Preliminary Development of a Powerful and Backdrivable Robot Gripper Using Magnetorheological Fluid

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Abstract –

Currently, humans work in high-risk environments such as earthwork sites with construction machine. Such works are expected to be replaced by robots, but autonomous technologies of current robots are not sophisticated enough to deploy to such tasks. Thus, it is reasonable to use robots that can assist humans in cumbersome tasks and dangerous situation. These robots must have high repeatability, speed, power, and safety. As a preliminary study on human assistive robots, this paper designs and develops a powerful and backdrivable robot gripper. To provide powerful output suitable for construction works, we adopt an oil-hydraulic-driven actuator. To provide backdrivability for geometric and mechanical adaptability, we adopt magnetorheological fluids (MRFs), which can change its apparent viscosity, quickly, continuously, and reversibly, based on the strength of the applied magnetic field, as the working fluids in the actuation system. MRF largely affects the dynamic range of viscosity and response time, so we develop special type of MRF suitable for construction works. We then develop a small size vane type rotary actuator that consists of a passage in the vane and an electromagnetic circuit to efficiently apply the magnetic field to MRF passing through the passage. The backdrivability can change based on the current applied to the coil and output torque can change based on the flow rate from the pump to the electro-hydrostatic actuator. Finally, we develop a robot gripper (similar to the size of human hands) with two fingers (three interconnected joints) actuated by one MRF actuator. From preliminary evaluation experiments, we confirmed that the developed robot gripper could change backdrivability and output torque depending on the coil current and pump flow rate.

Keywords –

Robot gripper; Magnetorheological fluid (MRF); Electro-hydrostatic actuator (EHA)

1 Introduction

Robot grippers and manipulators have been extensively researched in the past decades and they have become one of the most popular research topics in robotics. This is due to the fact that there is a wide demand of robot grippers in the field of industrial robots, medical field, and for humanoid robots. Generally, robot grippers are involved in the task of grasping of objects. However, it is not just limited to that. If the robot gripper is attached to a manipulator, it can be used for object manipulation and pick and place operation as well.

Robot grippers have different classification types. They can be classified based on the number of fingers, which includes robot gripper with two fingers [1], three fingers [2] with some even commercially available. Also, there are flexible [3] or multiple fingers [4], [5], and the most famous ones in the recent days is the grain filled flexible ball gripper (universal gripper) [6]. Another type of classification is based on actuation system. The grippers can be classified as tendon driven, pneumatic [7], vacuum [8], [9], electric, and hydraulic. Each has its own advantages and disadvantages as described in Table 1.

From Table 1, we can understand that the hydraulic actuation system provides high force output. This is useful for construction machinery and heavy-duty operation. However, in case of a sudden collision, we need to ensure safety which can be achieved through backdrivability. In most robotic systems, backdrivability is introduced with the use of series-elastic actuators [10]. The major problem in using this is the difficulty in design of elastic elements to damp the oscillations. By considering the problems, we use a different type of hydraulic system called electro-hydrostatic actuator (EHA) [11]. The principle involves using same number of pumps with actuator. This system provides ease of maintenance due to its modality and backdrivability due to absence of valves. This principle has been used in knee joint of robot [12],

Table 1. Different types of actuation system

Actuation type	Merits	Demerits
Tendon driven	Low weight	Complex to control, loosening of tendon with high force (low durability)
Pneumatic	Small size, low weight	Complex to control, high cost
Vacuum	Versatility	Cannot be used for complicated objects
Electric	Low cost, easy to control	Low force output
Hydraulic	High force output	High maintenance cost

wearable robot [13], and tendon driven hand [14]. We combine the advantages of EHA system with a different type of functional fluid called magnetorheological fluid (MRF).

