Control and Planning of Variable Stiffness Links for Inherently Safe Physical Human Robots Interaction#

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I. INTRODUCTION

Traditional industrial robots may not suitable for direct interaction with human workers in the same workspace. Recently, researchers have shown increasing interest in studying collaborative robot (corobot) which is designed for working with human side by side. Therefore, the safety becomes a critical issue considering the possibility of physical human robot interaction (pHRI). The safety of pHRI can be achieved in different ways. Typically, an impact between a robot and a human can be divided into three phases: pre-impact phase, impact phase, and post-impact phase. For impact phase and post-impact phase, strategies like collision detection and reaction [1] [2] [3] can significantly reduce injury severity. However, it is worth to mention that such active strategies for impact phase and post-impact phase cannot decrease the injury severity of the impact in some situations such as high speed and rigid impact [4]. To achieve inherent safety, only measures in the impact phase and post-impact phase are not enough. New mechanical designs and control approaches for the pre-impact phase is also needed to enhance safety. To address the pre-impact design problem, methods such as obstacle avoidance [5] [6], mechanical design optimization [7] [8] and variable stiffness concept [2] [9] [10] [11] are proposed. Among those approaches, variable stiffness link (VSL) is a synthesis of software (control, planning) and hardware (mechanical design) which is the focus in this study. By tuning the link stiffness, VSL can compromise safety and efficiency in a better way. A low-stiffness configuration allows a faster motion while the safety is ensured. A high-stiffness configuration attenuates the vibration thus improve the positioning performance.

However, the control design for safe VSL robots is quite a challenge due to its complicated dynamics and safety requirements. For safe robots with VSL, control objectives and their challenges can be summarized as follows. (1) Tracking of the desired joint trajectory (uncertainties and disturbances). (2) Vibration suppression (varying flexibility). (3) Inherent safety (pre-impact, impact, and post-impact phase).

To address these challenges, in this note, (1) we develop a dynamics model of VSL robots by the pseudo-rigid-body model (PRBM) [12] [13]; (2) we formulate the feedback linearization to VSL robots, inspired by previous works on conventional flexible robots such as [14] [15]. To improve the robustness in engineering practice, the linearization-based controller is further enhanced by using an extended state observer (ESO). A deflection feedback is designed based on the singular perturbation theory to achieve better vibration suppression; (3) For the inherent safety of the VSL robots, we propose a trajectory planning method based on optimal control theory. By converting the safety criterion such as human injury criterion (HIC) to velocity limit, the trajectory planning problem is transferred to a constrained time-optimal control problem with input constraints and state constraints [9]. In this note, we give a closed-form solution to the rest-to-rest motion trajectory based on optimal control theory.

II. VARIABLE STIFFNESS LINK

A. Variable Stiffness Link Design

In this work, we studied a variable stiffness link with significant stiffness variation using the jamming technique [16] [17]. Our design features a set of parallel-guided beams covered by overlapped friction layers that encapsulated in a sealed polyurethane bag. The center beam has a very low stiffness due to the thin backbone structure. Friction layers lay on the flat surfaces of multiple T-shaped supports. These T-shaped supports are designed to augment the effect of friction by increasing its leverage but not to touch each other when the beam is deformed, thus retaining the beam's flexibility. More details about this design can be found in [18].

B. Pseudo-Rigid-Body Model (PRBM)

The pseudo-rigid-body model (PRBM) [19] is a method for analysis and design of compliant mechanisms with lumped stiffness and discretized links. For the VSL robot investigated in this study, the flexibility of each side of the link is lumped to two torsional springs in PRBM [20]. For the parallel-guiding VSL robot, there are four torsional springs in total, two for each side of the link. Note that the four torsional springs in PRBM are virtual joints. The dynamics model of the VSL robot is established by the Euler-Lagrange equations on top of the PRBM. More details about PRBM can be found in [21].

C. Stiffness analysis

In our VSL design, the stiffness is related to the pressure difference. In this work, the relationship between the pressure and the stiffness is fitted by the experimental results as the following function: $K_L = 264.3 + 2982.4\ \exp(2.87E-6p) -3081.2\ \exp(-2.85E-4p)$. The unit of the pressure p and the stiffness of the link K_L are Pa and N/m, respectively.

III. CONTROL DESIGN AND TRAJECTORY PLANNING

In this section, the input-output feedback linearization (FL) based controller is introduced first. Based on this controller, improvements including the extended state observer and deflection feedback are augmented to address the concerns on robustness and vibration. Then, the safe trajectory planning is formulated and the analytical solution to the problem is given.

