OPTO-MECHANICAL COMBINATION OF A LINE SCANNING CAMERA AND A MICRO LASER SCANNER SYSTEM

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ABSTRACT:

Line scanning cameras are used in photogrammetric applications to record images with a very high resolution and a field of view up to 360° horizontally. In order to generate 3D information more than one image is required, which limits the flexibility at complex object geometries. On the other hand terrestrial laser scanner systems are used in numerous applications since some years as a versatile tool for recording 3D geometry in terms of 3D point clouds. For the analysis of the laser scanner data additional image information is often very useful for interactive modelling purposes and for automation of the analysis. Producers of terrestrial laser scanners therefore implement digital cameras to their laser scanner systems. This is mainly done by mounting a digital camera on the laser scanner. This approach requires an accurate orientation between both devices, and it makes the system bulky. Furthermore, the existence of occlusions due to different positions of camera and laser scanner is unavoidable.

The paper presents an approach, which combines the advantages of both, reliable 3D information of a laser scanner and high resolution image information of a panoramic camera in one single device. For this combination a concept of an opto-mechanical configuration was developed, where the laser scanner beam and the image information run through the same optical path. One important precondition is the use of a single silicon micro scanning mirror, which was courtesy of IPMS (Fraunhofer Institute for Photonic Mikrosystems) for the investigations. Both, the opto-mechanical integration and the use of a micro scanning mirror, allow for miniaturisation of combined camera and laser scanner systems. Furthermore, the components have a fixed orientation due to the compact construction and there are no occlusions, since both system components use the same optical path and record the same object elements.

The opto-mechanical system was simulated, whereby the parameters of the optical parts of the systems were optimized. Finally the simulated and optimized system was tested in terms of an experimental setup. Thus, the functioning of the system could be showed in principle. Future steps on the way to a combined measurement system are the integration of a signal analysis unit, in order to receive distance values, as well as the calibration of the system and the investigation of the accuracy potential.

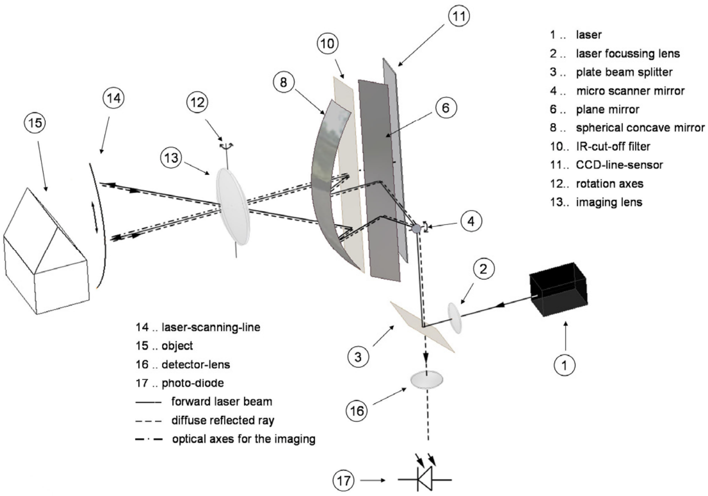

Figure 1: Optical path of a combined panoramic camera and laser scanner system

1. INTRODUCTION

Today laser scanners and digital cameras are well-established photogrammetric measurement instruments. While the analysis of analogue stereo-pictures is common practice for more than 100 years, computer based methods such as laser scanning and digital photogrammetry were developed independently in the past 15 – 20 years.
Laser scanning and digital photogrammetry are used to generate three-dimensional digital models of real objects, which appear in city modelling, documentation and protection of cultural heritage, creation of planning criteria or facility management as well as in the field of virtual reality and computer vision.

