Compliant 5-DOF Robot: Mechanical Design*

Sergey Pisetskiy and Mehrdad R. Kermani[1]

***Abstract*— this paper presents the design of a back-drivable 5-DOF manipulator for physical Human Robot Interactions (pHRI). The compliant behaviour of the manipulator is achieved using antagonistically working pairs of Magneto Rheological (MR) clutches in each joint of the robot. The drive train of the manipulator consists of a single brushless DC motor located at the base of the robot and 5 pairs of antagonistic MR clutches. Multiple design concepts for development of the manipulator's drive train are presented and the advantages and disadvantages of each concept are described. The most efficient drive train concept is further developed and the design of the entire manipulator including the mechanical structure of the MR clutches, transmission mechanism, and motor actuation is presented. Some simulation rendering along with preliminary experimental results are presented to conclude the paper.**

I. INTRODUCTION

In recent years, robots have gradually moved out of isolated labs, enclosed work cells, and safeguarding cages and been introduced into the human environment. These robot are now involved in such applications as rehabilitation, medical care, search and rescue, entertainment, and service, to name a few. In many of these areas, instead of directly replacing a human worker, robots complement and help operators with their daily tasks. An important requirement for such cooperation and physical proximity is safety. This requirement was promptly recognized, established, and codified in the U.S. and in Europe in robotic safety standards [1], [2], [3], [4].

In the developed standards, the four basic collaboration methods to reduce risk during human/robot interaction are classified as following,

1. Safety-rated monitoring stop: As long as the operator is in the Collaborative Work Space (CWS), the robot is not allowed to move.

2. Hand guiding: The robot is allowed to move with limited speed and only when the operator intentionally activates an input device to induce the desired movement.

3. Speed and separation monitoring: Physical contact between the operator and the robot is eliminated through the continuous control of the operator's location in the CWS.

4. Power and force limiting: Physical contact between the operator and the robot is considered as a normal event. The static and transient forces that the robot can impart to the operator are limited to the safe values.

*This work was supported in part by Canada Foundation for Innovation (CFI) and Natural Sciences and Engineering Research Council (NSERC) of Canada under grant No.25031 and RGPIN-346166.

[1]The authors are with the Electrical and Computer Engineering Department, the University of Western Ontario, London, ON N6A 5B9 Canada `spisetsk@uwo.ca, mkermani@eng.uwo.ca`

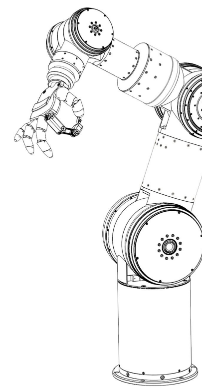


Fig. 1. Visualization of the compliant 5-DOF robot with a possible anthropomorphic compliant hand.

In practical applications, some of the requirements for the collaboration methods can be satisfied with the variety of safety sensors and controllers available today. At the same time, the requirements for proper limiting of static and dynamic forces described in the 4th class present significant challenges. The approaches for satisfying these requirements may vary.

A common approach is to reduce the power of the actuators with lightweight robot links. This approach was successfully implemented in a number of manipulators, such as UR3/5/10 [5] from Universal Robots, Kinova JACO robotic arm [6], [7], [8], Franka Emika [9], and YuMi from ABB [10]. These robots have small payloads ranging from 0.5 to 10 kg, and the total weight of the structure ranges from 9.5 to 30 kg.

Another approach is to use compliant links and compliant joints in the robot. While solutions with compliant links are still under development [11], [12], robots with compliant joints are becoming commonplace. In this regard, sensor-based compliant joints can be realized using torque measurements of individual joints. A prime example of such an approach is KUKA collaborative robots starting from LWR III [13] model and following LWR 4+, iiwa 8, iiwa 14. The high cost of implementation and high inertia beyond controllable bandwidth are the prohibitive factors in this approach. Alternatively, compliant joints can be realized using inherently compliant elements . Series elastic actuator (SEA) [14] is one approach commercially used in Baxter [15] and Sawyer [16] from Rethink Robotics. Series Damper Actuator (SDA) using a rotary damper in series with the motor drive is an another realization for compliant joints [17]. Both approaches substantially reduce the controllable bandwidth of the joint.

Variable Impedance Actuation (VIA) uses a variable elastic transmission combined with a variable damping to enhance the SEA and SDA approaches. VIA permits changing both the elastic and the damping properties of the actuator during operation.

Compliant actuation using pneumatic muscles is another realization for joint compliance with safe characteristics [18], [19], [20]. The practical use of these actuators is somewhat limited due to insufficient range of motion.

