

Development of 3-DOF Force Feedback System Using Spherical Arm Mechanism and MR Brakes

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Abstract—In this research, a new 3-DOF force feedback system featuring a spherical arm mechanism and three MR brakes is proposed. One rotary MR brake is integrated in the waist joint to reflect the horizontal tangent force, another rotary MR brake integrated in the shoulder joint to reflect the elevation tangent force while a linear MR brake is integrated in the sliding joint of the arm to reflect the radial force (approach force). With this configuration, a 3-DOF desired force acting on the operator at the end-effector of the arm can be archived by independently controlling the current applied to the coils of the MR brakes. After the introduction, configuration of the proposed force feedback system is presented. After that, design and simulation of the MR brakes for the systems are conducted. A prototype of the force feedback system is then manufactured for experiment and some experimental results are obtained and presented with discussion.

Index Terms—MR fluid, spherical arm, force feedback system, haptic system, rotary MR brake, linear MR brake

I. INTRODUCTION

In recent years, a variety of researches on development and application of force feedback techniques have been conducted. The force feedback techniques cover a wide range of application including medical engineering, aerospace technologies, military applications, computer games and virtual reality devices such as virtual rehabilitation [1-2]. There have been several approaches to build a haptic system such as DC motors [3-5], electromagnetic actuators [6-7], pneumatic actuators [8-9], shape memory alloy [10], dielectric elastomeric actuators [11-12], eccentric rotating mass motors [13-15], etc. Recently, there have been many researches on haptic system featuring magneto-rheological fluid (MRF) [16-18], which all showed that MRF is a good candidate for haptic applications. Recently, Nguyen et al. [19] have developed a 3DOF haptic manipulator system featuring MR brakes. In that research, a haptic telemanipulator system consists of a slave manipulator which is a commercial industrial articulated manipulator and a haptic master manipulator, which has similar kinematic chain with the mater, featuring three rotary MR brakes

located at the joints to generate a desired force at the operator. The required torque at the joints of the mater was calculated from the desired force based on static modeling of the manipulator and a PID controller was used for each brake to achieve the required torques. Because of inaccuracy in using static modeling, the calculated torques are not the exact required values which result in the inaccuracy of the feedback force. In order to improve the force feedback accuracy, recently Nguyen et al [20] have conducted some modifications, in which the required torques of the MR brakes are estimated from measured armature current of the corresponding motors of the slave and the advanced results are validated by experimental works. An implicit disadvantage of force feedback system using articulated manipulator mechanism is that the required torques have to be determined from coupled equations which results in implicit values of the required torques.

In order to solve the implicit torque calculation of the articulated manipulator based force feedback, in this research a force feedback system based on a spherical arm mechanism is proposed. In order to reflect a required force to the operator, two rotary MR brakes and a linear MR brake are employed. With this configuration, a 3-DOF desired force acting on the operator at the end-effector of the arm can be archived by independently controlling the current applied to the coils of the MR brakes.

II. HAPTIC TELEMANIPULATOR SYSTEM

Fig. 1 shows the configuration of the proposed 3-DOF force feedback system. As shown in the figure, the system consists of a spherical arm mechanism with three joints: the waist revolute joint, the shoulder revolute joint and the arm prismatic joint. On the shaft of the waist joint, a rotary MR brake is attached to reflect a desired horizontal tangent force. The housing of the brake is fixed to the frame (base) of the spherical arm while the brake shaft is connected to the joint shaft. On the other end of the brake shaft, an encoder is attached to measure angular position of the body link (azimuth angle). On the body link, the shoulder joint is installed. On the shaft of the shoulder joint, another rotary MR brake is installed to reflect a desired elevation tangent force. The housing of

the brake is fixed to the body link while the brake shaft is connected to the shaft of the shoulder link. The other end of the brake shaft is connected with an encoder to measure angular position of the arm link (elevation angle). The linear MR brake is installed on the shoulder link which is attached to the shaft of the shoulder joint. The housing of the linear MR brake is fixed inside the hole on the shoulder link while its shaft can move back and forth as a sliding arm. At the end of the shaft, a 3-DOF force is attached to measure the reflected force acting on the operator. A linear encoder is employed to measure position of the sliding arm (radius).

