Advances in Industrial Control

Ling Zhao
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Pneumatic Servo Systems Analysis

Control and Application in Robotic Systems

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Series Editor's Foreword

Pneumatic Servo Systems Analysis, Control and Application in Robotic Systems is a new monograph, which comes to enrich the series *Advances in Industrial Control*. This volume is especially timely because pneumatic systems and pneumatic robots, in particular, are becoming increasingly important in the contexts of Industry 4.0, and of surgical and biomedical applications.

The first examples of pneumatic technology date back to the first century. Yet the first air pump, used to study the phenomenon of vacuum, was only invented by the German physicist Otto von Guericke in 1650, and it is necessary to wait until 1800 to see the great impact of pneumatics on society. In the first three decades of the nineteenth century the first air compressors were developed. The water-jacketed cylinders, so important for the automotive industry, were invented in 1872. In 1867, the first example of a pneumatic subway train was showcased at the American Institute Exhibition of New York, demonstrating how passengers could be transported along a sort of pipe just by exploiting pneumatic power.

Afterward, Pneumatic pipes were used in post offices to transport letters from one part of the building to others, as well as in department stores to transfer cash from cashiers to the safe-box or vice versa. The pneumatic drill and the pneumatic-powered hammer were invented in the 1870s and 1890s, respectively. Then in the twentieth century pneumatics reached full maturity with plenty of pneumatic components employed in a variety of sectors. They were mainly used to replace manpower in heavy or repetitive tasks, creating the conditions for the diffusion of automatic control devices in industry, and for the establishment of industrial automation as a reality.

Nowadays, digitally controlled pneumatic devices are used in numerous industrial fields, from manufacturing to the food industry, from the production of medical devices to the avionics sector. The amazing thing is that research on pneumatic systems and efficient control systems based on them has not yet stopped, as evidenced by the fact that innovative solutions, more and more efficient, less expensive, and significantly more precise, are still being put on the market with a certain regularity.

Pneumatic actuators are often among the essential parts of industrial automation systems. In fact, by virtue of their better cost–benefit ratio, pneumatic systems are replacing servo systems based on hydraulic devices in many industrial applications. Apart from being economical, using pneumatic systems is also environmentally friendly, since air is available at no cost and can be easily stored in tanks after being compressed.

In contrast to the advantages just mentioned, however, there is a major drawback which cannot be ignored when considering the use of pneumatic devices for industrial applications, i.e., the difficulty of controlling them and reaching the high precision normally required by industrial production standards. This is mainly due to the fact that pneumatic components are inherently nonlinear and often do not allow the formulation of sufficiently accurate linearized models of their behaviors.

The present book is aimed at tackling the issues related to the design and developing of pneumatic servo systems in a clear but rigorous manner. It is a book very rich in terms of contents. It starts from an overview of pneumatic servo system applications, also accurately describing the control methods that have been applied so far to address the nonlinear control problems associated with them. Then, it discusses, in a very detailed way, different plants that rely on pneumatic servo systems: a manipulator driven by pneumatic artificial muscles, a pneumatic dexterous hand, a pneumatic motion simulation platform, a pneumatic rod–cylinder servo system, and a pneumatic right-angle composite motion platform. All the examples are extremely interesting and useful for learning the essential elements of nonlinear control theory applied to this class of systems.

In the book, the authors address feedback control systems based on observers, then they deal with backstepping-based controllers of adaptive type and finally they also discuss sliding mode control. The control algorithms considered are of advanced type, but their presentation is very readable, so that even a non-control-expert reader can understand the fundamental concepts and appreciate the distinguishing characteristics of the various set-ups by following step-by-step the developments reported in the chapters.

With this volume, the series *Advances in Industrial Control* is enlarged with a new monograph that helps to make the series more varied, but, at the same time, confirms the mission of the series itself to be a tool for people who deal with industrial automation to keep up-to-date and learn about the various facets that industrial automation presents.

