Experimental investigation of the startup time difference between high-speed cameras

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High-speed cameras are widely used in experimental research and industrial measurement. Although multiple cameras are commonly used, whether the cameras are triggered at the same time is typically overlooked. This study measures the startup time difference between two high-speed cameras employing a proposed measuring system. A series of comparative experiments was conducted to consider the complex factors that can lead to a time difference. The system recorded the startup time differences for different combinations of two cameras at different frame rates, and thus acquired the dependence of the time difference on these factors. Suggestions are made on the basis of the experimental results.

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High-speed cameras (HSCs) are widely used in research and industry to investigate rapid processes. With the help of advanced photometric algorithms[1], HSCs have also been used to make precise measurements where it was once only possible to conduct a general qualitative analysis. In the field of experimental mechanics, for instance, HSCs can be combined with photomechanical methods[2] to measure the propagation speed of a fast fracture[3,4] and the dynamic mechanical behaviors and responses[5–7] of materials and structures. In the most precise measurements using HSCs, the time axis of the captured images is determined such that the image-measured quantities correspond with other quantities, such as the time and load. Although the startup time difference (STD) between HSCs was found and tried to be evaluated[8–10], the comprehensive research, especially measuring and summarizing about the start time difference, has not been reported. In a general imaging system that does not use special external timing equipment[11], the time that the first image is captured is set as the zero point on the time axis and the times at which other images are captured are determined by the frame rate[12]. In some special circumstances, such as when measuring a large area that cannot be covered by a single HSC[13] or when measuring three-dimensional deformation[14–16] by applying a stereo-vision technique, the measuring system requires more than one HSC. Taking the case of two HSCs as an example, in current applications, the cameras are usually started by the same trigger and are assumed to start up absolutely simultaneously[4]; i.e., the zero points of the time axes of the two HSCs are assumed to coincide.

However, the assumption of a simultaneous startup might not always hold. When a HSC receives the electrical trigger signal, a module in the camera will "check" the signal and then "start" the image recording, and there should be a time delay, although very short, for the "check and start" operation. For different cameras, especially when the cameras are of different models, there are probably small differences between the trigger modules, and the "check and start" time delay for the two cameras may thus be different. Therefore, the image recordings of the two cameras may not start up simultaneously, and there may be a STD. Consequently, there is a time offset between the two time axes, and a corresponding image offset between the two recorded image series. Obviously, this will lead to measurement errors, if the time axis is determined in the traditional way. In some cases, the measurement results will be meaningless if the STD is large. However, the STD of HSCs has not received the attention of researchers.

This Letter systematically studies the STD of HSCs. A STD measuring system based on a specially designed light signal generator is first constructed, and the STDs of different HSC assemblies consisting of one brand of HSC (Photron) are systematically measured. It is found that there is a large STD in a certain percentage of triggers for all HSC assemblies, even when the two cameras are of the same model and the same batch, and are synchronized with a suggested synchronizing line[17]. The STD error can be as large as several hundred microseconds, which is equivalent to an offset of tens of images at a high frame rate. The STD distributions and the percentage of instances of STD error are also studied for different HSC assemblies.

The system shown in Fig. 1 was developed to measure the STD for two HSCs. A laser diode, which is powered and modulated by a high-frequency signal generator, projects a light spot onto a white board, with the intensity changing in a sinusoidal manner. In the experiment, the generator and light are first powered on, and the two cameras then begin to record images once they receive the same trigger.

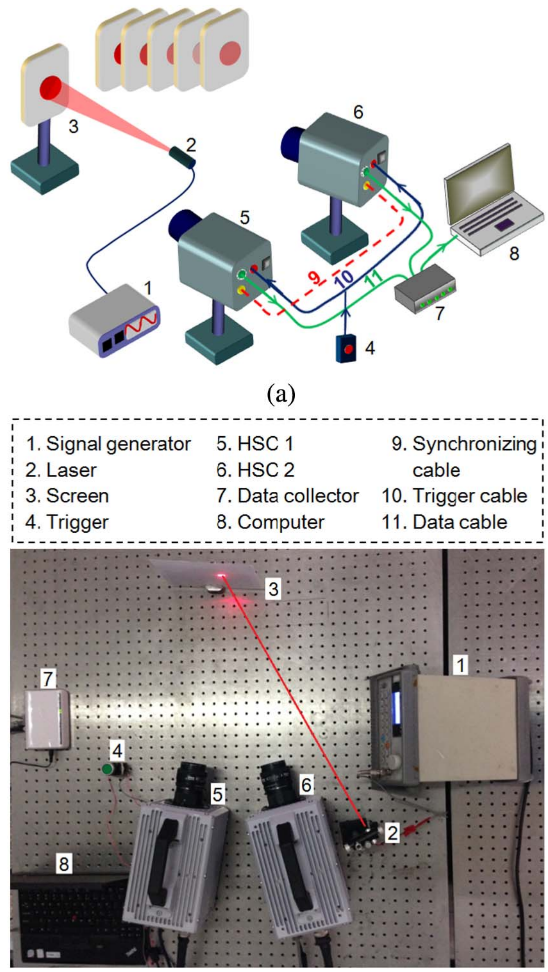

Fig. 1. Measurement system: (a) Schematic setup. (b) Experimental setup.

