On the accuracy of framing-rate measurements in ultra-high speed rotating mirror cameras

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Abstract: Rotating mirror systems based on the Miller Principle are a mainstay modality for ultra-high speed imaging within the range 1-25 million frames per second. Importantly, the true temporal accuracy of observations recorded in such cameras is sensitive to the framing rate that the system directly associates with each individual data acquisition. The purpose for the present investigation was to examine the validity of such system-reported frame rates in a widely used commercial system (a Cordin 550-62 model) by independently measuring the framing rate at the instant of triggering. Here, we found a small but significant difference between such measurements: the average discrepancy (over the entire spectrum of frame rates used) was found to be 0.66 ± 0.48%, with a maximum difference of 2.33%. The principal reason for this discrepancy was traced to non-optimized sampling of the mirror rotation rate within the system protocol. This paper thus serves three purposes: (i) we highlight a straightforward diagnostic approach to facilitate scrutiny of rotating-mirror system integrity; (ii) we raise awareness of the intrinsic errors associated with data previously acquired with this particular system and model; and (iii), we recommend that future control routines address the sampling issue by implementing real-time measurement at the instant of triggering.

OCIS codes: (170.7160) Ultrafast technology, (320.3980) Microsecond phenomena.

References and links

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1. Introduction

Many dynamic phenomena occur with such rapidity that very high specification imaging systems are required in order to capture the essential action with sufficient temporal resolution. Acquisition of full frame photographic sequences at framing rates within the MHz range and with appreciable sequence depths, has, until relatively recently, been the preserve of rotating mirror camera systems based on the Miller Principle [1]. The most advanced incarnations of the instrument boast framing rates of the order of tens of MHz, with sequence depths running into hundreds of individual frames per file [2,3], often with 8-10 bit dynamic range. Thus, whilst the emergence of ultrafast single chip systems [4] heralds a new dawn in terms of user-friendliness and compact architectures, the popularity of rotating-mirror systems

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is likely to endure for some time yet due to the superior resolution and sensitivity of the CCDs, together with the comparatively long sequence record depth.

For the purposes of the present study, we focused on determining the performance of a popular rotating mirror system available from the UK Engineering and Physical Sciences Research Council (EPSRC) equipment loan pool (http://www.eip.rl.ac.uk) - a Cordin Model 550-62 [5].

The essential architecture of this instrument, highlighting the components along the optical path from target to imaging chip [albeit for a single CCD element only], is illustrated in Fig. 1 below. The combination of rotating mirror with exit aperture and exit lens serves as an effective opto-mechanical shutter, limiting the exposure time at each CCD as the target scene is swept along the recording arc wherein the CCDs lie, and endowing the instrument with its high frame-rate capability.

The present measurements served to provide independent corroboration of the system's self-reported mirror rotation rate: that is, we attempted to confirm the temporal integrity of the system.

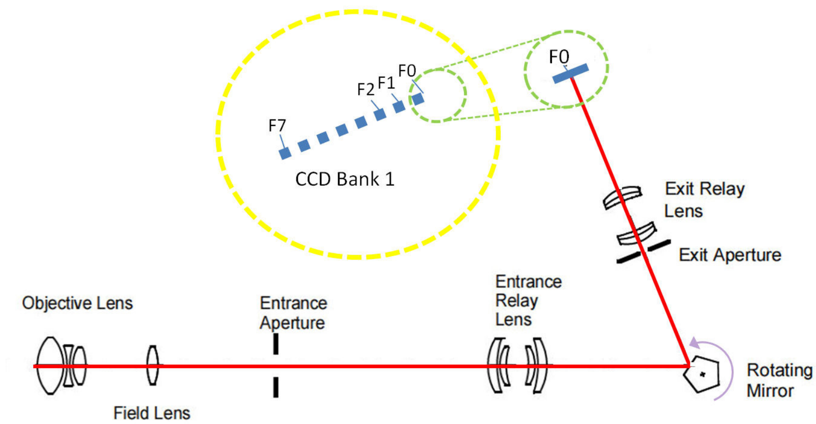

Fig. 1. Schematic (not to scale) illustrating the key optical elements along the optical path. Light from the target is brought to a focus as close as possible to a facet on the pentagonal rotating mirror. The mirror itself serves to redirect the light onto a series of 62 CCDs arranged in two 72° arcs around the mirror.

