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Robust Robotic Grasping Based on Nonlinear Force Feedback Control

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ABSTRACT: Robotic hands for dexterous manipulation and robust grasping have always been in high demand. Many applications of pneumatic devices are enabled due to recent developments in pneumatic actuation technology, for which previously only electric motors were suitable. Low stiffness and direct drive capabilities of pneumatic actuators enable smooth compliant geared electric motor systems. A new robotic hand was developed to lift an object to a position without losingcontact or slip as fast as possible. A nonlinear force feedback controller is designed to control both the position and velocity of the end effector and the constraint force between the gripper and the environment. Simulation studies were performed to illustrate the efficacy of the developed control method.

KEYWORDS: Grasping, Force feedback,Nonlinear control.

I. INTRODUCTION

Based on the force control current researchers have studied the grasping robot, gripper and finger of the manipulator. However the requirement of the dexterous manipulation of an object with robotic mechanism in sophisticated tasks and the difficulties in realizing such dexterity are stimulating many researchers to tackle the problem regarding the development.Bicchi[1] proposed a parallel approach to force and position control, where position trajectories are sacrificed due to force demands. For physiotherapy, specifying specific position demands would be difficult, as they would be masked by the dominance of the force loop. Force is controlled in constrained directions, while position is controlled in unconstrained directions [2,4,6,7,8,9].Shimoga and Goldenberg [5] have studiedmodeling and controlling the impedance of a soft finger and showed experimentally how the presence of passive damping helps reduce the peak impact forces that occur as a rigid object is grasped by fingers of a robotic hand from soft materials. Another approach to control robot hands is several force and position control schemes devised for robotic interaction tasks. Hirai and Wada [3] have divided the finger forces into two different forces, manipulation force and internal force, defined the manipulation force, which generates the required external object force.

Additionally, the technology has enabled the automation of many process, however, these are mainly focused on grasping without slip. In the grasp of rigid objects, additional considerations have to be made with respect to manipulation, gripping, and sensor required. Such objects may slip during operation of robot for example by increasing mass of object or obtaining external force which may result in drop of the object grasped by the gripper of robot.

II. DESCRIPTION OF INTELLIGENT PNEUMATIC GRIPPER (IPG)

The gripper is a critical component of an industrial robot since it interacts with the environments and object, which is grasped and manipulated. Among many problems such as rigidity, lightness, multi-task capability and lack of maintenance, basic requirements for an industrial robot gripper can be recognized in a low-cost and reliable design. Recent developments in pneumatic actuators and valve allow them to be considered for application which previously only electric motors were suitable. Pneumatic system's inherent low stiffness and direct drive capabilities enable smooth compliant geared electric motor systems. Moreover, pneumatic actuators can cost up to 10 times less than electric motors, while offering a higher power to weight ratio.

Each joint of the IPG arms is revolute and actuated by apneumatic actuators consisting of a low frictionpneumatic cylinder and a regulator valve with a position sensor. Each valve supplies regulated pressure to a single chamber of pneumatic cylinder. The pneumatic cylinder extends gradually with the applied force-causing side arm to grasp. As stated earlier, the grasping motion of IPG is produced by four pneumatic cylinders as shown in Fig 1.

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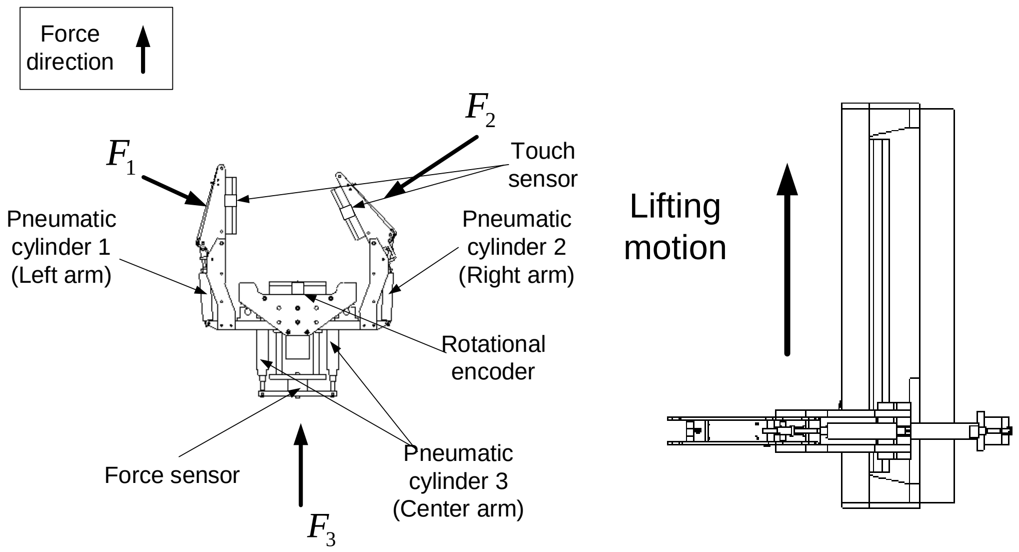

