Design and Development of a Magneto-Rheological Linear Clutch for Force controlled Human Safe Robots

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Abstract— **This paper proposes a Magneto Rheological linear clutch for use in human safe robotic applications. The force transmitted to the links of the robot must be precisely controlled for any manipulator if it has to be operated safely alongside humans. The traditional approaches to this problem is using various compliant actuating schemes like Series Elastic Actuators, Joint Torque Control etc. Research on the usage of smart materials that change their properties on application of electrical or magnetic fields for human safe robots have gained momentum recently. Studies on the feasibility of Magneto-Rheological actuators has been done already. This paper introduces a MR clutch which can control the force transmitted by a linear actuator. The electromechanical model of the linear clutch has been developed, implemented in hardware, and tested using a prototype one Degree of Freedom arm. The design of the clutch is detailed and the performance is characterized thorough a series of experiments. The results suggest that the linear clutch serves well for the precise force control of a linear actuator.**

I. Introduction

Robots with adaptable force control is of prime importance in human friendly applications, in which the robot may work alongside a human. In traditional industrial automation applications, the stiffness of the position controlled robot is often more valued. Such a stiff robot manipulator can impart serious injury to a human if it is not operated properly. Despite the numerous safety mechanisms existing, such accidents continues occurring and causes numerous human injuries each year [1]. The occurrence of such mishaps are not limited to those occurring during normal operation of the robot, but also during programming, maintenance, testing, calibration and setup. New class of robot manipulators called Collaborative Robots or CoBots are increasingly being deployed in environments which require human – robot interaction. These robots rely on different technologies like compliant actuators, torque controlled joints etc.

In this paper we propose a new mechanism for the precise force control of a robot manipulator using a linear clutch. The clutch uses Magneto-Rheological(MR) Fluids to control the ratio of force transmitted from the input to output. This paper is organized into VI sections. Section II briefly reviews the current state of Human-Safe Robots, Section III introduces MR Fluids and its suitability in human safe robotics. In Section IV, the design, analysis and construction of the linear MR Clutch is detailed. Section V deals with the experimentation and validation of the linear MR Clutch by implementing it in a one Degree of Freedom (DOF) robot arm. Finally section VI wraps up with concluding remarks.

II. Human Safe Robots

The safety of humans working along with robots are given high importance and much research is done to improve the workspace safety. An extensive study of the safety of humans during human-robot interactions is done in [2].Traditionally, the Head Injury Criterion (HIC) [3] has been used to measure the likelihood of injury arising from a collision impact in the automotive industry. HIC is also applicable in the context of human safety in robotic applications and is discussed in [4]. HIC is the measure of head acceleration for an impact that lasts for a certain duration and is given mathematically as,

$$HIC_{\Delta t} = \Delta t \left[\frac{1}{\Delta t}\int_0^{\Delta t} a(\tau)d\tau\right]^{2.5}. \tag{1}$$

Where $a(\tau)$, is the head acceleration normalized with respect to gravity g and Δt is the measurement duration. Robot specific metrics based on HIC are also proposed in literature. [5] Proposed a metric based on HIC called Manipulator Safety Index (MSI) that is a function of the effective inertia of the manipulator.

Robot manipulators can be made human friendly and safe using either by new mechanical design and actuation or by safety critical control system design or better, a combination of both. Safety implemented in mechanical design and actuation ensures safety even in the unlikely situation of loss of control system or software errors. This often relies on designing lightweight robot arms so as to reduce the impact force by lowering the kinetic energy and inertia. New actuation methodologies like joint torque control [6], Series Elastic Actuators (SEA) [7] and Variable Impedance Actuators [8] can be used to make robots safer. Joint torque control employs integrated torque sensors on all the actuated joints to monitor any abnormalities in the joint torques caused by any collision. A couple of robot manipulators in the market like Kuka iiwa, which is based on the DLR (German Aerospace Center, Deutsches Zentrum fur Luft-und Raumfhart) lightweight arm[9], makes use of this methodology. Even though excellent force control characteristics are possible in DLR arm due to the near zero low frequency impedance, the joint torque control is ineffective in reducing the impedance at above the control bandwidth. The open loop characteristics make difficult achieving the inherent safety.