Magneto-rheological clutches provide inherent compliance for mechanical transmission. The clutch can transmit high torques in comparison with actuators of similar mass and inertia. The unique ability to rapidly and precisely control the transmitted torque without introducing non-linearities such as torque ripple makes MR clutches a good candidate for a modern compliant actuation. [21], [22].

In this paper we present an innovative design for a 5-DOF manipulator with intrinsically compliant joints based on MR actuation. The main focus of the paper will be on the design and structure of the transmission system and on the integration of an MR clutch pair in each joint.

II. OVERVIEW

A. Manipulator Design Objectives

The main design requirements for the intended manipulator are to have 5 degrees of freedom, a maximum payload of 10 kg, and a reach of 900 mm. A single motor is used to drive all joints, each of which includes a pair of MR clutches in antagonistic configuration.

B. Basic principles of an MR clutch

The MR fluid used in MR clutches is a functional fluid that can rapidly, continuously, and reversibly change its viscosity under an applied magnetic field. The field induces magnetization of the micron-sized iron particles dispersed in the fluid. Magnetized particles form chain-like structures along the direction of the magnetic field, that when sheared develop a yield stress. The magnitude of the yield stress increases with the intensity of the applied magnetic field within a millisecond. The yield forces induced against relative displacement of the moving surfaces are used in an MR clutch to transmit the torque. The total amount of force transmitted is proportional to the area of input (or output) surface and the yield stress of MR fluid.

In a typical rotary MR clutch the moving surfaces take the form of disks or drums or their combination. A simple disk-type MR clutch is shown in Fig. 2.

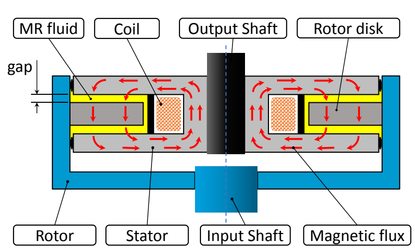


Fig. 2. Section view of a single-disk MR clutch.

The MR clutch has a rotor carrying a ferromagnetic (input) disk and connected to the input shaft rotated by the external actuator (e.g. a motor). The MR clutch stator comprised of ferromagnetic (output) disks and an electromagnetic coil, is connected with the load (e.g. a robot link) via an output shaft. The gap between the disks is filled with the MR fluid. The magnetic field generated by the coil increases the yield stress of the fluid in the gap and the transmitted torque increases. Accurate control of the current in the electromagnetic coil ensures precise regulation of the transmitted torque.

A comparison of different types of MR clutches can be found in [23], [24], [25].

C. DASA MR actuation approach

A magneto-rheological (MR) clutch is the key component of a proprietary actuation concept termed Distributed Active Semi-Active Actuation (DASA) [26]. DASA will be used for actuating the designed manipulator.

In DASA constant rotational motion of a single source of power (e.g. a motor) is distributed to a number of loads (e.g. robot links) via a pair of antagonistically configured MR clutches. The pair of MR clutches spinning in opposite directions allows bi-directional actuation of the load. The schematic of DASA is shown in Fig. 3.

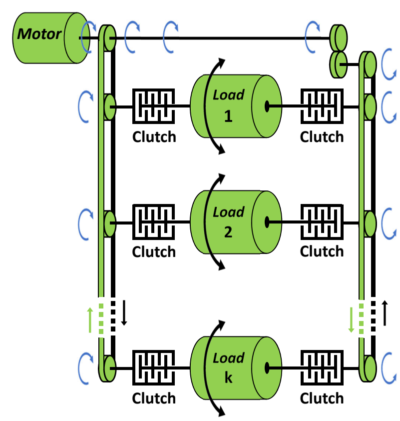


Fig. 3. Distributed Active Semi-Active actuation approach.

An important advantage of the proposed antagonistic approach is that it can use any conventional transmission with relatively cheap components. The transmission system continuously rotates in a given direction; therefore, the possibility of a backlash appearance is completely eliminated.

In addition to this, the unique properties of the MR clutch ensure compliant and precise control of the load movement, while disengaging the reflected inertia of the motor and a ”direct drive” configuration.

III. EARLY DESIGN CONCEPTS

An elbow configuration (Fig. 4) with revolute joints was chosen as the kinematic arrangement of the 5-DOF manipulator.

Given the intended payload and the reach of the robot, the desired torque at each joint starting from the base (joint 1) was determined as 15, 200, 80, 15, and 15 N·m, respectively.

