The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-2/W12-2026
11th Intl. Workshop 3D-ARCH "3D Virtual Reconstruction and Visualization of Complex Architectures", 10–12 February 2026, Ancona, Italy

The Fast and the Distorted – How Sensor Readout Shapes Image-based 3D Modelling

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Keywords: CMOS sensor, Image-based 3D modelling, Rolling shutter, Sensor readout architecture, Shutter classification

Abstract

A photographic shutter regulates the duration of light reaching a photosensitive surface. Modern digital cameras employ diverse mechanical, electronic, or hybrid shutter technologies to synchronise light admission with a sensor's capacity to collect and reset charge. To clarify longstanding terminological inconsistencies, this paper first introduces a systematic, four-dimensional framework for classifying camera shutters alongside standardised terminology for describing key temporal quantities in the image-formation pipeline. It then focuses on progressive (i.e., rolling) exposure mechanisms in CMOS-based cameras, where sequential row-integration results in intra-frame temporal offsets across the image sensor that distort image geometry during camera or subject motion. A simple experimental setup utilising a 1,000 Hz flickering LED enables direct measurement of these temporal offsets, revealing substantial delays in electronic rolling shutters compared to mechanical or hybrid rolling-blind focal-plane types. Here, these effects are described by refining the broadly adopted notion of sensor readout into the proposed concept of shutter transit time. Finally, real-world image-based 3D modelling experiments on architectural case studies in Vienna, Austria, highlight the impact of slow shutter transit times in two typical rolling-shutter sensors. Subsequent bundle adjustments in Agisoft Metashape Professional demonstrate that even imperceptible rolling-shutter artefacts can significantly degrade camera exterior orientation and 3D surface quality, although the use of compensation algorithms markedly improves results. Overall, the paper highlights that sensor readout architecture—rather than exposure duration alone—is a decisive factor in determining the geometric fidelity of image-based 3D surface reconstructions.

1. Introduction

A photographic shutter acts as a controllable gate, regulating the duration of light reaching a photosensitive surface. Modern digital cameras employ various mechanical, electronic, or hybrid shutter technologies with distinct spatio-temporal behaviours. While computer vision, photogrammetry, and photogrammetric computer vision (hereafter all termed Image-Based Modelling or IBM) often treat a photo as a single frozen moment, many shutter mechanisms introduce significant temporal offsets across the image sensor. These offsets can lead to geometric distortions that compromise both image integrity and IBM results.

A critical shutter distinction for IBM lies in the temporal pattern by which different portions of the image plane are exposed. In a **global exposure**, all photosites of the image sensor integrate light simultaneously. Whilst this was a feature of earlier Charge-Coupled Device (CCD) sensors, the industry has transitioned to Complementary Metal-Oxide-Semiconductor (CMOS) sensors for their superior speed and power efficiency. However, most CMOS sensors lack a dedicated, shielded memory node for every photosite. Because the entire sensor cannot be read at once, exposure proceeds row by row: each row is reset, integrates light, and is then read out. Consequently, each sensor row begins and ends its exposure interval slightly later than the previous one. This sequential process is known as a **rolling shutter**.

For IBM, a rolling shutter is problematic. If the camera or subject moves during this readout interval, the geometric relationship between the object and the perspective centre changes for every image row. This effectively breaks the fundamental collinearity condition (i.e., the mathematical bedrock of IBM), which assumes that all light rays forming a given image pass through a single perspective centre at a single instant. Whilst newer, high-end stacked CMOS sensors minimise these offsets through rapid readout, the delay in many consumer and action cameras remains significant: typically from 1/10 s to 1/60 s. The resulting intra-frame geometric rolling-shutter distortions can degrade both camera orientation and 3D surface quality in IBM pipelines, even when deformations appear imperceptible in the 2D image.

Recognising that these distortions are often overlooked and that the terminology describing them is frequently ambiguous, this paper provides: (i) a systematic, four-dimensional framework for shutter classification; (ii) a clarification of essential photographic and sensor terminology that can avoid misunderstandings; (iii) a series of realistic tests that isolate rolling-shutter effects in typical IBM workflows, showing that the primary risk factor for geometric degradation is the intra-frame temporal offset rather than exposure time.

2. Four-Part Shutter Classification

The classification of photographic shutters has historically been inconsistent, with many sources conflating criteria like position, mechanism, and exposure timing. For example, the term 'focal-plane shutter' combines a positional concept (operation at the image plane) with a mechanical realisation (typically travelling curtains), whereas an electronic shutter also operates at the image plane but relies on an entirely different actuation principle. To avoid such ambiguity, shutters can be classified most coherently according to three independent but complementary principles:

- The **actuation principle**, or how exposure is controlled: mechanical, electronic, and hybrid shutters.
- The **exposure sequencing**, or how exposure proceeds across the image area: global and progressive shutters.
- The **physical placement**, or where the shutter operates within the optical system: in front-of-the-lens, in-lens, behind-the-lens, and focal-plane shutters.

The **shutter morphology** can be considered a fourth, complementary dimension that applies solely to mechanical shutters. Shutter morphology describes the motion pattern and geometric configuration of the light-blocking components, irrespective of the shutter's placement. It distinguishes between designs that open radially (leaf type), rotate about an axis (rotary-disc type), or translate linearly as a moving slit (rolling-blind type). These morphological classes inherently define the spatio-temporal behaviour of the exposure on the photosensitive surface: whether it expands, rotates, or travels.

