The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Using a Dual Differential Rheological Actuator as a High-Performance Haptic Interface

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I. INTRODUCTION

Most modern robotic systems are fast and repeatable position controlled machines. However, because of their inability to interact safely, robustly and in a versatile manner, they mostly remain confined to controlled areas where they execute specific preprogrammed actions. Providing high performance motion simultaneously with the ability to physically interact significantly remains a challenge.

To increase productivity, accessibility and usability of robotic systems, robots must safely manage intentional and unintentional physical contacts by controlling the interaction force imposed by their actuators, even while performing fast, high force and high precision tasks. An actuator transforms, in a controllable manner, a particular form of energy into mechanical power, and vice versa. The quest for high performance motion and simultaneous capacities for safe and versatile interactions justifies the need for low impedance (inertia and friction), large torque bandwidth, accurate torque generation capabilities and high torque density, requirements that are usually difficult to combine [1]. Geared electromagnetic (EM) servomotors are the most widely used actuator technology for motion control of robotic systems. However, inertia, internal friction and backlash still limit accelerations, positioning precision and make controlled interactions challenging and unsafe. Even actuators designed for interaction tasks still struggle to deliver high performance in convenient, cheap and high-torque density packages [2][3].

This project addresses these limitations with a new concept named Dual Differential Rheological Actuator (DDRA) [1], to create an actuator with high performance torque and position control characteristics, in addition to versatile, safe, robust and easily controllable robotic interactions. DDRA's design is based on the use of two magnetorheological (MR) brakes coupled to an EM motor and to the system's output through a dual differential mechanism that also serve as a speed reducer. MR brakes are semi-active actuators that make use of MR fluids. Compared to active actuators, MR brakes are small, light and have low inertia. Their current-to-torque relationship is roughly linear [1]. The configuration is such that output torque is controlled in both directions by a combination of the two braking forces. Differential Elastic Actuator (DEA) [4], Double Actuator Unit (DAU) [5] and the Hybrid Ultrasonic motor and Clutch Actuator (HUCA) [6] are the few existing actuators taking advantage of a differential coupling. DAU uses a geared motor to control the output reference position. The reference frame of the gearbox is connected to a 2nd geared motor used to modulate the interaction behaviour around this reference position. This decouples position and interaction behaviour control, which simplifies control. Nonetheless, with a geared motor, it is possible to achieve high torque density (with high speed reduction ratios), or good force control capabilities (with very low reduction ratios), but generally not both simultaneously. DAU does not seem to circumvent this basic limitation. Also, by using two motors, each supporting the load (not sharing it), weight and bulkiness could remain a problem. HUCA uses one differentially coupled electrorheological brake to control the coupling torque between the load and an ultrasonic motor. Advantageously, the clutch isolates the load from the impedance of the motor, similar to the DDRA. However, in the HUCA latest prototype, the clutch drag friction limits low forces control capabilities (±0.005 Nm drag torque, ±0.05 Nm actuator range [6]). Also, the output torque depends on the velocity control of the motor, limiting the force control bandwidth to about 10 Hz. Finally, backlash limits stable controller gains (max 1 Nm/rad stiffness). DDRA's unique dual differential configuration addresses each of these limitations.

Many advantages come with DDRA's concept: (1) Small friction – because of the symmetry of the design, undesired brake dry friction torques are not transmitted to the output; (2) Small viscous damping – brake viscous torques are balanced when output velocity is zero; (3) No backlash – it is eliminated by opposite reaction forces; (4) Extremely small inertia – the output is decoupled from the geared motor; (5) Inherently stable force control – torque is controlled by modulating the current sent to the brakes; (6) Robustness and impact tolerance – during impacts, excess energy is dissipated in the brakes.

[‡] F. Michaud holds the Canada Research Chair (CRC) in Mobile Robotics and Autonomous Intelligent Systems. Support for this work is provided by the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chair program and the Canadian Foundation for Innovation.

