

Article

Single-Shot Laser Triangulation for Drone-Based Geometry Measurements

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Highlights

What are the main findings?

- A drone-mounted single-shot laser triangulation system with imaging capability is realized.
- The measurement system achieves an axial resolution of 126 μm and a lateral sampling pitch of 1.75 mm, and it successfully detects surface defects with millimeter size.

What are the implications of the main finding?

- Single-shot laser triangulation is a viable approach for high-resolution drone-based surface defect inspections of hard-to-reach structures.
- UAV-based optical metrology shows great potential for future automated inspections of wind turbine blades, bridges, and pipelines.

Abstract

Small surface defects on large structures such as wind turbine blades, bridges, and pipelines pose significant safety risks if left undetected. Therefore, a laser triangulation system is designed for contactless surface geometry inspection from a flying drone at a working distance of 2 m. To enable single-shot triangulation measurements in dynamic aerial environments, a single-shot-capable approach is realized by means of a laser and a diffractive optical element for creating a dot-matrix illumination pattern and a camera for image recording. The setup, with 101×101 measurement points, is calibrated by using an interferometer as a reference, which shows a sub-pixel resolution capability. As a result, the depth resolution capability for each point amounts to 126 μm , while the lateral resolution capability is determined by the laser spots' size of 0.6 mm and the spots' interspacing of 1.75 mm. With the present configuration, unambiguous depth detection is possible for local surface gradients of up to 2.3 times the interspot distance between adjacent measurement points, and the field of view is 17.56 cm $\times$ 17.56 cm. Finally, surface defects with lateral sizes on the order of 1 cm and 0.5 cm are currently detectable, as is demonstrated by experimental results from in-flight measurements. Thus, the potential and challenges of single-shot laser triangulation for drone-based inspection in real-world scenarios are presented.



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Keywords: drone-based inspection system; laser triangulation; single-shot imaging; defect detection; optical inspection; active triangulation; coherent light defect detection; in-flight measurement and flying triangulation

1. Introduction

1.1. Motivation

Small surface defects on large structures, such as wind turbine blades, bridges, and pipelines, can propagate over time, potentially leading to structural failure. Regular inspection is essential for ensuring operational safety, but manual methods are labor-intensive and hazardous due to difficult-to-reach locations at high elevations or above water. Therefore, a flying, remote-controllable optical surface inspection system that is able to perform contactless geometry measurements in the proximity of the structure is required.

1.2. State of the Art

Optical measurement techniques enable non-contact three-dimensional mapping in a wide range of applications, including industrial inspection and infrastructure monitoring [1]. For systems mounted on drones and intended to detect fine surface defects on large structures such as wind turbine blades, the selection of an appropriate measurement principle is governed by specific requirements: the system must be of low complexity to ensure it can be reliably integrated into a drone platform, and it must allow for single-shot acquisition capability to reduce the risk of motion blur during measurement. Furthermore, it must offer a measurement resolution better than 1 mm from a working distance of at least 2 m to resolve small-scale surface features with sizes on the order of 1 cm and below.

Various optical measurement principles have been designed for three-dimensional surface reconstruction. Some of the prominent techniques are interferometry, time-of-flight sensing, photogrammetry and laser triangulation [2,3]. Optical interferometry achieves the highest measurement resolution by analyzing phase shifts in coherent light waves that are reflected from the target surface. Digital phase-shifting interferometry or multibeam interferometry can be used to analyze surface topography [4]. Despite their high accuracy, which can reach the nanometer scale, interferometric systems are highly prone to mechanical vibrations and environmental changes [5,6]. In optical interferometry, the measurement laser requires coherent reflection from the target surface [7]. Consequently, retro-reflective elements are often necessary to enable stable interference patterns. However, this requirement limits practical applicability for large-scale structures, such as wind turbine blades or bridge undersides, where placing retro-reflectors on the measurement surface is not feasible. Moreover, integrating the optical components required for interferometry into a drone platform is challenging due to vibrations and motion during operation.

Time-of-flight systems determine distance by measuring the time it takes for a light pulse to travel from the sensor to the target and back. In [8], a time-of-flight-based terrestrial laser scanner was used to determine the axial and lateral positions of a wind turbine head. The laser scanner achieves surface acquisition via line scanning with 1000 measurement points but has an uncertainty larger than 5 mm at a measuring distance of 150 m. Because of their simplicity in integration, time-of-flight sensors are suitable for integration with mobile platforms [9]. In time-of-flight-based inspection systems, the absolute uncertainty increases with measurement distance. State-of-the-art time-of-flight cameras, as evaluated by Paredes et al. [10], achieve axial resolutions of approximately 3.5 mm at 1 m. Since their precision deteriorates with distance, they are not considered suitable for resolving ≤ 1 cm surface defects at typical drone-to-target ranges of a few meters.

Photogrammetry is a well-established technology for aerial surveillance and 3D reconstruction, particularly due to the seamless integration with drone platforms and the availability of small high-resolution cameras [11]. By capturing multiple overlapping images from different viewpoints, photogrammetric techniques approximate the surface geometry using feature matching [12,13]. However, its precision is very sensitive to surface texture and lighting. Homogeneous or shiny surfaces, such as newly produced composite

blades or metal components, often lack sufficient visual features, leading to low-quality reconstructions [12]. Projected structured-light photogrammetry requires more power in outdoor environments because the projector must overcome ambient illumination. Sunlight can exceed the projected signal by 2–5 orders of magnitude, necessitating a higher optical power to maintain the required signal-to-noise ratio and depth quality [14]. In contrast, coherent-light-based measurement principles such as laser triangulation exhibit greater robustness under bright outdoor conditions, as they rely on narrowband illumination, enabling measurements with lower optical power requirements.

