Human-like Compliance for Dexterous Robot Hands

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Abstract: This paper describes the Active Electromechanical Compliance (AEC) system that was developed for the Jau-JPL anthropomorphic robot. The AEC system imitates the functionality of the human muscle’s secondary function, which is to control the joint’s stiffness; AEC is implemented through servo controlling the joint drive train’s stiffness. The control strategy, controlling compliant joints in teleoperation, is described. It enables automatic hybrid position and force control through utilizing sensory feedback from joint and compliance sensors. This compliant control strategy is adaptable for autonomous robot control as well. Active compliance enables dual arm manipulations, human-like soft grasping by the robot hand and opens the way to many new robotics applications.

Keywords: Active Compliance, Compliant Control, Dexterity, Fingered Hands, Teleoperation.

Introduction

Human muscles have two functions: they position the joint and control its stiffness. Robot joint drives are stiff; they do not have compliance capabilities. Many tasks such as assembly operations or dual arm manipulations are difficult to perform without compliance. Instead, the robot relies on sensor feedback and highly accurate positioning to perform such tasks.

A multi-fingered robot hand is faced with an even more difficult task: Several finger linkages of each finger have to align to a randomly shaped object to grasp it tightly. This can only be done efficiently if the robot hand has compliance especially since incorporating sensors in the confined space of fingers is very problematic.

Providing the robot with controllable compliance is thus an important step in the development of more sophisticated robots. It can be done in different ways: Many robot end effectors already have passive compliance, provided through soft or flexible linkages, springs, shock absorbers, dampers, special purpose fixtures, soft materials, such as rubber, and so on. Actively controlled compliance can be implemented through backdrivable gear trains with low gear ratio, direct drive motors, computer controlled soft actuators, etc. In general, active compliance systems are used to control the robot’s joint stiffness so that the robot can be stiffened to perform certain tasks. Stiffening the joint allows the robot to perform tasks that are difficult to perform without compliance. Instead, the robot can be controlled in the force control mode for such operations.

Description of the Active Electromechanical Compliance (AEC) System

The Jau-JPL dexterous robot imitates the proven human concept for providing active compliance: The robot joint drives have stiffness adjustability built into their joint drive train. With it, the human muscle’s dual function of joint positioner and stiffness controller can be imitated.

Fig. 1 shows the actuation system of a compliance controllable joint. The joint is being moved by joint motor Mj, which actuates spindle nut Sn, which moves the entire compliance mechanism in a linear direction. The figure shows the compliance mechanism in its compliant mode. On the compliance mechanism are two compliance springs Sc which center pin Pn inside housing is. Attached to pin Pn is joint actuation cable Jc, which drives joint J1 by means of a pulley. The finger drives also use sections of flex cables (not shown) before the cable reaches joint Jc, to enable passive wrist motion following. The joint angle is sensed near joint J1 so that the true joint position is always known. In free, unobstructed motions, joint J1 is not blocked from the outside. q‘bus, its rotational speed is directly proportional to the relational speed of joint motor Mj, disregarding the stiffness setting of the compliance mechanism.

Abstract: This paper describes the Active Electromechanical Compliance (AEC) system that was developed for the Jau-JPL anthropomorphic robot. The AEC system imitates the functionality of the human muscle’s secondary function, which is to control the joint’s stiffness; AEC is implemented through servo controlling the joint drive train’s stiffness. The control strategy, controlling compliant joints in teleoperation, is described. It enables automatic hybrid position and force control through utilizing sensory feedback from joint and compliance sensors. This compliant control strategy is adaptable for autonomous robot control as well. Active compliance enables dual arm manipulations, human-like soft grasping by the robot hand and opens the way to many new robotics applications.