Construction and heavy-duty operations which are currently being performed by human operators often involve cumbersome tasks and dangerous environments that are potential risks for the operators. The barrier to the automation of such tasks has been the development of versatile, powerful, and efficient grasping tools, i.e., robotic grippers. Grippers are also very useful for the teleoperation applications [15] where the human is moved away from an unsafe environment. Therefore, in these types of applications, it is reasonable to develop robot grippers. These robots must have high repeatability, speed, power, and most importantly, they need to be safe. As a preliminary study on human assistive robots, in this paper, we discuss the design and development of a powerful and backdrivable robot gripper which can be used to assist on-site human workers. As discussed previously, the backdrivability is essential to provide for safety. When a system is backdrivable, it can be pushed back to its initial position which will help in situation when there is an occurrence of collision.

To provide powerful output suitable for construction works, we adopt an oil-hydraulic-driven actuator. To provide backdrivability for geometric and mechanical adaptability, we adopt magnetorheological fluids (MRFs) as the working fluids in the actuation system. MRFs are a functional fluid that can changes its apparent viscosity, quickly, continuously, and reversibly, based on the strength of the applied magnetic field. MRFs largely affect the dynamic range of viscosity and response time, so we also discuss the use of special type of MRF which is suitable for application in construction robots because most of the current commercially available MRF is not suitable for robotic applications, and then we develop several MRFs suitable for robot grippers. Subsequently, we develop a small size vane type rotary actuator that consists of a passage in the vane and an electromagnetic circuit to efficiently apply the magnetic field to MRF passing through the passage. The backdrivability can change based on the current applied to the coil and output torque can change based on the flow rate from the pump to the electro-hydrostatic actuator (EHA) system. The EHA system gives us the merits of the electrical system of ease of control and hydraulic/hydrostatic system gives us the high force output. Finally, we develop a robot griper (similar to the size of human hands) with two fingers and the finger has three inter-connected joints actuated by one MRF actuator. The main advantages of our gripper are:

- High power output
- Safety due to backdrivability
- Ease of control and robustness

From preliminary evaluation experiments, we confirmed that the developed robot gripper could change backdrivability and output torque depending on the coil current and pump flow rate of the functional fluid.

The rest of this paper is organized as follows. Section 2 describes the functional fluid and design of actuation system and gripper. Section 3 reports the experiments that were conducted and describes the results that were obtained. Section 4 draws conclusions and discusses possible future work.

2 Design of Robot Gripper

In this section, we explain about the design of robot gripper with high output force and backdrivability. We make three distinction while describing the design process (i) functional fluid, (ii) actuation system, and (iii) gripper design.

2.1 Functional Fluids

The commercially available products are MRF-122EG, MRF-132DG, and MRF140-CG, respectively, and all these MRF are manufactured by LORD Corporation [16]. We previously developed compliant linear device using MRF [17]. They are differentiated by the number of magnetic substances present inside the oil suspension. When the commercially available MRFs are kept ideal for long time, in the system or outside the system, the magnetic substances inside it settle down. The settling takes place due to the gravitational force and leads to stability and dispersibility issues in MRF. Due to these issues, the MRFs cannot guarantee the reliability when precise control is needed. To overcome these shortcomings, we have developed a special anti-sedimentation type MRF. This MRF is more stable, more powerful, and hence more suitable for next generation human-coexistence robots. We discuss its development and related experiments in [18]. We use this anti-sedimentation type

MRF as the functional fluid for the actuation system.

2.2 Actuation System

We use an EHA system which consists of various components. Firstly, we have made a hydraulic vane type rotary actuator. The actuator uses MRF as functional fluid. The actuator provides a rotation of up to 90°. The upper drawing of Figure 1 shows the internal structure of the actuator. There are two ports, one inlet and one outlet. Both ports are connected to a single bidirectional hydraulic pump via a connector. The pump is responsible for pushing the MRF in and out of the actuator. Inside the actuator we have a vane which rotates when it is pushed by the fluid. We have a small space above the vane shaft. This gets filled with MRF and create a low friction fluid seal. This seal is created by fluid being always presented in the small gap at high pressure. When we fill the fluid inside the actuation system, we ensure that high pressure is maintained in it. Solid seal and no seal approaches have been tried before and they have resulted in problems such as low power, poor backdrivability, oil leakage etc. Hence, in our approach with this new type of seal, we overcome the above problems and achieve high response rate as well.

