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Design, Modeling, and Parametric Analysis of a Syringe Pump for Soft Pneumatic Actuators

Wu-Te Yang[1], Motohiro Hirao[2], and Masayoshi Tomizuka[1]

***Abstract*— Syringe pump has been applied to actuate soft pneumatic robots. Most previous works focus on designs of the syringe pump, its applications, and improvement of its problems such as leaking air, inefficient motions, etc. This paper introduces dynamical modeling and parametric analysis of a syringe pump. The syringe pump is made of a commercial syringe and a linear actuator. The dynamic equation is derived from the motions of the linear actuator, the air dynamics in the syringe, and the airflow inside the soft actuator. Because of the high-elastic materials, the volume of the soft actuator is a time-varying parameter. Therefore, the variation of volume is estimated by the Kalman filter instead of relying on the traditional design method. The dynamic model is also utilized to select optimal parameters which are verified by the experiments for the syringe pump. Two system controllers are designed with and without consideration of the pressure dynamics. The controller considering pressure dynamics outperforms. This work shows the benefits of pressure dynamic of the syringe pump for both system design and advanced controller design.**

I. INTRODUCTION

Soft robotic research is gaining popularity in recent years. Soft robots, fabricated with high elastic materials, possess high compliance. The compliant soft robots are favorable to work in complex and clustered environments [1], [2], ensure the safety of human-robot collaboration [3], and help them handle delicate objects in the food industry [4]. Instead of using traditional motors, soft robots are actuated by electroactive polymers, cable-driven, shape memory alloys, or pneumatic actuators [5]. Among those choices, pneumatic actuators are becoming the preferred option to drive soft robotic systems [5], [6] because they have light weights, reasonable costs, and high power density.

Despite their advantages, control, and actuation of soft pneumatic actuators are still a challenge [7]. Since the pneumatic actuators rely on pressurized air to adjust their motions(bending angle), the common actuation strategies include an air pump with the pressure regulator and a solenoid valve [8]–[10] or syringe pump made of a linear actuator and a commercial syringe [11], [12]. The former method has a large operating range and generates sufficient air pressure to drive soft actuators, but the control of the solenoid valve is relatively complex and the air pump is bulky. The latter provides precise differential pressure control and it is easier to control. Although the operation range is limited by the syringe's volume, this drawback can be improved by using a larger syringe [8]. Furthermore, several dynamic models for soft pneumatic actuators are developed but they are unable to catch the whole motions. The errors are caused by ignoring the dynamics of pneumatic supply systems. The nonlinear and unpredictable pressure dynamics should also be considered especially when designing controllers for soft actuators [9], [13]. Therefore, the controllers can regulate the errors, and systems can achieve higher accurate dynamics.

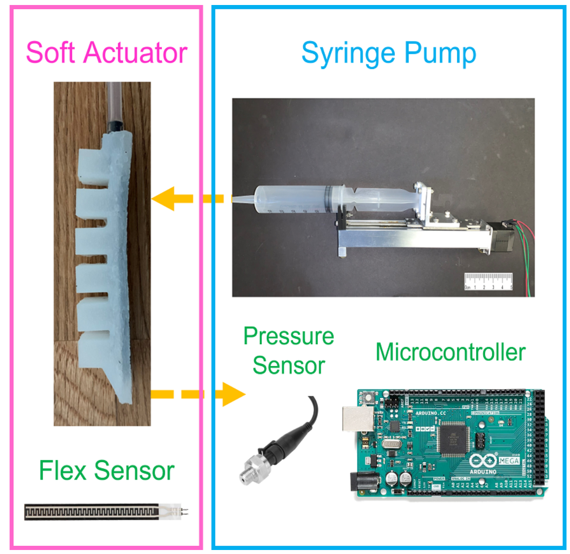

Fig. 1. The configuration of the syringe pump (with scale bar), soft actuators, and the sensors such as flex sensor and pressure sensor. The controller is programmed in the Arduino Mega board.