2. Methodology & Apparatus

The Cordin 550-62 employs a pentagonal beryllium mirror driven by a gas turbine which can rotate at a maximum of 12,500 revolutions per second and allows the camera to achieve framing rates up to 4MHz [5].Together with an arrangement of mirrors and fixed lenses, as illustrated in Fig. 1, the system relays sequential image information to an array of 62 CCD image sensors arranged in 8 banks around the camera body, and set in two symmetric 72° recording arcs either side of the mirror. [Note that whilst each CCD bank controls 8 individual CCDs, 1 CCD is removed from the central position in each of both arcs to allow access of the light from the target, hence there are 62, rather than 64 CCDs altogether.]

To synchronize the shuttering and integration time of each CCD, information regarding the rotational position of the mirror, and thus the whereabouts of the reflected image, is required. Therefore, in addition to each image sensor CCD at every frame location, there is also an infrared (IR) sensor that detects the output from a continuous IR laser placed upstream in the optical path, and distributed by the same rotating mirror [5]. The IR laser system not only provides synchronization of the essential timing processes, such as the triggering of active CCD integration during data acquisition, but is also exploited to return framing rate information for camera users – a parameter that we term the 'system- reported' frame rate.

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To capture an independent measurement of frame rate for direct comparison to the system-reported value, the 'Index Pulse' (IP) port on the Cordin 550-62 was utilised. To provide some context: the IP outputs a + 5V pulse each time the IR sensor passes the first frame position (Frame F0 in Fig. 1). The period of these pulses, that is, the time taken for the reflected laser (and *ipso facto*, the target scene itself) to visit each of the available 64 frames, is thus a direct measure of the image rotation time (IRT). Frame rate is then simply calculated by taking the product of total number of frames (i.e. 64) with the reciprocal of the IRT.

In the independent measurement approach, we extracted the IP signal and relayed this directly to the external trigger input on a waveform generator (Model -TTI TGA1242, Thurlby Thandar, Huntington, England) which was set to produce a single sinusoidal pulse upon any triggering event (Fig. 2). This output was in turn relayed to an oscilloscope (PicoScope ADC-212, PicoTechnology, England) and was recorded in order to provide the basis for measuring framing rate [as the interval between sine pulses]. In order to capture the IP synchronised sine waves as close as possible to the instant the camera was triggered, the 'Flash 1' port on the Cordin camera [without any programmed delay] was relayed to the trigger input of the PicoScope (Fig. 2). Note that this slightly elaborate set-up was necessary as use of the PicoScope by itself was found to be less reliable in registering the IP signals at certain time-bases.

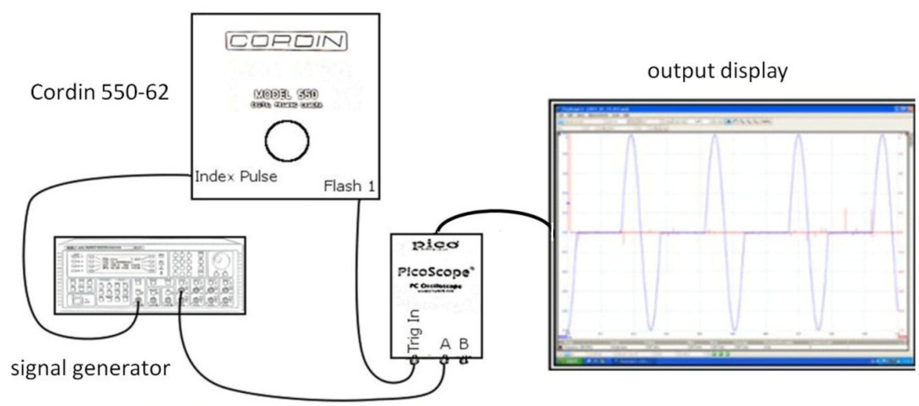

Fig. 2. Illustration of the independent measurement apparatus. BNC connectors were linked to extract the index pulse each time the first frame IR sensor (at the F0 CCD position) was illuminated by the continuous IR laser. This output was fed direct to the signal generator, which was programmed to produce a single sine pulse output upon each index pulse detected. The sine pulses were recorded in a downstream scope that was itself triggered by the Cordin camera's 'Flash 1' output.

