Output Force Control of a Pneumatic Soft Gripper with a Jointed Endoskeleton Structure

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Abstract. Soft grippers are suitable for gripping various objects without damage owing to their high flexibility. But current soft grippers have a general problem of insufficient gripping force. To grip objects with different mass and sizes on assembly line safely and reliably, a novel pneumatic soft gripper with a jointed endoskeleton structure was developed and fabricated successfully. The actuation and force bearing functions of the gripper were separated to increase the gripping force. Moreover, to control the output force of the finger tip of the soft gripper, a fuzzy auto-tuning PID controller was designed and the relevant parameters of the controller were determined. Furthermore, a test platform with the designed fuzzy auto-tuning PID controller was developed to control the output force of the finger tip. The test results showed that the controller was able to maintain the desired target output force with a maximum deviation of 0.6 N. At last, the soft gripper was used to grip material objects for testing. From the experiment, it indicated that the output force of the finger tip can reach up to the desired values accurately and various objects can be gripped safely and reliably.

1. Introduction
Grippers act as an important part of modern industrial manufacturing lines to grip and transport workpieces automatically. With the improvement of productivity level and labor efficiency, new manufacturing technologies such as mixed flow production put forward higher requirements to the functional diversity of grippers, especially to grip objects with different mass and sizes safely and reliably. The soft robotics has become a current research focus, in which pneumatic soft gripper has been applied widely owing to its high flexibility, low fabrication process, rapid response and excellent environment adaptability [1-2].

A series of pneumatic soft actuators have been developed at home and abroad. The concept of soft grippers was proposed firstly by Harvard University. Ilievski et al. developed a fully soft starfish-like gripper fabricated by PneuNets technology, which was used for gripping small objects such as eggs and guinea pigs without damage [3]. A rapidly bending pneumatic actuator was designed by Mosadegh. The inner chamber was divided into two parts to expand and extrude each other, which caused the bending motion [4]. Such fully soft grippers act as both actuators and executors, which lead to the low clamping force and load capacity. Meanwhile, the soft material lacks stiffness which will generate undesired deformation such as radial expansion and irregular stretch. Further, a composite fluidic actuator with a circumferential fiber-reinforced structure has been studied by Polygerinos et al. With the circumferential fiber-reinforced structure, radial expansion could be effectively reduced such that the rigidity and gripping force could be increased [5]. But local unexpected deformations still...
exist, which consumes the energy and the gripping force is insufficient.

Furthermore, gripping the target object safely and reliably is the most basic function of a gripper so that the output force control of the gripper is necessary. Guoliang Zhong of Central South University proposed a novel soft pneumatic dexterous gripper that consisted of four soft fingers and a movable sucker. The gripper had four grasping modes namely as perpendicular mode, parallel mode, two-finger mode, and sucker mode [6]. John Morrow achieved low steady-state error and overshoot in position and force of a soft pneumatic actuator with rigid fingernails using feed-forward models that related pressure, force, and curvature along with a PID controller [7]. Useok Jeong proposed the use of a position-based impedance controller to control a soft wearable robotic hand with a slack enabling tendon actuator [8]. Minou Kouh Soltani introduced a nonlinear hybrid force/position control strategy for soft tendon driven catheters and the catheter was capable of regulating the force of 4.9 mN [9]. At present, the research of the control of pneumatic soft grippers, especially the control of force is comparatively little and the control method should be improved.

Therefore, it is crucial to increase the gripping ability, decrease or even limit the unnecessary deformation of the gripper and to control the output force accurately. To solve the above-mentioned problems, a novel pneumatic soft gripper with a jointed endoskeleton structure which separated the actuation and force bearing function has been proposed and fabricated successfully. Besides, a fuzzy auto-tuning PID controller is applied on the control of the output force of the finger tip to increase the force accuracy and to grip the target object safely, reliably and precisely.

2. Structure
A jointed endoskeleton structure is proposed in this paper. The design principle is that: an endoskeleton consist of several jointed skeleton units acts as the force bearing mechanism; the outer actuation part made of silicon rubber with an embedded radial-restrained fiber achieves the bending motion by pressurized. Thus the gripping force can then be increased and high flexibility can be maintained.