This paper focuses on modeling and parametric analysis of a syringe pump to optimize its design parameters and output responses. Firstly, we design a syringe pump and then build its pressure dynamic model. According to the pressure model, the parametric analysis is conducted to verify the derived dynamic model. Also, the optimal design parameters are determined and the corresponding components such as the linear actuator, size of the commercial syringe, and stepper motor are chosen to build the system. Lastly, the pressure model includes a time-dependent parameter, the volume of the soft actuator, since it will change with the input pressure. The Kalman filter is utilized to estimate the volume change of the soft pneumatic actuator, so the model predicts the dynamics of the system precisely. The syringe pump is applied to drive a self-built soft actuator [14].

Several works have proposed a pressure dynamic model for pneumatic systems and the applications of the syringe pump. Kalisky et al. [11] implemented a set of syringe

[1]The authors are with Department of Mechanical Engineering, University of California, Berkeley, MSC Lab, Etcheverry Hall, USA wtyang@berkeley.edu; tomizuka@berkeley.edu
[2]Motohiro Hirao is with NSK Ltd. Japan, and is a visiting fellow of the University of California, Berkeley, USA hirao@berkeley.edu

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pumps to control a soft robot that had three channels. The syringe pumps achieved differential pressure(small motions) control. However, this work did not consider the system's pressure dynamic model which influenced the performance of the designed controller. Xavier et al. [13], [15] developed pressure dynamic models for their pneumatic supply systems. The controllers, which regulated the soft actuator's motions precisely, were designed based on the both actuator's and pressure models. But their pneumatic supply systems were different since they used an air pump with a pressure regulator and a solenoid valve. Besides, the volume of the soft actuator was time-dependent which decreased the accuracy of the model. This issue was solved by using a buffer tank(increasing the volume), so the volume change is negligible. By contrast, our work utilizes the Kalman filter to estimate the volume change of soft actuators. What's more, it is discovered that volume change has a relationship with the bending angle, used in the Kalman filter to estimate the desired state. The buffer tank, thus, is not needed. Joshi et al. [16] conducted the parametric analysis and optimized the design parameters. Our works are similar but different in some places. We derive the pressure dynamic model and perform parametric optimization based on the model. Also, the configuration of our pneumatic supply system and design parameters are quite different. In addition, recent research [17], [18] proposed electro-pneumatic pumps which were compact and portable for the actuation of soft robots. Unfortunately, those pumps could not provide enough pressure ranges to actuate general soft actuators. Overall, we intend to derive the pressure dynamic model for the syringe pump, optimize the system's parameters according to the model, and design an appropriate controller considering the pressure model. That is, the derived model would not only predicts system dynamics accurately but also helps design a suitable controller for soft actuators.

The remainder of this paper is organized as follows. Section II introduces the derivation of the pressure dynamic model and parametric analysis. Section III discusses controller design based on the derived dynamic model. Section IV demonstrates the experimental results, and Section V concludes the work.

II. System Design and Dynamic Modeling

The main configuration of the syringe pump includes a syringe and a linear actuator as in Fig. 2. The commercially available syringe can store air which acts as the tank of the air pump, but it has a smaller capacity and is not bulky. The slider of the linear actuator is connected to the syringe, and the linear actuator, driven by the stepper motion, can push and pull the syringe to regulate the air pressure inside the soft actuator.

A. System Modeling

Next, we model the dynamics of the syringe pump in order to do the parametric analysis and select an optimal size of the syringe, a suitable linear actuator, and the stepper motor. We begin the modeling from the linear actuator. The velocity of

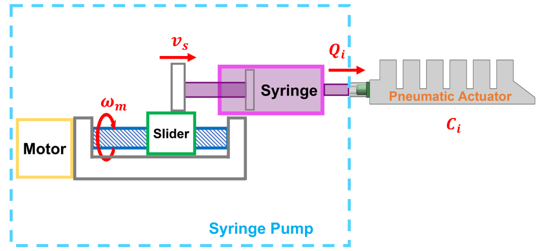

Fig. 2. The structure of the syringe pump. It is mainly composed of the linear actuator, driven by a stepper motor, and a commercial syringe. The parameters used to derive the dynamic equation are labeled.