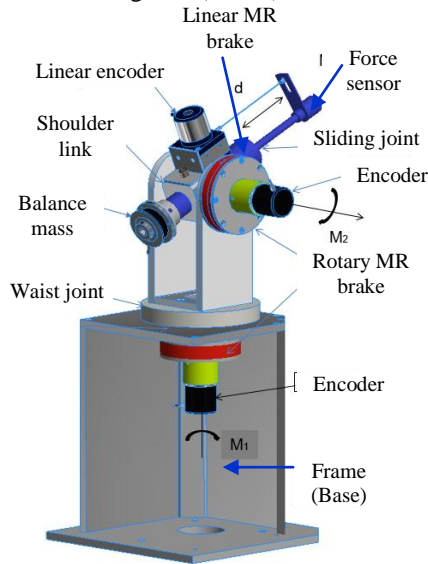


Figure 1. Configuration of the 3-DOF spherical force feedback system

Fig. 2 shows significant dimensions of the force feedback system which are selected based on its required working space and manufacturing convenience. It is noted that the maximum reflected force in each direction (horizontal tangent force, elevation tangent force, approach force) is set by 40N considering the conformable operational effort of the operator. From these required forces, it can be determined that the maximum required torque of the rotary MR brakes is $8Nm (=200mm*40N)$ while the maximum required force of the linear MRB is obviously 40N.

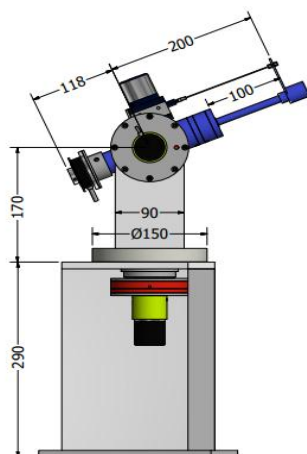


Figure 2. Significant dimensions of the force feedback system

III. MR BRAKES FOR THE FORCE FEEDBACK SYSTEM

A. The Rotary MR Brakes

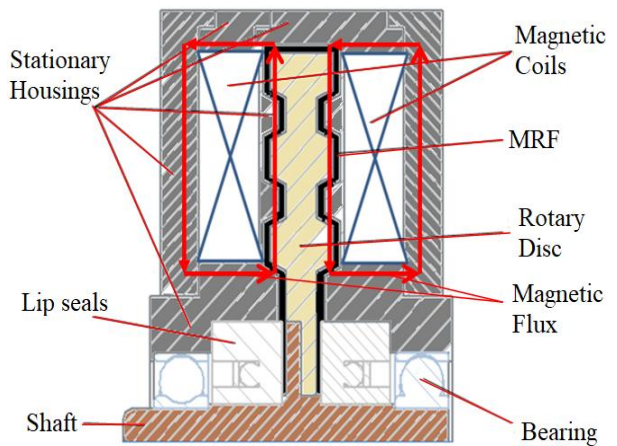


Figure 3. Configuration of the rotary MR brake

In this study, a new configuration of MR brake with tooth-shaped rotor shown in Fig. 3, is used for the rotary MR brakes. As shown in the figure, the MR brake has a disc (rotor) made of magnetic steel, fixed to the flange of the shaft made of nonmagnetic steel. The disc is placed inside a stationary envelope (housing) made of magnetic steel. The gap between the disc and the housing is filled up with magnetorheological fluid (MRF). In order to create a magnetic field with magnetic flux going across the MRF gap, a magnetic coil is placed on each side of the brake housing. Two counter currents are applied to the coils to generate a mutual magnetic field in order to produce the braking force. It is noted that the disc and the housing have tooth-shaped counterpart faces that allow a large contact surface between the MRF and the disc, and also a higher magnetic flux density across the MRF gap; thereby, the induced braking torque is expected to increase notably.

