Video Article

# Gain-compensation Methodology for a Sinusoidal Scan of a Galvanometer Mirror in Proportional-Integral-Differential Control Using Pre-emphasis Techniques

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URL: https://www.jove.com/video/55431
DOI: doi:10.3791/55431

Keywords: Engineering, Issue 122, galvanometer mirror, optical path, sinusoidal scanning, proportional-integral-differential (PID) control, high-speed, pre-emphasis technique

Date Published: 4/4/2017

Citation: Hayakawa, T., Watanabe, T., Senoo, T., Ishikawa, M. Gain-compensation Methodology for a Sinusoidal Scan of a Galvanometer Mirror in Proportional-Integral-Differential Control Using Pre-emphasis Techniques. *J. Vis. Exp.* (122), e55431, doi:10.3791/55431 (2017).

## Abstract

Galvanometer mirrors are used for optical applications such as target tracking, drawing, and scanning control because of their high speed and accuracy. However, the responsiveness of a galvanometer mirror is limited by its inertia; hence, the gain of a galvanometer mirror is reduced when the control path is steep. In this research, we propose a method to extend the corresponding frequency using a pre-emphasis technique to compensate for the gain reduction of galvanometer mirrors in sine-wave path tracking using proportional-integral-differential (PID) control. The pre-emphasis technique obtains an input value for a desired output value in advance. Applying this method to control the galvanometer mirror, the raw gain of a galvanometer mirror in each frequency and amplitude for sine-wave path tracking using a PID controller was calculated. Where PID control is not effective, maintaining a gain of 0 dB to improve the trajectory tracking accuracy, it is possible to expand the speed range in which a gain of 0 dB can be obtained without tuning the PID control parameters. However, if there is only one frequency, amplification is possible with a single pre-emphasis coefficient. Therefore, a sine wave is suitable for this technique, unlike triangular and sawtooth waves. Hence, we can adopt a pre-emphasis technique to configure the parameters in advance, and we need not prepare additional active control models and hardware. The parameters are updated immediately within the next cycle because of the open loop after the pre-emphasis coefficients are set. In other words, to regard the controller as a black box, we need to know only the input-to-output ratio, and detailed modeling is not required. This simplicity allows our system to be easily embedded in applications. Our method using the pre-emphasis technique for a motion-blur compensation system and the experiment conducted to evaluate the method are explained.

## Video Link

The video component of this article can be found at https://www.jove.com/video/55431/

## Introduction

Various optical actuators and control methods suitable for various optical applications have been proposed and developed[1,2]. These optical actuators are able to control the optical path; galvanometer mirrors especially offer a good balance in terms of accuracy, speed, mobility, and cost[3,4,5]. Actually, the advantage offered by the speed and accuracy of galvanometer mirrors has led to the realization of a variety of optical applications, such as target tracking and drawing, scanning control, and motion-blur compensation[6,7,8,9,10,11,12]. However, in our previous motion-blur compensation system, a galvanometer mirror using a proportional-integral-differential (PID) controller provided a small gain; hence, it was difficult to achieve a higher frequency and a faster speed[11].

On the other hand, PID control is a widely-used method, as it satisfies a certain level of tracking accuracy[13]. A variety of methods have been proposed to correct the gain in PID control. As a typical solution, PID control parameter tuning is conducted manually. However, it takes time and special skill to maintain. A more sophisticated method, an auto-tuning function to automatically determine the parameters, has been proposed and is widely used[14]. The tracking accuracy for high-speed operations is improved using the auto-tuning function when the proportional gain value P increases. However, this also increases the convergence time and noise in the low-speed range. Hence, the tracking accuracy is not necessarily improved. Although a self-tuning controller can be tuned to set suitable parameters for PID control, the tuning introduces a delay because of the need to obtain suitable parameters; therefore, it is difficult to adopt this method in real-time applications[15]. An extended PID controller[16,17] and an extended predictive controller[18] have been proposed to extend general PID control and to enhance the tracking performance of galvanometer mirrors for a variety of tracking paths, such as triangular waves, sawtooth waves, and sine waves. However, in those systems, the galvanometer system was regarded as a black box, whereas a model of the control system was required, and the control system was not regarded as a black box. Hence, those methods require that their model for each galvanometer mirror be updated. Moreover, although Mnerie *et al.* validated their method of focusing on a detailed output wave and phase, their research did not include the attenuation of the entire wave. In fact, in our previous research[11], the gain was significantly decreased when the sinusoidal frequency was high, thereby indicating the necessity to compensate for the gain of the entire wave.

In this research, our procedure for gain compensation with PID control[12] is based on the pre-emphasis technique[19,20,21]—a method to enhance the quality or speed of communication in communications engineering—which enables the construction of an experimental system using existing equipment. **Figure 1** shows the flow structure. The pre-emphasis technique is able to obtain in advance the desired output value from an input value, where PID control is not effective, even if the galvanometer mirror and its controller are regarded as black boxes. This enables them to expand the frequency and amplitude range in which a gain of 0 dB can be obtained without tuning the PID control parameters.

