A Novel Approach for Solving Compliant Motion of Robot Manipulators

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ABSTRACT
This paper presents new concept for controlling manipulators in compliant motion tasks. Compliant motion requires interaction control strategies governed by indirect force control (Compliance and Impedance control) or direct force control. Impedance control and compliant behavior for safe human-robot physical interaction of industrial robots, normally can be achieved by using active compliance control of actuators based on various sensor data. Alternatively, passive devices allow controllable compliance motion but usually are mechanically complex. We demonstrate a unique method using a novel actuation mechanism based on magneto-rheological fluid (MRF) that incorporates variable stiffness directly into the joints. This brings much simple interaction control strategy compared to other antagonistic methods. In this studies, we have examined and analyzed fundamental characteristics of MRF actuation mechanism and presented the analytical model. Then we have developed the static and dynamic model based on experimental test results. Classical sliding mode control approach is adopted for implementing position control. Finally, we discussed three essential modes of motion needed for human-robot manipulation interactive tasks.

Categories and Subject Descriptors
H.4 [Safe human robot interaction]: Intelligent Control Robotics; Modeling, simulation and control; D.2.8 [Control Engineering]: Metrics—safety measures, complexity measures, torque analysis

1. INTRODUCTION
Future generation of robots will have to cope with physical contact with human tasks under uncertainty in a stable and safe manner [6]. Fundamental success of such physical human robot (HR) interaction is based on the capability to handle interaction between the robot and the environment.

Robots have recently foreseen to work side by side, share workspace with humans and give assistance in performing various tasks involving physical HR interaction. However, current industrial robot manipulators are still very far from HR coexisting environments, because of their unreliable safety, rigidity and heavy structure.

Force/torque control is necessary when robot need to interact with unknown environment. Robot arm can improve the safety and performance due to its functional characteristics similar to the human arm as shown in [13]. Active compliant devices [14], [8] necessitate various sensors data (e.g. feedback signals from force/torque sensors), therefore this scheme provides a delayed contact response, high cost, unreliable safety (during electrical failure) and needs complex control algorithms. Besides all these limitations, active compliance control is still acclaimed due to its high programming ability. On the other hand, passive compliant devices [3], [1] based on passive mechanism like spring, sliding axles and knee joints, usually achieve the compliance on the cost of higher system complexity. Mechanical compliance achieved by using dampers, ensures the safety only up to certain extent during physical HR interaction. Previously, friction brakes have been used as dissipative and coupling elements, resulting undesired effects such as vibration, friction and slow response time [9].

The previous studies on compliance were mainly focused on design methods for accuracy (in accomplishing the defined task) and advanced control for safety. Even feasible in realistic conditions, this approach generally leads to structural complexity. Therefore, we propose a new approach, which aims to achieving safety with inherently compliant components and simplified control algorithms, keeping the desired accuracy.

This paper elaborates some aspects of a safe robot manipulator design by using smart materials for the actuation mechanism. The compliance can be rendered by controlling the properties of these materials. Electro-rheological fluids (ERF) and magneto-rheological fluids (MRF) are well known smart materials that change their rheological properties when electric or magnetic field applied respectively. We decided to use MRF-based mechanism.

Our MRF actuation mechanism is an assembly of MRF brake / clutch and DC-servo motor. Compliance is controlled by the application of magnetic field where as position control is achieved by standard DC motor control. This results in much simpler compliance control algorithm compared to the compliance control strategies used in active and

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passive compliant devices [7], [11]. However, MRF based compliance control needs deeper analysis of the MRF actuator characteristics under different operating conditions. In this study, we present the experimental approach for finding a model of the actuator.

The plan of the paper is as follows. In Section 2, we present the construction of a robot arm system with MRF actuation mechanism. In Section 3, overall system modeling is described. Experimental setup and the experiments performed for building static and dynamic model are discussed in details in Section 4. Position control achieved by sliding mode control is shown in Section 5. In Section 6, investigated modes of motion essentially required for safe HR interaction based on compliance/stiffness on demand are presented while in the concluding Section 7, possible future investigations are indicated and a brief summary of the paper is reported.