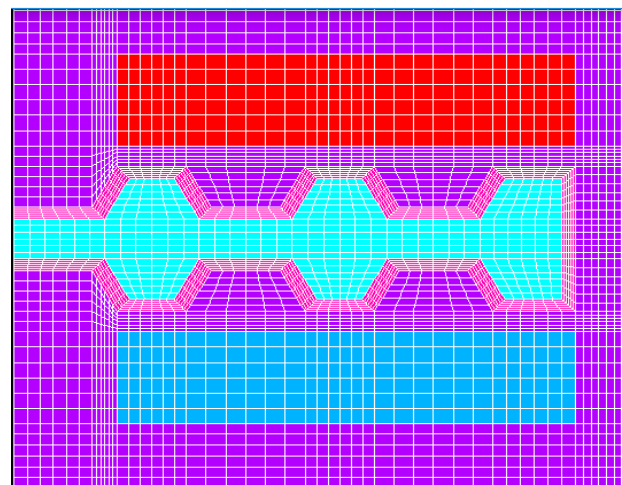


Figure 4. Finite element model for magnetic analysis of the MR brake.

An optimal design of the MR brake is conducted based on finite element analysis of the magnetic field of the MR

brake. The finite element model using 2D-axisymmetric couple element (PLANE 13) of ANSYS software for magnetic analysis of the MR brake is shown in Fig. 4. In the optimal design, objective function is the mass of the MR brake while the maximum induced braking torque is constrained to be greater than $10Nm$ (the required is $8Nm$). The MRF used in this research is the commercial one, MRF132-DG, made by Lord Corporation. The copper coil wires are sized as 24-gage (diameter = $0.511mm$). Table I show the optimal results of the MR brake.

TABLE I. OPTIMAL SOLUTION OF THE ROTARY MR BRAKE

Design variable (mm)	Optimized performance characteristics
<p>Size of coils: width $w_c=4.6$; height: $h_c=19.4$; no. coil turns =283 Housing: Outer radius $R=41.4$; Overall length $L=29.0$, thickness $t_h=3.25$; thin wall: 1mm Disc: Inner radius: $R_i=15$; Outer radius: $R_o=38.7$, Shaft radius=6.0 Tooth profile: Total depth=2.5, Top thickness: 2.0, bottom thickness: 4.15 MRF gap: 0.6</p>	<p>Maximum braking torque: $10Nm$ Mass: $1.2kg$ Off-state torque: $0.1Nm$ Power consumption: $16.5W$ Coil radius: 3.6Ω</p>

B. The Linear MR Brake

In this study, the configuration of two-coil linear MR brake without using non magnetic bobbin developed by Song et al [21] shown in Fig. 5, is used for the linear MR brake. In the same way for optimal design of the rotary MR brakes, the optimal design of the linear MR brake is conducted based on finite element model shown in Fig. 6. The optimal results are shown in Table II, from which detailed design of the MR brake is conducted and shown in Fig. 9.

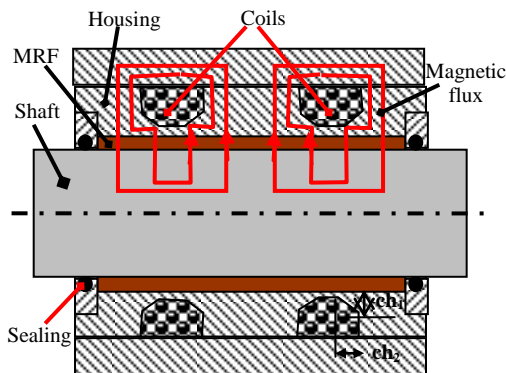


Figure 5. Configuration of the linear MR brake.