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Preface

The pneumatic servo system is an automatic control system which can make the output change with the input target arbitrarily. It takes a air compressor as driving source, and the compressed air is used as working medium for energy transmission. Various pneumatic servo systems have been investigated widely because of their advantages, such as clean, low cost, simple structure, and convenient maintenance. Pneumatic servo systems are used extensively in mechanical operations, medical areas, automation systems, robots, and many other fields. However, it is difficult to achieve higher position control precision for the pneumatic servo systems because of strong nonlinearity which is caused by air compressibility, large friction forces and nonlinear properties of servo valves. Therefore, it has great significance to conduct further research on position control for the pneumatic servo systems. The active disturbance rejection control (ADRC) technique is a new practical technology which absorbs achievements of modern control theory and develops essences of PID. The ADRC does not depend on an accuracy mathematical model which are hardly obtained because of strong nonlinearity, unmodeled dynamics and external disturbances for the pneumatic servo systems. Therefore, it is a key idea to solve these uncertain factors effectively by using the ADRC for the pneumatic servo systems. This book aims to analyze the position control of the pneumatic servo systems via the improved ADRC.

In Chap. 1, an overview on application and a motivation on the research are provided for typical pneumatic servo systems. In Chap. 2, an overview on control methods is introduced to deal with nonlinear problems in pneumatic servo systems.

Then this book is divided into five parts:

Part I: Three kinds of controllers are designed for a pneumatic manipulator system with an one degree of freedom (DOF) joint driven by pneumatic artificial muscles (PAMs). In Chap. 3, a pneumatic manipulator platform is designed and introduced. In Chap. 4, a linear error feedback controller combining with compensation of disturbances is designed to ensure response speed for the pneumatic manipulator system. In Chap. 5, a nonlinear error feedback controller is designed to control the pneumatic manipulator system via a reduced-order extended state observer. In Chap. 6, a sliding mode controller based on an extended state observer is designed to guarantee stability of the pneumatic manipulator system.

Part II: Some results on a pneumatic dexterous hand system are presented. In Chap. 7, an experimental platform of the pneumatic dexterous hand system is designed and introduced. In Chap. 8, a backstepping nonlinear error feedback controller is designed to study the position problem of the pneumatic dexterous hand system via an extended state observer. In Chap. 9, a sliding mode controller with an extended state observer is proposed to cope with nonlinearities and disturbances for the pneumatic dexterous hand system. In Chap. 10, an ADRC technique is proposed to improve precision for the pneumatic dexterous hand system.

Part III: Three kinds of controllers are designed for a pneumatic motion simulation system driven by PAMs. In Chap. 11, an experimental platform for the pneumatic motion simulation system is designed and introduced. In Chap. 12, a nonlinear error feedback controller based on a linear extended state observer is applied in the pneumatic motion simulation system under varying load conditions. In Chap. 13, a linear error feedback controller based on a nonlinear extended state observer is introduced for the pneumatic motion simulation system. In Chap. 14, an adaptive backstepping controller based on an adaptive extended state observer (AESO) is presented for the pneumatic motion simulation system.

Part IV: Some results on position control are given for a pneumatic rod cylinder servo system. In Chap. 15, an experimental platform for the pneumatic rod cylinder servo system is designed and introduced. In Chap. 16, a finite-time controller is designed to improve response rapidity and anti-interference ability of the pneumatic rod cylinder servo system based on super-twisting extended state observer. In Chap. 17, a nonsingular fast terminal sliding mode (NFTSM) finite-time tracking control strategy is presented for the pneumatic rod cylinder servo system via an extended state observer. In Chap. 18, a generalized nonlinear extended state observer (GNESO) is applied in the pneumatic rod cylinder servo system with varying loads.

Part V: Some developments of position control are introduced for a pneumatic right-angle composite motion system. In Chap. 19, an experimental platform for the pneumatic right-angle composite motion system is introduced. In Chap. 20, an ADRC technique is given for the pneumatic right-angle composite motion system. In Chap. 21, a multi-point position is study for the pneumatic right-angle composite motion system by using the ADRC. In Chap. 22, a linear error feedback controller is applied to improve response speed of the pneumatic right-angle composite motion system.