The timing accuracy of the experimental arrangement was itself assessed to determine the extent of any delay or lag that could influence the measurement. This was accomplished in two stages. In the first instance, to verify the synchronisation of the camera trigger and 'Flash 1' output, images of a light emitting diode (LED) triggered by the 'Flash 1' output were examined. Due to the short rise-time of the LED (<< 1μs), the delay between the camera beginning its recording cycle and the LED triggering could be attributed solely to the delayed signal from the 'Flash 1' port. This lag was measured over the range of framing rates from 50kHz to 1MHz and is shown graphically in Fig. 3 below. The ramifications for this are highlighted in the discussion section below. Secondly, in order to ensure that the waveform generator (WG1) itself did not induce a time delay, a second waveform generator (WG2) was introduced in place of the Cordin 550-62 camera. Here a square waveform pulse was transmitted simultaneously to both WG1 (which produced a single sine output as before) and the oscilloscope input, in order to enable a direct measurement of any time lag. In the event, a lag time of a mere 260ns +/− 10ns was observed.

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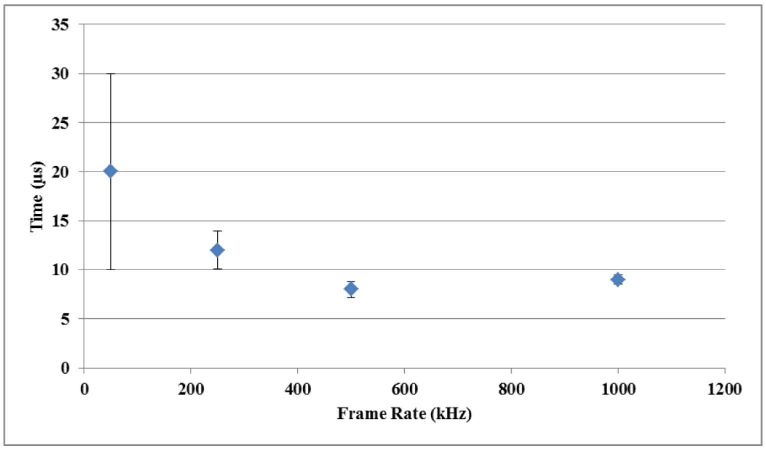

Fig. 3. Lag-time between LED activation (driven off the Flash 1 port at the instant of camera triggering) as measured using the independent apparatus illustrated in Fig. 2.

3. Results

In the measurement procedure, automatic control over the mirror speed was retained, such that a user-defined framing rate was declared to the software, and the rotating mirror was then automatically ramped-up towards that value. However, rather than relying on the resident 'autospeed' triggering mode [5], manual control was instead exercised over the triggering process. Here, the real-time frame-rate was monitored on the camera display interface and allowed to overshoot the target value, whereupon mirror deceleration was initiated automatically, and triggering was then fired under judicious manual control. In parallel, that same trigger signal also activated recording of the independent measurement of framing rate,

