Department of Precision and Microsystems Engineering

3DOF($xy\theta_z$) measurement of a planar stage with one single 1D CCD from a 2D Moiré pattern

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Challenge the future

3DOF($xy\theta_z$) measurement of a planar stage with one single 1D CCD from a 2D Moiré pattern

by

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Summary

Introduction
As technology is advancing, the need for precision stages is increasing. These stages are being used with (electron) microscopes for scientific research and industrial applications. They can be operated manually or by actuators, where the motorized stages are quite expensive in general and the cost increase significantly if better performance is required. The increased cost is mainly due to the used sensors, such as linear encoders for stacked stages and laser interferometers for planar stages. It is a trade-off between the performance and cost. Therefore, it is important to look at the different sensors used in precision stages and if alternative low-cost sensor systems can be used in precision stages.

Research on low-cost planar stages and linear CCD as position sensor
The Mechatronic System Design (MSD) group at the Technical University of Delft has been researching low-cost precision stages with micrometre up to nanometre precision. One of their recent low-cost stages is a 3 degrees of freedom (DOF) ($xy\theta_z$) planar precision stage based on ferrofluid bearings. By using a simple camera module and a pattern with QR-like codes, the system is able to determine the position in x and y and the rotation θ_z. The system achieved a translational (xy) precision of 16 µm with a low control bandwidth of 10Hz. This low bandwidth is caused by the low sample rate of 16 Hz. Which is due to the 8 million pixels (MP) of the 2D image sensor, which all needs to be read out and processed by an image-recognition software.

Instead of using a 2D pixel array, it might be feasible to use a 1D pixel array for planar 3DOF position measurements. A linear charge-coupled device (CCD) is such a sensor with only 1 row of pixels and is limited to a maximum of a few thousand pixels. With such a sensor the system can still be relatively low-cost and it might be possible to achieve the same precision as with a 2D image sensor. While a significantly higher sample rate can be achieved as fewer pixels need to be read out and processed. In case of a 1D sensor of 2000 pixels vs. an 8MP 2D sensor, results in a factor 4000 fewer pixels. Hence, this thesis investigates on 3DOF($xy\theta_z$) measurement of a planar stage with one single 1D CCD.

From the literature research on the MSD and other state-of-the-art stages and their used sensors, none of them used a single linear sensor for planar 3DOF positioning. Therefore, literature research on the linear CCD as a position sensor has been performed as well. From this research, there are no sensor systems found which uses only a single linear CCD for planar 2DOF or 3DOF position measurements. Only 1DOF (x, along the pixels) or 2DOF (xz) measurement systems have been found with e.g. edge detection or marker tracking.

Conceptual design of using a single linear CCD for planar 3DOF positioning
The proposed sensor system concept uses a linear CCD with a self-designed 2D Moiré pattern and spatial averaging to obtain relative 3DOF($xy\theta_z$) position information of a planar stage. A conceptual design sketch for a microscope application can be found in Figure 1. Another advantage of this concept besides the above-mentioned precision, cost and sample rate, is that the range of motion can be increased easily with low-cost. This can be achieved by extending the pattern and print it on a bigger sheet of paper with an inkjet printer. And unlike linear encoders, which can only be used for 1DOF position measurements, this concept can also be used for 2DOF and 3DOF planar position measurements.

Moiré pattern analysis
By using the properties of a linear CCD, a Moiré pattern with sinusoidal gradients as seen in Figure 1 has been designed in order to obtain the relative planar 3DOF position information from the line scan data stream of a single linear CCD. By using sinusoidal gradients, the whole pixel array is used and spatial averaging can be applied. This Moiré pattern has been analysed with a self-developed line scan simulation tool in MATLAB. With the simulated output of the line scan, analysis of the algorithm to fit the data could be performed as well. The analysis of the simulations verified that it is feasible to obtain

relative planar 3DOF position information with the self-designed Moiré pattern and a single linear CCD.