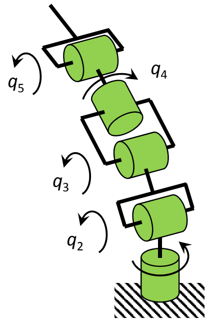


Fig. 4. Symbolic representation of the chosen kinematic arrangement for a 5-DOF manipulator.

Several design concepts with the different transmission systems were initially evaluated. Three such concepts are compared in the following.

A. Concept 1: Single belt transmission

Concept 1 (Fig. 5) represents a transmission system using a single belt. The motor and the gearbox are located in the first link. The timing belt passes through all 5 joints of the manipulator.

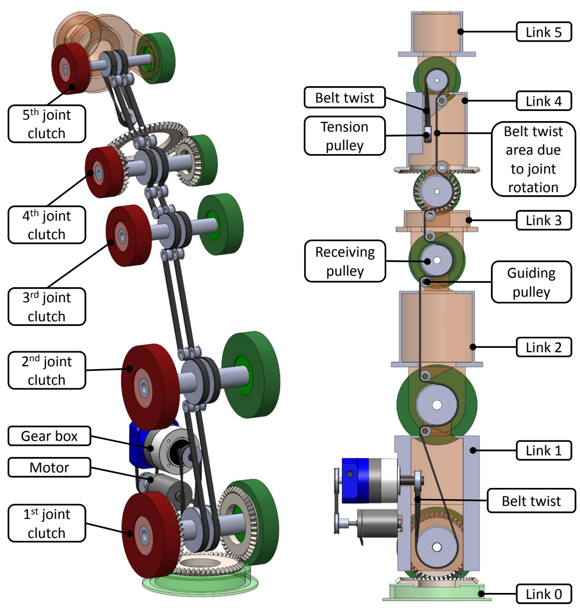


Fig. 5. Concept 1: 5-DOF robot with a single belt transmission.

The part of the belt moving from joint 1 to joint 5 rotates one of the pair of antagonistic clutches of each joint in clockwise direction, while the part moving back from joint 5 to joint 1 rotates the other pair of each joint in counterclockwise direction. The 1st joint and the 4th joint use bevel gears to provide 90° rotation between the axes of rotation of MR clutches and that of the joint.

A single belt allows minimizing the diameter of the links, reducing the number of receiving pulleys in the joints, and using a single tension mechanism in the robot. On the other hand, a single belt requires a number of guiding pulleys to ensure sufficient contacts between the belt and the receiving pulleys, limited radii of the bending when passing through the guiding pulleys, and twisting when passing through the tension mechanism as well as joint 4. These factors require improved flexibility of the timing belt and introduce additional stresses that may negatively affect the reliability of the transmission. Additionally, due to limited belt twisting ability, joint 4 has limitations in rotational angle.

B. Concept 2: Multiple shafts transmission

Concept 2 (Fig. 6) represents a manipulator with shaft transmission. In this concept, miter gears are used at each joint to ensure rotation of the clutches in opposite directions. Moreover, bevel gears are used at 2nd and 3rd joints to transmit the motion to upper links without compromising the joint flexibility.

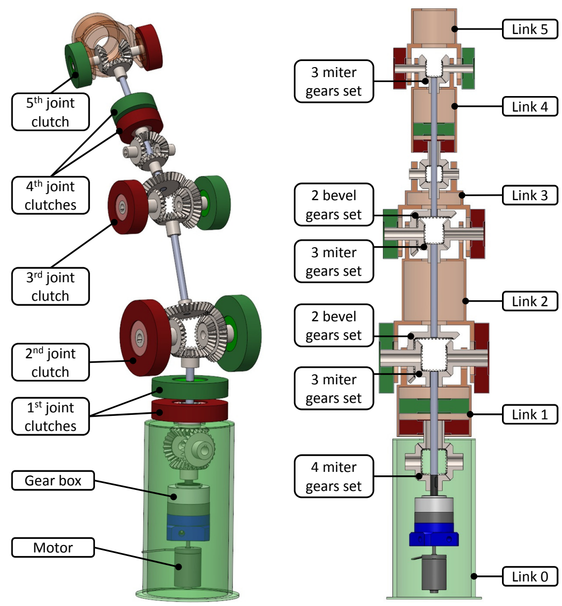


Fig. 6. Concept 1: 5-DOF robot with multiple shafts transmission.

Using shafts allows an increase in the range of joint movements. On the other side, implementation of the miter and bevel gears at the joints increases the total weight of the links.