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Contents

Symbols and Acronyms

R	Field of real numbers
R^n	n-dimensional real Euclidean space
$R^{n \times m}$	Space of $n \times m$ real matrices
C	Field of complex numbers
I	Identity matrix
A	System matrix
A^{-1}	Inverse of matrix A
A^T	Transpose of matrix A
$A \geq 0$	Symmetric positive semi-definite
$A > 0$	Symmetric positive definite
$A \leq 0$	Symmetric negative semi-definite
$A < 0$	Symmetric negative definite
lim	Limit
min	Minimum
max	Maximum
SMC	Sliding mode control
PAM	Pneumatic artificial muscle
PAMs	Pneumatic artificial muscles
DOF	Degree of freedom
ADRC	Active disturbance rejection control
TD	Tracking differentiator
ESO	Extended state observer
AESO	Adaptive extended state observer
GNESO	Generalized nonlinear extended state observer
NFTSM	Nonsingular fast terminal sliding mode
$\text{rank}(A)$	Rank of matrix A
$\lambda(A)$	Eigenvalue of matrix A
$\lambda_{\min}(A)$	Minimum eigenvalue of matrix A
$\lambda_{\max}(A)$	Maximum eigenvalue of matrix A
$\sigma(A)$	Singular value of matrix A

$\sigma_{\min}(A)$	Minimum singular value of matrix A
$\sigma_{\max}(A)$	Maximum singular value of matrix A
$\mid x \mid$	Absolute value (or modulus) of x
$\Vert x \Vert$	Euclidean norm
$\Vert x \Vert_2$	The second norm for vectors
$\Vert x \Vert_{m\infty}$	The infinite norm for vectors
$\forall$	For all
$\in$	Belong to
$\subseteq$	Inclusion sign
$\rightarrow$	Tend to, or mapping to (case sensitive)
$\sum$	Sum
$G(\cdot)$	Characteristic equation
$\exp(x)$	e^x
$\mathrm{sign}(x)$	The sign function of x
$\mathrm{sat}(x)$	The saturation function of x
sup	Supremum
inf	Infimum

Chapter 1
Introduction

1.1 Background

With the implementation of national strategies, such as German industry 4.0, advanced manufacturing in America, made in China 2025, and so on, great changes in the manufacturing industry have been promoted by the new industrial revolution, which brings important opportunities and challenges for robots. Pneumatic robots have received more and more attention for manufacturing, in which pneumatic systems play important roles in driving mechanical devices [1]. For various advantages such as clean, safety, low cost, convenient maintenance, and good flexibility [2, 3], the pneumatic systems are extensively used in textile industry, chip manufacturing, automobile manufacturing, pharmaceutical manufacturer, food packing, and so on [4–6]. Pneumatic artificial muscles (PAMs) and pneumatic cylinders are two types of main pneumatic actuators in robots. There are different shapes and specifications for different types of actuators to meet various application requirements.

Compared with other kinds of driving units, the PAMs have unique advantages in flexibility and bionics. The PAMs are contractile and linear motion engines operated by gas pressure. Their core element is a flexible reinforced closed membrane, and it attaches at both ends to fittings by which mechanical power is transferred to a load. As the membrane is inflated by gas, the membrane contracts axially and thereby exerts a pulling force on its load. The force and motion thus generated by this type of actuator are linear and unidirectional [7]. Therefore, when the pneumatic artificial muscle (PAM) is inflated, its shape will thicken radially and its length will be shortened, which results in axial displacement and tension. Otherwise, there will be no output force and bearing capacity for the PAM in the non-inflated state. This working principle is very similar to the human muscle. The characteristics of the PAM are mainly summarized as high power-weight ratio, high degree of energy transformation, good flexibility, good self cushioning ability, good bionics, no piston structure inside, no lubrication, no crawling phenomenon, easy miniaturization, and easy to realize low-speed movement. Therefore, the PAM receives much attention

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(a) Air muscle (b) Fluid muscle

Fig. 1.1 Different types of PAMs

(a) Pneumatic cylinders (b) Bellows cylinders

Fig. 1.2 Different types of pneumatic cylinders

from researchers in robotics and industrial automation. The two types of representative PAMs include air muscle produced by Shadow in London in Fig. 1.1a and fluid muscle produced by Festo in Germany in Fig. 1.1b.

In linear reciprocating motion, the pneumatic cylinder is a typical actuator in the industrial scene. It converts the pressure energy of compressed air into mechanical energy and makes the driven mechanism works as expected. With the expansion of application fields and the development of new technologies, the types of cylinders are increasing, such as piston cylinder, plunger cylinder, diaphragm cylinder, rod cylinder, rodless cylinder, bellows cylinder, and so on. Different types of pneumatic cylinders are shown in Fig. 1.2a. The bellows cylinder produced by Festo is shown in Fig. 1.2b, which is used as a spring element or for reducing oscillations. The pneumatic cylinder is widely used in semiconductor, printing, robot, food processing, and other fields.

