Development of image stabilization system for remote operation of walking robots

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Abstract

Walking robots have high adaptability for terrain variation, and thus, have been expected as effective moving platform on uneven terrain, stairs, forest, marshy surface, and on ice.

On the other hand, mobile robots that perform several hazardous tasks such as mine detection or the inspection of an atomic power plant are typically controlled by operators from distant places. For a remote operation system, use of visual information from a camera mounted on a robot body is very useful. However, unlike wheeled vehicles, the camera mounted on the walking robot oscillates because of the impact of walking, and the obtained unstable images cause inferior operation performance.

In this paper, we introduce an image stabilization system for remote operation of walking robots using a high speed CCD camera and gyrosensors. The image stabilization is executed in two phases, that is, the estimation of the amount of oscillation by the combination of the template matching method and gyrosensors, and change of the display region. Pentium MMX instruction is used for template matching calculation, and the estimated amount of oscillation is outputted in every 12 [msec.]. Furthermore, developed image stabilization mechanism can be used an external attitude sensor from the visual information, and the damping control of the robot body while walking is also possible.

Experimental results showed stabilized images that eliminates the oscillation component are taken even when the robot moves dynamically or in long distance, and verified that the performance of attitude control using the developed image stabilization system is almost same as the case using an attitude sensor.

1 Introduction

In comparison with wheeled vehicles, legged walking robots have several interesting characteristics, for example,

1. the robots have high adaptability for the abrupt changes of terrain conditions.
2. foot positions can be chosen freely and discontinuously within the work space of the leg under the restriction of kinematic stable conditions.
3. the robots can stride over small obstacles.
4. the robots can change the moving direction without slippage at foot positions.
5. legs can be used as manipulator arms.

Therefore, the walking robots have been expected as effective moving platform on uneven terrain, stairs, forest, marshy surface, and on ice. Until now, as applications of walking robots, mine detection and removal system by quadruped walking robots in a forest [1] or academic investigation on steep slopes around the crater [2], etc. are reported.

On the other hand, a mobile robot that operates instead of a human worker in hazardous or inaccessible environment, such as disaster field or on other planet, is being developed. In the future, it is expected that artificial intelligence will be equipped with these mobile robots, and adequate tasks will be planned automatically from the sensory information and world model. However, practical intelligent system for a mobile robot has not been developed yet, and thus, remote control systems by human operator will be utilized at present.

In order for the operator to recognize the surrounding environment around the robot appropriately and to control with high operation performance, acquisition of images from a camera mounted on the robot body and presentation for the operator is indispensable . However, unlike wheeled vehicles, the camera mounted on the walking robot oscillates because of the impact of walking, and the obtained unstable images cause inferior operation performance for the operator. Therefore, image stabilization systems that eliminates the oscillation component of images caused by the disturbance and presents the stabilized images for the operator is requisite for the practical remote operation system for a walking robot.

Several techniques of image stabilization are considered, for example, i) special camera universal head or lens, ii) oscillation component removal by the image processing, and iii) damping control of the robot body. Technique (i) has already been used for the shake prevention of the video camera, but the mechanism that can be used even for the large angular velocity of walking robots, is light weight and small is costly. Thus, in this paper, we develop a low cost and high speed image stabilization mechanism that uses the techniques (ii) and (iii). This system consists of high speed CCD camera, gyrosensors and image processing system utilizing the Pentium MMX instruction, and stabilized images are taken in every 12 [msec.] . In addition, this image stabilization mechanism can be used an external attitude sensor from the visual information, and the damping control of the robot body while walking is also possible.

The remained part of this paper is as follows: in section 2, we explain the developed mechanism and technique of image stabilization, and in section 3, we introduce the remote operation experiment. Next, in section 4, we report the damping control experiment of the walking robot using the developed image stabilization system.

2 Image stabilization system

2.1 Experimental system for remote operation

Quadruped walking robot, TITAN-VIII, for remote operation experiment is shown in **Fig. 1**. This robot equips with a high speed CCD camera (ES310, Kodak), computer board (Pentium 200MHz, Japan Data System), AD/DA board, Ethernet card, silicon disk, 3-axes attitude sensor, (Maxcube, Japan Aviation Electronics), and two gyrosensors (Gyrostar, Murata).

Gait planning, position and attitude control, and estimation of shape of floor are all executed in every 10 [msec.] by the equipped board computer, and the robot is controlled from the remote operator by using the joystick connected to the remote computer.