2. THE ROBOT ARM SYSTEM
The two-link planar robot prototype shown in Fig.1, is our research setup. Variable stiffness is accomplished by incorporating MRF actuator at each joint.

2.1 System overview
Figure 2 demonstrates the Lord corporation’s MRF brake / clutch used and the proposed MRF actuation mechanism respectively. By varying the magnetic field, we control the torque transmitted to the respective link. The fully activated brake/clutch transfers nearly the entire torque produced by the motor to the actuated robot link, giving in this way the highest stiffness of the actuation mechanism. When deactivated, the brake/clutch transfers nearly zero torque, which corresponds to the highest compliance of the actuation mechanism.

2.2 The controllable fluid clutches
Controllable fluid clutches have input and output rotating shafts. These rotating parts are surrounded by a thin layer of a rheological fluid. No physical contact between the input and output shafts, results in smooth and frictionless transition between shear stress levels when exposed to the applied fields [9]. Smoothness in operation was justified through investigations.

3. SYSTEM MODELING
The differential equation representing net torque at each joint, is defined in terms of its inertial and damping parameters as follows:

$$J_i \ddot{\omega}_i + D_i \dot{\omega}_i = \tau_{\text{out}}^i - \tau_{\text{load}}^i \quad i = 1, 2,$$  \hspace{1cm} (1)

where, $J_i$ denotes the mass moment of inertia, $D_i$ is the damping parameter and $\omega_i$ is link’s angular velocity. Stable equilibrium refers to the condition where the generated output torque is equal to the load torque

$$\tau_{\text{out}}^i = \tau_{\text{load}}^i \quad i = 1, 2,$$

whereas, dynamic motion is achieved when the output generated torque of the actuator is greater than the load torque

$$\tau_{\text{out}}^i > \tau_{\text{load}}^i \quad i = 1, 2.$$

3.1 Electromagnetic circuit modeling
Electromagnetic coil can be represented by the RL-circuit. $V_s$ is the voltage over RL-circuit, $V_R$ is the voltage over the
coil resistance and \( V_L \) is the voltage over the coil winding itself, concerning the effects of inductance
\[
V_S = V_R + V_L.
\]  
(2)

According to Faraday’s law of induction
\[
V_L = d\Phi_m/dt.
\]

As the magnetic flux is \( \Phi_m = L \cdot i \) we get
\[
V_L = d(L \cdot i)/dt = dL/dt + L di/dt
\]
and respectively
\[
V_s = i \cdot R + L di/dt.
\]

The transfer function is defined as
\[
i(s)/V_s(s) = \frac{1}{Ls + R}.
\]

Due to the small coil inductance \( L \) and low coil resistance \( R \) the time constant is of about few milliseconds.

### 3.2 MR fluid modeling

The Bingham’s plastic model [15] describes the properties of the MR controllable fluids. The output torque equation derived by this equation is
\[
\tau = \tau_y(H) + \eta \dot{\gamma}
\]  
(3)

where \( \tau \) is the shear stress, \( \eta \) is the dynamic viscosity, \( \dot{\gamma} \) is the shear rate, \( \tau_y \) is the yield stress and \( H \) is the magnetic field intensity.

The first term of the right hand side of the Eq.3 produces a torque dependent on the magnetic field and the second term represents a viscous torque based on material characteristics and therefore it is constant. Viscous torque is negligible as compare to the magnetic field dependent torque. Rosensweig’s laminae model [15] explains the relationship between the yield stress (torque) and the magnetic field as follows:
\[
\tau_y = \frac{\mu_0 H^2}{4} \left[ \phi(1 - \phi)\chi_m^2 \right]
\]  
(4)

where \( \mu_0 \) is the vacuum permeability, \( \phi \) is the volume fraction of iron particles and \( \chi_m \) is the susceptibility of magnetic material laminae.

