On Using Off-the-Shelf Micro Projectors for 3D Metrology

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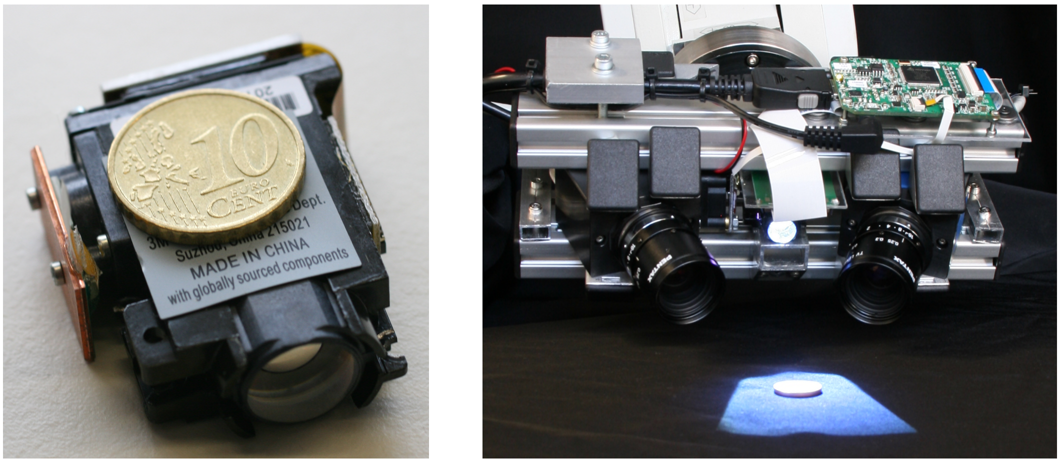
Abstract
Modern projectors offer sufficient light intensity, contrast and resolution to perform highly accurate 3D measurements on a large variety of surfaces by projecting coded patterns observed by cameras. Yet, for mobile measurement systems or inspections of specimen which are hard to reach, common projecting devices are often too heavy and too bulky.
Recently, a new projection technology has emerged, employing a reflecting Liquid Crystal Display (LCD) panel called Liquid Cristal on Silicon (LCoS) which allows to build small and light micro projectors. These new devices have a low power consumption and are comparatively cheap. Since no previous experience with these devices for metrology applications is available, an off-the-shelf micro projector is evaluated regarding its capability in a structured light setup.

1 Introduction

In computer vision, 3D reconstruction using stripe projecting devices is a popular technique. Especially in industrial measurement applications, structured light is a common tool to inspect surfaces of various samples.
Existing devices, which employ LCD panels or digital micromirror devices (DMD), are well-established in 3D metrology systems. On the one hand, they are capable of performing structured light regarding light intensity, resolution and contrast. On the other hand, DMD or LCD based sensors with a size of at least $150mm \times 50mm \times 100mm$ and a weight of more than 1kg, are not suitable for mobile or robotic applications. Here, a compact, light and power efficient measurement sensor is desirable.
Within the last years, a new technology called *Liquid Cristal on Silicon* (LCoS) has emerged. This technology allows the production of small and cheap projecting units for pocket beamers and mobile phones. Recently, the first micro projectors were commercially available. The big advantage of these devices besides size and weight is the fact that they have a low power consumption which even permits to run them in battery mode. One big drawback of available pocket beamers is the poor native resolution.
Until now, no experiences with micro projectors used in computer vision are available. In this work we evaluate the performance of an off-the-shelf pocket projector in a compact structured light setup for 3D reconstruction (see Figure 1).
Related work on 3D reconstruction using structured light is described in Section 2 and the reconstruction principle is sketched in Section 3. A brief overview about projector technology of DMD and the newer LCoS devices is explained in Section 4. An elaborate analysis of the projector's switching frequency, temperature caused effects and its capability in a structured light setup are presented in



(a) LCoS micro projecting unit.

(b) Experimental structured light setup with stereo cameras and a micro projector inspecting an object.

Figure 1: Compact prototype of a structured light sensor using a micro projector with LCoS technology as projection unit.

Section 5.