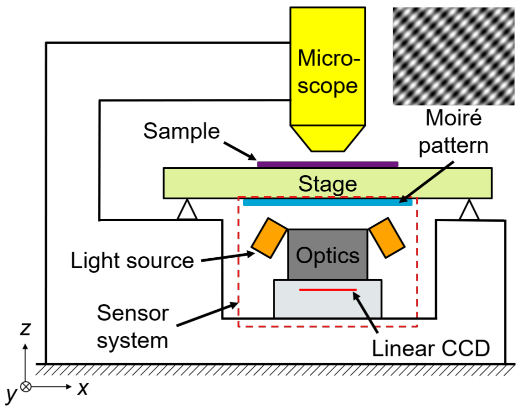

Figure 1: Conceptual design sketch for a microscope application. The planar stage can move in 3DOF($xy\theta_z$), mainly in x and y, while θ_z is measured for alignment. It has a sample on top and the Moiré pattern attached to the bottom side of the stage. The sensor system is placed under the stage, where the linear CCD is facing the pattern. Scanning the pattern with the sensor system will give the relative 3DOF($xy\theta_z$) position information.

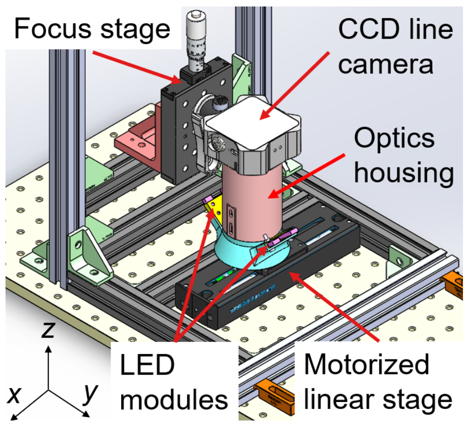

Figure 2: 3D CAD model of the demonstrator. The sensor system consists of a CCD line camera, optics housing and the LED modules. A manual linear stage can adjust the focus of the system. The CCD sensor faces the topside of the moving platform of the motorized linear stage, where the Moiré pattern can be attached to. The motorized linear stage can be rotated with 90° or replaced with a rotation stage in order to measure each of the 3DOF($xy\theta_z$) individually.

Demonstrator

A demonstrator has been developed in order to validate that the concept can be used for 3DOF planar positioning, which can achieve the same precision as the 2D image sensor system but with a significantly higher bandwidth. The demonstrator will also be used to analyse the sensitivity of the different elements of the sensor system. This demonstrator (Figure 2) is designed to measure each of the planar 3DOF individually. The sensor system consists of a CCD line camera, a biconvex lens and diaphragm for the optics parts, LEDs for the light source and the printed Moiré pattern. The line camera, with the linear CCD facing downwards, is attached to a focus stage in order to adjust the focus manually. The CCD is looking at the Moiré pattern which is attached to a stage. A motorized linear stage has been used to move the pattern, so x and y measurements can be performed. This stage can be interchanged with a rotation stage to measure the rotation θ_z.

Results

Multiple line scans of the pattern have been taken while the pattern is fixed. The noise within the data of the different line scans is not very constant, this results in a deviation of the obtained information from the algorithm, causing position errors. Quasi-static measurements have been performed in the x-direction (along the CCD pixels), by scanning the pattern on 2 predefined positions with the motorized linear stage. This resulted in a translation precision in the x-direction of 8 µm (3σ). The maximum achieved sample rate to obtain position data with the algorithm from a line scan is about 20 Hz.

Conclusion

This research presents a new methodology to obtain relative 3DOF($xy\theta_z$) position data for planar precision stages with a single 1D CCD sensor and a self-designed 2D Moiré pattern. The pattern has been analysed with a self-developed line scan simulation tool in MATLAB to verify the feasibility to obtain relative planar 3DOF position information with a linear CCD and a Moiré pattern. A demonstrator has been built in order to validate the concept by measuring each of the 3DOF separately and to analyse the sensitivity of the different elements of the system. Compared to the 2D image sensor system, this sensor system achieved similar precision and the sample rate is not limited by the sensor, but by the algorithm which processes the data. The fitting algorithm in MATLAB is not designed for the speed performance, but primarily to analyse the data. The sample rate of the system can be increased by using a more efficient algorithm and implementing this in an FPGA.