It predicts that the transmitted output torque is proportional to the square of the magnetic field intensity, while the expression in the brackets of Eq.4 is a constant. Since the magnetic field intensity itself a function of the current induced in electromagnetic coil, the output torque eventually becomes a function of the induced current:
\[
\tau = f(i).
\]  
(5)

### 3.3 The system

Combining all these equations, we derived the MATLAB / Simulink block diagram of the system consisting of MRF actuation mechanism and the respective link dynamics shown in Fig. 3. Note that the mechanics block requires mass moment of inertia \( J_i \) and the damping parameter \( D_i \) as external inputs.

![Figure 3: System Block Diagram.](image)

### 4. EXPERIMENTS

The experimental setup block diagram is given on Fig.4.

![Figure 4: Experimental Setup Block Diagram.](image)

4.1 Static model

Experiments are conducted in the speed range of 10 to 100 % of the full scale (FS) speed supplied by the DC servo motors and in the current range of 5 to 75% of the FS current induced in the MRF brakes/clutches respectively. Fig 5 and Fig 6 show the surface plot of torque characteristics response as a function of coil current and the motor speed for each joint actuation mechanism respectively.

From these experiments, it can be observed that output torque is dependent mainly on the coil current whereas speed dependence is negligible at the speed higher than 20% of...
Figure 5: Static Analysis of MRF Actuator (Link 1).

the FS. This confirms our statement expressed by Eq.4 and Eq.5.

However, at low speed ranges, below 20% of FS, torque dependencies are observed. It can be clearly seen for link 2 in Fig.6. This dependency might have occurred due to particle settling in MRF brake/clutch (if left unused for a long period of time) and also by the occurrence of in-use thickening [12] (if MR fluids are subjected to high stress and shear rates for a long period of time). All these phenomena may lead to a performance deterioration and should be taken care of for achieving optimal results.

Figure 6: Static Analysis of MRF Actuator (Link 2).

Non linear nature of Eq.4 and Eq.5 can be linearized as shown with dotted and dashed lines in Fig.7 and Fig.8 and a piecewise function $K_j$ of the following form is proposed as torque gain for each actuator, j.

$$K_j = \begin{cases} k_{ja}i + k_{jb}, & i < 30\% FS \\ k_{jc}i + k_{jd}, & i \geq 30\% FS \end{cases} \quad j = 1, 2$$

The coefficients, $k_{ja}$, $k_{jb}$, $k_{jc}$ and $k_{jd}$ are the torque gain linearized parameters.

4.2 Dynamic model

For building the dynamic model we conducted the experiments at the motor speed of 50% of the FS.

The measured transient responses represent actuator’s output transmitted torque as a function of time, shown on Fig. 9 and Fig. 10. The noisiness in the torque output response is attributed to a number of factors including imprecise experimental and mechanical setup.

Time constants $T_1$ and $T_2$ are estimated as 35 and 33 milliseconds respectively. The proposed clutch transfer function $T_f(s)$ (Eq.6) of first order describes the relationship between output transmitted torque $\tau_{out}$ and the input coil current $i_{in}$.

$$T_f(s) = \frac{\tau_{out}}{i_{in}} = \frac{K_j}{T_j s + 1}$$
With the help of Eq.1 and Eq.6, system transfer function,

\[ P_c(s) = \frac{1}{sJ_i + D_i} \times T_f(s) \]  

The analytical model of MR fluid presented in Eq.4 and Eq.5 is based on well known Rosensweig’s laminae model and Bingham’s plastic model which are widely used for MR fluid modeling. Experimentally fitted linearized model of the order one shown in Eq.6 nearly approximates the proposed MR Fluid analytical model.

5. CONTROLLER DESIGN

Control of robotic manipulators in constrained motion tasks requires high accuracy in position control as well as in compliant motion control. Therefore, such tasks necessitate two kinds of control loops to be implemented simultaneously. Outer loop guarantees the positioning accuracy while the inner loop provides the desired compliance to the system based on feedback sensor data.