We have a small extension on the side of the actuator which is made of soft Magnetic Steel (KM-31) whereas, the rest of the actuator is manufactured using Aluminium (A2017). On this extension, we wound a coil to create an electromagnet which can switch ON/OFF using a control strategy. We use MRF as functional fluid which can change its rheology with the application of electromagnetic field as discussed in Section 2.1. Depending on the strength of the magnetic field, the fluid will change its properties. When the magnetic field is high, the flow rate is slow. When the magnetic field is low, the flow rate is high. The strength of magnetic field and flow rate are inversely proportional. The direction of the flow of MRF inside the actuator is solely controlled by direction of rotation of the bidirectional pump. However, the flow rate of MRF is controlled by both, the bidirectional pump and also the strength of the magnetic field. The system has high backdrivability because the end effector of the actuator can be pushed back to its original position in case of a contact with any obstacle.

The size of the actuator is 41 mm x 75 mm x 45 mm. The pump is connected to the rotary actuator using a connector. This connector is specially designed to have two ports to fill the MRF in the actuation system at high pressure. The bidirectional pump that we use is TFH-080 a small axial piston pump by Takako Inc. We selected it because it is small in size and produces a displacement of 0.80 cm^3 which is sufficient for our application. We use a small brushless DC motor which rotates the pump shaft in clockwise or anti-clockwise direction as per our need. We use Faulhaber BP4 with a planetary gearhead of type

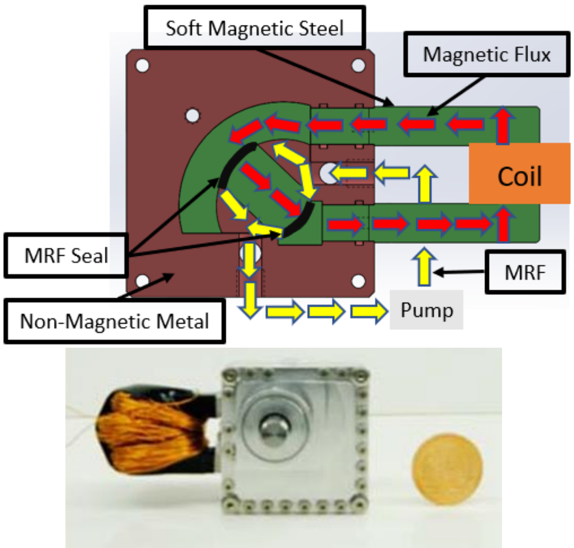

Figure 1. Vane type rotary actuator

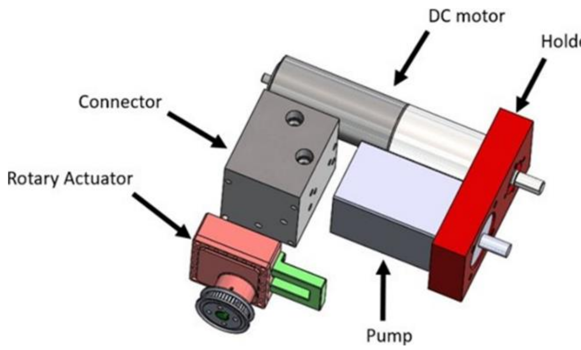

Figure 2. Exploded view of actuation system

32/3R. The pump and the brushless DC motor are attached to a holder and connected using timing pulley and belt. The exploded view of the actuation system is given in Figure 2.