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The spindle of joint motor $M_j$ is non-backdrivable. However, joint $J_1$ can be moved externally because compliance springs $S_c$ enable such motions: If joint $J_1$ is externally moved, pin $P_n$ is pulled out of housing $H_s$ and compresses one of the springs. If the load at joint $J_1$ is removed, compliance spring $S_c$ will return pin $P_n$ to the centered position inside housing $H_s$, thus returning the joint to its commanded position. This flexing capability of the joint is its compliance. The pin’s motion relative to housing $H_s$ is sensed. It is the compliance displacement sensing which provides the input signal for compliant joint control.

To stiffen the joint, compliance motor $M_c$ is activated. The compliance actuator pulls the center wire of flex cable $F_c$ which moves plates $P_l$ closer together, thus squeezing compliance springs $S_c$ toward pin $P_n$. In the extreme position, the compliance springs are fully compressed, thus not yielding to pin $P_n$ any more. This is the stiff mode where no yielding can occur in the joint transmission. The distance between plates $P_l$ and housing $H_s$ is sensed; it is the stiffness setting. The stiffness setting does not influence the joint drive actuation: The joint can be moved equally well if the stiffness setting is in its non-compliant mode.

If a robot linkage comes into contact with the environment, for instance when the fingers grasp an object, the object will prevent the finger linkages from moving any further. An object is indicated in Fig. 1 as an obstruction $O_b$. Even though joint $J_1$ is no longer able to move any further, joint motor $M_j$ is still moving the compliance mechanism during the first moments after initial contact is established. This drives pin $P_n$ out of housing $H_s$ unless the joint is in its non-compliant mode. In that case, tbc joint overload release mechanism would provide temporary yielding. The controller stops the joint drive motor when a pre-specified small compliance displacement has been reached. It prevents the compliance spring from being compressed by the pin by more than the small displacement amount should the finger linkage become free from the obstruction. Reaching the compliance displacement limit causes the controller to switch control to the force control mode, which will regulate compliance motor $M_c$.

In the force control mode, compliance motor $M_c$ controls joint $J_1$'s torque. By reducing the distance between plates $P_l$ and housing $H_s$, the compliance springs are squeezed at increasing strengths. The actual length of spring $S_c$ is computed by subtracting the compliance displacement from the stiffness setting. The force acting on pin $P_n$ can be computed by knowing the spring’s current length and its spring constant. The force acting on the pin is equal to the force that pulls joint cable $J_c$. Thus, the joint’s torque can be computed and the robot can be controlled in the force control mode. An initial compliance displacement is maintained so that tbc spring is able to press upon pin $P_n$. Due to the non-backdrivability of the mechanism, the one reached position and clamping strength can be maintained indefinitely, even if the robot loses power.

Fig. 2 is a partial view of the anthropomorphic forearm, including the finger drive actuation systems. The joint motors are the cylindrically shaped objects at the far right in this picture. The compliance mechanisms are in the center part of the forearm. Clearly visible are sets of three bright objects which are the two plates $P_l$ and housing $H_s$ between the plates. The motor drive below the main forearm section is the compliance actuation system. The wrist actuation system, located in the forearm near the elbow, is outside the right boundary of this picture.

Each finger has four joints of which three are compliant (the outermost finger joint of each finger does not have a compliance mechanism). One compliance motor adjusts the compliance settings for all three compliant joints of the same finger, thus providing an equal stiffness setting for all three compliant joints of the same finger. Wrist compliance follows the same principle: One compliance motor pro-

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**Fig. 1: Schematic Diagram of Compliant Joint**

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vides the compliance setting for all three wrist joints. In similar fashion, one compliance motor would provide the stiffness setting for the robot’s upper arm joints. However, our anthropomorphic forearm is currently attached to a PUMA upper arm, which does not have any compliance. Fig. 3 shows the anthropomorphic sections of the master-slave telerobot system. The system has been previously described in several publications [7,8] and will not be described here.

To control a compliant joint in teleoperation, a glove controller is used. The glove is a stiff mechanical harness with non-compliant joints. The glove’s joints can only be moved if the glove is being backdriven by sensory signals from the slave hand. The glove’s configuration reflects the true slave hand configuration so that the operator always has a true sense of operating on location and is made aware of any motions by the slave hand. The stiff glove enables the operator to push against the harness to provide input signals.

