Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Dissertation Synopsis

論 文 題 目
Dissertation Title

Development of Soft and Compliant Actuator System using Magnetorheological Materials

磁性粘弾性材料を用いた柔軟なアクチュエーションシステムの開発

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Due to the aging society getting severe in recent years, robotic technology is growing faster than at any other time. The revolution of robotic technology brings an amount of productivity in the industrial field. In these fields such as industrial and manufacturing, robots are requested to work in a huge force and rapid speed. To generate enough force and speed, the robots are equipped with powerful actuators. These actuators often can be categorized into electric and hydraulic. However, due to the property of these actuators, they can only be applied in the cage without humans approaching. Also, they can be only used for rigid and heavy objects.

Nevertheless, with the development of society, the personality diversity of human beings becomes multiple and easily changeable. With fixed action, robots that are settled on the production line can no longer fit the requirement of consumers requirements. Therefore, the next generation actuators are required to be compliant and soft for co-existing and co-working with humans. With these compliant and soft actuations, delicate manipulation especially for objects that are fragile, and complex can be operated successfully. All in all, soft actuators with compliancy can prevent the safety of the operators as well as the safety of the target objects.

We first focused on building actuators that can obtain intrinsic backdrivability. Intrinsic backdrivability is the ability to express the easiness of force transmission from the output axis to the input axis driven by an external force. For humans, when the muscle is relaxed, the limbs can be moved easily by others, which exhibits high intrinsic backdrivability. This flexibility can mitigate possible damage for humans and facilitate interacting objects. For the same reason, human-like high intrinsic backdrivable robots are required for human-centered robots. Currently, servo systems with electric motors are one of the most widely used compliant actuation systems. They are often applied to lightweight collaborative robots. However, for human-collaborative heavy-duty tasks, such as those in construction and manufacturing, the servo systems are no longer suitable. Actuation systems that can generate a higher force and adaptability to unstructured environments are required. Nevertheless, it is hard to create high backdrivability for contraction and heavy-duty machines. Since these machines are often actuated by hydraulic actuator systems. And these actuators often own rigid hardware and a narrow bandwidths controller. Thus, it is necessary to develop a hydraulic actuator system with both ‘intrinsic backdrivability’ and ‘high output’ that does not rely on the complex controller.

Then we focused on build a new soft actuation system. Soft actuators have been developed by the inspiration from soft organisms or structures. The use of the soft actuators enables the robots to handle the above diverse and fragile objects. The most widely employed and studied soft actuations are soft pneumatic actuators (SPAs). SPAs are formed by silicone structures and are actuated by the pressurized air supplied from an air compressor. Silicone-made SPAs can freely design the configuration of air chambers. Due to the softness of silicone, they can provide various modes of movement, such as bending and locomotion. By the nature of pressurized air, we can design an inflation area as a deformable actuation component. However, they need sealing, which degrades the robustness and stability. Also, the pressurized air needs to be transmitted by tubes, which greatly degrades the independency of robots. Other soft actuators are based on smart materials, such as shape memory alloy (SMA), electrothermal actuator (ETA), dielectric elastomer actuator (DEA), and magnetic elastomer. However, they need external pressure sources, are easily deteriorated or used in millimetric-scale, which leads to increase of the independency, instability, and vulnerability.

The application of soft functional materials is expected to be an efficient solution to build a compliant and soft actuation system. Here, the material we used is called magnetorheological materials. By changing the material's dispersion medium, they can appear in different forms (i.e., fluid, or solid) and obtain different properties. When the dispersion medium is oil, the material exhibits the uncompressible same as oil and is named magnetorheological fluids (MRFs). When the dispersion medium is the elastomer, the material exhibits the elasticity as elastomer and is named magnetorheological elastomers (MREs). In addition to the properties obtained from the dispersion medium, due to the magnetic materials inside (i.e., ferromagnetic particles), the magnetorheological materials can be also activated by a magnetic field showing changeable rheological properties and controllable deformation. For MRFs, with the magnetic field applied, the fluid can transform into a pseudo-solid solution leading to viscosity change. The property of the oil and controllable viscosity makes the material suitable for applying in hydraulic systems to achieve high output and intrinsic backdrivability. For MREs, with the magnetic field applied, they can be attracted by the magnetic source due to the magnetic force between the magnetic generator and MREs. And due to this non-contact force, the magnetic force-based actuation can make soft actuators independent, which is hard to achieve by SPAs. Moreover, elastomer-based MREs are allowed to design the structure for various applications.

