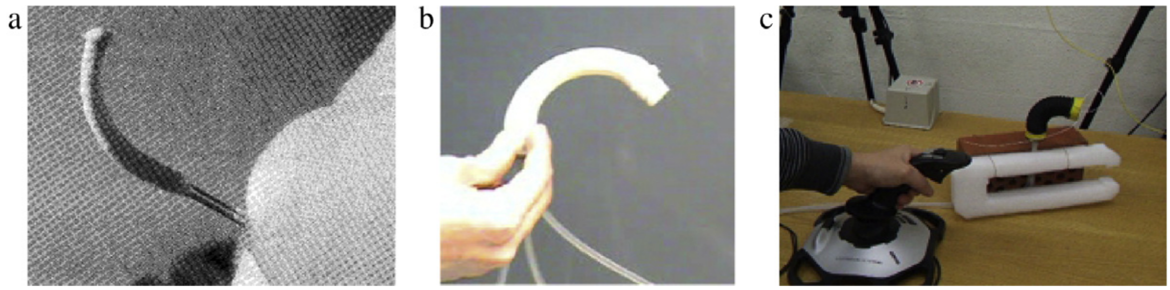

Fig. 1. Featured PLSA prototypes: (a) Flexible Micro-Actuator by [5]. (b) Colobot by [6]. (c) An early design of the STIFF-FLOP actuator.

shape. The worked models are ineffective in handling the coupling effect between each chamber. Unlike the PMAs, this internal effect cannot be neglected in the PLSA cases, because the latter are structured in one integral rubber material. The radial expansion of each individual chamber is not constrained as the way by the individual bellow suits used in a PMA. Besides, the above modellings do not include the complex nonlinear dynamic relation between the actuating pressures and the chamber lengths, which is an independent open problem too. A recent work by [13] started to tackle the issue of lacking the actuator dynamics based on the previous work in [12]. The proposed model correctly accounts for the identified hysteretic behaviour using the Bouc–Wen restoring force method. This research is on the right track, but it is mainly investigated for the PMAs. Due to the structural difference, the involved intermediate step of the separate pressure–elongation identification for a PMA's individual bladders cannot be applied to the internal chambers of a PLSA. And the internal coupling issue has not been formally studied. Besides, another work by [14] directly used a second-order linear transfer function to approximate the pressures–shape relation. But only the single chamber bending situation was partially studied. The model is only valid for a small degree of bending. The deformation was measured based on the deflection distance projected onto the horizontal base plane. However this kinematic variable does not naturally represent the bending deformation in a linear manner.

The primary contribution of this paper is a unified identification approach for the general PLSAs. For a single segment PLSA, it can practically give reliable approximations for the nonlinear dynamical relation between the actuating pressures and the two principal Degrees Of Freedom (DOF), the bending and the steering. The identification approach has three features:

1. It is based on the measurement of the tip surface orientation of a single segment PLSA. This auxiliary kinematic setting is incorporated into the mainstream kinematic framework and can be easily implemented by on-shelf gyroscopic technologies.
2. It is based on a newly developed model structure, of which parameters are statistically defined. Hence specific mechanical parameters such as the material elasticity, the chamber placement and the chamber dimensions are not required. This makes the modelling capable of covering general designs of the PLSAs.
3. It preserves characteristics of local dynamics through linear approximation; no weighting term is used to fit the observed nonlinearities of PLSAs. The resultant model structure becomes a type of switched linear systems. Mature linear control techniques can be used in later control design.

The paper is arranged in the following way: the structure and the nonlinearities of the PLSAs are discussed in Section 2. It states the need to build a new suitable identification model structure. Section 3 studies the auxiliary kinematic setting regarding Feature 1. Some aspects in the mainstream kinematic configuration are discussed in Section 3.1 firstly. And then the new setting is introduced in Sections 3.2 and 3.3. Regarding Features 2 and 3, the unified identification approach is developed in Section 4. General concerns and fundamental theories are briefly discussed and introduced in Sections 4.1 and 4.2. Section 4.3 studies the new proposed identification model structure in detail and summarises the unified identification procedure at the end. Section 5 shows the implementation and results. The conclusion and future work are presented in Section 6.

2. The PLSAs

2.1. The structure of a single segment PLSA

The PLSAs commonly have the 1-, 2-, 3- and 4-chamber designs. Among them, the 3-chamber design is the most versatile type for robotic applications. It has all three DOFs compared with the 1- and the 2-chamber ones, and at the same time it uses one less chamber in contrast to the 4-chamber one. Our work will focus on the general 3-chamber PLSA design as sketched in Fig. 2(a). Optimally it is designed in a very symmetric way. Three identical pneumatic chambers are regularly disposed at 120° apart, and they are together parallel to the central longitudinal axis of the actuator.

Fig. 2(b) gives a brief explanation for the ideal bending. The outer covering of a PLSA usually wear a kind of bellow suits so that the radial expansion induced by the fed-in pressure is largely reduced and can be neglected. The individual chamber elongations are the main type of the deformations structured by the bellow. Thereby they deterministically drive the deformation of the entire actuator. The related DOFs are classified as *bending*, *steering*, and *elongating*. As the case in Fig. 2(b), Chamber 2 takes the longest incremental length Δl_2^c as it is subjected to a higher pressure than Chambers 1 and 3, which makes Chamber 2 lead the bending direction.

2.2. The observed nonlinearities

Fig. 3 shows a typical example of the single chamber deflection[1]—actuation relation from our experiments. The test consists of 28 local step responses, each of which starts the initial condition from its predecessor's final condition. And both the pressure increase and the decrease situations are taken.

The first nonlinearity type that can be spotted is the deadzone effect at the initial pressure range. It is due to the gas fill-in phase during the initial actuation. Secondly, in the pressure increase cases, it can be seen that the steady state values of each local step response are not in a linear relation with their input ones. The similar things happen in the pressure decrease cases. By further comparing both the increase and the decrease cases, it is not hard to figure out an underlying hysteresis loop. The cause of

[1] The *deflection* can be seen as the complementary motion of the *bending*. And they are equivalent under the constant curvature condition. In the rest of the paper, we will use the two words interchangeably when no confusion is caused.