C. Concept 3: Combined transmission

Concept 3 (Fig. 7) represents a combination of shaft and belt transmission. In this concept, rotational motion of a single motor is transmitted to all 5 joints through a set of shafts, belts, and bevel gears.

Concepts 3 provides the best engineering trade-offs between efficiency, cost, complexity, and maintainability and is chosen as the preferred design concept of the designed manipulator. Fig. 7 presents the computer aided (CAD) model of the transmission and the kinematic diagram of the robot.

In the developed configuration, a harmonic drive (HD drive) is used as a speed reducer for a gear reduction. As it is shown on the kinematic diagram, the output of the HD drive provides rotation to the clutches of the 1st joint and a

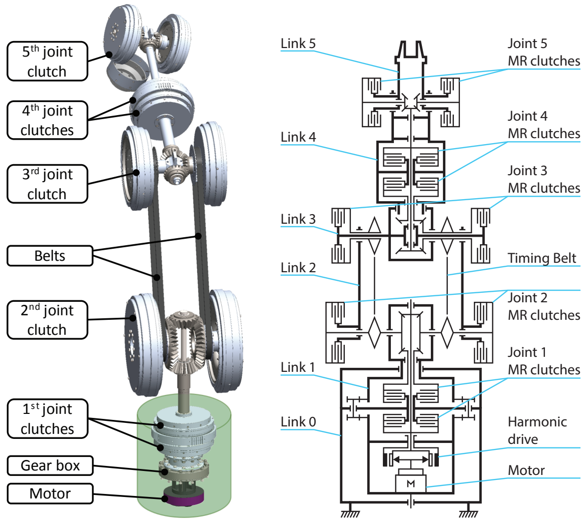


Fig. 7. Concept 1: 5-DOF robot with combined transmission. Computer aided design (CAD) model and kinematic diagram.

set of bevel gears (within the 2nd joint) using a long inner shaft. The clutches of the 2nd joint are driven using the side gears of the bevel gear set in the joint. The clutches of the 3rd joint receive rotational motions from a timing belt system. The clutches of the 4th joint are driven using a pair of coaxial shafts coupled to the miter gears in the 3rd joint. Finally, the MR clutches of the 5th joint are driven using a single shaft and a set of miter gears in the joint.

IV. Manipulator Mechanical Design

The manipulator consists of 5 cylindrical links connected with revolute joints according to the chosen elbow kinematic arrangement shown above in (Fig. 4).

A. Mechanical design of Link 0 and Joint 1

Link 0 of the manipulator (a base, Fig. 8) is designed as a cylindrical structure that comprises a motor, harmonic drive, joint 1 MR clutch pair, concentric shafts, and encoder. The base has structural elements that allow supporting of all the load from the upper robot links.

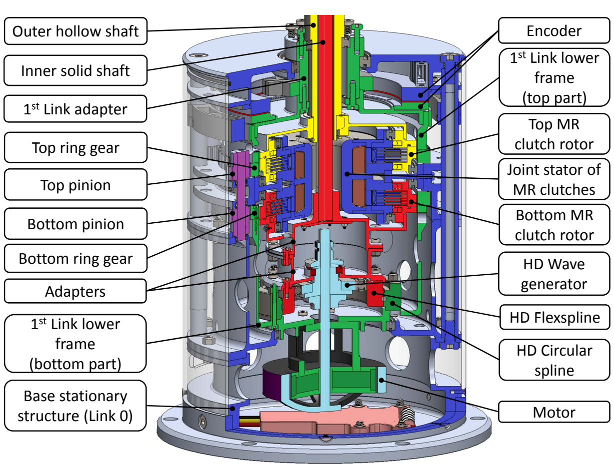


Fig. 8. Manipulator base zonal section view.

The rotation of the brushless motor Hacker Q80-13XS is reduced by the HD drive SHD-25-100-2SH with the ratio 1:100. The output of the HD drive is directly connected to the 1st joint bottom MR clutch and to the inner solid shaft going to the 2nd joint. The top MR clutch of the 1st joint is driven by the outer hollow shaft coming from the 2nd joint and spinning in opposite direction relative to the inner solid shaft.

Motor, HD drive, and 1st joint MR clutch pair are mounted on the lower frame of the 1st link inside the link 0 structure. The lower frame of the 1st link is split into 2 parts that are kinematically connected together through the spur gear arrangement. The arrangement ensures the rotation of two separate frame parts as one unit. At the same time the gap between the frame parts is used to attach the stators of the 1st joint MR clutches to the stationary link 0 structure.