2 Related Work

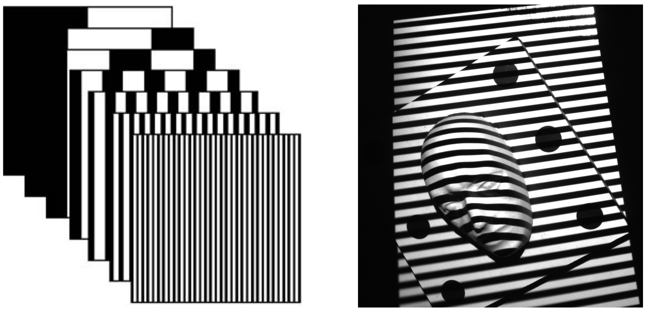
At the moment, several commercially available optical 3D measurement systems exist. An overview about existing systems is presented in this Section.
The *Fraunhofer Institute for Applied Optics and Precision Engineering* developed a dedicated 3D measurement system called *Kolibri ROBOT* based on structured light. The system is non-stationary and can be carried by an industrial robot arm. Measurement areas of $460mm \times 350mm$ can be inspected within 3-5 seconds and an uncertainty of 25μm [5].
A miniaturized version of the *Kolibri ROBOT* is the *Kolibri CORDLESS*, a measurement system with the size of a shoebox and a weight of about 1kg. The sensor consists of a projecting unit and two cameras and offers a hand-held operation mode with a WLAN connection to a stationary base unit, permitting the reconstruction of areas which would be inaccessible for common systems. The measurement of a single sequence can be done within 0.25 seconds in a measurement area of $220mm \times 170mm$ and an accuracy of 50μm-150μm [4].
A competitive product, the *z-Snapper*, is offered by *Vialux*. A single camera and a LED projector using the DMD technology (see Section 4.1) is used to perform 3D measurement procedures with structured light and a phase shift algorithm as explained in Section 3. The sensor is able to run in battery mode and exhibits an accuracy of 20μm-50μm in a field of view of 350mm [11].
Another small 3D sensor based on the structured light principle is the ATOS system with a dimension of $490mm \times 300mm \times 170mm$. A variable measurement area from $150mm \times 150mm$ to $2000mm \times 2000mm$ can be inspected within 2 seconds. About 4 million points are sampled with the area resulting in a point distance of 0.07mm-1mm [3].
The *MiniRot-Kombi* system from *ABW* is a projector-camera measurement sensor using fringe projection. It generates 3D data within one second over a measurement area of $600mm \times 400mm$. The projector's light source is a 150W halogen bulp. The sensor's dimension is $75mm \times 200mm \times 600mm$

and its weight is 7.4kg [1].

3 Structured Light

Structured light is a 3D computer vision reconstruction method using one or more cameras and a projector. In [10], Salvi gives an extensive overview of existing techniques. Depth information of surfaces can be gathered by consecutively projecting known patterns onto objects while observing them with cameras (as shown in Figure 2(a)). Point correspondences between the projector and the observing device can then be extracted by calculating a code for each observed pixel.

In a calibrated camera-projector setup, each image pixel is intersected with the projector pixel column or row uniquely identified by the pattern code. The limiting factor regarding reconstruction accuracy in this case is usually represented by the projector's resolution. Therefore, sub-pixel methods as explained in [2] can be applied using phase shift procedures in such a way that the effective resolution can be reduced to $1/28$ of the physical resolution. According to [6], a reduction to $1/64$ of the actual line width is possible.



(a) Structured light stripe pattern sequence as shown in [10].

(b) Projected stripe pattern on an object as observed by a camera.

Figure 2: 3D reconstruction using structured light.

4 Technology

State-of-the-art projectors employ a variety of technologies such as static projections, *Liquid Crystal Display* (LCD) panels, *Digital Micromirror Devices* (DMD) or recently the *Liquid Crystal on Silicon* (LCoS) panels. In this section, the main principles of DMDs (as mainly used for 3D metrology tasks) and the novel LCoS projectors are explained.

