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The Development Of An Image Stabilization System Using An Extended Kalman Filter Used In A Mobile Robot

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Abstract This Paper Proposes A Robust Image Stabilization System For A Mobile Robot Using An Extended Kalman Filter (Ekf). Though Image Information Is One Of The Most Efficient Data Used For Robot Navigation, It Is Subjected To Noise Which Is The Result Of Internal Vibration As Well As External Factors Such As Uneven Terrain, Stairs, Or Marshy Surfaces. The Camera Vibration Deteriorates The Image Resolution By Destroying The Image Sharpness, Which Seriously Prevents Mobile Robots From Recognizing Their Environment For Navigation. In This Paper, An Inclinometer Was Used To Measure The Vibration Angle Of The Camera System Mounted On The Robot To Obtain A Reliable Image By Compensating For The Angle Of The Camera Vibration. In Addition The Angle Prediction Obtained By Using The Ekf Enhances The Image Response Analysis For Real Time Performance. The Experimental Results Show The Effectiveness Of The Proposed System Used To Compensate For The Blurring Of The Images.

Keywords: Image Stabilization, Mobile Robot, Inclinometer, Extended Kalman Filter

1. Introduction

Image stabilization is the process which removes the unwanted fluctuations found in the image sequences captured by the cameras, improving, therefore, the visual quality. Image information is one of the most important qualitative features used for mobile robot navigation. In order for the mobile robot to recognize its surrounding environment for navigation, the acquisition of reliable images from a camera mounted on the robot is indispensable. Image stabilization, which plays an important role in many vision tasks, such as tele-operation, navigation, ego-motion(Ed Note: “self-motivation”?) and scene modeling, is the method that removes an image's distortion caused by the camera's unwanted movement. There has been much research into image stabilization for military and tele-operation programs, as well as applications in commercial palmcorders. The fundamental methods for stabilizing an image have several different approaches. In [1], they proposed a new digital video stabilization approach based on a 2.5-D motion model with inertial filtering using springs and dampers. In [2] and [3], an image stability done by actuating the camera was proposed and implemented. [4] and [5] proposed image stabilization approaches using image compensation for the deteriorated image. The stabilization technique using springs and dampers can only be used for small ranges of camera vibration and has a heavy calculation burden which results in a time delay for the entire process. Image stabilization by actuating the camera is one of the basic methods for image stabilization, since it is compact and consumes little energy.[6]

Various techniques for image stabilization have been

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developed, but they are mostly inadequate for a mobile robot because of their large size. Moreover, it is hard to find research on image stabilization for legged robots that take into account the robot's motion. Several techniques for image stabilization have been implemented due to the development of the digital camera. However, they have been applied mostly for wheeled robots having little vibration when they move. In other words, they are inadequate for legged robots because of the large shaking motions when they navigate.

Quality in vision systems is not solely from the quantitative features such as the resolution of the cameras, the frame rate or the sensor gain, but also by the qualitative features such as sequences free of unwanted movement, fast and good image pre-processing algorithms and real-time response.

We propose an image stabilization system which compensates for the walking oscillations of a legged robot. The proposed image stabilization system combines two image stabilization methods. One is the stabilizing method done by rotating the camera mechanically from the motion of the robot. The other stabilizes the image by predicting the angle using EKF. The proposed system is basically a 1-DOF camera system embodied in the robot mechanism, where the vibration is measured by using an inclinometer. For image stabilization, the EKF predicts the vibration using the vibration data. As shown in both the simulation and experimental results, the proposed system using EKF provides a more stable image compared with conventional approaches.

In Section II, we review some of the conventional image stabilization systems used in digital cameras. In Section III, we propose the image stabilization system that is applicable to a mobile robot. Basically the system size is critical since it is supposed to be mounted on the robot. The performance of the proposed system based on the EKF is evaluated through a simulation in Section IV. In Section V, the experimental results show the performance of the proposed system when applied to some specified vibration inputs.