An absolute encoder Zettlex INC-9-150-171001 is mounted at the top of the manipulator base for angular position measurements between link 0 and link 1.

B. Mechanical design of Joint 2

Joint 1 is mounted on the upper frame of link 1 as shown in Fig. 9.

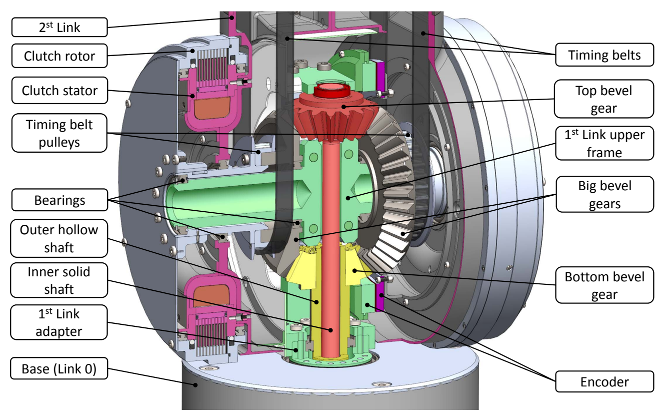


Fig. 9. Joint 2 zonal section view.

It carries a set of bevel gears in order to ensure the rotation in opposite directions of the two large MR clutches connected to "big" gears on the sides. The top bevel gear receives rotation from the solid inner shaft coming from the 1st joint. The bottom bevel gear rotates the outer hollow shaft going to joint 1.

Besides MR clutches, each side bevel gear is connected with the timing belt pulley in order to transmit the motion in both directions to the upper joints.

To measure the angular position between link 1 and link 2, the absolute encoder Zettlex INC-9-175-171001 is attached to link 1 upper frame.

C. Mechanical design of Joint 3 and Joint 4

Joint 3 MR clutches receive rotational motion from the two timing belts coming from joint 2 as shown in Fig. 10. The belt pulleys are driving two MR clutches in opposite directions. One of the pulleys is connected to the miter gear from the set of 3 gears. Two other miter gears are mounted on the concentric shafts coming to the 4th joint. The set of miter gears is used to obtain the rotation at a 90-degree angle in two opposite directions for the MR clutches in joint 4 (Fig. 10). Joint 4 ensures the ”roll” rotation of the link 4 perpendicular to the axis of the 3rd joint.

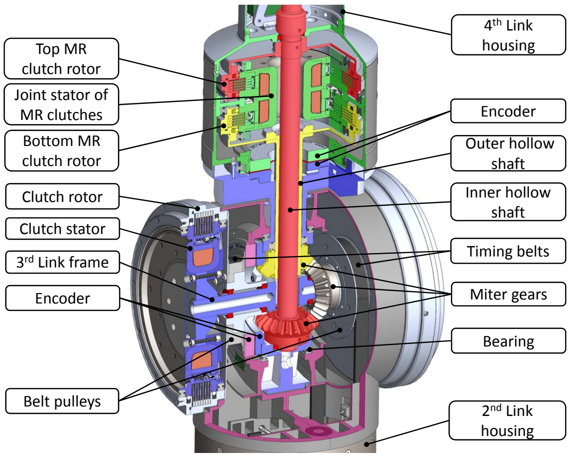


Fig. 10. Joint 3 and 4 zonal section view.

To measure the angular position of the 3rd and 4th joints, the absolute encoders Zettlex INC-4-100-161001 and INC-4-75-151001 are used.

D. Mechanical design of joint 5

The miter gear set in Joint 5 receives rotational movement through the hollow shaft coming from the 4th joint. Two side miter gears rotate MR clutches in opposite directions as shown in Fig. 11.

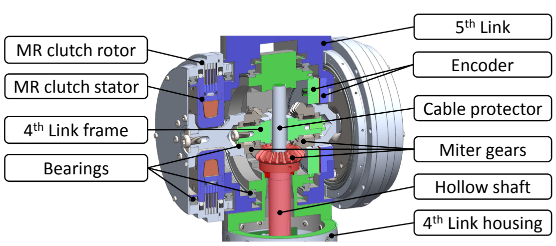


Fig. 11. Joint 5 zonal section view.

The absolute encoder Zettlex INC-4-75-151001 is used to measure the angular position of the joint.

V. Mechanical design of the MR clutches

In our previous work [27], we developed, assembled, and tested the hybrid disk-type MR clutch for 5th joint of the 5-DOF robotic manipulator (Fig. 12).

