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High-precision motion control of a stage with pneumatic artificial muscles

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ABSTRACT

Pneumatic artificial muscles (PAMs) have been applied in bionic robots, welfare devices, and parallel manipulators because of their many advantages over traditional actuators; such advantages include their high power-to-weight ratio, high power-to-volume ratio, high degree of safety, and stick-slip-free operation. However, significant nonlinearities in PAMs cause low controllability and limit their application. This research aims to provide a practical controller design method for high-precision motion of PAM mechanisms, and this paper proposes a simple and practical controller design method. This controller is designed based on our previous positioning controller and includes a phase-lead element that reduces residual vibration and a simple modified feed-forward element that improves its following ability. The proposed controller design procedure can be easily implemented in PAM mechanisms without an exact dynamic model. This system's motion control performance was evaluated experimentally. The positioning results indicate that the maximum steady-state error is reduced to 0.7 μm and that the transient response's overshoot is eliminated using a reconstructed step-like reference signal. The experimental results show that the maximum errors are less than 2 and 5 μm under 0.1- and 0.5-Hz sinusoidal tracking control, respectively. Moreover, the designed control system's robustness for positioning and tracking was examined in experiments using an additional mass.

1. Introduction

McKibben muscles are generally called pneumatic artificial muscles (PAMs), which belong to a class of compliant actuators. A PAM is comprised of an inflatable rubber inner tube covered with a braided mesh. When the inner tube is pressurized, the muscle inflates and contracts in the radial direction. Simultaneously, a pulling force is generated in the direction of contract.

Compared with other actuators, PAMs have many advantages, such as stick-slip-free operation [1], a high degree of safety [2], a high power-to-weight ratio, and a high power-to-volume ratio. For PAMs, these ratios are about 5 times higher than the ratios of electric motors or hydraulic actuators [3]. In addition, a PAM can exert about 10 times the force of a comparably sized cylinder [4]. Because of these excellent properties, PAMs have been applied in bionic robots [5,6], welfare devices [7–9], and parallel manipulators [10,11].

However, PAMs have significant nonlinearities, including nonlinear mechanical characteristics [12], creep phenomena [13], and hysteresis [14]. These issues result in low controllability, and consequently, it is difficult to move PAMs accurately. Thus, all PAM usage is currently restricted to imprecision applications.

In recent years, various control methods have been developed to realize excellent control performance for PAM mechanisms. These methods can be categorized as conventional proportional-integral-derivative (PID) control, nonlinear model-based control, and intelligent control. Conventional PID controllers are typically simple to design, but they cannot sufficiently compensate for the nonlinearity inherent to PAMs, and these controllers result in poor accuracy. The motion accuracy produced by conventional PID controllers is on the level of 0.1° for rotational positioning of PAM mechanisms and 1° for rotational tracking [16–18]. Except for the results in our prior research [19], the highest positioning accuracy generated by a PID controller for a linear PAM mechanism was reported to be 200 μm [18].

Nonlinear model-based control is another important approach for controlling PAM mechanisms. However, because of inaccurate modeling, the positioning accuracy for such devices is on the order of a micrometer, and the tracking accuracy is on the order of 100 μm [20–22]. Li and Kawashima proposed a nonlinear dynamic model consisting of a viscous damping coefficient and a force that is a function of the PAM's operating pressure and contraction length [23].

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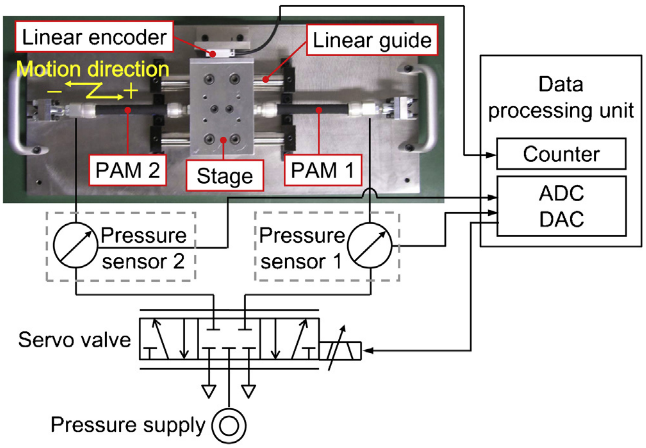

Fig. 1. Experimental setup.

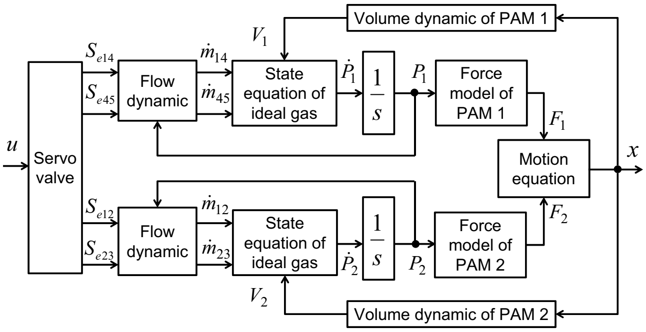

Fig. 2. Schematic diagram of the dynamic model [22].