2.3 Gripper Design

For the gripper, we developed two identical fingers. We designed this gripper with the following goals in mind:

- Efficient transmission of torque from actuator shaft to fingertip.
- Maximum contact between object and finger for an adequate grasp.
- Ability to grasp variety of objects.

The idea is to ensure that the object gets grasped by contact between the distal phalanx and the proximal phalanx with the extra support provided by the palm cavity created by the arrangement of the fingers in front of each other. The finger is designed using a six-bar linkage mechanism. The primary actuation is provided by a shaft

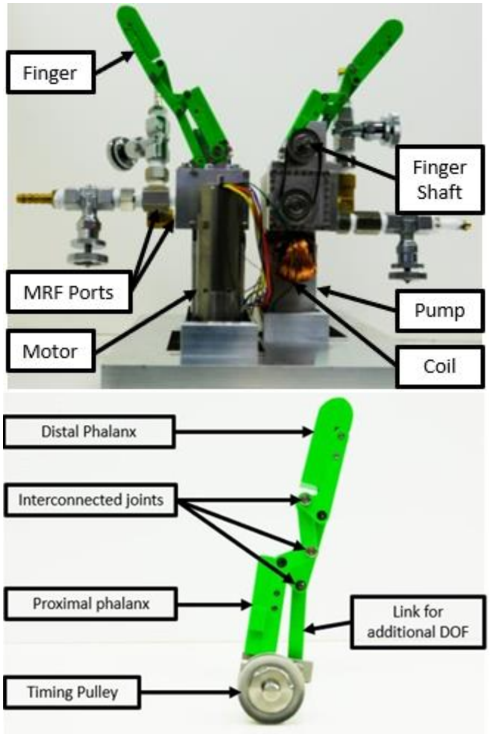

Figure 3. Gripper and finger design

which is connected to the actuator shaft via a timing pulley and belt. There is a holder which serves the dual purpose of supporting the shaft for free rotation and also as mechanical stoppage for finger. The stoppage ensures that the finger does not open beyond the angle of 120° when we want to use it for grasping objects. There is another link at the back of the finger which is responsible for transfer of actuation to the distal phalanges (fingertip). We use a clamp link to connect it with the main actuation shaft. For each of the fingers we achieve a two-degree-of-freedom (DOF) operation with one actuator. A robot gripper with fingers resembling the human finger is designed. Each finger has two phalanges giving two DOF because the motion of the proximal phalanx is directly coupled to the motion of the distal phalanx via a link. This is how we achieve underactuation. Figure 3 shows the gripper and the finger design.

For the rotation/ movement of link, we use hinge pin with ring which rotates over a bushing made of polyacetal resin. The hinge pin and bushing arrangement ensures that play maintained between the links is minimum. The links are made using Zortrax M200 Plus three-dimension (3D) printer.

3 Experiments and Results

We conducted two type of tests; torque test and grasping test. The first test is to evaluate the torque output at the actuator shaft. The second one is the grasping test in