the slider on the linear actuator is influenced by the screw's lead inside the linear actuator and the speed setting of the motor speed, so the equation is described as

$$v_s = \frac{l}{2\pi}\omega_m \tag{1}$$

where v_s is the velocity of the slider in the linear actuator, l is the lead of the screw inside the linear actuator, and ω_m is the motor speed. As the slider is moving, the air flows from the syringe to the soft actuator. The output air flow rate is

$$Q_i = Av_s = \frac{Al}{2\pi}\omega_m \tag{2}$$

where Q_i is the output air flow rate of the syringe, and A is the cross-sectional area of the syringe. Lastly, pressure changing rate is obtained by dividing the output air flow rate by the capacity of the soft actuator

$$\dot{P} = \frac{Q_i}{C_i} = \frac{Al}{2\pi C_i}\omega_m \tag{3}$$

where C_i is the capacity of soft actuator. This equation describes the pressure changing rate in the chambers of the soft actuator.

B. Design Parameter Analysis

Based on the Eq. (3), the equation consists of A, l, ω_m, and C_i as shown in Fig. 2, which influence the pressure changing rate in the soft actuator. The capacity of the soft actuator will change with the input pressure, so we temporarily assume it is a constant in the analysis stage. This issue will be addressed in Sec. III-B. The remaining parameters, A, l, and ω_m, represent the size of the syringe, screw lead of the linear actuator, and speed of the stepper motor inside the linear actuator respectively. We choose different sizes of syringes and distinct leads of linear actuators to analyze the Eq. (3). The motor speed can be adjusted by setting the controller under the motor's speed limit.

We select two variations for every parameter. Clearly, we select two linear actuators (Fulride and Monocarrier by NSK Ltd.). The Fulride has a screw lead of 8 mm and the Monocarrier has a lead of 2 mm. Since there is the need for differential control of air pressure, we do not select the

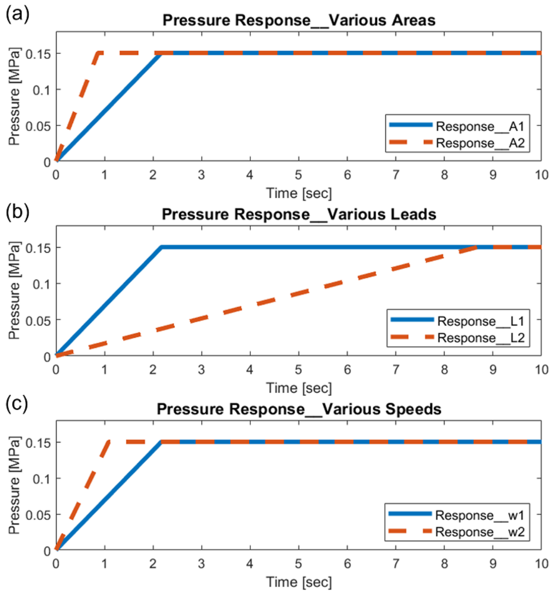

Fig. 3. (a) The responses of syringe pump with different cross-sectional areas of syringes. (b) The responses of the pump with distinct screw leads of linear actuators. (c) The responses of the pump with different motor speeds.

linear actuator with a large screw lead such as 20 or 30 mm. Another consideration is that the high torque motor is needed if we choose a large lead. A higher torque motor usually has a slower speed and would reduce the pressure changing rate. Because of the sizes of the Fulride and Monocarrier, we choose two commercial syringes whose volumes are 60 mL and 200 mL respectively. Larger or smaller volume syringes cannot fit into the selected linear actuators. Last but not least, the size of the stepper motor is also constrained by the selected linear actuators. The Nema 17 stepper motor is selected to drive the linear actuators.