2. A Review Of Image Stabilization Systems

2.1 Optical Image Stabilization (OIS)

The OIS can be implemented in both still images and motion images. This system is sometimes referred to as "optoelectronic image stabilization" because it uses the optical path to compensate for vibration. A moveable lens shifts the optical path in order to avoid blurring. The correction element's motion is perpendicular to the optical axis in an opposite direction to the handshake. As shown in Figure 1, the OIS detects camera shake by using two angular velocity sensors for the x-axis (pitch) and one for the y-axis (yaw). This system is one of the most common image stabilization methods.

A microprocessor linked to the velocity sensors calculates the shaking angle using the measured angle/velocity. This data is transmitted from the microprocessor to the control unit, which calculates the movable lens's angle and direction and drives a voice-coil motor (VCM). This system gets a stable image without blurring.

The function of the OIS is very similar to the Electro-Mechanical Images Stabilization (EMIS). That is referenced next, since both of them stabilize the image by moving some mechanical parts. However, the EMIS and the OIS use a CCD assembly and a lens, respectively.

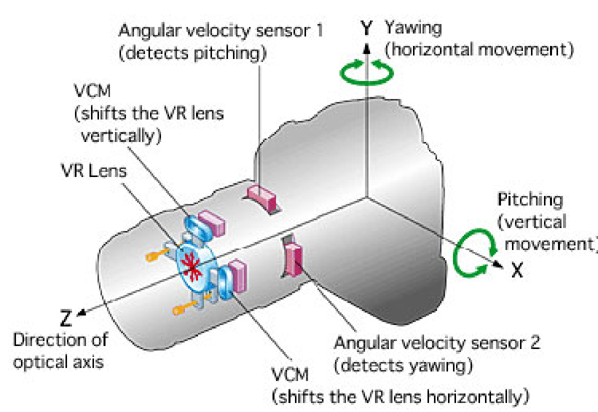

Fig. 1. Optical Image Stabilization[7]

2.2 Electromechanical Image Stabilization (EMIS)

The specific feature of EMIS directly moves an image sensor to compensate for handshake. Unlike optical stabilizers, it is possible to use any lens with the camera body equipped with EMIS. Fig. 2 shows the CCD-Shift mechanism.

Most image sensors are based on a free-floating sensor design, but the PENTAX SR uses no guide rails, allowing the sensor to oscillate in three directions-horizontally, vertically, and rotationally. This SR system uses a ball-bearing-mounted oscillator unit with four electromagnets that hold the free-floating image sensor. Angular velocity sensors detect the camera movement and relay the amount of compensation necessary to the electromagnets that move the sensor to compensate for any shake. As a result, this mechanism compensates for a shaking image in a brief time. The SR system provides a crucial advantage when shooting a handheld camera with a telephoto or tele-zoom lense, at macro distances, or in any other situation that magnifies the effects of camera shake. The SR system also helps considerably when taking non-flash pictures indoors, at dusk, or other low light situation, without using a tripod.

Fig. 2. The CCD-Shift Mechanism[8]

2.3 Digital Image Stabilization (DIS)

DIS is different from the previous mentioned techniques. It is exclusively independent of hardware. In general, the DIS consists of two parts. One part estimates several local motion vectors from other locations using the Block Matching Algorithm[9]. The other part decides upon the motion vector of the system using the local motion vector obtained in the previous part.

Because the motion vector is subject to the moving object in an image or a deliberate panning, the motion vector of the total frame is decided with the motion vector decision. The final output image is made by reading a proper block of the input image from a frame's memory.

The motion estimation plays an important role in digital image stabilization. The global block matching method is considered as one of the best methods because it covers the whole area. However, it has a large calculation burden, processing time, and a complex hardware system. To compensate for the demerits of the system, new image stabilization by bit plain matching was developed. This method uses a binary calculation, while maintaining the

