Design, Modeling and Control of Magnetorheological Fluid-Based Force Feedback Dampers for Telerobotic Systems

Farzad Ahmadkhanlou*

Abstract

The overall goal of the research conducted in this paper is to develop next generation force feedback systems by combining novel Magnetorheological (MR) fluid based systems with microstructural analysis and advanced control system design. Two MR fluid based telerobotic systems are designed, prototyped and tested with medical applications. Force feedback control is employed to replicate in the master those forces encountered in the slave. The test results show the appropriate performance of MR fluid based systems used in haptic and force feedback applications.

1. INTRODUCTION

Recently, force feedback techniques have been utilized to increase the effectiveness of human-machine interfaces. These systems can be used in a variety of applications including biomedical, light industrial, military training applications, aerospace and entertainment and gaming.

For minimally invasive cardio-thoracoscopic (MICT) surgery, the present state of the art is a telerobotic surgical system where the surgeon sits at a workstation and controls a robot, which conducts the surgery. Some of the benefits of using telerobotic MICT surgery are smaller incisions, less pain, lower risk of infection, less scaring, and reduction in the recovery time.

* Scott Lab, Intelligent Structures and Systems Lab, 201 W. 19th Ave, Columbus, OH 43210, I would like to thank my advisor, Prof Gregory Washington, and my co-advisor, Prof Stephen Bechtel.

However, the surgeon only has visual feedback from a camera (scope) inserted in the patient. In fact, because of the limited field of view from the scope, there have been reports of bones being broken.

A teleoperation system consists of a pair of manipulators: master and slave. The operator handling the master directs control signals to the slave which acts on an external object. In force feedback systems the slave receives motion commands from the master and transmits information from its environment back to the master when comes into contact with an external object. Recent technology in teleoperation systems has the following limitations: (1) System instability (2) Large active components (3) Cost associated with these systems. The primary aim of this research is to address the aforementioned problems with traditional force feedback systems by the application of MR fluid-based force feedback systems.

Magnetorheological (MR) fluids consist of micron-sized ferrous particles suspended in a Newtonian fluid. These fluids belong to a special class of fluids whose yield stress (or threshold stress for initiating fluid flow) increases with an applied magnetic field. The advantages of using MR fluids in haptic devices stem from the increase in transparency gained from the lightweight semi-active system and controller implementation.

There are a number of simple models used to describe MR fluid operation such as the Bingham model [1] and Herschel-Bulkley viscoplasticity model [2, 3]. While present rheological based modeling techniques of MR fluids work well for modeling dampers, clutches, and brakes [4-22], there are some advanced applications (e.g. tactile and force feedback systems) that require higher fidelity models, force feedback, and variable compliance.

In this study the authors develop haptic systems for telerobotic surgery. The research outlined in this document is subdivided into the following sections: (2) microstructural modeling,

(3) characterization of the MR fluid, (4) MR fluid device analysis and design toolbox (5) 2-DOF MR fluid-based joystick (6) 5-DOF MR fluid-based telerobotic manipulator, control, transparency, and system stability, (7) experimental results, and (8) conclusion.

2. THE KINETIC THEORY-BASED ELASTIC DUMBBELL MODEL OF MR FLUIDS

Magnetorheological fluid consists of micron sized magnetizable particles in a carrier fluid. In kinetic theory-based models, the suspended particle is considered as either an elastic dumbbell or a rigid dumbbell. The distributed force from the carrier fluid on the particle is idealized as being localized on the beads at the ends of the particle, with a rigid or elastic connector between the beads. Macroscale constitutive equations relating flow, stress, and particle orientation are produced by integrating the coupled equations governing forces, flow, and orientation over a representative volume of particles and carried fluid. In the elastic dumbbell model of the iron particles, two beads of mass m are joined by a spring. The connector **q** between two beads is representative of the orientation of the iron particle in the carrier fluid (Figure 1). The evolution equation for particle orientation is deduced from the kinetic equation that describes the rate of change of orientation **q** with time:

$$\dot{q}_i = \underbrace{\left(L_{ij} - \mu D_{ij}\right) q_j}_{\textbf{carrier fluid flow}} + \underbrace{a_{ij} \frac{2kT}{\psi} \frac{\partial}{\partial q_k}\left(\xi_{kj}^{-1}\psi\right)}_{\textbf{Brownian motion}} + \underbrace{2a_{ij} f_j^{(c)}}_{\textbf{intraparticle force}} + \underbrace{a_{ij}\left(f_{1j}^{(m)} - f_{2j}^{(m)}\right)}_{\textbf{magnetic field}}$$

The left hand side of this equation is the Lagrangian time derivative of particle orientation, and the terms on the right hand side arise from the four physical effects that can contribute to this change of orientation. Definitions of all parameters and coefficients, and details of the derivation, are developed in [23] and summarized here for clarity. We consider the particles to be elastic with modulus β, so that the internal particle force is $f_i^{(c)} = \beta q_i$ and introduce

$f_{1i}^{(m)} - f_{2i}^{(m)} = \dfrac{c\dot{\gamma}}{(1+\chi)|\mathbf{H}|} q_i$. The total stress tensor τ of the composite system of iron particles and carrier fluid is given by

$$\tau_{ij} = -\left(p + nkT\right)\delta_{ij} + 2\eta_s D_{ij} + n\left\langle q_i f_j^{(c)} \right\rangle + \frac{1}{2} n \left\langle q_i \left(f_{1j}^{(m)} - f_{2j}^{(m)} \right) \right\rangle$$