When the gain is amplified, the response characteristics of the galvanometer mirror generally differ at different frequencies, and therefore, we need to amplify each frequency with amplification coefficients. Thus, a sine wave is suitable for the pre-emphasis technique, as there is only one frequency in each sine wave. In this research, because we apply gain compensation to accomplish motion-blur compensation, the control signal is limited to sine-wave scanning, and the sine-wave signal constitutes a single frequency, unlike other waves, such as triangular and sawtooth waves. Further, the input signal into the galvanometer mirror is updated immediately within the next cycle because of the open loop after the pre-emphasis coefficients are set. In other words, we need to know only the input-to-output ratio to regard the controller as a black box, and detailed modeling is not required. This simplicity allows our system to be easily embedded in applications.

The overall goal of this method is to establish an experimental procedure of motion-blur compensation as an application by gain compensation using the pre-emphasis technique. Multiple hardware devices are used in these procedures, such as a galvanometer mirror, a camera, a conveyor belt, illumination, and a lens. Central software user-developed programs written in C++ also constitute part of the system. **Figure 2** shows a schematic of the experimental setup. The galvanometer mirror rotates with gain-compensated angular velocity, thereby making it possible to evaluate the amount of blur from the images.

## Protocol

# 1. Acquisition of Gain Data for a Galvanometer Mirror

1. Fix the galvanometer mirror such that it is stabilized to protect it from damage while oscillating. Not only the galvanometer mirror, but also the body of the galvanometer mirror, moves if not fixed in place using a custom-made metal jig with a circular hole for the galvanometer mirror. Fix the jig onto an optical carrier and an optical bench.
2. Connect BNC cables from the AD/DA board through a terminal block to the input and position sockets in the servo driver of the galvanometer mirror.
3. Program the sine-wave function generator as a graphical user interface (GUI) using the SDK of the AD/DA board with C++, which is able to set an arbitrary frequency, amplitude, and duration, as shown in **Figure 3**.
   NOTE: This customized function generator contributes to cutting the temporal cost for continuous trials in step 1.5, since the trial is conducted many times.
4. Set the frequency to vary from 100 Hz to 500 Hz in 100-Hz intervals, and set the amplitude to vary from 10 mV to 500 mV in 10-mV intervals in the GUI. Overall, 250 combinations exist. To test 250 combinations, a double loop is efficient to implement. The first loop is for frequencies from 100 Hz to 500 Hz, which is implemented 50 times. The second loop is for amplitudes from 10 mV to 500 mV, which is implemented for 50 times.
5. Add the sine-wave path signal into the AD/DA board for 2,000 samplings as duration in the GUI. Simultaneously record the position signal of the galvanometer mirror to read the analogue value of the AD/DA board. In C++ coding using a library of AD/DA board, use the same thread for writing and reading in programming. Calculate the current angle of galvanometer mirror θ (writing information) by this equation
   $$\theta = A_{in}\sin(2\pi f t)$$
   where *t* is time, $A_{in}$ is amplitude, $f$ is frequency.
6. Save the position signal data as a .csv file and include the value of the frequency and amplitude in its filename.
7. Repeat steps 1.4 - 1.6 for 250 iterations.

# 2. Calculation to Get Pre-emphasis Coefficients

1. Apply a median filter for the csv files (recorded signals) to avoid noise effects. The spatial size of the median filter is 5.
2. Run the script to calculate the peak-to-peak value (corresponding with the amplitude multiplied by 2), using MATLAB for each of the csv files, as shown in **Figure 4** (the graph represents the data of the sine-wave path).
3. Plot the peak-to-peak data on a graph to determine the linearity at each frequency, and limit the usage region of the input amplitude when the plots are nonlinear, as shown in **Figure 5**.
   NOTE: The nonlinear part of the graph represents saturation of the PID control; hence, it is advisable to avoid using them to secure the limitation of specification of control.
4. Execute linear regression for peak-to-peak data in a spreadsheet to obtain the linear interpolation coefficients of each frequency. In this process, five sets of slopes and intercepts are obtained. They correspond with the frequencies from 100 Hz to 500 Hz at each 100 Hz. An approximation of the straight line of 300 Hz is displayed in **Figure 5(A)**, and the linear interpolation coefficients of each frequency are shown in **Table 1**.
5. Using quadratic multiple linear regression, execute quartic interpolation to obtain the quartic interpolation coefficients (pre-emphasis coefficients) in the spreadsheet for the linear interpolation coefficients of each frequency. The pre-emphasis coefficients are shown in **Table 2**.
   NOTE: In this research, the linear interpolation coefficients vary in the form of a quadratic curve; however, other types of functions, such as quadratic and cubic equations, are applied if the error is minimal.