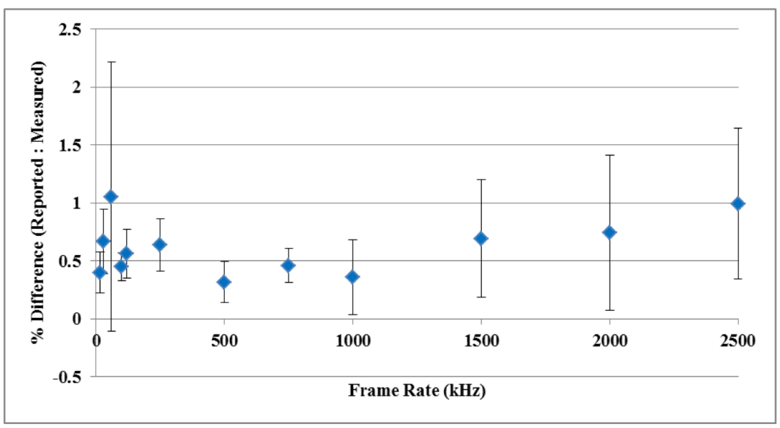

Fig. 4. Percentage difference between reported and measured values of framing rate. Positive values signify that system-reported values were greater than those measured independently by the apparatus illustrated in Fig. 2, and it is clear that this observation held consistently over all frame rates. Error bars represent the standard deviation over multiple measurements.

as described in §2. This procedure was repeated over a wide range of framing rates (from 15,000 to 2,500,000 frames per second) in order that a general assessment of any deviation between 'system-reported' and independently measured values could be made. The results are illustrated graphically in Fig. 4 above. Here, measurements were recorded in triplicate at each frame rate, and the percentage difference between the system-reported and independently measured framing rates ranged from 0.09% to 2.33%. Interestingly, and perhaps somewhat counter-intuitively, the system-reported measurements in this particular triggering mode were

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consistently *higher* than the independently measured counterparts – an observation that certainly warrants further attention given that the on-screen framing rate was observed to be falling at the point of triggering. We intend to follow-up this observation in an extended study during a future loan period.

4. Discussion

Outwardly, the most striking aspect to this investigation is that there is a small but significant difference between the system-reported frame rate, and the independently measured counterpart, as underscored in Fig. 4 above. In attempting to uncover the reason for this discrepancy, subsequent discussions were undertaken with the engineering staff at the camera manufacturer and one particularly salient fact came to light. It transpires that the Cordin 550-62 system hardware samples and calculates the framing rate (via the interval between index pulses), at a rate of 10Hz. Furthermore, the sample value that is ultimately read out as the system reported frame rate is designated as that occurring directly following the act of triggering [6]. This means that the intrinsic timing error involved with this process is 50ms (half the interval between consecutive sampling points) and that it is obviously delayed relative to the instant of triggering. Moreover, this comparatively low frequency sampling strategy also means that the window of opportunity for generation of the system-reported frame rate could theoretically be delayed, relative to the trigger, by up to 100ms, as suggested in the illustration in Fig. 5 below.