Figure 1 and 2 Grasping direction of IPG

As a result of the IPG physical configuration, the force exerted on the arms depends on the position of stroke of the rightand left arms. In IPG, grasping motion is initiated by the pneumatic actuators with two touch sensors for ensured grasping of the object. Lifting motion is engaged after grasping motion. Figures 1 and 2 illustrate the grasping and lifting motion of the IPG gripper system.

III. CONTROL DESIGN

Exemplar based Inpainting technique is used for inpainting of text regions, which takes structure synthesis and texturesynthesis together. The inpainting is done in such a manner, that it fills the damagedregion or holes in an image, with surrounding colour and texture. The algorithm isbased on patch based filling procedure. First find target region using mask image and then find boundary of target region. For all the boundary points it defined patch and find the priority of these patches. It starts filling the target region from the highest priority patch by finding the best match patch. Thisprocedure is repeated until entire target region is inpainted.

The primary objective of the IPG gripper is to lift an object to a position without losingcontact or slip as fast as possible. Hence, it is necessary to control both the position and velocity of the end effector and the constraint force between the gripper and the environment. First, grasping motion is initiated by applying a force to the object based on its weight for secure grip. Then, lifting motion is engaged to move up the object to a desired position. In case slip of the object occurs, the grasping force is controlled to maintain stable grasp while the reference trajectory for lifting is modified on line to improve stability of the object. Therefore, the control system to be developed has two active controllers – one for grasping and the other lifting. The developed control method will have a closed-loop structure similar to hybrid control methods.

The IPG system can be modeled using a Lagrangian formulation expressed by a set of differential-algebraic equation. Let $q \in R^n$ be a generalized coordinated vector and $\dot{q} \in R^n$ be a generalized velocity vector. Suppose the holonomic constraints of the system are described by

$$\phi(q) = 0 \tag{1}$$

where $\phi^T = [\phi_1, \ \cdots \ \phi_m]$ is at least twice differentiable. The potential and kinetic energy functions are denoted by $p(q)$ and $k(q,\dot{q}) = \frac{1}{2}\dot{q}^T M(q)\dot{q}$, respectively, where $M : R^n \to R^{n\times n}$ is a positive definite inertia matrix, and the potential energy function $P : R^n \to R^{n\times n}$ is at least twice differentiable. A Lagrangian function is defined as

$$L(q,\dot{q}) = K(q,\dot{q}) - P(q) . \tag{2}$$

Using the definition of L , the equation of constrained motion can be expressed as

$$M(q)\ddot{q} + F(q,\dot{q}) = J^T(q)\lambda + u \tag{3}$$

The constrained dynamics are described by n second order differential equations as shown in Eq. (3) and m algebraic equations as shown in Eq. (1) in terms of $n+m$ variables q and λ. The vector of the variable λ determines the constraint forces.

Regulation vectors are specified by a desired constant position vector $\phi(q_d) = 0$ and $f_d = J^T(q_d)\lambda_d$ for some constant vector $\lambda_d \in R^m$. To achieve regulation of position and force to the specified position and force vector (q_d, f_d), it is necessary to guarantee the desired values are an equilibrium of the closed loop equations. This can be achieved by the following controller:

$$u = \frac{\partial P(q)}{\partial q} - \frac{\partial P_d(q)}{\partial q} - C\dot{q} \tag{4}$$

where $P_d(q)$ is a desired potential energy function that is chosen to satisfy the following equation:

$$\frac{\partial P_d(q_d)}{\partial q} = f_d \tag{5}$$

Thus, (q_d, λ_d) is an equilibrium of the closed loop system Eq. (6), which requires that the gradient of the desired potential energy function $P_d(q)$ at q_d be parallel to the constant force vector f_d. The $n \times n$ matrix C is assumed to be symmetric and to satisfy $\dot{q}^T C\dot{q} > 0$ for all $\dot{q} \neq 0$ satisfying $J(q_d)\dot{q} = 0$.