4.1 Digital Micromirror Devices

A well-established projector technology uses *Digital Micromirror Devices* (DMDs). This principle is also known as *Digital Light Processing* (DLP) and is a reflective display technology consisting of an array of micro-mirrors representing projector pixels. According to [9], images are created by redirecting light beams (usually originating from a halogen lamp or recently from an LED) through the projector's lens onto the projecting surface (see Figure 3). Depending on the chip resolution, the mirrors on the array have a size of 10-16 microns and can be tilted from -12 degrees to 12 degrees

separately within a few microseconds. Constantly switching each mirror at a frequency of several kHz and varying the duty cycle permits the control of the pixel's intensity by directing the beam of light to the projector's lens or into a light trap (which *turns off* the light for a certain pixel) [8].
The generation of colored images can be achieved by using either a color wheel with a single DMD

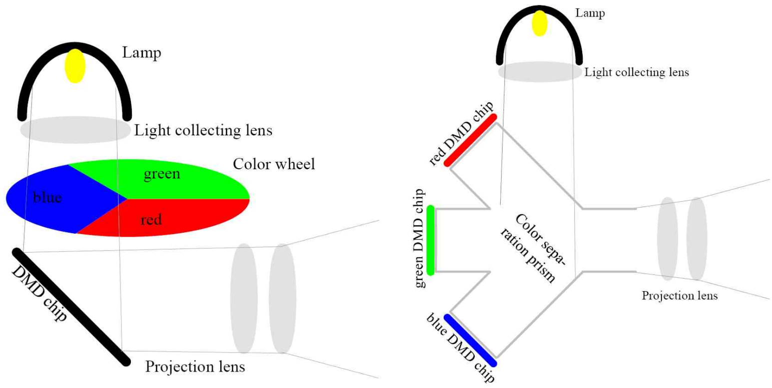


Figure 3: Schematic DLP technology with a single chip DLP unit in combination with a color wheel (left) and a three-chip architecture for RGB (right) as illustrated in [9]. The DMD chip, consisting of an array of tilting mirrors, is able to control light intensities by redirecting beams of light either to a heatsink (to absorb intensity) or to the projection lens.

or by using three DMDs in combination with a prism-based color separator. When using only one DMD, light is absorbed by the color wheel. For that reason, projectors using three DMDs exhibit higher light intensities but usually are more expensive and bigger in size. In general, DMD projectors offer good image quality regarding contrast and light intensity. The projected images tend to be very crisp because of a very narrow pixel arrangement on the chip compared with LCD panels and the hardware does not degrade after long term operation. A disadvantage of using a single DMD device is the weak color saturation and the appearance of rainbow effects caused by the rotating color wheel.

4.2 Liquid Crystal on Silicon Projecting Units

Recently, the *Liquid Crystal on Silicon* (LCoS) technology (which is also known as *Direct-driven Image Light Amplifier* or short D-ILA) used for projectors became popular. Actually, this principle already existed for several years but lately micro projecting units were developed which can be used in mobile phones or as pocket beamers.
Instead of tiny mirrors that are used to reflect light as explained in Section 4.1, a liquid crystal display is applied on a reflective mirror layer.
As illustrated in Figure 4 according to [9], images are created by redirecting a light source (usually an LED) through a *polarized beam splitter* (PBS) onto the LCoS panel. Each pixel on the panel can be switched to a transparent mode, reflecting light, or turned off to an opaque mode.
Alike DLP projectors, single panel solutions and three panel designs (for RGB) are available for the LCoS principle. For lack of space, a single LCoS chip is provided for micro projectors only. In that case, to produce color, an LCoS chip is used which provides micro color filters by dividing each pixel into three sub-pixels (RGB) [7].
The big advantage of this technology is the possibility to build extreme small and light micro beamers. Additionally, the power consumption of LCoS panels and LEDs is comparably low - pocket projectors even run in battery mode. A disadvantage of this principle is that contrast and light intensity is also low in micro projectors.

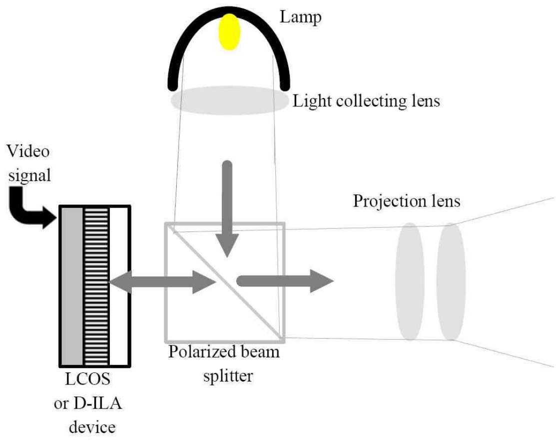


Figure 4: A single LCoS projection unit according to [9]. The LCoS chip consists of a reflective liquid crystal array capable of switching each pixel between transparent and opaque to control the reflected light intensity.

