The compliance of robotic hands – from functionality to mechanism

Rui Li, Wei Wu and Hong Qiao
Institute of Automation, State Key Laboratory of Management and Control for Complex Systems,
Chinese Academy of Sciences, Beijing, China

Abstract

Purpose – The purpose of this paper is to introduce the physical structure and the control mechanism of human motor nervous system to the robotic system in a tentative manner to improve the compliance/flexibility/versatility of the robot.

Design/methodology/approach – A brief review is focused on the concept of compliance, the compliance-based methods and the application of some compliance-based devices. Combined with the research on the physical structure and the control mechanism of human motor nervous system, a new drive structure and control method is proposed.

Findings – Introducing the physical structure and the control mechanism of human motor nervous system can improve the compliance/flexibility/versatility of the robot, without bringing in more complexity or inefficiency to the system, which helps in the assembly automation tasks.

Originality/value – The proposed drive structure and control method are useful to build up a novel, low-cost robotic assembly automation system, which is easy to interact and cooperate with humans.

Keywords Grippers, Robotics, Compliant mechanisms, Automatic assembly, Cooperative robots

Paper type Conceptual paper

1. Introduction

1.1 The concept of compliance in the robotic system

Compliance is one special characteristic of the robotic system. In cases such as dexterous manipulation and human-robot interaction, researchers use the concept of compliance to make strategy investigation, eliminate the error and improve the safety of the robot.

The concept of compliance has not been defined in a strict way. Many researches have focused on compliant control, which is a kind of control algorithm, to achieve compliant motion (Zollo *et al.*, 2005, Goldberg, 1993). Currently, the methods for achieving compliant motion are divided into three types, namely, active compliance, passive compliance and semi-active compliance (Ahmed, 2011; Schiavi *et al.*, 2009), and the corresponding compliant devices are provided separately.

In this paper, the concept of compliance is generalized as follows:

> Compliance is the characteristic of a robotic system, which is based on the physical structure of the system and the constraints formed by the environment, to increase the flexibility of the system.

There are two main aspects of this concept:

1. a special kind of physical structure, such as a mechanical design or drive mechanism, which is able to adapt to the contact force generated by the human or the environment; and
2. a kind of algorithm, such as control method or manipulation strategy, which is able to use the constraints formed by the environment to achieve compliant motion.

The application of this concept is versatile. Qiao, (2002) proposed a compliance-based concept “Attractive Region in Environment” to eliminate the errors in robotic manipulation; Su *et al.* (2012b) analyzed sensor-less insertion strategies for a crankshaft and bearing assembly system; Sentis *et al.* (2010) presented a new methodology for handling the interactions between the robots and the environment. There are also many compliant devices in markets which can achieve simple but fast robotic manipulation tasks.

1.2 The robotic hands

Different kinds of robotic hands, as the main end effector of the robotic system, have been studied for years to improve the structure design, drive type, sensors, control, etc.

Currently, the simple two-fingered gripper has been widely used in manufacturing. Such gripper is low-cost and easy to use. Before the practical stage, these grippers have to be designed in consideration of size, shape, force, etc., to meet the application requirements. Some guidelines have been studied to help design these grippers (Causey, 2003, Causey and Quinn, 1998), and some CAD software has been developed (Brown and Brost, 1999) to make the procedure

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automated. The main problem of such grippers is that, once applied, the objects to be grasped cannot change because the grippers are customized.

It seems that there is no compliance in the simple two-fingered gripper. But combined with some compliance-based method, it can achieve some high-precision manipulation tasks, such as peg-hole insertion (Su *et al.*, 2012a). In addition, if the gripper is installed with a flexible wrist, for example, a remote center compliance (RCC) device, it can also gain compliance to some extent.

Meanwhile, dexterous robotic hands have also been investigated by researchers (Mattar, 2013). These hands are usually pneumatic or electric, with carefully designed mechanical structures and various sensors. The main problem of these dexterous hands is that they are too expensive for practical use, and also the control and maintenance is very difficult, as there are a number of joint variables and parameters.

1.3 From functionality to mechanism

In manufacturing, people have noticed that the concept of compliance is of great importance to achieve high-precision manipulation tasks. The idea is derived from human workers, who can achieve all kinds of high-precision and complex manipulation tasks after some time of training and practice.

From the aspect of compliance, the advantages of human workers arise from both the structure of the hands and the control method. The human hands are very dexterous. The fingers and palms can achieve firm grasps, and the skin offers enough frictions as well as high-sensitive sensors to help understand the environment; the human workers can use the compliance of the environment to help achieve the manipulation tasks.

Up to now, researchers have introduced the functionality of human hands to increase the compliance of the robotic system. Many methods of achieving compliant control and compliant motion have been proposed, and a large number of RCC devices have been produced. However, these works have mimicked the compliance from the aspect of functionality, which means that there are some limitations in these methods and devices.