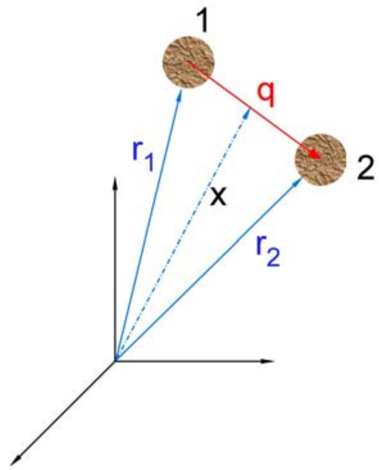
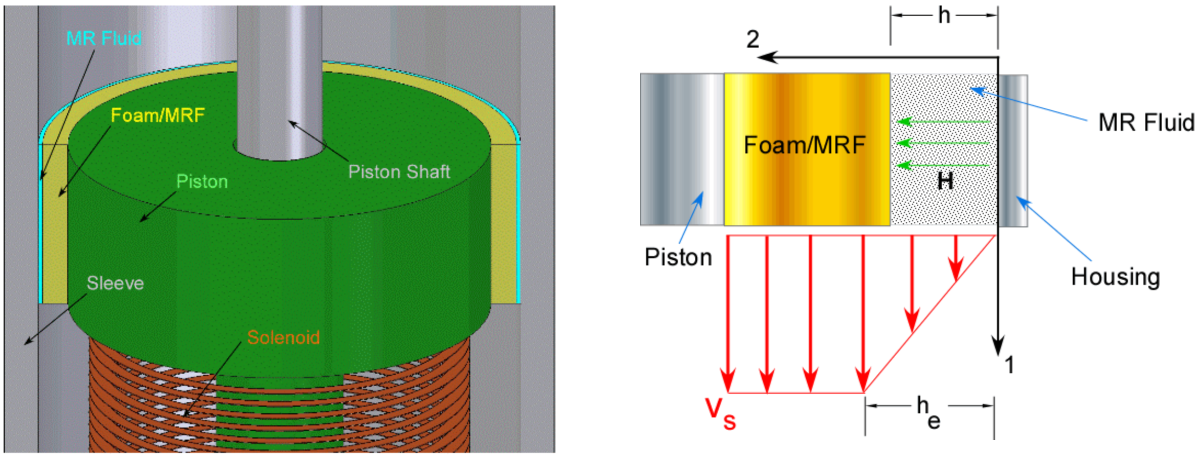


Figure 1: Dumbbell model

To evaluate the modeling choices of $f_i^{(c)}$ and $f_{1i}^{(m)} - f_{2i}^{(m)}$ against experiments, we apply the 3-D theory to the 1-D case of steady simple shear in the presence of a transverse magnetic field by inserting the special velocity and magnetic fields $\mathbf{v} = \left[\dot{\gamma} x_2 \quad 0 \quad 0\right]^T$, $\mathbf{H} = \left[0 \quad H \quad 0\right]^T$, with positive constant shear rate $\dot{\gamma}$ and magnetic field strength H (Figure 2). This reduces the above constitutive equations for the 3-D stress tensor to a 1-D constitutive equation for shear stress in simple shear

$$\tau_{12} = \eta_s \dot{\gamma} + \frac{nkT\,\zeta}{4\left(\beta + \dfrac{c\dot{\gamma}}{2(1+\chi)H}\right)} \dot{\gamma}$$

Explicitly, the scalar τ_{12} in this equation is the component of the stress tensor accompanying the velocity and magnetic fields. From experimental results we observe that this expression replaces the strict yield stress of the Bingham/Herschel-Buckley-type visco-plastic models with a steep gradient, which is in better agreement with experimental observation (Figure 3).



(a) (b)

Figure 2: (a) Linear sponge-based MR damper for characterizing the MR fluid samples; (b) Simple 1-D shear in the presence of a transverse magnetic field

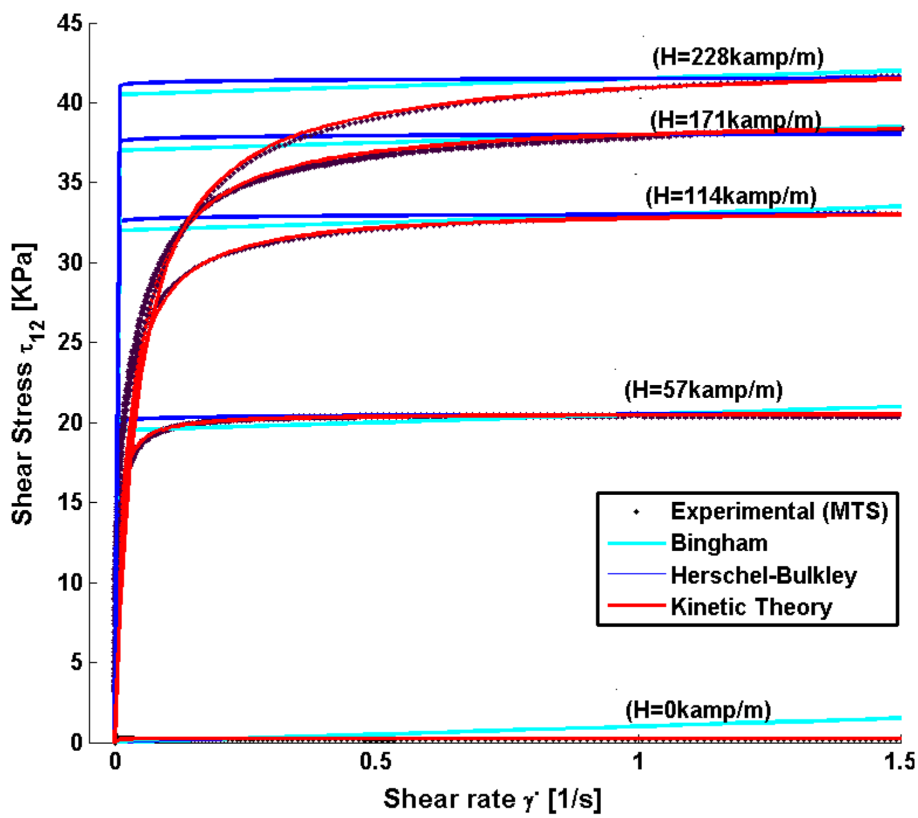


Figure 3: Experimental measurements and predictions of Bingham plastic, Herschel-Buckley, and kinetic theory models for MR fluid behavior in steady simple shear

3. PREPARATION AND CHARACTERIZATION OF MR FLUIDS

Thirty one different MR fluids were employed in the investigation of this paper, consisting of carbonyl iron powder in two different particle size ranges (2-5μm and 4-7μm) mixed with silicone oils with five different viscosities (η=0.00935, 0.01906, 0.34055, 0.974, and 12.1875 Pa-s). Weight ratios of carbonyl iron powder to silicone oil ranged from 75 to 85 percent.