After the experiment, the images recorded by the two cameras are exported for analysis. As shown in Fig. 2(a), the average intensity in each image is calculated and the intensity variations of the image series are obtained. In order to compare the two cameras' data, the gray level is normalized in $[-1, 1]$. The normalized gray-level intensity of the data points recorded by the two HSCs are then fitted to sinusoidal curves with the least square fitting method and plotted on one graph. The temporal difference is then analyzed. As shown in Fig. 2(b), there are some value fluctuations in the data set of statistical gray levels. These fluctuations confound the two data sets, and this bring uncertainties to the STD determination. In order to guarantee the STD determination, a technique to distinguish the two data sets is used by defining and comparing the three parameters, $d1$, $d2$, and d. The nearly linear part of the sine curve is chosen as the analyzing part. The range of fluctuations of the data set of the two cameras are represented by $d1$ and $d2$, and the distance between the two fitted curves is represented by d. If the distance d is smaller than half the sum of the fluctuation range of the two data sets

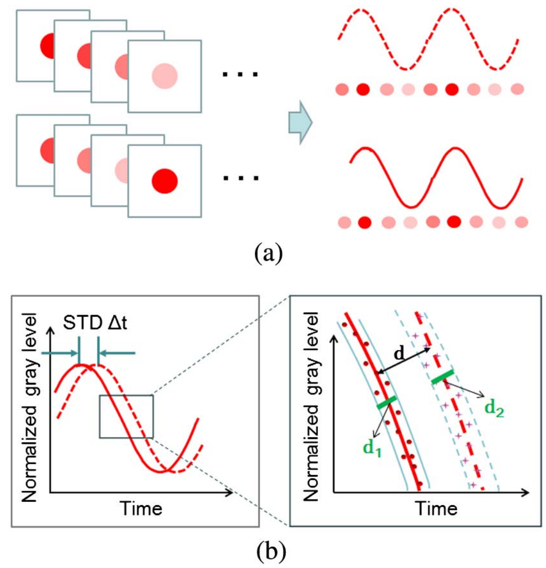

Fig. 2. Principle of STD determination.

$(d1 + d2)$, the experiment is recorded as having no STD error. Otherwise, it is recorded as having a STD error (as shown in Fig. 3). For the latter case, the specific STD error is calculating by picking and comparing the time values of the first peaks of two curves.

To investigate the STD of two-camera systems, an experiment was conducted using two different models of HSCs, the Photron Fastcam-SA1.1 (monochrome) and the Fastcam-SA2 (color). In the experiment, the image

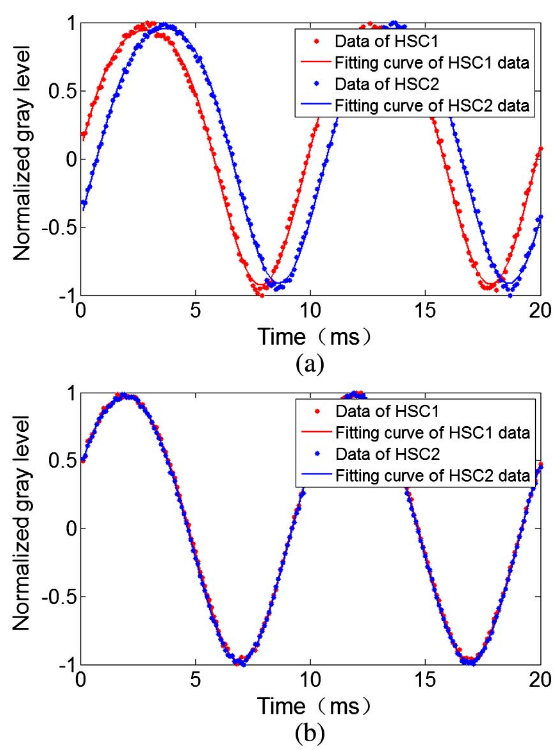

Fig. 3. Examples of two situations of STD: (a) STD error. (b) No STD error.