The stationary part of the clutch (stator), consists of an electromagnetic coil on a carbon steel core, permanent magnet, and four carbon steel disks. The moving part of the clutch (rotor) comprises five carbon steel disks arranged in between the disks of the stator. The clutch weighs 1.8 kg and able to transmit 20 N·m at 2 A coil wire current.

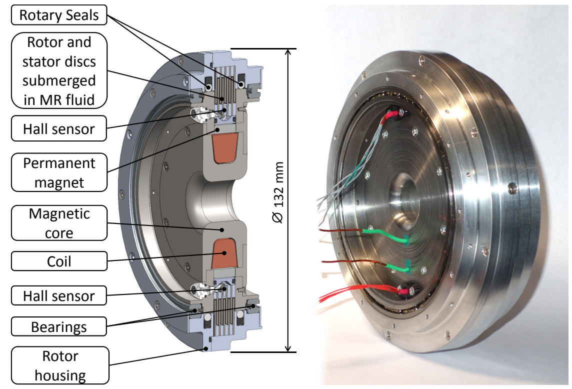
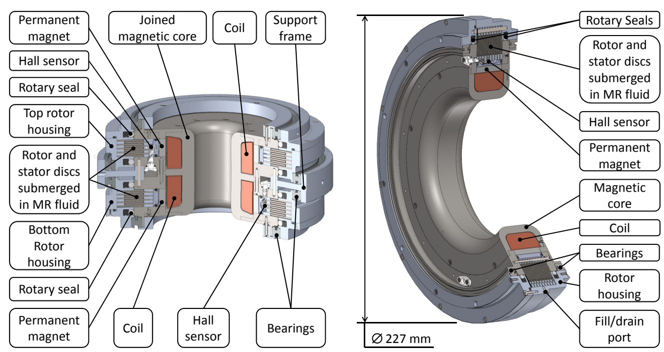


Fig. 12. Section view of the 5th joint MR clutch.

The configuration of the 5th joint clutch is typical for the clutches in other joints. The pairs of clutches in the 1st and 4th joints have a common electromagnetic core as is shown in Fig. 13 (a). However, the rotors have the same design as the rotors of the 5th joint clutch.



(a) Joint 1 and Joint 4 MR clutch pair. (b) Joint 2 MR clutch pair.

Fig. 13. Section view of the 1st and 4th joint MR clutch pair and of the 2nd joint MR clutch.

The two most powerful clutches are located at the 2nd joint. Alike, they have similar configuration to the 5th joint clutch (see Fig. 13 (b)). However, the MR clutch, which is designed to transmit up to 200 N·m torque, has 227 mm OD (outer diameter) and weighs 6.8 kg.

For each joint the design of the MR clutches was optimized using COMSOL Multiphysics Finite Element Method software.

Fig. 14 shows the examples of the magnetic flux density distribution in the 5th joint MR clutch.

It can be observed that for the case shown in Fig. 14 (a) the density of the flux in the central part of the clutch is similar to the density in the area where disks are submerged in the MR fluid. This is a result of the combined effect of the magnetic field generated by the coil (2 A wire current) and by the permanent magnet (B = 1.35 T). Permanent magnet helps to reduce the field density in the ferromagnetic core to avoid saturation. At the same time, the density of the field in the area with MR fluid is increased.

In order to totally cancel the field in the MR fluid area, the coil is energized with the reverse current (-1.5 A wire

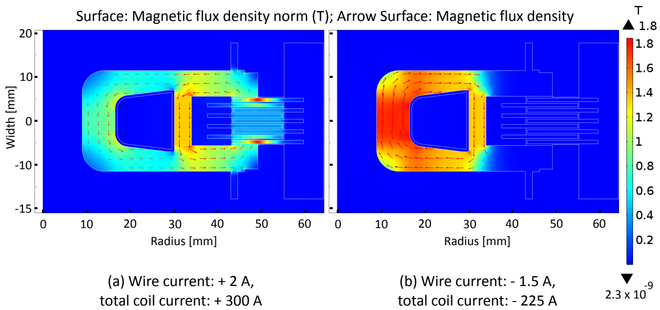


Fig. 14. MR clutch pair Magnetic flux density contour map in the 5th joint MR clutch for the cases of coil wire current 2.0 A and -1.5 A.

current) as shown in Fig. 14 (b).

VI. Assembling and Testing the Robot Components

At the current stage of the project, the prototype of the 1st joint MR clutch pair is assembled as shown in Fig. 15. Both clutches are filled with the MR fluid, tested for performance, and installed in the manipulator base.

Fig. 15. Assembled MR clutch pair for joint 1.