1.1 Digital cameras

In principle, there are two ways to acquire digital pictures as a basis for photogrammetric applications. While conventional camera systems are based on a solid state array sensor, line scanning cameras acquire the 2D image by a rotation of the entire camera head including the CCD-line sensor. The axis of rotation contains the second principle point of the imaging lens.
Line scanning cameras presently have a two to three times higher resolution than cameras with matrix-sensors. Thus, in most cases they are used for exacting photogrammetric applications. In addition, 2D images with a horizontal field of view up to 360° are characterized by very high accuracy, e.g. 0.2 pixel (relative precision 1:50'000) with the EYESCAN M3 panoramic camera (Schneider and Maas, 2004). This accuracy cannot be attained with a stitched multi-shot panorama image taken by matrix cameras.

In order to generate 3D information for a completely scanned 360° panorama at least three images recorded at different positions are required, which is time-consuming. At complex object geometries this approach limits the flexibility and is only feasible with static objects.

1.2 Laser scanner

Laser scanners sample the surface of an object point-by-point. The 3D-coordinates of every object point will be obtained by measuring the horizontal and vertical deflection angle of the laser beam and the distance information. Today, laser scanners are very popular for terrestrial industrial applications with lower requirements for resolution and colour information.
Due to quasi-randomised measurement points, it is difficult to detect edges of an object.
Furthermore, the dense point cloud does not conform to the used human vision and consequently the observation and interpretation during interactive actions on the computer screen is limited.
Therefore, some manufacturers of terrestrial laser scanners provide digital matrix cameras, which are capable of being adapted or attached to colour point clouds (Studnicka, 2004).

The advantage of laser scanners is the reliable, efficient and direct generation of 3D-data. Thus, a high level of automation of the data analysis can be achieved. Over the past years, the scanning velocity was increased and reaches values in the order of magnitude of around 100.000 points per second.

1.3 Combined measurement instrument

An optimal solution for close-up range photogrammetry might be represented by the combination of the two above-mentioned methods. The aim is to compensate the disadvantages of one system with the advantages of the other one in order to create a measurement system, which records simultaneously high-resolution colour images as well as reliable, direct, fast and pixel-synchronic depth information.

It is state-of-the-art to benefit from the advantages of each method by a fusion of separately recorded data sets. Due to the time lag, the fusion of the data sets to digital 3D-models with a sufficient accuracy is only applicable to absolute static objects. In this context algorithms and software for the combined and automated analysis of panorama pictures and laser scanner data as well as for the supported and combined calibration were investigated (Reulke, 2004).
The potential of the combination of laser scanner and line scanning camera has not been utilised with these investigations.

The only way to efficiently record distance information and imaging data is a fixed combination of the two setups including the related beam paths and opto-mechanical components.

The aim of this project was to develop a combined and compact camera and laser scanner system on the basis of the line scanning camera EYESCAN M3 metric without obscuration of the image sensor but under the perpetuation of a maximal vertical scanning range of the laser scanner.
The technical challenge was the integration of the laser scanner with its opto-mechanical components into the imaging light-path of the line scanning camera. The basic idea was to use the imaging lens as a combined lens for the image and distance data acquisition.

2. OPTICAL DESIGN

2.1 Basic design approach

As aforementioned the role of the objective is twofold. It ought to act as a lens for the photogrammetric image acquisition and as a laser scanner lens. These two properties should not affect each other adversely. The high photogrammetric image quality must not be degraded by insertion of additional optical components needed to couple in the laser beam.

A second problem is related to the largeness of the required scan angles. Unlike in ordinary laser scanner systems it is unfavourable to put the scanner device in the rear focal plane of the objective. In this case for large angles the laser beam misses the lens completely (Figure 2). In order to exploit the full field of view the deflected laser beam has to pass through the centre of the exit pupil of the imaging lens for any scan angle. Since the exit pupil is the image of the aperture stop this requirement holds for the centre of the stop, too.

To achieve a sufficient large depth of field the laser beam should be collimated in object space for arbitrary scan angles.