Series Elastic Actuators employ an elastic element like a spring in between the output of the actuator and the link of the robot. The high frequency impedance of the actuator is then limited to the stiffness of the spring or elastic coupling. It provides low output impedance across the bandwidth of

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operation. Examples of robots using SEA include Baxter [10] by Rethink Robotics. However the introduction of an elastic element brings down the bandwidth of the actuator [11]. Discussions on the various methodologies for compliant human safe robots are discussed in [12]. There exists Variable Stiffness Actuators (VSA)[13], in which the stiffness of the actuator can be controlled on the fly. Variable Impedance Actuators are an extension of SEA in which a variable damping element is also adding along with the variable stiffness mechanism [14].

III. MAGNETO-RHEOLOGICAL FLUIDS

Magneto-Rheological (MR) Fluids[14,15] are stable non-colloidal suspensions of micro-sized magnetizable particles in a carrier fluid of low permeability, like silicone oil. They constitute a class of smart materials that can change the viscosity under the effect of an external magnetic field. Under normal conditions, the microscopic particles are distributed randomly in the suspension. In presence of an external magnetic field, the microscopic particles will align to the magnetic lines of force and form chains. MR fluids are often modelled using the Bingham viscoplastic model, in which the shear stress of the fluid is a function of the applied field and shear rate [16] as follows,

$$\tau = \tau_y(\boldsymbol{H}) + \eta \frac{dv}{dz}, \quad \tau > \tau_y. \tag{2}$$

Where τ is the shear stress, τ_y is field dependent yield stress, $\boldsymbol{H}$ is the applied magnetic field intensity, η is the Newtonian viscousity, dv/dz is the velocity gradient in the direction of the field.

MR fluids can operate in three different modes- valve mode, direct shear mode and squeeze mode. The shear mode is of particular interest in which the MR fluid functions in between a stationary plate and a parallel moving plate with the magnetic field perpendicular to the plates. The moving plate induces shear stress in the fluid and its magnitude is controlled by the strength of magnetic field. The feasibility of using MR fluids for human friendly robotics was studied in [17]. A Magneto-Rheological fluid based rotary clutch was developed and its characteristics was studied. Further to this a hybrid MR Clutch was developed in [18] in which permanent magnets were used in addition to the electromagnetic coils to add or negate the magnetic field to any desired value. The design optimization of the rotary MR clutches are studied in [19]. All the aforementioned studies were done on rotary MR clutches. Little or no research has been done in linear MR clutches. The proposed linear MR clutch is a development in this unexplored category of MR clutches

IV. MAGNETO-RHEOLOGICAL LINEAR CLUTCH

The linear clutch for force control uses MR fluids in shear mode for its operation. The cross sectional view of the clutch is shown in Fig 1. The input shaft can move in and out of the mechanism. Any type of linear actuator, either electric, hydraulic or pneumatic type can be used to power the input shaft. The input shaft runs along the entire length of the clutch, transferring force to the MR fluid. The input shaft is made of hard anodized lightweight aluminum, thereby offering a significant reduction in the overall weight and thereby the inertia of the system.

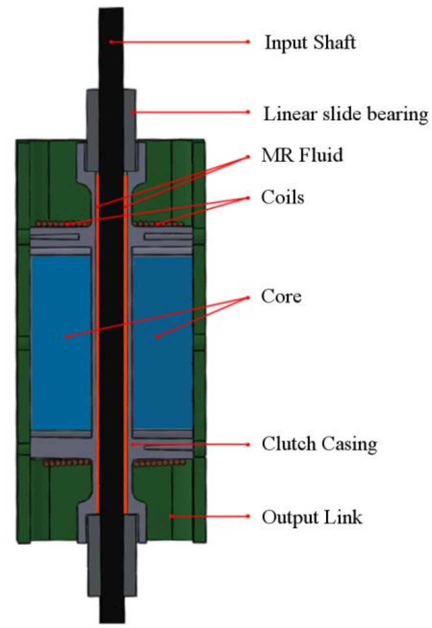

Fig. 1. Cross Sectional view of the linear clutch.

The output of the external linear actuator is coupled to the input shaft through a 3D printed shaft coupler, which is specific to the model of linear actuator used. The input shaft is supported by two linear shaft bearings and runs inside a cylindrical clutch casing filled with a thin film of MR fluid. The input shaft is immersed in the MR fluid and moves through it. The linear shaft bearings have rubber seals which prevents the MR fluid from leaking outside. The force imparted to the system through the input shaft is coupled to the clutch casing through the MR fluid. The CAD model of the clutch is shown in Fig. 2.