These MR fluid samples were utilized in a linear damper designed and constructed by the authors [24]. Conventional MR fluid-based dampers have a reservoir of MR fluid sealed by an o-ring or gasket; these mechanical seals create sizable off-state resistant shear viscosity. The authors' damper saturates an open-celled polyurethane sponge with MR fluid, confining the fluid and eliminating the need for seals, thereby reducing the off-state viscosity.

The damper was used to characterize the MR fluid behavior: Solenoid was subjected to a controlled current ranging from 0 to 4 amps, generating a transverse magnetic field across the foam saturated with MR fluid. An MTS machine was used to control the axial motion of the piston in the damper and measure the required axial force.

The MR fluid used by Rabinow in his investigation [4] consisted of 9 parts by weight of carbonyl iron to one part of silicone oil; we investigated MR fluids with a range of particle sizes, carrier fluids, and weight ratios, to measure the dynamic range (the ratio of maximum viscosity in on-state to minimum viscosity in off-state) as a function of the MR fluid ingredients. Among all the 31 different samples, the 12 samples made with reported 1000 and 12500 cSt silicone oils were too viscous to saturate the foam. All other samples were tested in a tensile testing machine. The resulting force vs. displacement measurements of the damper for varieties of MR fluids were used to characterize the behavior of each MR fluid/damper system.

The MR fluid suitable for a haptic device should have the following characteristics: very low off-state viscosity, large dynamic range, and low particle settlement. The MR fluid sample made of 5 parts by weight carbonyl iron powder (4 to 7μm) to one part Silicone oil (10 cSt) was determined to be the one most appropriate in the MR fluid-based haptic system in the next section.

4. MR FLUID DEVICE ANALYSIS AND DESIGN TOOLBOX

An interactive toolbox has been developed for the design of MR fluid based systems (Figure 4). One of the features of this toolbox is sensitivity analysis, which can be used for the optimum design of MR dampers in general. Sensitivity analysis clarifies how the resistance torque generated by MR damper is changed with respect to changes in MR damper dimensions, current and wire gage size. The main features of this toolbox are: MR fluid modeling, MR damper/brake analysis and design, sensitivity analysis, optimization of MR damper design, automatic preparation of calculation sheet, 2-D stress analysis, MATLAB interface

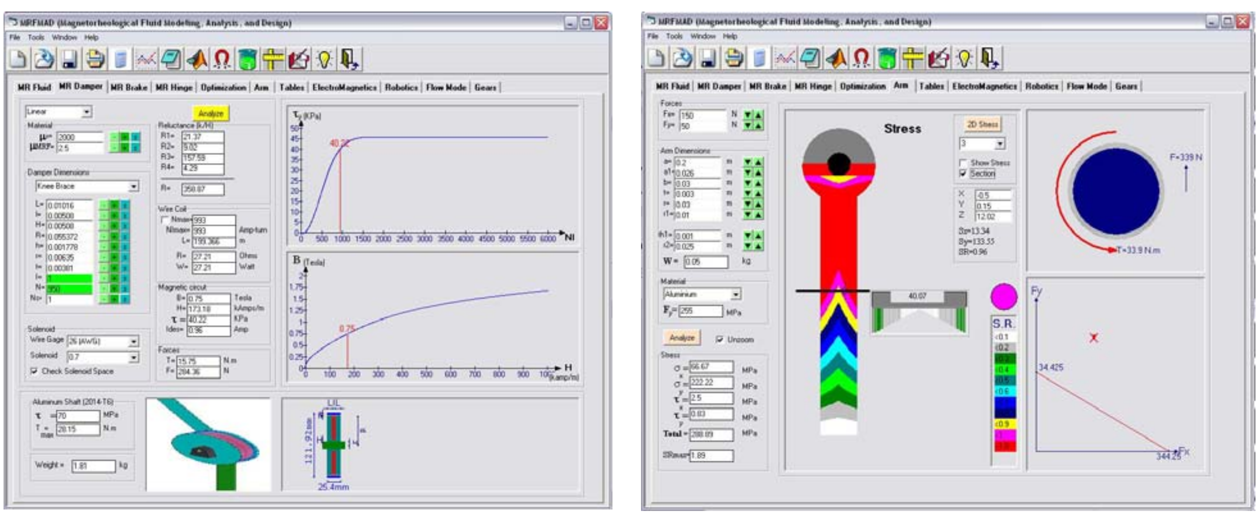


Figure 4: Interactive toolbox for designing MR fluid devices

5. TWO DEGREE OF FREEDOM FORCE FEEDBACK JOYSTICK

This system provides the user with tactile information in a two-degree-of-freedom environment. The end-effector for this system is a probe that can sense deflections in two planar directions. This probe is connected to a five bar linkage that is able to move in the horizontal plane. The motion of the five bar linkage is controlled by an innovative MR force feedback joystick (Figure 5). Three single rotary dampers are designed for this system: the smaller Y-axis dampers are energized when the probe hits a barrier in the x direction and similarly the larger X-axis damper on works when the probe hits a barrier in y-direction. A 24 gauge copper coil with 1400 and 900 coil turns is used for the small and large dampers respectively. There are two encoders (angle sensor) on the x and y shafts to send the handle movement signal to the 5-link bar system. The small and large dampers are designed to generate resistance torques of 2.5 and 5 N.m. respectively. The 2-DOF system is designed to trace a two dimensional curved path (Figure 6).