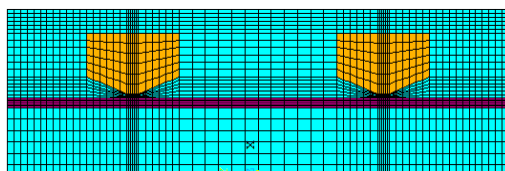


Figure 6. Finite element model for magnetic analysis of linear brake

TABLE II. OPTIMAL SOLUTION OF THE ROTARY MR BRAKE

Design variable (mm)	Optimized performance characteristics
<p>Size of coils: width $w_c=1.5$; height: $h_c=11.3$; the chamfer: $ch_1=3.7$, $ch_2=5.0$, no. coil turns =386 Housing: Outer radius $R=21.8$; Overall length $L=39.2$; thin wall: 0.5mm Shaft: Shaft radius=5.0. MRF gap: 0.6</p>	<p>Maximum braking force: $40Nm$ Mass: $0.46kg$ Off-state torque: $6.0N$ Power consumption: $11.5W$ Coil radius: 2.5Ω</p>

From the optimal design, the MR brakes are manufactured and installed on the spherical force feedback system which is shown in Fig. 10. In order to evaluate braking torque of the rotary MR brakes and braking force of the linear MR brake, experimental works are conducted directly on the prototype shown in Fig. 7. Fig. 8 shows the measured braking torque of the rotary MR brake at the waist joint. It is noted that, in the experiment, the horizontal tangent force at the end of the arm is measured by the force sensor and the arm is fixed in horizontal direction with the arm length of $100mm$. Thus, the braking torque of the MR brake is calculated by the product of the measured force and the arm length ($100mm$). During the experiment, the arm is rotated about the waist joint and the average value of the force at different value of the applied current is recorded. In the same manner of the MR brake at the waist joint, the braking torque of the MR brake at the shoulder joint is experimentally evaluated and the results are shown in Fig. 9. It is noted that in this case the arm is rotated about the shoulder joint axis during the experiment. Fig. 10 shows the braking force of the linear MR brake at the function of the applied current. In this case, the arm is fixed in horizontal direction and the shaft of the MR brake is moved back and forth.