 

## 3. Online Signal Amplification Based on the Pre-emphasis Technique

1. Execute the software that calculates the updated input amplitude value $A'_{in}$ from the ideal input amplitude value $A_{in}$ and the frequency $f$ using the pre-emphasis coefficients.
    1. Save the pre-emphasis coefficients as constant values in the C++ software. When the device is updated, these constant values are also updated.
    2. Program a function
    $k_{(i,f)} = a_i f^4 + b_i f^3 + c_i f^2 + d_i f^1 + e_i \ (i = 0,1)$
    in the C++ software and obtain the linear interpolation coefficients. Substitute them for $a_i$, $b_i$, $c_i$, $d_i$, and $e_i$ from the equation and **Table 2**.
    3. Program a function
    $A'_{in} = k_{(0,f)} A_{in} + k_{(1,f)}$
    in the C++ software and obtain an updated input amplitude value $A'_{in}$ to substitute for $A_{in}$ and the linear interpolation coefficients that were obtained in step 3.1.2.
2. Repeat steps 1.4 - 1.6 for arbitrary times with $A'_{in}$ using the pre-emphasis technique in the GUI.NOTE: To avoid saturation of the region of PID control, set 400 mV for up to 200 Hz, 200 mV for up to 300 Hz, 100 mV for up to 400 Hz, and 50 mV for up to 500 Hz.
3. Repeat step 2.2 and plot peak-to-peak data as a graph to view the improvement in the gain.

## 4. Experiment on Motion-blur Compensation

1. Prepare a conveyor belt that can move at 30 km/h using a belt that can adhere to sticky textures. The custom-made conveyor belt is composed with a speed-control motor, an iron rubber belt, and so on. It can be replaced with ready-made conveyor belt which can control speed.
2. Print a fine-texture pattern onto printable tape and paste it onto the conveyor belt.
NOTE: The pasted texture is shown in **Figure 6**. The stripes are programmed using a library "ofxPDF" in openFrameworks, and the photographic image is from a stock photo company.
3. Set up optical devices such as a camera, a lens, and an illumination, as shown in **Figure 2**. Place the galvanometer mirror in front of the lens which is connected to the camera, and place the illumination to illuminate the conveyor belt.
    1. Set the camera frequency to 333 Hz, the exposure time to 1 ms, and the number of pixels to 848 * 960 (width * height).
4. Synchronize the rotational timing of the galvanometer mirror and the exposure time of the camera. In the software, when the angle of the galvanometer mirror arrives the position where to start exposure, the program sends a software trigger into the camera. The timing of software trigger is illustrated in **Figure 7**.
5. Input the speed of the conveyor belt $v_t$ (30 km/h) and the distance from the camera to the conveyor belt $L$(3.0 m) to calculate required angular velocity $\omega_r$ of the galvanometer mirror in the GUI as in **Figure 8**. $\omega_r$ is calculated as follows:
$\omega_r = 2\tan^{-1}\frac{v_t}{L}$
6. Input the frequency $f$(330.0 Hz) in the GUI as in **Figure 8** to calculate original input amplitude $A_{in}$. Calculate $A_{in}$ as follows:
$A_{in} = \frac{\omega_r}{4f}$
7. Copy and paste $A_{in}$ into the source code, and rotate the galvanometer with the pre-emphasized control value θ for the galvanometer servo driver as follows:
$\theta = A'_{in} \sin(2\pi f t)$
where $t$ is time. **Figure 7** illustrates how θ is calculated from $A$.
8. Record images when the conveyor belt is moving at $v_t$ (30 km/h).
NOTE: **Figure 9** illustrates the motion of the conveyor belt.

## Representative Results

The results presented here were obtained using an AD/DA board and a camera. **Figure 1** shows the procedure of the pre-emphasis technique; therefore, it is the core of this article. It is unnecessary to set the parameters of the PID control after the initialization state; hence, the online process is significantly simple.

**Figure 10** shows the results obtained by applying the pre-emphasis technique to our system. As shown in **Figures 10(A)** and **10(B)**, respectively, it was revealed that almost all output plots are on the line $y = x$ and almost all amplitude plots are on the line $y = 0$ dB.

**Figures 11 and 12** show the results of our application system. Despite the fact that the images in **Figures 11(D)** and **12(D)** had degraded sharpness compared with those in **Figures 11(A)** and **12(A)**, the sharpness of the images in **Figures 11(D)** and **12(D)** had improved significantly compared to **Figures 11(B)** and **11(C)** and **12(B)** and **12(C)**. **Figure 11** shows the profiles obtained by quantitatively analyzing the performance of our motion-blur compensation system. The profiles in **Figures 11(B)** and **11(C)** are entirely flat, whereas that in **Figure 11(D)** is bumpy, because the contrast between the black and white stripes is improved. The profile in **Figure 11(C)** is slightly bumpy compared with that in **Figure 11(B)**, since the gain was reduced at high frequency. On the other hand, we prepared a texture image of a circuit board and pasted it on a conveyor belt in **Figure 12**, and its sharpness was improved by the pre-emphasis technique.