In this paper, the mechanism of human hand movement and human motor nervous system will be discussed, which may help bring in more compliance to the robotic systems. Human workers have outstanding capabilities in vision and motion with the aid of their nervous system. Introducing these mechanisms to the robotic system may improve the speed, stability, compliance and learning ability.

2. Compliance-based methods for robotic hands

As stated above, compliance is the characteristic of a robotic system, which is based on the physical structure of the system and the constraints formed by the environment. Compliance can be evaluated in the structure of the system, information processing, control, etc.

There are various operations for an autonomous manipulation system, such as localization, grasp, assembly, welding, and grinding. Usually, these operations should be executed with high precision and high speed. In a practical system, this should be considered in two aspects:

1 some kind of manipulation strategy should be made, with which the required tasks can be finished step by step; and
2 some controllers or methods should be developed, which could deal with the errors in the system to guarantee the high-precision and high-stability.

Based on the concept of compliance, researchers have carried out a lot of work by using the constrained region formed by the environment to help design strategies to achieve different robotic manipulation tasks and to eliminate errors in the system to achieve high-precision.

In this chapter, two compliance-based methods, Caging and Attractive Region in Environment will be reviewed to show how these methods utilized the environment.

2.1 Caging

The caging problem was originally proposed by Kuperberg (Kuperberg, 1990) as a problem of finding a set of placement of fingers that prevents a polygon from moving arbitrarily far from its given position:

> Let P be a polygon in the plane, and let C be a set of k points which lies in the complement of the interior of P. The points capture P if P cannot be moved arbitrarily far from its original position without at least one point of C penetrating the interior of P. Design an algorithm for finding a set of capturing points for P.

The caging method has been studied by many researchers. The concept and conditions for the caging problem have been improved in a series of works.

The concept of caging is mainly applied to grasping area. Rimon and Blake (1999) studied the relationship between caging configurations and grasp configurations. Rodriguez *et al.* (2012) analyzed the relationship between cages and grasps of a rigid body, and proposed a method to use cages as waypoints to form a stable grasp.

In terms of compliance, caging provides a way to combine the information of object and the environment, which leads the state of the gripper to a stable grasp. The method has been applied to two-fingered grippers and three-fingered robotic hands (Vahedi and van der Stappen, 2008).

2.2 Attractive region in environment

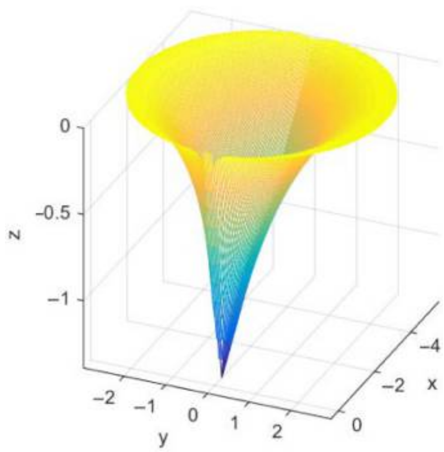
The "Attractive Region in Environment" (ARIE) has been used to eliminate the uncertainty of the system and to establish strategies for high-precision robotic manipulations, such as assembly (Su *et al.*, 2012b), grasping (Su *et al.*, 2009) and localization (Liu *et al.*, 2011).

The ARIE is a kind of constrained region formed by environment, which exists in the configuration space of the robotic system. In the previous work, the definition and the generalized conditions of ARIE have been given and discussed (Qiao *et al.*, 2014). As shown in Figure 1, if the initial state of the system is within the ARIE, it will finally converge to the stable point of this region, with the effect of a state independent input.

In terms of compliance, the ARIE establishes the relationship between the physical space and the configuration space, and then the environment can be used to help achieve high-precision tasks.

Based on the concept of ARIE, for the assembly task, the basic relationship among the inputs to the peg-hole system, the movements of the peg and the contact forces between the

Figure 1 Attractive region in environment formed in the peg-hole insertion



peg and the hole were identified. It was found that with the constraint formed by the environment, the available range of the peg's state is within a constrained region in the configuration space of the peg-hole system. If there is a state-independent input with which the state of the peg can be "pushed" into the lowest point of the region, then there exists an ARIE in the configuration space of the peg-hole system.

Then, a theoretical model for the peg-hole aligning search was proposed to reduce the angular and translational errors during the insertion processing. According to the relationship between the shape of the peg and hole in the physical space and that of the constrained region in the configuration space, a series of strategy to achieve the peg-hole insertion can be designed. The range of the peg movement was also analyzed, which was useful in the sub-goals programming for the insertion operation.

With the above analysis and strategy design, high accuracy round-peg to round-hole insertion and convex polyhedron object insertion were successfully realized. Moreover, the strategy to the manufacturing processes was applied, such as the piston-rod-peg insertion of a car engine, and the eccentric peg-crankshaft insertion of a car compressor.