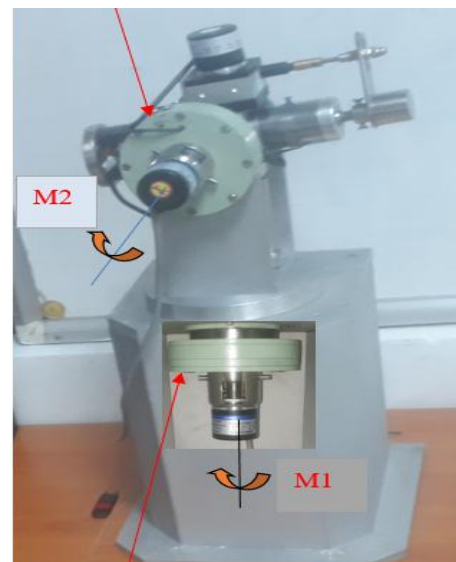


Figure 7. The 3-DOF spherical force feedback prototype

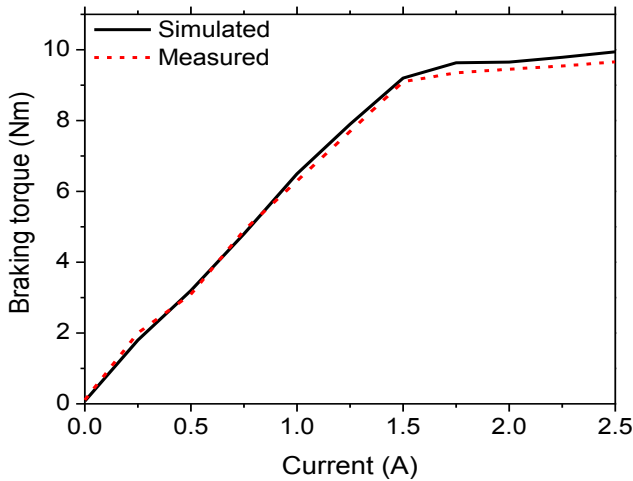


Figure 8. Braking torque of the waist MR brake vs applied current

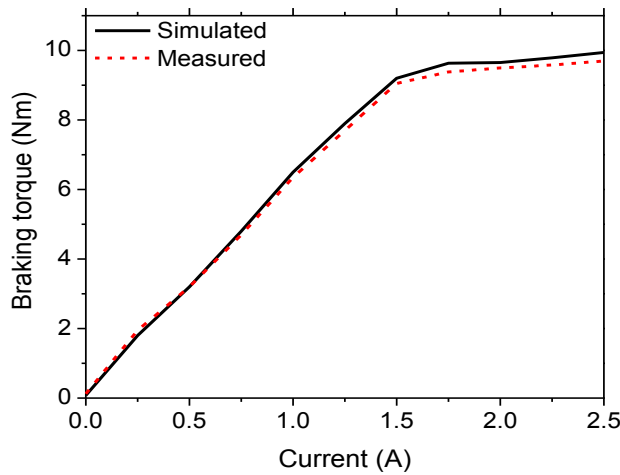


Figure 9. Braking torque of the shoulder MR brake vs applied current

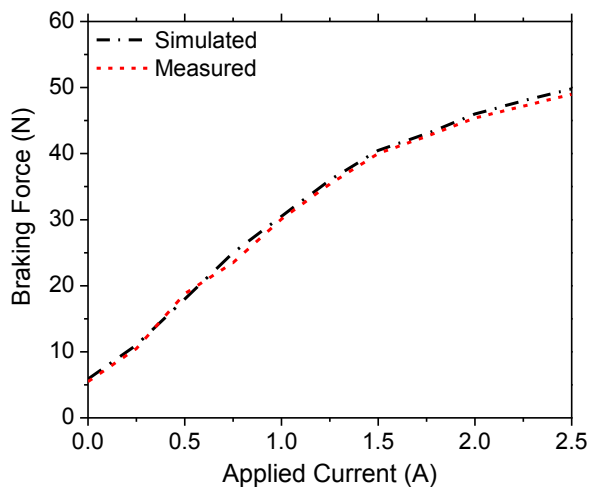


Figure 10. Braking force of the linear MR brake vs applied current

IV. CONTROL DESIGN FOR THE FORCE FEEDBACK SYSTEM

In this section, an open loop controller is design to reflect a desired force to the operator. Fig. 11 shows the

block diagram of the control system for the horizontal and elevation tangent forces while that for the radial force is shown in Fig. 12. As shown in Fig. 11, from the information of the encoders, position of end-effector of the arm is calculated. The braking torque of the waist MR brake is then calculated by Eq. (1) while that of the shoulder brake is calculated by Eq. (2)

$$T_w = F_h r \cos \theta \quad (1)$$

$$T_{sh} = F_e r \quad (2)$$

In the above, F_h is the desire horizontal tangent force, F_e is the desire elevation tangent force, r is the arm radius and θ is the elevation angle.

In order to archive a braking torque equal to the calculated one, the applied current to the coils of the MR brakes is determined from the experimental results shown in Fig. 8 and 9 using cure fitting method.

For the radial force, as shown in Fig. 12, from the desired radial force, the applied current to the coils of the linear MR brake is determined from the experimental results shown in Fig. 10 using cure fitting method.

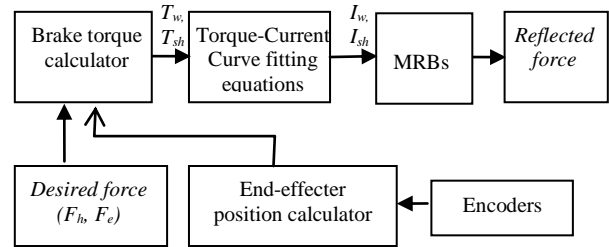


Figure 11. Block diagram of control system for tangent force

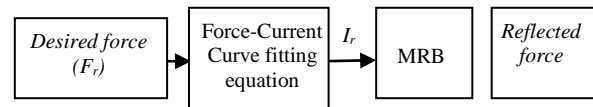


Figure 12. Block diagram of control system for radius force

V. RESULTS AND DISCUSSION

A. Experimental Setup

Fig. 13 shows the experimental set up for experimental work. As shown from the figure, the PCI card NI-6289 (National Instruments) is used for interaction between the manipulator system and the computer. A 3-DOF force sensor (OptoForce) is attached at the end-effector to measure the reflected force acting on the operator. When operator moves the master arm, angular positions are measured by the rotary encoders and the radial position is measured by the linear encoders. The information from the encoders is sent to the computer through the PCI card. From the encoders' information, the computer computes values of the applied currents for the MRBs. These currents are then sent to the coils of the MR brake through the PCI card and an amplifier.