They applied this nonlinear model to their PAM control system and reported that the highest positioning accuracy was 6 µm. The most accurate rotational tracking result for nonlinear model-based control was reported to be 0.1°. In that study, an adaptive robust control strategy was adopted to compensate for the parametric uncertainties and uncertain nonlinearities of a parallel manipulator driven by pneumatic muscles.

Even though nonlinear model-based control achieved motion accuracy exceeding the accuracy obtained with PID control of PAM mechanisms, its design procedures require both the modeling of complex and nonlinear mechanisms and a sufficient knowledge of advanced control theory. This requirement makes it difficult for engineers who are unfamiliar with the controller design to design these mechanisms and also makes the controller impracticable for real-world applications.

Intelligent control has also been widely used for PAM mechanisms. An intelligent switching control method to adjust the gains of the PID controller with neural networks was reported, and this method achieved a rotational positioning error of 0.05°, which is the most accurate positioning result achieved by intelligent control of PAM mechanisms [24]. An online-tuning gain-scheduling intelligent PID controller was reported to control a two-axis PAM robot arm system and achieved a tracking accuracy of 0.5° [25]. However, the issues relating to imprecise motion and complex controller design persist when intelligent control is applied to PAM mechanisms because of the necessity of having nonlinear models and having sufficient knowledge about intelligent algorithms.

Since PAMs possess the aforementioned advantages, precision motion control for PAMs has the potential to extend their applicability and provides motion systems with PAMs added value, such as cooperativity with persons and transportability enhancement. For example, precision motion control of PAMs could result in precision assembly robots that are lightweight and safer for the assemblers who work with these robots. In addition, some delicate support operations, such as administering injections and repairing clothes, can be provided by nursing care robots that have PAMs capable of precision motion. Hydraulic and pneumatic cylinders have been applied in a neurosurgical robot for precise positioning [15]. Because, compared with hydraulic and pneumatic cylinders, PAMs have superior characteristics when applied to welfare devices, the development of PAMs with precision motion could be a promising advancement for future neurosurgical robots. Therefore, precision motion control of PAMs is an important and unsolved subject.

The purpose of this research is to provide a practical controller design method for precision motion of PAM mechanisms. In our previous research, for only point-to-point precision positioning we proposed a controller design method in which the control elements were represented by input-output relationships that were derived from measured open-loop responses. Using that control system, positioning on the order of a submicrometer (maximum steady-state error = 0.9 µm) was achieved [19]. Based on our previous study, this paper describes the controller design method for both precision point-to-point positioning and precision tracking. In this paper, first, micro-dynamic characteristics of the PAM mechanism are examined to reduce the residual vibration that arises during positioning. Next, simple feed-forward element design is discussed for high tracking control. Finally, based on these results, the performance of the designed control system for precision motion is validated experimentally. Concluding remarks will follow these sections.

2. Linear motion stage with PAMs

2.1. Experimental setup

The experimental setup for this research is shown in Fig. 1. A stage connected to a pair of PAMs (PAM 1 and PAM 2) in a linear antagonistic structure is used as a controlled mechanism. This construction is widely used as the basic actuating element in many PAM applications [5,6,9].

The two PAMs (FESTO DMSP-10-100N-RM-CM) generate pulling forces to push and pull the stage (with a 1.75-kg mass) along the linear direction in a working range of −1 to 1 mm. Compressed air is injected from the pressure supply (0.4 MPa, gauge pressure) and controlled by a five-port three-way proportional servo valve (FESTO MPYE-5-1/8LF-010-B). The pressures in the two PAMs are measured using two pressure sensors (SMC PSE540A-01, resolution: 0.0012 MPa), which are not used as feedback sensors for control but are instead used to observe the air pressure. A linear encoder (GSI Mercury II 5800, resolution: 100 nm) is used as a single feedback sensor in this mechanism. The data processing unit is used as a controller device. The controller is implemented at a sampling rate of 10 kHz.

2.2. Nonlinear characteristics of the PAM mechanism

Fig. 2 shows a conventional dynamic model for the PAM mechanism. In Fig. 2, the blocks (except for the portion labeled “Motion equation”) express characteristics of the PAMs (including nonlinear characteristics) and the pneumatic devices for the PAMs. The process between input voltage u of the servo valve and change rate of pressure $\dot{P}_{1,2}$ can be represented by nonlinear algebraic equations [1,9,26–28]. The motion equation of the system can be written as the nonlinear second-order equation of Eq. (2.1) and described as Fig. 3 [2].

$$M\ddot{x} = F_1 - F_2 + F_{\text{fric}} = F_{ce}(P_1) - F_{ce}(P_2) - [K(P_1) + K(P_2)] \cdot x - 2B \cdot \dot{x} + F_{\text{fric}} \tag{2.1}$$