Together, these dimensions provide a complete and consistent framework for describing all shutter systems in photo cameras, from early mechanical designs to modern electronic and hybrid implementations. The following sections briefly explain each axis of this multidimensional shutter categorisation (Figure 1; Lipinski, 1955; Ray, 1983; Kingslake, 1989; Goldberg, 1992; Burke, 1996; Ray, 1999, 2002; Peres, 2007).

2.1 Actuation Principle

This dimension describes how exposure is controlled physically or electronically.

1. **Mechanical shutters** regulate exposure by physically blocking and unblocking the optical path through three principal mechanical architectures: leaf, rotary-disc, and rolling-blind shutters.
2. **Electronic shutters** control exposure by modulating the photoelectric charge within the image sensor rather than by moving parts. Electronic shutters operate in two modes: global electronic shutters, in which all photosites begin and end exposure simultaneously, and rolling electronic shutters, in which photosites are exposed and read sequentially, typically row by row, as in most CMOS sensors.
3. **Hybrid shutters** combine mechanical and electronic actuation. A typical configuration employs an **Electronic Front-Curtain Shutter (EFCS)**, which initiates exposure electronically and terminates it mechanically.

Outside of photographic cameras, a distinct class of shutters employs purely **electro-optic modulation**. These non-mechanical devices control light transmission electronically through transparent materials whose optical properties change in response to an applied electric field. Using electro-optic elements such as Kerr cells and Pockels cells, they modulate the polarisation state of light and, in combination with auxiliary optical components (typically crossed polarisers), can switch transmission without moving parts, thereby effectively achieving global exposure control. However, because these devices are not self-contained exposure-gating mechanisms but rely on polarisation modulation and auxiliary optical elements (often resulting in significant light loss in the 'open' state), they fall outside the functional class of photographic shutters considered here. They are mainly found in specialised scientific and ultra-high-speed imaging systems.

2.2 Exposure Sequencing

This axis characterises the temporal pattern by which different portions of the image plane are exposed. It describes whether exposure occurs instantaneously across the sensor or sequentially over space (and therefore over time).

1. **Global shutters** expose all points of the image plane (quasi) simultaneously for the same duration. Typical examples include global electronic shutters and leaf shutters.
2. **Progressive shutters** expose the image plane sequentially, but the way in which this non-simultaneous exposure occurs can differ:
   - **Progressive rolling shutters** (or **rolling shutters** for short) expose the image plane in a translational manner, with the active region moving horizontally or vertically across the plane. Mechanical rolling-blind shutters (see Section 2.4) and electronic rolling shutters (as in most CMOS image sensors) follow this principle. In the scientific literature, electronic and mechanical progressive rolling shutters are simply referred to as **rolling shutters**. This text will follow that terminology hereafter, to avoid confusion with the term 'progressive' in the context of progressive versus interlaced sensor scanning, which is unrelated to shutter behaviour.
   - **Progressive rotational shutters** (or **cyclic shutters** for short) expose the image plane via a rotating slit or an open sector in a disc, so that the exposed area sweeps angularly across the image plane. The moving aperture always operates periodically, with each revolution defining a new exposure interval, as in the rotary-disc shutters of motion-picture cameras.

   In both variants, different portions of the image plane begin and end exposure at slightly different times, resulting in intra-frame temporal displacement.

This classification is not strictly binary: exposure sequencing exists on a continuum, with certain shutters being technically progressive but functionally almost indistinguishable from truly global designs. A typical example is the leaf shutter. Although its blades open from the centre outward and then close symmetrically again, this introduces only a minimal temporal gradient, typically a few hundred microseconds to about one millisecond. As a result, exposure across the image plane is technically progressive but practically global (although often limited to about 1/1000 s to 1/2000 s, because moving the blades faster requires too much force and would tear them apart).

2.3 Physical Placement

This dimension specifies where in the optical system the shutter operates.

1. **In-front-of-the-lens shutters** modulate the light beam before it enters the lens, such as the guillotine shutter.
2. **In-lens (or between-the-lens) shutters** reside within the lens assembly, close to the aperture stop. A shutter explicitly placed at the aperture stop is termed a central shutter. This placement ensures a more uniform exposure across the entire image plane (sensor or film) by reducing vignetting that can occur when the light beam is gated at other positions within the lens barrel. A typical example is a leaf shutter.
3. **Behind-the-lens shutters** modulate the light beam before it reaches the image plane. Still, behind-the-lens means 'not at the focal plane'. A rotary-disc shutter would be a prime example.
4. **Focal-plane shutters** operate directly at the image plane, controlling exposure at the level of the film or sensor itself. They can be mechanical (such as rolling-blind shutters), electronic, or hybrid. Thus, focal-plane shutter refers to a position, not a mechanism, as is commonly implied in the photographic literature.