To fully investigate the potential of Magnetorheological materials and apply them to the compliant and soft actuator system, the methodology needs to be set first. A general methodology for the functional material-mechanism design loop was conceptualized. By applying this methodology, the functional material can be designed to fit robotics and haptics, and mechanisms can perform the maximum potential in the robot. In the big loop, three loops make sure the efficiency of development; they are the simulation loop, material design loop, and mechanism design loop. In the research, the functional material-mechanism design loop was followed to develop a compliant hydraulic actuator using MRFs and to develop a soft activation system using MREs.

For the MRF compliant actuator, a vane-type hydraulic rotary motor was selected as the prototype due to its simple structure. In this study, we develop a backdrivable MRF ‘actuator.’ First, the built-in MRF valve with bi-metal structure is designed. Two materials with different permeability were applied, i.e., magnetic material (K-M31) and non-magnetic material (aluminum). With the use of these materials and structures, the magnetic field can be conducted to the MRF valve without magnetic leakage. Based on the structure of magnetic circuit and property of the hydraulic system, a Multiphysics coupling model of electromagnetics, MRF magnetization, and fluid dynamics for the MRF actuator to maximize the dynamic range of output torque and backdrivability was created. To make the modeling as accurate as possible, in the magnetic flux density simulation, the magnetic permeability of MRF was considered. The Finite Element Method (FEM) results by ANSYS Maxwell prove the accuracy of the magnetic circuit simulation.

And in the torque simulation, the Hagen-Poiseuille equation, Bigham model, and volumetric and mechanical efficiency were considered and introduced. And the results are consistent with the experimental results. In this process, the critical parameters of components are clarified, which are possible to be used for actuator modification in the future. By changing these parameters, the actuator can generate larger output or higher backdrivability. With knowing the working principle of the MRF actuator and figuring out the key parameters, the built-in MRF valve can be designed precisely to make the actuator highly integrated to ease manufacturing, assembling, and installation in robot systems. Finally, we design a multi-variable controller based on active-drive modeling considering characteristics of flowrate and magnetic field control. Results showed that the MRF rotary actuator can generate the same-level output as the hydraulic actuator and obtains intrinsic controllable backdrivability. Additionally, we also applied it to pseudo inertia variable mechanism and robot arms.

For the MRE soft actuation system, a suction cup was developed as a robotic gripper for practical application. To utilize the magnetic property of this material, the design of the magnetic generator needs to be considered. Therefore, first, an electropermanent magnet (EPM) was designed with an axisymmetric shape. EPM is a switchable permanent magnet composed of Neodymium Iron Born (NdFeB, hard magnet) and Aluminum Nickel Cobalt (AlNiCo, semi-hard magnet). By altering the poles of the semi-hard magnet by a current pulse, the magnetic can be controlled to turn on and off. The power consumes only when applied with the current pulse. Thus, EPM has advantages of both electromagnets (controllable) and permanent magnets (low power consumption). With the axisymmetric design, the pull force (i.e., magnetic force) can be uniform.

To improve the system, the modeling of axisymmetric EPM was discussed. Based on the modeling, an efficient magnetic circuit was designed for the ON state and OFF state. Also, optimization was done to help the actuation system generate more force. The model was validated by both FEM and experiment. Results show that the modeling is accurate, and the design can effectively switch on/off the magnetic field.

Then, we designed the MRE suction cup by optimizing the membrane from full-MRE structure to bi-silicone structure. Since commercial silicone has a low solubility of iron powder and our MRE is easily broken. Thus, by combining these silicones and MRE, the MRE membrane can obtain good extensibility (from silicone) as well as high iron powder solubility (from MRE). The relationship between magnetic force, elastic force, and suction force was discussed. Based on bi-silicone structure and modeling, magnetic force can be optimized by maximizing magnetic force and minimizing elasticity. Finally, the evaluation of activation and deactivation of EPM was processed. Results indicated that the MRE suction cup can be activated in only 10 ms with 3 J. The suction force experiments were also conducted. As a result, the maximum suction force generated by the MRE suction cup can be up to 9.2 N. Results shows that MRE soft actuation system increases the independence and stability of the soft actuation system and provides low power consumption.