As shown in Figures 2 and 3, a two-fingered gripper is used to grasp a peg and insert it to the hole of the piston. Using non-compliance based method, the process is simply push the peg into the hole vertically. If there are small errors between the peg and hole, then the assembly cannot be achieved, and the parts and the robot arm may damage because of the jamming and collision. In contrast, using the concept of ARIE, it is found that when the rotation angles are fixed (but not all zeroes), the peg can be pushed into a three-point contact state, where the angular and translational errors are eliminated. And then the peg will be rotated back to finish the insertion process.

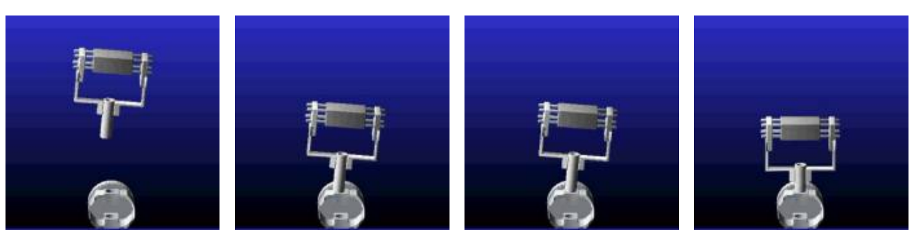
3. Neuro hand & bio-inspired hand motion model for robot

In last chapter, two methods to achieve compliance are reviewed. In nature, human can deal with various complicated tasked with compliance by their dexterous hands, via coordination with eyes and limbs. But the complex anatomical structure, dense tactile sensors and complicated motion control of the hands are the prerequisites for the achievement of various tasks. For example, fingers on the hands are one of the densest areas of nerve terminals on the body, are the

Figure 2 Peg-hole insertion using the non-compliance based method. If there are small positional errors between the peg and hole, the insertion will be jammed and the assembly cannot be achieved

(a) (b) (c) (d)

Figure 3 Peg-hole insertion using the compliance-based method. The small positional errors between the peg and hole can be eliminated during the contact process, the insertion will not be jammed and the assembly can be achieved



(a) (b) (c) (d)

richest source of tactile feedback, and have the greatest positioning capability of the body. Mimic the structure, function and control of human hands will definitely improve the compliance ability of robot hands.

3.1 Human hand anatomical structure

Hand has an intricately complex structure. There are 27 bones in the human hand. Together with forearm, there are more than 30 individual muscles working together to achieve flexibility, precise control and gripping strength for various tasks. Human hands consist two groups of muscles: the extrinsic and intrinsic groups. Extrinsic muscles, which contain long flexors and extensors, locate on the forearm to control crude movement; while intrinsic muscles locate within the hand and are in charge of fine motor functions. The most flexible parts of the hand are fingers, which are mostly controlled by strong muscles in the forearm. Thumb is extremely important to human's fine manipulation, as it opposes the other fingers. Other four fingers behave quite the same with similar musculature (Tubiana *et al.*, 1998).

3.2 Movement of human hands: tactile signals and motion control

3.2.1 Tactile signals are collected from the fingertips to ensure compliance.

When humans carry out any manipulation, the brain collects tactile afferent information during the whole process, which consists of magnitude, direction, shape of the surface, spatial distribution of contact forces and the friction between fingers and surfaces.

Many fast conducting afferent neurons can send signals to the brain from mechanoreceptors inside the hands. There are four functionally distinct types of tactile afferents: FA-I, SA-I, FA-II and SA-II afferents. FA-I (fast-adapting type I) afferents are sensitive to high-frequency dynamic skin deformations; SA-I (slow-adapting type I) afferents are excited by low-frequency skin deformations; FA-II afferents are optimized for detection of transient mechanical events; SA-II afferents are sensitive during object manipulation to lateral stretching of the skin (Johansson and Flanagan, 2008; Johansson and Flanagan, 2009; Vallbo and Johansson, 1984). Based on the feedback tactile signals from the hand, human can change posture, position, speed and forces of their hands for various tasks.

3.2.2 Neural signals to control the hand is dynamically tuned to ensure compliance in different situations

Around a quarter of the motor cortex of human brain is devoted to the muscles of the hands (illustration of the drawing of human sensory and motor cortex dedicated to individual parts of the body can be found in a study by Kandel *et al.* (2013). When the brain decided to make a movement, neuronal signals (i.e. spikes) will generate from the brain and send it in a hierarchical way to the corresponding muscles. The amount of force to be exerted by a muscle is determined by the number of spikes in motor neurons. With more spikes fired by motor neurons, the amount of force will increase for the motor unit. Thus, the muscles could switch state from slightly muscle contraction to tetanic contraction, which could exert different forces during the movement (Faulkner, 2003).