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2.4 Shutter Morphology

Within the class of mechanical shutters, several morphological variants can be distinguished according to the geometry and motion of their light-modulating components. The three principal forms used in still cameras are:

1. **Leaf shutters** are typically positioned within the lens near the aperture diaphragm. They regulate exposure by opening and closing around the optical axis, thereby exposing the entire image almost simultaneously and thus functioning as quasi-global shutters. Morphologically, two principal variants can be distinguished:
   - **Single-blade (or sector) leaf shutters**, in which a single rotating or pivoting vane uncovers and covers the aperture.
   - **Multi-blade (or diaphragm) leaf shutters**, composed of several overlapping metal blades that open and close radially from the centre.

   This subdivision is morphologically meaningful because blade multiplicity directly affects the geometry and symmetry of the aperture opening, and thus the spatio-temporal progression of exposure across the image plane.
2. **Rotary-disc shutters** consist of a rotating disc that modulates exposure as an open or transparent sector sweeps across the optical path. The most common form is the sector shutter, in which a wedge-shaped cutout defines the exposure interval (e.g., a 180 ° sector gives a 50 % duty cycle). Within this morphological class, different disc arrangements are employed, including single-sector and multi-sector designs, which differ in the number of exposure openings per disc revolution and thus in the temporal repetition of exposure. Because these differences affect exposure timing but not the geometric mode of image-plane exposure (i.e., all designs share the same fundamental angular sweep of the active aperture), they are treated as configurations rather than as distinct morphological sub-classes. Mirror-disc shutters represent a specific implementation of the single-sector configuration, whereas dual-disc shutters constitute a multi-sector configuration commonly utilised in cinematographic and scientific cameras.
3. **Rolling-blind shutters** expose the image sequentially through a narrow slit that travels across the optical path. The slit is formed by one or two plates, blinds, or curtains that move horizontally or vertically, their motion controlled mechanically by springs, drums, or gears. Early designs used either a single wooden plate or a flexible cloth blind with an adjustable slit, or two sequentially moving plates or blinds whose relative timing defined the exposure interval. Modern implementations employ paired metal or composite curtains operating on the same principle. By narrowing the gap between the leading and trailing components, these modern dual-actuator systems achieve extremely short effective exposure times without increasing the curtains' physical travel velocity. Although these various designs differ in how the slit is mechanically generated and timed, they all produce the same translating slit geometry and the same linear progression of exposure over space and time; for this reason, they are not morphologically distinct in the sense utilised here. Consequently, each point on the image plane receives light only during the slit's passage. Rolling-blind shutters are thus mechanical rolling shutters, regardless of their placement within the optical system and their historical material diversity.

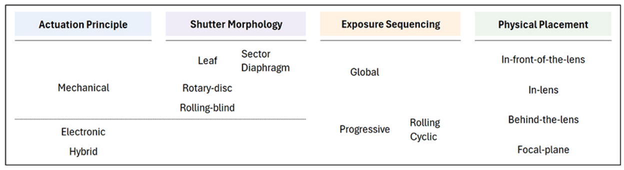

Figure 1. A four-dimensional classification framework for photographic shutters.

3. The Modern Shutter Situation

3.1 Three Main Shutter Mechanisms

Using the taxonomy introduced above, all shutter types—even ancient and exotic ones—can be coherently described. In practice, however, today's digital consumer and prosumer photo cameras overwhelmingly employ one of three shutter types:

- **Mechanical rolling-blind focal-plane shutters**: Still common in interchangeable-lens cameras (and hereafter referred to as mechanical rolling-blind shutters).
- **Electronic rolling focal-plane shutters**: The standard rolling-shutter mode of most CMOS-based imagers (hereafter referred to as electronic rolling shutters).
- **Hybrid focal-plane shutters**: Increasingly prevalent in mirrorless systems, combining electronic initiation with mechanical termination and commonly known as **Electronic First/Front Curtain Shutters** (**EFCSs**).

Together, these designs represent the culmination of decades of development in shutter technology. Many modern cameras offer two or even all three shutter modes, each with distinct pros and cons. For instance, mechanical shutters are noisier and more susceptible to timing errors and mechanical wear than their electronic or hybrid counterparts. Yet, they offer higher flash-synchronisation speeds and provide more consistent exposure under flickering illumination. Consequently, each shutter type exhibits a characteristic balance of benefits and limitations, explaining why multiple designs continue to coexist.

3.2 Mechanical versus Electronic Rolling Shutters

Despite their technological differences, modern mechanical, electronic, and hybrid focal-plane shutters all expose the image plane progressively via a travelling slit. Exposure is therefore inherently rolling rather than global, and a measurable temporal offset (i.e. the readout or transit time; see Section 4.1) exists between the first and last sensor rows. If the camera or scene undergoes motion during this interval, the assumption of a single, time-invariant camera exterior orientation per frame is violated, leading to characteristic intra-frame geometric distortions.

The key distinction for IBM thus lies not in the shutter's actuation principle, but in the magnitude of its transit time. Mechanical rolling-blind shutters employ physical curtains that traverse the sensor within a few milliseconds (see Section 5), rendering rolling-shutter-induced geometric distortion negligible in many practical situations. By contrast, electronic rolling shutters depend entirely on sensor readout architecture and often exhibit substantially longer transit times, particularly in consumer and action cameras. These prolonged temporal offsets significantly increase susceptibility to geometric distortion under camera or scene motion, even with short exposure times. To understand and analyse the impact of these offsets, it is first necessary to define several fundamental temporal quantities of image formation.

