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The feedback stability research of HDRI system

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In this paper, one kind of high dynamic range imaging (HDRI) system is analyzed and the feedback stability is optimized. In this system, space light modulator (SLM) is used to modulate the input illuminance with the feedback signals. Because of the illuminance uncertainty of the scene, the feedback may take too long or turn into oscillations. To acquire the optimized feedback configuration, PID theory is used to analyze the feedback process. After PID parameter is obtained, simulations are applied to study the parameters. The optimized value range and principle of choice for the feedback control are discussed. Lastly, imaging experiments are conducted to obtain high dynamic range images, and the results prove the validity of PID parameters.

Keywords: high dynamic range imaging (HDRI), PID, feedback, imaging.

1. Introduction

Many kinds of HDRI methods have been proposed by now, such as multi-exposure method [1, 2], spatially varying exposure method [3], logarithmic compression sensor [4], and spatial light modulating method [5, 6]. In this paper, the image stability problem of the SLM method is discussed.

This kind of HDRI system contains three parts [7]: optical lenses, SLM, and image sensor. The structure of this system is shown in Fig. 1.

In this HDRI system, a liquid crystal on silicon (LCoS) is used as spatial light modulator (SLM, Figs. 1–5). A polarized beam splitter (PBS) prism is used to split the beam. And a CCD is used as the image sensor (Figs. 1–3). There are two sets of lenses. The LCoS is located at the image plane of the first set of lenses and the object plane of the second set of lenses. The CCD is located on the image plane of the second lenses so that the LCoS and the CCD are on two conjugate planes.

The LCoS acts as a negative feedback device to extend the dynamic range of the image. It is an approximate one-to-one modulator. With fine adjusting processes,

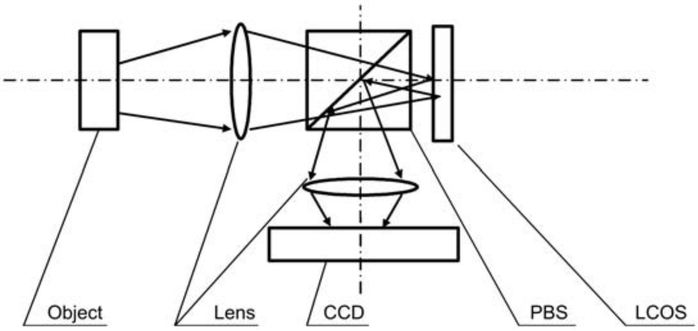

Fig. 1. Sketch of HDRI imaging system.

the image on the LCoS can be projected onto the CCD plane with the same size of the effective imaging area on CCD. The LCoS and the CCD are synchronized with the same refreshing rate. The whole system is a negative feedback system.

Due to the negative feedback, LCoS will be less reflective for the high illuminance area and be more reflective for the low illuminance area. Hence, a wide range of illuminance can be imaged and high dynamic imaging range is achieved. But how to realize this negative feedback is a very important problem.

2. System analysis

For the multiformity of the natural scene, changes of an object cannot be predicted properly during the dynamic imaging process. PID control is suitable for dealing with such a problem with unknown system parameters. PID algorithm has many advantages, such as simplicity, stable reliability, and robustness [8].

2.1. Feedback process in system

Figure 2 shows a schematic diagram of the feedback process. Firstly, the output signal is transferred from the image sensor to the digital image process unit. Then, the signal is sent to the SLM unit for feedback. SLM unit modulates the input illuminance

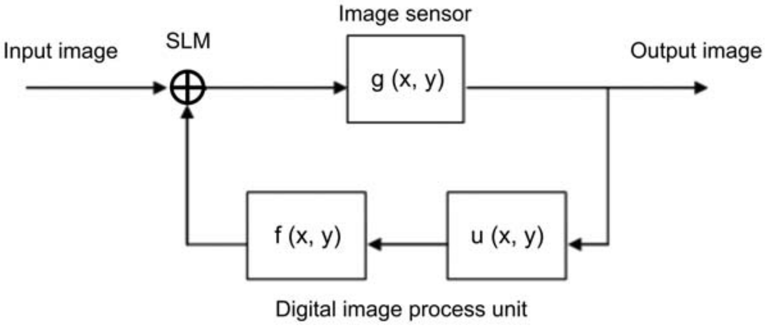

Fig. 2. Schematic diagram of feedback process.

according to those feedback signals. Hence, a closed-loop feedback system is constructed.

Feedback image can be calculated with the formula:

$$u(n) = F\left[g(n), g(n-1), g(n-2)\ldots\right] \tag{1}$$

Here, $g(n)$ is the output signal of the image sensor, n is the frame number of the images. The key issue is to find the feedback function F.

2.2. PID control

Since the whole HDRI system is a closed-loop control system, PID control theory can be used to find the feedback function F.

