Konstruktion und Modellierung eines mechanisch-rotatorischen Impedan-
zaktuators
Design and Modeling of a Mechanical Rotational Impedance Actuator

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Kurzfassung

Abstract
In this paper, a new prototype of an adjustable compliance actuator, named "Mechanical Rotational Impedance Actuator" (MRIA), is proposed. The device can be used to help the patients with neurological or orthopedic injuries in rehabilitation training. The new actuator is designed for continuous stiffness regulation and torque generation, and which is achieved by two motors. One motor is used for torque generation, whereas the other motor controls the compliance of joint independently. The continuous stiffness adjustment is thereby realized by four symmetric bending bars whose effective length can be changed by moving two sliders. In addition and based on the modeling of MRIA, the performance and dynamic process coupling are validated through simulations and experimental implementation in test bench, specially designed for a compliant joint.

1 Introduction
With the development and availability of technology, recent advances in rehabilitation robotics are reported [1]. One application in rehabilitation robotics is a body-attached exoskeleton, which is used to increase the walking ability of patients with partial or full gait disorders. This new technology is mainly driven by the demographic change with a massive demand in medical staff, which is caused by the increasing number of old people and patients with dyskinesia. In this paper, we present a new Mechanical Rotational Impedance Actuator (MRIA), which will be used to help those people who suffer from neurological function deficit with rehabilitation training.

In general, a high stiffness joint is favored in a traditional industrial robot, which makes it easier, for example, path control, position control, and so on. However, a safety human-machine interaction has become increasingly necessary for the application of an intelligent robot. Especially in the field of rehabilitation robotic and exoskeletons, many compliant joints have been researched extensively because of the advantages to humans. In 1995, a robotic joint was designed, which is named "series elastic actuators" (SEA) [2]. The SEA carries out the function of a passive compliance. In such case, the compliance is completely depended on the spring. This compliance element is linked with a stiff motor, and can generate a fixed compliance at the same time. Until now, the principal function of the SEA has been still referenced and researched as an important part in robotic compliant joint. Although the SEA can be used to generate a safe interaction and a comfortable wear but the drawback of SEA is the lack of adaptivity due to the fixed compliance. In recent years, the idea of SEA has been successfully popularized and improved by some researchers, where one of them is a powered ankle-foot prosthesis [3]. With this structure, a passive unidirectional spring, configured in parallel, is used as part of the compliance generation. And this device can generate a continuous power during walking, compared to some previous ankle-foot prostheses. Besides some improvements in these new designs, some changeable compliance joint, which can control the stiffness independently, have been started to be researched and validated for an optional walking speed in different working conditions. In paper [1], examples of some controllable stiffness joints were presented. The antagonist structures [4] are widely used to realize human-like muscles acting on a joint. For example, the function of the demic biceps and triceps can be replaced by two nonlinear elements respectively. To control the parallel nonlinear elements, the muscular contraction or stretch can
be implemented. In addition, based on mechanics principle, many other successful designs of compliant joints encompass some applications to change the stiffness dynamically. In a general way, some mechanical drive systems were introduced in order to achieve a manipulation of effective length of compliance elements, such as mechanical impedance adjuster [5]. Because of the simple construction of these actuators, they can come in a wide range of appearances, which can be easily assembled with the joint of an exoskeleton. However, in order to get a precise stiffness control, a low energy loss for the mechanical systems is necessary. Actually, in different practical applications, each existing compliant joint has its own unique advantage. Our aim was to design the MRIA, which should possess a light weight, easy assembly, and safety. Furthermore, this device can also be tested on a test bench of the compliant robotic joint.

2 Function of the MRIA

Based on the function of the MRIA, this structure can be categorized into a "Structure-Controlled Stiffness" actuator, which has been described in [1]. Meanwhile, some previous researches have also successfully been achieved by using the above methods, such as the VSJ [6]. To describe the principal function of the MRIA, a structure schematic (see Fig. 1) is presented in this section.

