Effects of Compliance in Parallel to Actuators on Grasping and Manipulation in Robotic Hands

Prashant Rao, Taylor D. Niehues, Pei-Hsin Kuo, Rachel Smith and Ashish D. Deshpande

I. Introduction

Humans exploit various arrangements of compliance, in form of musculo-tendon units, ligaments and joint capsules, to generate graceful and robust movements. With muscles as actuators, tendons represent *series compliance* while ligaments and joint capsules represent *parallel compliance*. Robots thus far have been unable to match the graceful and robust movement capabilities of humans. Implementation of compliance in robots has been shown to improve their performance. While the effects of compliance in series to the actuators on robotic joints have been analyzed extensively, the effects of parallel compliance have not been explored.

In this paper, we explore the role of parallel compliance in human hand dynamics and the effect of adding of parallel compliance in robotic joints. We will focus on analyzing the effect of parallel compliance with respect to actuators on light weight robotic joints such as fingers of robotic hands performing grasping and manipulation.

II. Role of Parallel Compliance in Human Hands

Human finger joints show both compliant and viscous properties. These passive properties result from a combination of muscles, tendons, ligaments, and joint capsules. Human subject studies were performed to observe and compare the contribution of compliance due to musculo-tendon units (MTU) and the capsule ligament complex (CLC) towards passive moment generation at the metacarpal joint (MCP) of the human index finger [2]. Results (Fig.1)

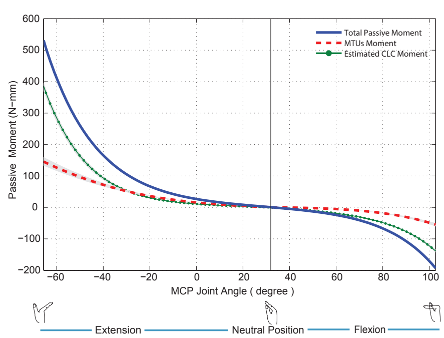

Fig. 1. Variations in the net passive moment at the MCP joint (blue solid line) of the index finger. The contribution due to CLC (green dotted line) dominates the contribution of the MTU (red dotted line) [2].

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The authors are with the Department of Mechanical Engineering, The University of Texas at Austin, Austin, Texas 78712, USA ashish@austin.utexas.edu

indicate that the *parallel* compliance due to the CLC has a dominant effect on the net passive moment generation at the MCP joint of the index finger as compared to the *series* compliance due to MTU.

Series compliance has been studied and implemented extensively in robotic joints but not much work has been done towards analyzing the effects of implementing parallel compliance in robotic joints. Towards the goal of building robotic hands that can match human movement capabilities, a thorough analysis of the effect of this dominant form of compliance in robotic joints is required.

III. Effect of Parallel Compliance in Robotic Joints[1]

To start the analysis, we modeled a generic robotic joint with compliance added in parallel to the actuator:

$$M\ddot{x} + B\dot{x} + k_{pc}x = u \tag{1}$$

where M and B are the combined mass and damping/friction of the joint and actuator unit, k_{pc} is the stiffness of the parallel compliance added to the system and u is the control input.

As grasping and manipulation require active interaction with the environment, position control strategies become unsuitable. Thus we design an impedance controller to enforce a desired stiffness and damping on the system to follow a reference trajectory:

$$u = k_p(x_d - x) - k_d\dot{x} + k_{pc}x_d \tag{2}$$

where k_p and k_d are the proportional and derivative gains and x_d is the desired position. The controller also includes a feed-forward term to compensate the parallel compliance.

Now that we have a model of our system, we want to analyze the effect of parallel compliance on light weight systems such as robotic fingers performing accurate tasks such as grasping and manipulation which require high desired stiffness.

