Development of Semi-active Universal Joint with Rotational Magnetorheological Fluid Damper for Unmanned Ground Vehicle

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Abstract— Tough unmanned ground vehicles (UGVs) ordinally move on level grounds. However, several types of tough UGVs have been designed and developed for locomotion on uneven grounds. They are employed in agricultural robots, disaster robots, and robots used for hazardous applications. Especially, semi-active damping elements are one of the smart structures and potential solutions for highly stable locomotive robots. In this study, we propose a vibration control unit with a Magnetorheological Fluid (MRF)-based semi-active universal joint (SAUJ) for stable delivery equipment that can be attached to a UGV operating on uneven ground. The basic structure and controller of the SAUJ are proposed. In addition, its performance is experimentally evaluated on the ground and a moving UGV. According to the experimental results, vibration control of the SAUJ successfully decreased the perturbation of a pendulum swing due to the acceleration of the UGV.

I. INTRODUCTION

Unmanned ground vehicles (UGVs) are a core technology for factory automation [1-2] and food delivery [3]. UGVs generally are operated on level ground. By contrast, several types of tough UGVs are designed and developed for locomotion on uneven grounds and to be utilized by robots for hazardous applications [4], agriculture robots [5], and disaster robots [6-7]. For such a UGV in a difficult environment, stable and safe locomotion on uneven ground is a challenging task from the viewpoints of locomotive manner, structure, sensing, and path planning. For the stability of moving objects, damping elements [8] are widely used as shock absorbers. In particular, semi-active damping elements are smart structures and potential solutions for highly stable locomotive robots.

Magnetorheological (MR) fluids are smart materials consisting of suspensions of noncolloidal and magnetically polarizable particles in a nonmagnetic medium [9]. When a magnetic field is applied, the particles become magnetized and form clusters along the lines of the magnetic force. This phenomenon is known as the MR effect and generates a large shear stress. Because MR fluids are reversible and responsive, they are used in several engineering applications, such as dampers, brakes, and clutches.

In many cases, Magnetorheological Fluid (MRF)-based shock absorption has been achieved using a piston-cylinder structure [10] and have been used for damping systems for wheel [11]. Such suspension system can be classified into three types: passive, active, and semi-active suspensions. Passive systems have a simple structure and can be used at low cost, but they cannot change the damping force, making it difficult to deal with disturbances. Active systems can provide high performance and active control functions, but their disadvantages include cost and mass, as they require actuators to drive the power. However, Semi-active systems can demonstrate the effectiveness of passive systems and achieve efficient control performance without using high energy [12].

Semi-active devices with two orthogonal axes are used in surgical articulated robotic arms as pneumatically driven torque control devices [13]. However, few studies of semiactive damping elements with orthogonal biaxial rotation using MR fluid. Therefore, by having rotational control in different axial directions, it can be applied as more versatile devices, such as robot arms for delivery equipment.

In previous studies, we developed several types of rotorshaped MR fluid devices based on multilayered disc structures [14]. These devices have successfully improved the torque/inertia ratio and have been used as haptic devices in remote surgical systems [15]. In this study, we utilized this device as a vibration control element of a manipulation unit attached to a UGV.

Herein, we propose a vibration control unit with an MRFbased semi-active universal joint (SAUJ) for stable delivery equipment that can be attached to a UGV moving on uneven ground. The basic structure and controller of the SAUJ are proposed. In addition, its performance is experimentally evaluated on both ground and a moving UGV.

II. SEMI-ACTIVE UNIVERSAL JOINT

A. Basic Structure

Universal joints have two directional rotational axes. The SAUJ was designed by installing a rotational MR fluid damper (RMRFD) on each axis. Figure 1 shows its basic structure (a) and appearance (b). The structure comprises a base plate, roll- and pitch-rotational shafts, a pendulum link, and two RMRFDs. We used this device as a suspension

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between the UGV and carrying cage. Further, we created a cylindrical adjustable weight instead of a carrying cage, and its shaft and base plate were attached to the bottom of SAUJ. The mass was adjusted to the range of approximately 2–10 kg. Each rotational angle was measured using a rotary encoder (Microtech Laboratory Inc., MEH – 20–7200P) with a resolution of 7200 pulses/round. The inner structure and detailed specifications are described in Section II-B. We mounted a mechanical stopper with a rubber coating at $\pm 60^{\circ}$ from center of rotation to prevent dangerous collisions with pendulum links.



Weight

(b) Appearance Figure 1. SAUJ

B. Rotational MRF Damper

The basic structure of an RMRFD has been reported previously [11]. A multilayered disk structure was used to enhance the torque/weight ratio of the output. In a previous study, the fluid gap between the disks was 0.05 mm to decrease magnetic resistance and increase torque performance. However, high precision is required in the mechanical processing of discs and spacers as well as in the assembly process.

