Calibration of Stopwatches by Utilizing High Speed Video Recordings and a Synchronous Counter

C. M. Tsui, Y. K. Yan, and H. M. Chan

Abstract: *A new method for the calibration of stopwatches, called video totalize method, has been developed at the Hong Kong Standards and Calibration Laboratory (SCL). The method starts with the taking of two short video clips of the display of the stopwatch under test, together with the reading of an in-house designed synchronous counter, with the two clips separated by an interval of six to seven hours. The 10-digit synchronous counter is driven by a 1 kHz clock which is phase locked to the cesium frequency standard of SCL. The elapsed times measured by the stopwatch and the synchronous counter are obtained by viewing the recorded video to search frame-by-frame for the instant at which the reading of the stopwatch changes. Using this method, the measurement uncertainty is no longer constrained by the display resolution of the stopwatch, but instead is limited only by the frame rate of the video recording. Digital cameras that can record video at 420 frames per second with usable image quality are commercially available. SCL has designed and built a synchronous counter that allows the reference time to be read from the recorded video with a resolution of 1 ms. The measurement uncertainty obtainable by this calibration method is less than 2×10^{-7} for a 95 % coverage interval.*

1. Introduction

A new video totalize method for calibration of a stopwatch (with digital or analogue display) using a commercially available high speed digital camera and an in-house designed synchronous counter has been developed at the Hong Kong Standards and Calibration Laboratory (SCL). The elapsed times measured by the stopwatch and the synchronous counter are taken from the recorded video clips and compared. The measurement uncertainty of this calibration method is less than 2×10^{-7} for a 95 % coverage interval.

2. Methods for Calibrating Stopwatch

Stopwatches can be calibrated using three methods: the direct comparison method [1], the time base method [3], and the totalize method [2].

In the direct comparison method, the time interval measured by the stopwatch under test is compared to that of a traceable time interval reference, which usually is an audio signal broadcast by the official timekeeper of a region. This method requires no special equipment, but its measurement uncertainty is larger than that of the other two methods.

In the time base method, the frequency of the time base of the stopwatch, which is likely to be a quartz oscillator, is measured directly. This method has a smaller measurement uncertainty than the other two methods. This method is also very fast. The measurement can be completed in a few seconds. However, since only the time base is tested, the functionality of the stopwatch is not checked. In addition, the relationship between the time interval displayed by the stopwatch and the frequency of its time base oscillator is not known.

In the totalize method, the display of the stopwatch is compared to the display of a laboratory time interval reference. The laboratory reference consists of a traceable frequency standard, a signal generator, and a universal counter. The measurement uncertainty of this method is smaller than that of the direct comparison method but larger than the uncertainty of the time base method. One advantage of the totalize method is that the major functions of the stopwatch are tested. SCL has adopted the totalize method for the calibration of stopwatches.