978-1-4244-6676-4/10/$25.00 ©2010 IEEE

II. 1 DEGREE-OF-FREEDOM (DOF) HAPTIC INTERFACE USING DDRA

We have designed a complete, fully operational, DDRA prototype with custom-made MR brakes, having the following characteristics [1]: 90 mm (diameter) × 137 mm, 2.4 kg, 20 Nm maximum torque with a maximum deviation of 0.5 Nm (caused by a small hystheresis), 11 Nm continuous torque (which is a conservative estimate limited by the EM used), 160 rpm, nominal power output of 150 W (with a 37 V power supply), 1.2e-4 kg.m inertia, 0.01 Nm.s/rad output damping, 1200 Nm/rad maximum virtual stiffness, 8.5 N.m.s/rad maximum virtual damping, and bandwidth superior to 40 Hz.

An experimental setup commonly used with MR brakes is to develop a 1-DOF haptic interface. Some of these demonstrations are semi-active [7], [8], [9], i.e., they use only MR brakes, and observe that MR brakes are adapted to the design of haptic devices. Others are active [10], [11], i.e., they combine an EM motor with MR brakes. The addition of an active component enables actuators to generate the desired torque instead of just resist to the operator displacement.

To illustrate DDRA's capabilties as an active torque-controlled device, we implemented a 1-DOF haptic interface. We began by identifying the function defining torque T according to currents I_1 and I_2 sent to the two MR brakes. A slow sinusoidal current was sent to one MR brake and then to the other. The resulting torque was mesured by a torque sensor fixed at the output. Defining T in relation to I_1 and I_2 makes it possible to not use any torque sensor in DDRA to minimize cost and especially weight. Then, we replaced the torque sensor by a 0.2 m lever, to create a haptic interface simulating different mechanical systems around an equilibrium point. Using a 16-bit position sensor directly connected to the output and by generating any desired torque, the relationship between the output position and the torque to apply is expressed by (1), where K_V simulate the stifness of a spring, B_V the coefficient of a damper, and I_V the gain of a position error integrator.

$$Z_V(s) = \frac{K_V}{s} + B_V + \frac{I_V}{s^2} \tag{1}$$

This 1-DOF DDRA haptic interface reacts differently to external disturbances (displacement from the equilibrium point) depending on the simulated impedance. For example, if a spring is simulated ($K_V > 0$ and $B_V = I_V = 10$ in (1)), the actuator applies a restoring force proportional to position error (just like a spring). It is possible to change online and in real-time K_V, B_V and I_V using sliders on a graphical user interface, to simulate various mechanical impedances. Also, as shown on the video, we have created a visualization interface to illustrate the type of mechanical impedances simulated. The user can move a square on the computer screen by moving the lever. When the square is between the left or right areas, the actuator is in free motion mode ($K_V = B_V = I_V = 0$). When the user brings the square on one of these two areas, a virtual impedance is calculated with the equilibrium point equal to the limit. With this visualization interface, the user can chose among four mechanical impedances for the two areas: two springs of different stiffnesses, a wall and a damper.

To implement a convincing virtual wall, the initial contact (when the operator passes from the free-motion zone to the wall) must be crisp, the surface must be hard, and the final release must be clean [12]. Other 1-DOF MR haptic interfaces that simulate a wall generate less than 5 Nm at the impact location of the virtual wall [10], [7]. At the impact, our wall generate a maximum of 15 Nm. We must therefore apply a force at least three times higher to get through the virtual wall created with DDRA. Its stiffness is 30 N/mm (limited at 75 N). The minimum stiffness required to give the illusion of a rigid virtual wall is about 25 N/mm [13].

The use of an accurate position sensor at DDRA's output and the high stiffness of our virtual wall satisfy the first two criteria to implement a convincing virtual wall, and there is no ”sticky” feeling at the release from the virtual wall, satisfying the third criterion. The addition of this display interface enhances the sensation of touch: by physically taking control of the square on a computer screen and by seeing this object compress the spring or touch the wall, the user has the illusion to really squeeze a spring or hit a wall.

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