With PID theory, $u(t)$ is supposed to be composed of proportional, integral, and derivative parts. Since all the units mentioned in this system are discrete devices, so $u(t)$ can be expressed as:

$$u(t) = K_p\left[e_n + \frac{1}{T_i}\sum_{i=0}^{n} e_i T + T_d \frac{e_n - e_{n-1}}{T}\right] \tag{2}$$

Take the efficiency and cost into account, only the current frame and previous frame images from the image sensor are used to calculate $u(t)$, so formula (2) can be simplified:

$$u(t) = k_p g(n) + k_i\left[g(n) + g(n-1)\right] + k_d\left[g(n) - g(n-1)\right] \tag{3}$$

$$u(t) = \left[k_p + k_i + k_d\right] g(n) + \left[k_i - k_d\right] g(n-1) \tag{4}$$

Assume $k_a = k_p + k_i + k_d$, $k_b = k_i - k_d$, then:

$$u(t) = k_a g(n) + k_b g(n-1) \tag{5}$$

After simplification, there are only two uncertain parameters left: k_a and k_b.

2.3. Determining the parameters

Because the system oscillations are unavoidable, what we can do is to choose the best feedback parameter to balance the imaging speed and image quality. So, our target is find a suitable parameter which leads to the minimum feedback times.

Since output image should be stable, and the input data $g(n)$ and output $f(n)$ are all 8-bit data, $f(n) \in [0, 255]$, the following formula should be satisfied:

$$k_a + k_b = 1 \tag{6}$$

By now, only one parameter k_a needs to be determined. Data simulations are taken to study this parameter.

Data simulations are carried out with Matlab. For the convenience of calculation, simplified models for SLM and CCD sensor are used.

The simplified model for SLM is:

$$S(l, t) = \frac{l}{u(t)} \tag{7}$$

$u(t)$ is the control signal at time t, which is just the feedback image, $u(t) \in [0, 255]$, l is the input relative illuminance, $l \in [1000, 62000]$. Relative illuminance here means the relative quantity of real-world illuminance; it belongs to an integer type without any unit.

The simplified model for CCD sensor is:

$$g(l, t) = \begin{cases} 0 & S \leq 0 \\ S(l, t) & 0 < S < 255 \\ 255 & S \geq 255 \end{cases} \tag{8}$$

According to the simplified PID formula discussed before, the control signal of SLM can be calculated as follows:

$$u(t) = k_a \bullet g(l, t-1) + (1 - k_a) \bullet g(l, t) \tag{9}$$

When $|g(l, t-1) - g(l, t)| \leq 1$, we think the output image is stable, and record the CCD sensor imaging times, that is, the feedback times for stable output.

Changing k_a from 0.1 to 1, with each k_a value, a feedback times value can be calculated. Plot the ka values and the corresponding feedback times values,one curve is obtained. Change the relative illuminance l from 1000 to 62000; at last 62 curves are plotted in Fig. 3.

It seems that the feedback times before reaching stable status have a U shape relationship with k_a. The minimum feedback time appears when $k_a \approx 0.5$. When k_a equals some other value, the feedback times rise very quickly, almost as much as twenty times the minimum value.

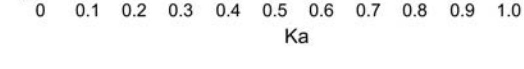

Fig. 3. Simulation results used to determine the parameter.

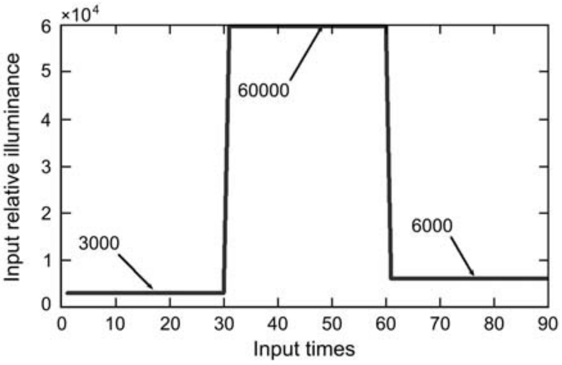

Fig. 4. Input step signals for simulation.

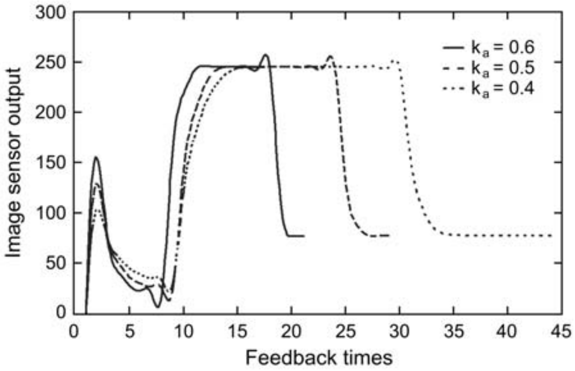

Fig. 5. Simulation output signals with different parameters.