Sensing

A compliant joint has three sensors: The joint’s position is sensed near joint $J$, pin $P_n$’s displacement, relative to housing $H_n$ is sensed, which is the compliance displacement sensing. The distance between plate $P$ and housing $H$ is also sensed; it is the stiffness setting.

Each master controller joint has two sensors. The torque at each joint is sensed with strain gages; the operator provides input torques by squeezing or pushing against the exoskeleton harness, causing joint torques at each finger joint. Thus, the master controller’s input sensing are exerted human forces and not position sensing, as commonly used in master-slave systems. The glove’s joint position angles are sensed to properly backdrive the joints.

Compliant Joint Control in Teleoperation

Due to control complexities of controlling the many joints of a nulli-fingered hand, our dexterous robot is currently being controlled through master-slave teleoperations. The sensing and control diagram for a compliant joint is shown in Fig. 4.

The upper part of the control diagram is the position control mode of a compliant joint $J$. It is used when the joint is in free, unobstructed motion: The strain gages at the master glove sense human input forces. The amplified strain gage signal drives the corresponding slave joint proportional to the strain gage signal strength. Thus, if the operator pushes harder against the exoskeleton harness, the slave joint will rotate faster. The changing slave position is sensed and backdrives the master joint to the equivalent position in traditional position control: the controller monitors the compliance displacement and stops joint drive motor $M$ when a pres-set displacement limit is reached. The controller will then switch to the force control mode. With the links no longer able to move, its clamping strength will be controlled instead.

The control flow now follows the dashed lines in Fig. 4: An increased squeezing force by the operator causes an increased strain gage signal at the master controller. The force controller uses this signal to servo the compliance motor to decrease the compliance spring’s length, thus causing an increased torque at the joint. If a spongy object is grasped, the joint’s grasping force and thus the compliance deflection might fail below the force control threshold. If that occurs, the controller will switch back to the position control mode, which will move the joint to compress the spongy object further. If a joint is being moved externally, the operator senses this motion because the equivalent master joint is backdriven.
Compliant Joint Control in Supervisory Mode

Fig. 5 shows the control diagram for autonomous operations. Instead of an operator providing inputs through a master controller, command inputs are provided from a higher-level computer controller, operating in position control mode. In unconstrained motions, position control is active and functions like any other robot controller. However, due to the complexity of configuring the mechanical hand with its 16 degrees of freedom, pre-specified hand motions will be recalled from previously executed hand motions that are stored as library functions.

Compliance displacement sensing will again sense external contacts with the environment and will initiate switching to the force control mode if the compliance displacement limit is reached. The clamping forces applied by the hand will be governed by real-time control and pre-specified library functions that will guide the configuration and clamping process of the whole hand.

Real-time hand configuration sensing will be compared to expected hand configuration library values of certain grasp types to monitor proper grasping. If, for example, the hand closes to a fist while an object is grasped, it would tell the controller that the object was missed.

Advantages of the Active Electromechanical Compliant System

Operating the robot in the compliant mode provides substantial benefits: The robot’s compliance is effective even at power failures, can act when the sensory system is not being used, and helps to protect the robot arm during collisions. Dual arm manipulations, rotational or curvilinear contour following capabilities, and assembly operations are enabled because the robot can flex at selected joints, thus providing the necessary give-and-take needed for those operations. Our experimentation proved that the compliant mode enables a tight grasp with the multi-fingered hand that otherwise would not be possible, especially since many finger linkages are not visible to the operator at any given time. A soft touch capability while contacting objects with the robot hand will enable many new applications. Time delayed teleoperations also benefit from compliance because, due to time delays, it is impossible to guide the robot accurately. A mixture of teleoperations and sensory guided temporary supervisory control will improve time delayed operations substantially.

References