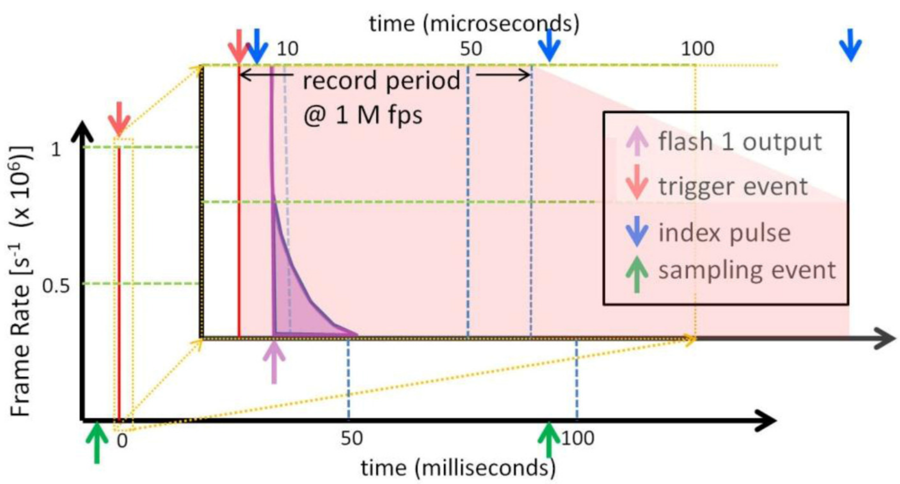

Fig. 5. Schematic illustration of the salient and distinct timings for various events that occur during operation of the Cordin camera, as a function of framing rate [and assumed to be framing at 1 million fps on this occasion]. The main (lower) x-axis time unit is in milliseconds, and two consecutive sampling events, separated by 100ms, are indicated (green arrows). The temporal window, as delineated by the orange dashed box, close to the instant of triggering (i.e. at red arrow at t = 0 on both scales) has been magnified by a factor of 1000 in the inset, such that the x-axis unit in the inset is in microseconds. The system recording time, Δt, as a function of framing rate is highlighted by the pink region [Δt = 64μs at 1M fps, as here]. The effective delay of the flash 1 port output (Fig. 3 data), again as a function of frame rate, is highlighted in purple. Positions of randomly allocated index pulses, separated by 64μs (i.e. Δt at 1M fps), are indicated by blue arrows on the inset axis.

The independent measurements on the other hand (taken via the arrangement shown in Fig. 2), are a truer reflection of the actual framing rate at the point of triggering, given that they are calculated from the interval of the first two IPs occurring directly after triggering – a period that is, on average, very much closer to the active recording period, compared with the system reported sampling interval. The absolute time period within which this can occur is evidently a function of framing rate, however as Fig. 5 illustrates (for frame rates at 1 million fps, which might be regarded as the lower bound range for rotating mirror systems given the

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availability of competing systems, such as high speed video at slightly lower framing rates), then the independent measurement time, t_i, can be achieved within the period: IRT < t_i <2 x IRT. This corresponds to a measurement within 64 - 128μs of the actual recorded data when framing at 1M fps and reflects the random nature of the initial CCD frame used in the active recording process upon first triggering. In the actual independent measurements (Figs. 3 & 4 data), as implemented using the Flash 1 port trigger output and using the arrangement highlighted in Fig. 2, there is a further added delay of roughly 9μs when a framing rate at 1M fps is used (purple region in Fig. 5). In absolute terms, this means that the independent measurements are at best within 14% of the true measurement, and at worst, mistimed by 114%. The system reported values on the other hand are, at best, in exact coincidence with the true measurements – this would correspond to a [highly unlikely] time when the [randomly allocated] sampling event coincided exactly with the trigger (i.e. in the context of Fig. 5, that the red arrow (trigger) and the green arrow (sample) occur at the same point in time), but, and somewhat alarmingly, at worst mistimed by over 150,000%.

In the event, the inertia of the mirror and the level of frictional drag appear not to conspire to have the reported frame rate differ by more than 2.33% on any single observation run, even with the long sampling time intrinsic to the Cordin software. However, the point that we make here is that this discrepancy is avoidable. Moreover, for very high accuracy work, for example comparing real data with models and simulations, then this restriction to the presently reported framing rate validity will affect the longer term prediction power of such quantitative models.

One further point warrants attention, and this is the somewhat counterintuitive observation highlighted in Fig. 4 indicating that the reported (delayed) frame rate measurements are apparently consistently higher than those occurring at the point of triggering. These observations ideally require parallel and continuous recording over the same temporal window of the gas flow to the turbine controlling the mirror's rate of rotation. This will allow direct corroboration of the time dependent driving forces with their resultant dynamics.

5. Conclusions

We developed a straightforward means to measure the instantaneous framing rate in a high speed rotary mirror camera and compared our measurements with system-reported frame rates on the EPSRC loan-pool system (a Cordin 550-62). We noted a small but significant discrepancy between system reported, and true frame rates, and this was traced to the implementation of an inappropriately slow sampling routine on the camera hardware. The discrepancy in this reported frame rate introduces an otherwise avoidable error, which affects the accuracy of interpretation and analysis of the high speed phenomena so measured. The main recommendation is that the camera manufacturer act to update the sampling algorithm on subsequent system production release, and indeed, we have received confirmation that future Cordin models will be updated to sample at these more appropriate rates [6].

Acknowledgments

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