The motor system can also adapt to the changing circumstances with the order sending from the brain. Motor system determines the necessary forces and coordination at each joint to produce smooth motion of the hand.

3.3 The framework to simulate human hand motion

There are at least three ways to simulate human hand movement to improve the compliance of current robot hand:

1. sensors, which collect information as tactile afferents within human hands, should be planted on the robot hand to send back real-time signal during the manipulation;
2. as human can adjust the exerted forces during the manipulation, the posture and force of the robot hand should also possess the ability to adjust the forces elastically during the manipulation; and
3. the control of the hand posture, position and exerted forces should be adjusted in a "coarse-dedicate" manner.

4. The combination of compliance and robotic hands

Sections 2 and 3 present attempts from aspects of control method/strategy and structure design to gain compliance for the robotic hand system. In these years, many different robotic hands have been developed, such as Shadow Dexterous Hand, Barrett Hand, ROBOTIQ Grippers, Righthand ReFlex Hand, etc. Some of these hands have been applied to industrial applications, such as ROBOTIC two-finger gripper. Such hands share a simple structure, which keeps a low cost for the robotic system. In usual case, these robotic hands should be customized according to the specified situation, including size, shape and force.

On the other hand, the multi-fingered robotic hands, are less seen to be used in industry due to the high cost for purchase and maintenance, and the difficulty in control. Based on the current research progress, the combination of compliance and robotic hands are needed to create the new robotic hands which are cheap and easy to use.

In this section, some compliance-based devices and some combination of the above works will be discussed.

4.1 The compliance-based devices

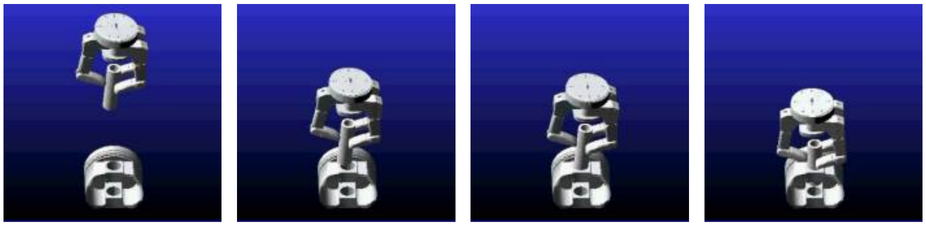
In robotics, an RCC is a mechanical device that facilitates automated assembly by preventing peg-like objects from jamming when they are inserted into a hole with tight clearance(Ardayfio, 1987).

RCC devices help realize compliant motion for error correction during assembly. Simunovic (1975) and Whitney and Rourke (1986) analyzed the utilization and design principles of the flexible wrists. In these years, different kinds of RCC devices have been developed and equipped in robotic assembly tasks. Jain *et al.* (2014) and Jain *et al.* (2013) demonstrated ionic polymer metal composite (IPMC) fingers based micro gripper, in which compliance is added to the system to help achieve micro-peg-in-hole assembly.

The RCC devices are low cost and reliable for the peg-in-hole assembly, and have successful industrial applications. But, the RCC method has some problems as follows:

- it is no longer useful when the contact status of the peg and hole is complex; and
- the materials of the assembly parts are limited.

Figure 4 The piston-peg insertion using a three-fingered robotic hand, combined with the compliance-based method. When the peg approaches the hole in the piston, the push action is compliant, which avoids collision and jamming, and the piston-peg insertion can be finished easily



(a) (b) (c) (d)

4.2 The combination of compliance-based method and robotic hands

The concept of compliance may help in building a low-cost and dexterous robotic hand. First, the mechanical structure of the hand can be designed in a compliant manner according to the human hand anatomical structure. The sensors and material for the robotic hand should be carefully selected in consideration of the cost. What is important is that a muscle-like driving structure should be studied, which is the hardware basis of the bio-inspired model of motor nervous system.

Second, the control method and grasp strategy can be compliance-based. Combined with the bio-inspired model of motor nervous system, a fast robotic hand system with learning ability can be established. And then, the compliance-based method such as ARIE and caging can be introduced to uncover the relationship among the object, the hand and the environment, thus forming a strategy to realize a fast and stable grasp.

Figure 4 illustrates the idea of combining compliance-based method and robotic hands. Here, a three-fingered robotic hand is used. Combined with the bio-inspired model of motor nervous system and compliance-based method, the robotic hand can easily achieve the piston-peg insertion mentioned above.

5. Future work

In the future works, a bio-inspired robotic hand with muscle-like driving structure will be designed and tested, and the bio-inspired model of motor nervous system and the compliance-based method will be applied to the hand, which may result in a low-cost and fast robotic manipulation system with learning ability.

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Corresponding author

Hong Qiao can be contacted at: hong.qiao@ia.ac.cn