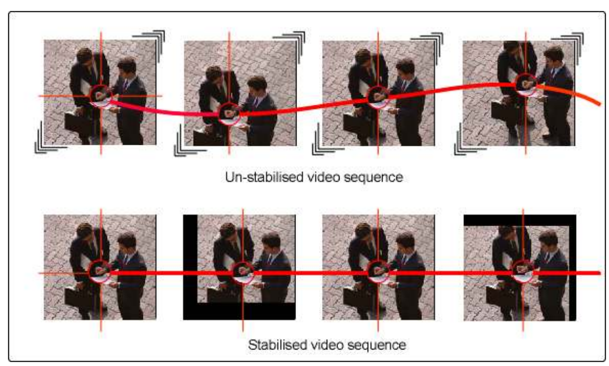

Fig. 3. The functionality of the DIS for motion pictures [11]

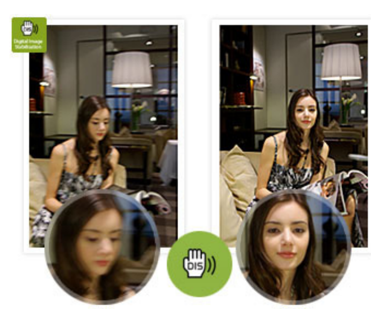

Fig. 4. Digital Image Stabilization

accuracy of the motion estimation. It enabled real-time processing[10].

3. The Enhanced Image Stabilizing System

3.1 The Target System

In this paper, we propose an image stabilization system that can be applied to a mobile robot system. For wheel type robots, the vibration in navigation has high frequency with small amplitude. In contrast, leg type robots have the vibration with low frequency and big amplitude when they navigate. The proposed system is designed to stabilize the burring of the camera image mounted on the leg type robot..

In this system, the roll axis vibration which has vibration range of -90 ~ 90 degree and frequencies of less than 5 Hz will be considered since the roll axis vibration is dominant in real situations.

3.2 The Proposed System

EMIS can be designed compact but is not suitable for the robots which need wide raged image. Though DIS does not need hard ware system, the processing speed of the embedded microcontroller is not good enough for image processing. In this paper, we propose an algorithm for angle estimation combined with OIS which has less image deterioration and is to implement. In the proposed system, the current vibrated angle is measured by inclinometer and the next angular state is estimated. DC motor is designed to rotate the camera by the estimated amount of angle in reverse direction to get stabilized image.

3.2.1 The Mechanical Mechanism

The proposed stabilization system, as shown in Fig. 5, consists of a motor, a harmonic drive which is connected directly to the motor, an inclinometer to measure the angle, and a controller behind the motor. The harmonic drive has a reduction ratio of 50:1 and has speed of 4,810 rpm in an unloaded case and 4,080 rpm in a normal operation. Using the system specifications, the speed of the start point of the motor and the end-point of camera can be calculated, as shown in Table 1. The start point stands for the gear part of the motor with the camera mounted at the end point, which is connected to the harmonic drive. As shown in Table 1, the system has an angular velocity of 570 degree/sec. for which real-time compensation is possible for the system operation.

Table 1. The Point Velocity

	Start Point(Motor)		End-Point(Camera)		
	rpm	r/s	r/s	Deg/s	Deg/s^2
No-load	4810	80.16	1.60	570	9.5
Normal	4080	68	1.36	489.6	8.16

Fig. 5. The prototype of the proposed system

3.2.2 The Electronic Mechanism

The camera vibration is measured by using an inclinometer with the revolution of 0.025 degrees and a measurement range of 360 degrees. Since it has a bandwidth of 2,250 Hz, the image of the vibration can be measured. Fig. 6 shows the configuration of the proposed system, which consists of the inclinometer, a control board and a motor.

3.2.3 The Control Mechanism:

In order to improve the performance of the image stabilization due to vibration, it is desirable to predict the different states. A novel and real-time stabilization can be obtained by using Kalman filters to remove the short term image fluctuations while retaining the smooth gross movements. The efficiency of the Kalman filer is due to the fact that the parameters of the resulting Gaussian figures can be computed in a closed form[12].

