Compact pneumatic clutch with integrated stiffness variation and position feedback

Yongkang Jiang[1,2,#], Junlin Ma[1,2,#], Diansheng Chen[1,2,*], and Jamie Paik[3,*]

***Abstract*— Stiffness variation and real-time position feedback are critical for any robotic system but most importantly for active and wearable devices to interact with the user and environment. Currently, for compact sizes, there is a lack of solutions bringing high-fidelity feedback and maintaining design and functional integrity. In this work, we propose a novel minimal clutch with integrated stiffness variation and real-time position feedback whose performance surpasses conventional jamming solutions. We introduce integrated design, modeling, and verification of the clutch in detail. Preliminary experimental results show the change in impedance force of the clutch is close to 24-fold at the maximum force density of 15.64 N/cm^2. We validated the clutch experimentally in (1) enhancing the bending stiffness of a soft actuator to increase a soft manipulator's gripping force by 73%; (2) enabling a soft cylindrical actuator to execute omnidirectional movement; (3) providing real-time position feedback for hand posture detection and impedance force for kinesthetic haptic feedback. This manuscript presents the functional components with a focus on the integrated design methodology, which will have an impact on the development of soft robots and wearable devices.**

***Index terms*—Compact clutch, integrated design, variable stiffness, soft robots, origami robots**

I. Introduction

The ability to adjust structural stiffness is crucial for soft robots and wearable devices in circumstances where large exerting forces are required to manipulate objects or assist the wearers, or high mechanical stiffness is needed to block motions in a specific direction [1, 2]. In recent years, we have seen a number of solutions for modulating mechanical stiffness, including jamming mechanisms [3-7], phase change materials [8-13], and antagonistic structures [14, 15]. However, the range of stiffness change, miniaturization, and the sensing ability still challenge current variable stiffness mechanisms. Additionally, real-time position feedback has a critical role in posture estimation and precise control for soft robots and wearable devices. Research efforts have strived to obtain the sensing ability, such as conductive-fluid-based soft sensors [16, 17]. Nevertheless, in most of today's work, stiffness variation structures and position sensors are designed and even fabricated separately. Then, these individual parts are put together simply to form a multi-functional system, which leaves room for optimizing and streamlining the integration step [18]. Therefore, we need a new integrated design method to realize stiffness modulation and position feedback in one step for soft robots and wearable devices.

As core components of many robotic systems, clutches play a vital part in changing various motion types and allowing stiffness variation with the antagonistic arrangement method [19]. There has been wide use of conventional rigid clutches [20], but they are rather bulky for soft robots and wearable devices. The recently proposed soft textile clutches [21] and electroadhesive clutches [22] show great advantages due to their flexible bodies; however, most of the soft textile clutches utilize vacuum power for jamming to generate high impedance force [23]. Similar to the existing layer-jamming mechanisms [24, 25], the relatively low force density, high hysteresis, lack of sensing ability, and cumbersome bodies might be limitations for these jamming-based solutions. For electroadhesive clutches that utilize electroadhesion force to block a specific motion, the high driving voltage, possible electric breakdown, and remaining adhesion could be their shortcomings [26]. Furthermore, a significant force drop has been observed when the external pulling force exceeds the maximum blocking force in electroadhesive clutches [27, 28], which means they are more suited to changing motion type by blocking specific movements, rather than realizing continuous stiffness variation. Previously, we used soft silicone actuators to push together two high-friction layers and confirmed that friction-force-based clutches have merits in continual stiffness changing [29]. However, the low force density, as well as cumbersome bodies, restricted their further application. As a new type of soft actuator, air pouches made of several layers of flexible materials have shown considerable potential as they are ultralight, customizable, and easy to fabricate [30], making them a perfect alternative to the soft silicone actuators of our previous work. Nevertheless, most of the existing effort has focused on taking advantage of the in-plane contraction of air pouches, which hardly exceeds 36% [31]. In comparison, it has neglected its large deformation rate (x100) in the out-of-plane direction. Indeed, actual work usually adopted small deformation plate theory, ignoring the elongation in the middle plane to describe the shape function of the air pouches, which could induce a significant deviation between analytical and experimental results [32]. To better predict the relationship between the input air pressure and friction force of a possible air-pouch-based clutch, we need to analyze the large deformation of the air pouches more comprehensively.

Here, we propose a compact clutch with an air pouch that actively modulates the impedance force and integrating a sensor to provide real-time feedback. The presented clutch uses positive air pressure for a fast-response layer-jamming

The research is supported by the National Key R&D Program of China (2018YFB1304600), National Natural Science Foundation of China (51775012), Beijing Natural Science Foundation (L182012), and Beijing Municipal Science & Technology Project (Z191100004419006).

[#] The authors contribute equally to this work.

[1] Institute of Robotics, Beihang University, Beijing, 100191, China.

[2] Beijing Advanced Innovation Center for Biomedical Engineering, Beihang University, Beijing, China.

[3] National Research Center for Rehabilitation Technical Aids, Beijing, 100176, China.