Fig. 1.3 Pneumatic robot

1.1.1 Application of Pneumatic System

Since late twentieth century, more and more attention has been paid to the automation and labor-saving in various fields of production and manufacturing. Due to its unique advantages, pneumatic systems are more and more widely used in the field of industrial mechanization and automation. Typical applications of the PAMs and the pneumatic cylinders are introduced in the following.

In the area of biorobotic and Industrial applications, the PAMs can produce high torque at low and medium speeds and can be easily installed without transmission device. Due to its light weight, the PAMs can be used as the actuator of portable machinery. In addition, the PAMs have natural compliance and impact resistance. It is a suitable solution for driving industrial machinery and industrial robots, especially safe industrial robots with human–computer interaction. Different pneumatic robots have been designed by PAMs. Bipedal robot in [8] could achieve vertical jumping, soft landing from a one-meter drop and postural control during standing. For the RoboThespian in Fig. 1.3 at [9], much of its human-like agility relies on the pneumatic fluidic muscles developed by Festo. The movement of the arms and hands is taken on by a total of two or eight fluidic muscles respectively in different sizes.

In the automobile manufacturing industry, most modern automobile manufacturing production lines have adopted pneumatic technology, especially in the welding production line, such as each car body moving and positioning, the welding gun moving, and welding spot control. In automobile assembly line, various pneumatic actuators and pneumatic control systems are adopted for tire installation, glass installation, engine delivery and assembly, and so on. Figure 1.4 shows a pneumatic servo system for automobile spot welding of SMC corporation.

In the area of production automation, the use of pneumatic system can also improve labor productivity and reduce production costs. With the increasing popularity of production automation, pneumatic systems have been used in various fields of production and manufacturing. In some assembly production lines of industries such as bicycles, watches, and washing machines, many operation processes of workpieces on the production line are automatically completed by pneumatic systems. Pneumatic air-jet looms, printing machine, automatic cleaning machines also use pneumatic systems to effectively reduce the heavy and monotonous human labor. In short, pneumatic technology is an environmental protection and low-cost automation technology. The pneumatic systems are important means to realize production

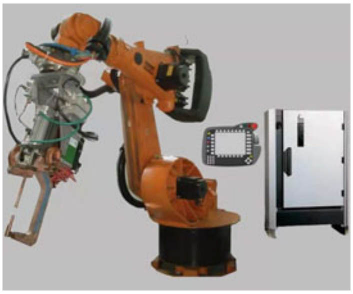

Fig. 1.4 Pneumatic welding

(a) Pneumatic assisted manipulator (b) Hot stamping machine

Fig. 1.5 Pneumatic systems in automobile manufacturing industry

automation, which makes them important in production and life. Figure 1.5a shows a pneumatic assisted manipulator driven by a pneumatic cylinder. The pneumatic assisted manipulator is a product of Suzhou Luokeweige Automation Co., Ltd. of China. Figure 1.5b shows a pneumatic hot stamping machine driven by a pneumatic cylinder.

1.1.2 Control Methods Overview of Typical Pneumatic Servo System

In the pneumatic systems, pneumatic control elements, pneumatic actuators, sensors, and other devices [10] are important components, which can compose a typical pneumatic closed-loop system shown in Fig. 1.6. The pneumatic control elements mainly include various proportional valves and on-off valves. The pneumatic executive elements mainly include pneumatic artificial muscles, pneumatic cylinders, pneumatic grippers, and vacuum cups. The sensors mainly include displacement sensors, pressure sensors, angle sensors, and speed sensors.

PAMs are pneumatic executive elements that are used to design various novel flexible mechanisms by domestic and foreign researchers, such as pneumatic dexter-