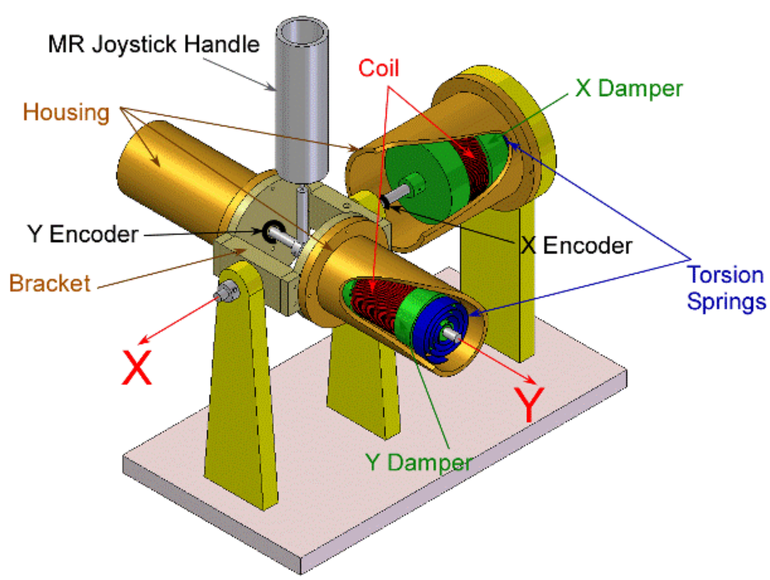


Figure 5: MR fluid-based force feedback joystick

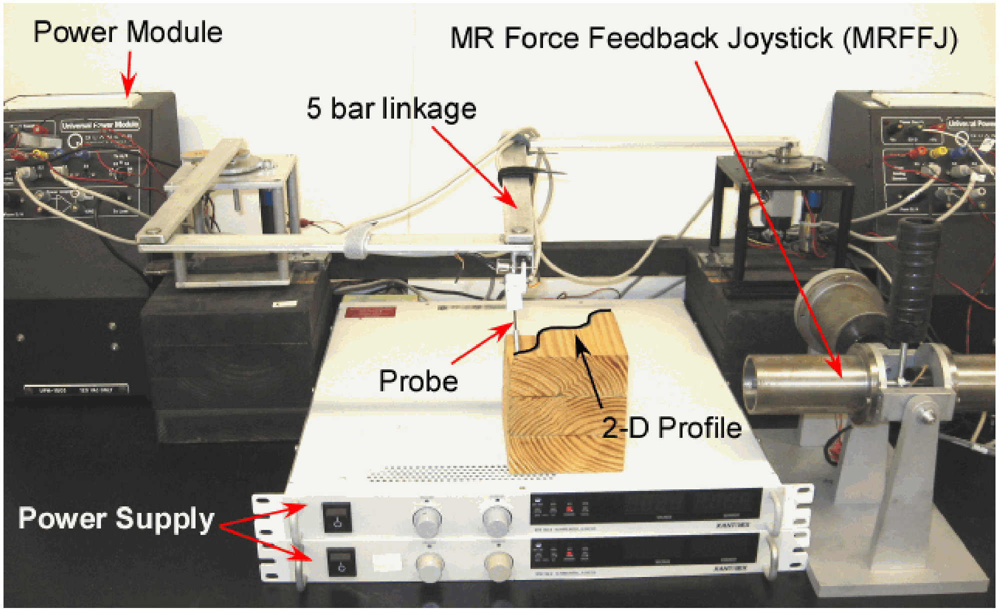
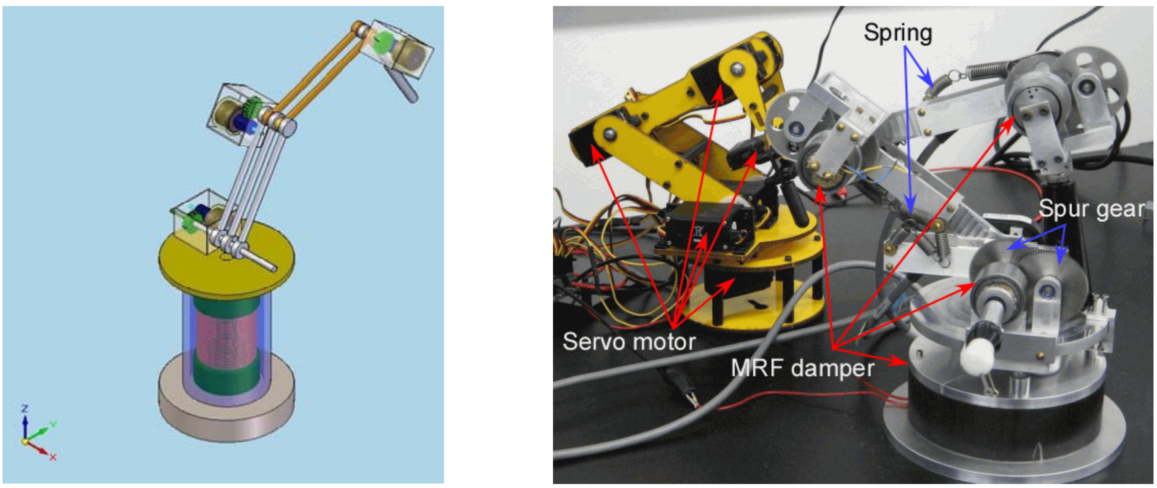