* Corresponding authors: Diansheng Chen (chends@buaa.edu.cn), Jamie Paik (Jamie.paik@epfl.ch)

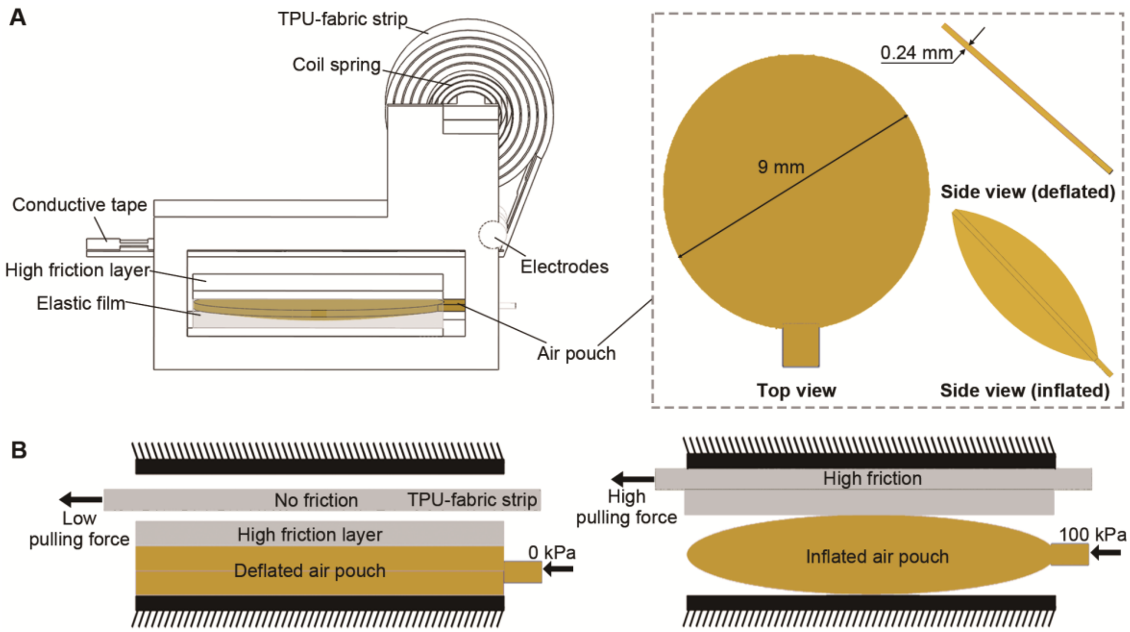

Figure 1. Schematic of the proposed clutch consisting of an air pouch for regulating the impedance force, a sensing layer for real-time position feedback, and a coil spring for recovery of the TPU-fabric strip. (A) System overview. (B) Working principle of the air pouch part.

for high impedance force enhancement, increasing the overall jamming force compared to the state of the art, which can only apply that maximum of negative vacuum pressure (85-90% vacuum). With this novel unified design, the above shortcomings of the conventional layer-jamming mechanisms such as high hysteresis can be avoided, and at the same time, a wide range of impedance force adjustment and sensing ability are achieved. We first describe the structure and working principle of the planned clutch to feature the integrated design method in this work. As a central part of the clutch, we provide a mathematical model of the air pouch in two layers based on a large deformation plate theory that explores the deformation-pressure response. Additionally, we present the relationship between the normal pushing force of the air pouch and the inside air pressure in detail to predict the friction force. We then verify the theoretical models experimentally. Other tests analyzed influence factors on the impedance force and sensing ability of the clutch. Finally, we evaluated the performance of the proposed clutch with three functional prototypes to highlight its potential applications in soft robots and wearable devices, including in (1) enhancing the grasping force of a soft gripper by modulating its bending stiffness; (2) enabling omnidirectional movement of a soft cylindrical actuator by selectively adjusting input air pressure inside the clutches; (3) providing real-time position feedback for hand posture detection and impedance force for possible kinesthetic haptic feedback in virtual reality (VR) applications.

The main contributions of this work are:

- Integrated design of a novel compact clutch with modulable stiffness and real-time position feedback;
- Modeling, validation, and characterization of the original high force clutch design;
- Performance evaluation of the clutch in three potential applications, including a soft gripper, a multi-DoF actuator, and a hand-motion tracker.

II. A Novel Compact Clutch with Modulable Stiffness and Position Feedback

Stiffness variation and real-time position feedback are pivotal in the design of a clutch. The main difficulty in enabling stiffness variation based on the antagonistic arrangement method is changing their impedance force over a broad-enough range. Furthermore, miniaturization of the clutch to make it suitable for soft robots and wearable devices is another obstacle. Here we present the system overview and working principle of a new clutch using an integrated design method to overcome these problems. A comprehensive model of the large deformation of the air pouch and the force-pressure response of the clutch can be found in the Appendix.

We illustrate the clutch, made up of three main parts, in Fig. 1A. Parts include an air pouch modulating the friction force on a TPU-fabric strip, a sensing layer detecting displacement and movement direction of the TPU-fabric strip, and a coil spring for recovering the TPU-fabric strip. Unlike other systems where stiffness variation and sensing parts have no common elements and work independently, in this design the TPU-fabric strip with a conductive tape can produce a high friction force when the air pouch pressure increases, and provide position feedback when the strip comes out of the clutch. This combined system not only reduces the size of the whole structure but also the mechanical interference between the layers.

The air pouch, also shown enlarged Fig. 1A, provides a normal pushing force generating large changes in impedance force. A high friction layer is utilized to avoid direct contact of the air pouch with the TPU-fabric strip to enhance durability. Likewise, elastic films promote fast recovery when the air pouch is deflated. The basic working principle of the clutch for regulating the impedance force on the TPU-fabric strip is illustrated in Fig. 1B: when the air pouch is deflated, the