A novel stiffness control method for series elastic actuator

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ABSTRACT

Compliance plays an important role in human-robot cooperation. However, fixed compliance, or fixed stiffness, is difficult to meet the growing needs of human machine collaboration. As a result, the robot actuator is demanded to be able to adjust its stiffness. This paper presents a stiffness control scheme for a single DOF series elastic actuator (SEA) with a linear spring mounted in series in the mechanism. In this proposed method, the output angle of the spring is measured and used to calculate the input angle of the spring, thus the equivalent stiffness of the robot actuator revealed to the human operator can be rendered in accordance to the desired stiffness. Since the techniques used in this method only involve the position information of the system, there is no need to install an expensive force/torque sensor on the actuator. Further, the force/torque produced by the actuator can be estimated by simply multiplying the deformation angle of the spring and its constant stiffness coefficient. The analysis of the stiffness controller is provided. Then a simulation that emulates a human operates the SEA while the stiffness controller is running is carried out and the results also validate the proposed method.

Keywords: Series Elastic Actuator, SEA, stiffness control, virtual spring, human-robot collaboration

1. INTRODUCTION

Conventional robotic devices are designed to finish positioning instructions as fast and accurately as possible, so their joints usually have very high impedance [1–3]. Since the trajectory tracking performance is the only goal, the controller of the stiff actuator ignores the situation that the robot can have contact with human or impact with the environment. Employing PID control scheme, an ongoing deviation between desired and actual position will result in an increasing driving force until the driver output is saturated. However, this kind of robot working mode will largely restrict the function of the new generation of robot. Because human-robot cooperation is the basic feature of the new generation of robot, the robot is required for certain flexibility to adapt to the changing tasks and environment.

Researchers have proposed a variety of methods to endow robots with compliance [4–8]. According to the different ways of compliance implementation, these methods can be roughly divided into two categories: 1) software achieved compliance and 2) hardware achieved compliance. Literally, the former means the compliance of the actuator is given by some control method (e.g. impedance control) which considers not only the tracking position but also the contact force with the human or the environment while keeping the actuator itself stiff, the later means the compliance of the actuator is given by the elastic properties of the actuator itself, generally a spring mounted in series with the actuator, or the famous Series Elastic Actuator (SEA) [9]. However, according to the above discussion of the novel robots having a lot of collaboration with people, a fixed flexibility is not enough for this kind of robot actuator. The actuator should be stiffer when doing a precise operation while softer when human-robot contact exists. If these two conditions exist at the same time, it is necessary to make a trade-off. In addition, the dynamic adjustment of stiffness can reduce the power consumption of the actuator [6]. Variable Stiffness Actuator (VSA) is a class of actuators committed to address these problems. Based on the different robot joint compliance implementation, researchers have put forward a variety of methods to adjust this compliance, which can be classified as software adjustment and hardware adjustment, respectively.

Compliance adjusted by software can be implemented by variable impedance control, through which the impedance parameters (inertia, damping and stiffness) can be tuned online. The KUKA-DLR LWR [10] can be considered as the representative work in this field. However, as [11], [12] summarized, by employing active impedance control, no shock can be absorbed due to the limited bandwidth of the controller.
On the contrary, the inherent flexibility of the actuator will naturally filter the shock loads from link side to motor side as well as sudden change output from motor side to link side [9]. Researchers have proposed a variety of methods to adjust the compliance of the actuator equipped with elastic component. Amir Jafari et al. have designed a VSA based on lever mechanism, through controlling the position of the pivot the stiffness of the joint can be adjusted accordingly [13], [14]. The stiffness of a leaf spring or beam can be easily changed by adjusting its effective length, and this concept is utilized in designing AVSEA [15] and Arched Flexure VSA [1]. Nonlinear spring or linear spring with nonlinear connector can also be used to develop VSA such as MACCEPA [2], VS-joint [16] and FSJ [17]. The stiffness is regulated by adjusting the pretension of the spring. Although these stiffness adjusting methods through mechanical structure have some advantages such as no need to run stiffness controller codes after the stiffness adjustment is completed, the additional adjustment mechanism occupies a large space and increases the robots complexity which may limits their application.