Laser triangulation measures surface profiles by projecting a laser beam onto the target surface while simultaneously measuring its displacement with a camera at a fixed baseline distance. Although triangulation does not achieve resolutions comparable to those of interferometry, it has a lower system complexity and is non-invasive [11], making it suitable for drone-based inspection. The fundamental uncertainty in laser triangulation is due to the diffraction-limited lateral resolution of the imaging optics, which constrains depth precision based on wavelength and numerical aperture [15]. This defines a lower bound for the accuracy of triangulation, regardless of the noise from the sensor. Auerswald et al. [16] presented a laser line triangulation system, combining high-speed scanning and dynamic threshold control, for surface acquisition of large reflective gear structures. However, the method relies on sequential scanning to reconstruct the surface geometry, making it sensitive to motion-induced distortions. In drone-based applications, scanning can lead to severe errors caused by the flying platform's motion. Kienle et al. [17] introduced an improved optical setup for error compensation in laser triangulation systems. The optical setup consists of beam splitters and a reference beam to compensate for environmental and mechanical perturbations. This approach demonstrated high precision with a resolution of 100 μm at a working distance of 1 m. However, the system is limited to single-point measurements and relies on a mechanically stable setup with external optics—factors that make it impractical for deployment on a drone platform. Idrobo-Pizo et al. [18] reported the complete calibration process of a laser scanner triangulation system integrated within a robotic arm. The sensor system achieves sub-millimeter accuracy at measurement distances of 25 mm to 650 mm. The method is based on static, rigid mounting and controlled environmental conditions. Furthermore, Ettl et al. [19] introduced the 'Flying Triangulation' concept, an optical 3D sensor principle that allows motion-robust, handheld scanning of complex surfaces, such as human teeth. Unlike conventional stripe pattern projection techniques that typically use phase-shifting or Gray code patterns for depth estimation [20], Flying Triangulation enables single-shot acquisition by projecting a sparse encoded pattern within a single frame. Although this method restricts the extent of uniqueness and point density in comparison to multi-pattern systems, it removes the necessity for temporal sequencing and thereby enhances its robustness to motion. Such a compromise turns out to be especially beneficial in dynamic scenes, where drone or hand movement would typically produce significant artifacts in multi-frame techniques. The system designed by Ettl et al. achieves a resolution of 30 μm at a measurement distance of 30 mm, without the need for external tracking, and it is inherently designed for close-range applications. The principle's inherent robustness to motion and lack of reliance on external tracking suggest its good potential for adaptation to drone-based inspection tasks, particularly if extended to operate effectively at a working distance of around 2 m.

Drone-based inspection of large-scale infrastructure is currently performed by camera-based visual inspection and infrared thermography, as these methods are comparatively simple to integrate with UAV platforms and enable rapid screening of large areas. Visual inspection systems provide high-resolution image data for the detection of visible cracks, erosion, or surface anomalies, while infrared thermography enables the identification of

subsurface defects through thermal contrast analysis [21]. Recent studies have demonstrated their applicability in monitoring the dynamic loading of bridges [22]. LiDAR-based systems extend UAV inspection toward three-dimensional surface reconstruction [23], but their measurement has a fundamental depth limitation that can limit the detection of small local defects in the centimeter range [3]. In contrast, laser triangulation is an active optical geometry measurement principle that directly captures local surface topography by evaluating the geometric displacement of projected laser features. As a result, it offers the potential for high relative depth sensitivity that is less dependent on natural surface texture or thermal excitation.

While active laser triangulation has shown strong performance in robotic and fixed scanning applications [18,19], its adaptation to drone-based environments has not been carried out yet. Many existing systems assume static conditions, such as fixed sensor–target distances or mechanically stable platforms [17], which do not hold under drone operation. Among the reviewed optical measurement principles, laser triangulation emerges as a promising candidate, offering, in principle, a sufficient measurement resolution; a simple, scalable setup for compact drone integration; and compatibility with single-shot surface acquisition when evaluating multiple laser points simultaneously, similarly to laser line triangulation. In particular, a single-shot triangulation approach enables such measurements under dynamic drone operation, making it a complementary measurement principle for UAV-based inspection tasks where local defect detection is required.

1.3. Aim and Outline

For the detection of local defects on large-scale structures, a laser-triangulation-based 2D geometry sensor system is designed for a flying drone. In order to achieve single-shot imaging capability, a 2D dot-matrix illumination pattern is created with a laser and a diffractive optical element. The dot pattern on the illuminated structure is captured with a camera, and the laser point centers are determined, so that the surface, including possible defects, is detectable. The respective sensor system is realized, and the fundamentally achievable measurement resolution for a safety working distance of about 2 m is clarified. In addition, the effect of the flying-drone environment on the measurement uncertainty is studied, and the measurement capabilities are demonstrated and discussed.

Section 2 explains the principle of single-shot laser triangulation for geometry measurements from a drone. Accordingly, the sensor design requirements are derived for enabling sub-mm resolution from a working distance of about 2 m. In Section 3, the experimental setup is described, detailing the measurement object, the drone and the sensor system. In Section 4, the experimental results of studies in the laboratory are discussed, determining the achievable measurement resolution and the influence of the drone environment on the measurement uncertainty. The findings are finally validated by a demonstration experiment on a rotor blade structure. In Section 5, the article closes with a summary of the key findings and an outlook on future research.