The motor, harmonic drive, absolute encoder, link 1 lower and upper frames with spur gear arrangement, bevel gear set, concentric shafts, - all the components are installed in the robot base as shown in Fig. 16.

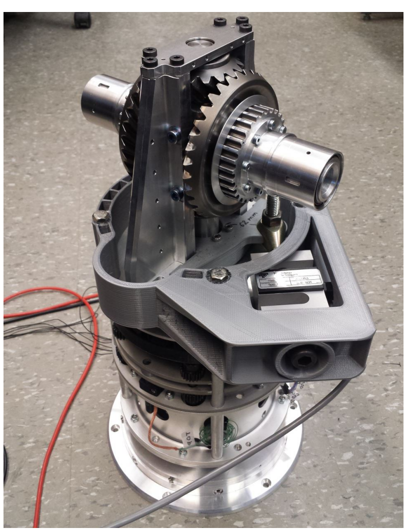


Fig. 16. Assembled manipulator base with the load cell mounted on the supporting frame.

To test the performance of the joint 1 in the assembly, a static load cell Transducer Techniques SBO-1K is mounted on the supporting frame on top of the base (Fig. 16). A motor driver AM AZ12A8 is used to supply current to the MR clutch coil. The real-time controller board dSPACE DS 1103 is used to control the test setup.

Fig. 17 compares the experimental (solid orange) and simulated (dashed blue) results.

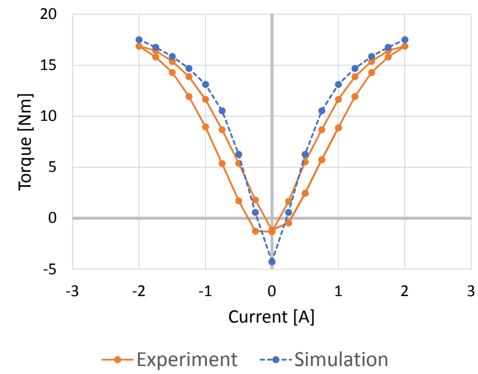


Fig. 17. Experimental and simulated results for the MR clutch pair used in the 1st joint: the relation between the current in the winding (A) and transmitted torque (N·m).

The good match between the experimental results and the simulation in COMSOL Multiphysics confirms the manipulator joint 1 functionality.

VII. Conclusion

An innovative design of a 5-DOF compliant manipulator is presented in this paper. Several concepts of the robot drive train are described and the detailed design of the chosen one is reported. Components of the first two robot links are manufactured and assembled. The results of the preliminary tests confirm the intended performance of the 1st joint of the robot.

Along the project execution, some drawbacks of the developed design are identified as follows:

- location of relatively heavy MR clutches at the robot joints increase the mass and inertia of the manipulator links;
- increased complexity of the transmission system due to use of single motor to actuate all the joints;
- additional power required to cancel the permanent magnets in order to keep the clutch pairs disengaged;
- increased wear of parts caused by stronger interaction forces in the clutches;
- changes in the hysteresis pattern in the MR clutches can complicate the robot control system.

Further work is in progress in order to complete the assembly of the robot upper links and develop the control system for the manipulator.

References

[1] ANSI/RIA R15.06-2012, "Industrial Robots and Robot Systems - Safety Requirements", ANSI American National Standards Institute, 2012.

[2] ISO 10218-1:2011, Robots and robotic devices Safety requirements for industrial robots Part 1: Robots, ISO, Geneva (2011).