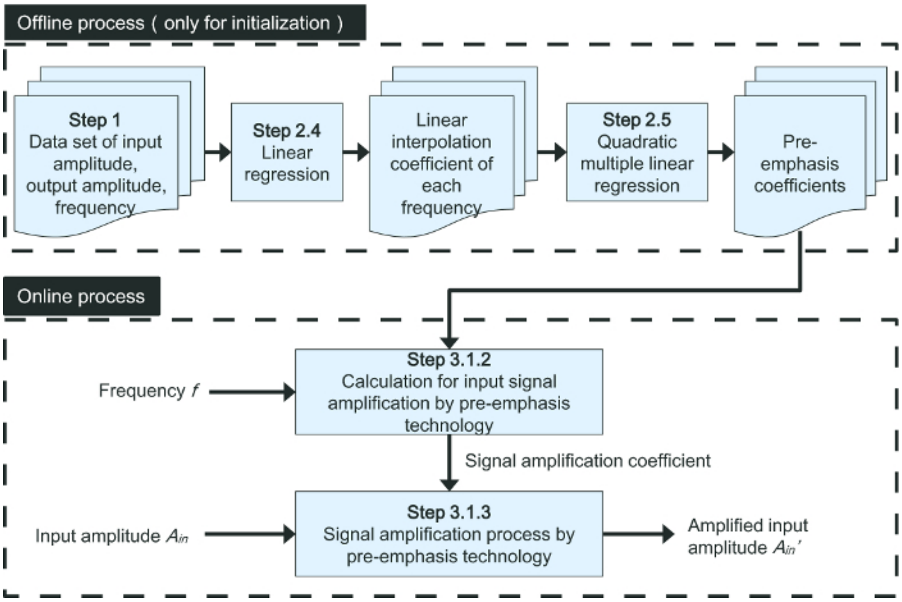


**Figure 1. Flow Chart of the Pre-emphasis Technique for Control.** The procedure is separated into an offline and an online process. Each action corresponds with each step in the procedure. This figure has been modified from Reference 12. Please click here to view a larger version of this figure.

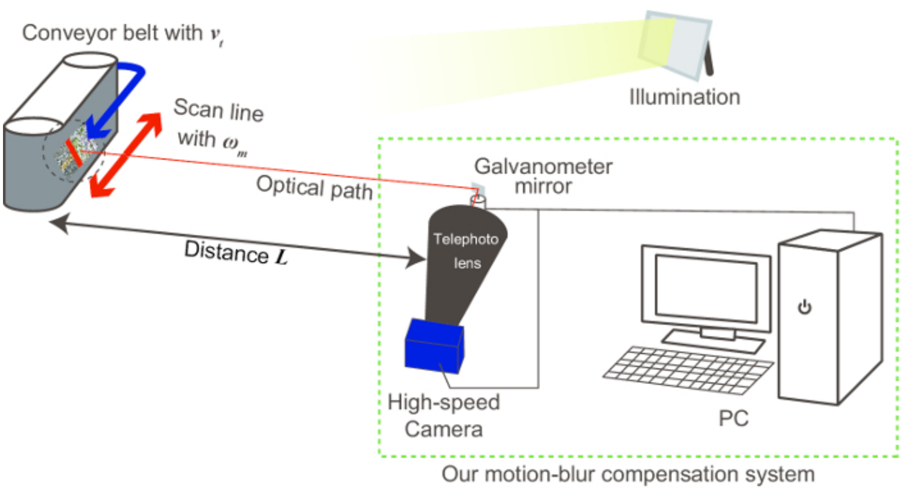


**Figure 2. Schematic of the Experimental Setup of the Motion-blur Compensation System.** The galvanometer mirror is used for gain compensation. The angular speed corresponds with the speed of the conveyor belt. The galvanometer mirror and the camera are controlled by a PC. This figure has been modified from Reference 11. Please click here to view a larger version of this figure.

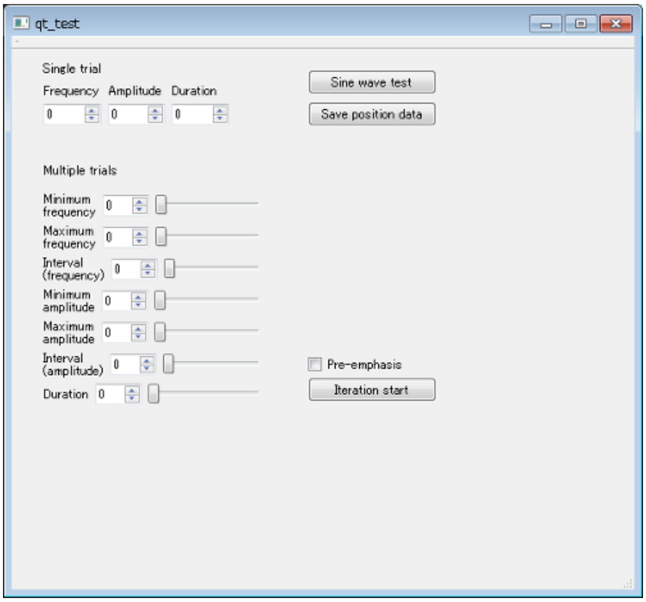


**Figure 3. A GUI of Sine-wave Function Generator.** A GUI to input parameters. User can input frequency, amplitude, and duration for single sine wave to save position data. For an iterative sine wave, user can set the range and interval of the frequency and amplitude. Additionally, user can set the availability of pre-emphasis technique using a check button. Please click here to view a larger version of this figure.