TABLE I

THE VARIANTS OF THE PARAMETERS OF PRESSURE DYNAMIC MODEL

	A [m^2]	l [m]	$\omega_m [rev/s]$
Parameter 1	6.61e-4	0.008	1.65
Parameter 2	16.62e-4	0.002	3.30

The design parameters are shown in Table I. The analytical results of the derived model are displayed in Fig. 3 which is simulated by using MATLAB®. The default parameter set(blue lines in Fig. 3) is A = 6.61e-4 m^2, l = 0.008 m, and ω = 1.65 rev/s. The analysis is conducted by changing A, l, and ω_m separately as Fig. 3(a), (b), and (c). From the simulation results, the larger the cross-sectional area(A), the screw lead(l), and the motor speed(ω), the higher the pressure changing rate. Higher pressure changing rates could enable faster and more efficient responses of the soft actuator. Thus, the optimal parameter set is A = 16.62e-4 m^2, l = 0.008 m, and ω = 3.3 rev/s. Nonetheless, the higher cross-sectional area of the syringe will generate a larger reverse force if the pressure inside the soft actuator increases as discussed in Sec. IV-D. To deal with this problem, a high-torque stepper

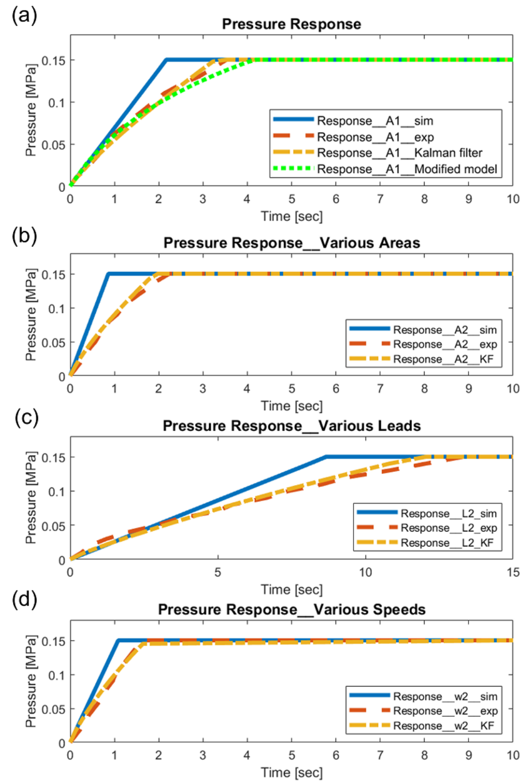

Fig. 4. (a) The responses of the syringe pump's different models are compared. (b) The simulation and experiment of the pump using a larger syringe(larger A). (c) The simulation and experiment of the pump using a smaller screw lead of linear actuator. (d) The simulation and true responses of the system using higher motor speed.

motor is required. Unfortunately, a high-torque motor usually has a slower operating speed. Therefore, the solution here is choosing a syringe with 60 mL whose cross-sectional area is smaller. The comparisons between analysis and experimental results will be introduced in Sec. V.

III. Controller Design

The dynamic model of the air supply system is derived in Sec. II-A. The transfer function can be obtained by taking the Laplace transform of Eq. (3)

$$\frac{\mathbf{P}}{\mathbf{\Omega_m}} = \frac{Al}{2\pi C_i}\frac{1}{s} \tag{4}$$

where $\mathbf{P}$ is the P in the Laplace domain, and $\mathbf{\Omega_m}$ is the ω_m in the Laplace domain. For simplicity and feasibility of analysis, we consider the capacity of the actuator C_i as a constant as discussed in Sec. II. However, the volume of the soft actuator varies with the pressure. This following subsections will handle this issue.

A. Modified Model

The prediction of Eq. (3)(blue solid line) differs from the true response(red dashed line) as in Fig. 4(a). It is caused by the capacity change, so we modify the model by changing

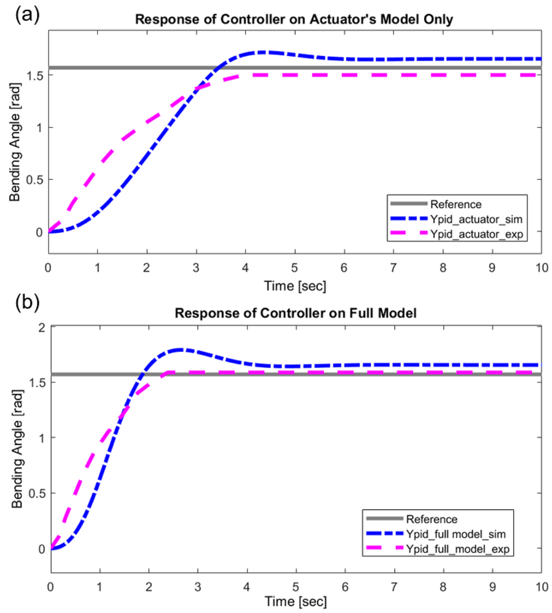

Fig. 5. The MATLAB simulations on two PID controllers. (a) The simulation and true responses of controller designed based on actuator's model exclusively (b) The simulation and real responses of controller designed based on full model.