4. Temporal Durations and Distortions

4.1 Temporal Parameters of Image Formation

To move beyond shutter terminology and address the root causes of geometric deformation, it is necessary to establish a rigorous distinction between four temporal parameters.

The **(image) exposure time** (or **integration time**) is the duration for which each individual photosite on the sensor integrates light. It is the parameter commonly known as **shutter speed**. While a fast exposure time (e.g., 1/2000 s) can be sufficient to prevent motion blur and ensure pixel-level sharpness, it does not necessarily prevent geometric distortion.

The **(shutter) transit time** (also called **readout time**) defines the temporal offset between the start (or end) of the exposure for the first and last lines of photosites. In the rolling-shutter mode typical of most CMOS sensors, this exposure-progression interval is dictated by the sensor's underlying digitisation rate. While mechanical rolling-blind shutters are limited by physical inertia and spring tension (typically taking circa 1/300 s, or about 3.3 ms, to transit the sensor), electronic transit times in consumer cameras often range from about 1/10 s (100 ms) to 1/60 s (17 ms).

The **(image) formation time** is the total duration required to physically create an entire image frame on the sensor, from the first row beginning its exposure to the final row finishing its integration. In a rolling shutter system, the formation time is essentially the sum of the transit time and the exposure time.

The **(image) acquisition time** represents the formation time with the temporal overhead imposed by the electronics of the imaging system before and after image formation. Chronologically, the acquisition time spans the shutter delay, the formation time, the Analogue-to-Digital Conversion (ADC) time, the buffering time, the processing time and the writing time. The acquisition time represents the total imaging system-level duration required until the camera is ready to generate and store the following image. As such, it determines the achievable frame rate.

The terms exposure and acquisition time retain their conventional meanings used in imaging literature (Burke, 1996; Nakamura, 2006; Holst and Lomheim, 2011; Kuroda, 2017). By contrast, the term image formation time is introduced here as a convenient label for the optically active interval, defined as the sum of the exposure and transit times. This work adopts the term transit time to denote exclusively the temporal displacement between the first and last photosites that complete exposure, which is precisely the duration that determines the intra-frame geometric distortions caused by a rolling shutter. This distinction is necessary because the more common term, sensor or rolling-shutter **readout (time)**, is ill-suited to mechanical shutters, while sensor datasheets also often implicitly include stages such as ADC time, buffering time, processing time, and even writing time, in the sensor readout.

4.2 Geometric Rolling-Shutter Distortions

The non-instantaneous or non-global exposure inherent to rolling-shutter image formation limits intra-frame geometric fidelity when camera or scene motion occurs during shutter transit. Because successive image rows or columns (hereafter, image lines) are captured at different times, motion during this interval causes the spatial relationships between scene features recorded early and late in the frame to differ. The resulting photo thus no longer represents a single instantaneous central projection, but a temporal composite of line-dependent camera poses or scene configurations. While individual lines may locally approximate a central projection, the image as a whole violates the single-pose assumption used in IBM. This intra-frame temporal disparity produces specific geometric distortions, whose form and magnitude depend on the transit direction and the relative motion between camera and scene (Meingast et al., 2005; Ringaby and Forssén, 2012):

- **Linear skew**: In rolling shutters (both mechanical blinds and electronic focal-plane shutters), the exposure slit moves linearly, typically vertically. Relative motion perpendicular to the slit's transit direction produces shearing, causing vertical lines to appear slanted. If the shutter instead transits horizontally (left-to-right or right-to-left), the skew rotates accordingly, such that vertical motion results in slanted horizontal features (Figure 2).
- **Compression or elongation**: Relative motion parallel to the shutter transit causes objects to appear stretched or squeezed. Because perspective projection inverts scene motion as it is projected onto the sensor, the resulting distortion depends on whether the projected motion aligns with or opposes the transit direction. Alignment yields elongation of the object, whilst opposing directions result in geometric compression. This logic applies regardless of whether the motion originates from the subject or the camera, and holds for both vertical (top-to-bottom and vice versa) and horizontal (left-to-right and vice versa) shutter transits (Figure 2).

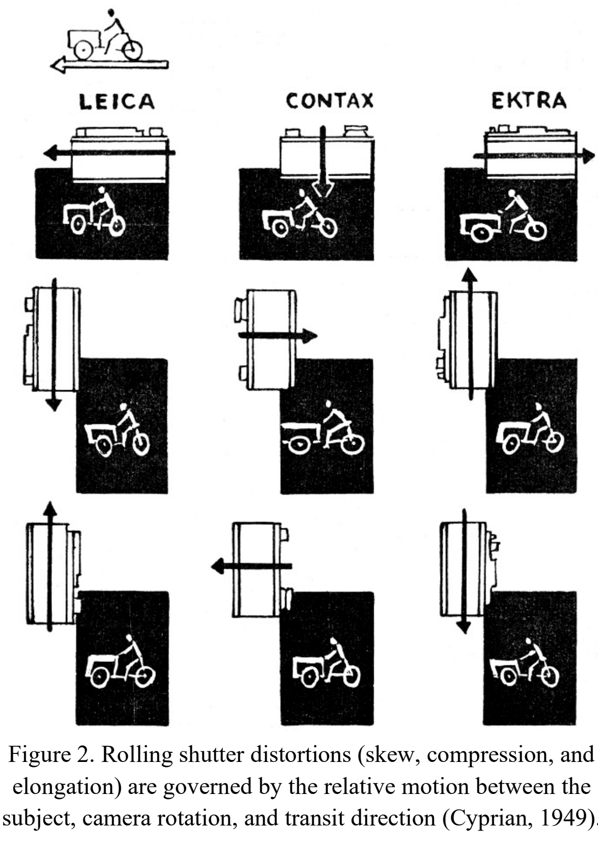

Figure 2. Rolling shutter distortions (skew, compression, and elongation) are governed by the relative motion between the subject, camera rotation, and transit direction (Cyprian, 1949).