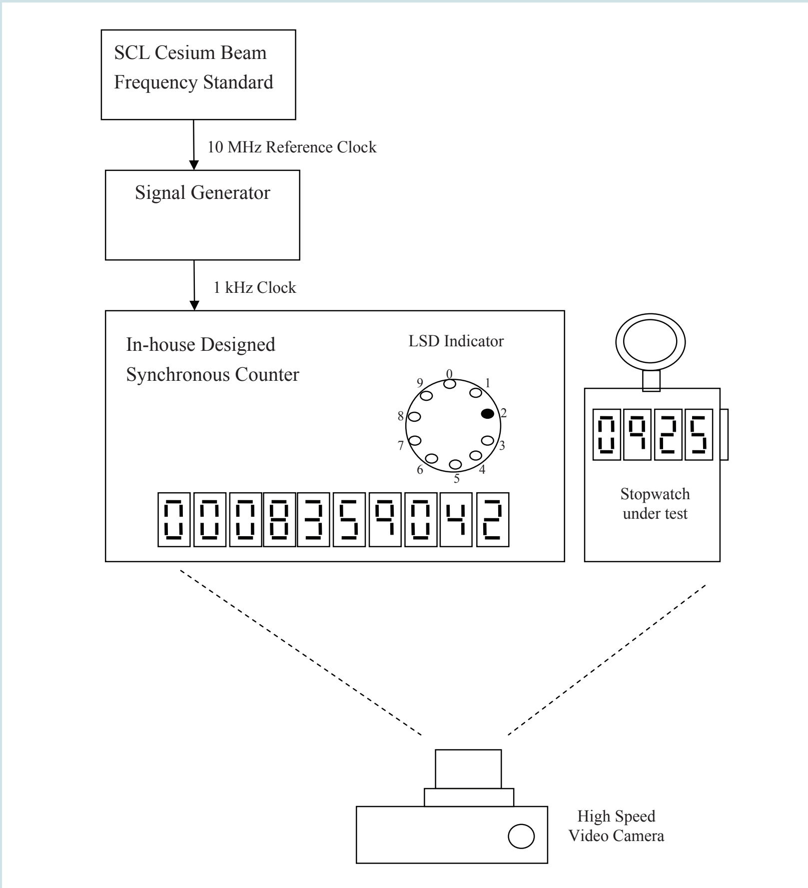


Figure 1. Equipment set up for the calibration of stopwatch using video totalize method showing the synchronous counter display, LSD indicator, and the stopwatch display.

3. Photo Totalize Method and Video Totalize Method

A photo totalize method has been proposed [4] in which a high speed camera is used to take photographs of the stopwatch and a universal counter when both devices are counting. After a suitable time has elapsed, another photo is taken. The elapsed time measured by the stopwatch and the universal counter can then be obtained from these two photos and compared. This method eliminates the uncertainty due to human reaction time. Since only two photos are taken, the measurement uncertainty is limited by the display resolution of the stopwatch.

SCL has modified this method by utilizing video recordings instead of photographs to obtain readings of the stopwatch. The instant when the reading of the stopwatch display changes is found by examining the recorded video frame-by-frame. In this way, the measurement uncertainty is limited by the frame rate of the video recording rather than the display resolution of the stopwatch. Digital cameras that can record high speed video at 240 frames per second (fps) or 420 fps are commercially available. Using such cameras, the measurement uncertainty can be reduced significantly. At high frame rates, it can be seen that the display of a normal universal counter cannot keep up and does not update at uniform intervals. To compensate for these shortcomings, SCL has designed and built a synchronous counter that allows its count to be easily read from a recorded video with a resolution as small as 1 millisecond.

Authors

C. M.Tsui — cmtsui@itc.gov.hk
Y. K.Yan — ykyan@itc.gov.hk
H. M. Chan — scl_rf@itc.gov.hk
Government of the Hong Kong Special Administrative Region Standards and Calibration Laboratory
36/F Immigration Tower
7 Gloucester Road, Wan Chai
Hong Kong

4. The Calibration Method

A signal generator is set up to feed a 1 kHz clock signal to the synchronous counter. This 1 kHz clock is phase locked with the laboratory cesium frequency standard (actually, any frequency standard with an uncertainty ($k = 2$) of less than 10^{-10} is good enough for this method). A high speed digital camera (Casio EX-FH100)[1] is used to record a 10 second video clip at 240 fps or 420 fps for the stopwatch under test and the synchronous counter when both devices are counting. See Fig. 1 for the equipment set up.

The recorded video is viewed frame-by-frame to search for the frame at which the display of the stopwatch starts to change to a new value. The readings of the stopwatch, T_{uut_start}, and that for the synchronous counter, T_{ref_start}, are then taken from the frame immediately preceding this frame. The least-significant-digit (LSD) of the synchronous counter is indicated by the circular LED display above the 10-digit display. The value corresponds to the LED which lights up at the most clockwise position. A digital watch is used to illustrate this process in Fig. 2. This method can also be