Figure 6: 2DOF system test setup

6. FIVE DEGREE OF FREEDOM TELEROBOTIC MANIPULATOR

MR fluid is used in the design of a novel five degree of freedom (DOF) MR sponge-based haptic system (master) for controlling a telerobotic arm used in telerobotic surgery. The master 5-DOF joystick controls the movement of a 5-DOF slave (Figure 7). A novel multi-axis force sensor is designed by the authors and used at the end effector (EE) of the slave for force feedback control. Force and displacement sensors in the slave sense the environment conditions along which the end effector moves. When the EE contacts a solid object or barrier, the exerted force is sensed by the force sensor and the signals are sent to the 5-DOF MR based master to activate the MR dampers accordingly to replicate the force. The user feels the force from master joystick proportional to the force encountered at the slave. For example if the slave encounters soft tissue (low force, small to no deceleration) a relatively small current signal will be sent to the MR damper which will give the user the slight resistance associated with soft tissue. Likewise if the slave encounters bone (high force, large deceleration) a large signal will be sent to the MR damper, which will give the user a larger resistance. The main objective of any force feedback system is to reproduce the forces encountered by the actual or virtual system at the user's end. This can be seen as a tracking problem where the goal is to track the force at the 'virtual end' and regenerate it at the user end. The development of the controller must be comprehensive enough that it can handle models that will grow in complexity from both an analytical and experimental point of view. There are two control methodologies in this research: motion control of the slave and force feedback control.



(a) (b)

Figure 7: (a) Five DOF MR fluid-based telerobotic haptic system; (b) Master (right) and Slave (left)

Control, Transparency, and Stability of the System

The main objective of any force feedback system is to reproduce the forces encountered by the actual or virtual system at the user's end. This can be seen as a tracking problem where the goal is to track the force at the 'virtual end' and regenerate it at the user end. The development of the controller must be comprehensive enough that it can handle models that will grow in complexity from both an analytical and experimental point of view.

The control methodology in this research is categorized in two sub-sections: motion control of the slave and force feedback control. Figure 8 shows the block diagram of the telerobotic system with motion and force feedback control. Vector $\mathbf{X_m}$ is the commanded motion by the operator hand, $\mathbf{F_m}$ is the force applied to the master by the operator, $\mathbf{X_s}$ is the motion of the slave end-effector, and $\mathbf{F_e}$ is the force exerted to the end-effector by the external environment.

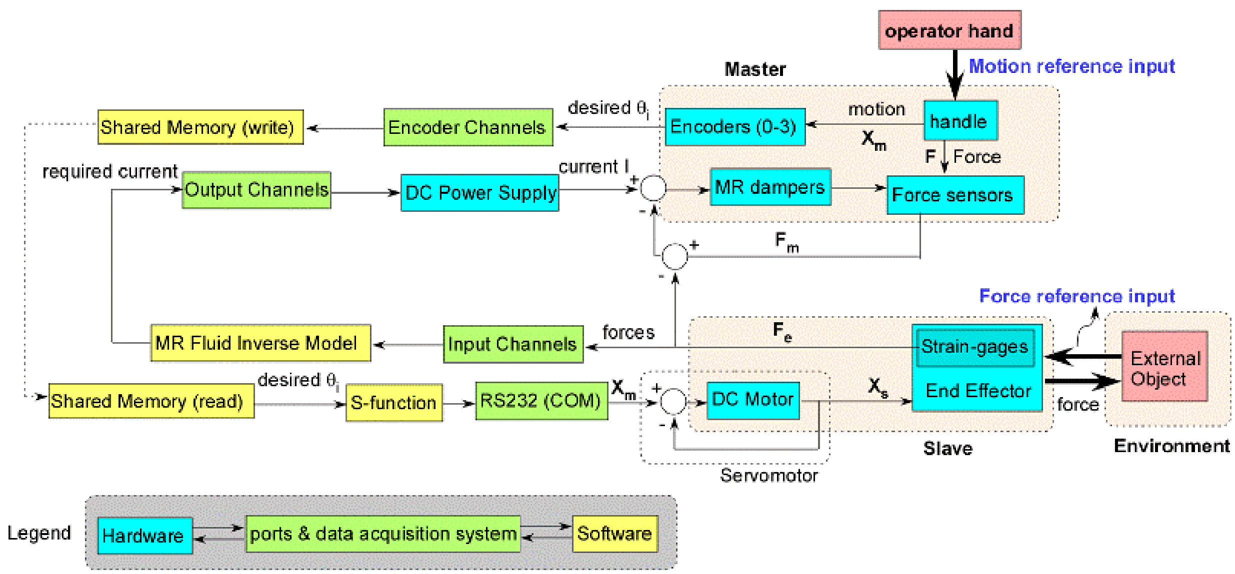


Figure 8: Control block diagram of the telerobotic force feedback system

An encoder is placed on each joint of the 5-DOF MR-based master robot. The encoders send the signals to a data acquisition board. This data is stored in shared memory through a compiled Simulink file. Another Simulink file is used to read the data from the shared memory. A *mex c-file s-function* is used to send the required command to the slave robot joints through a RS232 (COM) port to follow the master motion. The data is sent to all the servo-motors in the slave.

A 2-D force sensor is designed and placed at the slave end-effector (Figure 9). Two strain-gages are used for this purpose. Each strain gage is placed on a plate and the plate is connected to the end-effector with a special designed connection. The connection is fixed in one direction and hinged in the other direction. The plates and connections are designed and made such that when a force is applied perpendicular to each strain gage the other strain gage does not get activated.