To improve the balance between precision requirements and torque performances, the fluid gap was changed to 0.1 mm, and the inner electric magnet was redesigned. Figure 2 and Table I show the structure and specifications of the RMRFD. The structure has mainly two parts: the casing (fixed parts) and the inner magnet (rotor parts). The fixed and rotor discs are alternately stacked with the fluid gaps, and the MRF (140CG. Lord corp.) is filled in the gap. The magnetic rotor is composed of an iron-based magnetic core, a magnetic coil, and rotor discs. When current is applied to the coil, magnetic flux in the MRF layers is generated via the magnetic core, which changes the rheological properties of the MRF.

Figure 3 shows the torque performance of the RMRFD. The torque measurement method has previously been reported [11]. The horizontal and vertical axes represent the input current and the output rection torque, respectively. The torque performance curve exhibits an S-shaped nonlinearity. Its maximum torque is approximately 5.0 Nm at 1.0 A. The reference current was modeled using a third-order polynomial equation for the required torque.



(a) Overview

(b) Basic structure

Figure 2. Structure of rotational MRF damper

TABLE I. SPECIFICATIO	ONS OF RMRFD
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Total thickness	32 mm
Outer diameter mm	52 mm
Diameter of disks	40 mm
Number of disks	9 (input) + 8 (output)
Number of MRF layers	18
Gap size of MRF layers	0.1 mm
Number of turns of coil	191
Idling torque	0.15 Nm
Maximum torque at 1 A	5.0 Nm
Mass	240 g



Figure 3. Reaction torque performance of RMRFD

C. Dynamics

To design the vibration controller for the SAUJ, a mathematical model was established using an equation of motion. Figure 4 and Table II present the mechanical model of the SAUJ and its parameters, respectively. θ_1 and θ_2 are the independent variables of the system, which denote the relative rotational angles of the first and second shafts of the SAUJ, respectively. The mass of link 1 (pendulum link) is ignored because it is smaller than the adjustable weight of link 2. The adjustable weight is included in link 2, and the length from the rotational center of joint 2 to the gravity center is defined as the length of link 2 (L_2).



Figure 4. Mechanical model of SAUJ

TABLE II. SYSTEM PARAMETERS AND VARIABLES FOR SAUJ

Weight of link 1	М
Length of link 1	L_1
Rotation angle of link 1	$ heta_1$
Moment of inertia around z_1 - axis of link 1	I ₁
Torque of RMRFD 1	$ au_1$
Damping coefficient of RMRFD 1	<i>D</i> ₁
Weight of link 2	т
Position of center of gravity of link 2	P_{G}
Length to center of gravity of link 2	L ₂
Moment of inertia around x_2 - axis of link 2	I ₂
Rotation angle of link 2	θ_2
Torque of RMRFD 2	τ ₂
Damping coefficient of RMRFD 2	<i>D</i> ₂

The equations of motion for the aforementioned mechanism are equations (1) and (2), which were derived from Lagrange's equations of motion.

$$\begin{pmatrix} I_1 + mL_1^2 + mL_2^2 \cos^2\theta_2 + 2mL_1L_2 \cos\theta_2 \end{pmatrix} \ddot{\theta_1} - \begin{pmatrix} mL_2^2 \sin 2 \\ \theta_2 + 2mL_1L_2 \sin\theta_2 \end{pmatrix} \dot{\theta_1} \dot{\theta_2} + mg(L_1 \sin\theta_1 + L_2 \sin\theta_1 \cos\theta_2) = \tau_1 - D_1 \dot{\theta_1}$$
(1)

$$(I_2 + mL_2^2)\ddot{\theta_2} + \left(\frac{1}{2}mL_2^2\sin 2\theta_2 + mL_1L_2\sin \theta_2\right)\dot{\theta_1}^2 + mgL_2\cos \theta_1\sin \theta_2 = \tau_2 - D_2\dot{\theta_2}$$
(2)

For simplicity to control, the angles are assumed to be small. In that case, Eqs. (1) and (2) can be linearized as Eqs. (3) and (4), respectively:

$$(l_1 + mL_1^2 + mL_2^2 + 2mL_1L_2)\ddot{\theta}_1 + mg(L_1 + L_2)\theta_1 = \tau_1 - D_1\dot{\theta}_1$$
(3)

$$(I_2 + mL_2^{\ 2})\ddot{\theta_2} + mgL_2\theta_2 = \tau_2 - D_2\dot{\theta_2}$$
(4)

As shown in Eqs. (3) and (4), the simplified dynamics of the double pendulum is independent of each angle and is simply described in Eq. (5).

$$J_i \ddot{\theta}_i + D_i \dot{\theta}_i + K_i \theta_i = \tau_i \text{ (for } i = 1,2) \tag{5}$$