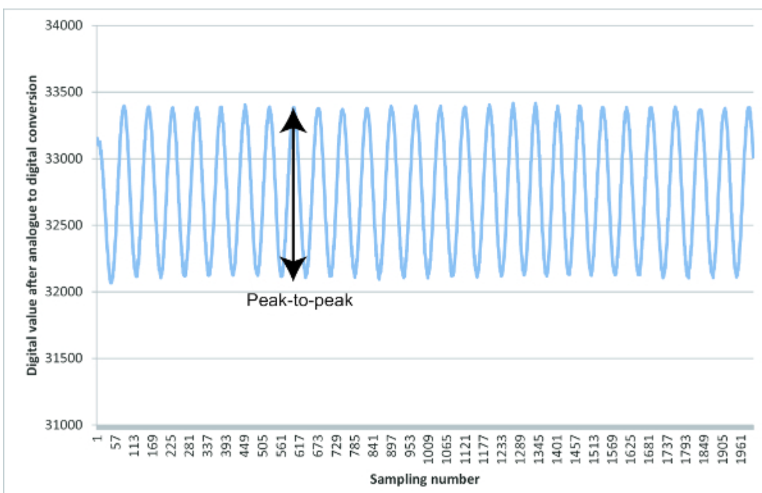


**Figure 4. Raw Data of the Sine-wave Path Obtained through AD Conversion.** A frequency and amplitude of 300 Hz and 300 mV, respectively, were used. We obtained the peak-to-peak value from these data. Please click here to view a larger version of this figure.

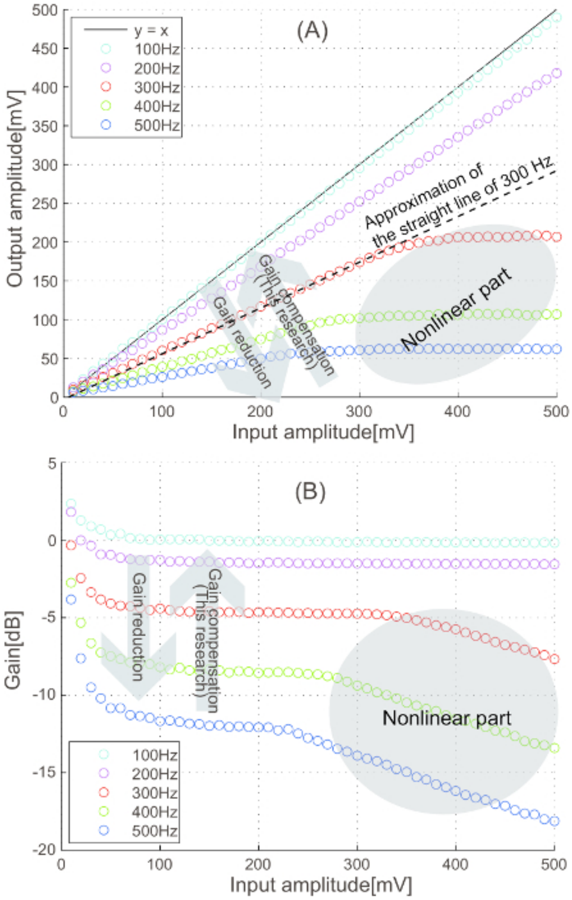


**Figure 5. Response Characteristics of the Galvanometer Mirror. (A)** Input signal (mV) and output signal (mV). **(B)** Input signal (mV) and gain (dB). This figure has been modified from Reference 11. Please click here to view a larger version of this figure.

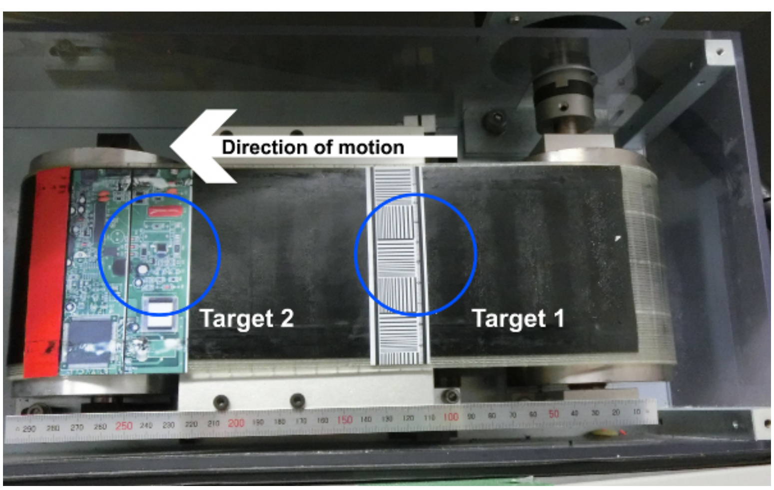


**Figure 6. Conveyor Belt and Textures Pasted onto the Belt.** We prepared two targets on the conveyor belt. This image was taken when the conveyor belt was stopping. Target 1 is a sheet of scales and target 2 is a color copy of the circuit board. The conveyor belt moves horizontally. Please click here to view a larger version of this figure.