5 Evaluation and Experiments

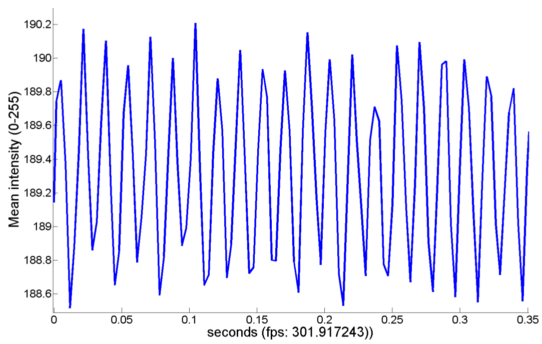
In order to evaluate the capability of micro projectors in a structured light setup for industrial measurement applications, several experiments are conducted. Generally spoken, a projector used for structured light has to fulfill some requirements concerning signal quality, signal stability, projecting speed, light intensity and contrast on varying surfaces. For the purpose of long-term operations, heating aspects have to be considered as well.
In this section, an off-the-shelf micro projector of the type *3M MPro 110* (see Figure 1(a)) is analyzed regarding its signal characteristics, speed in switching signals between the minimal and maximal light intensity, its long-term operability, its brightness and contrast.

5.1 Signal Quality

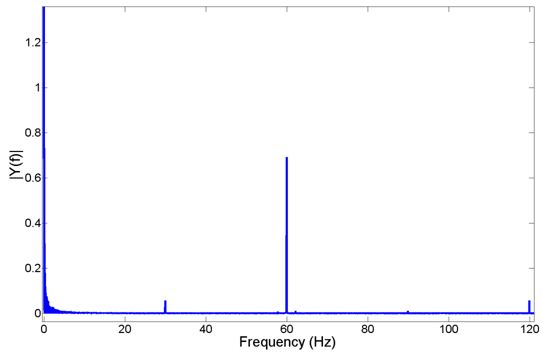
In a first step, the projector's signal quality is analyzed. This is done by observing a steadily projected gray value on a planar surface with a grayscale CMOS camera. Image patches of 16×16 pixels on the center of the beamer's projection area are acquired at a framerate of about 300 frames per seconds. The mean gray value of the image patch is stored for each received frame and is analyzed over time. As illustrated in Figure 5.1, a signal oscillation can be observed.
The signal oscillates with a 60 Hertz frequency, leading to the assumption that this effect is caused by the projector's refreshing rate. The signal's amplitude may vary depending on the currently projected gray value and time as discussed later.
In order to receive a stable signal, an average filter over the length of the fivefold 60 Hertz oscillation should be computed. When using the micro projector within a structured light setup, this averaging can be done implicitly by using an exposure time of at least 83ms for the image acquisition of projected patterns.

5.2 Switching Speed

Since the structured light procedure requires the subsequent projection of varying stripe patterns, switching times between patterns are crucial for the duration of the entire 3D reconstruction. The faster frames can be projected, the shorter the reconstruction process duration. This is of utmost importance for two reasons. Firstly, accurate measurements can only be done if there are no vibrations



(a) Periodical oscillation observed over time.



(b) Signal in frequency spectrum after a fast Fourier transformation.

Figure 5: Analysis of a steadily projected gray value with a CMOS camera at a framerate of about 300 frames per second. The mean value over a 16×16 pixel patch is plotted over time as shown in Figure 5(a). After a Fourier transformation (see Figure 5(b)), a frequency of 60 Hertz, the projector's refresh rate, is clearly visible.

or movements that could change the relative position between the sensor and an object to inspect. Secondly, industrial measurement tasks usually require tight cycle times since each lost second is critical.

To find out the projector's ability of switching patterns concerning speed, a high-speed CMOS camera is installed, directly looking into the projector's lens such that the projector's dynamic range is observable.

While grabbing 10k frames with the CMOS camera at 2137 frames per second and with a patch size of 16×16 pixels, a black-white sequence is projected. A delay of 0.04 seconds between switching the projected pattern from maximum to minimum intensity seemed to be sufficient for the projector to reach its saturation level. Each acquired image patch is averaged and a mean gray value of the projected light intensity is stored. Figure 6 schematically illustrates the projection of a black-white-black sequence and defines the nomenclature in the following.