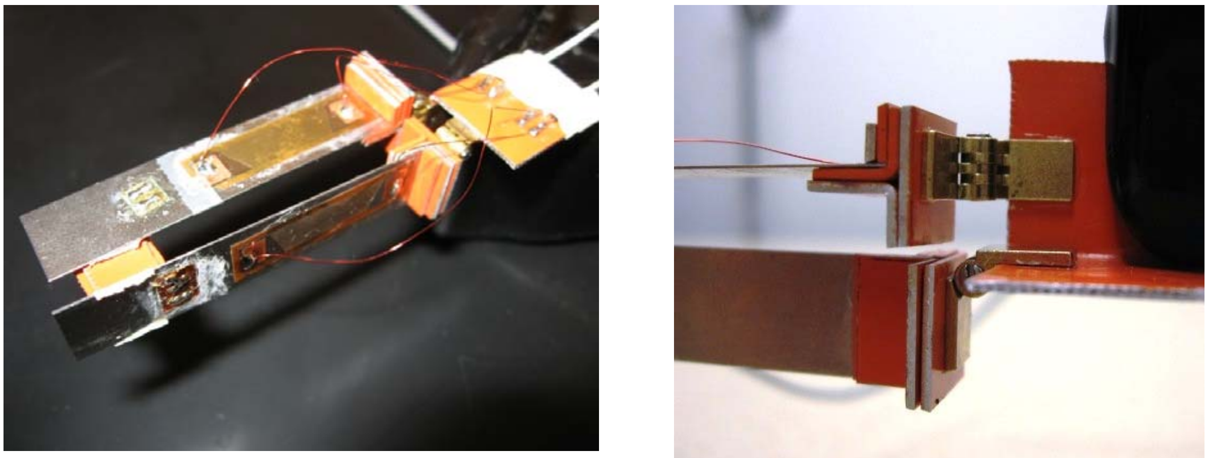


Figure 9: Prototyped 2-D strain gage placed on the slave end-effector

When the operator controlling the master has the feeling of direct interaction with the remote environment, the system is `called “transparent” (Figure 10). It physically means that the impedance of the environment (external object) is equal to the transferred impedance from slave to the master or operator’s hand [26-28]. In this case for the same force we will have the same motion. There are two variables to change in order to match the impedance of master to the impedance of slave: damping and stiffness/compliance. The damping coefficient is a function of shear stress developed in the MR damper and the stiffness/compliance is a function of MR damper spring.

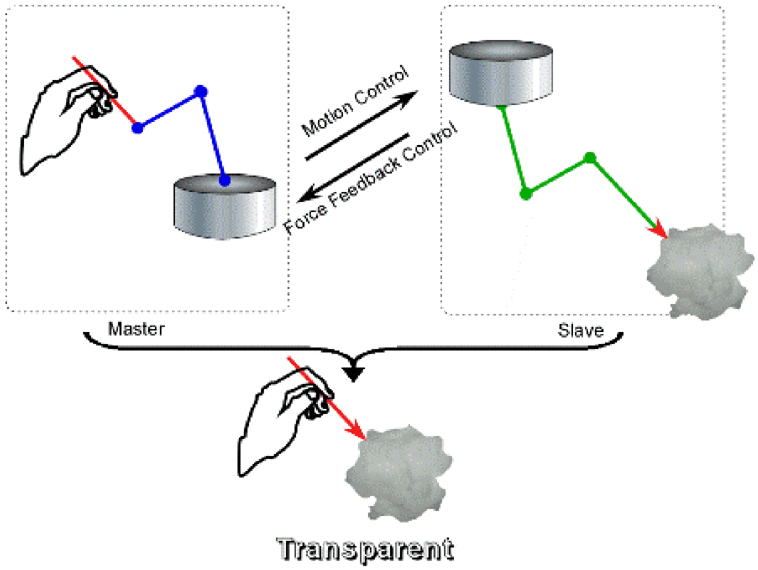


Figure 10: Transparent telerobotic system

7. EXPERIMENTAL RESULTS

As the user moves the 2-DOF joystick handle the x and y axis digital encoders sense the position of the joystick. The encoders signals are sent to a data acquisition system that, in turn, sends voltage to the five-bar linkage actuators. When the probe comes into contact with boundaries of a curved path, the probe pivots and the angular changes are sensed by a second set of encoders which are directly connected to rotary springs. This coupling allows one to infer the force that the probe experiences. This calibrated signal is then sent to data acquisition board and the corresponding control commands are sent to a DC power supply and as a result the current sent to joystick dampers is increased. This activates the MR fluid within the dampers and the user feels the boundaries of the curved path. For tracking purposes, the 2DOF force feedback system gives a more accurate result compared to visual only feedback (Figure 11).

The MR-based joints of the 5-DOF master robot where tested separately in the tensile testing machine. The resulting resistive torque-current for each joint is found and in plotted in Figure 12. Then the joints are assembled to make a 5-DOF robot. The MR-based master robot is used to control the motion of a slave. The test setup is shown in Figure 13. Wheatstone bridges and strain gage amplifiers are used to amplify the output signals of strain gages. DC power supplies are used to send the required currents to the MR damper in the master to generate desired resistive torque at each joint. A cutter is placed at the end effector. The slave is used to cut different objects with different stiffness and compliance. Based on the forces sensed at the end effector through the 2-D designed force sensor, the MR fluid-based dampers in the joints of the master are activated to replicate the resistive forces/torques encountered at the slave.

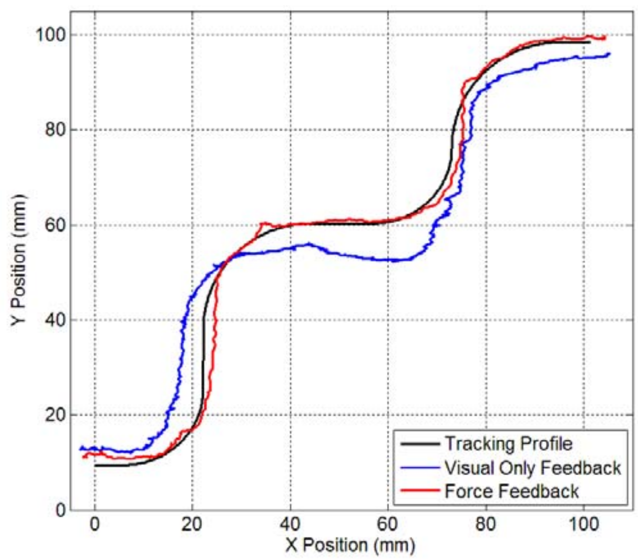
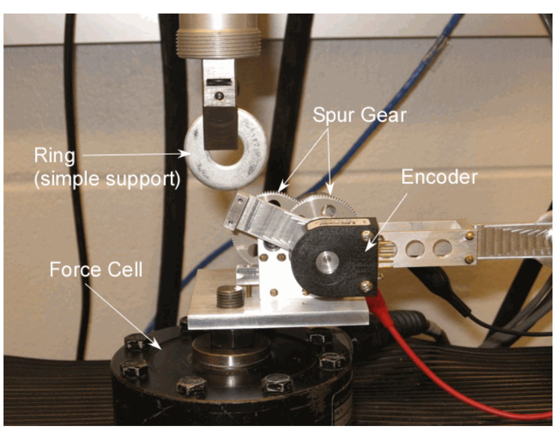