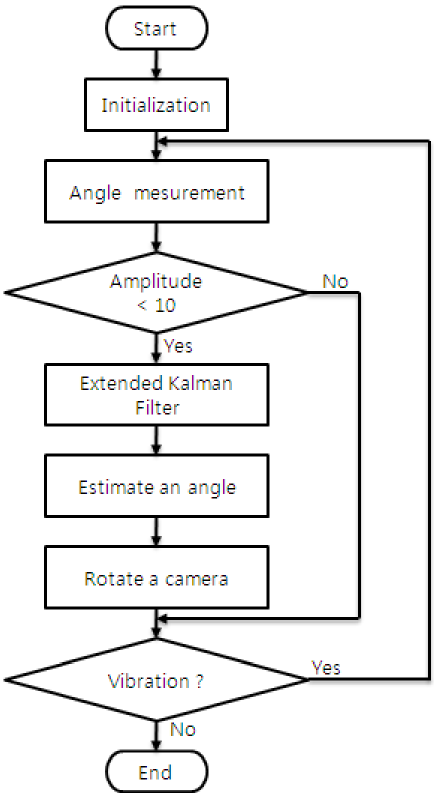

Fig. 6. The flowchart of the proposed system

Unfortunately, the state transitions and measurements are rarely linear in practice. It is well known that an EKF based predictor shows a good performance in nonlinear systems, such as vibration, which have nonlinear characteristics. The image is stabilized by compensating for the angular fluctuation due to the vibration based on the current and estimated angles.

The assumption that the observations are linear functions of the state and that the next state is a linear function of the previous state are crucial for the correctness of the Kalman filter. The observation that any linear transformation of a Gaussian random variable results in another Gaussian random variable plays an important role in the derivation of the Kalman filter algorithm.

As shown in Fig 7, the vibration can be expressed as a trigonometric function y:

$$y = Asin(\omega_{(k)}\mathrm{nT}) \tag{1}$$

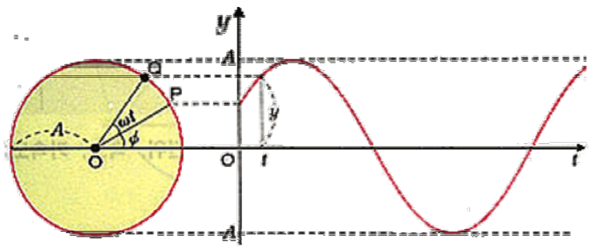

Fig. 7. The vibration modeling

Where A is the amplitude and $\omega_{(k)}$ is the angular velocity, respectively.

When the measured data are applied to the EKF, the state vector of the system has the form of:

$$\overline{x}_{(k)} = [\theta, \omega]^T,\ \overline{z}_{(k)} = [\theta, \omega]^T \tag{2}$$

The state equation of the system can be expressed as:

➢ Prediction model

$$\begin{aligned} \overline{x}_{(k+1)} &= f(\overline{x}_{(k)}) + w_{(k)} \\ \theta_{(k+1)} &= \theta_{(k)} + \omega_{(k)} A\,Tcos(\omega_{(k)} nT) \\ \omega_{(k+1)} &= \omega_{(k)} \end{aligned} \tag{3}$$

➢ Measurement model

$$\overline{z}_{(k+1)} = h(\overline{x}_{(k+1)}, m_{(k)})\, v_{(k)} \tag{4}$$

To linearize f, the following Jacobian matrix is used:

$$f_{(k)} = \begin{bmatrix} 1 & A\,Tcos(\omega_{(k)} nT) - A\omega_{(k)} nT^2 \sin(\omega_{(k)} nT) \\ 0 & 1 \end{bmatrix} \tag{5}$$

where T and n are the sampling time and the step number, respectively. The function can be used to compute the predicted state from the previous estimate, and similarly the predicted measurement from the predicted state. However, f and h cannot be applied to the covariance directly. To apply them to the EKF, using the already explained system model, first the predictions of the state and the covariance are computed by:

- Time update

$$\hat{x}_{(k+1|k)} = f(\hat{x}_{(k)}, Q)$$
$$P_{(k+1|k)} \equiv F_{(k)} P_{(k|k)} F_{(k)}^{T} + Q_{(k)} \quad (6)$$