Figure 1. Configuration of the soft finger of the gripper
The configuration of the finger of the soft gripper is shown in Figure 1. The outline of the soft
finger imitates the octopus tentacles. A smooth taper shape is formed from the fingertip to the finger root with a size that increases gradually. The shape of the contact surface of the finger is the ridge style which can increase the friction when gripping. The endoskeleton consists of a series of skeleton units that can rotate from $-45^\circ$ to $180^\circ$ at the hinge joints. The outer silicon rubber layer is bonded with the endoskeleton by super soft glue, which constitutes a series of inner chambers. To increase the operational efficiency and realize a greater number of postures, the entire finger is divided into three independent finger segments that can be independently pressurized using different air pressures to control the bending angle. Each finger segment consists of 5 finger joints that work together to acquire the bending motion of one finger segment.

When the soft finger works, compressed air flows through the channels from the finger root to control three finger segments, and the air pressure is marked as $p_1$, $p_2$, and $p_3$, respectively, for the three finger segments. Bending deformation occurs at each finger joint under the air pressure and the tension of the silicon rubber. The expected output bending angle and torque could be obtained. The total bending angle of the finger is the sum of each finger joint’s bending angle, and the total output torque of the finger is the sum of each finger joint’s torque.

The soft gripper is set up by three soft fingers through the palm. The three fingers are evenly distributed on the circumference of the palm. The angle between the two adjacent fingers is $120^\circ$, and the angle between the axis of a finger and that of the palm is $35^\circ$. The palm comprises flow channels passing to the fingers. The operation of the soft gripper is convenient and both enveloping gripping mode and fingertip gripping mode can be chosen.

### 3. Fabrication

The soft gripper is made of several materials. Light and rigid material should be used for the endoskeleton so that fatigue damage is not apt to occur after repeated bending. Then PolyPlusTM (a polylactic acid material produced by Polymaker) is used for making the endoskeleton by 3D printer. The actuating layer is made of Smooth-on Dragon Skin silicon rubber with the Shore-hardness of 10A. The palm is also fabricated by 3D printed so that its streamline surface can fix the finger well. Fibers are used for the embedded reinforced layer to limit the radial deformation.

The soft gripper is fabricated through modular components. The fabrication process is shown in Figure 2. First, two skeleton units are linked by two cylindrical pins and a spring [Figure 2(a)]. A series of skeleton units composes the endoskeleton [Figure 2(b)]. Then three air tubes are embedded into the endoskeleton so as to control different finger-segment independently [Figure 2(c)]. The soft actuating layer is cast through three steps. In the first step, one silicon rubber layer is glued surrounding the endoskeleton [Figure 2(d)]. In the second step, circumferential fiber is evenly winded on the surface [Figure 2(e)]. In the last step, the outer silicon rubber layer is glued to form the finger [Figure 2(f)]. At last three fingers are connected with the palm to complete the fabrication of the soft gripper [Figure 2(g)]. Figure 2(h) shows the bending state of the soft gripper.
4. Control algorithm
The pneumatic soft gripper with jointed endoskeleton can be used to grip multiple objects with different masses and shapes safely and reliably. Gripping methods include enveloping gripping and fingertip gripping. Fingertip gripping is also known as accurate gripping. The fingertip touches the surface of the object and the object is clamped. The object relies on the fingertip to realize a stable state. High dexterity, reliable accuracy and more operation styles will be acquired under fingertip gripping. It requires accurate control of the output force of the finger tip. Because the soft gripper is a coupled pneumatic system which consists of large nonlinear deformation and multiple materials, the mathematical model is complex and difficult to achieve the desired control effect. Therefore, an algorithm to design the controller without a mathematical model of the system is needed.

The PID controller has been used in the industrial automation field because of the advantages of the simple principle, convenient application and strong adaptability. The control variables of PID consist of proportion (P), integration (I) and differentiation (D) of the control deviation linearly. The control law can be described as

\[ u(t) = K_p \left\{ e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + \frac{T_d}{T_i} \frac{de(t)}{dt} \right\} \]  

where \( K_p \) is the coefficient of proportion; \( T_i \) is the coefficient of integral time; \( T_d \) is the coefficient of differential time.