2. Principle

Laser triangulation is a non-contact optical method for measuring distance based on the geometric principle of triangulation [3]. It relies on a spatial arrangement of a laser source and a camera with an imaging lens, both positioned in a triangular configuration (see Figure 1). The laser beam projected onto the object surface is reflected back at the camera, and the position v_L of the spot on the camera varies depending on the object's distance, d . Accordingly, the displacement of the laser spot on the camera is used to compute the distance to the surface through trigonometric relationships. When configured under the Scheimpflug condition [24], as illustrated in Figure 1, the planes of the detector, the lens,

and the laser line intersect at a single point. The equation for calculating the distance then reads [17]

$$d = \frac{f}{\cos \alpha} \cdot \left(1 + \frac{\sqrt{b^2 + \left(b \cdot \tan \alpha - \frac{f}{\cos \alpha} \right)^2}}{v_L + v_{\text{offset}}} \right) - b \cdot \tan \alpha + l_z, \quad (1)$$

The five parameters are the base distance b , defined as the distance between the laser source and the center of the lens; the lens offset l_z , the displacement between the laser and the center of the lens; the focal length f of the imaging lens; the camera's position offset v_{offset} , representing the shift along the detector axis v ; and the angle α denotes the tilt (inclination) of the lens. The blue dotted lines in Figure 1 illustrate the detector, lens and laser planes that intersect at one common point and thus satisfy the Scheimpflug condition. The variable v_L represents the image coordinate position of the laser spot on the camera, which is indicated by a green dash. The spot position v_L is extracted from the image using sub-pixel localization algorithms. Since the five geometric parameters are constant, mapping v_L over the corresponding distance d yields the calibration curve.

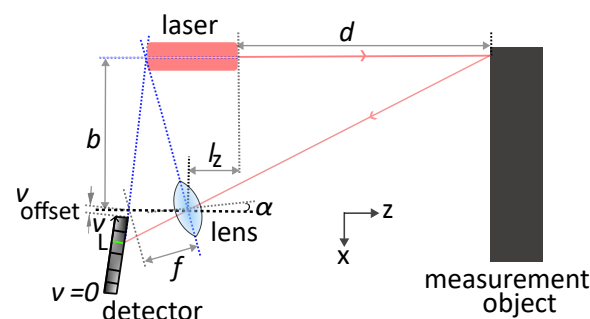


Figure 1. The principle of a laser triangulation system setup in the Scheimpflug condition. The measurement quantity is the distance d to the measurement object, which is derived from the position v_L of the laser spot on the photodetector array (camera).

In order to describe the design considerations, Figure 2 shows the calculated relationship between the measurement distance d and the laser spot position v_L on the sensor by means of Equation (1), where the five parameters are chosen to correspond to the intended drone-mounted system. The focal length f is 50 mm, the lens offset l_z is 100 mm, the offset v_{offset} is 1 mm, the angle α is 9° , and the three considered different baseline lengths are $b_1 = 175$ mm, $b_2 = 375$ mm and $b_3 = 575$ mm. The three resulting calibration curves are shown in Figure 2 for a distance range of 0.1 to 10 m. The assumed working range for a drone-based measurement system (1.8–2.5 m) is indicated by two vertical dashed lines. As the measurement object moves farther away, the position v_L of the laser spot image increases non-linearly. And as expected, the larger the baseline length, the higher the depth sensitivity, i.e., the higher the slope of the curve. Thus, larger baseline lengths are needed to meet the measurement resolution requirement. However, in drone-based applications, the maximum usable baseline is ultimately constrained by the available mounting space and payload capacity, which must be taken into account.

Accurately resolving local surface defects requires an imaging capability with a high spatial density of measurement points. In addition, a single-shot-capable approach is needed for drone-based laser triangulation systems, since the motion of the flying platform will disturb scanning-based image acquisition. In order to ensure imaging capability with a single camera frame, a diffractive optical element (DOE) is integrated into the optical path of the laser, which shapes the laser output into a structured illumination pattern, such as a grid or a matrix of spots. When projected onto the surface, the camera observes this pattern within the known triangulation configuration. The position of each spot on the

camera carries local depth information, enabling the simultaneous acquisition of multiple surface points. The single-shot approach is illustrated in Figure 3. It eliminates the need for mechanical scanning and is thus advantageous in drone-based in-flight measurement scenarios, where stable conditions cannot always be guaranteed.

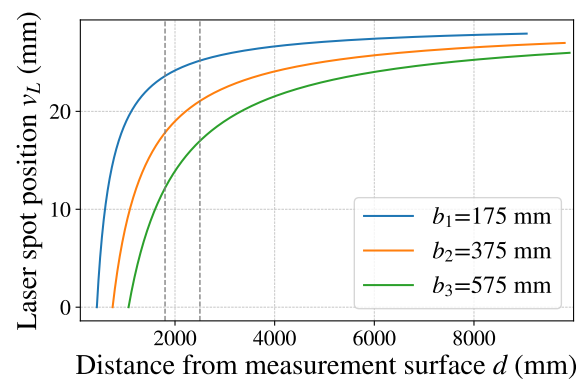


Figure 2. The relationship between measurement distance d and detected laser spot position v_L for three different baseline lengths $b_1 < b_2 < b_3$. The calculation is based on Equation (1) using $f = 50$ mm, $l_z = 100$ mm, and $v_{\text{offset}} = 1$ mm. The dotted region shows the planned measurement distance range, i.e., from 1.8 m to 2.5 m. Larger baselines yield greater sensitivity in the planned operational distance, which improves depth resolution in laser triangulation.