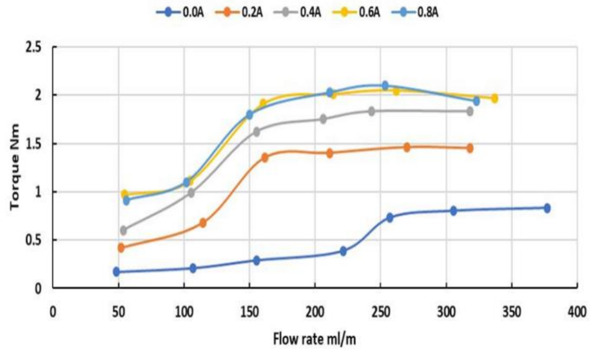

Figure 4. Torque v/s Flow rate

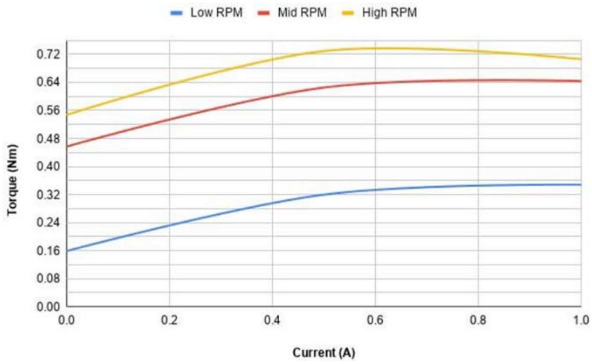

Figure 5. Torque v/s current

which we show the grasping operation of the gripper and evaluate the size limit in which the gripper can operate.

3.1 Torque Test

For this test, we measure the static torque at the actuator shaft by changing the speed of motor rotation. With pressure sensors, we measure the flow rate of the MRF inside the system. We plot the graph of torque (Nm) v/s Flow rate (m*l*/m). We use current control to switch On/Off the magnetic field. When the current is high the electromagnetic field is higher and vice-versa. We record values for the graph for current at 5 stages; 0 A, 0.2 A, 0.4 A, 0.6 A, and 0.8 A. We observe that the flow rate increases with increase in the speed of motor. The result is a non-linear relationship between torque and flow rate as shown in Figure 4. Also, we observe that the torque increases as we increase the current in the coil. This happens due to solidification of MRF inside the system. More force is required to achieve same flow rate when the MRF in the system has been solidified due to electromagnetic field. In Figure 4, we also observe a slight decrease in torque output at higher current and a state of stagnation after the achievement of a certain flow rate. We perform another torque test at a constant speed as we increase the current to electromagnet, as shown in Figure