[3] ISO 10218-2:2011, Robots and robotic devices Safety requirements for industrial robots Part 2: Robot systems and integration, ISO, Geneva (2011).
[4] ISO/TS 15066:2016, Robots and robotic devices Collaborative robots, ISO, Geneva (2016).
[5] Universal Robots, "Universal Robot UR3" https://www.universal-robots.com/products/ur3-robot/. Accessed: 2019-03-17.
[6] Kinova, Kinova JACO product page. https://www.kinovarobotics.com/en/products/assistive-technologies/kinova-jaco-assistive-robotic-arm. Accessed: 2019-03-17.
[7] V. Maheu, P. Archambault, J. Frappier, and F. Routhier, Evaluation of the JACO robotic arm: Clinico-economic study for powered wheelchair users with upper-extremity disabilities, in *Proc. IEEE Int. Conf. on Rehabilitation Robotics (ICORR)*, 2011, pp. 15.
[8] A.Campeau-Lecours, V.Maheu, S.Lepage, H.Lamontagne, S.Latour, L.Paquet, and N. Hardie, JACO Assistive Robotic Device: Empowering People With Disabilities Through Innovative Algorithms, *Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Annual Conference*, 2016.
[9] Franka, "Franka Emika Technical Data." http://robotforum.ru/assets/files/Franka_Emika_pdf/FRANKA-EMIKA-technical-data_new.pdf. Accessed: 2019-03-18.
[10] ABB Robotics, IRB 14050 Single-arm YuMi Collaborative Robot. https://new.abb.com/products/robotics/industrial-robots/irb-14050-single-arm-yumi. Accessed: 2019-03-17.
[11] J.Lopez-Martinez, J.L.Blanco-Claraco, D. Garcia-Vallejo, and A.Gimenez-Fernandez, Design and analysis of a flexible linkage for robot safe operation in collaborative scenarios, in *Mechanism and Machine Theory,* 2015, 92, pp. 116.
[12] Y. She, H.-J. Su, C. Lai, and D. Meng, Design and Prototype of a Tunable Stiffness Arm for Safe Human-Robot Interaction, in *ASME 2016 International Design Engineering Technical Conferences, Computers and Information in Engineering Conference,* Charlotte, NC, Aug. 2016, p. V05BT07A063.
[13] R.Bischoff, J.Kurth, G.Schreiber, R.Koeppe, A. Albu-Schffer, A.Beyer, O.Eiberger, S.Haddadin, A.Stemmer, G.Grunwald, and G.Hirzinger, The KUKA-DLR Lightweight Robot arm - a new reference platform for robotics research and manufacturing, in *International Symposium on Robotics (ISR),* 2010, pp. 18.
[14] G. Pratt and M.Williamson, Series elastic actuators, in *Intelligent Robots and Systems (IROS), 1995 IEEE/RSJ International Conference on,* volume 1, 1995, pp. 399-406.
[15] S.Cremer, L.Mastromoro, and D.O.Popa, "On the Performance of the Baxter Research Robot," in *Assembly and Manufacturing (ISAM), 2016 IEEE International Symposium on,* IEEE, 2016, pp. 106-111.
[16] Rethink Robotics, Sawyer Specifications. https://www.rethinkrobotics.com/sawyer/tech-specs/. Accessed: 2019-03-17.
[17] C.-M. Chew, G.-S. Hong, and W. Zhou, "Series damper actuator: a novel force/torque control actuator," in *Proc. 4th IEEE/RAS Int. Conf. Humanoid Robot.,* vol. 2, 2004, pp. 533-546.
[18] D. G. Caldwell, G. A. Medrano-Cerda, and M. Goodwin, "Control of pneumatic muscle actuators," *Control Systems,* IEEE, vol. 15, no. 1, pp. 40-48, 1995.
[19] C.-P. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *Robotics and Automation,* IEEE Transactions on, vol. 12, no. 1, pp. 90-102, 1996.
[20] B. Tondu and P. Lopez, "Modeling and control of mckibben artificial muscle robot actuators," *Control Systems,* IEEE, vol. 20, no. 2, pp. 15-38, 2000.
[21] A. S. Shafer and M. R. Kermani, "On the feasibility and suitability of MR fluid clutches in human-friendly manipulators," *Mechatronics, IEEE/ASME Transactions on,* vol. 16, no. 6, 2011, pp. 1073-1082.
[22] N. Takesue, J. Furusho, and Y. Kiyota, "Fast response MR- uid actuator," *J. Soc. Mech. Eng. Int. J. Ser.C:,* vol. 47, no. 3," pp. 783-791, 2004.
[23] Q. Nguyen and S. Choi, Optimal design of a novel hybrid mr brake for motorcycles considering axial and radial magnetic flux, *Smart Materials and Structures*, vol. 21, no. 5, p. 055003, 2012.
[24] Q. Nguyen and S. Choi, Selection of magnetorheological brake types via optimal design considering maximum torque and constrained volume, *Smart Materials and Structures*, vol. 21, no. 1, p. 015012, 2012.
[25] W. Li, P. Yadmellat, and M. R. Kermani, "Design optimization and comparison of magneto-rheological actuators," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on.* IEEE, 2014, pp. 5050-5055.
[26] M. R. Kermani and A. Shafer, "Magneto- and electro-rheological based actuators for human friendly manipulators," Sep. 30, 2014, US Patent 20 150 107 395.
[27] S. Pisetskiy and M. R. Kermani, "Development of MR Clutch for a Prospective 5 DOF Robot," *Intelligent Robots and Systems (IROS), 2018 IEEE/RSJ International Conference on,* 2018.