TWO LINK COMPLIANT ROBOT MANIPULATOR FOR HUMAN ROBOT COLLISION SAFETY

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Keywords: Motion control, Adatable compliance actuator, Smart materials, Magneto-rheological fluid, Collision safety, Human robot interaction.

Abstract: For successful human robot interaction (HRI), collision safety as well as position accuracy are equally important. Robot is required to demonstrate safe sharing of work space with humans and to exhibit adaptable compliant behavior that comply with interaction forces generated upon contact. We present an approach for acquiring reconfigurable compliance using semi-active actuation mechanism, where compliance is achieved by controlling the viscous properties of magneto-rheological (MR) fluid. In this paper, we have discussed three essential modes of motions required for safe physical HRI. Then, we have shown collision safety of our robot based on static and dynamic collision testing in different motion modes. Finally, experimental results validate the significance of our proposed approach for human robot collision safety and high position accuracy.

1 INTRODUCTION

Next robotic generation requires to have direct and physical contact with human in performing robotic tasks. The successful pHRI requires to handle the interaction forces in smart way assuring high level of human safety by preventing injuries and damages. This leads to development of ideal safe robot manipulator offering high stiffness in non contact phases and low stiffness in contact phases of the task, maintaining collision forces within the human pain tolerance limit and to display high position accuracy. These characteristics necessitate the use of compliant actuation mechanism instead of stiff actuation.

Active compliant mechanisms (T.Lefebvre et al., 2005), (M.Kim et al., 2004) posses severe threat to the joints upon rigid impacts (S.Haddadin et al., 2007) and usually suffers from delayed contact response, higher cost and complex control strategies. *Passive compliant mechanisms* (C.M.Chew et al., 2004), (B.Vanderborght, 2007) having passive elements (springs, sliding axels) achieve the compliance on the cost of higher system complexity. Variable stiffness (A.Bicchi and G.Tonietti, 2004), (T.Morita et al., 1999), (B.Vanderbrought et al., 2006) is achieved by using elastic element in the joints with the cost of reduced position accuracy and energy losses.

We have proposed an approach based on *semi active compliant actuation mechanisms* with magneto rheological (MR) fluid based actuator. Our actuation mechanism is an assembly of MR fluid brake/clutch and DC-servo motor. Compliance is controlled by the application of magnetic field to drive the viscous properties of fluid while the position control is achieved by a standard DC motor control. This results in much simpler control system compared to the compliance control schemes used in active and passive compliant devices (M.Danesh et al., 2006), (R.Carelli et al., 2004). Here we have analyzed the human robot collision safety for HRI tasks based on static and dynamic collision while keeping high position accuracy.

2 ADAPTABLE COMPLIANCE

Robots lack one major skill compared to biological systems, namely adaptable compliance or variable stiffness property. The successful execution of safe interaction task necessitates the use of compliant motions, allowing a robot to comply with the interaction forces generated by its contact. This property can be mimicked by using safe actuator mechanism with adaptable compliance instead of traditional stiff actuation mechanism.

Human skeletal antagonistic pair of muscles is the biological similitude of the ideally safe and adaptable compliant robotic actuator where humans have the di-

Rehan Ahmed M. and Kalaykov I..
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DOI: 10.5220/0003178405180521
In *Proceedings of the International Conference on Bio-inspired Systems and Signal Processing* (BIOSIGNALS-2011), pages 518-521
ISBN: 978-989-8425-35-5

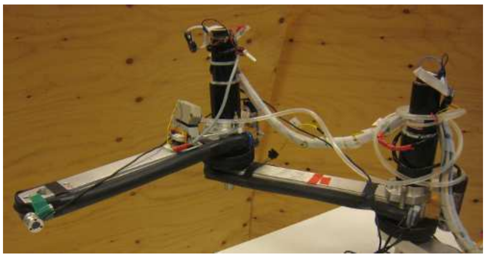


Figure 1: Two link planar robot prototype.

rect control over these muscles to generate almost any desired motions. Human arm exhibits the required three principle modes of motions (stiff, compliant and soft) by controlling the tension between their antagonistic set of muscles. Thus, a pair of continuously controlled antagonistic muscles ensures the required level of adaptable compliance and position accuracy.