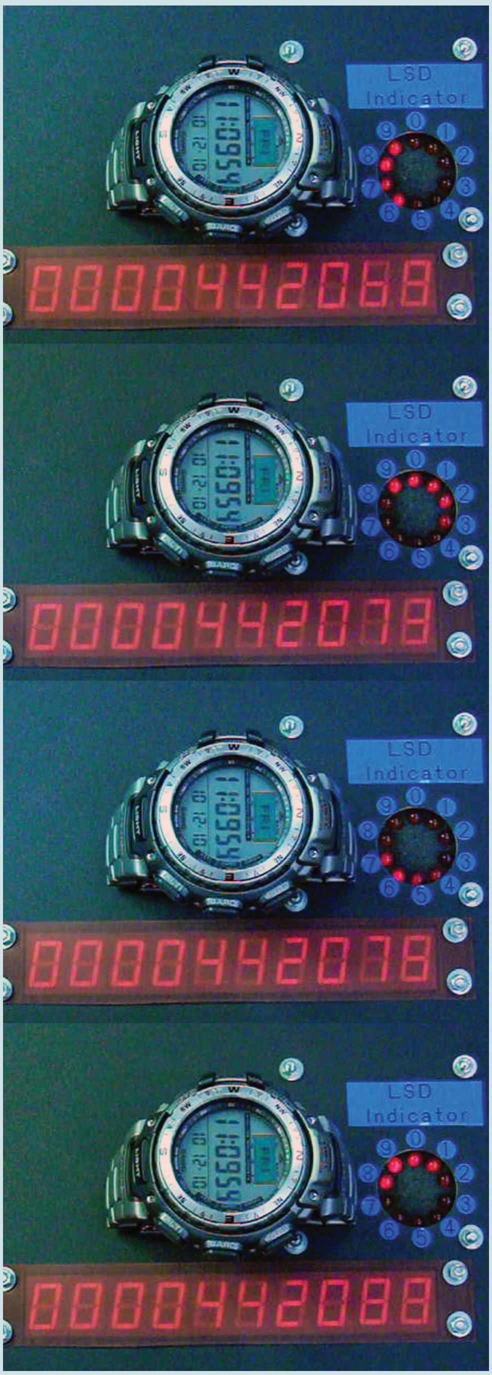
[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the author or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

applied to stopwatches with analog displays as shown in Fig. 3. In both figures the video clips were captured at 240 fps. After a suitable time interval of six or seven hours, the above process is repeated to again obtain T_{uut_stop} and T_{ref_stop}. The relative correction of elapsed time reported by the stopwatch is defined as the following:

$$\text{Relative Correction} = \frac{\text{Time elapsed reported by laboratory standard} - \text{Time elapsed reported by UUT}}{\text{Time elapsed reported by laboratory standard}} \quad (1)$$

or

$$\text{Relative Correction} = \frac{(T_{ref\_stop} - T_{ref\_start}) - (T_{uut\_stop} - T_{uut\_start})}{(T_{ref\_stop} - T_{ref\_start})} \quad (2)$$



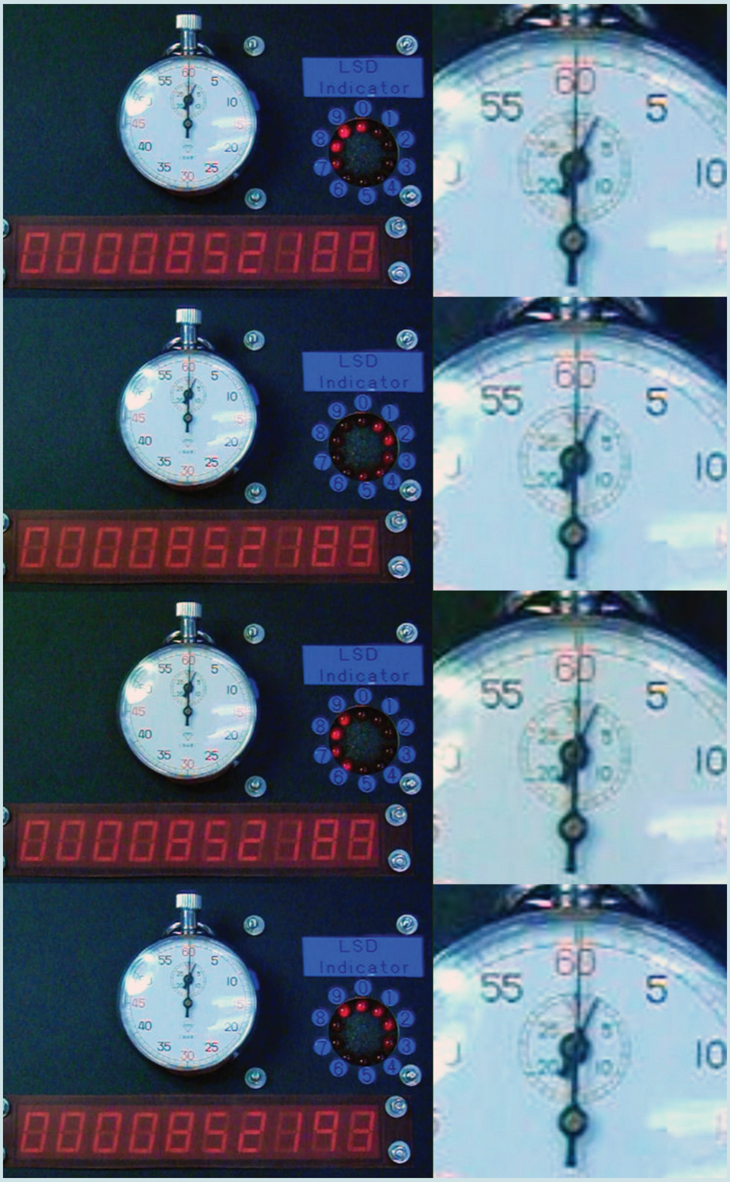
The reading of the synchronous counter is 442.069 s. (442.06 can be read from the 7-segment LED display directly. In the circular LSD indicator, the LED that lights up in the most clockwise position is “9”, hence the LSD is 9.) The reading of the digital watch is 11:09:54.