the C_i as the $C_i + c \times Q_i t$ because the C_i will change with Q_i and the Eq. (3) becomes

$$\dot{P} = \frac{Q_i}{C_i + cQ_i t} = \frac{Al}{2\pi(C_i + c\frac{Al}{2\pi}\omega_m t)}\omega_m \tag{5}$$

where c is a constant and is larger than 0 and smaller than 1 and the system's transfer function becomes

The pressure response of Eq. (5)(green dashed line) has been corrected especially when the pressure is above 0.1 MPa. Unfortunately, the errors still exist compared to the true system response. The modified model tends to over-estimate the capacity changes at higher pressures (> 0.10 MPa). The error is around 10 % when pressure exceeds 0.10 MPa as in Fig. 4(a).

B. Kalman Filter Estimation

According to Fig. 4(a), the Eq. (5) is still unable to catch the dynamics accurately due to the imprecise estimations of the actuator's volume changes. We turn to apply the state estimator, Kalman filter, to deal with this problem. The Kalman filter is an algorithm that uses the system's measurements to estimate unknown variables [19], [20]. Thus, the Kalman filter is implemented to estimate the time-varying capacity change during operations. What's more, it is observed that the capacity of the soft actuator relates to its bending angle. The capacity change is assumed to have a linear relationship with the capacity. The state vector includes capacity and bending angle, so the state space equation is

$$\mathbf{x}_{K+1} = A\mathbf{x}_k + w_k \tag{6}$$

$$\mathbf{z}_{k+1} = H\mathbf{x}_k + v_k \tag{7}$$

where

$$\mathbf{x} = \begin{bmatrix} C_i \\ \theta \end{bmatrix}, \mathbf{A} = \begin{bmatrix} 1 & k \\ 0 & 1 \end{bmatrix}, \mathbf{H} = \begin{bmatrix} 0 & 1 \end{bmatrix}, \tag{8}$$

where k is a constant. The Kalman update process [19], [20] is operated to estimate the instant volume of the soft actuator based on the state space equation Eq. (6) and (7).

The Kalman filter estimation(yellow dashed line) is demonstrated in Fig. 4(a). The estimation nearly matches the true response of the syringe pump(red dashed line). The error, compared to the true response, is within 5 %. Thus, the Kalman filter is included in the control block diagram as Fig. 6(a). The syringe pump generates pressure to bend the soft actuator. The bending angle of the soft actuator is measured by an embedded flex sensor [21]. Then, the Kalman filter estimates the volume of the soft actuator by using the measured bending angle.

C. Dynamic Model of Soft Actuator

The syringe pump aims to control soft actuators. A soft actuator which was optimally designed and manufactured in our previous work [14] is used to validate the accuracy of pressure dynamics. The dynamics of the soft actuator can be approximated as a second-order system [13]. The damping ratio and natural frequency are obtained by fitting the system's responses. The equation of the soft actuator is described as

$$\theta(t) = C_0 \; + \; C_1 e^{-at} \; + \; C_2 e^{-bt} \tag{9}$$

where C_0, C_1, and C_2 are constant coefficients, and a and b are related to time constants. Consequently, the dynamic equation can be rearranged as

$$\ddot{\theta} \; + \; (a+b)\dot{\theta} \; + \; (ab)\theta = F/M \tag{10}$$

$$\ddot{\theta} \; + \; 2\zeta\omega_n\dot{\theta} \; + \; {\omega_n}^2\theta = F/M \tag{11}$$

where ζ is the damping ratio, ω_m is the natural frequency, M is the mass of the soft actuator, and F is the force at the tip of the actuator. By the linear model assumption, the F is assumed to have a linear relationship ($P \leq 0.15MPa$) with the pressure P controlled by the syringe pump, $F = C \times P$. (When the material used to make soft actuator deforms below 100 %, its deformation is still linear [22].) The parameter C is a constant obtained by experiments.