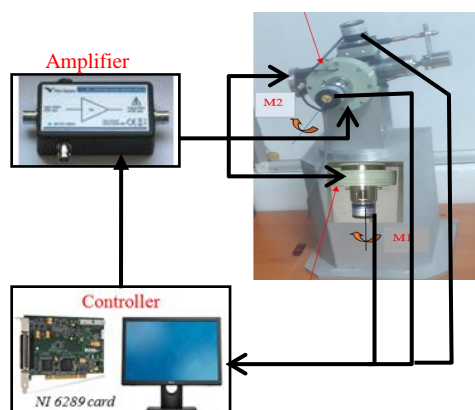


Figure 13. Braking torque of the optimized MRB vs applied current

B. Experimental Results

Fig. 14, 15 and 16 show experimental results of force feedback system. In the experiment, the force feedback arm is located in an arbitrary position; a sinusoidal desired feedback force is set for each component of the feedback force (the horizontal tangent, the elevation tangent and the radial force). During the experiment, the operator holds the end-effector and moves it in an arbitrary trajectory in the working space. It is observed from Fig. 14 that the actual feedback horizontal force well agrees with the desired one. However, the actual feedback force can not be smaller than $1.5N$. It is obvious because the uncontrollable torque (the off-state torque of the MR brake). From Fig. 15, it is also observed that the actual feedback elevation force well agrees with the desired one. In this case, the minimum achievable force is $1.8N$. From Fig. 16, it is observed that the actual feedback radial force quite well agree with the desired one. However, In this case, the minimum achievable force is quite high, around $6N$, which is almost equal to the off-state force of the linear MR brake. The above results show that the proposed 3-DOF force feedback system can be used to reflect an arbitrary desired force to an operator.