D. Controller

The main objective of a controller is to dampen the swinging. For this purpose, a velocity controller was designed. As shown in Eq. (6), the time derivative of angle θ_i is defined as ω_i . Additionally, the proportional term of the angle is defined as a disturbance. For the control rule, we adopted the PI controller, as shown in Figure 5. The system parameters and control design are described in Section III-A.

$$J_i \dot{\omega}_i + D_i \omega_i = \tau_i - K_i \theta_i \text{ (for } i = 1,2) \tag{6}$$



Figure 5. Block diagram of velocity control

Arduino Due was selected as the main controller owing to its control performance and selectable electric functions. Figure 6 shows the control system. Two angle data (pulses) are inputted into the main controller, the rotational angle and angular velocity for each axis were calculated, and the PWM signals for the motor driver (CJMCU Inc., VNH3ASP30) are the output. All electric circuits and the two RMRFD were driven using two 9 V batteries (700 mAh).





Figure 6. Control system for SAUJ

III. IDENTIFICATION AND DESIGN

A. Method

To identify system parameters such as inertia, damper, and elastic element, we conducted swing experiments on stable ground. As shown in Figure 7, the pendulum swings from the initial angle (30°) without any damping control of the RMRFD. The parameters were identified from the waveform of an uncontrolled state. After identification, the servo gain of the PI controller was designed using secondorder delay system theory. This process was conducted independently for both the roll and pitch axes.



Figure 7. Setting position of roll axis (Left: equilibrium position; Right: initial position)

B. Results

In Figures 8 and 9, the solid and dashed lines show the angular trajectories during the swing experiment with and

without control, respectively. The horizontal and vertical axes represent the time and angle during the swing, respectively. Table III summarizes the identified and designed parameters.



Figure 8. Damping performance of roll angle



Figure 9. Damping performance of pitch angle

TABLE III. IDENTIFIED SYSTEM PARAMETERS AND DESIGNED SERVO GAINS

Parameters	Values
Inertia of link 1, J_1	0.160 kgm ²
Damping coefficient of joint 1, D_1	0.098 Nm/(rad/s)
Proportional gain, K_{P1}	2.302 Nm/rad
Integral gain, K_{I1}	16 Nm/rad s
Elastic modulus of joint 1, K_{i1}	0.173 Nm/rad
Inertia of link 2, J_2	0.070 kgm ²
Damping coefficient of joint 2, D_2	0.064 Nm/(rad/s)
Proportional gain, K _{P2}	0.986 Nm/rad
Integral gain, K_{I2}	7 Nm/rad s
Elastic modulus of joint 2, K_{i2}	0.020 Nm/rad
Length of link 1, L_1	0.08 m
Weight of link 1, M	0.719 kg
Weight of link 2, m	3.80 kg

C. Discussions

As shown in Figure 9, the control system achieved significant attenuation compared to the uncontrolled case. Vibrations of the pendulum converge at approximately 1.5 s for both axes. Also, the rotation angle during control was less than 20% of the maximum angle at the start.

IV. EXPERIMENT WITH UGV

A. Method

To validate the damping performance of the SAUJ, it was installed on a UGV (Figure 10), and driving experiments were conducted on an uneven test course. Bunker mini (AgileX Robotics corp.) was utilized as the UGV. The weight capacity of the UGV was 25 kg, and the mass of the SAUJ was 16.8 kg including the aluminum frames. As additional sensors, Inertial Measurement Unit (IMU) sensors (LP-RESEARCH Inc., LPMS-B2) were installed on the body of the UGV (IMU 1) and the adjustable weight of the SAUJ (IMU 2). The coordinate systems of the IMUs are shown in Figure 10.

Figure 11 illustrates the test course. The test course is composed of a 10-degrees ascending slope, a 5-degrees downhill slope, and a 10-degrees cross slope. A drop of approximately 50 mm exists between the ascending and downhill slopes. The UGV was driven by an examiner using a manual remote controller to guide the UGV along the centerline of the ascending slope in a straight path at approximately 0.3 m/s. Acceleration and rotational velocity were measured using IMUs.



Figure 10. UGV with SAUJ and IMU sensors



(b) Overview Figure 11. Test course

B. Results

Figure 12 shows the acceleration of the UGV acquired from IMU 1, in the x-, y-, and z-axes directions, respectively. Figure 13 shows the angular velocities of the adjustable weight acquired from IMU 2, in the x-, y-, and z-axes rotations, respectively. In these figures, the left and right side are the results without / with the control, respectively.





Figure 13. Angular velocity of IMU 2

(Left: Without control; Right: With control)

C. Discussions

As shown in Figure 12, although the UGV is driven manually, the accelerations during the testing are similar.