In our research work, position control is achieved by the use of sliding mode control while the compliance control is realized initially on demand, by controlling the current to MRF clutch. The design of more elaborate adaptive compliance control strategies is the subject of our next studies.

In position control tasks, robots own dynamics contributes crucial role on its performance. Typically, the problem of model mismatching occurs between the actual plant and the mathematical model developed for controller design. This discrepancies can be due to un-modeled dynamics, variation in system parameters or the approximation of complex plant behavior by a simple model [2]. Position control design objective is to achieve the required performance despite such plant - model mismatch.

In this section, we will present the dynamic equation model of the robot manipulator and some basics of sliding mode control (SMC) for position control of robot manipulators.

5.1 Dynamic equation model

The dynamic equation model representing n-link robot manipulator is as follows:

\[ J(q) \ddot{q} + D(q, \dot{q}) \dot{q} + G(q) = \tau \]  

where, \( q = [q_1, ..., q_n]^T \) is \( n \times 1 \) vector of joint positions (angle), \( \dot{q} = [\dot{q_1}, ..., \dot{q_n}]^T \) is an \( n \times 1 \) vector of joint velocity (angular rates), \( \ddot{q} = [\ddot{q_1}, ..., \ddot{q_n}]^T \) is an \( n \times 1 \) vector of joint acceleration (angular accelerations), \( \tau \) is an \( n \times 1 \) vector of control input, \( J(q) \) is an \( n \times n \) inertia matrix, \( D(q, \dot{q}) \) is an \( n \times n \) matrix of coriolis and centrifugal forces and \( G(q) \) is an \( n \times 1 \) gravity vector.

Robot manipulators are highly nonlinear and time variant systems, having model uncertainties (external disturbances, parameter uncertainty, sensor errors etc). It is important to note that the matrices \( J(q) \), \( D(q, \dot{q}) \) and \( G(q) \) are derived from the system modeling. Therefore, these parameter matrices are implicitly known with uncertainty. This
leads to the development of robust control methods capable of producing required performance under uncertainty. One particular candidate to robust controller design is variable structure control methodology.

5.2 Variable control structure

Variable structure control systems (VSCS) are defined by a suit of feedback control laws and a decision rule [2]. These control laws are intentionally changed during the control process based on the decision rules. These decision rules are characterized as switching function and depend on the state of the system. Hence VSCS can be regarded as the combination of subsystems (fixed control structures) which are defined for specified region of system behavior.

5.2.1 Sliding mode control

Sliding mode controller is a special kind of VSCS used to stabilize single input systems and usable for both linear and non linear systems [4], [5]. Control law for SMC is itself discontinuous and therefore there is no requirement on continuity [2]. In SMC, VSCS are designed, first to derive sliding mode. With this control configuration, second link becomes hard upon collision, and hence continuously changes its trajectory while in contact with the obstacle. Once there is no contact, it switches to stiff mode again and execute the position reaching task.

The tracking error, $e$ shown in Eq.9 is the difference between joint position $q$ and the desired position $q_d$. The control objective is to minimize this tracking error, $e$.

$$e = q - q_d$$  (9)

Sliding surface referred as switching function, $s(e,e)$ is defined as:

$$s(e,e) = e + \lambda e$$  (10)

where, $\lambda = \text{diag}[^{\lambda_1,...,\lambda_i,...,\lambda_n}]$ and $\lambda_i$ is a positive constant.

Control input $\tau$ can be chosen as:

$$\tau = \dot{s} - W \text{sgn}(s)$$  (11)

where, $\dot{s}$ is the estimate of $s$ and $W = \text{diag}[w_{11}, ..., w_{ii}, ..., w_{nn}]$ is the diagonal positive definite matrix where $w_{ii}$ is a positive constant.