A. Input-Output Feedback Linearization

The feedback linearization can decouple the system variables

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either partially or globally. By linearizing the system, linear control law can be implemented on the decoupled system. In this work, we apply the input-output feedback linearization to the nonlinear system dynamic model, PRBM, to decouple the motor angle (q_1) and the virtual angle of PRBM (q_2). Here, we choose the motor angle, q_1, as the output. By choosing appropriate motor control law and controller parameters, the tracking error of the motor angle, q_1, will converge to zero asymptotically. Given the physical property of the VSL links, the zero dynamics is critically stable. In practice, flexible links usually have internal damping such as viscous friction. With the damping term, the zero dynamics can be asymptotically stable. Then the origin of the closed-loop system is asymptotically stable. Though the aforementioned controller has achieved the tracking of the trajectory, some issues may arise during practice. First, the feedback linearization procedure needs accurate model information such as mass, payload, and dimensions. However, it is common that some parameters may be inaccurate or even unknown in practice. Besides, the mechanical transmissions such as the motor and gearbox may introduce unexpected disturbances, such as friction. With the uncertainties and disturbances mentioned above, the robustness and the performance of the closed-loop system may be attenuated. Next, we will introduce the implementation of the extended state observer to address the robustness problem.

B. *Extended State Observer*

To deal with the robustness problem in the feedback linearization, we propose to use the extended state observer (ESO) to deal with the uncertainties and disturbances. We consider external disturbance such as friction and in the unmodeled dynamics. We then formulated an observer, and the generalized disturbance d can be estimated by the observer state. The internal stability of the system can be guaranteed by choosing appropriate ESO parameters. Furthermore, because the generalized disturbance is bounded, the bounded input-bounded output stability (BIBO) can be inferred. The analysis of the zero dynamics of the system remains.

Note that the estimation error of ESO does not converge to zero asymptotically. Therefore, the estimation errors may have some fluctuations around zero at steady state, especially when the gain of ESO is small. If the gain is too large, the convergence of the estimation error at the beginning may have significant overshoot. These two features may excite undesired vibrations of the link, especially when the gain of the ESO is not proper (too small or too large). To address the vibration suppression, we propose a deflection feedback design based on the singular perturbation theory.

C. *Deflection feedback*

In this section, a deflection feedback mechanism is designed to overcome the aforementioned drawback. Compared with the motion of the motor angle (q_1), the vibration is a relatively fast varying variable. In this work, we treat the PRBM joint torsional angle (q_2) as the fast variable and we will design deflection feedback based on the singular perturbation theory. First, we rewrite the system dynamics into the standard form of the singular perturbation problem. By choosing an appropriate deflection feedback term, we can ensure the origin of the boundary-layer model exponentially stable. The control law now can improve the performance on vibration suppression with deflection feedback.

D. *Optimal Trajectory Planning*

In this study, we consider Head Injury Criterion (HIC) to evaluate the safety level of the trajectory. With given permissible HIC, velocity limit VC can be calculated. Limits on actuators (motor torque, stiffness actuator) can be converted to acceleration limit AC in practice. To attenuate vibrations of the flexible link, the jerk limit JC is also considered in trajectory planning. With those kinematic constraints, a time-optimal trajectory planning problem for the rest-to-rest task can be formulated as follow:

$$\min \int_0^T 1\text{dt} \ \text{ subject to:}$$

$$\begin{cases} q_1(0)=0,\, q_1(T)=q_d \\ \dot{q}_1(0)=0,\, \dot{q}_1(T)=0 \\ \ddot{q}_1(0)=0,\, \ddot{q}_1(T)=0 \end{cases} \quad \text{and} \quad \begin{cases} |\dot{q}_1| \le VC \\ |\ddot{q}_1| \le AC \\ |\dddot{q}_1| \le JC \end{cases}$$

where the first column are the initial and terminal conditions. q_d is the desired position. VC, AC and JC are velocity limit, acceleration limit, and jerk limit, respectively. The time-optimal problem is an optimal control problem with state variable inequality constraints (SVIC). The planning problem considers kinematic constraints and works for the rest-to-rest task. First, we show the solution to this problem is a bang–bang control. Second, with a bang–bang control, solutions in different situations are given. After that, the analytical solution of the optimal trajectory can be obtained from integral with corresponding boundary conditions. The planning problem considers kinematic constraints and works for the rest-to-rest task. We then conducted experiment on VSL with respect to the motion testing and impact testing, and results showed the desired performance (trajectory tracking, robustness, vibration suppression, fast and inherent safe).

IV. CONCLUSIONS

In this work, modeling, control design and trajectory planning for a single-link VSL robot are introduced. Dynamic modeling of the parallel-guided VSL is developed by the pseudo-rigid-body model. After that, the motion controller is designed based on the model and feedback linearization. The extended state observer and the deflection feedback are implemented to address the robustness and vibration suppression. In the trajectory planning problem, the safety criterion is converted to a velocity constraint. Besides velocity, jerk and acceleration constraints are considered to make the trajectory smooth, which can attenuate the potential vibrations during the motion. The analytical solution of the trajectory planning problem is given by the optimal control theory. Motion test shows that the controller achieves trajectory tracking and vibration suppression successfully. In the impact test, VSL shows better performance on safety for both rigid impact and soft impact. HIC and impact force can be reduced by the VSL. The proposed control and planning designs for VSL achieve the tracking and inherent safety simultaneously.

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