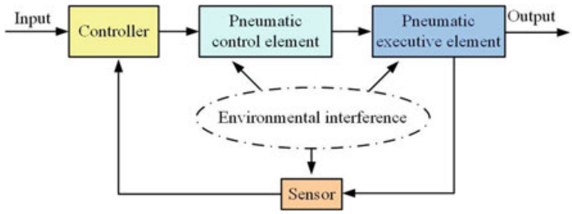

Fig. 1.6 A typical pneumatic closed-loop system

ous hands, pneumatic bionic mechanical arms, pneumatic rehabilitation apparatuses, robotic systems [11, 12]. In addition, a highly flexible manipulator [13], a hand rehabilitation gloves [14], and an ankle rehabilitation robot [15] are all driven by PAMs. To achieve desired movements, the above mechanisms have high requirements for modeling and control. Some accurate dynamic models of PAMs have been established by methods such as an optimizing parameter identification [16], an artificial neural network [17], an empirical model of mechanical properties [18], and so on. In order to achieve good tracking performances, many researchers have tried to control the PAMs by fuzzy control [19], robust control [20], sliding mode control [21], model predictive control [108], and other control methods. However, these control methods still have some limitations under conditions of coupling structures, l oad changes, and external disturbances. It is a challenge for us to improve the control accuracy of pneumatic flexible systems. In this book, three experimental platforms driven by PAMs are studied, which are a pneumatic manipulator platform for a pneumatic manipulator system, a pneumatic dexterous hand platform for a pneumatic dexterous hand system and a pneumatic motion simulation platformfor a pneumatic motion simulation system.

The pneumatic manipulator platform is a bionic device that can perform specific operations. There are many advantages for the pneumatic manipulator system driven by PAMs, such as high power–weight ratio, application safety, simple structure, and environmental protection. The pneumatic manipulator system is applied widely in robotics [22], industrial automation [23], and so on. The pneumatic manipulator system has many functions in practice, such as fitness equipment, accident rescue, and rehabilitation training. It is a novel pneumatic equipment which is also applied in scientific research teaching, algorithm verification, advancing nursing, and a lot of fields. In [24], a manipulator driven by PAMs has been designed to deal with uncertainties and disturbance in tracking control via a reduced-order ESO. In [25], a manipulator driven by PAMs has been presented to study positioning control performance by using active disturbance rejection controller. In [26], a manipulator driven by PAMs has devoted research as a primary work of the multi-DoF manipulator system.

The pneumatic dexterous hand is a bionic device which can grasp objects in a particular position under different working conditions. There are many satisfactory advantages for the pneumatic dexterous hand driven by PAMs, such as strong degree of flexibility, high safety performance, low cost of processing, and good safety performance. Originally, traditional pneumatic dexterous hand is widely applied in various fields, such as industrial robots [109], bionic robot [110], and space robots [27]. Nowadays, a class of pneumatic dexterous hand is also used in health care, food packaging, and other fields. In [28], a sliding mode controller with ESO has been proposed to cope with nonlinearities and disturbances for a dexterous hand system which is driven by PAMs. In [29], an adaptive recurrent neural networks controller derived from adaptive theory has been implemented to adjust parameters conveniently for a serial two-joint manipulator driven by PAMs. In [30], a two-axis planar articulated robot driven by four PAMs has been presented to study a system compensated by nonlinear effects.

The pneumatic motion simulation platform is a mechanism with PAMs which can achieve a desired motion trajectory with three degrees of freedom. Originally, the motion simulation system was used in military field, such as flight simulation training, chariot road test, and submarine swaying test. Nowadays, a class of similar motion simulation system is widely applied in rehabilitation treatment, theme park, dynamic cinema , and so on [31]. The motion simulation platform has many functions, such as uniform speed, acceleration, and turning. The motion simulation system mainly uses hydraulic, pneumatic, or electric motor servo system. Due to advantages of rapid response, low cost and high power–weight ratio, PAMs are widely used in the motion simulation platform [32]. A two-axis planar articulated motion robot driven by four PAMs has been introduced in [30]. An adaptive wearable ankle motion robot manufactured by PAMs has been presented in [33]. In [34], an adaptive robust posture controller has been designed for a parallel motion platform driven by PAMs with a redundant degree of freedom. In [35], an integrated direct/indirect adaptive robust controller has been proposed to improve control performance for a parallel motion platform driven by PAMs.