An analysis of the gathered data showed that the mean rising time t_{rising} takes about four times longer than the mean falling time $t_{falling}$. A detailed summary of the experiments on the switching time can be found in Table 1. Switching from the projector's minimum to its maximum intensity ap-

Attribute	mean	std. deviation
gradient g_{rising} [gray value]	22.2380	0.3402
gradient $g_{falling}$ [gray value]	-62.3420	4.1834
A [frames]	2.5000	2.6771
B [frames]	33.2805	3.6819
C [frames]	1.3864	0.2803
D [frames]	5.4248	0.5604
t_{rising} [frames]	46.2800	3.6574
$t_{falling}$ [frames]	10.8000	0.7071

Table 1: Summary of the experiment on turning the projected pattern from the projector's maximum intensity to its minimum intensity with a delay of 0.04 seconds between the switching. An amount of 10k points are sampled with a CMOS camera at a framerate of 2137 frames per second. The projected signal is subsequently switched 27 times from black to white. The nomenclature is defined according to Figure 6.

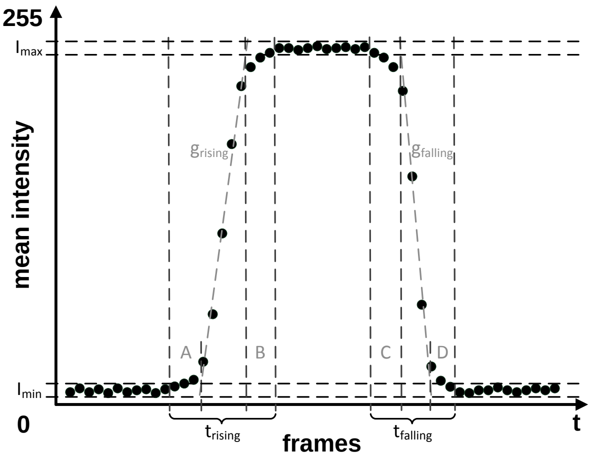


Figure 6: Schematic illustration of a projected black-white-black sequence observed with a CMOS camera at a framerate of 2137 frames per second. The mean values of a 16×16 pixels patch are plotted as dark dots over time. Gray values I_{max} and I_{min} represent a 3σ threshold around the mean values of the projector's saturation level. The lines g_{rising} and $g_{falling}$ describe the linear rising and falling edges between the saturated levels of the projector, where the gradient of adjacent points is larger than a threshold. Regions A, B, C and D are denoted as the periods lasting between the saturated levels and the regions where a linear rising and falling could be observed.

proximately lasts 21.7ms. The change from the maximum to the minimum intensity is done in about 5.1ms. These delays must be considered when using the micro projector in a structured light setup to avoid observing an unstable signal.

5.3 Contrast

When a projector is used for structured light, contrast is a quite important attribute for the segmentation of stripes in the reconstruction procedure. Especially when performing structured light with phase shift, contrast between fine stripes is crucial. In an experimental evaluation, the contrast signal which can be observed with a CCD camera is investigated under stripe projections with varying width.

A structured light setup is built with a 2.5 megapixels CCD gray scale camera and the micro projector sharing a field of view of about $50mm \times 30mm$. For the setup's contrast evaluation, stripe patterns with varying stripe thicknesses are projected and an image is acquired with the camera and sufficient exposure time to suppress oscillation effects as mentioned above. Then, the inverted pattern is projected and grabbed with the camera. A differential image between the regular stripes and the inverted stripes is computed to receive the observable intensity difference for each pixel in the image. This procedure is repeated 30 times for 9 different stripe patterns. Each mean signal and its noise is analyzed. Figure 7 shows a section of the horizontal profile representing the mean signal and the 3σ boundary when observing stripes at the finest resolution used during the structured light procedure. The mean intensity difference for patterns width a thickness of 2 projector pixels is 41.47. Experiments show that the mean intensity difference of broader stripe patterns even rises up to 205.8. Signal noise only exhibits a mean of 1.66 to 2.1 gray values for the varying stripe resolutions. This leads to the assumption that contrast quality is sufficient for structured light using binary patterns and noise does not seriously interfere measurements, even for fine stripe resolutions.