The cylindrical clutch casing is having two hollow fins placed bilaterally and running along the entire length axially. The coils are wound over the fins and the hollow space inside the fins are filled with laminated thin plates of silicon steel as core, which is having high permeability and low hysteresis losses. Laminated thin plates are used to reduce the eddy current effects and the high permeability helps to concentrate the magnetic flux lines thereby creating a stronger magnetic field. The narrow hysteresis curve means the response time of the coil is low and thus helps in high bandwidth force control by the clutch.

The coils are wound over the silicon steel core fins. The currents flowing through the coils are in such a way that the magnetic flux lines produced by each of them are in same direction and passes radially through the cylindrical cavity of the clutch casing. This ensures that the magnetic field lines are perpendicular to the direction of motion of the input shaft. Since the current in the two coils are in same direction, the

Fig. 2. CAD model of the linear Clutch

magnetic fields produced by each of them sums up. The magnetic fields produced inside the clutch can be calculated using the Biot-Savart's law,

$$\partial\vec{B} = \frac{\mu_0}{4\pi} I \frac{\overrightarrow{dL} \times \hat{r}}{4\pi r^2} \tag{3}$$

Where $\partial\overrightarrow{B}$ is the magnetic field at a point at distance $\hat{r}$ from a current carrying conductor of length $\overrightarrow{dL}$ due to a current I. Applying this to the two rectangular coils of the clutch gives the magnetic field produced at the center of the clutch as follows,

$$|B| = 2N.\frac{\mu_0\mu_r}{4\pi}\ I \left[\frac{a^2}{\left(\left(\frac{a}{2}\right)^2+d^2\right)\sqrt{d^2+2\left(\frac{a}{2}\right)^2}} + \frac{b^2}{\left(\left(\frac{b}{2}\right)^2+d^2\right)\sqrt{d^2+2\left(\frac{b}{2}\right)^2}}\right] \tag{4}$$

Where N is the number of turns of the coil, μ_0 is the permeability of free space, μ_r is the relative permeability of the core, I is the current flowing, a and b are the length and width of the rectangular coil and d is the distance from the coil to the centre of the cavity. Since all other parameters except the current I is kept constant, the strength of magnetic field depends only and directly on the current.

The characteristics of the linear MR clutch was modelled and verified using Finite Element Methods (FEM) prior to the detailed design and hardware implementation. The FEM characteristics are shown in Fig.3. It can be noted that the magnetic field is constant over the area of MR fluid and flux lines are perpendicular to the input shaft. This ensures that the chains formed by the alignment of microscopic particles in the MR fluid will be perpendicular to the axis of motion and thus maximum utilization of the stress force can be done. Fig. 4 shows the prototype linear clutch.

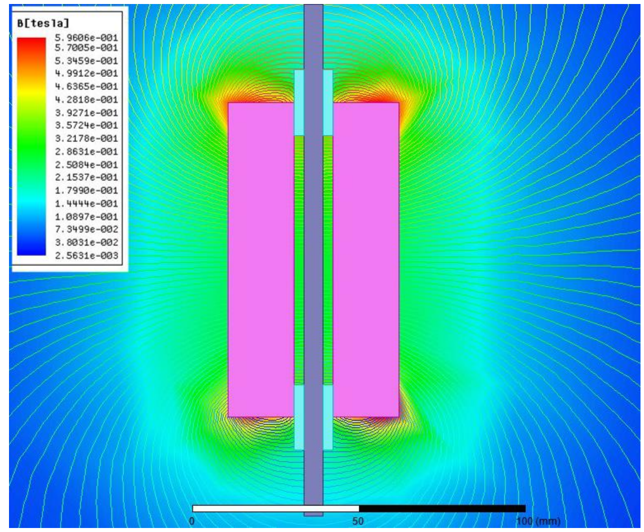

Fig. 3. Magnetic field and flux line distribution inside the MR clutch

The cylindrical clutch casing, the two fins, bearing holders and the holding support which acts as the output link are all made using 3D printing technology. This helps in bringing down the prototyping time, cost and the weight of the entire system. The MR fluid couples the input force, brought in by the input shaft to the walls of the cylindrical clutch casing. The magnitude of force coupled depends on the amount of stress handled by the MR fluid, which in turn depends on the magnetic field. The force coupled can be calculated as,

$$\partial\vec{F} = 2\pi r\vec{l} \times \vec{\tau} dl. \tag{5}$$

Where r is the radius of the input shaft, l is the length of the shaft immersed in MR fluid and τ is the shear stress.