Pneumatic cylinders are another type of executive elements for pneumatic system. Pneumatic cylinders can be applied in flexible manufacturing systems, surgery assisted robots, and other industries because it has a certain sense of internal pressure and a certain flexibility. However, it is difficult by traditional classical control theories to achieve satisfactory performances for pneumatic cylinder servo systems due to some negative effects caused by complex modeling, various friction forces, air compressibility, and so on. Therefore, many researchers have put forward a lot of control strategies to improve control accuracy for pneumatic cylinder servo systems [36]. An adaptive robust control has been applied by Professor Guoliang Tao of Zhejiang University to track the synchronization trajectories of multiple cylinders [37]. A multifaceted sliding mode controller has been proposed by YiChang Tsai in Taiwan science and Technology University for a pneumatic cylinder servo system with variable load [2]. An adaptive backstepping sliding mode controller has been designed by R. A. Rahman in Canada to improve the position control accuracy for a low consumption cylinder [38]. In fact, the accuracy of modeling and the robustness of system are always difficult problems for research of complex pneumatic cylinder servo systems. How to realize an accuracy control of the pneumatic cylinder servo system is a subject with high value of application under conditions of incomplete models, external disturbances, and so on. In this book, two experimental platforms driven by pneumatic cylinders are studied, which are a pneumatic rod cylinder servo platform and a pneumatic right angle composite motion platform.

The pneumatic rod cylinder servo platform is a common product which achieves straight reciprocating motion. The pneumatic rod cylinder servo system is applied widely in medical equipments, military equipments, robots, and other fields due to their advantages of clean, safety, low cost, quick reaction, and so on [36, 39]. In addition, due to the flexibility of the pneumatic rod cylinder servo system platform, it is also used in flexible devices, such as automatic door operators and pneumatic surgical robot. The pneumatic rod cylinder servo system platform has many functions in practice, such as precise fixed-point and reciprocating handling [40]. A pneumatic rod cylinder servo system which is applied in the wearable robotics has been established in [41] to study precise position control. A human walking assist system, which is mainly made up of pneumatic rod cylinder servo system, has been presented in [6]. A pneumatic rod cylinder servo system has been used to simulate a handling device under loads [42]. Meanwhile, control methods of the pneumatic rod cylinder servo system platform have been proposed by more and more scholars [43–45].

The pneumatic right angle composite motion platform is an automatic production equipment which can perform certain operations in three-dimensional space. For various advantages, such as rapid response, reliable operation, and high power–weight ratio, the platform driven by rodless cylinders is used extensively in food fields, health care, industrial automation, and so on [1, 46]. The pneumatic right angle composite motion system has many functions in practice, such as location, periodically motion and complexly trajectory tracking [47]. Various improved PID controllers with simple structures and easy implementations have been designed in some similar pneumatic actuated system platforms [39]. A sliding mode controller has been designed to ensure good performances for a pneumatic cylinder motion system due to its strong robustness and high tolerance for uncertainties [48]. A backstepping control technique has also been introduced for the stability analysis and controller design problems of the nonlinear pneumatic system [40].

1.2 Problems Studied in This Book

Nonlinear control will be studied based on the following five experimental platforms on pneumatic servo systems in this book: Pneumatic manipulator platform, pneumatic dexterous hand platform, pneumatic motion simulation platform, pneumatic rod cylinder servo system platform and pneumatic right angle composite motion platform. The nonlinear control methods are designed for the five experimental platforms which are described by five pneumatic servo systems: Pneumatic manipulator system, pneumatic dexterous hand system, pneumatic motion simulation system, pneumatic rod cylinder servo system, pneumatic right angle composite motion system. Moreover, the effectiveness of the nonlinear control methods are also shown by experimental results on the five pneumatic servo systems.

1.2.1 Pneumatic Manipulator System

Pneumatic manipulator platform, which can achieve rapid response and precise control, is an experimental equipment with one degree of freedom driven by PAMs. Due to highly nonlinear and time-varying behavior caused by the elasticity and compressibility of air, it is difficult to achieve accurate control in PAM systems. The faultiness of PAM systems has promoted many researches into a number of control strategies, such as PID method [49], adaptive robust control strategy [50], and sliding mode control [51]. In order to deal with nonlinearities and uncertainties, the ADRC method is designed to estimation and compensation these nonlinearities and uncertainties. As an important part of the ADRC, ESO can be used to estimate the strongly nonlinear in the nonlinear or uncertain systems. Both unknown dynamics and disturbance are assumed to be total disturbance which will be estimated in real time with an observer in the ADRC [52]. Since the design of an ESO does not need an accurate mathematical model, it has been widely used in many complex systems, such as permanent magnet synchronous motor servo systems [53], hypersonic vehicles [54], and nonlinear multi-agent systems [55]. Some strategies on the ADRC are adopted with the linear ESO to deal with the strongly nonlinear for the pneumatic manipulator platform.

