Towards Safe Control of a Compliant Manipulator Powered by Pneumatic Muscles

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In the trend towards more human-centered robotics, safe human-robot interaction is becoming an important issue. A promising way to achieve a safer interaction is the use of actuators with inherent compliance. In this work, the compliant actuator of choice is the Pleated Pneumatic Artificial Muscle.

The focus of this dissertation is on controlling systems actuated by pleated pneumatic artificial muscles in such a way that they can safely interact with people. The investigated techniques are applied to a two-degree of freedom planar robotic arm. This system is lightweight (around 2.5 kg), and very compliant, two important factors in what is generally considered to constitute safe robotic hardware.

In most traditional robot control techniques, safety is not explicitly considered. Safety and good tracking, which in itself is not easy to achieve in a system actuated by pneumatic muscles, are thus difficult to combine. It is shown that the 2-DOF manipulator can be unsafe to humans around it when under PID control, in spite of its good hardware safety features. In case of a collision, the impact force can be high enough to do serious damage to the human body. In order to obtain a safer system, safety has to be built-in not only on the hardware level, but on the control level as well.

This is the case for Proxy-Based Sliding Mode Control (PSMC), a novel control method introduced in 2006 by Kikuuwe and Fujimoto. Proxy-Based Sliding Mode Control (which does not exhibit fast switching in its output, in spite of the controller's name) combines responsive and accurate tracking during normal operation with smooth, slow and safe recovery from large position errors. It can also make the system behave compliantly to external disturbances.

In the dissertation, a modified version of PSMC, which isn't as model dependent as the original PSMC, is shown to provide good tracking performance as well as a significant improvement of system safety. Safety is evaluated by means of the Head Injury Criterium (HIC) and by the maximum interaction force between the human head and the robot in case of collision.

The design of the manipulator (which is not entirely straightforward due to the varying force-length relationship of the muscle), a traditional sliding mode controller that accounts for actuator dynamics, the original PSMC, algorithms to estimate external forces acting on the manipulator and an admittance-control based interactive mode are also discussed.

Although the dissertation is focused on the control of a manipulator actuated by pneumatic muscles, it is possible to draw some conclusions that are valid for systems actuated by compliant actuators in general:

• Proxy-based sliding mode control effectively improves safety, while still achieving good control performance.

• Low weight and high compliance are not by themselves sufficient to obtain a safe system. This lack of inherent safety implies that controller software errors can have serious consequences.

• Passive compliance can be a double edged sword -- in some situations, it improves safety, while in other situations its ability to store energy can make a robot more dangerous.

• As long as there is some form of passive joint compliance, the impact force in the case of a human-robot collision is mainly dependent on the inertia of the impacting link, and independent of the value of the compliance.