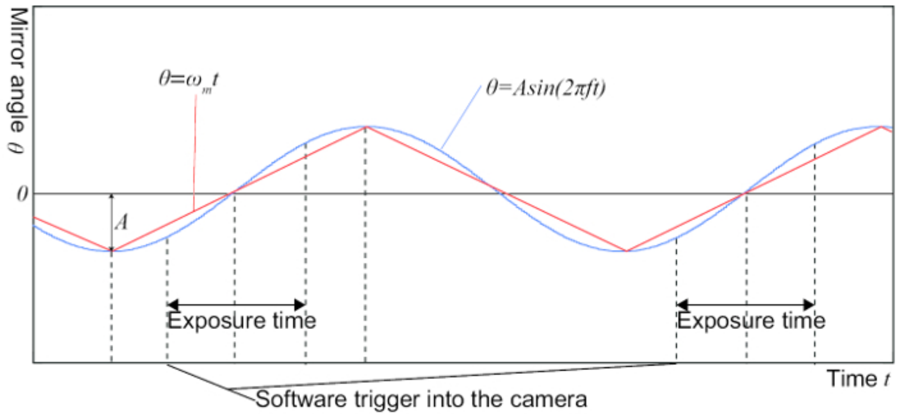


**Figure 7. Timing Chart of Control Signal.** Sine wave signal (blue line) and ideal triangular wave signal (red line). Software trigger occurred at the start of exposure time. This figure has been modified from Reference 11. Please click here to view a larger version of this figure.

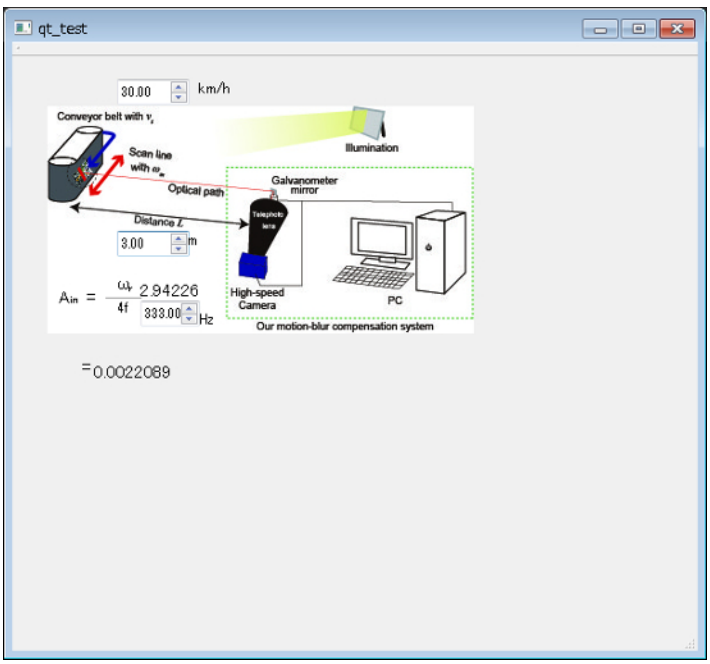


**Figure 8. A GUI to Calculate Original Input Amplitude.** A GUI to input parameters. User can input velocity of the conveyor belt, distance from the camera to the conveyor belt, and control frequency. At last, user can get original input amplitude. Please click here to view a larger version of this figure.

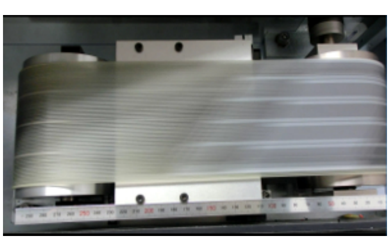

**Figure 9. Motion of the Conveyor Belt.** The conveyor belt is moving at $v_t$ (30 km/h). We recorded this movie by using a normal, commercially-available compact digital camera. Please click here to view this video. (Right-click to download.)