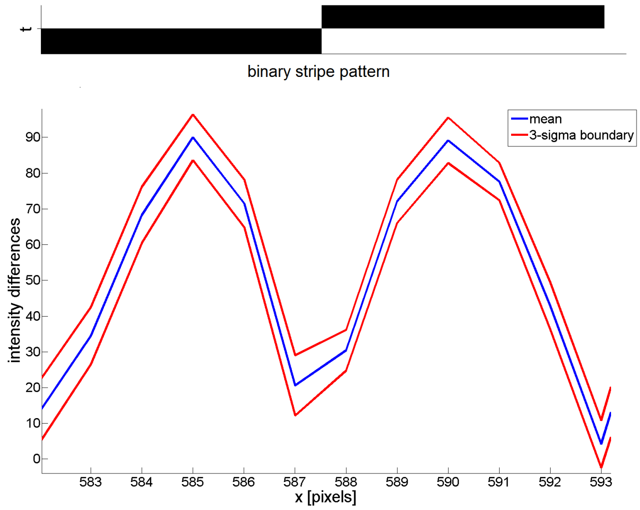


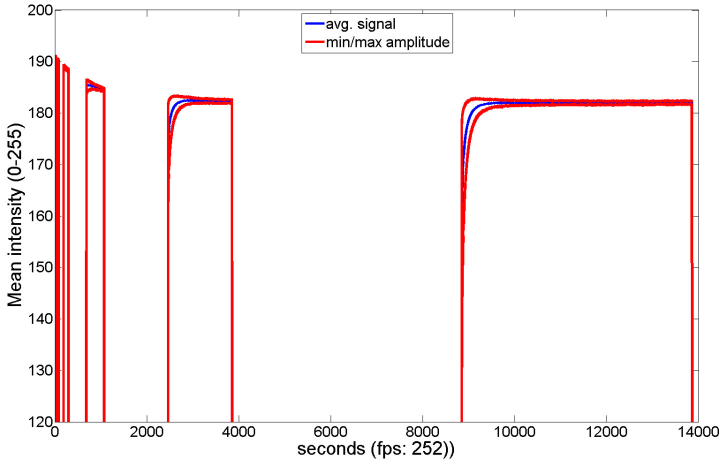
Figure 7: Mean profile of the difference of observed intensities between a black and white stripe projection and its inverted pattern after 30 repetitions. One stripe has a thickness of two projector pixels. The three-σ boundary shows that the observable contrast is still high enough to perform measurements at a fine stripe resolution.

5.4 Long Term Test

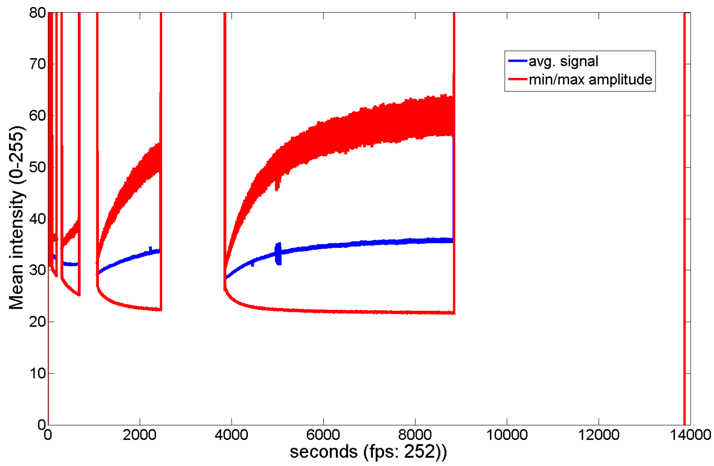
As mentioned before, a 60 Hertz oscillation of the projector signal could be clearly observed. The amplitude of the oscillation depends on the projected gray value and the duration of the projection. Because of that, a long-term test is done to analyze the effect of the oscillation and its influence.
Again, a CMOS camera is used to acquire data at approximately 250 frames per second, in the same manner as for the signal quality test discussed above. This time, the projection of black and white is changed in logarithmic time intervals over a period of roughly four hours. Since it is not possible to monitor the micro projector's maximum and minimum saturation with the same camera parameters, the test is run twice - once for the evaluation of the projector while projecting black with opened camera aperture and once for the white level with closed aperture.
For some reason, the signal's amplitude rises from 3 to 15 gray values when steadily projecting black with the micro projector (see Figure 5.4). Since the LCOS panel absorbs the light sourced from an LED when pixels are set to black, we assume that there might emerge heating problems causing the rising amplitude when steadily projecting a black pattern over a longer period.
Measuring temperature on the projector unit's chassis during the long term test shows that the device heats up from room temperature to 36°C within the first 50 minutes of the test, where it evens out. Changes in temperature are not noticed between the switching from white to black.
Besides to oscillation effects, one can identify that the light intensity slightly drops during the test sequence over several hours. The mean filtered gray value at the beginning of the test procedure in the projector's maximum saturation level is about 190. At the end of the test, almost four hours later, the mean value is only in the range of 181. A direct correlation between the light intensity's decrease and temperature change is not noticeable.