After taking the Laplace transform, the Eq. (11) is shown as

$$T_{spa} = \frac{C \times P/M}{s^2 + 2\zeta\omega_n s + {\omega_n}^2} \tag{12}$$

The full model is the combination of pressure dynamic model and soft actuator's bending model.

$$T_{full} = \frac{lA\omega_m C/2\pi C_i(t)M}{s^3 + 2\zeta\omega_n s^2 + {\omega_n}^2 s} \tag{13}$$

where $C_i(t)$ is the time-varying parameter estimated by the Kalman filter. The equation is the third-order system.

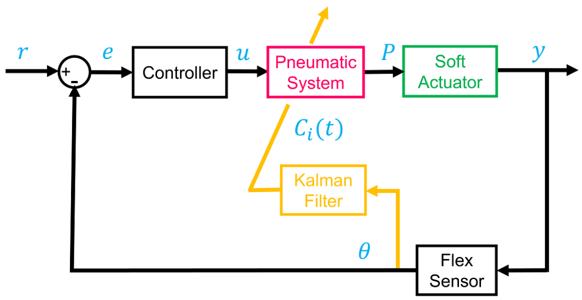

Fig. 6. The control block diagram of the whole system.

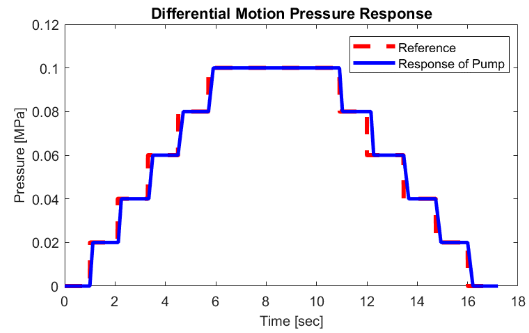

Fig. 7. Differential motions control test of the syringe pump.

D. PID Controller Design

Two PID controllers are designed for the Eq. (12) and Eq. (13) separately. We implement the Ziegler-Nichols tuning method to design the proportional-integral-derivative(PID) controller for the pneumatic control system [23]. We use the time response tuning of Ziegler-Nichols. Trial-and-error is used to fine-tune the gains after obtaining the PID gains by the Ziegler-Nichols.

The simulations of the controllers are done in MATLAB®/Simulink to preliminarily test the performance of the controller and system. The step responses of the pneumatic with two PID controllers are displayed in Fig. 5(a) and (b). The controller based on exclusively the actuator's model achieves a steady state in about 5 seconds. By contrast, the controller based on the full model has a settling time of around 2.5 seconds. Thus, the pressure dynamics do influence the performance of the controller. Note that the volume of the soft actuator is assumed to be the initial value when designing the PID controller.

IV. Experimental Evaluation

This section would verify the parameters determined in Sec. II-B, and compares them with the experimental results. Also, the syringe pump is used to control a soft actuator to validate the influences of pressure dynamics on the controller design.

A. Hardware System Setup

1) Syringe Pump Setup: Since the parameters are determined, the corresponding components are the Fulride linear actuator(l=8mm), a syringe of 60 mL, and a Nema 17 stepper motor. Although the size of the stepper motor is constrained by the linear actuator, the speed can be adjusted. Those components are assembled by using several 3D printed components and can be seen in the upper right of Fig. 1.

2) Experimental Setup: The experimental setup is demonstrated in Fig. 1. The soft actuator is actuated by the syringe pump. A pressure sensor (Walfront, Lewes, DE) with a sensing range of 0 to 80 psi is implemented to monitor the air pressure and is synchronized with Arduino MEGA 2560 (SparkFun Electronics, Niwot, CO). The microcontroller is based on the Microchip ATmega 2560. The soft actuator has been embedded with a flex sensor [21] to get bending angle measurement which is used to estimate the real-time volume of the soft actuator during operations. The microcontroller is also synchronized with a computer to log sensing data.