Once we have the measures of the angle, the innovation and the covariance of the innovation can be computed by (7) and (8):

$$\widetilde{A}_{(k+1|k)} = z_{(k+1)} - h(x_{(k+1|k+1)}, 0) \quad (7)$$

$$S_{(k+1)} = H_{(k+1)} P_{(k+1|k)} H_{(k)}^{T} + R_{(k+1)} \quad (8)$$

where H is the Jacobian matrix of the observation model. The Kalman gain can be computed by:

$$K_{(k+1)} = P_{(k+1|k)} H_{(k+1)}^{T} S_{(k+1)}^{-1} \quad (9)$$

Finally, the estimation of the state and covariance of the system are obtained by:

$$\hat{x}_{(k+1|k+1)} = \hat{x}_{(k+1|k)} + K_{(k+1)} \widetilde{A}_{(k+1)} \quad (10)$$

$$P_{(k+1|k+1)} = P_{(k+1|k)} - H_{(k)}^{T} + K_{(k+1)} S_{(k+1)} K_{(k+1)}^{T} \quad (11)$$

4. Simulation

The efficiency of the angle prediction done by the proposed method has been verified by using a MATLAB simulation. The sample input for the estimation has a sine wave form with amplitude of 10 degrees. The simulation results show how the angles are estimated in EKF which is used for vibration modeling. According to the simulation results shown in Figs 8-11, the estimated signal traces the input signal faithfully, with little error. As shown in the figures, the error is reduced after the 2nd period dramatically.

Table 2 shows the result of the error average. The error increases as the frequency increases in the range of 5 % of error. Therefore, the angular estimation is acceptable in real applications.