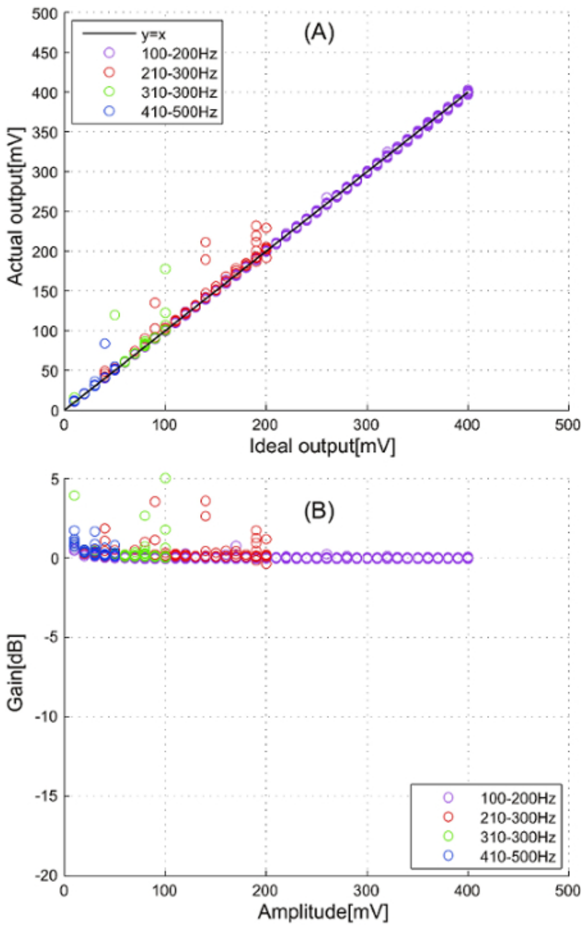


**Figure 10. Results of the Pre-emphasis Technique. (A)** Amplitudes of ideal and actual output voltages after applying the pre-emphasis technique. **(B)** Gain resulting from the pre-emphasis technique. This figure has been modified from Reference 12. Please click here to view a larger version of this figure.

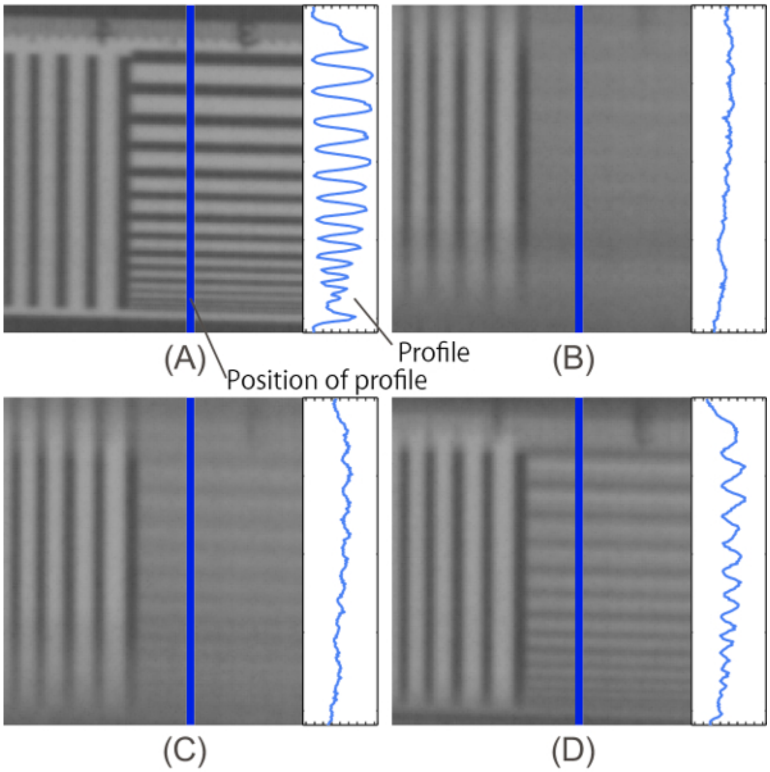


**Figure 11. Results of Applying the Pre-emphasis Technique with our System by Setting $v_t$ to 30 km/h Vertically and Vertical Profiles Corresponding to the Blue Lines (the Images are Trimmed to 240 * 225 px for the Aligned Display). (A)** Still image. **(B)** Image when $v_t$ = 30 km/h (motion-blur compensation was inactive). **(C)** Image when $v_t$ = 30 km/h (motion-blur compensation was active and pre-emphasis was inactive). **(D)** Image when $v_t$ = 30 km/h (motion-blur compensation was active and pre-emphasis was active). This figure has been modified from Reference 12. Please click here to view a larger version of this figure.