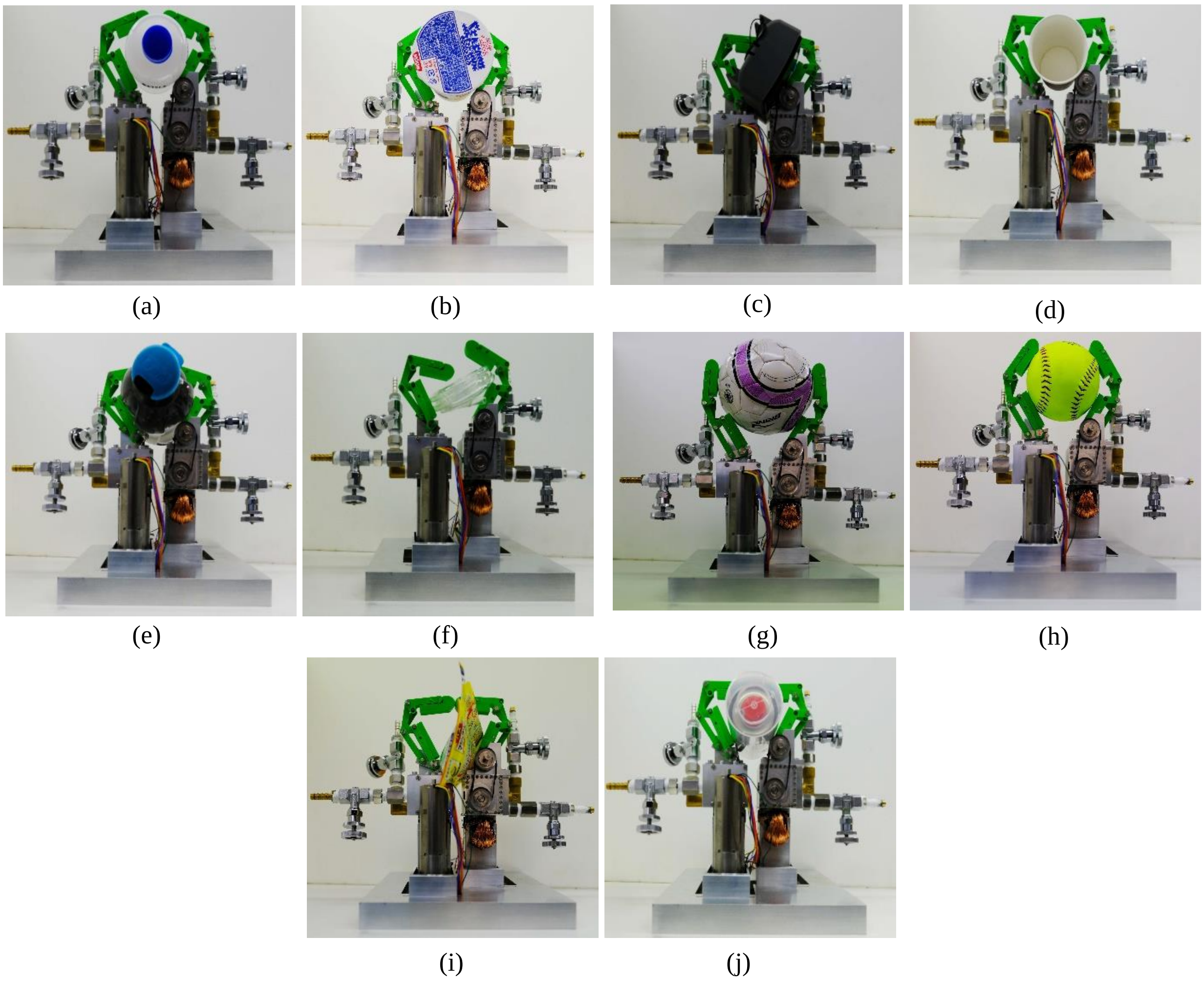

Figure 6. (a) small bottle, (b) cup noodles, (c) multi-meter, (d) cup (e), water bottle, (f) folded tube, (g) small football, (h) baseball, (i) detergent, and (j) spray can

5 to verify our observations. From the tests, we can conclude that the actuator can achieve a maximum torque output of 2.1 Nm.

3.2 Grasping Test

We perform the grasping test using different type of objects. Some of the objects that we used are (a) small bottle, (b) cup noodles, (c) multi-meter, (d) cup, (e) water bottle, (f) folded tube, (g) small football, (h) baseball (i), detergent , and (j) spray can, as shown in Figure 6. Our desired goal of grasping objects which are heavy is achieved. In some cases, like small objects which are heavy, the gripper is unable to grasp them. We believe that the reason this happens is because the size of the finger is large which renders grasping ineffective. Also, sometimes there is a difficulty in the grasping of objects which have a smooth exterior. The texture of the 3D printed distal phalanges causes this issue. With the use of an anti-skid tape on the phalanges, we solved this problem. We also tried removing object without opening the grasp. We did this to demonstrate reaction of the gripper for the condition in which object hits an obstacle/ collision during the process of grasping or pick and place. The gripper held on to the object based on the threshold value that we decided for constant grasping.

4 Conclusion and Future Works

This paper presented a robot gripper using electro-hydrostatic actuator (EHA) system. With the EHA system we combine the advantages of high power of hydraulic system with ease of control of electric system. As functional fluid, instead of using oil and conventional hydraulic fluid we use magnetorheological fluid (MRF) whose viscosity can be controlled by varying the magnetic field. We used a special type of MRF which is suitable for robotics applications. Through this, we achieve speed and stiffness variation in finger motion. We explained the internal structure of the actuation system, the design of the finger and its working. We achieve backdrivability because of the design of our hydraulic actuation system. Hence, the system is safe. We performed Torque test and grasping test to verify our design and its functioning.

In future, we plan to work on a few key points. Firstly, to reduce the size of finger to increase the dexterity of object grasping and manipulations. This will help in making the gripper more robust. Also, we plan to use tactile sensors on phalanges. The sensor data can be analyzed and trained to be used for the purpose of object recognition in future applications.

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