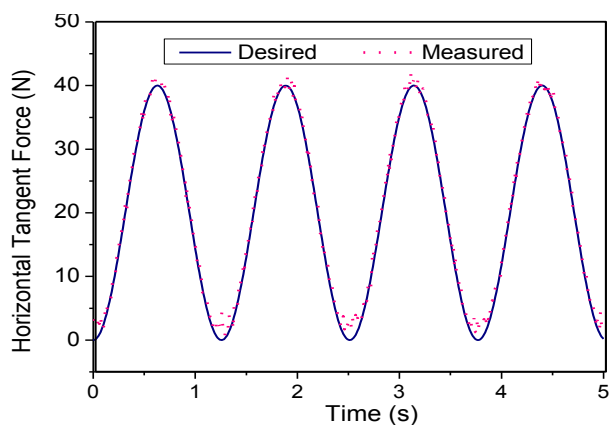


Figure 14. Experimental results of horizontal force reflection

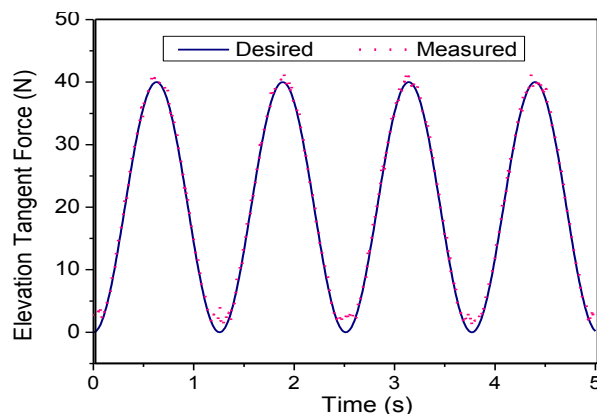


Figure 15. Experimental results of elevation force reflection

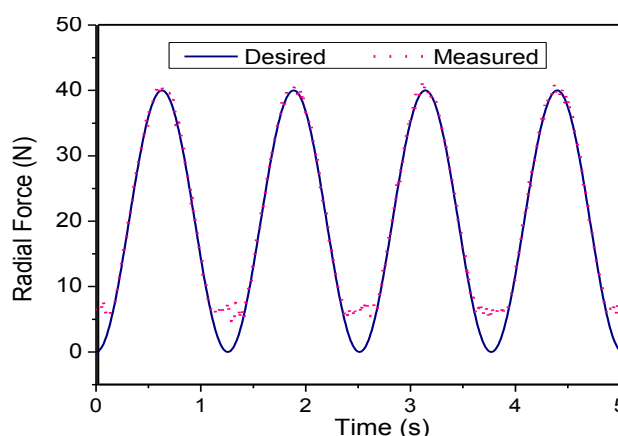


Figure 16. Experimental results of radial force reflection

VI. CONCLUSIONS

In this research, a new 3-DOF force feedback system featuring a spherical arm mechanism and three MR brakes (two rotary MR brakes and one linear MR brake) has been proposed. With this configuration, a 3-DOF desired force acting on the operator at the end-effector of the arm can be archived by independently controlling the current applied to the coils of the MR brakes. After the introduction, configuration of the proposed force feedback system was presented. After that, design and simulation of the MR brakes for the systems were conducted. For the rotary MR brake, a configuration of MR brake with tooth-shaped rotor was employed. For the linear MR brake, a MR brake without using nonmagnetic bobbin was used. In order to reflect a desired force, an open loop controller based on experimental performance of the MR brakes was used in this study. A prototype of the force feedback system was then manufactured for experiment. Experimental results show that a desired feedback force can be well archived by the force feedback proposed system. However, due to the off-state torque and force of the MR brake, the system can not reflect small force to the operator, which is $1.5N$ for the horizontal fore, $1.8N$ for the elevation force and $6N$ for radial force).

CONFLICT OF INTEREST

We confirm that this research work is original and conducted by the authors, ourselves with no conflict of interest.

AUTHOR CONTRIBUTIONS

Hung Q. Nguyen is the corresponding author of this research work. He is in charge of conceptual generation, final editing of the manuscript; Thang D. Le conducted the optimization of the MR brake; Diep N. Nguyen is a PhD student working in this research. He is in charge of configuration design, detailed design, data analysis and write the first draft of the manuscript; Tuan D. Le, Thang V. Lang, Thang V. Ngo are research assistants. They are in charge of prototype manufacturing, experimental setup and data collection for this research;

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REFERENCES

[1] H. Kawasaki and T. Mouri, "Design and control of five-fingered haptic interface opposite to human hand," *IEEE Transactions on Robotics*, vol. 23, no. 5, 2007.

[2] Z. Nawrat and P. Kostka, "Polish cardio-robot 'Robin Heart'. System description and technical evaluation," *Int. J. Med. Robot. Comp.* vol. 2, no. 1, pp. 36-44, 2006.

[3] M. Solazzi, A. Frisoli, and M. Bergamasco, "Design of a novel finger haptic interface for contact and orientation display," in *Proc. IEEE Haptics Symposium*, 2010, pp. 129-132.

[4] M. Gabardi, M. Solazzi, D. Leonardi, and A. Frisoli, "A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features," in *Proc. IEEE Haptics Symposium*, 2016, pp. 140-146.

[5] Sarakoglou, N. Garcia-Hernandez, N. G. Tsagarakis, and D. G. Caldwell, "A high performance tactile feedback display and its integration in teleoperation," *IEEE Transactions on Haptics*, vol. 5, no. 3, 2012, pp. 252-263.