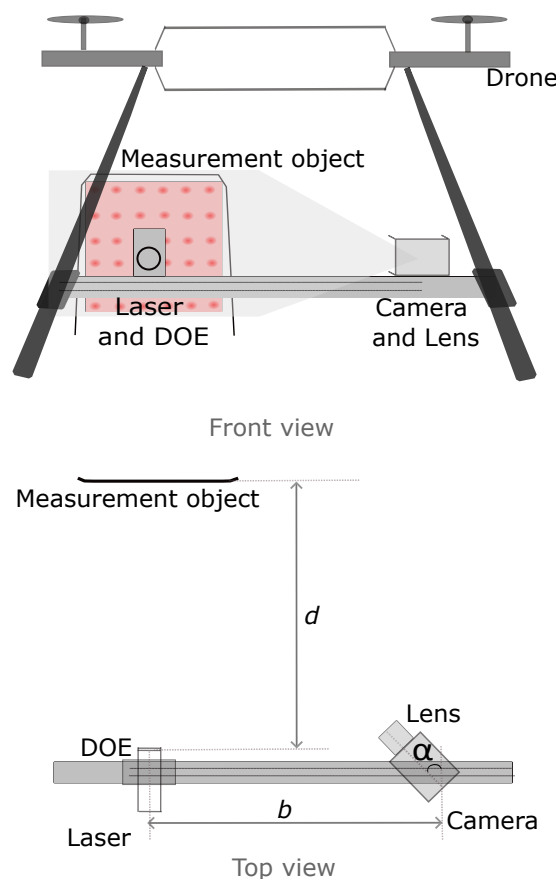


Figure 3. The concept for the drone-based laser triangulation sensor system, comprising a laser source and a diffractive optical element (DOE) for creating a dot-matrix illumination pattern and a camera for detecting the position of the laser spots. The projected structured light illuminates the target surface (shown in red colour), and the axial distance to each point is determined by evaluating the captured image.

To ensure imaging capability, the camera chip must be large enough to capture the full dot matrix across the entire working range. Hence, the desired lateral field coverage must be matched to the detector size, while the lateral extent of the DOE-projected pattern increases linearly with distance according to its divergence angles. Otherwise, parts of the projected dot-matrix pattern may move beyond the image boundaries, reducing the amount of usable measurement data. For a given working distance, the field of view is primarily determined by the focal length and sensor dimensions. A larger baseline b enhances depth sensitivity, as illustrated in Figure 2. Therefore, the baseline, focal length, and sensor dimensions must be jointly optimized to ensure that the complete DOE pattern remains within the camera's field of view throughout the measurement range.

3. Experimental Setup

3.1. Drone

The drone used in the experiment is shown in Figure 4. It is a custom drone from the company Copting GmbH (Braunschweig, Germany). It is a modular unmanned aerial vehicle (UAV) designed for the deployment of payloads for in-flight measurements. The drone features six X6 Pro brushless motors with 58 cm carbon-reinforced foldable propellers, driven by 80 A motor controllers. The propulsion system supports a maximum takeoff weight of 30 kg, with a nominal operating configuration of approximately 20 kg, including the four batteries onboard. The drone includes foldable arms secured by threaded locking mechanisms to facilitate transport. The structural parameters include a diagonal span of 183 cm and an overall height of 158 cm. The control system is based on a Pixhawk 2.1 autopilot, with external communication handled via a 2.4 GHz link (H16 controller), supporting manual and semi-autonomous operation. Power is supplied via a four-LiPo-battery pack, configured in two serial pairs. The full system voltage at nominal charge is 52.2 V, and the battery configuration delivers power for both propulsion and sensor operation. A fully charged set of batteries allows for a flight time of 12–15 min.

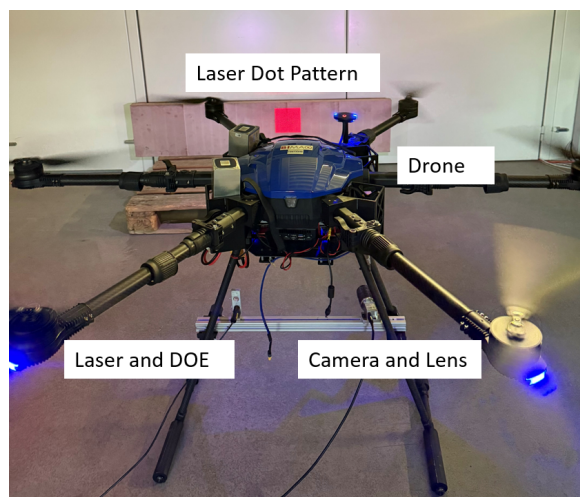


Figure 4. The drone with the laser triangulation system attached as the payload. The measurements are made on a measurement object made of polyurethane (background).

3.2. Laser Triangulation System

The complete laser triangulation system, along with the mounting, is shown in Figure 4. The laser triangulation system is constructed on a rigid aluminum profile to ensure mechanical stability during calibration and deployment. The baseline length, b , is selected to maximize depth sensitivity, as longer baselines improve spatial resolution and thus depth discrimination of triangulation systems, as shown in Figure 2. However, to

remain compatible with drone integration, the baseline must be chosen so that the overall sensor assembly fits within the drone's structural envelope and does not interfere with airflow, rotor downwash, or the center-of-gravity constraints. As a result, the designed measurement setup has a maximum baseline length of 378 mm between the laser source and the center of the detector lens. The chosen baseline length represents the maximum allowable distance within the payload compartment of the drone. Depending on the baseline length and the measurement distance, an inclination angle α of 9° is achieved. The system is not configured to satisfy the Scheimpflug condition. In triangulation systems, Scheimpflug alignment is typically applied when short object distances are required and the entire sensor area must be exploited for depth measurement. However, in the present configuration, the minimum working distance is limited by the drone geometry to approximately 1.8 m, such that the full chip height is not required. For this reason, a standard alignment without Scheimpflug adjustment is selected.