The reading of the synchronous counter is 442.073 s. It can be seen that the LSD of the digital watch reading is starting to change from “4” to “5”. The lowest segment of the digit “5” is noticeable in this picture. If this is selected as the start time of measurement, then T_{uut_start} = 11:09:54 and T_{ref_start} = 442.069 s (i.e., the last frame).

The reading of the synchronous counter is 442.077 s. The reading of the digital watch is changing from 11:09:54 to 11:09:55. The change is obvious in this picture.

The reading of the synchronous counter is 442.081 s. The reading of the digital watch is changing from 11:09:54 to 11:09:55.

Figure 2. Video frame sequences at 240 fps for calibration of a digital watch.



The reading of the synchronous counter is 852.180 s. (852.18 can be read from the 7-segment LED display directly. In the circular LSD indicator, the LED that lights up in the most clockwise position is "0", hence the LSD is 0.). The reading of the unit under test (UUT) is 00:02:00. The second hand has remained stationary at this position for over 20 frames.

The reading of the synchronous counter is 852.185 s. It can be seen that the second hand of the stopwatch has moved a little bit. If this is selected as the start time of measurement, then T_{uut_start} = 00:02:00 and T_{ref_start} = 852.180 s (i.e., the last frame).

The reading of the synchronous counter is 852.189 s. The movement of the second hand is quite obvious in this picture.

The reading of the synchronous counter is 852.193 s. The movement of the second hand is more obvious in this picture.

Figure 3. Video frame sequences at 240 fps for calibration of an analogue stopwatch.

5. Use of the High Speed Digital Camera

A high speed digital camera (Casio EX-FH100) is used to record video. It supports the high speed video modes listed in Table 1.

The image size for the 1 000 fps mode is too small for practical use. The shutter speed for the 120 fps mode was found to be around 10 ms which is too slow for this calibration method. However, either the 420 fps mode or the 240 fps mode can be used. The 420 fps mode is suitable if the stopwatch has a large and clear display. Otherwise the 240 fps mode is recommended. The recorded video can be viewed frame-by-frame on the LCD screen of the camera. Alternatively, the video file can be uploaded to a personal computer and viewed by a media player that has frame-by-frame playback capability.

When shooting high speed video, more light is required for higher frame rates due to the higher shutter speed. The video should be captured in a well-lit environment. To enhance the contrast of the captured video, the "BLUE" color filter of the video camera is selected.

6. The In-house Designed Synchronous Counter

It was observed that the display readings of many commercial universal counters did not update synchronously with the input clock signal. This means that there is an unknown delay between the display reading and the input clock, which is probably due to internal

Frame Rate	Image Size (Pixels)
120 fps	640 × 480
240 fps	448 × 336
420 fps	224 × 168
1 000 fps	224 × 64

Table 1. High speed video modes of Casio EX-FH100.