These researches followed the functional material-mechanism design loop. After processing with the simulation loop, material design loop, and mechanism design loop, the Magnetorheological materials powered soft and compliant actuators were successfully achieved. The author hopes the functional material powered mechanism can be implemented into the real applications rapidly in the future.

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種類別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む） (theme, journal name, date & year of publication, name of authors inc. yourself)
Academic papers (Journal papers)	○Peizhi Zhang, Mitsuhiro Kamezaki, Member, Kenshiro Otsuki, Shan He, Zhuoyi He, Gonzalo Aguirre Dominguez, and Shigeki Sugano, “Development and Evaluation of a Backdrivable Vane-Type Rotary Actuator Using Magnetorheological Fluids,” IEEE/ASME Transactions on Mechatronics, pp, 2022.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Zhuoyi He, Hiroyuki Sakamoto, and Shigeki Sugano, “EPM–MRE: Electropermanent Magnet–Magnetorheological Elastomer for Soft Actuation System and Its Application to Robotic Grasping,” IEEE Robotics and Automation Letters (with IROS2021 option), Vol. 6, Issue. 4, pp. 8181-8188, Oct. 2021.
Academic papers (International conferences)	○Peizhi Zhang, Qichen Wang, Mitsuhiro Kamezaki, Zhuoyi He, Yuhiro Iwamoto, Yasushi Ido, Hiroyuki Sakamoto, and Shigeki Sugano, “Development of a ‘Calf Muscle Pump’ Inspired Reconfigurable Soft Pump Module Using Permanent Magnetic Elastomer,” Proceedings of 2022 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2022), pp. 1-6, Jul. 11-15, 2022.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Ryuichiro Tsunoda, Zhuoyi He, Sahil Shembekar, Shigeki Sugano, “Development of a Backdrivable High-Torque Robot Arm with Magnetorheological Fluid (MRF) Vane actuators,” Eighteenth International Conference on Flow Dynamics (ICFD2021), pp. 267-270,Oct. 27-29, 2021.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Kenshiro Otsuki, Zhuoyi He, Hiroyuki Sakamoto, and Shigeki Sugano, “Development of a vacuum suction cup by applying magnetorheological elastomers for objects with flat surfaces,” Proceedings of 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2020), pp. 777-782, Jul. 6-10, 2020.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Kenshiro Otsuki, Zhuoyi He, Hiroyuki Sakamoto, and Shigeki Sugano, “Development of Anti-Sedimentation Magnetorheological Fluids and Its Implementation to a MRF Damper,” Proceedings of 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2019), pp. 400-405, July 8-12, 2019.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Kenshiro Otsuki, Zhuoyi He, Hiroyuki Sakamoto, and Shigeki Sugano, “Development of Anti-Sedimentation Magnetorheological Fluids and Preliminary Evaluation,” Proceedings of 2019 IEEE-RAS International Conference on Soft Robotics (Robosoft2019), paper no. M09, April 14-18, 2019, Seoul, Korea.
	○Peizhi Zhang, Mitsuhiro Kamezaki, Kenshiro Otsuki, Shan He, Gonzalo Aguirre Dominguez, and Shigeki Sugano, “Preliminary Design of a Pseudo-Inertia Adjustable Mechanism Based on Bidirectional Releasing of Stored Kinetic Energy,” Proceedings of 2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2018), pp. 1136-1142, July 9-12, 2018.