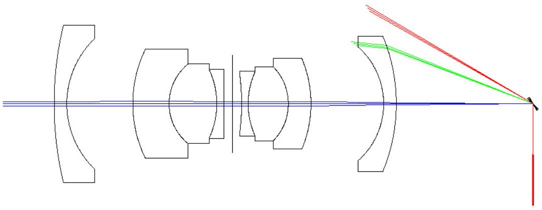

Figure 2: Micro scanner device located in the rear focal plane of a lens (blue 0°, green 21°, red 30° optical deflecting angle)

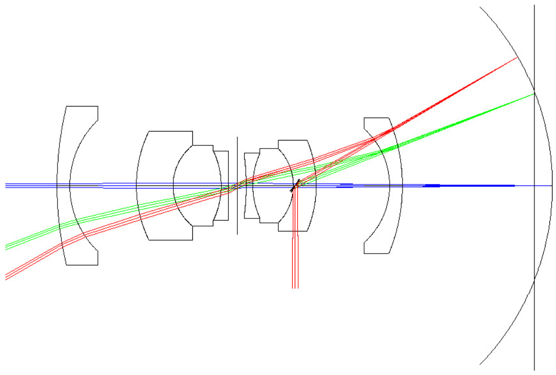

Figure 3: Use of a concave mirror acting as a field lens (blue 0°, green 21°, red 30° optical deflecting angle)

The above-mentioned requirements could be met by placing a field lens near the image plane of the objective. The laser light would be redirected into the objective without seriously affecting the image. Unfortunately ordinary refractive lenses cannot be employed for this purpose. Due to the large scan angles of ±30° the speed of this lens would have to be extraordinary high. A rough estimation shows that the corresponding f-number is less than 0.3. It is impossible to manufacture such a lens.

The basic idea is to replace the field lens by a concave mirror which images the micro scanner device into the centre of the exit pupil. The corresponding magnification depends on the maximum scan angle needed for the application. In case that the half field of view of the objective and the maximum scan angle of the micro scanner device are approximately the same, a 1:1 magnification is the best choice. Hence, both the deflecting unit and the exit pupil are located in the centre of curvature of the concave mirror. In this way the light rays hit the surface of the mirror at a right angle and travel the same way back.

To avoid obscuration of the image sensor the concave mirror has to be placed alongside the imaging light path. By use of a chromatic beam splitter the laser light is separated from the rest of the visible spectrum.

To allow for collimation in object space the laser must be focused in the focal plane of the objective. However, without the aid of additional optical components the focal point of the moving beam lies on a sphere. In order to keep the design as simple as possible the light beam is focused on the concave mirror. Due to the increasing difference from the focal plane the collimation gets worse for off axis image points. The curvature and position of the mirror is chosen so that the average collimation error across the field of view is minimized (Figure 3).

2.2 Optical path in detail

A sketch of the optical path is shown in figure 1. The whole setup can be divided into two parts. Part one contains the laser source as well as the photo detector needed to receive the reflected laser light. Part two consists of the imaging lens and some additional optical components.

The light emerging from the laser diode (1) is focused on the concave mirror (8) by a lens (2) and impinges on a plate beam splitter (3). Here 20% of the light is reflected towards the deflecting unit whereas the remaining 80% is transmitted and subsequently absorbed by a light trap. After deflection by the scanner unit (4) the laser beam passes through a group of two mirrors (6, 8) and one interference filter (10). Since the space behind the filter is occupied by the image sensor (11) as well as the corresponding electronics a fold mirror (6) is required. The role of the concave mirror (8) has been described in the previous paragraph. The main function of the interference filter (10) is to block NIR light during image acquisition. In addition it acts as a chromatic plate beam splitter to separate the laser beam from the imaging light path. The wavelength of the laser light is chosen so that it is reflected by the filter. The light then travels through the objective (13) and impinges on the object (15) where diffuse reflection occurs.

Together with some ambient light necessary for the photogrammetric image acquisition it passes through the optical system in reverse order. At the filter (10) the visible part of the light is transmitted whereas the laser light is directed towards the detector (17).

Due to the tilted optical components, the deflected laser rays do not reach the concave mirror centrically. The result is a deviation of the virtual intersection in the centre of the aperture plane in x-direction and a curved scan course in object space (see Figure 4).