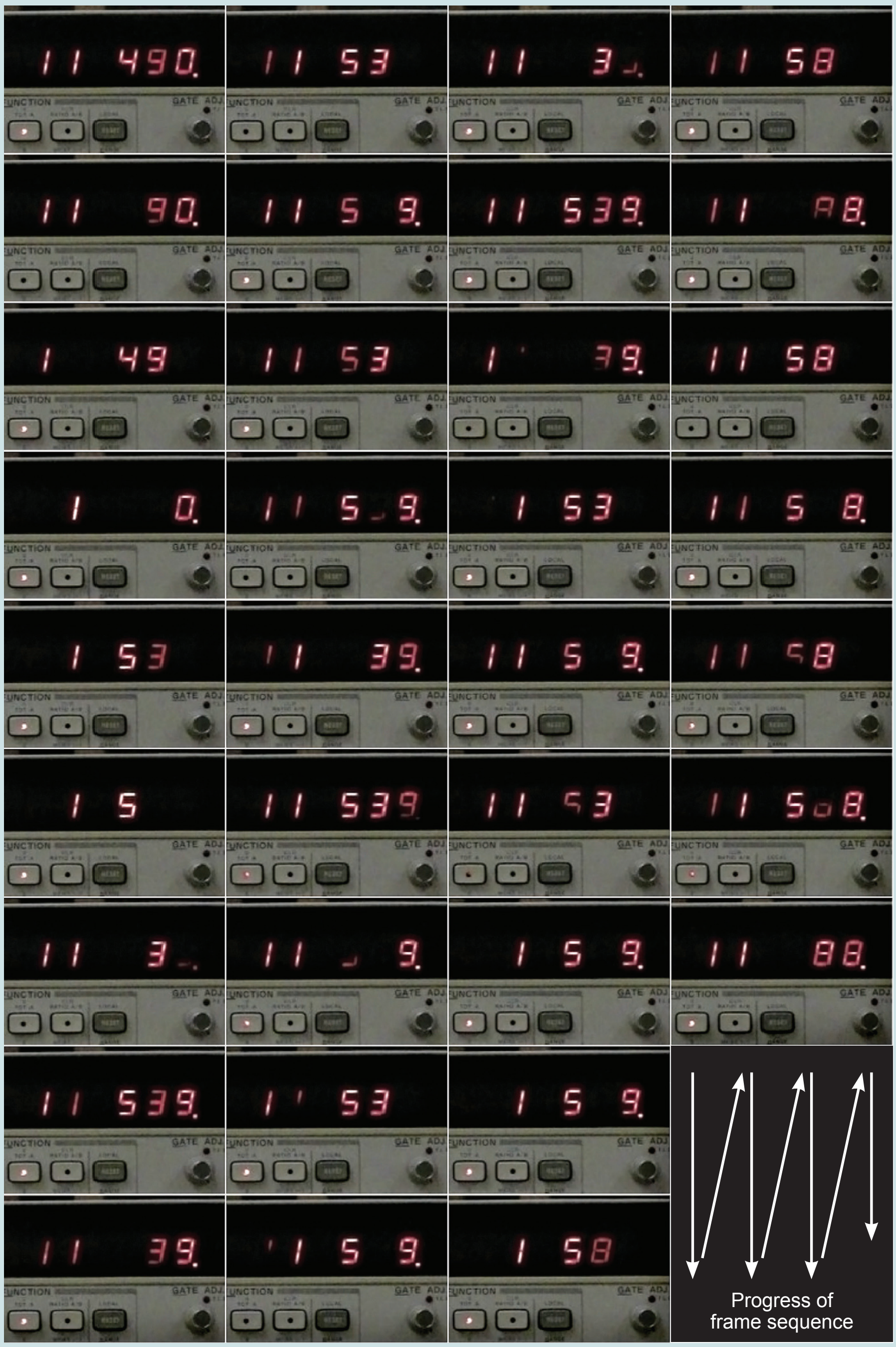


Figure 4. Display of a universal counter captured by a high speed digital camera at 420 fps or every 2.38 ms.

processing of the instrument. Figure 4 shows the display of a commercial universal counter captured by a high speed digital camera at 420 fps. The time interval between video frames is about 2.38 ms. The figure shows 33 video frames, covering a time period of 76.2 ms. The universal counter is driven by a 1 kHz clock input. If the display of the universal counter was truly synchronous to the clock input, we would expect the reading to increment by a count of 2 or 3 with each new frame. However, we can only observe three readings during this 76.2 ms period: 11 490, 11 539 and 11 588. The universal counter seems to only update its display about once every 49 ms.

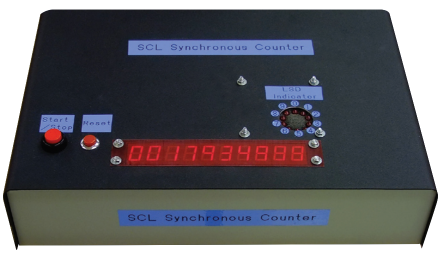


Figure 5. The in-house designed synchronous counter.