For structured illumination, a 635 nm, 100 mW laser source is used in combination with a DE-R231 DOE, both manufactured by Picotronic GmbH (Koblenz, Germany). The DOE, made of polycarbonate, is directly mounted onto the laser module. The aperture of the DOE is 8 mm in diameter (excluding the mechanical holder). It generates a static 101×101 dot-matrix pattern, which enables dense spatial sampling of the target surface within a single camera exposure. The divergence angles of the DOE govern the physical extent of the projected pattern on the measurement surface. Specifically, the divergence angles are $\tilde{\alpha} = 7.4^\circ$, $\tilde{\beta} = 5.2^\circ$, $\tilde{\gamma} = 0.05^\circ$ and $\tilde{\delta} = 5.2^\circ$, where $\tilde{\alpha}$ defines the diagonal spread of the pattern, $\tilde{\beta}$ and $\tilde{\delta}$ define the side spread, and $\tilde{\gamma}$ refers to the interspot distance. At a measurement distance of 2 m, the divergence of the projected pattern results in a field of view with a diagonal length of 258 mm, a side length of 181 mm, and an interspot spacing of 1.75 mm between adjacent laser points, with an average spot diameter of 0.6 mm. Note that the interspot spacing limits the unambiguous detectability of local surface height changes. With the present configuration, this means a maximum local height difference of 2.3 times the interspot distance between two neighboring measurement points. In order to cope with higher surface gradients, previous knowledge can be used, or the interspot spacing has to be increased. The selection of the laser source is determined by both optical compatibility with the DOE and operational safety requirements. The employed DOE exhibits maximum transmittance in the wavelength range of 635–680 nm. To improve robustness to ambient illumination during outdoor operation, the optical system employs narrowband coherent laser illumination at 635 nm, which concentrates the emitted optical power within a limited spectral range and provides a high local signal contrast compared to broadband background light. The optical power of 100 mW was selected to ensure sufficient spot intensity for detection under outdoor conditions. In addition, the use of a monochrome camera improves sensitivity to the projected laser signal, while fixed exposure settings and subsequent image pre-processing, including contrast enhancement and filtering, further improve the signal-to-background ratio and suppress false detections caused by ambient illumination. In addition, for safe operation in drone-based applications, the laser must comply with eye-safety standards. Consequently, a Class 2M laser source with an output power of 100 mW is used. The classification is ensured by the beam expansion introduced by the DOE, which distributes the optical power over a 101×101 spot matrix. Assuming a uniform power distribution, the average optical power per spot is approximately 9.8 μ W. Furthermore, due to the angular spread of the projected pattern, only a limited fraction of the beams can enter the pupil simultaneously, in the worst case. Thus, the effective power that can reach the eye is substantially reduced, enabling safe operation under in-flight measurement conditions and accidental exposure scenarios.

For imaging, a monochrome camera from the company Basler AG (Ahrensburg, Germany) of the type a2A5320-23umPRO is used with a Sony IMX542 CMOS sensor (Tokyo, Japan). The camera sensor has a pixel size of $2.74\text{ }\mu\text{m}$ and a full resolution of 5328×3040 pixels. To prevent motion-induced distortions during aerial imaging, a global shutter operating mode is used. The exposure time is set to $7000\text{ }\mu\text{s}$. Image acquisition is performed with a frame rate of 22.3 fps, which corresponds to a sensor readout time of 37.8 ms. The camera is operated in free-running mode and triggered with the help of a Python v3.12 script. No image binning or compression is applied. The acquisition parameters are selected to ensure a sufficient signal-to-noise ratio for laser spot detection while avoiding overexposure.

The imaging lens used is a Basler AG C11-5020-12M 50.0 mm focal length lens with a C-mount. It is designed for sensors up to 1.1 inches in size. The focal setting is adjusted to produce a sharp image at a distance of approximately 2 m, corresponding to the planned working range of the system. The iris is manually closed to a near-minimum aperture, estimated slightly below $f/16$, to maximize the depth of field. This adjustment ensures that the laser spot pattern remains in focus throughout the measurement range, including during small fluctuations in drone position during flight. The coordinates of the images from the camera are (u, v) .

3.3. Calibration

For the laboratory calibration procedure, a high-precision Jena Optics ZLM 500 laser interferometer (JENAer meßtechnik gmbh, Göschwitzer, Germany) was used to establish ground reference distances. This interferometer was aligned with a manual linear stage, enabling accurate control over axial displacement. The calibration was carried out by projecting the structured-light pattern from the laser and DOE onto a white planar target. The complete setup is depicted in Figure 5a. Following alignment and pattern projection, a calibration range of 1800–1930 mm was selected to ensure optimal sharpness of the DOE pattern under a fixed focus configuration. This approach represents the intended in-flight operation, where the optical system remains mechanically stable without the need for refocusing.

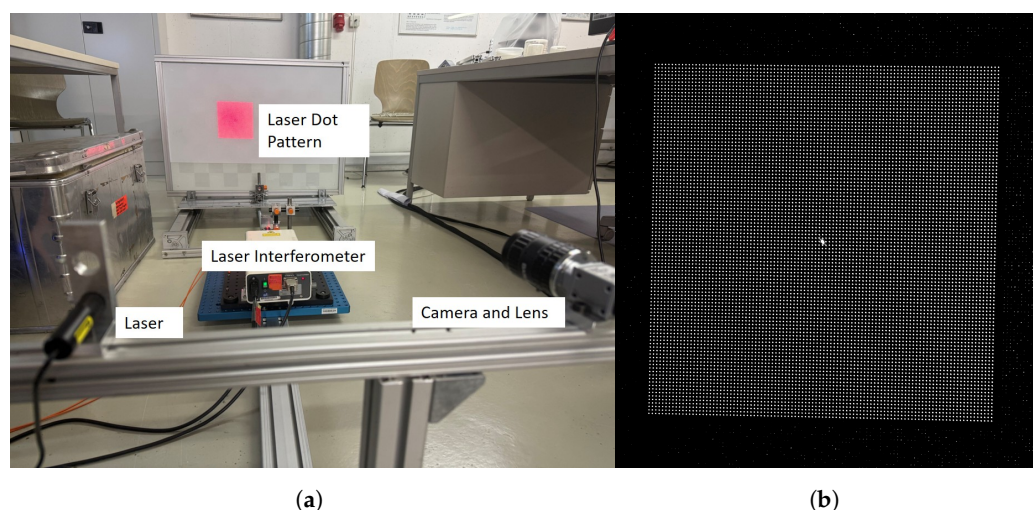


Figure 5. (a) The laser triangulation system during calibration with an interferometer as a reference. The laser projects a predefined pattern of 101×101 dots onto the target surface (b), which are recorded with a camera. Note the bright spot, which marks the center of the dot-matrix pattern. From that image, the sought distance d is calculated for each dot.