- **Wobble (Jello effect)**: This arises from high-frequency vibrations (e.g. UAV motor oscillations) occurring during the shutter transit. If the camera oscillates back and forth multiple times while the shutter is transiting the image plane, vertical features appear wavy or undulating rather than slanted.

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- **Rotational (angular) distortion**: This results from either an angular exposure sweep (as in rotary-disc shutters) or significant angular rotation (pitch, roll, or yaw) during the shutter transit. Both produce non-linear, fan-shaped distortions. Unlike affine linear shear, where lines remain straight, rotational distortion and wobble map straight lines to curves. These complex geometric artefacts are typically much harder to estimate and correct than other rolling-shutter-induced distortions.

However, it is still critical to note two things. First, 'rolling-shutter artefacts' is an umbrella term that includes photometric effects (such as banding from flickering illumination and partial exposure) and the geometric distortions detailed above. Second, exposure time and shutter transit time are decoupled temporal quantities. Exposure time governs image blur via temporal integration at each photosite, whereas transit time determines the magnitude of spatio-temporal offsets between different image lines. Although these effects are conceptually independent, their consequences may compound, with the severity depending on the relative camera–scene motion during both temporal intervals.

As summarised in Figure 3, these intervals define four distinct imaging regimes. While long exposures (**Regimes 1 and 2**) are generally avoided in IBM due to motion blur, **Regime 3** (characterised by a short exposure and a slow transit time) is particularly insidious for 3D modelling. In this scenario, images appear radiometrically sharp, ensuring reliable feature detection. However, the slow shutter transit introduces significant temporal offsets that violate the single-pose collinearity assumption of classical IBM. This leads to erroneous camera orientation and degraded 3D surface reconstruction. This 'fast but distorted' regime is typical of many consumer-grade CMOS cameras and represents the primary target of the experimental tests in Section 6. In contrast, **Regime 4** (short exposure and near-instantaneous transit) represents the professional standard, yielding images that are radiometrically sharp and geometrically consistent. This regime will serve as the reference case against which the rolling-shutter effects of Regime 3 are compared.

	Slow transit	Fast transit
Long exposure	***Regime 1*** Motion-blurred pixels Distorted geometry	***Regime 2*** Motion-blurred pixels Consistent geometry
Short exposure	***Regime 3*** Sharp pixels Distorted geometry	***Regime 4*** Sharp pixels Consistent geometry

Figure 3. The interaction between exposure and shutter transit time yields four imaging regimes.

4.3 Rolling Shutter Tests

Based on this classification, the experimental tests presented in Section 6 deliberately focus on the two most relevant regimes for IBM: Regimes 3 (short exposure–slow transit) and 4 (short exposure–fast transit). By contrasting these two regimes under otherwise comparable acquisition conditions, the experiments isolate the geometric impact of electronic rolling-shutter-induced geometric distortion independently of motion blur, allowing its effect on camera orientation and 3D surface reconstruction to be assessed in a relevant manner.

To operationalise this comparison, the following section first determines the effective shutter transit time of the electronic and mechanical rolling-shutter modes of the Nikon Z 7II and the electronic rolling shutter of the GoPro HERO11 Black, the two representative photo cameras used in these tests.

5. Determining Shutter Transit Time

A practically applicable method for estimating the transit time of rolling-shutter cameras is to image a light source whose radiant output is temporally modulated at a known frequency. In this study, a high-intensity LED driven by a stable 1000 Hz square-wave signal is used as a temporal reference. When imaged with a rolling shutter, each sensor line integrates light over the same exposure duration but within a temporally shifted window, such that different rows sample different phases of the LED's on–off cycle, producing characteristic banding patterns whose orientation reflects the sensor's transit direction.

The visibility and spacing of these bright and dark bands depend on the relationship between exposure time, LED modulation period, and shutter transit time. If the exposure is long relative to the modulation period, banding averages out. With sufficiently short exposure times, the temporal structure of the illumination is preserved, and the spatial displacement of recurring intensity transitions across the image directly reflects the temporal offset between sensor lines (Figure 4). By relating the spacing of these transitions to the known modulation frequency, the cumulative temporal offset across the sensor (and thus the effective shutter transit time) can be estimated. A complete mathematical formulation of this approach, together with automated methods for extracting shutter transit time from image data, will be provided in an upcoming, more technical companion paper.

Figure 4. Estimating the transit times for the electronic focal-plane rolling shutters of the GoPro HERO11 Black and Nikon Z 7II. The latter was also tested in mechanical shutter mode.