B. Verification of Parametric Analysis

The parametric analysis is completed in Sec. II-B. There are 3 sets of simulations that change 3 parameters separately. This subsection attempts to verify the analytical results of simulations by experiments. Therefore, different syringe pumps are made corresponding to the design parameters discussed in Sec. II-B, and then test their responses as shown in Fig. 4(b), (c), and (d). The results in Fig. 4(b) show that a larger cross-sectional area can increase the speed of responses. The volume change of the soft actuator also influences the accuracy and causes some errors. Then, we test the syringe pump with a smaller screw lead of the linear actuator as in Fig. 4(c). The response time is reduced by the smaller screw's lead. Lastly, the validation of increased motor speed can be seen in Fig. 4(d). The error appears to be smaller at higher motor speeds. Generally, the responses are close to the model predictions in low pressures but the errors can be up to 30 % at high pressures. Also, the volume change of the soft actuator makes the responses slower than the model predictions. However, the errors caused by volume change can be corrected by the Kalman filter as the yellow dashed lines in Fig. 4(b), (c), and (d), and the errors are reduced to around 5 %.

C. Control of Soft Actuator

The importance of the pressure dynamics will be verified in this subsection since the pressure model has an influence on the responses of soft actuators. Two controllers are designed in Sec. III-D based on the actuator's model exclusively and the full model(pressure model + actuator's model). Their results are displayed in Fig. 5(a) and (b), and their performance is quite different. The controller designed based on only the actuator's model (Eq. (12)) has a longer settling time, around 3.95 seconds. Its steady-state error is around 5 degrees. By contrast, the controller designed based on the full system (Eq. (13)) has a shorter settling time, 2.38 seconds. That is, it responds faster. The steady-state error also has been improved and is approximately 2 degrees. Hence, considering the pressure dynamics assists in designing a better controller.

The differential motions control of the soft actuator is demonstrated in Fig. 7. The reference function increases and decreases gradually and the setpoint holds for 1.2 seconds after each increment or decrement. The syringe pump can track the reference, but there is a little delay during rising or falling edges. The pump takes around 0.2 seconds to reach the desired command change. According to the performance in Fig. 7, the syringe pump can track the reference and is suitable for differential motion control.

D. Discussion

Based on the results in Fig. 3 and Fig. 4, the optimal parameters of the syringe pump are a high cross-sectional area of the syringe, larger screw lead of linear actuator, and higher motor speed. However, the syringe pump does not use a syringe of 200 mL but a medium size (60 mL). Although the larger cross-sectional area of the syringe enables faster responses, the reverse force will act on a larger area. That causes non-smooth motions of the syringe pump which influence the control accuracy. Also, we hope the syringe pump has a suitable operating pressure range ($\geq$ 0.15 MPa). A smaller volume implies a smaller operating pressure range. To summarize, a suitable cross-sectional area with a relatively longer length of syringe might be an appropriate option for smooth motion control.

In addition, we observe that a larger screw lead with a smaller cross-sectional area achieves the same pressure responses as the smaller screw lead with a larger cross-sectional area according to Eq. (3). The main difference between the two combinations is the volume of the syringe. The larger cross-sectional area of the syringe usually has a larger volume. The pump's operating pressure range becomes larger and it is suitable for soft actuators with a larger volume.

V. CONCLUSIONS

This work presents a pressure dynamics modeling and parametric analysis methodology for a syringe pump. An air dynamic model has been built according to the configuration of the syringe pump. The time-dependent parameter in the model is estimated by the Kalman filter, which reduces the estimation errors to below 5 %. Then, the model is used to analyze the syringe pump in order to select an optimal set of design parameters. The optimal parameters enable the system to respond efficiently and smoothly and achieve differential motion control for soft actuators. The pressure model cascaded with the soft actuator's model is utilized to design a PID controller. The controller is superior to another one designed based on solely the actuator's model. The settling time has been reduced by 40 %, and steady-state error has also been decreased. This analytical modeling method provides a helpful and efficient tool for the study of a syringe pump.

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