[6] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer, "Gravity: A wearable haptic interface for simulating weight and grasping in virtual reality," *UIST 2017*, Oct. 22-25, 2017, Québec City, Canada

[7] S. Kapoor, P. Arora, V. Kapoor, M. Jayachandran, and M. Tiwari, "Haptics - Touchfeedback technology widening the horizon of medicine," *J Clin Diagn Res.*, vol. 8, no. 3, 2014, pp. 294-299.

[8] D. G. Caldwell, N. Tsagarakis, and C. Giesler, "An integrated tactile/shear feedback array for stimulation of finger mechanoreceptor," in *Proc. IEEE Int. Conf. Robotics and Automation*, vol. 1, 1999, pp. 287-292.

[9] G. Moy, C. Wagner, and R. S. Fearing, "A compliant tactile display for teletaction," in *Proc. IEEE Int. Conf. on Robotics and Automation*, vol. 4, 2000, pp. 3409-3415

[10] M. Solazzi, W. R. Provancher, A. Frisoli, and M. Bergamasco, "Design of a SMA actuated 2-DOF tactile device for displaying tangential skin displacement," in *Proc. IEEE World Haptics Conference*, 2011, pp. 31-36.

[11] I. M. Koo, K. Jung, J. C. Koo, J. D. Nam, Y. K. Lee, and H. R. Choi, "Development of soft-actuator-based wearable tactile display," *IEEE Transactions on Robotics*, vol. 24, no. 3, 2008, pp. 549-558.

[12] G. Frediani, D. Mazzei, D. E. De Rossi, and F. Carpi, "Wearable wireless tactile display for virtual interactions with soft bodies," *Frontiers in Bioengineering and Biotechnology*, vol. 2, 2014.

[13] S. Pabon, E. Sotgiu, R. Leonardi, C. Brancolini, O. Portillo-Rodriguez, A. Frisoli, and M. Bergamasco, "A data-glove with vibro-tactile stimulators for virtual social interaction and rehabilitation," in *Proc. Annual Int. Workshop on Presence*, 2007.

[14] F. Sanfilippo, L. I. Hatledal, and K. Pettersen, "A fully-immersive haptic-audio-visual framework for remote touch," in *Proc. IEEE International Conference on Innovations in Information Technology*, 2015.

[15] J. Footit, D. Brown, S. Marks, and A. Connor, "Development of a wearable haptic game interface," *EAI Endorsed Transactions on Creative Technologies*, vol. 16, no. 6, 2016.

[16] Q. H. Nguyen, P. B. Nguyen, and S. B. Choi., "Optimal design of a Hybrid MR Brake for Haptic Wrist Application," in *Proc. SPIE 7977, Active and Passive Smart Structures and Integrated Systems*, 2011

[17] J. S. Oh, W. K. Shin, C. H. Uhm, S. R. Lee, Y. M. Han, and S. B. Choi, "Control of haptic master - slave robot system for minimally invasive surgery," *Journal of Physics: Conference Series*, 2014

[18] J. S. Oh, W. K. Shin, C. H. Uhm, S. R. Lee, Y. M. Han, and S. B. Choi, "Control of haptic master - slave robot system for minimally invasive surgery," *Journal of Physics: Conference Series* 412, 2013

[19] N. D. Nguyen, X. H. Nguyen, N. N. Tuyen, Q. H. Nguyen, "Development of a 3-DOF haptic tele-manipulator system using magnetorheological brakes," in *Proc. International Conference on Advances in Computational Mechanics, Lecture Notes in Mechanical Engineering*, 2018, pp. 793-805.

[20] N. D. Nguyen, S. D. Nguyen, N. T. Nguyen, and Q. H. Nguyen, "Development of a haptic telemanipulator system based on MR Brakes and estimated torques of AC servo motors," *IntelliSys 2018, Advances in Intelligent Systems and Computing*, vol. 868, 2018

[21] B. K. Song, Q. H. Nguyen, S. B. Choi, and J. K. Woo, "The impact of bobbin material and design on magnetorheological brake performance," *Smart Materials and Structures*, vol. 22, no. 10, 2013.

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