2.1 Modes of motion for safe HRI

In HRI tasks, purely motion control strategy for controlling the robot interaction forces is not enough, mainly due to imprecise modeling of the robot manipulator and the highly unpredictable nature of the HRI itself. For safe HRI, robot has to execute simultaneously multiple-axes motions based on feedback signals. This usually involves a combination of several motions varying from fully stiff to fully compliant. The contact situations may vary depending upon the specific requirement of interaction task, but in all cases the robot has to execute three different modes of motion namely:

Stiff motion, refers to robot motion in unconstrained free work space. The reaching of desired position is achieved by a standard position and velocity control. It manifests zero compliance, therefore only this motion mode is not sufficient for performing HRI tasks.

Soft motion, refers to robot motion in a dynamically constrained work space. The dilemma of avoidable/unavoidable collision with a sudden, unexpected intrusion of an obstacle for example, human body or part of it, implies the necessity of switching from fully stiff to zero-stiff joint in order to cut the transmission of a torque to the adjacent robot link.

Compliant motion, represents all transitions between stiff and soft motion. In some situations the human wants to superimpose its motion over the robot's specified motion. For such conditions the robot has to accomplish compliant motion mode.

For our research two-link planar experimental robot prototype was set-up (Figure 1). The desired adaptable compliance or variable stiffness is introduced by our dedicated MR fluid actuator, one for driving each joint. Operational smoothness in the performance of the MR fluid actuator mechanism is shown in (R.Muhammad.Ahmed et al., 2008). Fully activated MR fluid actuator (max clutch current) corresponds to stiff motion mode. Alternatively, fully deactivated MR fluid actuator (zero clutch current) conforms to soft motion mode. All levels between fully activated and deactivated actuator refers to the compliant motion mode. These transitions can be tuned depending upon the type, geometry and modalities of the contact object accordingly.

2.2 Collision Safety Analysis

Previously, achieving high position robot accuracy was considered as the main objective. Now, with the emergence of new trends and applications in service robotics, there is a strong belief that both position accuracy and the collision safety are equally eminent and indispensable for tasks involving HRI. A contact phase is considered to be safe, only when the robot exerted collision forces remain under the human pain tolerance limits and never causes injury to the human. This, consequently, formulates a criterion for the collision safety analysis of the robot manipulator based on static and dynamic collision.

Static collision, appears in situations where robot manipulator is directed to collide with the human, and the collision is performed at very low speed, typically less than 0.2 m/s. In order to evaluate the safety performance several researchers have suggested a collision force of 50N as a human pain tolerance limit (Y.Yamada et al., 1996). Therefore, we have employed collision force threshold of 50N as a boundary between the unsafe and safe regions of operation. We did static collision tests and analyzed the static collision safety performance in both the stiff and compliant modes of motion.

Dynamic collision, replicates the condition where robot is forced to collide with the human at higher speeds. Since the topic of human robot collision safety in dynamic collision is relatively new in robotics, no specific standard has been established yet. However, in order to evaluate the safety performance at dynamic collision, head injury criterion (HIC) and abbreviated injury scale (AIS) are currently employed (A.Bicchi and G.Tonietti, 2004), (J.Versace, 1971). Head injury criterion (HIC) defines the index for injury severity (damages) and used by automobile industry for car crash. HIC value greater than 1000 refers to a very severe head injury. For the normal operation of machines, a HIC value of 100 is suggested. Therefore, for the safety perfor-

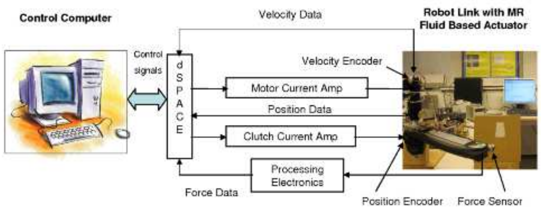


Figure 2: Experimental setup block diagram.

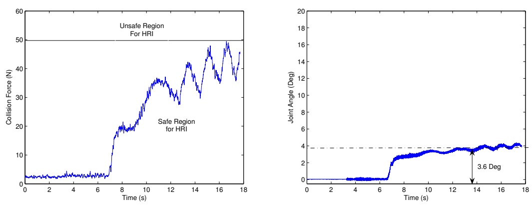
mance evaluation of our proposed actuation mechanism, robot link is forced to collide with a fixed obstacle at a certain speed in both stiff and compliant modes of motions.

3 EXPERIMENTS

Our experimental setup is shown on Fig 2. Real time interface between the robot and the control computer is realized through dSPACE hardware, the Real-time workshop of Matlab and dSPACE control desk.