This contribute presents a stiffness control scheme for an SEA utilizing spiral spring, thus it can be classified as hardware achieved compliance with software adjustment. Its main goal is to eliminate the additional mechanism and motor for adjusting the stiffness of the joint while retaining its inherent flexibility. Through simulation it is obvious that the low frequency stiffness of the actuator can be rendered by this proposed controller, but as emphasized by [9], at high frequency the actuator always acts its natural impedance due to the limited bandwidth of the controller.

The rest of this paper is organized as follows. In Section 2 we introduce the mechanical design of a SEA without stiffness regulating mechanism and then we do the modeling. The proposed stiffness control scheme is presented in Section 3 and Section 4 includes the simulation results. Section 5 summarizes the work of this paper.

2. SERIES ELASTIC ACTUATOR MODELING

Since [9] introduced SEA, various forms of SEA were designed and studied [1], [2], [6], [18–23]. As [2], [18], [19], [21] indicate, torsional planar spiral spring shows a good linearity and space compactness for SEA design. In this paper, a spiral spring with Archimedes’ curve is designed and used for the SEA implementation and later with which the stiffness control method is proposed.

2.1 Mechanical design of the SEA

The structure of a SEA can be divided into four parts: the motor, the gear reducer, the spring and the link. Figure 1 shows the schematic diagram of mechanism of the SEA. The spring is installed in between the gear reducer and the link, so it acts as a mechanical filter that can absorb the shock load from link side to the motor side, and also the mutation movement from the motor side to the link side.

According to previous experience, we selected Archimedes’ curve as the basic shape of the spring. The curve can be expressed as the following equation in polar coordinates system

\[ r = r_0 + \alpha \theta \]  

where \( r > 0 \) is the distance from the point on the curve to the origin, \( r_0 > 0 \) denotes the initial position of the curve, \( \alpha > 0 \) is the Archimedes helix coefficient and \( \theta > 0 \) denotes the helix angle. According to the principle of material mechanics, the deformation angle and restoring force of the spring meet the following equation

\[ \Delta \theta = \frac{Tl}{EI} \]  

where \( \Delta \theta \) means the deformation angle of the spring, \( T \) is the restoring force generated by the deformation, \( l \) denotes the arc length of the spring, \( E \) means the young’s modulus of the spring material, and \( I \) is the moment of inertial of cross section of the spring and can be calculated as

\[ I = \frac{bh^3}{12} \]  

where \( b \) and \( h \) is the width and thickness of the spring respectively as illustrated in Figure 2.
Figure 1. The schematic diagram of mechanism of the SEA consists of motor, gear reducer, spring and link.

Since \( l \) can be calculated from (1) as
\[
\theta = \int_0^{\theta_e} \sqrt{r^2 + r'^2} \, d\theta
\]
where \( \theta_e \) is the end helix angle of the curve. According to the definition of the stiffness of spring, the stiffness coefficient can be derived from (2) and (3) as
\[
K = \frac{Ebh^3}{12l}
\]
where \( K \) is the constant stiffness coefficient of the spring. Table 1 provides a set of reasonable values for the parameters those determine the stiffness, and Table 2 gives the corresponding values for the spring length and stiffness.

In order to simplify the control task, a worm gear mechanism is utilized and thus the motor can be considered as a position generator, and no load will be transmitted from link side to motor side due to the phenomenon of self-locking. Two potentiometers are installed on the actuator to measure the absolute angular position of the link and the deformation angle of the spring. The complete 3D CAD model of the actuator is shown in figure 3.

