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Note: High frequency vibration rejection using a linear shaft actuator-based image stabilizing device via vestibulo-ocular reflex adaptation control method

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In mobile robotics, obtaining stable image of a mounted camera is crucial for operating a mobile system to complete given tasks. This note presents the development of a high-speed image stabilizing device using linear shaft actuator, and a new image stabilization method inspired by human gaze stabilization process known as vestibulo-ocular reflex (VOR). In the proposed control, the reference is adaptively adjusted by the VOR adaptation control to reject residual vibration of a camera as the VOR gain converges to optimal state. Through experiments on a pneumatic vibrator, it will be shown that the proposed system is capable of stabilizing 10 Hz platform vibration, which shows potential applicability of the device to a high-speed mobile robot. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4812638]

Operational domain of mobile robot is not only indoor but now extended to outdoor unstructured environments. Image quality of a camera mounted on such system is prone to be affected by platform fluctuation resulting from irregular ground profile. Obtaining stable image is crucial to such systems to guarantee the overall system performance. There have been several approaches about employing a mechanical structure to compensate unwanted platform motion. Most of them have developed with the gimbal structure.[1,2,8] On the other hand, Hayashi proposed a floating camera stabilization device that isolates the camera from the mobile robot using ball bearings, and its position is controlled by the principal of satellite orientation control.[3] From our previous experiments, we found that the clarity of image is mostly degraded by high frequency vibration, and vibration frequency is generally increased with the speed of mobile robot.[4] However, previous studies typically tend to focus on evaluating the feasibility of stabilization system under the low frequency vibration within 2 Hz.[3,6,8] In this study, we are aiming to develop an image stabilization system that can reject a high frequency vibration to enhance the operational performance of mobile robot.

There are several design criteria for developing the targeted image stabilizing device. First, it has to be small and light enough to be mounted on the mobile robot. Second, actuator has to generate enough power to compensate high frequency vibration disturbance. Third, components and structure should be chosen and designed to achieve precise motion control. In general, size and weight of an actuator is increased proportionally to output power, so that the first two design criteria conflict each other. Rotary type actuator may be one choice since majority of inertia stabilization devices have been developed with this kind of actuator. However, the rotary type actuator is not appropriate for high-speed reciprocal movement. Therefore, we decided to adopt linear shaft actuator since it has good force versus size ratio and low backlash characteristic which is a critical feature for precise motion control. Considering these aspects, we developed a new type of image stabilizing device incorporating high-speed linear shaft actuators as given in Fig. 1.

The conceptual description of each joint is illustrated in Fig. 1(a). The linear motion is transformed to rotational motion by a slot joint in-between. As seen in Fig. 1(b), the device is designed to rotate about roll and pitch axes since the vibration of those axes are significant on the mobile robot (Fig. 1(d)).[4] The inner joint is a roll joint, and the outer joint is a pitch joint. In order to balance mass distribution of the roll joint, a bushing mechanism is placed at the opposite side of the actuator. A camera is chosen to the Webcam for simple image acquisition. Detailed specifications of the device is listed in Table I.

Most previous researches of image stabilization control are focused on how appropriately the system controller rejects unwanted disturbances generated from the platform vibration.[5,6] Therefore, stabilization performance is sorely dependent on the types and characteristics of the designed controller. On the other hand, human have rather simple but very effective gaze stabilization mechanism which is typically known as vestibulo-ocular reflex (VOR). To put it shortly, VOR is a reflex eye movement that stabilizes images on the retina during head movement of a human by producing an eye movement in the opposite direction to it for preserving the target image on the center of the visual field, or fovea.[7] A distinctive feature of VOR is that it does not depend on visual input, but, only the vestibular system detecting head rotation. Thus, VOR functions as a *open-loop control* system. The semicircular canals detect head rotation and exert direct control signal, which is proportional to the head angular velocity, over the pairs of eye muscle. A "gain" of VOR is defined as an eye angular velocity divided by head angular velocity during a head turn. In general, the VOR gain is -1. However, if the VOR gain is wrong, the cerebellum re-calibrates the VOR