Preface

During my final year at the TU Delft, I learned a lot. Not only about the topic of this thesis, but also on the other projects of my fellow students in the Mechatronic System Design group. At the start of the graduation project, I had no idea what I would like to research as many topics were very interesting. After meeting with my supervisor and some brainstorm sessions, we came with the idea to use a simple line sensor for position measurements. This was very challenging and sometimes even frustrating. However, it was very rewarding to solve these challenging problems I encountered during the project.

Acknowledgement

In this section, I would like to express my gratitude to everyone who has contributed to this thesis and who supported me during my graduation project.

First I would like to thank my supervisor Jo Spronck. As he always supported me during the graduation project, giving advice and constructive feedback on the project and asking the right questions to guide me with the problems I encountered. I could not wish for a better supervisor.

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Contents

1 Introduction

As technology is advancing, the need for precision stages is increasing. These stages are being used with (electron) microscopes for scientific research and industrial applications. They can be operated manually or by actuators, where the motorized stages are quite expensive in general and the cost increase significantly if better performance is required. The increased cost is mainly due to the used sensors, such as linear encoders for stacked stages and laser interferometers for planar stages. At this moment the sensors are the main limitations, it is a trade-off between the performance and cost. Therefore it is important to look at the different sensors used in precision stages. And to look if other alternative low-cost sensor systems can be used in precision stages in order to achieve good performance compared to existing sensor systems used in precision stages.

1.1. State-of-the-art low-cost precision stages and sensors

Most of the research regarding precision stages are focused to increase their performances while reducing the cost is less important [1]. The Mechatronic System Design (MSD) group of the faculty Precision and Microsystems Engineering at the Technical University of Delft (TU Delft), has been doing research on precision stages in general and later on, they focused on low-cost precision stages with micrometre up to nanometre precision.

Within the MSD group of the TU Delft, a 6 degrees of freedom (DOF) precision stage based on ferrofluid bearings [2] was developed, this was done by Café [3]. This stage was however not intended to be low-cost at all, the research project was a feasibility study to explore the possibilities of using ferrofluid bearings in high precision, low load applications. The best equipment in the lab was used for this research. To measure the 6DOF up to nanometer precision, three laser interferometers and three capacitive sensors were used. Where the laser interferometer cost approximately €10000 each and the capacitive sensors €1000 each. Also, an expensive dSPACE DS-1103 system of €20000 has been used to run the controller.

But having the knowledge of this ferrofluid stage, made it possible to develop alternative relative low-cost precision stages and utilizing cost-effective sensors. It started with Habib [4], who did not use expensive laser interferometers as the positioning sensor for his planar 3DOF ferrofluid bearing stage. Instead, Habib used a single 2D Position Sensitive Detector (PSD) with LEDs to determine the position. This 2D PSD cost approximately €750, and was first investigated by He [5] as a possibility for a 6DOF stage position measurement system. Habib implemented this 2D PSD in his stage to achieve a translational range of 9 mm x 9 mm and is able to rotate 360°. With a translational precision of 0.2 μm (3σ) and rotational precision of 0.15 mrad (3σ). The sensor system was reduced in cost, however, the other parts in Habib's stage were high-quality components, such as the dSPACE DS-1103 system used by Café and self-built linear current amplifiers with a component cost of about €1000 [6].

Another low-cost precision stage was developed by Mok [7], who used 2 low-cost optical computer mouse sensors to measure the planar 3DOF of the planar stage. However, due to the internal working of the mouse sensor (low encoder readout and heavy digital filtering), the scope of the research and limited time, the sensor system is only able to measure the translational DOFs. The system has a 3σ precision of 9.7 μm, with an overall component cost of only €200.