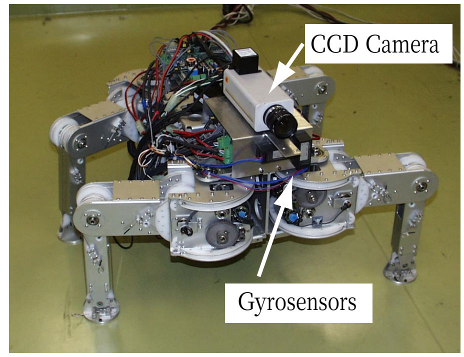


Figure 1: 4-legged walking robot TITAN-VIII

Acquired images from CCD camera are processed through remote computer and displayed on the HMD (Eyetrek, Olympus) of the operator.

Mounted high-speed CCD camera (ES310, Kodak) can outputs the 80 progressive images of the 648x484 pixels in every second. Acquired images are transmitted to the main memory of the remote computer (Pentium III, 600 MHz) through image acquisition board (MaxPCI, Datacube), and processed using Pentium MMX instruction. Therefore, in case that image processing time is 12 [msec.] or less, the whole throughput becomes 12 [msec.], and is almost equal to the sampling time of the walking robot, 10 [msec.].

2.2 Image stabilization method

Fig. 2 shows the adopted image stabilization method that combines the information from the gyrosensor and CCD camera based on the template matching method. In this system, we first choose the specific regions as initial templates, and pursue the movement of regions corresponding to the initial templates by calculating the correlation between them, and find the matching point. Here, the search area of corresponding region of each template is set to the point that is given by adding the matching point at previous time and camera movement measured by the gyrosensor. Then, actual display region that is slightly smaller than the input image is shifted so that the template is always located in the same position in the display region, and consequently, the stable image can be obtained.

This system, at first, roughly compensates the image oscillation by the gyrosensors, and then, absorbs the remaining error that is due to the processing or communication delay et al. by template matching method

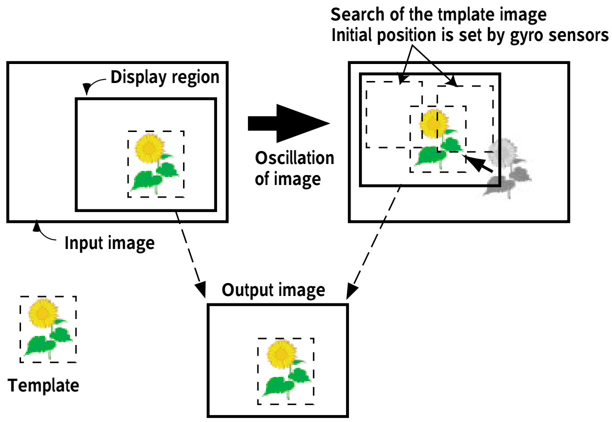


Figure 2: Image stabilization method with CCD camera and gyrosensor

using the actual images that should be stabilized.

As described above, calculation of template matching is executed using MMX instruction of Pentium III processor and image acquisition and change of display region are done by image processing board (MaxPCI, Datacube). Processing time of correlation calculation for one template is 0.22 [msec.], where template size is 16x16 pixels and search region is ±5 neighborhood pixels.

2.3 Comparison of image stabilization using various sensors

As shown in **Fig. 3**, we developed the experimental system to verify the effectiveness of proposed system and compared the image stabilization ability for various sensors and their combination.

This experimental system consists of a plate that rotates around a horizontal axis by the linear actuator in constant amplitude and frequency, and three attitude sensors, (Maxcube JAE, GU-3020 Datatec, and TA7233 Tamagawa Seiki) gyrosensor (Gyrostar, Murata), and CCD camera. By driving the linear actuator in reciprocating way, image taken from CCD camera oscillates and attitude of CCD camera to compensate the oscillation is measured by these sensors, respectively. The experiment is carried out for following five conditions, and each image stabilization performance is compared by changing the frequency of oscillation.

1. Attitude of CCD camera is measured by attitude sensors.

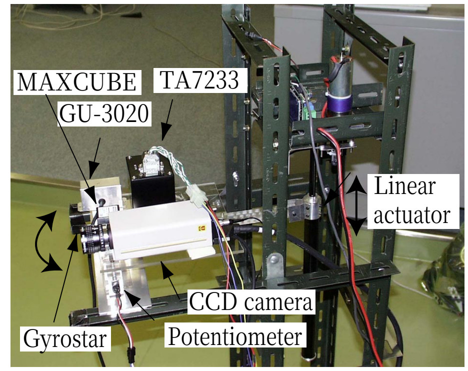


Figure 3: Experimental system

2. Gyro sensor is used.
3. Template matching method using acquired CCD camera image (without gyrosensor).
4. The combination of CCD camera and gyrosensor. Search region is shifted in constant distance (5 pixels) to estimated direction of camera movement measured by gyrosensor.
5. The combination of CCD camera and gyrosensor. Search region is shifted in estimated distance to estimated direction of camera movement measured by gyrosensor.

