A cable-driven robotic arm powered by magnetorheological clutches for upper-limbs physical interaction in virtual reality environment*

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Abstract— **Virtual reality (VR) is a recent technology connecting man and machine that is finding a growing number of applications, notably in gaming and simulation. A challenge to the widespread adoption of virtual reality is the development of high-fidelity haptic interfaces that can provide users with simulated force fields to interact with virtual objects while being simple enough for mass production. This paper presents a feasibility study of using a cable-driven robot powered by magnetorheological clutches to provide high fidelity representation of Cartesian forces applied to the upper limbs during a virtual reality experience. A 3 DOF proof-of-concept prototype is presented, fabricated, and tested. Results show the approach to be promising as it is able to meet human-level performance metrics of a minimal force of 5 kgf, bandwidth superior to 10 Hz, and excellent backdrivability such that physical interactions in a custom-made zombie videogame are seen as natural and transparent by test subjects. The proposed approach is also robust to impacts and misuse while being well suited for high production volumes at low costs.**

I. Introduction

Virtual Reality can be used in a multitude of applications such as entertainment and gaming, manual task training like welding or surgical tool manipulation, and simulation of critical procedures in space exploration or military missions [1]. Even though VR creates amazing visual experiences, it still misses the sense of touch (haptic) [2]. With the addition of a high-fidelity haptic system for the upper body, VR has the potential to become a total immersion experience and become the next generation of computer / user interface [3]. At term, users could touch and manipulate objects like in the real world and navigate in virtual worlds as represented in fiction novels such as *Ready Player One*. However, todays robotic systems are limited by their actuation technologies, and cannot provide a high-quality force feedback to both hands that is “transparent” to a human user while being robust and cost-effective for mass production [4].

Some commercial solutions are available targeting virtual simulation. These devices, such as the *Sensable technologies’ Phantom Omni* face an inevitable performance trade-off between force density and dynamic response due to the reflected inertia of the motor that increases with the square of the reduction ratio. When used without gearboxes, DC motors have good dynamic response with their low output inertia and good quality of force [5], but their high mass make them not practical [5]. Using gearboxes with DC motor reduces system weight, but drastically increases inertia thereby considerably reducing dynamic response [5]. The result is that force-feedback powered with conventional actuators haves limited dynamic responses due to the inertia of the system output which decrease the quality of control [5] and/or low forces.

This paper presents a feasibility study of using magnetorheological clutches to activate a cable driven robot to provide a strong and fast but yet cost effective and robust haptic interface for virtual reality environments. Functional requirements are derived and a mechanical system is presented. An open-loop controller coupled to the virtual reality environment program is implemented on a Speedgoat real-time platform. The system is successfully put to the test by confirming its 5 kgf open-arm force, +10Hz bandwidth, excellent backdriving smoothness and by showing a positive user experience quality on specially developed game.

II. System Design

A. Functional requirement

In order to satisfy the user’s need, the ideal robot manipulator and controller should have the performances contained in Table 1.

Table 1 : Ideal performances

Spec.	Description	Value	Units	Flexibility
A	Dynamic response	10	Hz	Minimum
B	Force generated at end-effector at any time	50	N	Minimum
C	Be inexpensive			
D	Resist to impacts			

The robotic arm should have a dynamic response superior to human (10 Hz) to ensure a transparent experience to the user [6]. A minimum of 50 N is required to give high force haptic sensation to the user. Be inexpensive and resist to

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impact are necessary conditions for a widespread adoption of a future commercial product.

B. Mechanical design

A 3 DOF robot configuration, as shown in Figure 1, is chosen. This configuration enables the robotics arm to generate 3D forces while having a simple design. Each DOF is actuated with 2 antagonistic MR clutches, for a total of 6 MR clutches. Many MR clutches are required for such configuration. However, MR clutches require practically no close tolerance parts, thus are very cheap. To achieve a reach of 900 mm, arm and forearm length are respectively 525 and 375 mm long.

To minimize the inertia of the robotic arm, thus increasing the dynamic response, actuators are remote mount in the robot base. Ball-bearing pulleys are used everywhere to redirect cables from the actuators to the robot's joints with minimal friction (see Figure 2).

To achieve high force and high speeds at any possible configurations, mechanical power is shared between all joints, and comes from a single industrial motor *Kollmorgen AKM43L* (1.2 kw AC motor). Power sharing provides significant cost and weight reductions over traditional one motor per joint approaches where multiple high-quality, high-power gearmotors must be used.

A 3-axis gimbal links the robotic arm with the user to give rotational displacement freedom to the user. Thus, only linear X-Y-Z force fields are transmitted to the user's hands.