To decrease the cost of the existing stages within the MSD group, van Moorsel [8] came up with another 3DOF planar precision stage based on ferrofluid bearings, which uses ArUco (similar to QR codes) and a 2D complementary metal–oxide–semiconductor (CMOS) camera sensor to determine the position of the stage. This is one of the first stages with a large planar translation, 30 mm, as well infinite rotations with only one moving part and a single sensor. The 8 megapixel (MP) image sensor, with a price of €30, in combination with the ArUco markers on the stage, made it possible to achieve a precision of 16.0 μm (3σ) in translational directions and approximately 0.028° (3σ) with a control bandwidth of 10 Hz and sample rate of 16 Hz. The overall cost of the developed stage was only €300.

While these precision stages has been developed to be low-cost, some improvements has been done in order to achieve a better performance like the research of Florijn [9], which has improved the stage of van Moorsel by using a laptop, other image sensor and improved control to achieve a precision of 1.5 μm (3σ) at a control bandwidth of 15 Hz.

Or a stage has been reduced in cost by replacing expensive components for low-cost ones while trying to maintain the original precision as much as possible. The research of Jutte [6], reduced the cost of Habib by using a low-cost microcontroller and pulse-width modulation base amplifiers to replace the expansive and bulky dSPACE DS-1103 controller and linear current amplifiers in the original design. Jutte made it possible to reduce the cost from the original design which was over €20000, to about €700 in the new design. The original translational precision of 0.2 μm (3σ) at 60 Hz was not fully maintained with this heavy cost reduction, but the new design still had a very good performance of 1.5 μm (3σ) at 25 Hz.

1.2. State-of-the-art precision stages and sensors

In general, the most used sensors for planar 3DOF precision stages are either encoders or laser interferometers [10]. Where the encoders are used in combination with multiple stacked stages. A conventional 3DOF precision stage consists of 3 stacked stages, each for every DOF in order to move the platform in x,y and θ_z. 2 linear stages for the translations in x and y and 1 rotation stage for the rotations around the z-axis. The positions of the linear stages are measured with linear encoders, while the rotation is measured with a rotary encoder.

For a planar stage, where the moving platform is actuated in-plane, the positions can not be measured by these encoders. Planar stages commonly use laser interferometers to measure the planar 3DOF positions. Other solutions on the market include grid encoders (Heidenhain) and planar encoders (NanoGrid Optra) for x and y measurements.

A research study on state-of-the-art 2D-nanopositioning stages is conducted by Torralba et al. [1]. Where most of these nanopositioning stages are using laser interferometers for the metrology loop. One of them includes a self-designed surface encoder for sub-micron positioning in the planar 3DOF.

1.2.1. Planar 3DOF surface encoder

A $xy\theta_z$ surface encoder for sub-micron positioning has been developed by Gao et al. [11] for a surface motor-driven xy planar motion stage. The surface encoder is composed of an angle grid plate and a 2D angle sensor to read the local slopes of the angle grid surface. The angle gird plate has a micro-structured sinusoidal surface, this has been fabricated using diamond turning with a fast tool servo [12]. The grid surface is a superposition of sine waves along the x- and y-directions, where the x- and y-motions of the angle grid plate relative to the sensor unit can be obtained independently from the 2D outputs of the angle sensor. The surface encoder uses the wavelengths of the grid as the graduations to obtain the relative position information. With this surface encoder, it was expected to have a resolution of 10 nm level with proper interpolation of the encoder graduation. By using a second 2D angle sensor it is also possible to obtain the rotation around the z-axis (θ_z).

The planar motion stage has a moving element (platen) and a stage base. The platen is levitated by air bearings and actuated by linear motors, each consisting of a paired magnetic array and a stator (coils). The angle grid plate is attached to the platen and the sensor unit on the stage base. A schematic view of the planar motion stage system can be found in Figure 1.1.