Another issue revealed by this high speed video clip is that the universal counter does not simultaneously display all of the digits of its reading. Instead, the digits seem to be turned on one by one, which produces additional problems. If the shutter speed of the camera is too slow, the digits of two consecutive readings will be mixed together in the same video frame. For instance, if the bottom two frames on the third column of Fig. 4 (one is the partial image for reading 11 539 and the other 11 588) are merged, then an incorrect reading of 1589 will be obtained. On the other hand, if the shutter speed is too fast, then only part of the reading, like the frames shown in the figure, will be captured. Hence, there are severe limitations when the video totalize method is employed with some commercial universal counters.

The synchronous counter designed by SCL (Fig. 5) was built with logic circuits that ensure its 10-digit LED display will be updated synchronously with the input clock. It is driven by a 1 kHz clock generated by a signal generator phase locked to the laboratory cesium frequency standard. The synchronous counter has a resolution of 1 ms. It can

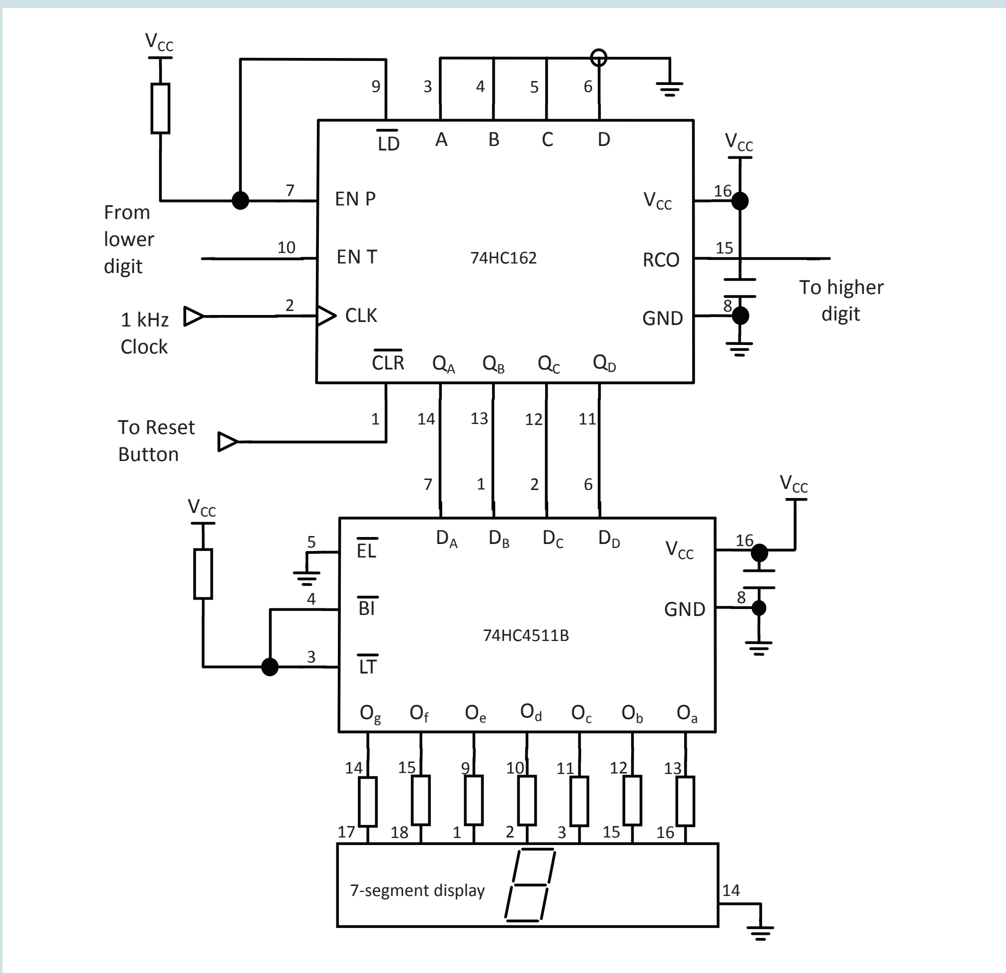


Figure 6. Simplified circuit diagram for a single digit of the synchronous counter.

display elapsed time intervals of up to 9 999 999.999 s.