Table 2. The Comparison of the Simulation Results

	0.25Hz	0.5Hz	2.5Hz	5.0Hz
Error	-0.003424	-0.017394	-0.283652	-0.557989

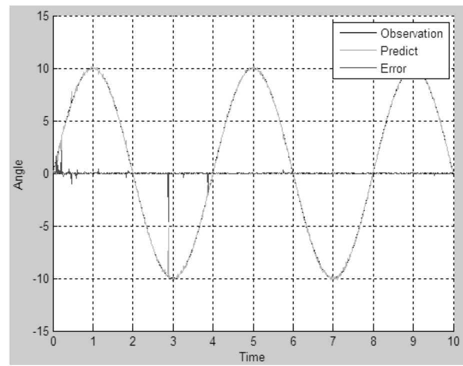

Fig. 8. The simulation result for the frequency of 0.25Hz

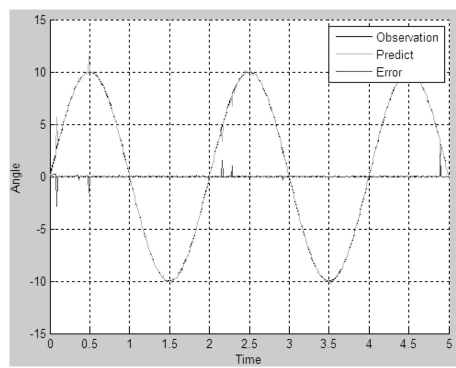

Fig. 9. The simulation result for the frequency of 0.5Hz

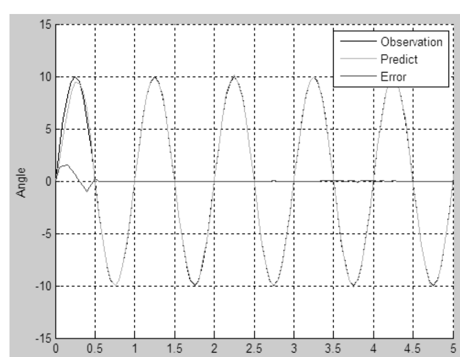

Fig. 10. The simulation result for the frequency of 1.0Hz

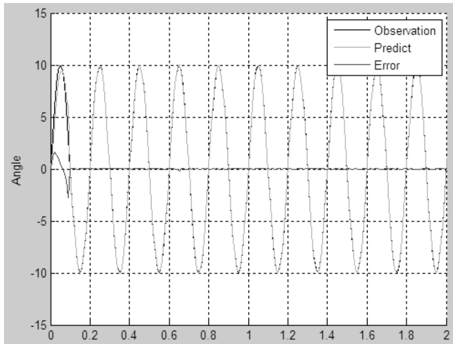

Fig. 11. The simulation result for the frequency of 5.0Hz

5. The Experimental Results

5.1 The Experimental Apparatus

In order to evaluate the performance of the proposed system, we built an image capturing system where the frequency and amplitude of the applied vibration are adjustable. As shown in Fig. 12, the experimental apparatus has a cylindrical shape connected with a DC motor. It generates the vibrating signals with a -10 ~ 10 degrees of amplitude and five steps of frequency between 0.25 ~ 5 Hz as the inputs to the system under evaluation. The compensation is performed using a servo motor for the movement. The proposed system receives the target image, shown in Fig. 13, as an input through the camera attached to the end of the system. The number of corners of the image is counted by using the Harris Corner Detection algorithm and is used as data for the performance index

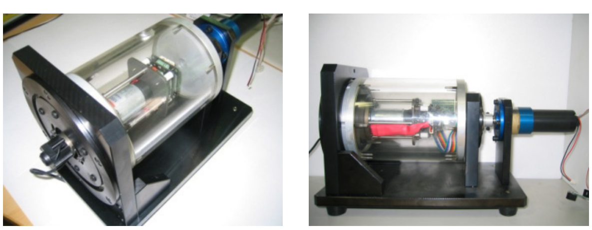

Fig. 12. The experiment equipment

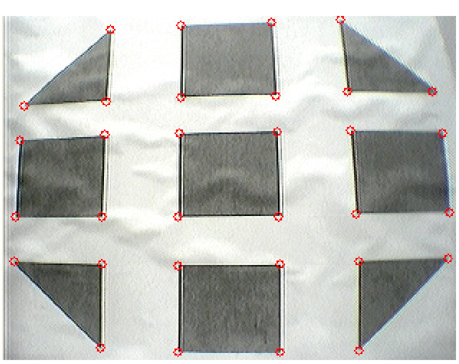

Fig. 13. The target image for the experiment

5.2 The Experimental Results

The number of the corners of the image, shown in Fig. 13, is 32. The detected number of corners of the image when the system is in vibration denotes the stability index of the captured image. The closer it is to 32, the more reliable the system is. The following figures show the difference in the numbers between the number of detected corners and 32.

Fig 14 shows the experimental result in the case of 0.25 Hz of frequency. In the case of 0.5 Hz, the lowest frequency in the experiment, the EKF based method shows a slightly better stabilization. As shown in the figures below, the proposed system using the EKF is especially effective for image stabilization in the case of 0.5, 1.0 and

