Graduate School of Creative Science and Engineering
Waseda University

博　士　論　文　概　要
Doctoral Thesis Synopsis

論　文　題　目
Thesis Theme

Development of Backdrivable Hydraulic Actuators Using Magnetorheological Fluids
磁性流体を用いたバックドライブ可能な油圧アクチュエータの開発

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The advent of the digital age brought along a new industrial revolution marked by the introduction of robotics technology into various industries. As a result, interaction between humans and robots is expected to increase in the coming years. Recently, there is also a rising interest in deploying robotic applications in construction and disaster relief operations, to minimize the risk and hazards for humans in such environments. For these applications, it is indispensable to ensure the safety for robots, their environment, and the people around them. Therefore, several systems for robust safe robotic actuation have been designed. Nevertheless, most of them are aimed at small power systems for human collaboration, and do not meet the requirements of more demanding applications. Despite the high power required to perform heavy tasks in construction and disaster relief, these applications require additional mobility to navigate complex environments, good energy efficiency to operate longer periods using batteries, and versatility to perform a variety of tasks with different requirements. Moreover, robotic applications for harsh environments could also benefit from mechanically compliant systems. Using this technology provides a degree of protection to their limbs during operation, while also protects other collaborative robots in their environment. This also simplifies the control system, which is required to perform complex manipulation in environments with limited visibility, unreliable communication in tele-operated tasks, or simultaneous grasping with high power. . Given the practical necessity, this research focuses on the development of actuators with high power densities and soft actuation capabilities for mobile robotic applications.

Typically, safe robotic applications employ complex control strategies, such as impedance control. However, these strategies are limited by the bandwidth of the controller, making them prone to fail when rapid unexpected events occur. For that reason, mechanical compliance has been used as a more robust alternative to overcome the complexity of interactions, and the limitations of control systems. Nowadays, many safe systems use spring elements in series with traditional rigid actuators to achieve compliant motion. Other mechanisms use dissipative elements in their drivetrains to achieve backdrivability, and absorb the energy from interaction forces. Nevertheless, state-of-art research on safe actuators with high power output appears to offer limited alternatives.

An electro hydrostatic system was optimised to provide a degree of backdrivability by balancing the hydrostatic forces between the pump and the actuator. This approach is straight forward to implement, and provides forces that match conventional hydraulic actuators. However, it lacks the ability to adjust the backdrivability of the system, limiting its adaptability to perform different tasks. On the other hand, a high power hydraulic system based in magnetorheological (MR) fluids with adjustable backdrivability was built, but it was only tested with very low output forces. Due to the number of components used it can be bulky and energy inefficient, which makes it difficult to integrate in a mobile application. Moreover, many parts also reduce its reliability making it prone to failure and instable for safe applications. Nevertheless, MR fluid based actuators have been widely used and now are present in a wide range of high power applications. From seismic isolation for buildings, to active dampers for high-end cars, these systems are known to provide very high changes in damping force with very fast responses, in the order of milliseconds. These properties make them good candidates for robotic actuation with variable damping. This research tries to overcome the observed disadvantages of current devices, by proposing a new concept for safe high power actuation. It is hypothesised that it is possible to develop a compact device with a powerful yet safe force output by effectively combining the properties of electro-hydrostatic systems and MR fluids.

After researching current literature on MR fluid based actuators, it was found that the most suitable alternative for such system was to use annular flow piston dampers, because of their high forces and compact movable heads. However, after analysing most common designs, it was discovered that they lacked customization options, and probably have inefficient magnetic circuits. This motivated the conceptualization of an alternative configuration inspired by toroidal electromagnets, which consists of a novel toroidal array of MR valves, contained within the piston head. The device was theorised to offer better energy efficiency by increasing the interaction area between the MR fluid and the magnetic field, and less magnetic leakage by exploiting the material properties the materials used in its construction. In order to test this novel idea a piston prototype was designed, built, and tested. Experiments show that the prototype is able to precisely control the output force of the actuator with fast response times, proving the feasibility of the toroidal magnetic circuit, and highlighting its potential in force control applications to provide a wider range of custom. Nevertheless, its measured force and energy efficiency were very limited when compared to the conventional system.

In order to better understand the observed performance, a mathematical model was constructed. Unlike current complex models, the mechanical, electromagnetic, and hydraulic models for the new actuator are constructed using simplified equations, based on the reluctance method, and an approximation of the Buckingham Reiner equation. This makes it possible to understand the relations between relevant parameters of the actuator, in order to identify the key parameters of the system. However, during the validation of the models the results showed a significant discrepancy with the experimental data, probably caused by the assumptions used in the electromagnetic model. Thus, a magnetic Finite Element Method (FEM) analysis was conducted to confirm this. The analysis shows unaccounted magnetic leakage in the circuit. After, integrating the results of the analysis into the model equations, the prediction improved. However, its accuracy can be improved, probably by finding accurate values for the material properties used in the model.

The observations obtained from the modelling and simulations provide valuable information about ways to improve the performance of the prototype. Using this information, a new conceptual prototype is designed. An analysis, based on an iterative search for valid permutations of parameters, revealed that there is an optimal relation between the magnetic flux density, and the active area exposed to the MRF. It also identified the key parameters relating these properties, which are then optimised. The results from the new prototype show that the optimisation procedure successfully improve the performance of the prototype, achieving twice the original force and twelve fold energy efficiency.

The improved prototype of the system is connected to a gear pump, to test the performance of the proposed system as an actuator. The results of the experiments reveal that the speed and force of the actuator can be controlled independently achieving accuracy of 98% on the output force, even during collisions, outside the friction deadband, where force is still uncontrollable. Additionally, the small correlation between speed and force reveals its potential to realise different operation modes. A proposal for an intelligent control strategy using these operation modes makes clear how future applications could achieve faster reaction times, improved backdrivability, and better energy efficiency.

As a final step, the theory behind the linear prototype is adapted into the conceptualization of a rotatory device. The new concept yields two different prototypes based on a traditional vane motor. They realise backdrivable operation by using passages through the vane and centre shaft. The results show that the unique hydraulic vane motor with 4Nm is a successful adaptation of the original concept, demonstrating the versatility and adaptability of the technology. In the future this technology can be implemented not only in collaborative robots for construction and disaster relief, but also in many other solutions for mobile applications where compact high power and safe actuation are a critical necessity.

The theoretical and empirical evidence presented in this study shows that it is feasible to develop a backdrivable hydraulic actuator using MR fluids that simultaneously provides high power output and intrinsically soft actuation characteristics. Introducing a new toroidal array of MR valves in the piston head makes it possible to achieve a greater degree of configuration options when compared to other conventional systems. Nevertheless, technical limitations, such as high friction, weight and integration of the hydraulic components into a single unit, prevent the immediate application of the system in safety critical tasks. These limitations can be overcome using practical know-how of hydraulic systems, such as seal-less designs, and fully integrated hydrostatic transmission models to improve the friction performance, weight and size of the actuator. Future studies should also refine the mathematical models in order to provide solid basis for the development of an intelligent control system, which can make full use of the capabilities of this device. Finally, it is necessary to implement the system in a concrete application to evaluate its performance in different practical tasks. I hope that in the future this device can reach its full potential to bridge the gap in actuation system, offering many solutions for mobile applications where high power and safe backdrivable actuation are necessary.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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Academic Papers (Journals)	○[1] G. Aguirre Dominguez, M. Kamezaki, and S. Sugano, “Proposal and Preliminary Feasibility Study of a Novel Toroidal Magnetorheological Piston”, Transactions in Mechatronics, vol. PP, no. 99, Oct. 2016 [IN PRINTING]
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