When recording video at 420 fps and 240 fps, the shutter speeds of the Casio EX-FH100 were found to be about 2 ms and 4 ms, respectively. Because the LSD of the synchronous counter updates every millisecond, it is not possible to accurately read the value of the LED display from the recorded video. During the 2 ms or 4 ms period that the shutter is open, two or more indications of the LED display will be overlapped in a single image. To overcome this problem, a special LSD indicator was designed. The LSD indicator consists of 10 LEDs arranged in a circle. Each LED corresponds to a decimal value and illuminates for about 1 ms during every 10 ms period. When recorded at a shutter speed of 4 ms, four to five consecutive LEDs will be illuminated in the recorded image. The LED which lights up at the most clockwise position is the correct value of the LSD, and allows the counter to be read with a resolution of 1 ms.

The simplified circuit diagram for a single digit of the synchronous counter is shown in Fig. 6. The circuit diagram for the LSD indicator is shown in Fig. 7.

7. Measurement Uncertainty Evaluation

The measurement model for the relative correction, *RC*, of elapsed time counting of a stopwatch is shown below. The measurement uncertainty components in equation (3) are summarized in Table 2.

$$RC = \frac{(1 + C) \times (T_{ref\_stop} - T_{ref\_start}) - (T_{uut\_stop} - T_{uut\_start})}{(1 + C) \times (T_{ref\_stop} - T_{ref\_start})} \qquad (3)$$

There are two methods to derive the combined standard measurement uncertainty for the final measurand which is the relative correction, *RC*. The first method is the GUM Uncertainty Framework (GUF) [5], while the second is the Monte Carlo Method (MCM) described in Supplement 1 to the GUM [6]. GUF is easier and faster to compute than MCM. However, the domain of validity of GUF is narrower than MCM. The conditions for valid application of GUF are described in details in Sections 5.7 and 5.8 of Supplement 1 to the GUM. One condition requires that the probability distribution function of the measurand

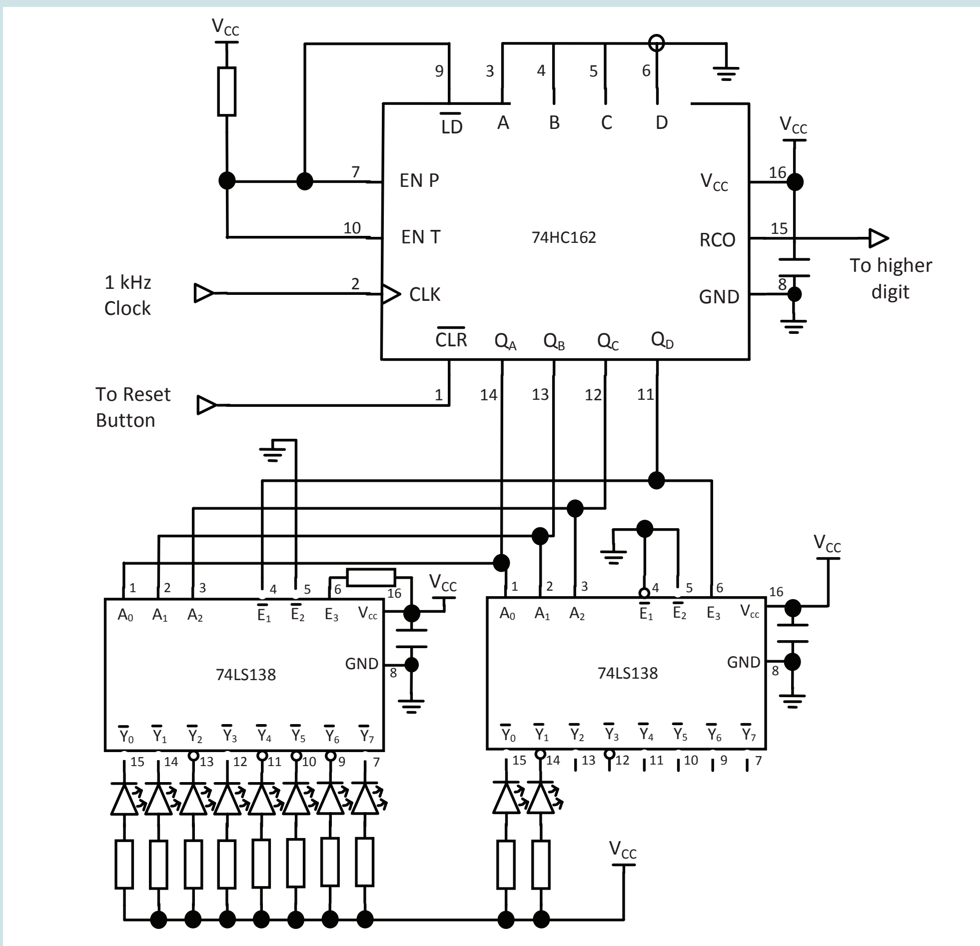


Figure 7. Circuit diagram for the least-significant-digit (LSD) indicator.