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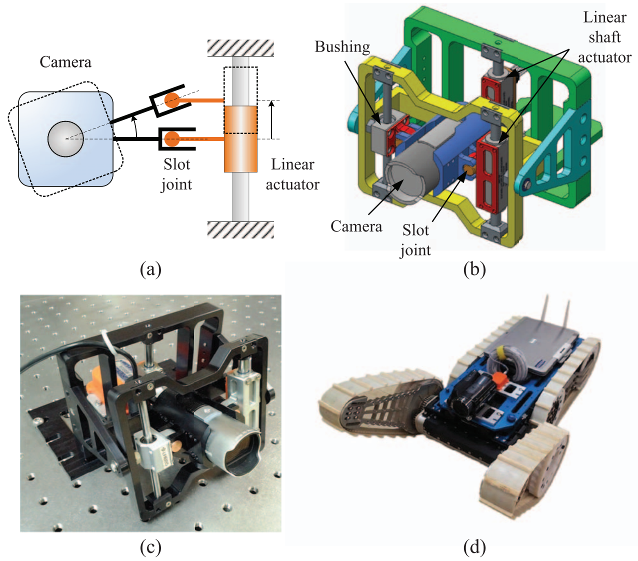

FIG. 1. A description of the image stabilizing device and its application. (a) The conceptual principle of each joint motion. (b, c) Detailed design of the image stabilizing device and a developed device. (d) The mobile robot application.

gain so that the retinal image slip is minimized. This is what is referred to as *VOR adaptation*.[7] Kaushik *et al*. have studied to implement the VOR feature to binocular vision system of quadrupedal robot.[8] However, they only considered angular motion of the head without the concept of VOR gain and its adaptive characteristic. In this paper, we propose a new method that includes aforementioned biological features of VOR in the image stabilization control perspective and apply it to our image stabilization system.

The cerebellum adjusts the VOR gain when head movements and retinal image slip, thought to be the stimulus for VOR adaptation, occur simultaneously. In other words, the VOR gain is tuned by both the base tremor and image slip error signal. In order to mimic these attributes, we devised a method that utilizes two gyro sensors placed at both the platform and camera. To this end, an overall control framework is depicted in Fig. 2 in comparison with the main components of VOR. In Fig. 2, ω_p and ω_c are angular velocity measurements from the platform and camera gyro sensor, respectively. ω_r is a relative angular velocity at the joint of stabilizing device. G_p and G_r are platform gyro and joint angular velocity sensor gains. G_C and P represent the controller and stabilizing plant, respectively. B is the viscous friction coefficient at the joint of device. The platform gyro plays a role of semicircular canal and measures rotational vibration of the mobile

TABLE I. Specifications of the developed image stabilizing device.

Size	71.25 × 124 × 92 mm
Weight	0.645 kg
Movement	Roll (±22.2°) and Pitch (±12.7°)
Sensors	Gyro sensors (platform & camera)
	Hall sensor (motor)
Actuator	FAULHABER LM 1247
Camera	Microsoft LifeCam Studio 1080p HD Webcam

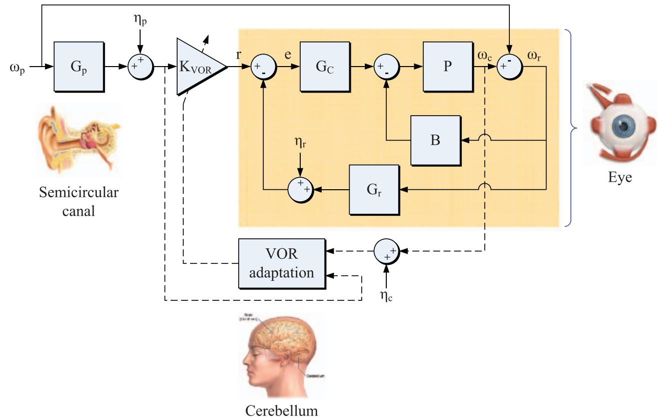

FIG. 2. Block diagram of proposed image stabilization control inspired by the VOR.