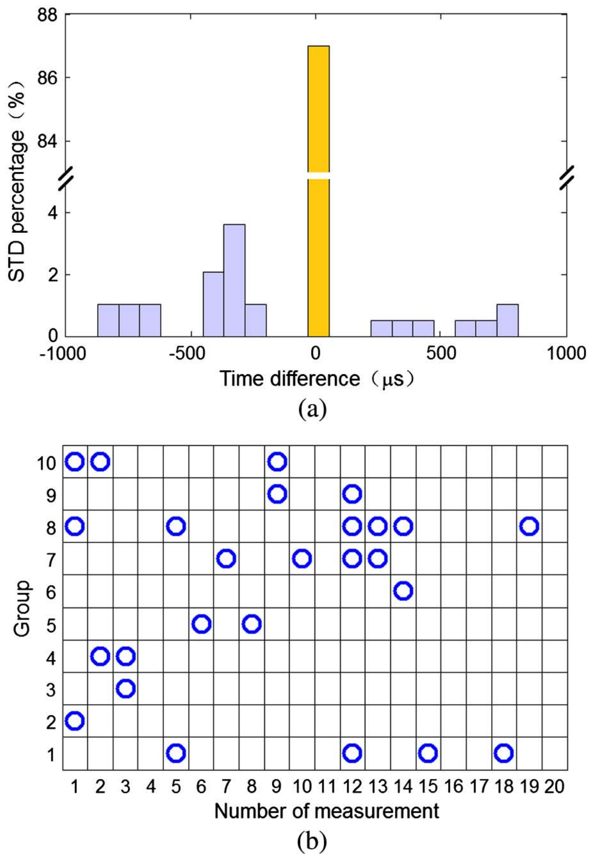

Fig. 4. Distribution of STD error: (a) Percentage of STD error. (b) Position of STD error.

capturing rates of the two cameras were set as 10000 frames per second (fps). Measurements were made in 10 groups. In each group of measurements, the two cameras were connected properly with the trigger first, and then the cameras and the laser were powered on for 30 min for preheating. Each group comprised 20 measurements. For each measurement, the two cameras were triggered and 5000 images were captured and then exported for analysis. After the 20 measurements were made, the cameras and laser were powered off and the trigger disconnected. After the experiments, the images were analyzed, and the STD for each measurement was obtained, as shown in Fig. 4.

Figure 4(a) presents the results for all measurements, showing that there was a STD error for approximately 13% of trigger events, while there was no STD error for the remaining events. In the cases of the STD errors, the absolute value of the STD varied from tens to hundreds of microseconds. The STD error could be positive or negative, meaning that either of the two cameras could start up more quickly than the other. Moreover, the position where the STD error occurred in the group was random, as shown in Fig. 4(b).

The effect of the image capturing speed on the STD error was investigated by conducting the above experiment for different frame rates of 10000, 20000, 30000, 40000, and 50000 fps. For each frame rate, 20 measurements were

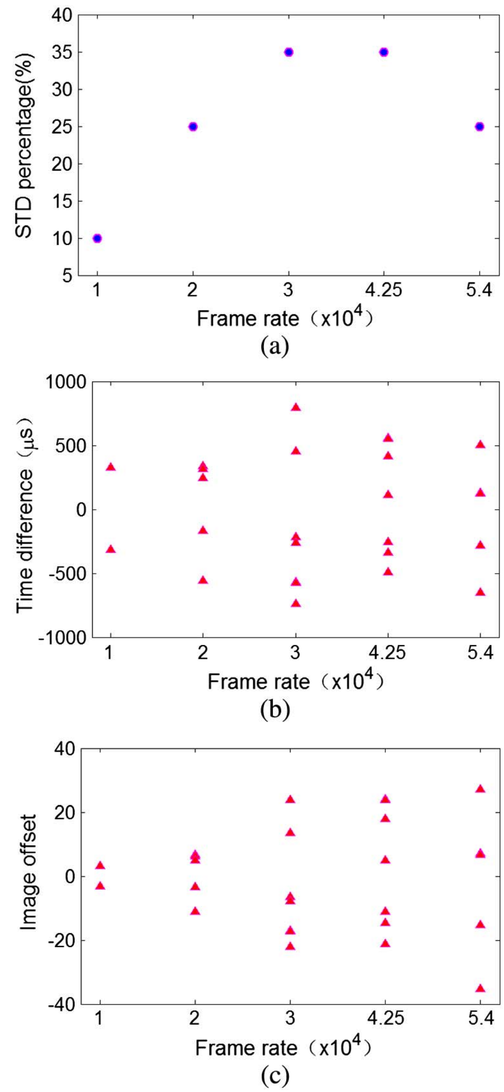

Fig. 5. STD error for different frame rates: (a) Percentage of STD error. (b) Time difference. (c) Image offset.