![Fig. 1 Working principle of the MRIA](image1.png)

Two independent motors can be used to drive the loads and control the joint’s stiffness respectively. The Motor 1 (denoted as M1) with gear box (i.e. a Harmonic Drive) is linked with four symmetric bending bars which are composed of spring steel. Meanwhile, M1 can also be seen as a prime power source, which leads the loads of the joint indirectly through the pin with sliding bearing. A mechanical transmission system (i.e. a lead screw and sliding component) is connected with Motor 2 (denoted as M2). When M2 controls the sliding component to take circular motions, the effective length (denoted as L) will be changed, which leads the stiffness to be variable and controllable. As it can be seen in Fig. 1, an assumed rotation angle (denoted as \( \theta_M \)) is set by a position control of M1. At the same time, the joint is driven indirectly, and can generate another angle (denoted as \( \theta_J \)). Afterwards, an angular deflection (denoted as \( \phi \)), between \( \theta_M \) and \( \theta_J \), is produced due to the elastic deformation of bending bar. Obviously, when \( \phi = 0 \), a zero torque will be generated on the bending bar since it is distortion-free. In other words, the equilibrium position of the joint is generated.

3 Design of the MRIA

The whole structure of this new MRIA (see Fig. 2) is showed in the beginning of this section.

![Fig. 2 The whole structure of the MRIA](image2.png)

The output link of M1, corresponding to the Harmonic Drive, is produced, which can be regarded as a main power driving part. The torque can be transferred between the Harmonic Driver and the loads of the joint through a sliding device. It implies that the power output and the loads are nonrigidly connected. The M2 can drive two symmetric sliding blocks through the lead screw in order to change the effective length of the bending bar, which results in a variable stiffness. The MRIA is made of two parts, and these two parts are described separately in the following.

![Fig. 3 The main power driver system with a Harmonic Driver](image3.png)

The main power driver system (see Fig. 3) is presented. M1 is a BLDC motor (brushless DC motor, flat type) from Maxon, which has a nominal torque of 444 mNm. Especially, due to the low thickness (around 30 mm), this motor can be easily comprised in a smart exoskeleton robot. The motor is fixed with the Harmonic Drive by using a way of keyless connection (assembles a clamping element into an adapter). The bending bar is rigidly linked with the output link of the M1.
The major components of the transmission system are a lead screw with two sliding blocks (see Fig. 4). Furthermore, the sliding bearing is located on a pin that is fixed with the sliding block, and it can be rotated on the surface of the bending bar for changing its effective length. One of the advantages of this system is that no continuous energy is needed when the sliding block does not move (stiffness is fixed). Further, the sliding chute and lead screw can support the sliding block in radial and axial directions, respectively.

The schematic drawing of experiment of test bench is shown below.

In order to realise an impedance control [7], two desired output feedback values, the torque and trajectory of the joint, can be acquired from a torque sensor (Dr2477) and absolute encoder (MHAD50), individually. Moreover, the dSPACE system is used for real-time control for this test bench.

### 4 Performance specifications of the MRIA

To describe the specification of MRIA in detail, the parameter of stiffness must be considered. In this section, the stiffness modeling will be described by using the methodology of mechanics analysis. Afterwards, the dynamic model of the MRIA, consisting of the two-motor unit with the compliance generation system, will be given. Finally, the analysis of the performance will be conducted on the basis of the modeling of MRIA.

#### 4.1 Modeling of the MRIA

Based on the stress analysis of the working principle of the MRIA, the stiffness can be obtained. The stress analysis (see Fig. 6) is shown as below.

Due to the systemic structure, the stress model of a quarter of MRIA is needed to be considered. Herein, the output link is assumed to be rotated in the clockwise direction. As has been mentioned before, the torque is transmitted between the bending bar and sliding bearing, which applies an acting force (denoted as $F$) on the contact surface. The bending bar will produce an elastic deformation. As it is shown in Fig. 6, one end of the bending bar is rigidly connected, which can be seen as a cantilever beam (one end is fixed and another end is movable). Let $W$, $T$, $\varphi$, and $\delta$, be the width, thickness, angular deflection, and deflection of bending bar, respectively. And let $R$ be the perpendicular distance from the fixed end of bending bar to the rotation center. Furthermore, $L_e(\theta_2)$ denoted as the dynamic effective length of the bending bar, and is also a function of the position of the sliding block that depends on the position control of Motor 2 (denoted as $\theta_2$).