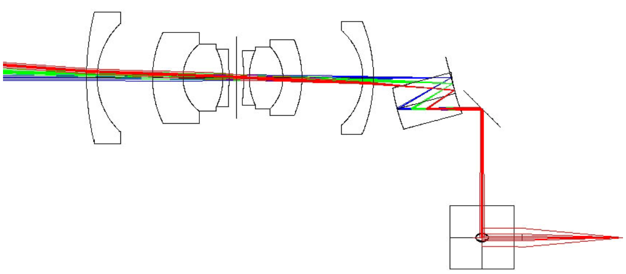

Figure 4: curved scan course

Hence, the distance measurement and the image acquisition of the same object-point will in general not be simultaneous. In a combined measurement setup this aberration could be taken into consideration by calibration of the two subsystems. A second possibility of aberration reduction is the symmetrical design of two identical oppositely tilted concave mirrors.
The same optical correction effect could be achieved with a synchronized rotation of the deflecting unit about the vertical-axes. However, this approach demands a higher electronic input.

3. EXPERIMENTAL SETUP

3.1 Laser scanner deflecting unit

It is well known, that ordinary laser scanners are large and heavy instruments. Like the imaging lens for line scanning cameras, the deflecting unit is an essential part in laser scanners. Today, the common way to deflect the laser-beam in vertical direction is to use large polygon or rotating mirrors. The miniaturisation of all optical and mechanical components is an important precondition for a compact and powerful combined measurement instrument. With micro-actors like thin-film actors made of shape memory alloy (Kapp, 2004) or silicon micro scanner mirrors, miniaturized scanning devices are available.

At the Fraunhofer-Institute for Photonic Microsystems (IPMS) a compact plug and play solution with a micromechanical scanner mirror and the driver circuit on one board (see Figure 5) was developed. This micro scanner module should be used in the experimental setup.

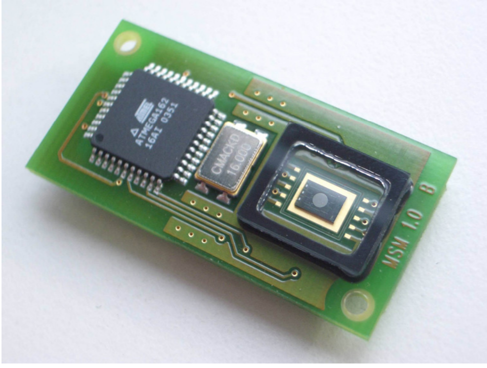

Figure 5: Plug and Play micro scanner mirror module

The resonantly driven micro scanning mirrors were designed for a large field of application with periodically one or two dimensional deflected laser light e.g. barcode and symbol reading, object measurement, projection, endoscopy, laser marking, NIR and IR spectroscopy.
They consist of a mirror plate which is suspended respectively by two torsional springs for every scan direction and of two driving electrodes.

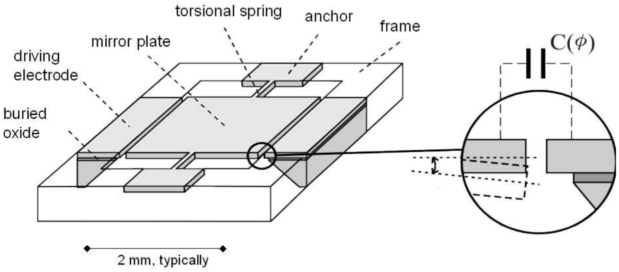

Figure 6: schematic 1D micro scanning mirror

The actuation principle makes use of a capacity variation during the oscillation. With increasing deflection angle of the mirror plate the capacitance is decreasing. Applying a voltage between the electrodes an electrostatic torque is generated pulling the plate towards its rest position. To prevent a deceleration of the plate movement after passing the rest position the voltage between the electrodes is switched to zero. At the maximum deflection angle the voltage is switched on again (Schenk, 1999; Schenk, 2000).
Micromechanical scanners are available with circular or rectangular mirror-surfaces. The dimensions of the mirrors cover the range from 0.5 mm up to 3.0 mm in side length or rather in diameter. It will achieve an optical deflection angle up to ±30° at a driving signal of 20 V. The IPMS have already produced devices with scan frequencies from 150 Hz up to 32 kHz.
For the application of the combined measurement system a one-dimensional micro mirror with a large scan range and a large mirror area is needed.