robot. Stabilization device which embodies the pairs of eye muscle rotates the camera in response to the platform gyro signal passed through the VOR gain (K_{VOR}). The camera gyro measurement which indicates the extent of image slip is fed to the VOR adaptation together with the platform gyro measurement, and then VOR adaptation adjusts the VOR gain to reduce the image slip. A key of the proposed stabilization method is a VOR adaptation rule. We proposed the VOR gain dynamics as

$$\dot{K}_{VOR} = -K_{adapt}\,\mathrm{sgn}(\omega_p)\,\omega_c,\; K_{VOR}(0) = -1, \qquad (1)$$

where $\mathrm{sgn}(\bullet) = \{+1, \text{if}\,(\bullet) \geq 0; -1, \text{if}\,(\bullet) < 0\}$. K_{adapt} is a user defined constant which specifies the speed of adaptation. The prime goal of image stabilization is to make ω_c zero by controlling the ω_r with G_C. However, if the controller is not optimally working so that ω_c is not zero, the proposed VOR gain dynamics adjusts K_{VOR} to minimize ω_c.

The proposed method is verified by experiments utilizing the pneumatic vibrator as shown in Fig. 3. There are two analog gyro sensors at both the base and camera, and the digital signal processor (DSP) measures both sensor signals using analog-to-digital converter (ADC). Then the DSP calculates a motor control signal by the internal PD controller as well as a reference signal (r) from the proposed method, and sends them to the motor driver through digital-to-analog converter (DAC) output. Finally, the motor driver imposes force to the linear shaft actuators by providing the current source according to the DSP output signal. The pneumatic vibrator generates sinusoidal vibration force to shake the base of stabilizing device.

An experimental result is shown in Fig. 4. In order to show details of the result, the intermediate time domain is omitted. The top graph shows the base vibration generated from the pneumatic vibrator. We applied 10 Hz, peak-to-peak 2.2 rad/s vibration for this experiment. The second graph shows the controlled angular velocity of the joint of device, and the third graph is the angular velocity measured by camera gyro sensor. The bottom graph represents the VOR gain transition. We started the VOR adaptation control at 1 s. As seen in the third graph, the camera vibration is significantly large before 1 s since the device cannot entirely reject the base vibration due to the poor controller performance. After

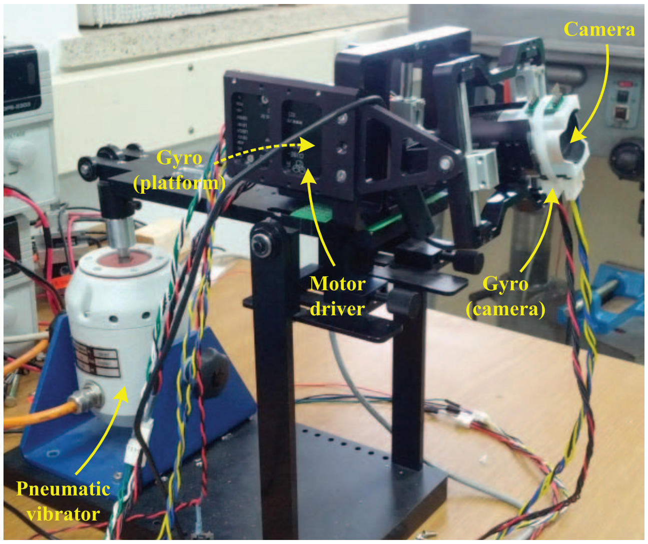

FIG. 3. Experimental setup using the pneumatic vibrator. The platform gyro sensor is not exactly shown and located behind the motor driver.