The surface encoder uses two 2D angle sensors in order to obtain the relative $xy\theta_z$ position information from the angle grid plate. The surface of the angle grid plate is a superposition of sine waves along the x- and y-directions, where the profile has identical amplitudes and wavelengths in both directions. The 2D angle sensor measures the 2D local slope of the grid surface. From the local slopes, the

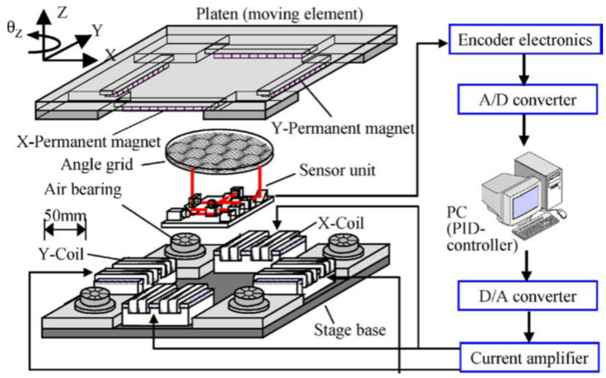

Figure 1.1: Schematic of the planar motion stage system [11].

x and y information can be obtained through interpolation. By using a second 2D angle sensor with a known distance from the other 2D angle sensor, the x and y position information can be obtained at a different point of the angle grid surface. With this additional information, the rotation θ_z can be obtained as well. A schematic of the surface encoder to obtain the 3DOF can be found in Figure 1.2.

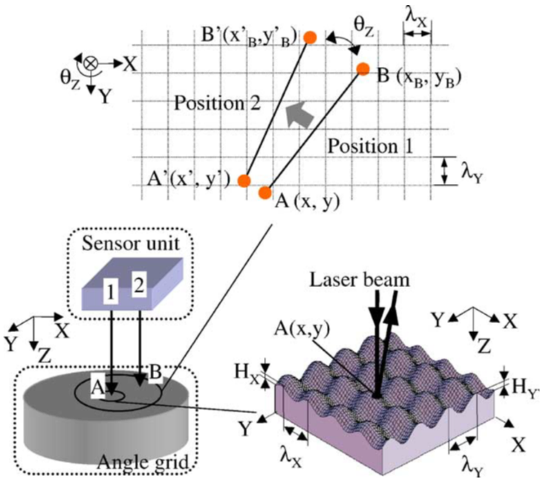

Figure 1.2: Schematic of the surface encoder for detecting x, y and θ_z [11].

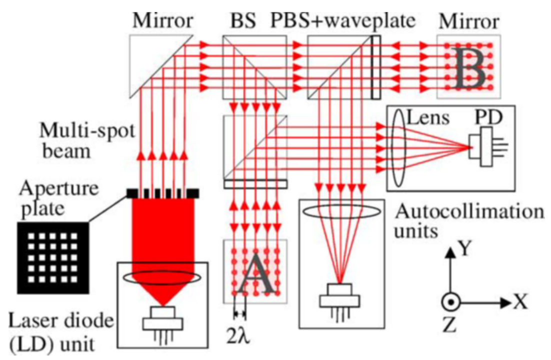

Figure 1.3: The optical configuration of the surface encoder [11].

The surface encoder utilizes some optical techniques in order to use quadrant photodiodes as photodetectors in the sensor for 2D detection from a collimated laser beam, the optical configuration can be found in Figure 1.3.

The resolution of the surface encoder was confirmed to be approximately 20 nm in x- and y-directions and 0.1 µrad in θ_z-direction. The surface encoder was also implemented in the xy planar motion stage, the positioning experiments have demonstrated that the x- and y-directions can be controlled independently with 200 nm resolution and the rotation θ_z with 4.85 µrad resolution. This surface encoder achieved a sub-micron positioning, but due to the complexity of the surface encoder, the cost of the system seems not very low-cost. The angle grid, for example, needs to be made with special tools and needs to be manufactured with high quality.