made, and the STD error was recorded and analyzed. Figure 5 shows that the percentage of STD error (i.e., the percentage of cases deemed to have STD error), the specific time difference (i.e., the STD) and the equivalent image offset (i.e., the number of images equivalent to the time difference) of the two cameras all depended on the frame rate. The percentage of STD error was as high as 35% [see Fig. 5(a)], the STD was as large as 800 μs [see Fig. 5(b)], and the image offset was as large as 30 images [see Fig. 5(c)].

Two synchronizing trigger modes are used in these five camera assemblies: parallel signal trigger and synchronizing cable trigger. For the first mode, a trigger signal is divided into two signals and then connected to the two cameras. For the second mode, a synchronizing cable is added to the two cameras based on the parallel signal trigger mode[17].

The different assemblies of the cameras listed in Table 1 were tested at different frame rates, and the average percentages of STD error for each assembly are presented in

Table 1. Assemblies of HSCs

Camera assembly	Model of camera 1	Model of camera 2	Synchronizing cable	Frame rate (×104)
I	Photron SA 1.1	Photron SA 2	No	1, 2, 3, 4.25, 5.4
II	Photron SA 1.1	Photron SA 2	Yes	1, 2, 3, 4.25, 5.4
III	Photron SA 5	Photron SA 5	No	1, 2, 3, 4, 5, 6, 7.5, 10, 15, 30
IV	Photron SA 5	Photron SA 5	Yes	1, 2, 3, 4, 5, 6, 7.5, 10, 15, 30
V	Photron SA 1.1 (2009)	Photron SA 1.1(2013)	Yes	1, 2, 3, 4.2, 5, 6, 7.5, 10, 15, 30

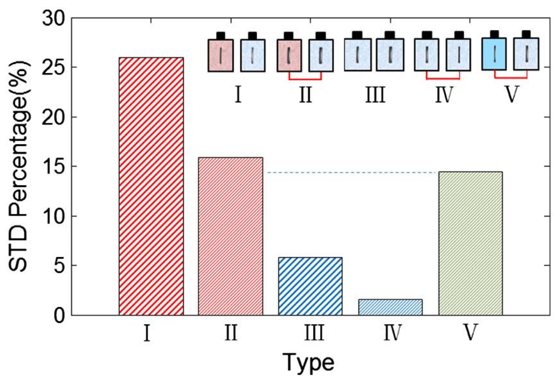

Fig. 6. Percentage of STD error for different assemblies of HSCs listed in Table 1.

Fig. 6. The figure shows two important pieces of information: 1) the percentage of STD error for the same model of camera was lower than that for different models. Even for the same model, the percentage depended on whether the cameras were of the same batch; 2) for the same assembly, the percentage of STD error when using a synchronizing cable was lower than when not using a cable. Furthermore, the percentage of STD error for the same models but without a synchronizing cable was lower than that for different models with a synchronizing cable.

The present study developed a system that measures the STD of two HSCs started by one trigger, and systematically studied the STD for one brand of HSCs (Photron). It was found that there was a STD error for a sizable percentage of triggers, and no STD for others. In the worst case, the percentage of STD error reached 35%. The STD could be positive or negative, because either camera could operate earlier than the other. In the worst case, the STD reached several hundreds of microseconds, which is equivalent to an image offset of tens of images. The STD was large enough and the percentage of occurrence of obvious STD high enough for the STD to be analyzed using different models of HSCs.

Systematic investigations of the percentage of STD error for different assemblies of HSCs showed that the uniformity of the two cameras was the most important factor affecting the percentage. Even a difference in batch number could lead to a high percentage of STD errors. The synchronizing cable was the second most important factor affecting the percentage. Using the synchronizing cable, the percentage could be reduced to 1/2 or 1/3. However, even in the most ideal situation (i.e., cameras of the same model and batch, synchronized with the cable), there was still a STD error in a certain percentage (about 2%) of measurements.

The existence and magnitude of the STD error must be addressed in experiments where the strict synchronicity of two HSCs is required. The random nature of the STD error observed in this study shows that the synchronicity must be monitored during an experiment. Experiments that can be repeated easily should be conducted again when there is a STD error. Meanwhile, two image series obtained in an experiment that can only be conducted once must be realigned using the measured STD. In practice, the STD can be monitored and measured using high-frequency sinusoidal light projected on the margin of the field of view, with the light being produced by a small electrical device and led by two optical fibers.

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