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Others (Patents)	Peizhi Zhang, Mitsuhiro Kamezaki, Yutaro Hattori, and Shigeki Sugano, “A Wearable Fingertip Cutaneous Haptic Device with Continuous Omnidirectional Motion Feedback,” IEEE International Conference on Robotics and Automation 2022 (ICRA 2022), pp. 8869-8875, 2022.
	発明者：亀崎允啓 (M. Kamezaki)，服部悠太郎 (Y. Hattori)，張裴之 (P. Zhang)，菅野重樹 (S. Sugano)，学校法人 早稲田大学，名称：触覚提示装置 (Haptic display device)，特願2021-34536，2021年8月20日.
	○発明者：坂本裕之(H.Sakamoto)，亀崎允啓(M.Kamezaki)，張裴之(P.Zhang)，出願人：日本ペイントホールディングス株式会社，学校法人早稲田大学，名称：ポンプ (Pump)，特願2021-022135，2021年7月26日.
	○発明者：坂本裕之(H.Sakamoto)，亀崎允啓(M.Kamezaki)，張裴之(P.Zhang)，出願人：日本ペイントホールディングス株式会社，学校法人早稲田大学，名称：開閉弁 (valve)，特願2021-022136，2021年7月26日.
	発明者：亀崎允啓(M.Kamezaki)，何卓颐(Z.He)，張裴之(P.Zhang)，菅野重樹(S.Sugano)，出願人：学校法人早稲田大学，名称：方向変換装置及び動力伝達システム (Direction convertor device and power transmission system)，特願2020-131382，2020年8月3日.
	発明者：亀崎允啓 (M. Kamezaki)，大槻健史郎 (K. Otsuki)，張裴之 (P. Zhang)，菅野重樹 (S. Sugano)，出願人：学校法人 早稲田大学，名称：アクチュエータシステム (Actuator system) 特願2019-38184，2019年3月4日.
	○発明者：亀崎允啓(M.Kamezaki)，ゴンサロアギーレ(G.Aguirre)，大槻健史郎(K.Otsuki)，張裴之(P.Zhang)，菅野重樹(S.Suagno)，出願人：学校法人早稲田大学，名称：回転型コンプライアント駆動装置 (Compliant Rotatory Drive Unit)，特許第6863562号，2021年4月5日.
Academic papers (Co-authered papers)	Sahil Shembekar, Mitsuhiro Kamezaki, Peizhi Zhang*, Zhuoyi He, Yuhiro Iwamoto, Yasushi Ido, Hiroyuki Sakamoto, and Shigeki Sugano, “Development of a Permanent Magnet Elastomer (PME) Infused Soft Robot Skin for Tactile Sensing,” 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2021), pp. 6016-6023, Sep. 27-Oct. 1, 2021.

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Academic papers (Domestic papers)	Zhuoyi He, Mitsuhiro Kamezaki, Peizhi Zhang, Sahil Shembekar, Ryuichiro Tsunoda, and Shigeki Sugano, "A Prototype Power Transmission System with Backdrivability and Responsiveness using Magnetorheological Fluid Direction Converter and Clutch,” Proceedings of 2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC2020). pp.3702-3707, Oct 11-14. Mitsuhiro Kamezaki, Peizhi Zhang*, Kenshiro Otsuki, Shan He, Gonzalo Aguirre Dominguez, and Shigeki Sugano, “Experimental Characterization of a Magnetorheological Damper with Multiple Cylindrical Passages and Toroidal Magnetic Field Generator,” Proceedings of the 10th JFPS International Symposiums on Fluid Power (JFPS2017), paper no. 2B02, Oct. 24-27, 2017. ○張裴之，亀﨑允啓，何卓頤，坂本裕之，菅野重樹，“永電磁石とMRエラストマーを用いたソフト吸盤機構の開発とグリッパーへの応用”，第39回日本ロボット学会学術講演会論文集(RSJ2021)，paper no. 1F3-02，2021年9月8～11日. ○張裴之，亀﨑允啓，大槻健史郎，何卓頤，菅野重樹，“磁気粘性流体を用いた逆可動性を有する油圧ロータリーアクチュエータの開発”，2019年度磁性流体連合講演会講演論文集，pp. 13-15，2019年12月6～7日. ○張裴之，亀﨑允啓，大槻健史郎，何卓頤，菅野重樹，“MRエラストマーを利用したサクションカップユニットの開発”，第37回日本ロボット学会学術講演会論文集(RSJ2019)，paper no. 1C2-07，2019年9月3～7日. ○張裴之，亀﨑允啓，大槻健史郎，何卓頤，菅野重樹，“運動エネルギーの双方向充放機構による擬似慣性可変システムの提案”，日本機械学会ロボティクス･メカトロニクス講演会2019論文集(Robomech’19)，paper no. 1P1-K06，2019年6月5～8日.