1.3. Literature research on linear CCD for positioning

A (linear) image sensor is a photosensor, which measures the intensity of the light on the photosensitive surface, the pixels, by the principle of the photoelectric effect [13, 14]. When the surface of the photosensor is exposed to light, photons will hit the surface, creating electron-hole pairs, and causing electrons to gather in a potential well. These electrons can be transferred by different methods (depending on the type of sensor) to a readout register. And the number of electrons per well is converted to a voltage, which is related to the intensity of the illumination hitting the surface of the sensor.

The CCD is well known as an image sensor together with the CMOS image sensor, these sensors technologies are commercially available and applied in e.g. digital cameras, webcams and smartphones. Where the CCD image sensor had better performance in past compared to the CMOS image sensor. However, the quality of the CMOS image sensor has been improved over the past years and it might match the CCD image sensor or even surpass it in the future [15]. These image sensors have a 2D array of many pixels. But the main advantage of the CCD is the significant low noise level compared to the CMOS sensor, that is for example why scientific cameras often have a CCD instead of CMOS sensor.

The 1D (linear) variant of these image sensors are the linear CCD and linear CMOS sensor, these sensors only have one line of pixels instead of the 2D array. They are used in application like barcode readers, scanners and line cameras. Because they only have one line of a maximum of a few thousand pixels, the scan rates can be significantly higher compared to the 2D image sensors, where the number of pixels is generally a few million to achieve the same image resolution.

However, these image sensors can also be used as a position sensor. In literature different methods has been found on how the image sensor can be used as a position sensor. This is done with either a linear array or an area array image sensor. Due to the better performance of CCD over CMOS sensors and the high scan rates of the linear image sensor, this literature research is focused on linear CCDs as a position sensor.

1.3.1. Linear CCD array with two ultrasonic sensors

In the paper of Yoon et al. [16] a position measuring system has been developed with a linear CCD and two ultrasonic sensors. The CCD has been used to measure the lateral position (x), and the two ultrasonic sensors measure two distances which can be converted to the longitudinal position (y) and the angle (θ) between the system and a flat target with a simple white marker on a black surface.

The linear CCD which has been used is the TCD1205D from TOSHIBA. Some information about the TCD1205D: 2048 pixels, pixel size: 14 µm by 200 µm on 14 µm pitch.

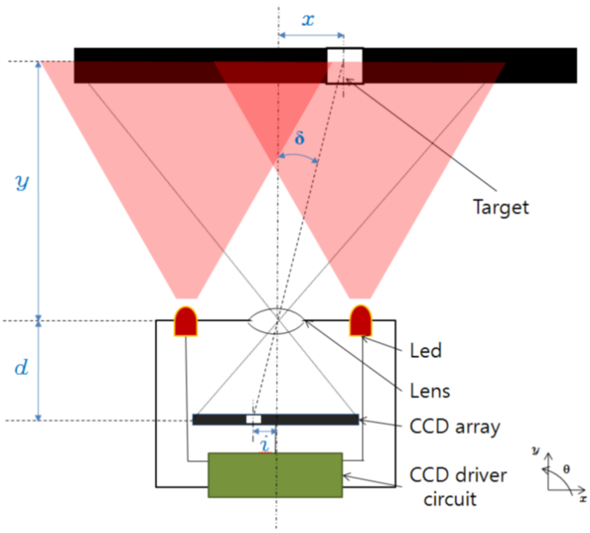

Figure 1.4: Schematic structure of the 1D CCD sensor system [16].

