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Design and control of a mechanical rotary variable impedance actuator

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ABSTRACT

To realize different tasks in human-robotic interaction, various mechanical variable stiffness actuators are being investigated. A mechanical-rotary impedance actuator (the MeRIA) is presented that is based on the controllable effective length of a mechanical bending bar, which can be implemented into an orthosis for future research on rehabilitation training. The actuator provides joint motion and variable stiffness, simultaneously. The control task can be decoupled to be a decentralized control structure for which the controller of the two motor power sources can be designed respectively. For the movement control-loop, a cascaded impedance controller with position-torque-velocity control-loops are designed to maintain a stable and safe working environment. Using an H_∞ loop-shaping methodology, a robust stabilization torque controller is achieved. The trade-off between the actuators performance and stability is taken into account to obtain a desired shape as a precondition of an H_∞ controller synthesis. The actuator is tested on a test bench using rapid control prototyping. A model reduction algorithm is implemented to simplify the controller, and a prefilter design reduces the control-loop overshoot, thereby improving the robust stability and tracking performance during application. Experiments show that the MeRIA meets all the requirements for a mechanical device attached to the body.

1. Introduction

Robotic devices are increasingly used in both industrial and human environments. This development is driven by technological advancements in semiconductors, sensors, energy storage and modern control theory. One such application is a lower-body exoskeleton [1]; this device can be used as a gait assistance device to overcome age-related diseases, or during rehabilitation to recover the motor function of patients with partial or full gait disorders.

Robotic rehabilitation therapy is feasible for several motor impairments [2] in which the muscle power and dexterity of individual's legs are supported by the robot. For example, post-stroke hemiplegic patients are often affected by spasticity and tremors. To eliminate the effects of these anomalous pathological characteristics [3], the actuator used in rehabilitation robotics should be able to absorb undesired motions by adding elastic elements to the actuation system. Instead of equipping a robot with a rigid actuator as is currently widely used, these compliant actuators help to guarantee a safe human-robot interaction whilst also being lightweight and providing accurate measurements [4]. Additionally, to automatically provide patients with physical assistance, the compliant actuators must be able to achieve tasks which can not be continuously provided during manually supported training [5]. However, it is not easy to properly evaluate the performance of rehabilitation training, due to the limited amount of test data derived from actual patients. Nevertheless, various concepts related to the design of a compliant actuator have proven to be conducive to the humanoid form.

A critical element of the human lower-extremity is the varying stiffness of the joints, which is dependent on a person's weight, height and gender. Moreover, when individuals are walking or running, joint stiffness changes accordingly [6,7]. Especially during the rehabilitation training process, the therapist can organize the recovery tasks step-by-step by setting the stiffness level from high to low in order to ensure patient safety and comfort [8]. Accordingly, mimicking of human movements provides the background required within research to design a variable stiffness actuator. In these machines, the mechanical stiffness can be changed to improving the abilities in energy savings, robustness against disturbance and adaptive control performance. As discussed in [9–11], one adjustable stiffness concept, i.e. the variable stiffness actuator based on the lever arm mechanism, is able to control the stiffness and joint motion independently; this particular type of actuator provides advantages such as high-precision torque/position control and low power consumption for compliance regulation as compared to the antagonistic setup (where two motors drive in opposite direction to generate a coupled torque on the joint).

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In the MeRIA design, the working principle is that one motor drives the joint, and another motor controls the stiffness by changing the effective length of a compliant element. Similarly, a linear drive for compliance regulation has been used in the AwAS [12] and AwAS-II [13] design. In this approach, two power sources are cross-coupled, which extends the actuator to be potentially integrated on the frame of an exoskeleton. For this purpose, a smaller and more compact actuator is needed. Therefore, a bending bar (leaf spring) presented by Morita, et al. [14] and by Choi, et al. [15] has been selected as the compliance element of the MeRIA. We assume that the bending moment can be measured directly without another torsion spring assembled with the actuator, which reduces the width. On the other hand, the bending bar is easily located. We propose that the bending bar is fixed on the gear reducer, which saves intermediate components. In line with the advantages offered by those available actuators in earlier literature, the design of the MeRIA has been taken into account by the following features: backdrivable, low output impedance, light weight and good linearity of stiffness.

Implementation of advanced control strategies can also enhance the performance of a lower-extremities support robot. A position-based impedance control methodology has been successfully developed to solve interaction problems with respect to unknown environments [16]. Here, the torque is indirectly controlled via the outer position control-loop, which actively achieves a desired trajectory control for the wearer, by means of an adjustable interaction torque [17]. For the MeRIA, a multivariable control problem occurs due to the coupled force between the joint driver and the real-time stiffness variation. To simplify the control strategy, a decentralized control can be implemented to design the controller for both decoupled stages separately [18]. It then becomes possible to design a robust torque controller based on the control knowledge of a single input single output (SISO) system. Additionally, an anti-overshoot structure of torque control-loop is proposed. In this new application, connecting the references signal by a constant prefilter can avoid a direct excitation of the plant output. To bound the controller gain between robust stability and performance, the control system of the actuator should possess a good tracking performance, adequate bandwidth and stability in the whole range of stiffness and impedance control.