3.2 Opto-mechanical design

As described in chapter 2.1 the experimental setup consists of several modules (see Figure 7).
The mount of the imaging lens (D) contains of standard-parts of the “EYESCAN M3 metric”. The IR interference filter (10), the fold mirror (6) and the concave mirror (8) are mounted to one mechanical part (C) that satisfies the criteria of stress relieved mounting and closed tolerances. The back side is designed to be the focal plane of the objective and thus the mount of the CCD-sensor. A further module (B) consists of the laser source, an adjustable plate beam splitter as well as the light trap and the gimbal-mounted micro scanning mirror module. The detector module (E) is composed of the photo detector, a focusing lens and mountable narrowband interference filter to separate the laser wavelength from the remaining reflected NIR light.
Besides the mechanical design of the experimental setup a detailed simulation to define the optimal curvature of the

concave mirror and distances between the optical components was required.

The line scanning camera “EYESCAN M3 metric” is normally equipped with the imaging lens "Rodenstock Apo-Sironar digital HR 4/60", which is designed for special applications with extremely high resolution CCD – sensors /[6]. In spite of the unacquainted data sheet with the whole optical design of this lens, the simulations were alternatively carried out in two steps.

First, the high-resolution imaging lens 5.6/47 made by Carl Zeiss Jena (GDG) with a known optical design was used to verify the general design-rule of the optimal radius for the concave mirror. For this purpose only the position of the exit pupil and the maximal field of view of the imaging lens are needed. With equation (1) the collimation error can be minimized.

$$R_{opt} = \frac{l_{EP} + BFL}{2}\left(\frac{1}{\cos\frac{\alpha}{2}} + 1\right) \qquad (1)$$

where R_{opt} = optimal radius
l_{EP} = position of the exit pupil behind the last lens surface
BFL = back focal length
α = full field of view

Thus, theoretically every objective has its own specific concave mirror in at a defined total distance from the last glass-air-interface of the imaging lens.

Unfortunately, the field of view of the Zeiss Jena lens is not ideal for an application with the line scanning camera “EYESCAN M3 metric”. Due to the short back focal length there is not enough design-space for mounting the concave mirror without obscuration.

However, it provides the opportunity to investigate the aberrations of the laser beam after travelling through the imaging lens.

In the second simulation, the Zeiss Jena lens was replaced by the Rodenstock lens characterised by the parameters for the exit pupil. Together with the corresponding concave mirror and the mechanical dimensions of the whole deflection-unit the optimal distances between objective, IR-interference-filter, concave mirror, fold-mirror and the scanning mirror could be obtained.

The distances between the modules were assigned to the base plate (A) with bearing surfaces for the exact and isogonic mounting of the lens panel (D), source-deflection-unit (B), detector module (E) and the beam-path-separating-unit (C).