As a result of the experiment, though it was possible that the oscillation was suppressed using methods (1) and (2) for any attitude sensors, it was not possible that the oscillation was perfectly eliminated because of the measurement error and time delay caused by communication and calculation processes. In method (3), the template could be tracked up to ±5 degrees of amplitude , 1.5 [Hz] vibration of frequency and 47 [deg./sec.] of maximum angular velocity. but often missed over 1.5 [Hz]. Moreover, method (4) could track up to 3 [Hz] of vibration frequency and 94 [deg./sec.] of maximum angular velocity, and method (5) could track up to 4 [Hz] and 126 [deg./sec.].

Here, in methods (3), (4), and (5), template size is 16x16 pixels and search region is ±5 neighborhood. In method (4), template searching ability is raised by shifting the search region with 5 pixels toward the moving direction estimated by the gyrosensor. Furthermore, in method (5), the distance and the direction of search region are both estimated by gyrosensor.

From the result of these experiments, it was proven that method (5) which combines CCD camera and gyrosensor has highest image stabilization performance against impulsivity, and we adopted this method in developing the image stabilization system.

3 Experiment of remote operation for walking robot

In order to verify the ability of developed image stabilization system, we performed the experiment of remote operation by using a walking robot named TITAN VIII shown in **Fig. 1**.

In the experiment, acquired image is divided into 100 regions of the size 16x16 pixels, beforehand. Then, in each region, eigen values λ_1 and λ_2 of following matrix Σ are calculated and some regions where $\min(\lambda_1, \lambda_2) > \lambda_{thresh}$ are chosen as initial template images (trackability [4]).

$$\Sigma = \sum_{i,j \in s} \begin{pmatrix} \left(\frac{\partial I_{i,j}}{\partial x}\right)^2 & \left(\frac{\partial I_{i,j}}{\partial x}\right)\left(\frac{\partial I_{i,j}}{\partial y}\right) \\ \left(\frac{\partial I_{i,j}}{\partial x}\right)\left(\frac{\partial I_{i,j}}{\partial y}\right) & \left(\frac{\partial I_{i,j}}{\partial y}\right)^2 \end{pmatrix} \quad (1)$$

Next, SAD (Sum of Absolute Difference) is calculated between acquired image and template image using Pentium MMX instruction within ± 5 pixels neighborhood of each acquired region. Then the regions where the minimum value of SAD is less than threshold value are categorized as able to be tracked. This process is executed for every template image and the offset value of display region is set as the average of the difference between template position that shows the minimum SAD value and initial position of template. Furthermore, when the number of trackable templates is less than the particular threshold number, calculation of trackability and selection of appropriate template are executed automatically, and the system can continue the image stabilization even after the robot moves long distances and initial templates go out of the acquired image.

Fig. 4 shows an example of the remote operation experiment. Left hand of **Fig. 4** shows the stabilized images and right hand shows raw images. As a result of experiment, stabilized images that eliminates the oscillation component are taken even when the robot moves dynamically or in long distance.