Figure 4 shows that the mechanical rolling-blind shutter of the Nikon Z 7II traverses the full-frame image sensor in ca. 1/300 s, roughly 20 times faster than the transit time of the Z 7II's electronic rolling shutter. In contrast, the effective transit time of the GoPro HERO11 Black's electronic rolling shutter is about 1/50 s. Assuming that shutter transit time scales linearly with active sensor height, the measured GoPro transit time can be expressed as a full-frame equivalent. Using an active sensor height of 5.52 mm for GoPro's Sony IMX677L image sensor (Kirschenbaum, 2022; Sony Semiconductor Solutions Corporation, 2023) yields a height ratio of 24.00 mm / 5.52 mm = 4.35. Scaling the measured GoPro transit time by this factor yields an approximate 1/11.5 s full-frame-equivalent transit time.

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6. Experimental Setups and Evaluation

To demonstrate the impact of typical electronic shutter transit times (as measured in Section 5) on IBM results, various architectural case studies in Vienna, Austria, were photographed with different cameras and acquisition setups. All photo networks were processed in Agisoft Metashape Professional v. 2.1.

6.1 Test 1: Graffiti-Covered Wall (2024)

Using two Nikon Z 7II cameras mounted side by side on a stereo bar, a 25 m-long, curved, graffiti-covered wall was photographed under overcast (cloudy) conditions on 7 February 2024. Both cameras were equipped with identical Nikon NIKKOR Z 20 mm f/1.8 S lenses and featured identical manual exposure settings: 1/400 s, *f*/4, and ISO 400; the white balance was set at 'cloudy', the in-camera RAW processing profile set to 'standard', while vibration reduction and autofocus were disabled. The lens focusing ring was also fixed with cellophane tape (after temporarily mounting the stereo bar on a tripod to focus both lenses at the same distance). The only difference between the two setups was the shutter type: one Nikon Z 7II used its mechanical rolling-blind shutter to acquire images, while the other was set to silent mode, forcing the use of its electronic rolling shutter.

Using this configuration, 51 largely overlapping photos of the wall were captured. Although the setup was handheld, the short exposure time prevented motion blur from user tremor. Both cameras acquired photographs quasi-simultaneously, with frames triggered every five seconds via their built-in intervalometer. Combined with the stereo-bar arrangement, this ensured that the 51 exterior orientations of both Z 7II cameras were effectively identical, thereby eliminating pose differences as a source of variation in the final results. Due to its significantly faster transit time (approximately 1/300 s), the mechanical rolling-blind shutter effectively acts as a 'pseudo-global' shutter in this handheld context, as the camera pose remains virtually constant during the frame formation. This allows the mechanical rolling-blind shutter dataset to serve as a control group against which the electronic rolling-shutter results can be compared.

Within Agisoft Metashape Professional, the resulting photos were oriented in separate blocks via SfM, using a limit of 40,000 key points and 4,000 tie points per image. A Helmert transform via three GCPs aligned each solution into the same coordinate reference system, enabling comparison. Afterwards, a Multi-View Stereo (MVS) and surface reconstruction step (using all image pixels; i.e., 'Ultra high' setting in Metashape) was run to generate a triangular, 3D surface mesh per block. Whereas the 51 images acquired with the mechanical rolling-blind shutter setup were only oriented using Metashape Professional's standard bundle adjustment, those of the electronic rolling shutter camera were oriented in four different ways:

- With the standard bundle adjustment without any **Rolling-Shutter Compensation** (RSC);
- With regularised RSC for the electronic shutter photos;
- With full RSC for those photos;
- With full RSC plus adaptive interior orientation (as advised by Agisoft LLC (2026).

Rolling-shutter-aware bundle adjustment as implemented in Metashape Professional extends the classical projection model (i.e., a single, static pose) by introducing a parametric time-dependence of the exterior orientation, allowing different image lines to feature slightly different poses (Hedborg et al., 2012; Oth et al., 2013). In the simplest translational rolling-shutter model, the camera centre is assumed to move linearly over the image-formation interval (i.e. described by three translational motion parameters), so that each image line is projected using a pose evaluated at its line time, typically by interpolating between the start and end times of the shutter transit. More complete six-parameter models additionally account for rotational motion during transit, in addition to the three translational motion parameters. Rofallski and Luhmann (2017) experimentally validated an IBM formulation of such an approach based on two exterior orientations per image and constant-velocity interpolation tied to the image row coordinate. However, many alternative formulations and parameterisations of rolling-shutter-aware bundle adjustment have been proposed (see, for example, Fan et al. (2023), and references therein).

By re-establishing a locally valid collinearity condition at the level of individual image lines, these models enable bundle adjustment to jointly estimate scene geometry and the line-dependent exterior orientations, thereby allowing explicit correction of intra-frame geometric distortion. This is a prerequisite for achieving accurate measurements and reliable 3D reconstruction when using rolling-shutter imagery.

Metashape Professional implements both a 'regularised' rolling-shutter model and a 'full' rolling-shutter compensation model. In the regularised variant, only in-plane translational motion is estimated; translation along the optical axis is intentionally excluded as a stabilising regularisation, likely due to its weak observability and strong coupling with object depth and principal distance. However, the parameterisation and implementation of both models are not publicly documented.