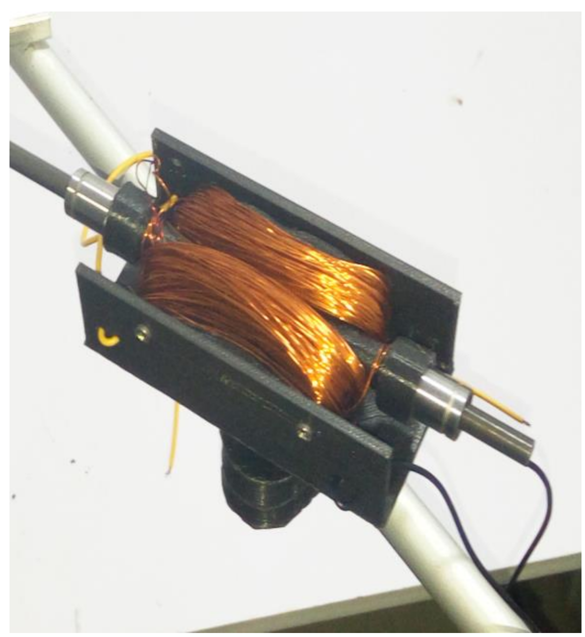

Fig. 4. Photograph of the prototype linear MR clutch

Integrating the above along the entire length gives the total force output of the clutch

$$F = 2\pi r \int_0^L l \times \tau dl \quad (6)$$

$$|F| = \pi r L^2 \tau \quad (7)$$

$$|F| = \pi r L^2 (\tau_y + \eta \dot{\gamma}) \quad (8)$$

Where τ_y is the shear stress component due to the magnetic field, η is the viscosity and $\dot{\gamma}$ is the shear rate which is given by,

$$\dot{\gamma} = v/h \quad (9)$$

Where v is the relative velocity between the input shaft and the walls of the cylindrical clutch casing, h is the separation between the moving input shaft and the stationary internal walls of the clutch casing.

Therefore assuming a constant input velocity, the force experienced by the cylindrical cavity depends only on the variable magnetic field, which in turn is modulated by the current flowing inside the coil. The force output is taken through the supports attached to the clutch casing and can be coupled to the link of the robot.

In the absence of magnetic field, there exists only pure viscous coupling and the force transmitted from input to output will be minimum and constant, assuming fixed velocity at input. With increasing currents in the coil, the magnetic field inside the MR fluid and correspondingly the viscosity of the fluid increases, thereby transmitting more force from input to output.

V. EXPERIMENTS AND RESULTS

In this section we present a one degree of freedom robot arm comprising of a revolute joint, implementing the proposed MR clutch. The CAD model of the experimental setup is shown in Fig. 5 and the actual implementation in Fig. 7. The arm is powered by an off the shelf electric linear actuator, which uses an internal lead screw to generate linear motion.

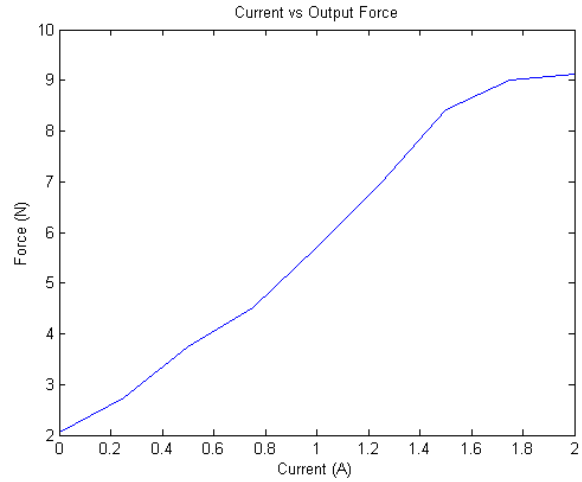

Fig. 6. Current verses Force output curve of the MR linear clutch.

The usage of a high gear ratio lead-screw results in a very stiff and nonbackdrivable actuator - the perfect mismatch for any application involving human-robot interaction as such. The nonmoving fixed base of the linear actuator is fixed to the proximal link of the robot through a passive revolute joint. The actuator has a peak force of 12N and backdriving force of 43N when powered off.

The output of the linear actuator is coupled to the input shaft of the clutch through a custom designed and 3D printed shaft coupler. The input shaft of the clutch takes in the force and transfers a part of it to the output cylindrical clutch casing. The magnitude of force coupled from input to output is controlled by the current flowing in the coil. The cylindrical cavity along with the coils and supporting mechanism are attached to an extruded U shaped part, which in turn couples the forces to the distal link through another passive revolute joint. All these components except the proximal and distal links, T slotted aluminum profile and input shaft are 3Dprinted.