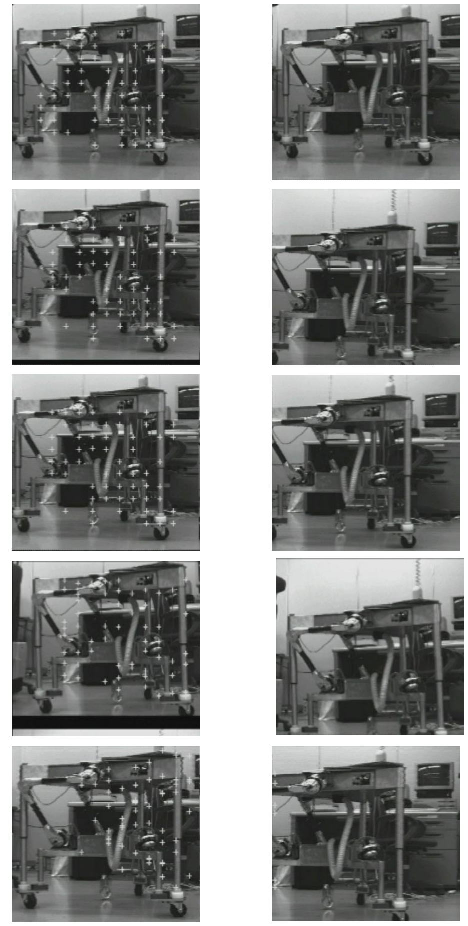


Figure 4: Results of image stabilization

4 Use of stabilization system as attitude sensor

Developed image stabilization system can be utilized as external attitude sensor of the robot body since the attitude of CCD camera can be estimated from the offset of template position and focus length. In the coordinate system shown in **Fig. 5**, the velocity (u, v) of the point (x, y) on the image plane placed on the z axis can be derived using the linear and angular velocity of robot body, (V_x, V_y, V_z) and $(\omega_x, \omega_y, \omega_z)$ as follows.

$$u = f\frac{V_x - xV_z}{Z} + fxy\omega_x - f(1 + x^2)\omega_y + fy\omega_z \quad (2)$$

$$v = f\frac{V_y - yV_z}{Z} + f(1 + y^2)\omega_x - fxy\omega_y - fx\omega_z \quad (3)$$

In **Fig. 5**, Σ_B is the robot body coordinate system and these axes are parallel to the axes of the camera coordinate system Σ_C

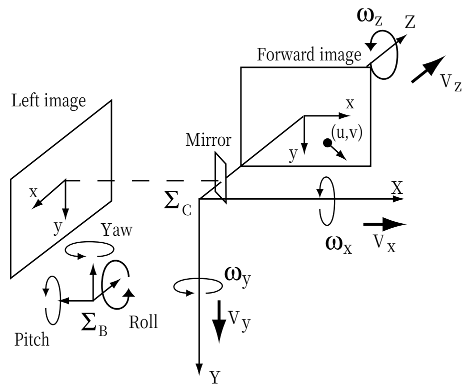


Figure 5: Camera and robot coordinate systems

Here, maximum values of actual linear and angular velocity of walking robot in above experiment are 0.01 [m/sec.] and 100 [deg./sec.], respectively, and therefore, the component corresponding to linear velocity, $\frac{V_x - xV_z}{Z}$ and $\frac{V_y - yV_z}{Z}$, can be neglected if Z is sufficiently large. Consequently, $(\omega_x, \omega_y, \omega_z)$ is derived as the linear equation of (u, v), and calculated by least square method if (u, v) is measured in several points. However, ω_z is likely to be affected by measurement error because the coefficient value is quite small, and accurate estimation of ω_z is difficult. Thus, we put a mirror in front of camera lens as shown in **Figs. 6,7**, and split the acquired image into front and left side images.

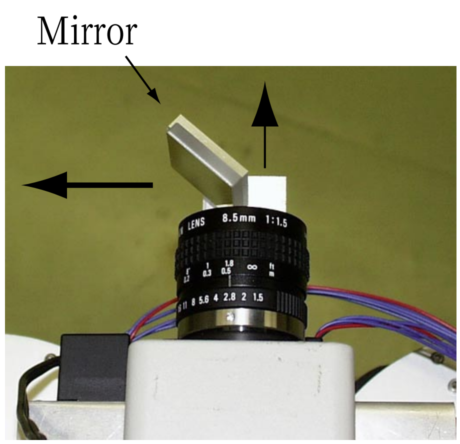


Figure 6: images partition by a mirror

On the left side image shown in **Fig. 5**, the image velocity (u, v) is written as

$$u = -f\frac{V_z - xV_x}{X} - fy\omega_x - f(1+x^2)\omega_y + fxy\omega_z \quad (4)$$

$$v = -f\frac{V_y - yV_x}{X} + fx\omega_x - fxy\omega_y + f(1+x^2)\omega_z \quad (5)$$

and $(\omega_x, \omega_y, \omega_z)$ can be given as linear equation of (u, v) if the linear velocity can be neglected same as above. Thus, we tracked the several templates on front and left images by the developed image stabilization system, and estimated $(\omega_x, \omega_y, \omega_z)$ precisely using least square method of these four equations. Actually, since we can measure the offset of template from the initial position, the offset of camera attitude from the period when the initial templates are chosen are estimated. Thus, the current attitude of robot body (roll, pitch, and yaw in **Fig. 5**) are given as addition of the initial attitude and measured offset values.