As shown in Figure 13, the angular velocity exhibit two phases in intervals 1 and 2 of the test course. In interval 1, the maximum angular velocity is 580 rad/s around the x-axis (Figure 13 a) without SAUJ control during the impact between the UGV and the ground. At this time, the pendulum link lightly contacted the stopper. However, this value decreases to only 260 rad/s with SAUJ control. The times to \pm 5% of maximum angular velocity (settling time) were 5.9 s and 2.7 s without / with the control, respectively.

On the cross slope of interval 2, the angular velocity around the y-axis changes significantly when climbing up and down the slope (Figure 13 b) without the SAUJ control, in which the angular velocity around the y-axis changes significantly when climbing up and down the steps of the slope. The maximum angular velocity was decreased by about 15%. However, the settling time decreased from 4.2 s to 1.6 s.

V. CONCLUSIONS

In this study, we described a vibration control unit with an MRF-based SAUJ for stable delivery equipment. We described the detailed structure of the SAUJ and its system for vibration control. The vibration control of the SAUJ was evaluated on the ground and when mounted on a UGV moving across rough terrain. According to the experimental results, the vibration control of the SAUJ successfully decreased the perturbation of the pendulum swing owing to the acceleration of the UGV.

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REFERENCES

- Bogh S., Hvilshoj M., Kristiansen M. et al., "Identifying and evaluating suitable tasks for autonomous industrial mobile manipulators (AIMM)" Int J Adv Manuf Technol vol.61, pp.713–726, 2012
- [2] Wang S., Jiang L., Meng J. et al., "Training for smart manufacturing using a mobile robot-based production line" Frontiers of Mechanical Engineering, vol.16, no.2, pp.249-270, Apr. 2021
- [3] Md Al Amin, Md Shamsul Arefin, Md Razib Alam, et al., "Using Mobile Food Delivery Applications during COVID-19 Pandemic: An Extended Model of Planned Behavior" Journal of Food Products Marketing, vol.27, no.2, pp.105-126, Apr. 2021
- [4] Siegwart R., Lamon P., Estier T., et al., "Innovative design for wheeled locomotion in rough terrain" Robotics and Autonomous Systems, vpl.40, no.2-3, pp.151–162, Aug. 2002
- [5] Singh S., Bergerman M., Cannons J., et al., "Comprehensive Automation for Specialty Crops: Year 1 results and lessons learned" Intelligent Service Robotics, vol.3, pp. 245–262, 2010.
- [6] Michael N., Shen S., Mohta K., et al., "Collaborative Mapping of an Earthquake Damaged Building via Ground and Aerial Robots" Field and Service Robotics. Springer Tracts in Advanced Robotics vol.92, 2014,
- [7] Ohno K., Kawatsuma S., Okada T., et al., "Robotic Control Vehicle for Measuring Radiation in Fukushima Daiichi Nuclear Power Plant" IEEE International Symposium on Safety, Security, and Rescue Robotics, Kyoto, Japan, pp. 38-43, Nov. 2011
- [8] MRAD C., Sakiichi O., Yoshitsugu K., et al., "Vibration Control of Mobile Robot Vehicle by Dynamic Vibration Absorber" JSME International Journal Series C, vol.42, no.1, pp. 62–70, 1999
- [9] Carlson D. J., Jolly R. M., "MR fluid, foam and elastomer devices" Mechatronics, vol.10, no.4, pp. 555–569, Jun. 2000
- [10] Yazid M. I., Mazlan A. S., Imaduddin F., et al., "An Investigation on the Mitigation of End-stop Impacts in a Magnetorheological Damper Operated by the Mixed Mode" Smart Materials and Structures vol.25, no.12, Nov. 2016
- [11] Tang X., Du H., et al., "Takagi-Sugeno Fuzzy Control for Semi-Active Vehicle Suspension with a Magnetorheological Damper and Experimental Validation" IEEE/ASME Transactions on Mechatronics, vol.22, no.10, pp.291-300, Feb. 2017
- [12] Wei X., Zhu X., Jia L., "A semi-active control suspension system for railway vehicles with magnetorheological fluid dampers" International Journal of Vehicle Mechanics and Mobility, vol.54, no.7, pp.982-1003, Apr. 2016
- [13] Aizawa K., Haraguchi D., Tadano K., "Load Reduction Control on Tool-Insertion Port for Laparoscopic Surgical Robot Using Semi-Active Joints" Journal of Robotics and Mechatronics, vol.32, no.5, pp.1000-1009, 2020
- [14] Kikuchi T., Otsuki K., Furusho J., Abe H., Noma J., Naito M. and Lauzier N., "Development of Compact MR fluid clutch for humanfriendly actuator," Advanced Robotics, vol. 24, no. 10, pp.1489–1502, 2010
- [15] Kikuchi T., Takano T., Yamaguchi A., Ikeda A., Abe I. "Haptic Interface with Twin-Driven MR Fluid Actuator for Teleoperation Endoscopic Surgery System" Actuator, vol.10, no.245, 2021