5.5 Signal Repeatability

Former experiments show that the projector's signal oscillation can vary depending on the projected gray values. For a standard structured light procedure using binary patterns only, the oscillation does not influence measurements. Reason for that is the fact that only relative intensity changes between



(a) Oscillated signal and average signal in the projecting unit's maximum saturation level.



(b) Oscillated signal and average signal in the projecting unit's minimum saturation level.

Figure 8: Mean filtered gray values of the long term test with black-white projections and the minimum and maximum amplitude of the signal, switching in logarithmic time intervals. Due to camera restrictions, the micro projector's maximum and minimum saturation level is observed separately in two acquisition procedures while projecting the same black-white sequences. During projection of black, the signals's amplitude rises. The amplitude decreases after projecting white light again. The averaged signal shows that the mean gray value of a stable projection color may change noticeably.

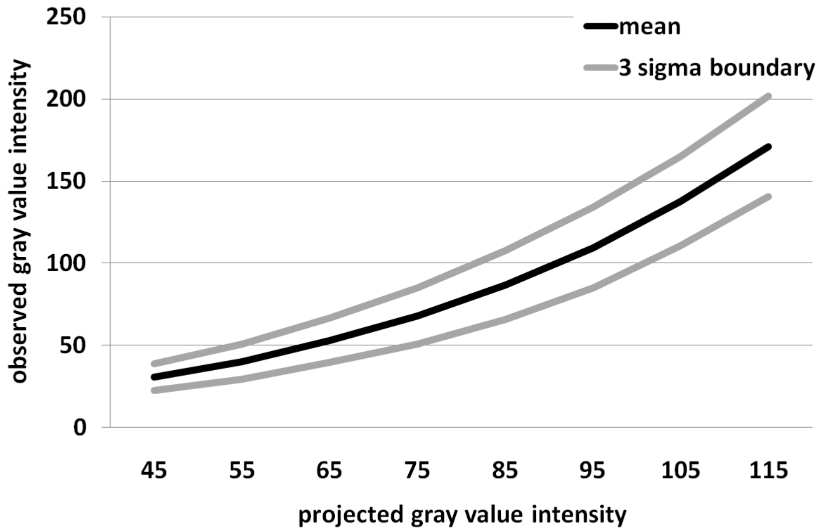


Figure 9: Repeatability of projected gray values. Eight gray values are projected consecutively with the micro projector onto a white and planar surface. A CCD camera, as used in a structured light setup, observes the mean gray value of the projection. This step is repeated for one hour resulting in 574 measurements for each projected gray value. The average values and their 3σ-boundaries are shown. The deviations for brighter gray values are obviously stronger than those for darker gray values.

the maximum and the minimum projections are calculated which can clearly be distinguished even with existing oscillations. When using structured light in combination with phase shifted patterns (as described in Section 3), certain gray values must be projected to simulate a phase over several projector pixels instead of pure binary stripes. This circumstance requires steady projections which should be repeatable for several measurements.

As discussed before, the oscillation effect can be smoothed by simply exposing *long enough* with observing cameras. If the micro projector's signal exhibits an oscillation with a strong amplitude, the signal indeed is not jammed by an oscillation when adjusting the camera's exposure time, but the mean intensity might be different from a former measurement with the same signal and a lower amplitude.