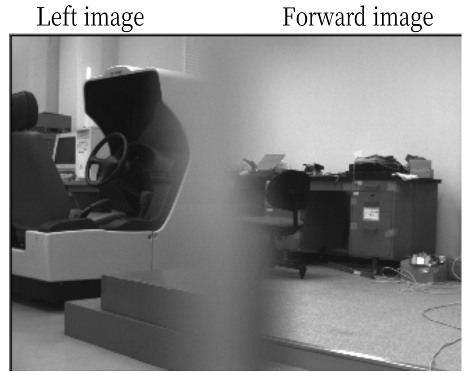
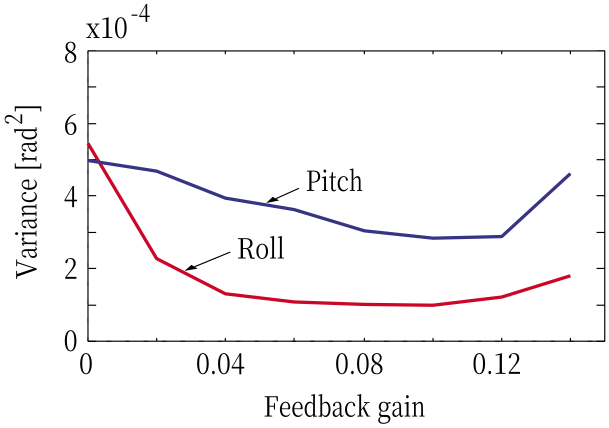


Figure 7: Split images

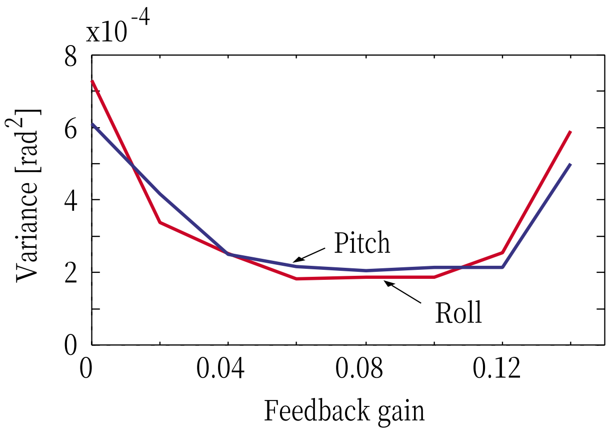
Fig. 8 shows the results of the experiment in which robot body is controlled to be stabilized by using the attitude sensor (Maxcube, JAE) and the image stabilization system, respectively. Vertical axis shows the variance of attitude of robot body and horizontal axis shows the feedback gain. From these experiments, the performance of attitude control using developed image stabilization system is almost same as the case using an attitude sensor. In particular, it is verified that the rotational angle around gravity axis is estimated much more accurately than conventional attitude sensors because there is no drift after long time measurement.

5 Conclusion

For the remote operation system of the walking robot, use of visual information from a camera mounted on



(a) Attitude sensor (Maxcube)



(b) Image stabilization system

Figure 8: Comparison of attitude estimation

a robot body is very useful. However, unlike wheeled vehicles, the camera mounted on the walking robot oscillates because of the impact of walking and discontinuity of supporting legs, and the obtained unstable images cause inferior operation performance.

In this paper, we introduce an image stabilization system for a remote operation of walking robots using a high speed CCD camera and gyrosensors. This system, at first, roughly compensates the image oscillation by the gyrosensors, and then, absorbs the remained error that is due to the processing or communication delay et al. by template matching method using the actual images that should be stabilized. We also reported the performance of the developed image stabilization system through vibration experiments using a CCD camera and several sensors, and walking experiment using a quadruped walking robot, TITAN-VIII. Furthermore, we showed that the developed image stabilization system can be utilized as the attitude sensor of robot body, and introduced an accurate attitude measurement mechanism by splitting the images using a mirror. Experimental results showed that the performance of attitude control using the developed image stabilization system is almost same as the case using an attitude sensor. In particular, the rotational angle around gravity axis is estimated much more accurately than conventional attitude sensors because there is no drift. Thus, combination of the proposed system and conventional attitude sensors is expected to realize a high performance and low cost attitude sensor for a mobile robot.

Future works will be the discrimination of image oscillation to the components that are caused by the undesired oscillation such as impact and desired oscillation such as operation command or gradient change of slope, and development of appropriate fusion system of sensory information from CCD camera and other sensors.

References

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