2.2 Modeling the SEA

The spring restoring torque is proportional to the deformation angle, thus we have
\[
\tau = K \left( \theta_w - \theta_l \right)
\]
Table 1. Spring parameters those determine its stiffness.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
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<td>$r_0$</td>
<td>5</td>
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</tr>
<tr>
<td>$\alpha$</td>
<td>0.8</td>
<td>mm</td>
</tr>
<tr>
<td>$\theta_e$</td>
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<td>rad</td>
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<tr>
<td>$E$</td>
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<td>GPa</td>
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<tr>
<td>$b$</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>$h$</td>
<td>2.5</td>
<td>mm</td>
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</table>

Table 2. The calculated spring length and stiffness coefficient.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
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<tr>
<td>$l$</td>
<td>126.5</td>
<td>mm</td>
</tr>
<tr>
<td>$K$</td>
<td>21.21</td>
<td>Nm/rad</td>
</tr>
</tbody>
</table>

Figure 3. 3D CAD model of the SEA.

where $\tau$ is the restoring torque of the spring, $K$ is the stiffness coefficient of the spring, $\theta_w$ is the angular position of the worm gear, and $\theta_l$ is the angular position of the link. In addition, we have

$$\theta_w = \frac{1}{N} \theta_m$$  \hspace{1cm} (7)

where $\theta_m$ is the motor output position and $N$ is the total gear ratio from the motor to the worm gear. We can simply consider the motor as a double-integrator as

$$\frac{\Theta_m(s)}{T_m(s)} = \frac{1}{J_m s^2}$$ \hspace{1cm} (8)

where $J_m$ is the equivalent moment of inertia of motor shaft. A PD controller can be used to track the desired motor angular trajectory

$$\tau_m = k_p (\theta_{m,d} - \theta_m) + k_d (\dot{\theta}_{m,d} - \dot{\theta}_m)$$ \hspace{1cm} (9)
3. STIFFNESS CONTROL SCHEME

3.1 Stiffness control approach

According to the definition of the stiffness of an actuator, the compliance felt by the human operator can be expressed as

\[ K_a = -\frac{\partial \tau}{\partial \theta_i} \]  

(10)

with (6) and (10) we have

\[ K_a = K - K \frac{\partial \theta_w}{\partial \theta_i} \]  

(11)

If the \( \theta_w \) and \( \theta_i \) are independent variables, then the second term of (11) will be zero, which is usually the situation. On the contrary, if they are not independent, we can adjust the appearance stiffness accordingly.

Concretely, we can define the desired stiffness as

\[ K_{a,d} = K'K \]  

(12)

where \( K' \) is an adjustable variable. Using (11) and (12) then we can get the partial differential equation about worm gear position as

\[ \frac{\partial \theta_w}{\partial \theta_i} = 1 - K' \]  

(13)

The integral of (13) is

\[ \theta_{w,d} = \theta_i - (K' - 1) \theta_i \]  

(14)

where \( \theta_i \) is an independent variable. Without loss of generality, we set \( \theta_i = 0 \) and the actuator stiffness will not be changed. From (7) and (14) then we have the stiffness controller cascaded outside the motor position controller

\[ \theta_{m,d} = N \theta_{w,d} = -N (K' - 1) \theta_i \]  

(15)

3.2 Analysis

From (8), (9) and (15) we have the close loop transfer function with input \( \theta_i \) and output \( \theta_m \) as following

\[ \frac{\Theta_m(s)}{\Theta_i(s)} = N \frac{(1-K')(k_d s + k_p)}{J_m s^2 + k_d s + k_p} \]  

(16)

So the system stability is determined by the motor parameter and the proportional and differential gains of the PD controller. Moreover, the DC gain of the system is \( N(1-K') \), this means that when \( K' = 1 \), the motor will remain motionless and the actuator shows the exact spring stiffness to the human operator; when \( K' = 0 \), the motor will track the human input and become a position servo system while regarding the human input as a reference signal. Additionally, when the human operator moves the link at a high frequency, then the value of the transfer function will be close to zero, thus no matter what the stiffness adjustment coefficient is set, the motor will not respond to that signal. This is the situation when a shock load is presented at the link side such as a collision to the environment. This can be considered as an intrinsic safety property as a result of the existence of the spring that the actuator will always show either the controlled stiffness or the nature stiffness.
4. SIMULATION

4.1 Simulation setup

The simulation is conducted to emulate a human operates the link of the actuator, we can express the motion of the human operator as a sinusoidal signal. The amplitude 1 rad and frequency 0.5 Hz were chosen.