The DOE, mounted on the laser source, and the laser module were focused to project a sharp 101×101 dot pattern, with the center of the pattern precisely aligned in the calibration

plane. Image acquisition was carried out in a single shot in steps of 5 mm along the optical axis. Each image was then evaluated and assigned to its corresponding ground-truth distance to obtain the calibration curve v_L over d for each laser spot.

3.4. Measurement Object and Experimental Procedure

For validation, a polyurethane reference object was fabricated (see Figure 6). Its dimensions are 900 mm in width, 320 mm in height, and 50 mm in thickness. To generate a precisely defined surface topology, a stepped geometry was machined into the block by removing the material in three sequential passes. Each pass milled 1 mm of material across a 300 mm wide segment, resulting in a three-step structure. Each step increases in height by 1 mm relative to the previous one, creating a progressive elevation profile across the surface. The machining was carried out using a milling system with a nominal accuracy of 0.1 mm, ensuring geometric fidelity of the reference target. On one of its 300 mm surfaces, surface defects were created by boring holes of 10 mm and 5 mm width.

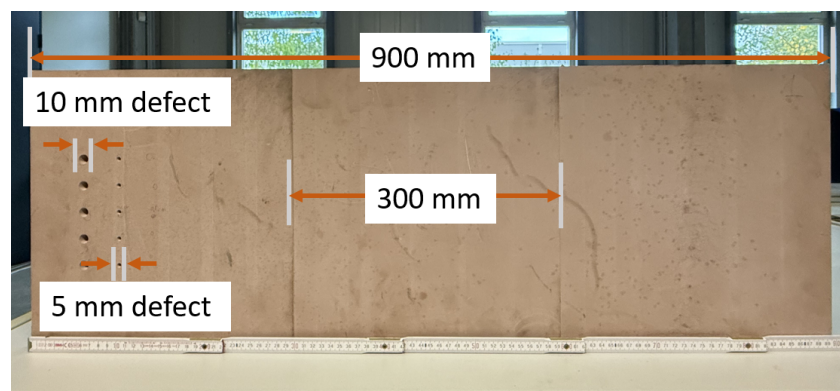


Figure 6. Polyurethane reference object (900 mm × 320 mm × 50 mm) featuring a three-step profile with 1 mm height increments per step. Surface defects in the form of 5 mm and 10 mm diameter holes are introduced on one 300 mm wide surface section.

Once calibration was complete, the measurement system was mounted on the drone for experimental evaluation. To characterize the system, measurements were first conducted in a laboratory environment with the drone fixed to the ground. The rotors were activated to introduce vibration effects under controlled conditions while maintaining a stabilized position without translational motion. Subsequently, in-flight experiments were performed. In-flight, the drone hovered at a distance of 1–5 m to 2 m from the measurement object, and the triangulation system was powered directly by the drone's onboard battery. Multiple images were recorded while the drone hovered in front of the measurement object. Recorded images with blur due to the motion of the drone were discarded manually, and the image with the sharpest projected dot pattern was selected for evaluation. Thus, the reported results correspond to valid measurements acquired within the defined calibrated interval.

3.5. Signal Processing

The workflow of the calibration signal processing procedure is shown in Figure 7. It was developed to extract the spot positions from 30 calibration images recorded within the calibration range of 1800 mm to 1930 mm. Each image contains 101×101 spots, from which each laser spot is detected and indexed, and this happens in three process steps. The first step is image pre-processing, which includes contrast enhancement, large-kernel edge detection to localize the matrix, and single-pixel erosion–dilation-based filtering to suppress secondary spots caused by the speckle effect. The second process step is the localization of the spot position. The center of each detected spot is determined using a

skewed Gaussian fitting algorithm. This algorithm determines an initial approximation of the center by using the center of gravity of the detected laser spot. Then, Gaussian fitting is performed to find the highest-intensity pixel around the initially determined center. The pixel with the highest intensity is assigned as the actual laser spot center. In the third process step, spot assignment ensures consistent indexing across all calibration images. Note that, in contrast to stripe pattern projection, the single-shot requirements in this application prevent the use of Gray code encoding, resulting in a limited range of unambiguity for point indexing. The signal processing framework is designed to ensure unambiguous spot correspondence for local surface height variations of up to approximately 4 mm between adjacent measurement points. The processed results, which include spot identifiers and spot center pixel coordinates, are stored in CSV files for the subsequent determination of the calibration curves. The data is acquired during flight and stored on the onboard computer, while the computationally intensive analysis and post-processing are performed on a ground-based computer after the flight.



Figure 7. A flowchart illustrating the signal processing sequence applied to the 30 calibration images.

For images acquired during laboratory and field measurements, the same signal processing pipeline used in the calibration procedure is applied. Each detected dot is interpolated from the established calibration curves. Based on this correspondence, a depth value d is assigned to each detected point according to its calibrated pixel position. The resulting set of point coordinates represents the reconstructed surface topology of the measurement object. This method enables direct generation of dense surface data from a single-shot image, without the need for sequential scanning.

4. Results

4.1. Achievable Measurement Resolution

The result of the calibration measurement is shown in Figure 8, with the laser spot at the center of the dot-matrix pattern used as an example. It shows the pixel displacement v_L of the laser spot over the distance d to the measurement object and exhibits an approximately linear response with a slope of 2.1 pixel/mm. While the triangulation principle is inherently non-linear, as described in Equation (1) and as shown in Figure 2, the measurement range is sufficiently narrow to justify a linear approximation. The slope of the plot indicates that an axial movement of 1 mm of the measurement object results in a shift of approximately 2.1 pixels on the image sensor; i.e., the calibration factor is 0.47 mm/pixel. Because the spot center position is localized with sub-pixel precision, and a conservative estimation for a feasible centroid position uncertainty amounts to 0.1 px [25], a measurement resolution of 47 μm seems, in principle, achievable under ideal measurement conditions. However, in the calibration experiment, the standard deviation of the 21 repeated measurements at a depth position amounts to 128 μm on average. Hence, the currently achievable measurement resolution in the experiment is 128 μm . While, due to speckle noise, the sub-pixel-resolution precision was decreased by a factor of three compared with the value initially expected, the measurement resolution is still considered sufficient to detect surface defects with a minimum size on the order of 1 cm.