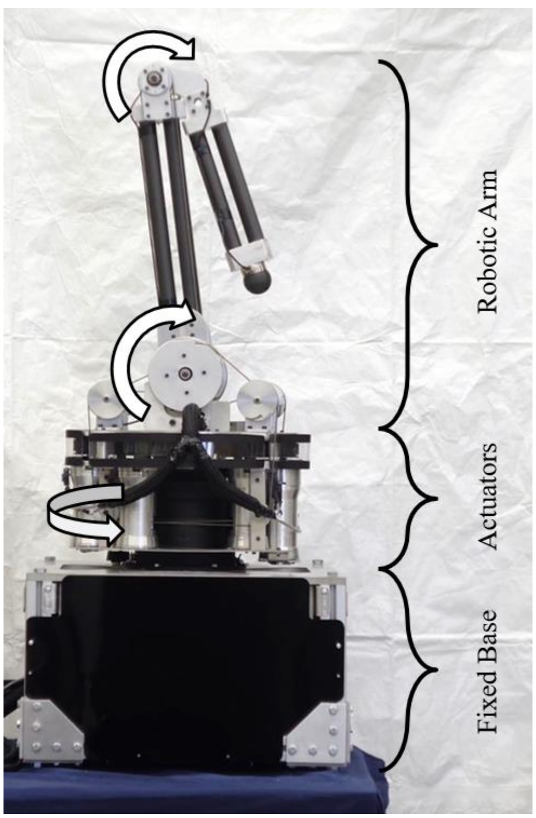

Figure 1 : Designed 3 DOF manipulator

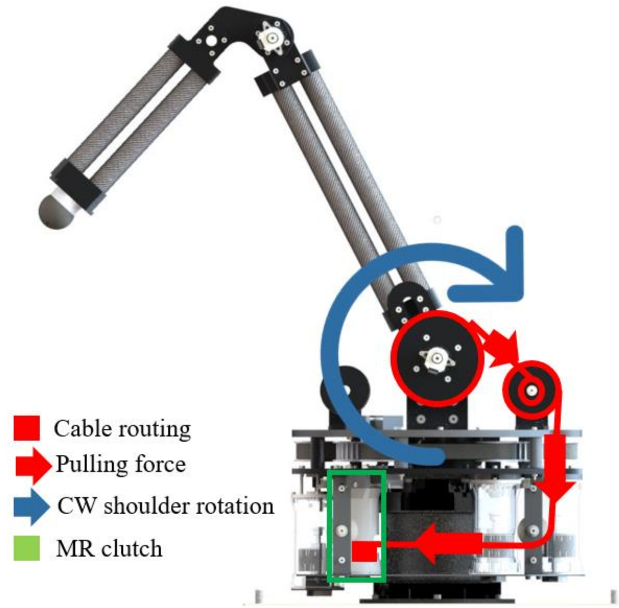

Figure 2 : Cable routing of an antagonist MR Clutch for CW shoulder rotation

C. Controller Design

Users interact with the VR environment with *Oculus Touch* hand held controllers while wearing an *Oculus headset*. The *Oculus* system is used because it is commercially available, popular and easy to use. Other platforms (e.g. HTC vive) or future *Oculus* version could easily be swapped on the robotic arm. Hand held controllers give the user's hands position to virtual environment (see Figure 3). Virtual environments are developed in *Unreal engine 4.21*. *Unreal engine* is a free and popular software used to develop games and has embedded physics. *Unreal engine*'s physics, *PhysX 3.3* by *Nvidia*, is used to generate cartesian reactions forces in real-time by detecting collision between the user's hands and virtual object. Those forces are outputted from *Unreal engine* and inputted in a *SpeedGoat* real-time machine target using serial communication.

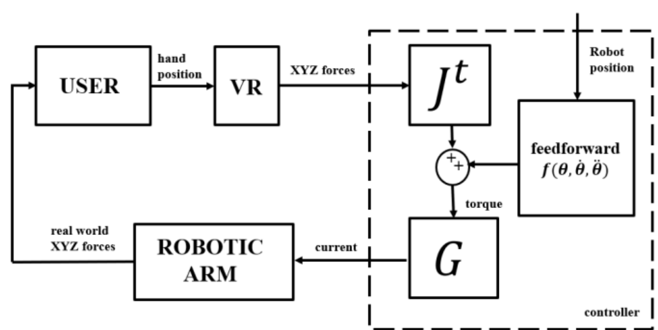

Figure 3 : VR system controller

An open loop controller is developed in Simulink and is compiled on the target. An open loop strategy is chosen to reduce the cost of the final system and to ensure reliable operation in real-life conditions. This controller uses the jacobian matrix to generate the required torque at joints to reproduce the cartesian forces. Gravity, friction and inertia compensation are coupled to the jacobian torques to offer a non-exhausting experience to the user. Theses compensations require position, speed and acceleration of each joints. Thus, the only sensors required are cheap encoders, *CUI AMT112*, installed on each joint to get the positions. Positions are derivated to get angular speed and angular acceleration.

III. EXPERIMENTAL RESULTS

A. *Specifications validation*

A characterization of the joints' torque has been done. Shoulder and elbow can respectively generates torques up to 56 and 23 Nm. The robotic arm was able to move a payload of 5.2 kg mass, even in full extension as shown in Figure 4.