Stability of the system can be evaluated by Lyapunov function;

$$V = \frac{1}{2} s^T J s$$  (12)

where, $J$ is symmetric and positive definite. For $s \neq 0$, Lyapunov function in Eq.12 will be $V > 0$

Therefore, in order to ensure the stability $\dot{V}$ must be negative (less than zero), as shown in Eq13.

$$V = s \dot{s} < 0$$  (13)

6. COMPLIANCE/STIFFNESS ON DEMAND FOR SAFE (HR) INTERACTION

Human-robot interaction characterizes several motions to be incorporated by a robot manipulator, based on feedback signals to perform any interactive task. These tasks usually involve the combination of several motions ranges from fully stiff to fully compliant depending on the situation and the uncertainty. For the proof of concept and validation of our methodology, we have performed different experiments to achieve these motions by controlling the compliance/stiffness of the MRF joint actuators. The investigated modes of motion needed for manipulator interactive tasks are the following three types.

6.1 Stiff mode

Robot manipulator acts as a normal stiff manipulator with fully activated MRF joint actuators. Task to reaching desired position within the manipulator workspace is accomplished through position and velocity control loop. The task executed in stiff mode has zero compliance and therefore, not suitable for interaction situations as well as the conditions under uncertainty. For the remaining situations this mode is activated.

6.2 Soft mode

Conditions where collision is unavoidable (uncertainty) such as sudden, unexpected intrusion of an obstacle, soft motion mode is activated by switching from fully stiff to highly compliant joints. This switching is done on demand by simply controlling the input current to the respective clutch. We have simulated a scenario in which an obstacle (a very fragile piece of paper held by an operator) comes unexpectedly within the robot workspace during trajectory execution task. Soft mode is activated on demand to the second actuator, results in touching the obstacle very softly without damaging it, while the first joint actuator operates in stiff mode. With this control configuration, second link becomes soft upon collision, and hence continuously changes its trajectory while in contact with the obstacle. Once there is no contact, it switches to stiff mode again and execute the position reaching task.

6.3 Compliant mode

HR interaction usually involves the conditions, where the human operator enforces the robot to superimpose its motion over the robot’s specified trajectory motion. These situations elaborate the requirement of variable compliance of the robots. In MRF actuator, the desired strength of the compliance is achieved by controlling the level of the input current to the clutches. The degree of strength ranges between 0 and 1, corresponding to zero compliance (stiff) to the full compliance. In order to simulate compliant motion mode, we have implemented a scenario in which our robot manipulator restores its pose after being changed by the human operator. Compliant mode to the actuators is activated with 0.5 degree of strength resulting in compliant behavior of the robot with the human. Upon release, the robot restores to its original position. This leads to the important aspect of high back drivability, inherent to the MRF actuators. With this embedded characteristics, the human operator can easily operate and command the robot manipulator.
7. CONCLUSIONS
We have studied the properties of MR fluid based actuators. We have developed the static response and dynamic response model of the MRF actuation mechanism. Validity of the proposed approach in transferring current dependent controllable torques (variable torques) is verified along with very fast response time. It has been analyzed that the dynamics of the MRF brake / clutch does not influence the dynamics of the system. Furthermore, it has been justified that the MRF actuators are capable of generating complete range of motions typically required for HR interaction applications with high inherent safety. Main characteristics of our proposed system (articulated robot arm) are as follows:

1. Each DOF of robot manipulator is driven by MRF actuators.
2. MRF actuators provides high back drivability extremely useful for HR interaction applications.
3. Because of using MRF actuators, the system displays large and variable force/torque presentation ability.
4. High safety is assured in mechanism level.

Further studies will be focused on the design and implementation of adaptive control strategies for actuator mode switching behavior under uncertainty while ensuring safe and optimal performance. Planning of interaction control strategies having indirect force control will be the subject of our future investigation.

Conclusively, we can say that this study can contribute to the effective solution to the compliant motion problem of articulated robots.

8. REFERENCES