	Mechanical	Electronic rolling shutter			
		no RSC	regular. RSC	full RSC	full RSC+ad. IO
tie points	22.2 k	24.6 k	24.1 k	***24.6 k***	24.6 k
RMS reproj. error	0.21 (0.8 px)	0.42 (1.6 px)	0.25 (1.0 px)	***0.18 (0.7 px)***	0.18 (0.7 px)
max reproj. error	0.65 (59.6 px)	1.29 (84.3 px)	0.77 (64.3 px)	***0.56 (33.1 px)***	0.56 (33.1 px)

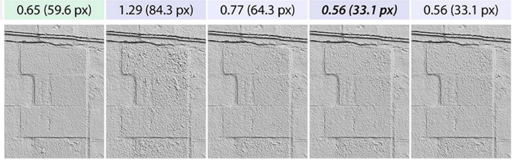

Figure 5. IBM of a graffitied wall using photos acquired with a mechanical rolling-blind versus an electronic rolling shutter.

Figure 5 illustrates the results of this first test. In the absence of RSC, the RMS reprojection error for the electronic rolling-shutter configuration was double that of the mechanical rolling-blind shutter setup. This discrepancy is expected. Although the 1/400 s exposure time effectively suppressed motion blur, it did not eliminate geometric distortion. The Z 7II electronic shutter has a transit time of 1/15 s, which exceeds the threshold for handheld stability—often generalised by the '1/focal length' rule for motion blur—meaning the camera's exterior orientation shifted during the shutter's transit. This resulted in intra-frame rolling-shutter distortions, leading to increased reprojection errors.

https://doi.org/10.5194/isprs-archives-XLVIII-2-W12-2026-495-2026

However, the most apparent influence is evident in parts of the triangular 3D surface mesh computed from these photos (Figure 5, lowest row), which clearly exhibit mesh artefacts. These artefacts are seriously reduced with any RSC. Still, the result is never as clean as that computed from photos acquired with a mechanical rolling-blind shutter. This is because the mechanical shutter's 1/300 s transit time is fast enough to ensure that the camera pose is effectively constant at the frame level, whereas the 1/15 s electronic transit time allows for camera-motion that even advanced RSC models cannot fully resolve.

The cleanest result from the rolling shutter photos (in terms of reprojection statistics and surface mesh quality) was achieved with the full RSC. Although the number of tie points should never function as an indication of geometric fidelity, it is remarkable that the number of established tie points was always higher for the electronic rolling-shutter imagery. When processed with full RSC, the reprojection statistics were also slightly better than those of the mechanical rolling-blind shutter photos. However, allowing Metashape to automatically select the interior orientation parameters to be estimated (via the 'adaptive camera model fitting' option) did not improve either mesh quality or reprojection statistics compared to using the standard Brown–Conrady lens distortion model. Since most cultural heritage IBM pipelines ultimately rely on 3D surface models for interpretation and measurement, surface quality can be regarded as a key indicator of reconstruction fidelity. Although the mesh quality improved considerably compared to an SfM-MVS pipeline without RSC, it still lacked the mesh cleanliness observed in the mechanical-shutter photos in certain areas.

6.2 Test 2: Otto Wagner Pavilion (1899)

For Test 2, Nikon Z 7II cameras were used to photograph the Otto Wagner Pavilion, an iron-and-marble structure designed by Otto Wagner and exemplary of Viennese Modernism. In contrast to Test 1, both cameras were equipped with a Nikon NIKKOR Z 50 mm f/1.8 S lens. The main aim of this test was thus to demonstrate the influence of a longer focal length (and hence a higher effective image scale, since the object distance was similar to that of Test 1) on the intra-frame rolling-shutter distortions. Manual exposure settings of 1/800 s, *f*/4, and ISO 250 ensured, once again, that user tremor would not affect image sharpness. As in Test 1, lenses were pre-focused, their focus rings were fixed with cellophane tape, and vibration reduction was disabled. Both cameras were again fixed on a handheld stereo bar and had different shutter types enabled. Images were acquired quasi-simultaneously every five seconds via the built-in intervalometer.

Using this configuration, 43 largely overlapping photos of the pavilion's rear facade were captured on 8 February 2024 in hazy sunshine. The images were subsequently grouped by shutter type. The block containing photos from the electronic rolling-shutter Nikon Z 7II was again oriented in four different ways. The statistics in Figure 6 confirm the smaller reprojection errors for the network of photos acquired with the mechanical rolling-blind shutter. Although the various RSCs markedly reduced the maximum and RMS reprojection errors, they never reached the level achieved with the mechanical rolling-blind shutter. In contrast to Test 1, the reprojection errors of the processed electronic rolling-shutter images in this test never dropped below those of the mechanical rolling-blind shutter image set. However, the tie point count was again lowest for the latter shutter setup.

The mesh screenshots in the lower row of Figure 6 show that, without RSC, the electronic rolling-shutter imagery yields an essentially unusable 3D surface mesh. Compared to Test 1, the artefacts are far more pronounced, reflecting the higher effective image scale associated with the longer focal length at a similar working distance. Under these conditions, identical angular and translational camera motion during shutter transit results in much larger image-space displacements, leading to severe intra-frame geometric distortion. Regularised RSC markedly improved the results, while full RSC performed even better. As in Test 1, enabling adaptive interior orientation did not yield any further improvement over the standard full RSC.