To find out more precise influence of k_a to the feedback process, make k_a consecutively equal to 0.4, 0.5 and 0.6. A step signal showed in Fig. 4 is used as the input signal to carry out the feedback simulation. The feedback process for each k_a is simulated. At first, the input signal rises from 3000 to 60000, and then drops to 6000. The results are shown in Fig. 5, from which the conclusion can be drawn that the bigger the k_a, the shorter the feedback time and the bigger the variation amplitude.

So, the k_a choice principle is that when the object scene changes slowly, make $k_a = 0.4$, the feedback image will be smoother and more stable, whereas with the object changing very fast, a bigger k_a must be chosen to meet the faster change of signals, *e.g.*, $k_a = 0.6$.

3. Experimental results

Use the HDRI system introduced in part one, make $k_a = 0.5$ and execute imaging experiments.

In the experiments, one LED lamp is used as a high illuminance object. At the beginning, the lamp is off. At some moment, it is turned on and reaches the highest illuminance in a very short time. After the HDRI output stabilizes, the LED is turned to half of the highest brightness. Form the step signal with three states of the lamp:

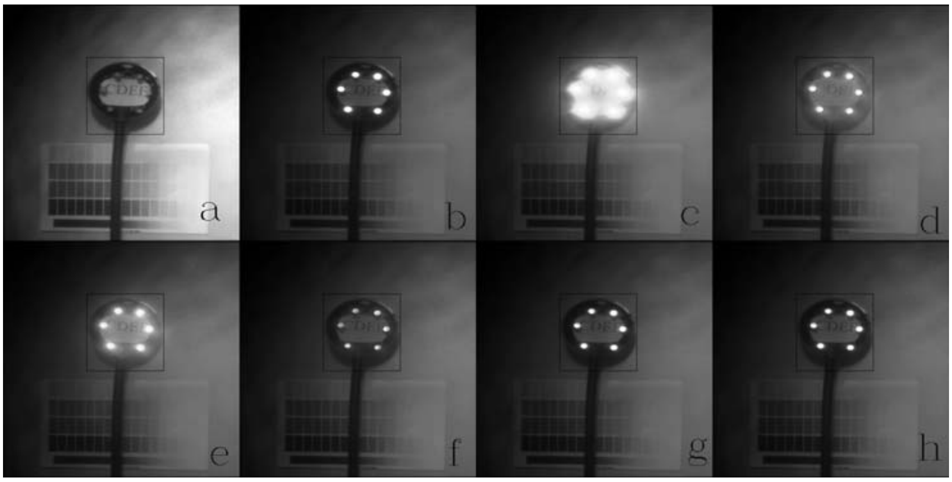

Fig. 6. Serials images obtained in the experiments.

off state, on state and half state. Serials images for this whole process are obtained. Typical images are shown in Fig. 6.

In Figure 6, part **a** is the off lamp, **b**–**e** is the feedback process with highest brightness lamp, while **f**–**h** is the feedback process with half-high lamp.

Consider the output image data in the rectangle area marked in each image of Fig. 6. The average value of 16 bit CCD data in this area is plotted in Fig. 7.

In the first three frames, the output value is zero, because at these moments, the lens is covered. At about the 6th frame, the first stable status is reached with the shut down lamp. At about the 15th frame, the lamp turns on with the highest brightness, the output value rises immediately. This feedback process takes about 10 frames to reach the stable status for the second step. At about the 27th frame, the lamp turns to about half-brightness, and the output value also decreases, within a few frames, it reaches the third stable status.

With this kind of method, there are several ways to reduce feedback times. One is improving the SLM contrast, which means that the proportion band of the *P* control

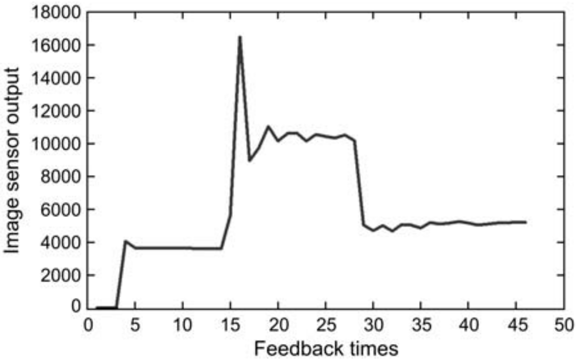

Fig. 7. Experimental results for the step signal.

will be reduced, the system oscillations will decrease faster. Another way to improve the imaging efficiency is choosing SLM and CCD with higher refreshing rate.

4. Conclusions

PID theory is used to analyze the feedback process in one kind of HDRI system. PID parameter is expressed with a simple formula. Data simulations are taken to study this parameter, the optimized value range and the principle of choice are determined. Imaging experiments are conducted to get high dynamic range image with input step signals. Conclusions can be drawn from the experimental results that HDRI system with PID controller has good effect during the imaging process. The feedback process is fast with few feedback loops. The output images are stable with high dynamic range. And the result proves that the PID parameter assures good effect.

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