The tuning of PID parameters is the core content of the control system design. The regulation quality and robustness of the controller are influenced by the quality of parameters directly. A typical PID controller can only be controlled by a group of fixed parameters, which can not take consideration of the contradiction between the dynamic and static performance of the system, the set value and disturbance suppression. Therefore, an intelligent control system should be introduced into the controller to improve the dynamic and static performance of the system by adding the tuning of parameters based on the initial PID values. The fuzzy control algorithm is robust and insensitive to the change of process parameters, which is suitable for the nonlinear time-varying system with large delay nonlinear. In this paper, a fuzzy auto-tuning algorithm is adopted to realize the automatic online optimal adjustment of PID parameters [10-11]. The control scheme is shown in Figure 3.

![Figure 3. Scheme of the fuzzy auto-tuning PID controller](image)

The fuzzy auto-tuning PID controller is double input and three output system. The force error \( e(t) \) and the change rate of force error \( \dot{e}(t) \) is the input language variable. The PID parameters \( K_p, K_i, K_d \) act as the output language variable, which is adjusted in real-time according to the fuzzy inference rules. The output of the PID controller \( u(t) \) is the duty cycle of control frequency of the high speed on-off valve, which is used to control the air inflow of the soft finger.

In order to reflect the dynamic characteristics of the output variables of the control system better, according to the measurement range of the flexible pressure sensor and the actual opening and closing
characteristics of the high speed on-off valve, etc., the fuzzy set of \( e(t) \) is defined to be \{NB, NM, NS, ZO, PS, PM, PB\}, the value range is \([-5, 5]\), the fuzzy set of \( \dot{e}(t) \) is defined to be \{NB, NS, ZO, PS, PM, PB\}, the value range is \([-2, 2]\), the fuzzy set of \( K_p, K_i, K_d \) is \{NB, NM, NS, ZO, PS, PM, PB\}, the value range of \( K_p \) is \([-10, -3, -0.5, 0, 0.5, 3, 10]\), the value range of \( K_i \) is \([-50, -15, -1, 0, 1, 15, 50]\), the value range of \( K_d \) is \([-1, -0.2, -0.01, 0, 0.01, 0.2, 1]\). Considering the stability, overshoot, response speed and steady-state error of the algorithm synthetically, the tuning principle of the PID parameters is as follows:

1. When \( |e(t)| \) is large, the value of \( K_p \) is larger, the value of \( K_d \) is smaller, thus the better tracking performance of the algorithm can be achieved; meanwhile, the value of \( K_i \) is taken 0 to avoid large overshoot.

2. When \( |e(t)| \) is middle, the value of \( K_p \) should be smaller to control the overshoot. Then the value of \( K_d \) has large influence on the response speed of the system, the value of \( K_i \) should be proper.

3. When \( |e(t)| \) is small, \( K_p \) and \( K_i \) should be larger to achieve better system stability. The value of \( K_d \) is determined by \(|\dot{e}(t)|\).

According to the above principles, the fuzzy inference rules are built as shown in Table 1. Fuzzy control rules of \( K_p, K_i, K_d \) lay from left to right in each cell.

### Table 1. The fuzzy inference rules

| \( \dot{e}(t) \) | \( e(t) \) |
|------------------|------------------|
|                  | NB               | NM   | NS   | ZO   | PS   | PM   | PB   |
| NB               | PM/ZO/P S        | PS/N/NS/P M | PM/NM/PM | NB/NB/ZO | NM/NM/ZO | NM/NM/ZO | NM/ZO/P |
| NS               | PB/ZO/N B        | PM/ZO/N S | PB/NB/N S | PB/NB/N S | NB/PB/N S | NM/ZO/P | NB/ZO/P |
| ZO               | PB/ZO/N B        | PM/ZO/N S | PB/NB/N S | PB/NB/N S | NB/PB/N S | NM/ZO/P | NB/ZO/P |
| PS               | PB/ZO/N B        | PM/ZO/N S | PB/NB/N S | PB/NB/N S | NB/PB/N S | NM/ZO/P | NB/ZO/P |
| PB               | PM/ZO/P S        | PS/N/NS/P M | PM/NM/PM | NM/NM/ZO | NS/NM/ZO | PM   | PS   |

The membership functions of each fuzzy state are generally symmetric triangle, symmetric trapezoid and normal membership functions. The shape of the triangle membership function is only related to the slope of its line, the operation is simple and the memory space is small, thus it is suitable for on-line tuning fuzzy control with membership function. Here the triangle style is selected as the membership function of the language variable.