In recent years, various control methods are popular to solve the issues about uncertainties of the model and strong nonlinearities for PAMs, such as [49, 50, 56, 57]. Nevertheless, it is difficult to get an accurate control in PAMs systems for the existence of highly nonlinear and time-varying dynamics caused by elasticity and compressibility of air. It is an important problem that how to design efficient ESO to estimate nonlinear terms, external disturbances and unmodeled dynamics for the PAMs systems. Owing to good estimation performance of ESO, different kinds of ESOs are used to deal with uncertainties and nonlinearities. In [58], a kind of linear ESOs for nonlinear time-varying plants is proposed, and a complete stability analysis of the proposed linear ESO is also presented. A sort of adaptive ESOs for nonlinear disturbed systems are adopted in [51, 59], and implemented to air–fuel ratio control of gasoline engines. Owing to some states that can be acquired in real time, these states need not be obtained. Therefore, in order to reduce the estimated burden of ESO, a reduced-order ESO is designed to estimate and compensate uncertainties and nonlinearities for the pneumatic manipulator platform.

In pneumatic manipulator platform, there exist highly nonlinear and time-varying dynamics in PAMs systems, which is caused by elasticity and compressibility of air. Therefore, it is necessary to improve the performances of PAMs via an algorithm that is deal with uncertainties and nonlinearities. It is important to design efficient controllers for the pneumatic manipulator platform. ESO is used to estimate the nonlinearities and uncertainties, and a good tracking effect is achieved by designing various controllers to compensate nonlinear terms. Due to sliding mod control can guarantee a performance of trajectory tracking for PAM driven joint systems with good robustness property [60], it has been applied to pneumatic systems in recent years. In [61], a terminal sliding mode controller is designed to achieve the robust control of PAMs robot manipulators. In [51], a sliding mode control based on nonlinear disturbance observer has been designed to obtain good tracking performance. In [62], a high-order sliding mode controller is employed to assure convergence of electro-pneumatic systems. Therefore, it is necessary to improve the performances of the pneumatic manipulator platform by adopting a sliding mode controller that combines with the estimate of the disturbances via a super-twisting ESO.

Summarizing the above results, two challenges still remain despite all the reported literatures on exploring control methods for many mechanisms of PAMs. The one challenge is that compressibility of air and nonlinear elasticity of rubber tube bring highly nonlinearities and time-varying behavior. The other challenging is improving control precision and response rapidity for the pneumatic manipulator platform via ADRC control approach. The second challenge is improving control precise and response rapidity for the pneumatic manipulator system via ADRC algorithm. The two challenges are important in both theory and practice, which motivated us to carry on this research work. Moreover, as an important part of the ADRC, the TD is investigated to provide a desired transient and differential trajectory for a desired input signal. The TD is also considered as a filter used in the control method. In addition, convergence analysis of the nonlinear ESO, the reduced-ESO and the super-twisting ESO are performed, which is a challenging in theory. Finally, experimental results show that the control methods have advantages in dealing with nonlinearities and uncertainties. In this part, we will mainly investigate improving the performances for the pneumatic manipulator platform.

1.2.2 Pneumatic Dexterous Hand System

Pneumatic dexterous hand platform is an experimental equipment with two degrees of freedom driven by PAMs. There exists an obvious advantage for pneumatic actuators compared with over rigid actuators, when robots need to interact with human beings [63]. However, compressibility of air and nonlinear elasticity of rubber tube bring many properties for PAMs, such as highly nonlinearities and time-varying behavior [64]. Hence, more and more attention are attracted to deal with the nonlinear problem of PAMs. Some conventional PID controllers are introduced to obtain trajectory tracking control for certain mechanisms driven by PAMs [53, 57]. In recent years, ADRC technology is increasingly used to solve nonlinear problems. As the core part of ADRC, ESO is used to estimate the nonlinearity in kinds of systems. Note that nonlinear ESOs have been proposed to deal with uncertain terms in nonlinear systems. In [65], a nonlinear ESO is presented to estimate nonlinear terms of the two-link flexible manipulator system. In [66], a nonlinear ESO is introduced to estimate uncertainties and external disturbances for a missile guidance system. Some strategies on the ADRC are adopted with the nonlinear ESO to deal with nonlinearities for the dexterous hand driven by PAMs.

As good characteristics of bionic muscle, PAMs are widely applied in robotic hands. In recent years, various control methods are researched to solve the issues