A Lyapunov function for the constrained system can be used to guarantee the local stability of the equilibrium (q_d, λ_d). In particular, the modified potential energy is represented as

$$P_{md} = P_d(q) - P_d(q_d) - \phi^T(q)\lambda_d . \tag{6}$$

The modified potential energy function can be used to form a Lyapunov function for the constrained system as

$$V(q,\dot{q}) = \frac{1}{2}\dot{q}^T M(q)\dot{q} + P_{md} \tag{7}$$

Therefore, (q_d, λ_d) is locally asymptotically stable based on the invariance principle. However in case of IPG, the force feedback is necessary due to applying in the direction normal to the constraint surface at the contact point during the gripping motion. Therefore, this is done by using the Jacobian matrix $J^T(q)$ as a projection. The reason is that $\dot{q}^T J^T(q) = 0$ or the range of $J^T(q)$ is normal to the velocity $\dot{q}$ which is on the tangent plane at the contact point. Therefore, the control with force feedback is

$$u = \frac{\partial P(q)}{\partial q} - \frac{\partial P_d(q)}{\partial q} - C\dot{q} + J^T(q)G_f(\lambda - \lambda_d) \tag{8}$$

where G_f is an $m \times m$ force feedback matrix. This control can be used for position/force control. It is straight forward to show that the closed loop system is asymptotically stable by using Eq. (7).

The controller, Eq. (4) is in general a nonlinear feedback controller. In the following, we choose a particular function $P_d(q)$ which results in a simple affine linear feedback control law. The desired potential energy function is chosen as

$$P_d(q) = P(q) - P(q_d) - \left[\frac{\partial P(q_d)}{\partial q} - J^T(q_d)\lambda_d\right]^T e + \frac{1}{2}e^T We. \tag{9}$$

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Where $e = q - q_d$ and W is a diagonal matrix. By checking Eq. (5) the modified energy function is

$$P_{cd}(q) = P_d(q) - \lambda_d^T \phi(q) \quad (10)$$

It is easy to verify that $P_{cd} = 0$ and $\frac{\partial P_{cd}}{\partial q} = 0$. Thus $P_{cd}(q)$ has a local minimum at P_d. With this choice, the controller, Eq. (8) takes the following specific form:

$$u = \frac{\partial P(q_d)}{\partial q} - C\dot{q} - J^T(q_d)\lambda_d - W(q - q_d) \quad (11)$$

Eq. (15) represents an affine feedback control law. The first two terms form a constant bias term, and the third and fourth terms represent the feedback of position and velocity errors. C is a diagonal matrix. In addition to Eq. (11), feedback of the constraint force error can be introduced to tune the constraint force error response. Such a feedback control, including feedback of the constraint force error, is

$$u = \frac{\partial P(q_d)}{\partial q} - C\dot{q} - J^T(q_d)\lambda_d - W(q - q_d) + J^T(q_d)G_f(\lambda - \lambda_d). \quad (12)$$

Here, Eq. (12) is the control with force feedback. However, when the IPG slips the object, the desired force and position should be changed to prevent the object from falling down. During the slipping motion, the energy E_p of the object is dissipated. Therefore, the energy to grasp the object should be added to the dissipated energy to prevent the object from falling down while the slip occurs. Also, the lifting velocity should be reduced to facilitate regrasp of the object subject to slip. Therefore, the new desired velocity is changed during slip as

$$\dot{q}_{nd} = \dot{q}_d - \dot{q}_s \quad (13)$$

where $\dot{q}_s$ is the reduction of the velocity due to slip. It is obtained from the slip sensor mounted on the IPG. In addition, the original grasping force is modified to a new one as

$$f_{nd} = \frac{E + E_d + f_d}{S} \quad (14)$$

where E is the energy of the IPG to grasp the object without slip, E_d is the dissipated energy during slip, and S is the position to increase the force of the gripper. Therefore during slip of the object, the lifting velocity of lift and the grasping force are modified on line.

IV. SIMULATION RESULTS

Simulation study of the IPG was performed to investigate efficacy of the developed control method. Figure 3 illustrates slip motion of the object employed for simulation study. The object slips to 0.05m between 3 to 4 second during a lifting motion. Simulation parameters were chosen as M_{11}=15 kg, M_{22}=5 kg, M_o=1.5kg, $W_{11} = 55$, $W_{22} = 24$, $C_{11} = 4.3$, $C_{11} = 5.3$, and $G_f = 5$ where M_{11} is the mass of the first link for lifting motion of IPG, M_{22} is the mass of the second link for grasping motion of IPG, and M_0 is the object mass .