In this paper, the mechanical structure of the MeRIA is introduced in Section 2. For the controller design and realization, the system modeling and identification are provided in Section 3. Sections 4 presents the trade-off conditions for the H_∞ torque controller design with an analysis of output impedance. Finally, the experiment and conclusions are presented in Section 5 and 6, respectively.

2. Mechanical design and functions of the MeRIA

This section introduces the structure and working principle of the actuator. Fig. 1 presents an overview of the MeRIA. Motor 1 (Brushless Direct Current Motor (BLDC), 90 W, EC90, Maxon Motor AG, Switzerland) with the Harmonic Drive (HFUC-20-100-2UH, Harmonic Drive AG', Germany) provides a continuous torque for the joint control, which can be seen as the prime power source. The compliance is generated by introducing two symmetric bending bars (spring steel sheets) that are rigidly connected with an output flange assembled with the output shaft of the Harmonic Drive. To realize the variable stiffness, a classical linear motion system is designed. Motor 2 (BLDC, 23 W, BX4 2232, Faulhaber GMBH, Germany) including a worm-gear reducer, is the power source for this system, and its controller is correspondingly fixed on the back. For a higher transmission efficiency, the lead screw transmits the sliding blocks with two linear bushings placed on a pair of symmetric linear shafts on both sides. Moreover, this structure can decrease the deformation on the lead screw due to the radial force caused by the output torque. The sliding blocks have two fixed cam followers, that can be driven to roll on the surface of the bending bar.

To describe the functions of the MeRIA, the motion analysis is presented in Fig. 1 (a) and (b). We assume that motor 1 rotates a position, θ_1, in clockwise direction and generates an interaction force, F, to drive the load. Simultaneously, the joint is driven by a position, θ_j, on the load side. A deflection angle, φ, results due to the coupling between the bending bar and the load; this implies that the actuator can generate a compliance due to the non-rigid connection of the physical interaction. The concept of variable stiffness can be calculated in a way similar to the stress analysis of a cantilever beam. For example, the derivation of stiffness modelling in [15] can be employed. For the MeRIA, the stiffness mechanism is presented in Table 1, in which the output stiffness function shows that the stiffness only depends on the effective length of a certain beam. When motor 2 actuates the cam followers to adjust the dynamic effective length, $L_e(\theta_2)$, (denoted as a function of the position of motor 2), the output stiffness of the actuator will obviously be changed, where another coupling between variable stiffness and load exists [12,13], [19]. Thus, a variable stiffness actuator is achieved. The mechanical specifications and safety requirements are also provided in Table 1.

3. System modelling and identification

3.1. Dynamic modeling of the MeRIA

A schematic diagram of the dynamics of the MeRIA is illustrated in Fig. 2, in which the power is transmitted both horizontally and vertically (x and y in Fig. 2) by motor 1 and motor 2, respectively. Based on the Newton's Law, the dynamics of the MeRIA are formulated as follows [12,13,19]:

$$T_{M_1} = \frac{T_j + T_{vs}}{\gamma_1} + J_1\ddot{\theta}_1 + B_1\dot{\theta}_1 \tag{1}$$

$$T_{M_2} = \frac{T_s}{\gamma_2} + J_2\ddot{\theta}_2 + B_2\dot{\theta}_2 \tag{2}$$

where, for $i = 1, 2$, T_{M_i} is the output torque of motor, J_i is the moment of inertia converted onto the motor shaft, B_i is the friction constant of the motor, θ_i is the rotation position of the motor, γ_i is the gear ratio, T_j is the torque of the spring, and T_s is the above-mentioned coupled torque to change the stiffness. Defining T_{vs} as the gravity moment generated by the mechanism for the variable stiffness transmission, the measurable interaction torque between the actuator and load, T_{out}, is given by

$$T_{out} = T_j - T_{vs} \tag{3}$$

Based on the Hooke's Law, T_j is given by

$$T_j = K_j\varphi \tag{4}$$

where K_j is the rotation stiffness of the actuator and $\varphi = \theta_1/\gamma_1 - \theta_j$ is the above-mentioned deflection angle.

For a general compliant actuator, using velocity control can improve the compensation of friction and tolerance to disturbance of the motor units [20]. Therefore, a cascade torque-velocity-current control-loop is presented in Section 4.1. To achieve that, the dynamics of motor 1 and 2 based on Kirchhoff's voltage law are given by

$$U_{in_i} = L_{M_i}\dot{I}_{M_i} + R_{M_i}I_{M_i} + K_{emfi}\dot{\theta}_i \tag{5}$$

where for $i = 1, 2$, U_{in_i} is the input voltage, and L_{M_i}, I_{M_i}, R_{M_i}, and K_{emfi} are the electric inductance, armature current, electric resistance, and back electromotive force constant of motor, respectively.

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