Figure 11: Tracking the 2-D profile by 2D force feedback joystick



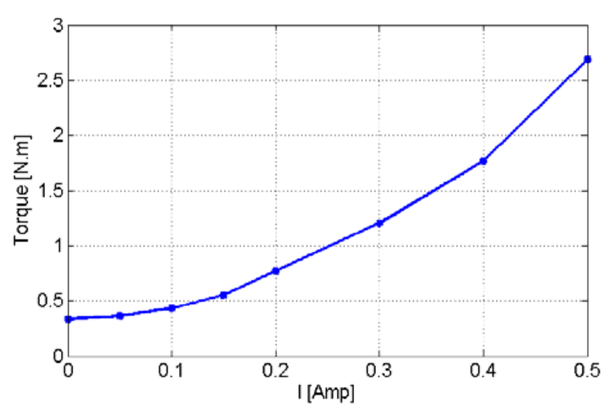


Figure 12: MTS machine test of one of the 5-DOF joints and the resulting torque-current graph

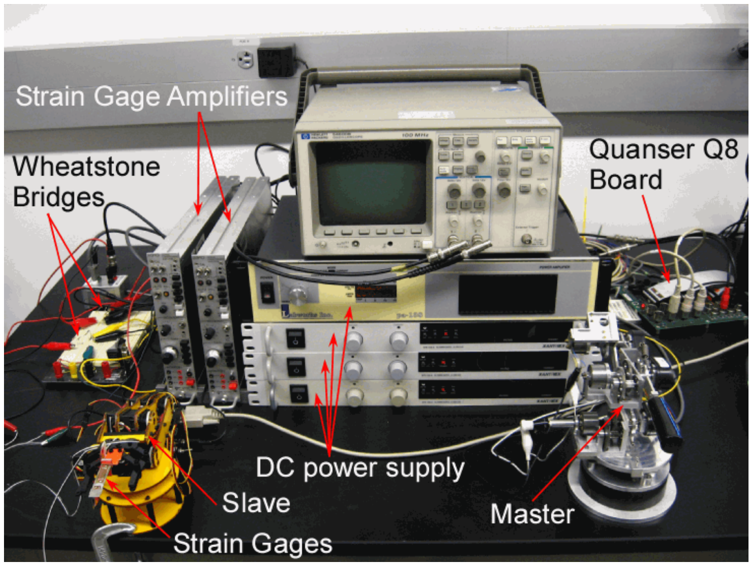


Figure 13: Test setup of the 5-DOF master-slave telerobotic system

The telerobotic system is used to remotely run into and cut objects with two different compliance and stiffness representing soft tissue and hard bone. By employing the force feedback the operator can feel the stiffness of different objects. By the forces sensed at the slave end-effector and replicated at the master joints the operator can distinctly determine which object is soft and which one is hard (Figure 14).

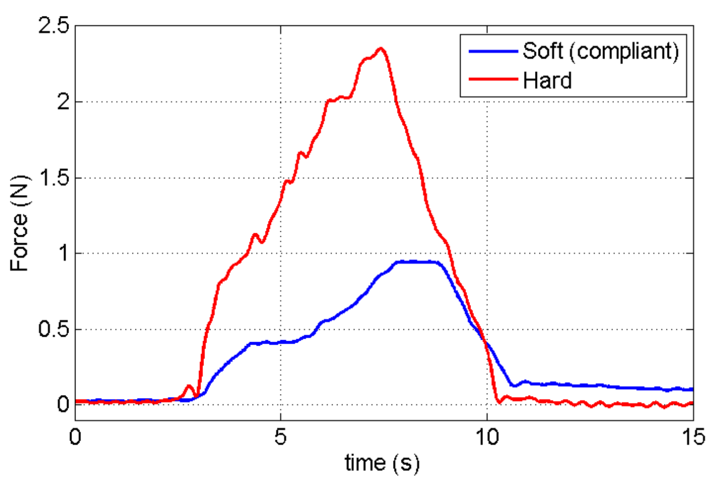


Figure 14: signals of the 2-D force sensor exerted by soft and hard external objects

8. CONCLUSION

Haptic systems greatly increase the effectiveness of a human machine interface. However, these systems use passive devices in force feedback systems that are unable to recreate a reactive force that helps in disengaging an object. The relative, simplicity and quick dynamics of an MR damper makes it a viable option for a myriad of haptic applications. This paper presents the design and implementation of a 2-DOF and a 5-DOF MR force feedback systems. Carbonyl iron powder and silicone oil was used to make the required MR fluid. MR sponge based dampers were designed using an interactive MR damper toolbox to simultaneously meet torque and magnetic circuit requirements. The results show good achievements in force feedback control of the system. The operator can sense the stiffness of external objects and distinguish hard and soft objects. The results of the new telerobotic system show that surgeon accuracy can be increased by at least a factor of 5 over systems with visual only feedback and that greatly improves the performance of the system and results in a safe MICT surgery. These systems can naturally be extended to those appropriate for telerobotic surgery.