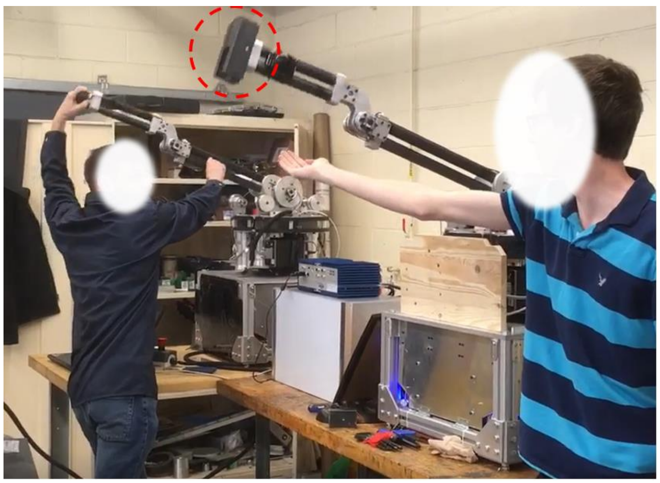

Figure 4 : 5.2 kg at end-effector in full extension position in a telepresence application

The robotic arm has a time response of 30 ms to a step current, consequently a dynamic response of 33 Hz. A force bandwidth test will be done in future work. Moreover, the robotic arm has been used intensively for many months and with more than 10 hours of continuous operation. The prototype has received many impacts without being damaged. There has been no failures and there are no signs of performance degradation so far. Thus, MR clutches have the potential to become a reliable technology for general collaborative robotics applications.

B. *User experience*

A specially developed game in Unreal engine to get user's feedback. In this game, the user needs to exterminate scary dragon and zombies using a virtual slingshot to demonstrate the high quality of force of the 3-DOF manipulator by simulating a spring. Figure 5 shows the player holding 2 robotics arm and the player's view.

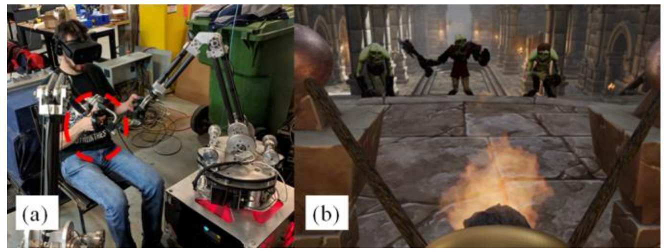

Figure 5: (a) player with 2 robotics arm; (b) player's view

Unreal engine is used to create spring forces and are generated at 3 DOF manipulator's end-effector. Figure 6 illustrate the desired X-Y-Z forces (Unreal) and the forces acquired by a force sensor *ATI mini45* at the end-effector transposed in real cartesian world. The open-loop control and manipulator are able to reproduce smooth force curves and close enough to target to give an immersive experience to the user.

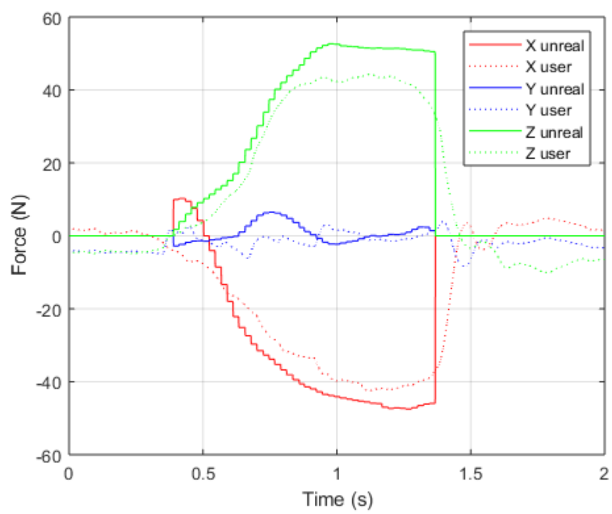

Figure 6 : Spring forces, *unreal engine* VS user

Slingshots are not the only weapon of the game. Protagonists can throw fireballs and punch objects. Throwing fireballs is perfect to simulate impulse response. When a fireball is thrown, a recoil force is suddenly generated, akin to a firearm recoil. Finally, punching a door is a great demo to simulate virtual walls and impacts.

More than 10 subjects have tested the MR system. All of them were easily immersed in the virtual environment, forgetting they were holding 2 robotic arms. Indeed, the gravity, friction and inertial compensation used provided a non-exhausting experience while the open-loop control and robotic arm generated forces at a high enough frequency to be transparent to the user.

IV. CONCLUSION

A proof-of-concept prototype of a cable driven robot using MR clutches to provide haptic feedback to upper-limbs in VR environment has been presented. The system uses a single, high power, electric motor to feed 6 low cost MR clutches that control the torques to 3 DOF on each arm. The system has a low reflected inertia due to its MR –clutches and thus, has high force bandwidth. The arm displays at least 5kgf in any configuration which is plenty to provide a natural force feedback. The clutches also provide a fluidic decoupling between the motor gearbox with translates into an excellent backdrivability and resistance to impacts. An open-loop controller was used to interface the virtual world to the users with representative and smooth forces. Overall, the technology is promising for its intended use in VR environments and has the potential for a widespread deployment in many gaming and simulation applications.

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