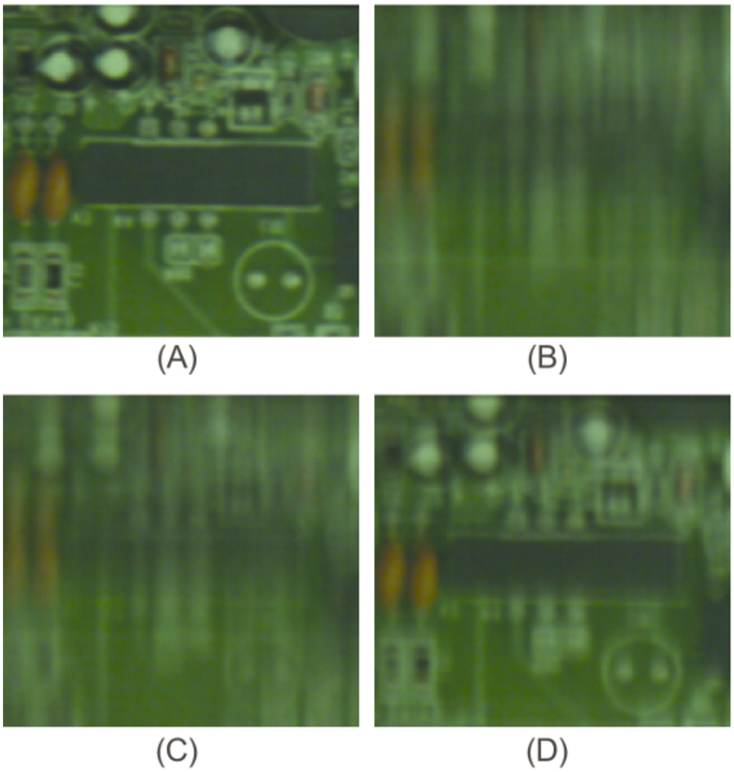


**Figure 12. Results of Applying the Pre-emphasis Technique to the Texture Image of a Circuit Board with our System When $v_t$ was 30 km/h Vertically (the Images are Trimmed to 264 * 246 px for the Aligned Display). (A)** Still image. **(B)** Image when $v_t$ = 30 km/h (motion-blur compensation was inactive). **(C)** Image when $v_t$ = 30 km/h (motion-blur compensation was active and pre-emphasis was inactive). **(D)** Image when $v_t$ = 30 km/h (motion-blur compensation was active and pre-emphasis was active). This figure has been modified from Reference 12. Please click here to view a larger version of this figure.

| | **Linear interpolation coefficients** | |
|---|---|---|
| *f* [Hz] | $k_{(1,f)}$ | $k_{(0,f)}$ |
| 100 | 1.0271 | -3.7321 |
| 200 | 1.2053 | -3.7107 |
| 300 | 1.7570 | -4.2157 |
| 400 | 2.7891 | -9.1564 |
| 500 | 4.3559 | -14.931 |

**Table 1. List of Linear Interpolation Coefficients for Each Frequency.** The parameters are calculated in step 2.4. This table has been modified from Reference 12.

| | **Quartic polynomial coefficients** | | | | |
|---|---|---|---|---|---|
| *i* | *a* | *b* | *c* | *d* | *e* |
| 0 | -2.16E-11 | 3.93E-08 | 5.51E-07 | -8.16E-04 | 1.07E+00 |
| 1 | 6.30E-10 | -7.81E-07 | 2.35E-04 | -2.50E-02 | -2.86E+00 |

**Table 2. List of Quartic Polynomial Coefficients.** The parameters are calculated in step 2.5. This table has been modified from Reference 12.

## Discussion

This article presents a procedure capable of expanding the sine-wave frequency range to achieve high-accuracy trajectory tracking with PID control. Because the responsiveness of a galvanometer mirror is limited by its inertia, it is critical to use a galvanometer mirror when the control path is steep. However, in this research, we propose a method to improve the specification of control and then prove the method by obtaining experimental results.

In our procedure, step 2.5 is the most critical step. We obtain the pre-emphasis coefficients from the linear interpolation coefficients to utilize an arbitrary frequency. Without this step, we can use only discrete frequencies. Our procedure has both offline and online parts. The offline part is necessary in order to use the device during the initial stage; however, it takes time to obtain pre-emphasis. Hence, it is sensible to shift from a manual to an automatic process. In step 2.4, we did not use the nonlinear part of the data manually, and it can be substituted by an automatic step with the ability to recognize the linearity. We prepared a separate script and process in MATLAB and in a spreadsheet; however, the procedure can be simplified by creating one program in C++ with a GUI.

The technique has the following limitation: it is not applicable to situations in which the amplified signal does not reach the ideal signal strength. In that case, the device itself would either require increased torque or the mirror should be lightweight. The advantage of this method is that it can contribute to cost reduction when updating control systems using any sine wave. Although an auto-tuning function is possible to determine parameters as an initialization, this method needs to determine parameters again when the frequency and amplitude are varied[14]. Additionally, a self-tuning controller can determine parameters in real-time, however the tuning takes delay[15]. This is because, unlike previous methods, the proposed technique readily improves performance without the need to change the control parameters of the actuators and PID control after the initialization state has ended and when the frequency and the amplitude vary[14,15]. Hence, the online process is significantly simplified and can be used in real time. However, as we tested our procedure in only one device, it is necessary to test it in other devices as well. Our method is commonly applicable to other devices, as we regarded the galvanometer system and controller as black-box systems, unlike existing methods[16,17,18]. An extended PID controller[16,17] and an extended predictive controller[18] are enable to enhance the tracking performance of galvanometer mirrors for a variety of tracking paths, however, their galvanometer systems and controllers are black-box systems.

Finally, in the future, this technique could be applied in optical applications such as target tracking and drawing, both of which use sine-wave path tracking. It would be possible to extend this technique to use an arbitrary wave signal constructed with a sine wave.

## Disclosures

The authors have nothing to disclose.

## Acknowledgements

The authors have no acknowledgements.

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