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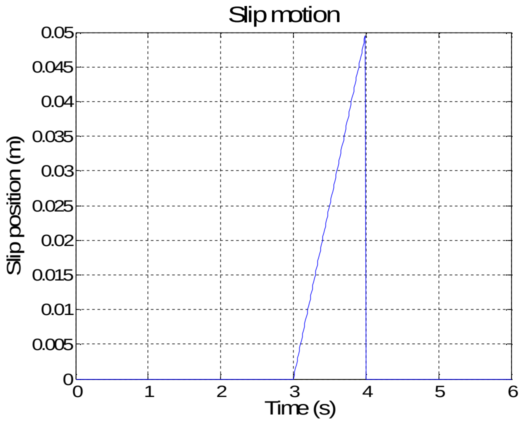
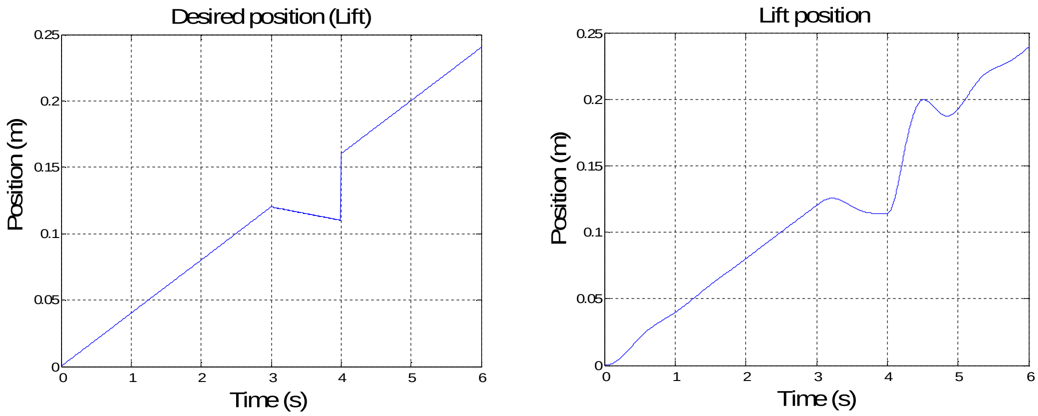


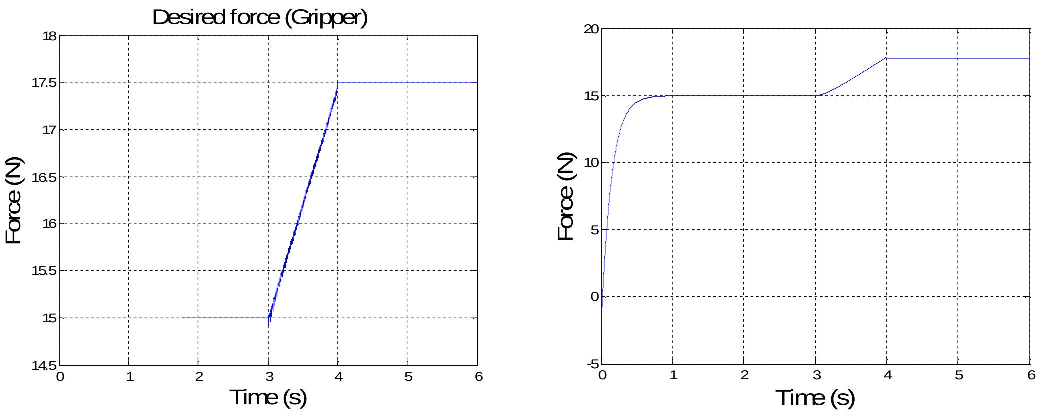
Figure 3 Slip motion of object

Figure 4 (a) shows a desired trajectory modified according to Eq. (13). The trajectory for lifting motion is modified based on the amount of slip. This means that when the object slips, the lifting velocity is reduced by the slipping velocity of the object. Figure 4 (b) shows the actual position of the lift, which is consistent with Figure 4 (a). Fig 5 (a) shows the desired grasping force by Eq. (14), which prevents further slip of the object. Fig 5 (b) shows the actual grasping force.



(a) (b)

Figure 4 New desired trajectory and output position of Lift of IPG



(a) (b)

Figure 5 New desired force and actual force of gripper of IPG

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Above Figures shows the results of text detection from an image and inpainting by using exemplar based Inpainting algorithm. Figs. 2, 3, 4 (a) shows the original image. (b) is the image obtained by applying first set of criteria. All objects whose area greater than 10000 and filled area greater than 8000 are eliminated and major axis lengths are in between 20 to 3000 are considered to be text. Still, some small non-text objects are detected. To eliminate small objects, connected component labelling is applied to the resultant image.(c) represents text detection by applying second set of criteria which eliminates all the objects whose area is less than 300 and filled area is less than 500.

V. CONCLUSION

A control method for the IPG system was developed based on the Lyapunov's direct method to control the lifting position and the grasping force of an object. The developed control system consists of a position and force controllers. The controllers work independently until slip of the object occurs. Once slip is detected, the controllers are coordinated to ensure the lifting motion of the object without further slip. In case slip of the object occurs, the grasping force is controlled to maintain stable grasp while the reference trajectory for lifting is modified on line to improve stability of the object.

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