The part of the linear CCD sensor system can be found in Figure 1.4. The sensor system works as follows: the target (white marker on a black flat surface) is being illuminated by two red LEDs, the light will reflect from the target through the lens on the CCD array, the contrast of the black and white surface will be scanned by the CCD array. The lateral position (x), the offset from the centre of the system to the centre of the target, can be found by the following relation:

$$tan(\delta) = \frac{i}{d} = \frac{x}{y} \tag{1.1}$$

where δ is the angle between the centre of the lens and the centre of the target, i is the index of the

CCD array, d the distance from the CCD array to the lens and y is the longitudinal position. The lateral position (x) can be found by:

$$x = \frac{i}{d}y \quad (1.2)$$

The experimental results of the CCD sensor system part shown in this paper, to get the lateral position (x) of the system, has only been tested for one fixed position. The position where the centre of the lens and CCD array coincides with the centre of marker, so a lateral position (x) of 0 mm. When the x position has been measured, the researchers stated that the reference position (0 mm) and the measured position are nearly the same. Concluding that it has 0 mm error for the x position. From this paper, it is not very clear what the performance of the CCD sensor system is capable of. However, it showed how a linear CCD can be used as a 1-dimensional positioning sensor by tracking a marker.

1.3.2. Edge detection

Another method which has been found in the literature to use a linear CCD as a position sensor is edge detection. Edge detection or the so-called shadow method is the position measurement of the shadow of an object projected partly on the CCD, while the rest is of CCD is illuminated by the light source. So a measurement will give a low signal output for pixels covered by the shadow (dark), and a high output signal for the illuminated pixels. So it basically gives a contrast image, where the interesting part is the transition from dark to light. A general overview of an edge detection principle can be found in Figure 1.5. The position of the shadow can be found with this method and with a correct setup and algorithm the position of the object can also be found accurately.

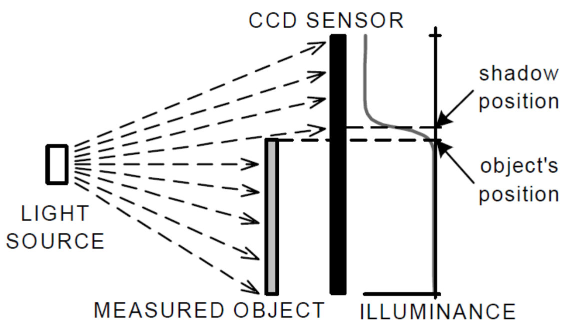

Figure 1.5: General principle of edge detection [17].

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Fischer and Radil described simple methods of edge detection in their paper [17]. The measured edge of the shadow in the illumination profile on the CCD and the position of the edge of the object is very dependent on the light source. Therefore, the paper described 2 methods to do position measurement with edge detection. The first method is by using a light source of parallel beams. The second method is by using a point light source.

A light source of parallel beams could be constructed by using a point light source with a collimation lens as proposed by the paper, see Figure 1.6. This is a common method to perform edge detection of an object. In the case of a collimated light source like in Figure 1.6, the measured position of the edge in the illumination profile (x_M), the edge of the shadow, is equal to the position of the edge of the object (x_E). However, the exact position of the edge can be determined from the diffraction of the light on the edge of the measured object. The exact position can be determined by comparing the illumination profile of the CCD with a threshold level of 25% of the signal's amplitude.

Fischer and Radil came up with a method to use a point light source to do the edge detection of an object instead of using a collimated light source. This point light source construction is simpler, cheaper and smaller in comparison with the collimated light source. However, by using a single point light source as seen in Figure 1.7(a), the divergence of the light beams will influence the illumination profile. The position of the object's edge (x_E) is now different from the position of the edge in the illumination profile (x_M), the edge of the shadow.