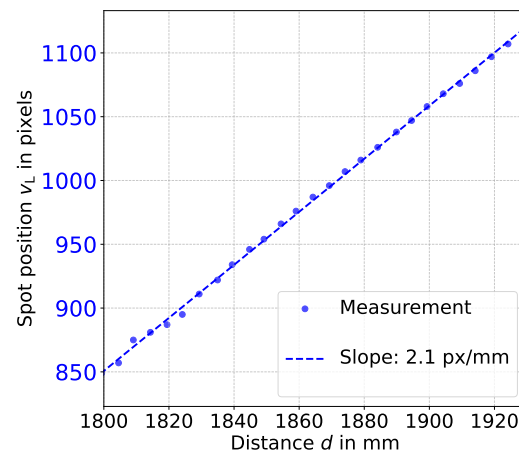


Figure 8. The result of the calibration for one of the 101×101 measurement points, as an example. The resulting calibration curve shows the extracted image coordinate v_L of the imaged laser spot over the distance d , where the distance to the measurement object was varied from 1800 mm to 1930 mm.

4.2. Measurement Uncertainty in Drone Environment

The uncertainty associated with sensor repeatability, as derived in Section 4.1, is $128 \mu\text{m}$. To assess the influence of rotor-induced disturbances on the measurement uncertainty, the calibration measurement was repeated with the triangulation system mounted on the drone and the drone's engines activated, while the drone was fixed to the ground. As a result of the vibrating drone environment, the sensor repeatability increased from $128 \mu\text{m}$ to $266 \mu\text{m}$. Hence, the measurement uncertainty associated with drone vibration is $233 \mu\text{m}$. On the one hand, the resulting total uncertainty is still at an acceptable level. On the other hand, it is important to note that the uncertainty component due to drone vibration is only relevant for measurements of absolute distance to the object's surface. Since the distance measurements of all points are equally affected, the effect of drone vibration on single-shot surface topography measurements—the focus of the present article—is negligible.

In addition to random errors (sensor precision), a systematic error (sensor accuracy) as a result of the calibration error contributes to the total measurement uncertainty. According to the residuals of the measurement data from the fitted curve shown in Figure 8, the residual's standard deviation amounts to $111 \mu\text{m}$. Thus, the combined standard measurement uncertainty is $170 \mu\text{m}$.

4.3. Drone-Based Field Measurements

For drone-based field measurements, the calibrated sensor system was placed as a payload on the drone. The measurements were performed while the drone hovered in front of the measured object. Due to the Global Positioning System-locked position hold, the inherent motion of the drone is substantially reduced. In addition, the single-shot imaging technique minimizes motion-induced disturbances. The axial and lateral resolutions of the measurement system are discussed in the following sub-sections.

4.3.1. Axial Resolution

To investigate the axial resolution capability, in-flight surface measurements of the measurement object were performed as described in Section 3.4 (see Figure 9).

The raw single-shot measurement result is shown in Figure 10a, where the expected object surface topography with a step of 1 mm is correctly resolved. Note that the relative distance between the two surface levels is displayed (i.e., the distance d_0 to one surface level is subtracted), because the focus of interest here is the inspection of the surface topography and not absolute distance measurements. The spatial standard deviation of the

measurement on each surface level amounts to $126\text{ }\mu\text{m}$, which is in excellent agreement with the sensor precision identified under non-flight conditions in Section 4.1. Hence, the influence of drone vibrations is indeed negligible, as already stated in Section 4.2. Here, the lateral resolution, i.e., the average distance between two adjacent measurement points, amounts to 1.8 mm . When reducing the axial resolution, for instance, by applying a 3×3 moving-average filter, the axial measurement resolution can be improved by a factor of 3. The spatially filtered measurement result is shown in Figure 10b, which now demonstrates areas with an axial resolution below $50\text{ }\mu\text{m}$ and thus below 5 % of the 1 mm height step. Note that lateral averaging works best in areas with high point densities. Therefore, currently, the standard deviation in the central area (high point density) is lower than in the outer regions, as low-contrast conditions lead to sparse point areas here. However, this demonstrates that axial and lateral resolutions can be balanced according to the application's needs. And it additionally proves that relative differences in surface topography height on the order of one millimeter are resolvable by means of the proposed drone-based laser triangulation system.



Figure 9. In-flight measurements on the measurement object.

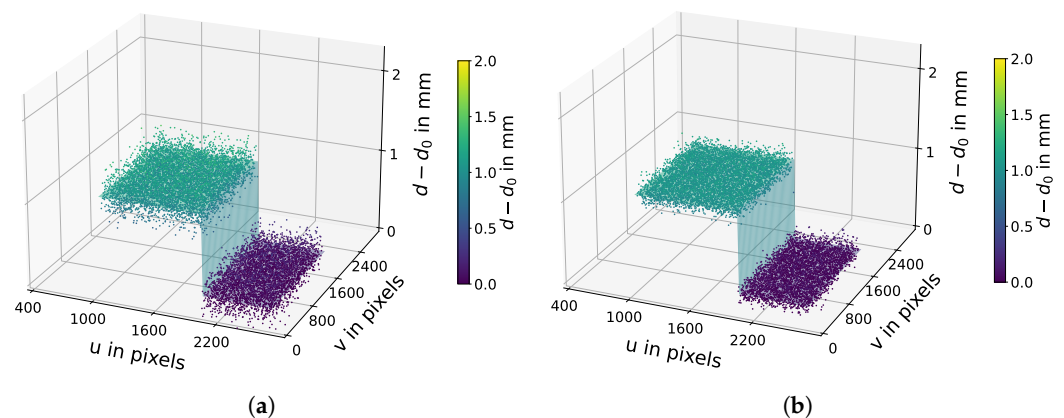


Figure 10. (a) The raw measurement result of the flying UAV-based laser triangulation system with 101×101 measurement points taken in a single shot, which successfully resolved the 1 mm step of the measurement object. (b) The measurement result after applying a spatial moving-average filter over 3×3 pixels, which improves the axial resolution to below $50\text{ }\mu\text{m}$.