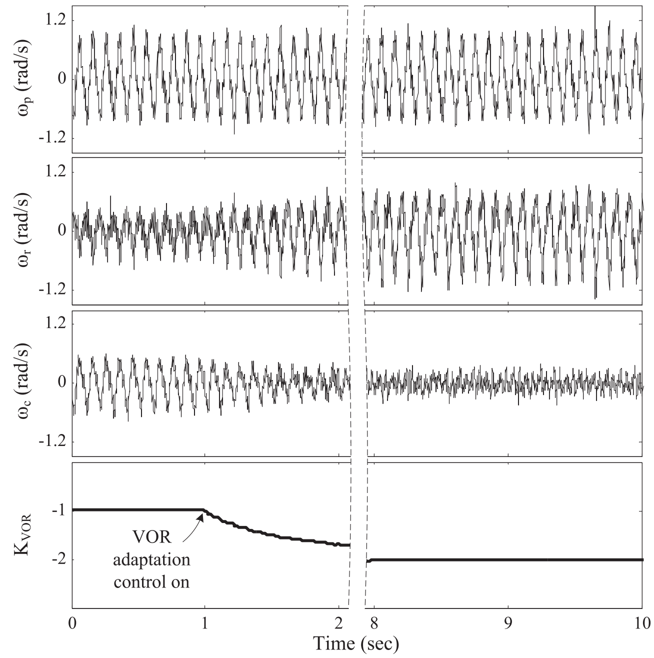

FIG. 4. Experimental result of VOR adaptation control with the 10 Hz base vibration (top: input vibration, second: controlled joint angular velocity of device, third: angular velocity of camera, bottom: VOR gain transition).

the beginning of the VOR adaptation control, the camera vibration is minimized, since the device rejects most base vibration as the VOR gain converges to optimal value. As a result, the camera vibration level is reduced to 27% of excited base vibration in the steady state. Here, K_{adapt} is arbitrary assigned to a low value to show the VOR gain transition, but convergence speed can be increased by selecting a large value. If the vibration entails multiple frequencies, the K_{adapt} has to be chosen large enough to track the frequency transition. Although the result here is demonstrated in 10 Hz base vibration, we had successful image stabilization results under the 10 Hz vibration as well. Over 10 Hz, the image stabilization effect is gradually decreased, so the additional vibration absorber or isolator is required to suppress the disturbance over 10 Hz (e.g., broadband noise). Considering the fact that experiments were conducted with non-optimal PD controller to verify the proposed VOR method, there is room for further performance enhancement by optimal controller design, but this will be considered in a separate study.

In this note, the development of a new type of image stabilization device utilizing linear shaft motor is addressed first, and a robust image stabilization control method inspired by human VOR function is newly proposed. The VOR has distinctive features such as open-loop control and adaptation characteristic. In order to realize these features, we devised a method that employs two gyro sensors placed at both the platform and camera for the proposed VOR adaptation control. Experiment was conducted using pneumatic vibrator with 10 Hz vibration excitation. The result showed that the proposed stabilization system can successfully reject 10 Hz base vibration when the VOR gain is at the optimal state. Through experimental validation, it was shown that the proposed image stabilizing device with VOR adaptation control has a high potential to be applied in high frequency vibration rejection under significant system uncertainties.

[1]H. Khodadadi, M. R. J. Motlagh, and M. Gorji, *International Conference on Electrical, Control and Computer Engineering* (Kuantan, Malaysia, 2011), p. 223.
[2]M. E. Orejas, Master thesis, Lulea University of Technology, Sweden, 2009.
[3]K. Hayashi, Y. Yokokohji, and T. Yoshikawa, *IEEE International Conference on Robotics and Automation Barcelona, Spain* (IEEE, 2005) p. 50.
[4]D.-Y. Koh, S. Kim, and K.-S. Kim, *International Conference on Control, Automation and Systems* (IEEE, Jeju, Korea, 2012), p. 2125.
[5]P. J. Kennedy and L. K. Rhonda, *Line of Sight Stabilization Primer* (P. J. Kennedy, 2008).
[6]A. A. Roshdy, H. F. Su, Y. Z. Lin, and T. Wang, Int. J. Mod. Eng. Res. **2**, 144 (2012).
[7]E. R. Kandel, J. H. Schwartz, and T. M. Jessell, *Principles of Neural Science* (McGraw-Hill, New York, 2000), p. 802.
[8]R. Kaushik, M. Marcinkiewicz, J. Xiao, S. Parsons, and T. Raphan, *IEEE International Conference on Robotics and Automation* (IEEE, Rome, Italy, 2007), p. 4861.