In order to verify the proposed stiffness controller, two approaches were carried out. In the first approach, the stiffness adjustment parameter $K'$ with two steps varies from 1 to 0.6 to 0.2 is set for the simulation. Then the response of the motor and torque generated by the spring were measured to examine the stiffness felt by the user. In the second approach, for showing the stiffness response of the SEA at different frequency, a chirp signal is given to $\theta_l$ while the stiffness adjustment variable is fixed to 0.5, we can see that the stiffness revealed to the human operator will start from half of the spring stiffness and then converge to the nature stiffness along with the increasing of the frequency according to the analysis of Section 3.2.

The model and PD controller parameters, including total gear ratio, the motor moment of inertia, proportional gain and differential gain, are provided in Table 3.

Table 3. The calculated spring length and stiffness coefficient.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$N$</td>
<td>460</td>
<td></td>
</tr>
<tr>
<td>$J_m$</td>
<td>$3.33 \times 10^{-6}$</td>
<td>$kg \cdot m^2$</td>
</tr>
<tr>
<td>$k_p$</td>
<td>$2.3 \times 10^{-4}$</td>
<td>$Nm / rad$</td>
</tr>
<tr>
<td>$k_d$</td>
<td>$6.5 \times 10^{-5}$</td>
<td>$Nm \cdot s / rad$</td>
</tr>
</tbody>
</table>

4.2 Simulation result

Figure 4 shows the result of the simulation with the stiffness adjustment variable varies from 1 to 0.6 to 0.2 and the amplitude of the motor response varies from 0 to 0.4 to 0.8 rad. The torque and link angle is plotted as the characteristics curve of the virtual spring, and three slops are presented on the graph corresponding to the $K'$ curve. The hysteresis in the plot is mainly caused by the limited bandwidth of the motor position controller.

As we analyzed in Section 3.2, the equivalent stiffness of the SEA will turn back to the nature stiffness of the spring mounted in series in the mechanism when it encounters a sudden shock at the link side, which is a high frequency signal. Figure 5 shows that a chirp signal was set to the link angle, and as the frequency increased, while the stiffness adjustment variable is fixed to 0.5, the slop of the characteristics curve increased to the constant stiffness coefficient of the spring.

Figure 4. The simulation result with the virtual stiffness varies from 1 to 0.6 to 0.2. The stiffness adjustment coefficient is shown in the left, the angular position of the link and motor is depicted in the middle, the virtual spring characteristics in the right.
From the simulation result, we can see that the appearance stiffness of the SEA is controlled through the method proposed in this paper. And the performance of the controller is analyzed with a chirp signal. When the user operates the SEA in normal situation, which means that the signal frequency is relatively low, the stiffness controller will work well and the stiffness felt by the user can be changed by command.

5. CONCLUSION

This paper has presented a stiffness control scheme for human–robot collaboration utilizing a series elastic actuator with a fixed stiffness spring. By analyzing how the stiffness is felt by human operator, a stiffness controller is cascaded outside the motor position controller. Then two simulation approaches were carried out and the results showed that the equivalent stiffness of the SEA is controlled to the desired values thus the proposed method can be validated.

The future work of this research will be focused on further experiments with a series elastic actuator prototype mounted with the designed Archimedes’ spiral spring. And we also plan to apply this proposed scheme to a rehabilitation robot.

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REFERENCES