A. Theoretical Analysis: Effect of Parallel Compliance on Controller Delays

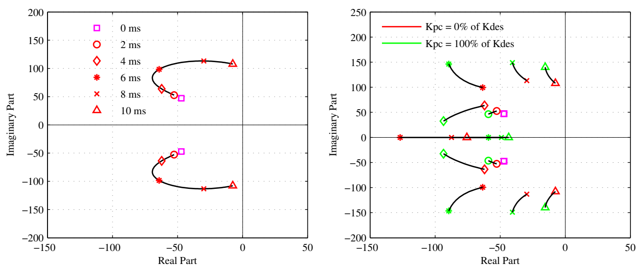
Time delays in controllers are unavoidable in real systems due to factors such as system complexity, non-collocation of sensors and actuators, sensor noise filtering etc. To analyze the effect of parallel stiffness on controller delays, we incorporate a fixed time delay t_d in the feedback loop of

[1] A part of this work has been presented in [5]

the control input. Mathematically, the resulting system can be realized in the frequency domain as:

$$\begin{aligned}\left(Ms^2 + Bs + k_{pc}\right) X(s) =& (k_p + k_{pc})X_d(s) \\ &- e^{t_d s}(k_p + k_d s)X(s)\end{aligned} \tag{3}$$

We analyzed the poles of this system with parameters that were chosen keeping in mind low inertia systems such as robotic fingers performing precision tasks such as grasping and manipulation where high stiffness gains are often required.



(a) (b)

Fig. 2. Effect of controller time delay increased from 0 ms to 10 ms in steps of 2 ms on (a) system without parallel compliance and (b) system where parallel compliance is added as 0% to 100% of the desired stiffness.

As time delays are increased in the system (Fig.2(a)), we observed that the system poles move towards instability, but the introduction of parallel compliance pushes the poles of the system towards stable regions (Fig. 2(b)).

This shows that addition of parallel compliance to robotic joints will make them robust even in the presence of large time delays in the system, an essential feature required for grasping and manipulation.

B. Experimental Analysis : Parallel Compliance in Robotic Joints

To experimentally validate our analysis of the effect of adding parallel compliance to robotic joints, we performed experiments on a light-weight 1-DOF antagonistic tendon driven joint with and without parallel compliance [5]. Parallel compliance was added in the form of standard extension springs with varying stiffness. Results show that parallel compliance improves stability and smoothness of trajectory tracking for rapidly changing trajectories in presence of time delays caused by communication lags and filtering of sensor noise.

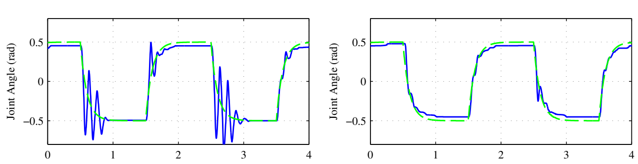


Fig. 3. Trajectory tracking performance of a 1-DOF joint with and without parallel compliance.

We then built a testbed of two 2-DOF robotic fingers to study the effect of passive parallel compliance in grasping and manipulation tasks. Results show that parallel compliance improves stability and robustness to impacts for low-inertia systems like robotic fingers.

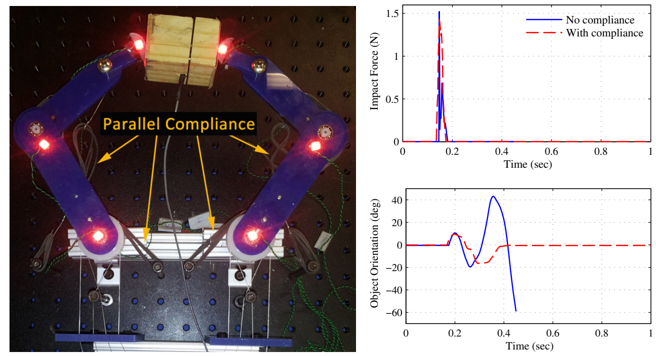


Fig. 4. Impact testing for two tendon-driven 2-DOF fingers grasping an object, showing the increased stability resulting from the addition of parallel compliance in the joints.

IV. Conclusion

Parallel compliance plays a significant role in the performance of human fingers based on human studies. Analysis and experimentation with a simple 1-DOF joint showed smoother and more robust behavior in robotic joints when parallel compliance was added even in presence of controller delays. A more complex system was analyzed and validated with a tesbed consisting of two 2DOF robotic fingers performing a manipulation task. Our results show that introduction of parallel compliance leads to improved stability, trajectory tracking performance and disturbance rejection in robotic fingers. All of which are essential requirements for precise and dexterous manipulation.

We will extend this work by analyzing the effect of human-like non-linear joint stiffness characteristics. For performing such an analysis we are designing a lightweight miniature passive variable stiffness joint for robotic fingers. We believe that a deeper understanding of inherent biomechanical features of human hands and their implementation in robotics would help us bring robotic hands closer to human-like dexterity and performance.

References

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