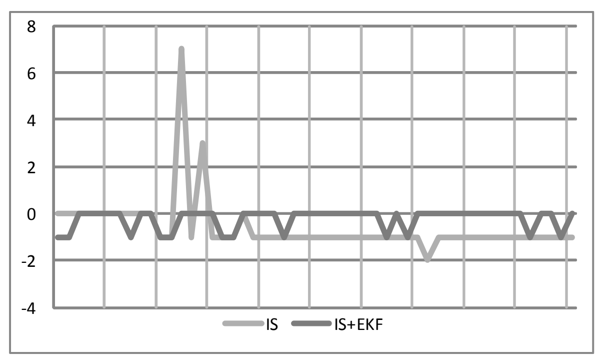

Fig. 14. The experimental result for the frequency of 0.25Hz

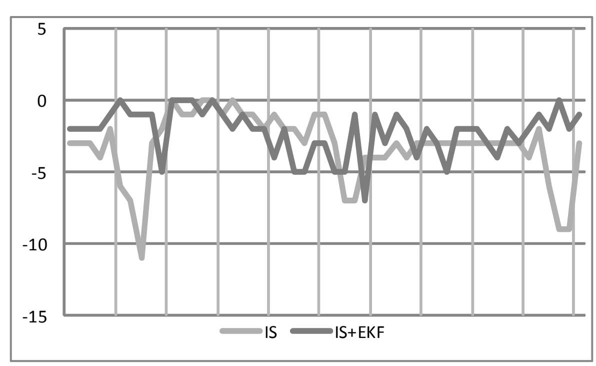

Fig. 15. The experimental result for the frequency of 0.5Hz

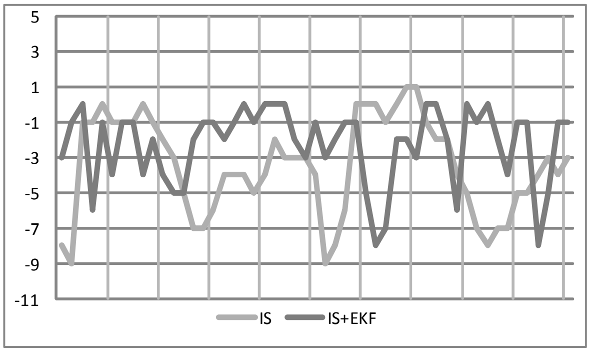

Fig. 16. The experimental result for the frequency of 1.0Hz

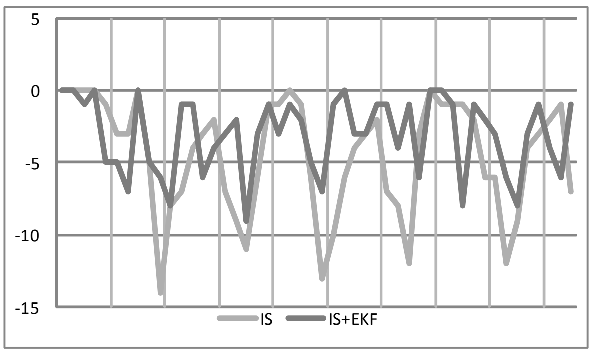

Fig. 17. The experimental result for the frequency of 2.5Hz

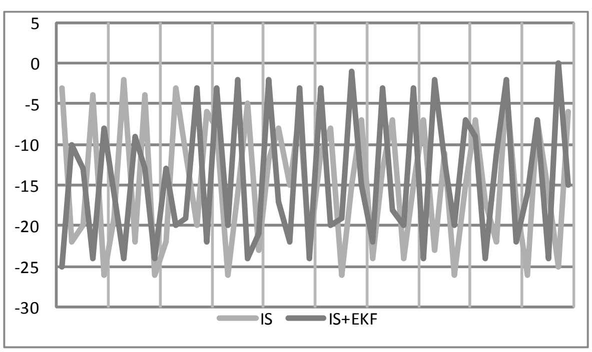

Fig. 18. The experimental result for the frequency of 5.0Hz

2.5 Hz. However, for the 5.0 Hz case, the EKF based algorithm results in a better image stabilization, but it is slightly out of phase.

Table 3 describes the experimental results of the corner detection rate in the case of IS and IS+EKF for different frequencies. According to Table 3, the EKF based approach shows a better performance in image stabilization compared to the IS for 5 different frequencies. As a result, the EKF method is more helpful for image stabilization.

Table 3. The Comparison of the Experimental Results

	0.1Hz	0.25Hz	0.5Hz	2.5Hz	5.0Hz
IS Only	98.19%	90.00%	89.38%	84.19%	54.38%
IS + EKF	99.31%	93.06%	92.88%	89.06%	58.88%

6. Conclusions

In this paper, we propose a novel image stabilization system based on EKF. The EKF based stabilization enables a real-time utilization and provides a successful performance for the fluctuation cancellation of camera movements. Different from the conventional system based on hardware, the proposed system is designed to enhance the stability and response by predicting the states using the previous states of velocity and angular velocity found in the system. The experimental results for image stabilization show a good performance for the proposed system for the input vibrations of 0.25, 0.5, 1, 2.5 and 5.0Hz. The performance enhancement is better in the first four cases, compared to the fifth case.

There are several important issues that need to be addressed in future research into this area for real world applications including: 1) performance verification of the proposed system in a wider range of frequencies and angular velocities, and 2) a 2-axis image stabilization for mobile navigation.

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