Display resolution of stopwatch under test.	Estimated measurement uncertainty of the relative correction, *RC*, for a 95 % coverage interval.			
	Video totalize method		Photo totalize method	
	Video recording at 240 fps	Video recording at 420 fps	Using the synchronous counter described in this paper.	Using a commercial
1 s	2.7×10^{-7}	1.6×10^{-7}	3.1×10^{-5}	3.2×10^{-5}
0.1 s	2.7×10^{-7}	1.6×10^{-7}	3.1×10^{-6}	7.0×10^{-6}
0.01 s	2.7×10^{-7}	1.6×10^{-7}	3.2×10^{-7}	6.2×10^{-6}

Table 3. Estimated measurement uncertainties for the calibration of stopwatches using either the video totalize method or the photo totalize method.

can adequately be approximated by a Gaussian distribution or a scaled and shifted t-distribution. This might not be the case if one uncertainty component has a non-Gaussian distribution and its value is dominant. It is difficult to verify these conditions directly. To solve this problem, Section 8 of Supplement 1 to the GUM describes a validation procedure for GUF by using MCM. Unfortunately, when applying the validation procedure on this measurement model, GUF failed. The reason is that this measurement model includes two dominant uncertainty components $u(T_{\text{uut\_start}})$ and $u(T_{\text{uut\_stop}})$ with rectangular probability distribution, violating the condition for valid application of GUF. Hence the computationally more demanding MCM needs to be used.

Assuming an elapsed time of seven hours between $T_{\text{ref\_start}}$ and $T_{\text{ref\_stop}}$, the estimated measurement uncertainties of the relative correction *RC* for a 95 % coverage interval, calculated using MCM, with video recordings at 240 fps and 420 fps respectively, are listed in Table 3. For comparison, the estimated measurement uncertainties for the photo totalize method are listed in the same table. If a commercial counter is used with the photo totalize method, the counter reading taken from the photograph is assumed to have an accuracy of 0.1 s, for the reasons stated in Section 6.

8. Conclusions

A new video totalize method for the calibration of a stopwatch has been developed. A commercially available high speed digital camera that can record video at high frame rates is used to capture the readings of the stopwatch under test and a synchronous counter. The synchronous counter was designed and built to allow the elapsed time to be read from the video with a resolution of 1 ms. When this video totalize method is employed, the measurement uncertainty is limited not by the display resolution of the stopwatch, but by the frame rate of the video recording. The measurement uncertainty for a 95 % coverage interval is less than 2×10^{-7} at video frame rates of 420 fps.

9. References

[1] R.M. Graham, “Stopwatch Calibrations Part I : The Direct Comparison Method,” *NCSLI Measure*, vol. 1, no. 1, pp. 72-73, March 2006.

[2] R.M. Graham, “Stopwatch Calibrations Part II : The Totalize Method,” *NCSLI Measure*, vol. 1, no. 2, pp. 72-73, June 2006.

[3] R.M. Graham, “Stopwatch Calibrations Part III : The Time Base Method,” NCSLI Measure, vol. 1, no. 3, pp. 74-75, September 2006.

[4] Jeff C. Gust, Robert M. Graham, and Michael A. Lombardi, “Stopwatch and Timer Calibrations (2009 edition),” *NIST Recommended Practice Guide, Special Publication 960-12*, 82 pgs., January 2009. (Available from the National Institute of Standards and Technology (NIST) Time and Frequency Publication Database: http://tf.nist.gov/general/publications.htm)

[5] “Evaluation of measurement data – Guide to the expression of uncertainty in measurement,” *Joint Committee for Guides in Metrology, JCGM 100:2008*, September 2008. (GUM 1995 with minor corrections and available from the Bureau International des Poids et Mesures website: www.bipm.org/en/publications/).

[6] "Evaluation of measurement data — Supplement 1 to the “Guide to the expression of uncertainty in measurement” — Propagation of distributions using a Monte Carlo Method," *Joint Committee for Guides in Metrology, JCGM 101*, First Edition, 2008. (Also available from the BIPM website.)