From the geometrical relationship in the above picture, the deflection angle is approximated as:

$$\delta = (R + L_e(\theta_2)) \cdot \varphi$$  \hspace{1cm} (1)

The general methodology for the calculation of a cantilever beam, including the factor of shape, is given as follows [6]:

$$F = \frac{E \cdot W \cdot T^3}{4 \cdot L_e(\theta_2)^3} \cdot \delta$$  \hspace{1cm} (2)

where $E$ is the modulus of elasticity of bending bar. As it mentioned above, the resulting torque, generated by the coupled MRIA system, can be described as:

$$T_J = 2 \cdot F \cdot (R + L_e(\theta_2))$$  \hspace{1cm} (3)

where $T_J$ is the output torque of the MRIA. With Eq. (1) and (2), Eq. (3) can be rewritten as:

$$T_J = \frac{E \cdot W \cdot T^3}{2 \cdot L_e(\theta_2)^3} \cdot (R + L_e(\theta_2))^2 \cdot \varphi$$  \hspace{1cm} (4)

From the above equation, the elastic potential energy (denoted as $U_J$) and the stiffness of joint (denoted as $K_J$) can be obtained respectively:

$$U_J = \int T_J d\varphi = \frac{E \cdot W \cdot T^3}{4 \cdot L_e(\theta_2)^3} \cdot (R + L_e(\theta_2))^2 \cdot \varphi^2$$  \hspace{1cm} (5)
The stiffness of joint can be obtained from equation (6), and the required parameters of the first version of MRIA are given in the table below:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>195 kN/mm²</td>
</tr>
<tr>
<td>$W$</td>
<td>20 mm</td>
</tr>
<tr>
<td>$T$</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Due to the symmetric structure, the stiffness is the sum of two bending bars. Namely, the stiffness of joint equals to $2 \cdot K_f$. Furthermore, for the future studies, it is necessary to research how the stiffness is variable in different ranges of the effective length and the lever arm of the bending bar (see Fig. 8). It is obvious that the stiffness is variable by changing the effective length, and its value is inversely proportional to the lever arm $(R+L_c(\theta_2))$.

**4.2 Preliminary analysis of the MRIA**

Based on the mathematical model in the above section, the analysis of the first type of MRIA will be described by using the method of simulation.
the center of mass and center of rotation. In addition, the walking speed, acceleration of the joint, and efficiency of the system, etc., are also included in this calculation. We assume the maximal applied torque at the joint $T_J$ is 24 Nm. In addition, the value of $R$, which affects the arm of force, is given by 30 mm. With Eq. (4) and (6), the angular deflection $\phi$, associated with the $T_J$ and different effective length of bending bar is presented (see Fig. 9):

\[ \phi = \frac{T_J}{R} \]

As can be seen from Fig. 9, the equilibrium position $\phi = 0$ generates a zero-torque on the joint, which is also almost linear with the output torque $T_J$ of the MRIA. Furthermore, the maximal $\phi = 0.33 \text{ rad}$ occurs when the torque efforts on the maximal effective length of the bending bar. Besides, to analyze the requirements of changing the stiffness is possible based on the above results, which can be used to preliminarily assess the performance of M2. With the geometric relationship in Fig. 6 and Eq. (2), the feeding force is applied at the sliders in order to change the effective length of bending bar. It can be described as $F \cdot \sin(\phi)$. Thereby, in different values of $T_J$ and effective length, the required feeding force (denoted as $F_S$) is shown below (see Fig. 10).

\[ F_S = \frac{F \cdot \sin(\phi)}{L_e} \]

5 Experiment of MRIA conclusion and future work

The actual picture of MRIA (see Fig. 12) was produced for research.

To evaluate the performance of MRIA, we were able to actually change the stiffness. In the experiment, the bending bar system was assembled with the flange directly, and the output loads was manually rotated. The deflection angle was measured by the absolute encoder (MHAD50). Fig. 13 shows the relations between the applied torque and angular deflection in different effective length ($L_e = 30 \text{ mm}$ and 40 mm). In order to validate, the results of theoretical calculation and experiment are both described. It can be easily seen that the curves of stiffness descend when the effective length becomes longer. Moreover, the deviation occurs due to the plastic deformation and calculation error of stiffness. In order to prevent those problems happen, a new joint is actually being designed.
According to the above, we present a new mechanical rotational impedance actuator named MRIA, which is capable of continuous stiffness regulation and torque generation. Future work will focus on a second version of MRIA that is based on the current works. This second version of MRIA will be assembled with an Orthosis, which leads to construct a real and wearable exoskeleton. Also, the new mechanical parts and control methods will be improved and introduced in the future.

7 References