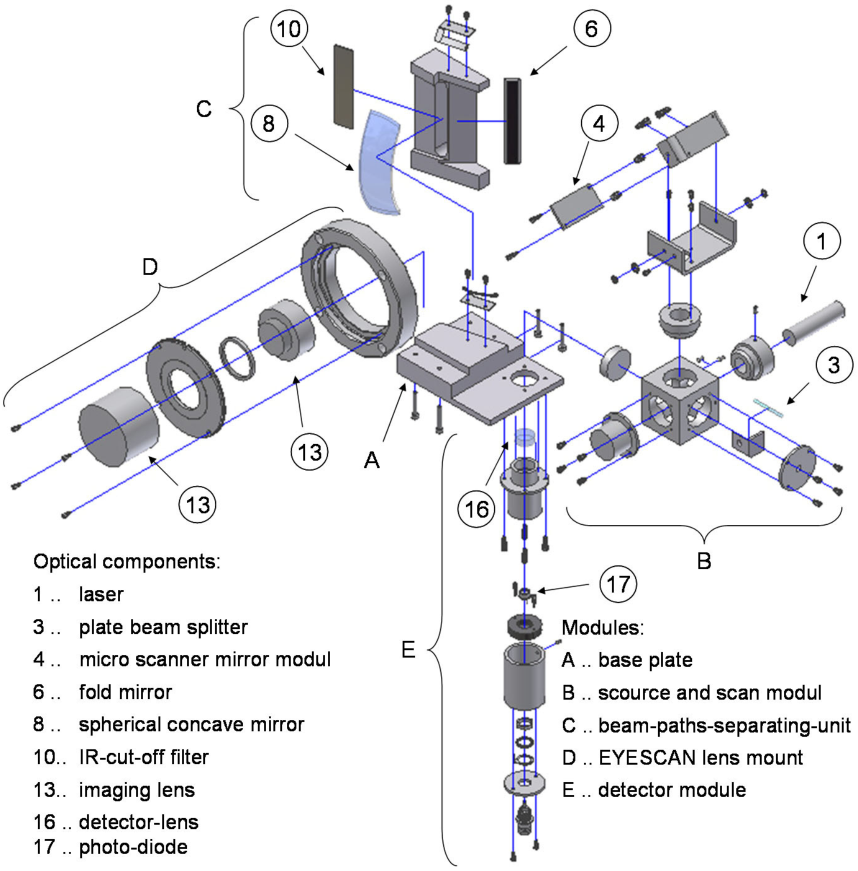

Figure 7: Exploded view

3.3 Initialisation of the experimental setup

With the help of the beam splitter plate and the gimbal-mounted scanner mirror module the alignment of the laser scanner beam path proved to be unproblematic. As predicted by the first simulation, the laser beam has a curved scan line at the object.
However, the aberration caused by the collimation error was not significant.
In first experiments with a simple silicon photodiode and a laboratory transimpedance amplifier, it was possible to detect the diffuse back reflection. With an avalanche photodiode and a special amplifier it would be possible to get a ten times higher sensitivity of the system.

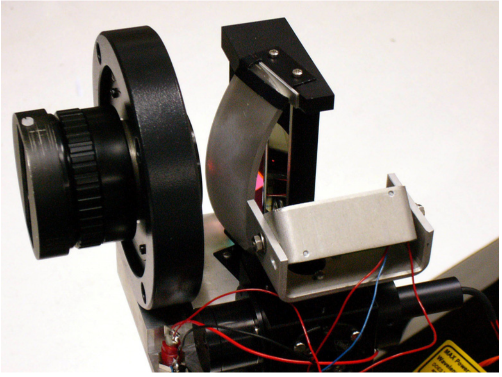

Figure 8: Experimental setup

4. FUTURE PROSPECTS

The further step is the design of a sensitive electronic signal analysis unit, in order to create depth data. Additionally, the development of a simultaneous calibration method and the investigation of the accuracy potential are on schedule.

5. CONCLUSION

Due to the increased time-efficiency, high resolution and colour accuracy, a combined measurement head consisting of a line scanning camera and a laser scanner would open new market segments in application areas, where nowadays the generation of high quality 3D object models are considered as too cost-intensive.

This paper presented the combination of the beam paths of both photogrammetric measurement methods, from the basic design approach to a compact experimental setup. It was succeeded in using a concave mirror in field lens function and a micro scanning mirror module, whereas the mirror was imaged with a 1:1 magnification into the aperture plane of the imaging lens.
With detailed simulations a lens-specific concave mirror and optimal distances could be defined for the experimental setup. Thus, the present aberrations caused in principle were minimized.

The experimental setup shows impressively the feasibility to integrate all components for a laser scanner into the back focal space of the line scanning camera "EYESCAN M3 metric".

All innovative solutions resulting from this project are applied for a patent.

6. ACKNOWLEDGEMENT

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The micro laser scanner module, Figure 6 and Figure 5 courtesy of Fraunhofer Institute for Photonic Microsystems (IPMS).

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