The coefficient weight average method is used to solve fuzzification. The formula is as follows:

\[
 u(t) = K \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} c_{ij} u_i[e(t)] u_j[\dot{e}(t)]}{\sum_{i=0}^{m} \sum_{j=0}^{n} u_i[e(t)] u_j[\dot{e}(t)]}
\]

where \( u(t) \) is the control signal of the high speed on-off valve; \( c_{ij} \) is the weight; \( u_i[e(t)] \) and \( u_j[\dot{e}(t)] \) are the values of membership functions of force error and its change rate respectively.
5. Experiment

5.1 Control test of the output force of fingertip

The prototype of the soft gripper was fabricated according to the previous design structure. After the successful design of the controller, the test platform was set up to control the precision of the fingertip output force. The flexible force sensor (FlexiForce a201-25) was selected to collect the force signal of fingertip. Different from the general force sensor, the flexible force sensor can deform with the soft actuator and output the force value on the basis of not damaging its electronic performance, which is very suitable for the soft gripper with high flexibility. Three pressure sensors (SMC ISE4-01-26) were used to collect the pressure of the air chamber of three finger segments. The high speed on-off valve (Festo P7944411) was used to control the air inflow of the soft finger.

The soft finger was placed horizontally on the test platform and the flexible force sensor was bonded on the finger tip. The bending deformation of the finger tip was limit to zero and the output force of the fingertip was controlled in this condition. Matlab Simulink software was used to build the control system. The signals of the flexible force sensor collected through the integrated circuit board of the industrial control computer in real-time were input to fuzzy auto-tuning PID controller after modulation, amplification and filtering. The controller output duty cycle signal of PWM to control the high speed on-off valve. Meanwhile, the pressure signals of each finger segment were collected. The schematic diagram of the test control circuit is shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** Circuit diagram of the control test for output force. 1. Air source; 2. Dryer; 3. Reducing valve; 4. High speed on-off valve; 5. Pressure sensor; 6. Flexible force sensor; 7. Soft finger; 8. Integrated circuit board; 9. IPC.

The output force values of 5 N, 10 N and 15 N are chosen to test. The curves of the response of the output force were acquired and drawn through Simulink, as shown in Figure 5. The stability time of the system is about 2s which is not influenced by the increase of the output force greatly. The initial overshoot is relatively large to increase the response speed. The maximum deviation final of the final output force is maintained within 0.6 N. It indicates that the system is satisfied with the actual control requirements.
5.2 Objects gripping demonstration

Gripping objects is the most basic performance of the gripper. In order to test the gripping performance of the soft gripper, fingertip gripping experiments were carried out on objects with different shapes, sizes and weights. The output force of the three fingers of the soft gripper was set to the same value and the output force values were planned and determined beforehand. The parameters of the test objects and corresponding output force values of the fingertip are shown in Table 2.

Table 2. The parameters of the test objects and corresponding output force

| Name    | Size (mm) | Mass (g) | Material | Output force (N) |
|---------|-----------|----------|----------|------------------|
| Golf ball | D42       | 46       | Rubber   | 3                |
| Cube    | 56*56*56  | 80       | Plastic  | 6.5              |
| Bulb    | About D130 | 98      | Glass    | 8                |
| Spirit  | About D56*164 | 196   | Plastic  | 14               |

Photographs of the soft gripper when gripping test objects are shown in Figure 6. Every test object was gripped by the soft gripper successfully according to the planned output force of fingertip. The gripping was stable and reliable which proved the correctness and effectiveness of the control algorithm of the output force.

6. Conclusion

A novel pneumatic soft gripper with a jointed endoskeleton structure is proposed and fabricated successfully, in which, the actuation and force bearing functions can be separated. The bending action is performed by the soft rubber with an embedded radial-restrained fiber through pneumatic actuation, while the gripping force is borne and transferred by the jointed endoskeleton. The gripping force can
then be increased, and high flexibility can be maintained.

A fuzzy auto-tuning PID controller is proposed and used to control the output force of the finger tip. Every parameter is debugged and determined. Through the fuzzy auto-tuning PID controller, the overshoot of the system is lower, the loading response time is shorter and the precision of the output force is higher.

A test platform is built and the closed-loop control of output force is conducted with the designed fuzzy auto-tuning PID controller. Through experiments, the maximum deviation is maintained within 0.6N. Moreover, the gripping test of several objects is carried out with the planned output force, which indicates that the soft gripper can complete the gripping operation safely and reliably.

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