4.3.2. Lateral Resolution

To evaluate the lateral resolution capability of the measurement system, a single-shot measurement of the measurement object was performed in the region of drilled holes with 10 mm and 5 mm diameters (see the description of the measurement object in Section 3.4). The raw camera image is shown in Figure 11a, which contains the laser spot images of the dot-matrix illumination pattern with a lateral spacing of 1.75 mm. At the object holes, laser spots also occurred, but they were discarded, as the point registration failed due to leaving the range of unambiguity. The corresponding laser triangulation measurement result is shown in Figure 11b. As expected, the circular defects with a diameter of 10 mm are clearly resolved, and the smaller, 5 mm defects still produce a distinct and measurable response in the measurement data. This demonstrates that the lateral sampling density of the current measurement setup is sufficient to capture surface features with sizes down to 5 mm. The demonstrated lateral and axial resolutions were obtained on a planar reference surface. For practical surfaces with stronger curvature or specular reflection, local changes in spot visibility due to occlusion and signal contrast are expected and will be addressed in future investigations.

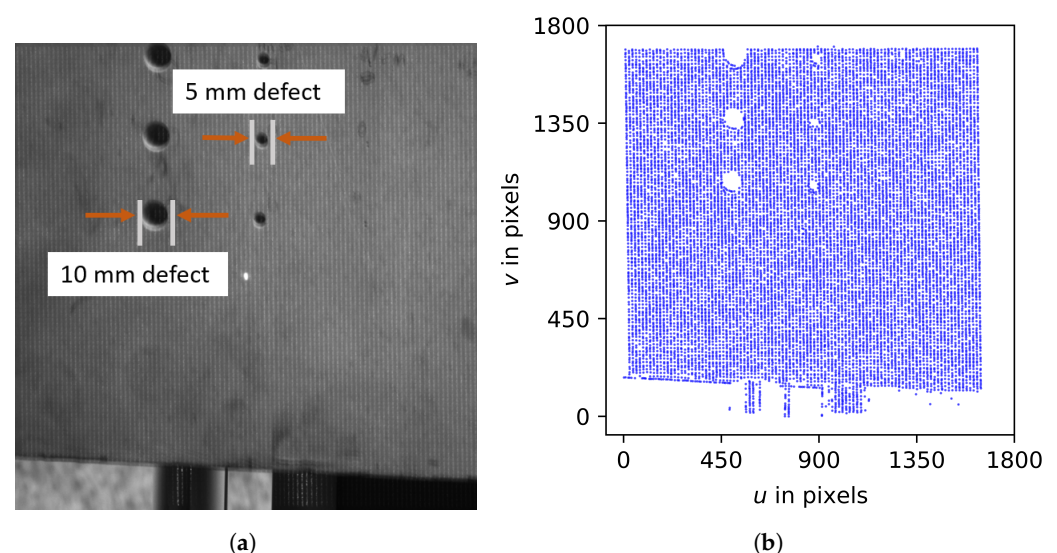


Figure 11. (a) A camera image taken during in-flight measurement of 10 mm and 5 mm defects on the measurement object, and (b) the laser triangulation measurement result of single-shot acquisition with the successfully resolved 10 mm and 5 mm defects on the measurement object.

5. Conclusions

This work presents the design, calibration, and characterization of a single-shot laser triangulation system integrated into a drone for the purpose of surface defect detection on hard-to-reach large-scale structures. The optical system, consisting of a laser and a DOE for creating a dot-matrix illumination pattern, as well as a high-resolution camera, was first set up, calibrated, and characterized under laboratory conditions using a Michelson interferometer as a reference. The calibration curve is almost linear within the working range of 1800 to 1930 mm, enabling depth estimation with a sensitivity of 0.47 mm per pixel, i.e., with sub-millimeter sensitivity. The combined standard measurement uncertainty of the system, which contains the uncertainty contributions from sensor repeatability and calibration, amounts to 170 μm .

The high-axial-resolution capability of the system was further demonstrated in an in-flight measurement experiment conducted outside. The results show that the reference step geometry of the measurement object with a step height of 1 mm is correctly resolved. Each step level shows a standard deviation of 126 μm , which exactly matches the axial

resolution capability determined under laboratory conditions. Thus, relative axial depth variations on the order of 1 mm are distinguishable with the drone-based laser triangulation system. On the other hand, unambiguous depth detection of adjacent measurement points is limited by the interspot distance. For the studied measurement setup, the maximum variation in surface height of two adjacent measurement points amounts to 2.3 times the interspot distance. Furthermore, the lateral resolution performance was verified through the successful detection of artificially added surface defects with diameters of 10 mm and 5 mm, indicating that the current spatial sampling density of 1.75 mm is sufficient to resolve local surface features with a lateral dimension larger than 5 mm.

As an outlook, future work will address point unambiguity, which occurs when local surface height variations exceed the uniqueness range of the calibration model. Strategies such as adaptive point association and multi-scale evaluation will be investigated. While the polyurethane reference material used in this study represents a polymer-based technical surface, differences in surface finish and reflectivity require further investigation under realistic application conditions. Future work will also extend the validation to surfaces with different optical reflection properties and different object geometries, since stronger specular reflections and increased speckle-induced intensity variations are expected to reduce spot contrast locally, and occlusion arising from curvature may reduce the detection rate.

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