AKNOWLEDGEMENT

This research is based upon work supported by the National Science Foundation under Grant Number 0528395.

REFERENCES

[1] E. C. Bingham, Fluidity and Plasticity. New York: McGraw-Hill, 1922.

[2] W. H. Herschel and R. Bulkley, "Model for time dependent behavior of fluids," in Proc. American Society of Testing Materials, 1926, p. 621.

[3] W. H. Herschel and R. Bulkley, "Measurement of consistency as applied to rubber-benzene solutions.," in Proc. Am. Soc. Test. Mater., Pt. II, 1926, pp. 621-633.

[4] J. Rabinow, "The Magnetic Fluid Clutch," AIEE Transactions, vol. 67, pp. 1308-1315, 1948.

[5] D. Lampe, A. Thess, and C. Dotzauer, "MRF- Clutch - Design Considerations and Performance," in 6th International Conference on New Actuators, Bremen, Germany, 1998.

[6] M. R. Jolly and J. D. Carlson, "A Controllable Squeeze Film Damper using Magnetorheological Fluid," in Actuator 96, Bremen, GY, 1996, pp. 333-336.

[7] G. M. Kamath, N. M. Wereley, and M. R. Jolly, "Analysis and testing of a model-scale magnetorheological fluid helicopter lag mode damper," J. American Helicopter Soc, vol. 44, pp. 234-248, 1996.

[8] G. M. Kamath, M. K. Hurt, and N. M. Wereley, "Analysis and testing of Bingham plastic in semi-active Electrorheological fluid dampers," Journal of Smart Materials and Structures, vol. 5, pp. 578-590, 1996.

[9] G. Yang, "Large-Scale Magnetorheological Fluid Damper for Vibration Mitigation: Modeling, Testing and Control," University of Notre Dame, 2001.

[10] G. Yang, H. J. Jung, and J. B.F. Spencer, "Dynamic Modeling of Full-Scale MR Dampers for Civil Engineering Applications," in US-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Region, Seattle, WA., 2001.

[11] B. F. Spencer, G. Yang, J. D. Carlson, and M. K. Sain, "Smart Dampers for Seismic Protection of Structures: A Full-Scale Study," in Second World Conference on Structural Control (2WCSC), Kyoto, Japan, 1998, pp. 417-426.

[12] S. Gopalswamy and L. Jones G., "Magnetorheological Transmission Clutch," United States, 1998.

[13] B. Kavlicoglu, F. Gordaninejad, C. A. Evrensel, N. Cobanoglu, M. Xin, C. Heine, A. Fuchs, and G. Korol, "A High-Torque Magneto-Rheological Fluid Clutch," in SPIE Conference on Smart Materials and Structures, San Diego, 2002.

[14] D. Lampe and R. Grundmann, "Transitional and solid state behavior of a Magnetorheological clutch," in the 7th International Conference on New Actuators, Bremen, Germany, 2000.

[15] J. D. Carlson, "Magnetorheological Brake with Integrated Flywheel," United States, 2001.

[16] M. Yokoyama, J. K. Hedrick, and S. Toyama, "A Model Following Sliding Mode Controller for Semi-Active Suspension Systems with MR Dampers," in Proceedings of the American Control Conference, Arlington, VA, 2001.

[17] C. Y. Lai and W. H. Liao, "Vibration control of a suspension system via a Magnetorheological damper," Journal of Vibration and Control, vol. 8, pp. 527-547, 2002.

[18] S. J. Dyke and B. F. S. Jr., "Seismic response control using multiple MR dampers," in Proceedings of the 2nd International Workshop on Structural Control, Hong Kong, 1996, pp. 163-173.
[19] L. Pang, G. Kamath, and N. Wereley, "Analysis and testing of a linear stroke magnetorheological damper," in AIAA/ASME/AHS Adaptive Structures Forum, Long Beach CA, 1998, pp. 2841 – 2856.
[20] S. Kim and Y. Park, "Constrained Rotary MR Damper Design and Its Application," in 4th International Conference on Motion and Vibration Control, Serial 4, Zurich, Switzerland, 1998.
[21] B. F. Spencer, S. J. Dyke, M. K. Sain, and J. D. Carlson, "Phenomenological Model of a Magnetorheological Damper," ASCE Journal of Engineering Mechanics, March 1996.
[22] J. Furusho, M. SakaGuchi, N. Takesue, and K. I. Koyanagi, "Development of ER brake and its application to passive force display," in Proceedings of the IEEE International Conference on Robotics and Automation, 2001, pp. 3825-3830.
[23] S. Bechtel, G. Washington, F. Ahmadkhanlou, and Y. Wang, "Microstructural Analysis and Control of Magnetorheological Fluid," in ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, 2004, pp. 509-518.
[24] V. A. Neelakantan, G. N. Washington, and R. Wolfe, "Force Feedback System using Magneto Rheological Fluids for Telerobotic Surgery," in SPIE Int. Conference on Smart Structures and Materials: Industrial and Commercial Applications of Smart Materials, San Diego, CA, 2002.
[25] F. Ahmadkhanlou, G. N. Washington, Y. Wang, and S. E. Bechtel, "The Development of Variably Compliant Haptic Systems using Magnetorheological Fluids " in 12th SPIE International Symposium, San Diego, CA, 2005.
[26] B. Hannaford, "A Design Framework for Teleoperators with Kinesthetic Feedback," IEEE Transactions on Robotics and Automation, vol. 5, pp. 426-434, August 1989 1989.
[27] D. A. Lawrence, "Stability and Transparency in Bilateral Teleoperation," IEEE Transactions on Robotics and Automation, vol. 9, pp. 624-637, October 1993.
[28] D. A. Lawrence, L. Y. Pao, M. A. Salada, and A. M. Dougherty, "Quantitative experimental analysis of transparency and stability in haptic interfaces," in in Proceedings of the Fifth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 1996.