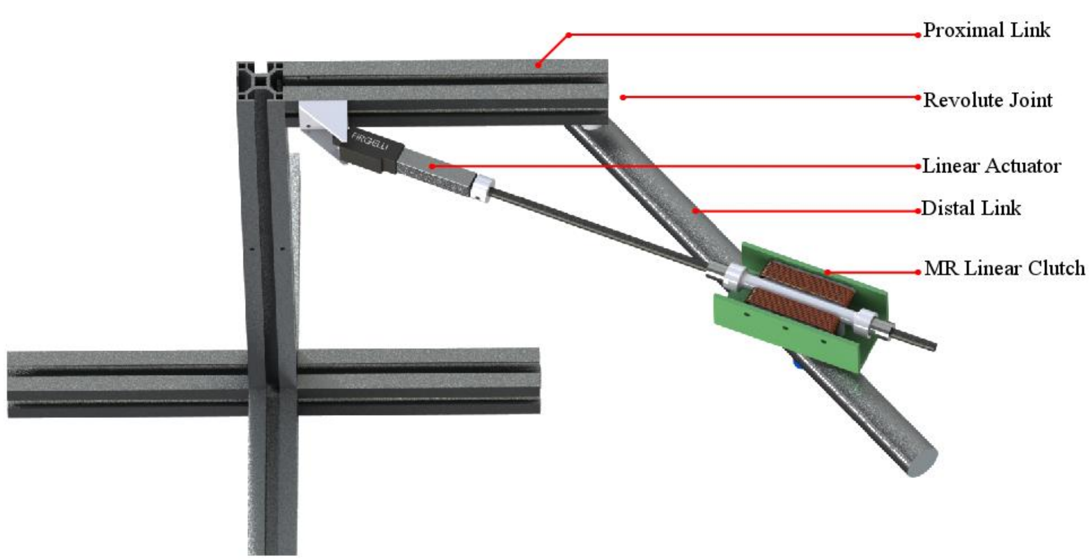

Fig. 5. CAD model of the experimental Setup. MR linear clutch is used in a revolute joint actuated by a linear actuator

Fig. 7. Photograph of the experimental one Degree of Freedom arm to characterize the MR linear clutch

In order to characterize the performance of the linear clutch, the linear actuator is driven and the force experienced at the distal link is measured using a force sensor. The linear actuator is a purely position controlled servo and controlled with Pulse Width Modulation (PWM) signals generated by an Arduino.The position value of the actuator is commanded from a laptop computer to Arduino over a serial link. The linear actuator is commanded to move from the fully retracted extreme position to fully extended extreme position. The linear actuator can exert a peak force of 12 N and move at a velocity of 23mm/s.

The force exerted by the distal link on an external body, when it is moving from one extreme position to the other is studied. The experiment is repeated for different values of the coil current and the changes in output force is measured using a load cell based force sensor and studied. The changes in output force with the current in the coil is observed as in Fig.6. Even when the coil is not actuated, and magnetic field is zero, there exists a certain amount of coupling in between the input shaft and output and a very small amount of force is transmitted. This can be attributed to the purely viscous coupling through the MR fluid. As the current and subsequently the magnetic field in the coil increases, the force coupled to the output also increases linearly until a point at which the output saturates and begins to flatten out. This saturation can be attributed to the maximum yield stress of the MR fluid. Increasing the coil current beyond 2 Amperes was impractical because of the excessive Joule heating of the coil. By varying the current in the coil, the force at the output was able to be controlled precisely from 2N to 9 N

VI. Conclusion

The proposed linear MR clutch can provide precise force control. MR fluid based clutches are ideal for human friendly manipulators. The force exerted by the actuator can be precisely controlled and is backdriveable. It is much simpler than a system with similar functionality implementing closed loop force control using force sensors and stiff actuators. Another advantage of the MR clutch is that the maximum force that can be transmitted from input to output is hard limited by the yield stress of the MR fluid. This guarantees safety even if the control system of the robot fails. Moreover, the MR clutches does not have wear and tear like friction clutches and can operate reliably for long periods of time. Further research on the MR linear clutch can focus on combining the rotary and linear MR clutches to develop a hybrid clutch. Another possibility is combining the linear actuator and clutch as a single piece which can help in reduction of size and weight.

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