3.1 Static Collision Safety Analysis

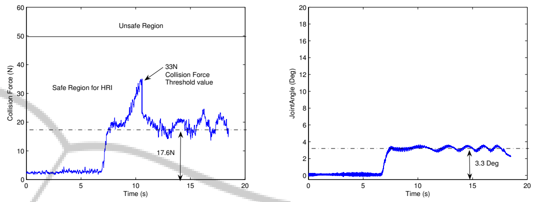
Figure 3 explains the static collision safety performance and position accuracy without the adaptable compliance control, where the MR fluid actuator is only working in stiff mode imitating traditional stiff actuation mechanism. In Figure 3a a constant bias of approximately 2N is present in a force sensor data, where as the approximate time at which the wall contact occurs is around 7 seconds. It has been noted that within 10 seconds of wall contact, the collision force rises to around 50N and robot goes into the region which is unsafe for HRI. Therefore, operating in stiff mode without adaptable compliance control is not suitable for interaction tasks involving HRI. Robot position accuracy in stiff motion mode during static collision is illustrated in Fig 3b.



(a) Collision force. (b) Joint angle.

Figure 3: Stiff mode static collision.

Figure 4 describes the static collision safety performance and position accuracy with compliance control. Collision force threshold value of 33N was set to analyze the static collision safety as shown in Fig 4a. Initially, MR fluid actuator operates in stiff mode and as soon as collision force reaches the threshold value, actuator mode switching occurs from stiff to compliant mode, thus keeping the robot to operate within the safe region of operation suitable for HRI and never allows a robot to go into unsafe region and to cause injury to human. Fig 4b demonstrate the robot position control accuracy in compliant motion mode.

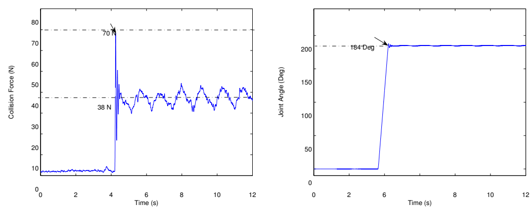


(a) Collision force. (b) Joint angle.

Figure 4: Compliant mode static collision.

3.2 Dynamic Collision Safety Analysis

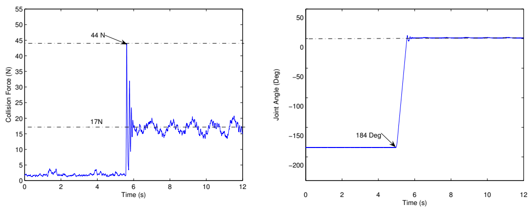
Figure 5 illustrates the dynamic collision safety performance and position accuracy without adaptable compliance control (MR fluid actuator in stiff mode). Fig 5a indicates a collision force of approximately 70N exerted on the fixed wall at the time of the contact. Then, the collision force settles down to approximately 38N. Fig 5b represents stiff mode position accuracy of the robot manipulator in dynamic collision.



(a) Collision force. (b) Joint angle.

Figure 5: Stiff mode dynamic collision.

Figure 6 demonstrates the robot dynamic collision safety performance and position accuracy with compliance control, where a robot manipulator operating in compliant mode is commanded to make hard collision with the fixed wall. With a speed of 60 percent of full scale, Fig 6a shows a collision force of approximately 44N exerted on the wall at the time of the contact, which is fairly small as compare to the collision force occurred in stiff motion mode (70N). Additionally, just after the contact, the collision force is reduced to approximately 17N, which is in accord with the collision force exerted upon the wall in compliant mode static collision. This comparison indicates the effectiveness of our proposed semi active



(a) Collision force. (b) Joint angle.

Figure 6: Compliant mode dynamic collision.

compliant actuator mechanism in terms of dynamic collision safety. Fig 6 explains the position control performance while performing dynamic collision in compliant mode.

4 CONCLUSIONS

We have proposed an efficient solution based on semi-active compliant actuation mechanism enabling compliant robot behavior needed for HRI tasks as well as providing high inherent collision safety originated by controlling the properties of smart materials. It has been justified that MR fluid actuator is capable of generating complete range of motions typically required for HRI applications with high inherent safety. We have demonstrated simultaneously, the superior capability of handling higher payload with eminent position accuracy and guaranteed collision safety focusing simultaneously on static and dynamic collision. Finally, it has been verified that semi-active compliant robot is demonstrating the required features of safe robot manipulator (provide high stiffness in non-contact phases and low stiffness in contact phases of the task) and maintaining collision forces well under the human pain tolerance limit.

Future studies will be focused on investigating the HIC for dynamic collision safety analysis.

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