	Mechanical	Electronic rolling shutter			
		no RSC	regular. RSC	full RSC	full RSC+ad. IO
tie points	9.5 k	10.0 k	10.4 k	***10.6 k***	10.6 k
RMS reproj. error	***0.14 (0.8 px)***	0.85 (3.5 px)	0.37 (1.7 px)	0.28 (1.3 px)	0.28 (1.3 px)
max reproj. error	***0.43 (30.4 px)***	2.67 (96.6 px)	1.14 (77.2 px)	0.87 (55.7 px)	0.88 (55.7 px)

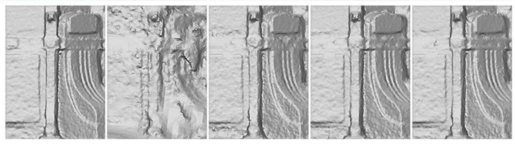

Figure 6. IBM of the Otto Wagner Pavilion using photos acquired with a mechanical versus an electronic rolling shutter.

6.3 Test 3: Wotruba Church (1976)

The final experiment evaluated the impact of rolling shutter distortion in a dynamic scenario. Two facades of the Wotruba Church, completed in 1976 and designed by Austrian sculptor Fritz Wotruba, were captured on a sunny 18 February 2024 with a Nikon Z 7II and a NIKKOR Z 20 mm f/1.8 S lens. This camera utilised its mechanical rolling-blind shutter to capture a reference network of 148 handheld photos. Settings were *f*/5.6 and ISO 200 in aperture-priority mode (with shutter speeds shorter than 1/200 s), with autofocus and vibration reduction disabled. These images were oriented via SfM using the same parameters as in Test 1.

Subsequently, 132 photos were acquired with a GoPro HERO11 Black while walking along the church at approximately 1 m/s to simulate the dynamic conditions typical of action camera applications. These images featured shutter speeds of 1/1000 s or shorter, *f*/2.5, and ISO 400 or less. The GoPro's fixed-focus lens and absence of vibration reduction ensured optically stable interior orientation throughout the image sequence. The average GSD was about 1.5 mm for the Nikon images and 1.4 mm for the GoPro imagery. The GoPro photos were oriented to the Nikon reference network via incremental SfM.

Incremental SfM was tested across three RSC modes: none, regularised, and full (omitting adaptive interior orientation based on the results of Tests 1–2). As shown in Figure 7, only the full RSC significantly reduced the RMS reprojection errors, while simultaneously increasing the tie point count. Without RSC, the RMS reprojection error reached 5 pixels, half the ~10-pixel translational shift expected for a GoPro HERO11 Black (1/50 s transit) carried at a walking pace of 1 m/s, 5 m from a surface.

https://doi.org/10.5194/isprs-archives-XLVIII-2-W12-2026-495-2026

To evaluate orientation accuracy, the mesh generated from the Nikon Z 7II images was textured with GoPro imagery (Figure 7). Compared with the Nikon-derived reference texture, all GoPro-derived textures showed visible displacement, except for the full RSC solution. In that instance, the small black construction holes in the texture align perfectly with the reference positions (indicated by coloured dots in Figure 7). Similarly, the left border of the church window (blue arrow) is only correctly generated in the reference and the full RSC GoPro textures.

	Nikon Z 7II	GoPro HERO11 Black		
		no RSC	regular. RSC	full RSC
tie points		24.4 k	28.0 k	***41.7 k***
RMS reproj. error		0.53 (5.0 px)	0.48 (4.3 px)	***0.30 (2.5 px)***
max reproj. error		1.26 (114.2 px)	1.19 (113.3 px)	***0.98 (84.4 px)***

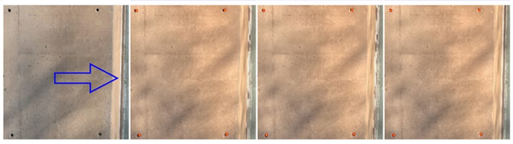

Figure 7. The IBM results of Test 3. Image by C.Stadler/Bwag.

7. Conclusion

A decade ago, Vautherin et al. (2016) demonstrated that explicitly modelling rolling-shutter effects during SfM-based orientation of UAV imagery substantially improves geometric accuracy. The experimental results of this paper extend this finding to terrestrial acquisition, showing that handheld photos (taken while standing still or walking) also benefit from RSC under long shutter transit times. Although camera motion during acquisition may appear imperceptible, a slow shutter transit can violate the assumption of a single central projection per frame.

Whilst Metashape's RSC significantly mitigates rolling-shutter-induced geometric distortions, the resulting 3D surface meshes do not reach the fidelity of those created by a mechanical rolling-blind focal-plane shutter. This indicates that, although algorithmic compensation is a powerful tool, it cannot fully replace the near-instantaneous, frame-level geometry provided by a mechanical shutter in both nominally static and dynamic handheld scenarios. To enable future, in-depth analysis of this issue, this paper also introduced a robust shutter classification framework alongside a standardised terminology for describing key temporal quantities in the image-formation pipeline.

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