Therefore, an experiment stating the beamer's repeatability of certain gray values is done. For this reason, a setup similar to a structured light setup is used to observe the micro beamer's projection on a white and planar surface. A list of certain gray values is subsequently projected onto the planar surface and observed by a CCD camera. After storing the mean gray value of the projection area in the camera's image, the next gray value in the list is processed. This procedure is repeated for eight gray values for the duration of one hour resulting in 574 measurements for each gray value. Figure 9 illustrates the experimental result.

As results show, the oscillation in brighter projections causes a clearer deviation from the actual projection intensity. For the structured light procedure using phase shift, deviations of about 10 gray values are still small enough to receive feasible results. Neighboring projected gray values of a phase shift pattern still offer variabilities of at least 70 gray values which should even be distinguishable with stronger amplitudes in the projector's signal.

5.6 Structured Light

To evaluate the micro projector's capability for industrial measurements, a structured light setup is assembled. Therefore, the *3M MPro110* beamer (native resolution: 640×480) is set up with a focal

length of 26.8mm and a 2.5 megapixel grayscale CCD camera with a focal length of 16mm and an opening angle of approximately 15 degrees between the two devices. This results in a measurement volume of about $500mm \times 375mm \times 20mm$. Intrinsic and extrinsic parameters are computed in a calibration process for both devices.
In order to evaluate the structured light procedure's accuracy with the micro beamer, a nominal planar surface is reconstructed. A structured light algorithm with phase shifting is used. A plane is fitted to the dense point cloud using a RANSAC algorithm with all points. The standard deviation from all points to the plane can be used as a quality measure for the reconstruction. This procedure is repeated using different exposure times during the acquisition phase to demonstrate the principle of smoothing the signal oscillation with an observing camera. For comparability issues, the projected stripe patterns are adapted concerning their intensity to measure the same mean gray value levels with varying exposures. For detailed results see Table 2.
When using the recommended exposure time of at least 83ms, the projector's signal oscillation can

Camera exposure time [ms]	Plane fitting inliers [$\%$]	std.dev. from plane [μm]
15	95.80	0.0354
35	93.22	0.0326
85	97.41	0.0267

Table 2: Structured light results of reconstructing a planar surface (approximately $10.5cm^2$) with a point density of 940 points per cm^2. The same region is reconstructed with varying camera exposure times and adapted pattern intensities to suppress the signal oscillation. The standard deviation of the distances between all points and the plane acts as error measure for the reconstruction.

be suppressed. This permits better reconstruction results since unavoidable oscillations are smoothed and do not influence measurements critically. This mainly effects an accuracy gain for the phase shift procedure since the repeatability of certain gray values is more stable in this case.

6 Conclusion

In this work, a cheap off-the-shelf LCoS micro projector is investigated regarding its capability in a structured light setup. Several experiences could be gathered when dealing with the *3M MPro110* projector.
A big advantage is the micro projector's size and weight. This circumstance allows an easy integration of the projection unit into a compact 3D measurement system. This provides the opportunity to build non-stationary structured light sensors which permit reconstructions of regions that are difficult to access.
A disadvantage of the projector is the unstable signal caused by a 60Hz oscillation. Because of this, some workarounds need to be done to receive reliable measurement results with a structured light setup. The oscillation can be handled by simply setting the observing camera's exposure time to at least 83ms. This results in a longer image acquisition procedure. The mean acquisition time of a single pattern, consists of switching to the desired stripe pattern (in worst case: 21.7ms) and acquiring an image (at least 83ms), lasts for not less than 104.7ms in theory.
Apart from the signal oscillation, the micro projecting unit seemed to be suitable for structured light applications regarding contrast and light intensity. The beamer's light source, a 5 Watt LED, is sufficiently bright - especially for short distances between the projecting unit and the projected area.
The reconstruction of a planar surface shows the capability of the micro projector acting as projecting unit in a structured light setup. When using the proposed exposure time of 85ms for the observing

device during the acquisition phase, admissible accuracies can be achieved at the expense of the reconstruction time. A planar surface of approximately $10.5cm^2$ is reconstructed with a deviation of 26.7μm and with a density of 940 points per cm^2.
In the future, micro projecting units for pocket beamers or mobile phones will probably capture the market. Then, tiny and affordable projecting units will be present, sooner or later exhibiting higher native resolutions which offers the possibility for high accuracy measurements with the help of such devices in extremely compact sensors.

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