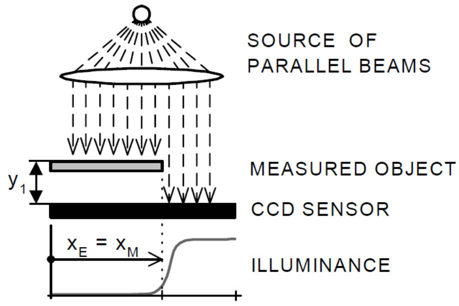
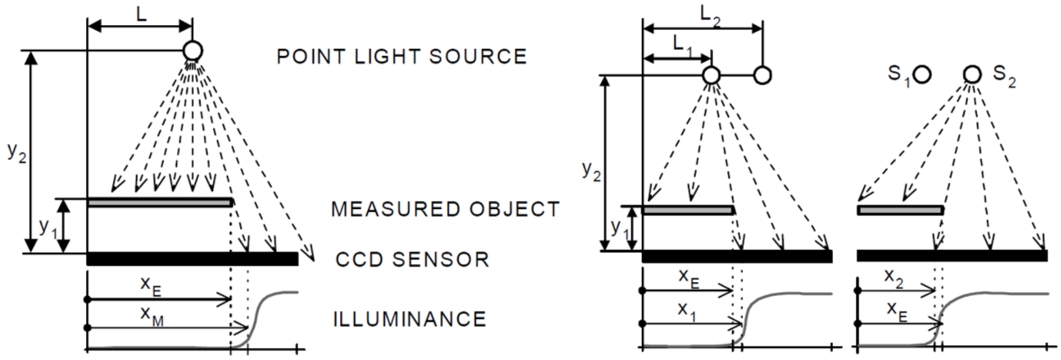


Figure 1.6: Principle of edge detection with parallel beams [17].



(a) One light source (b) Two light sources

Figure 1.7: Principle of edge detection with a point light source [17].

From the setup in Figure 1.7(a), the position of the object's edge can be determined from Equation (1.3):

$$x_E = \frac{y_1}{y_2}(L - x_M) + x_M \tag{1.3}$$

Where y_1 is the distance between the measured object and the CCD, y_2 the distance between the light source and the CCD, and L is the light source's position. In this case, y_1 must be known to determine the edge of the object, which can be a disadvantage. This could be solved by using two point light sources, as in Figure 1.7(b), where the light sources (S_1 and S_2) are alternating, so only one of the two light sources is on at a time. For example during a measurement first S_1 is turned on, while S_2 is off, and the shadow's edge (x_1) will be detected on the CCD. Now S_1 is turned off, while S_2 is turned on, and the shadow's edge (x_2) created by the illumination of the second light source will be detected by the CCD. From the known positions of the two point light sources (L_1 and L_2), the distance between the light source and the CCD, and the two shadow's edge positions (x_1 and x_2), the object's edge can be determined from Equation (1.4):

$$x_E = \frac{L_2 x_1 - L_1 x_2}{L_2 - L_1 + x_1 - x_2} \tag{1.4}$$

So for this method y_1, the distance between the measured object and the CCD, does not need to be known. But y_1 will influence the accuracy of the determination of the edge's position.

For the measurement with the collimated light source, a low-cost laser diode SLD6505A (5 mW) have been used with a standard photographic objective as the lens with a focal length of 50 mm. For the measurement with the point light sources, the same laser diodes has been used as for the collimated light source. In both cases, the CCD is the Sony ILX703A. Some information about the ILX703A: 2048 pixels, pixel size: 14 μm × 14 μm, pitch 14 μm. Results of the collimated light source: linearity error Δ was in the range of ± 30 μm and position resolution (standard deviation) was 0.8 μm. Results of the two point light sources: linearity error Δ was in the range of ± 6 μm and position resolution (standard deviation) was 0.9 μm.

Both methods showed that a relatively good position resolution could be achieved. This was possible by using an interpolation algorithm to get subpixel resolution [18–21]. The bigger error in linearity for the collimated beam was caused by the non-uniform illumination. This non-uniform illumination is due to effects such as diffraction of light on the lens's shutter, reflections in the housing of the laser diode and the non-homogeneous radiation across the laser diode chip's area. This bigger linearity error affects the accuracy of the position determination, resulting in linearity errors greater than the width of one pixel (14 μm).

Radil et al. implemented this method to perform dimension measurements of objects with circular cross-section [22]. And extended this work even to obtain 2 dimensional (xz) position information of objects with circular cross-section using a single linear CCD [23]. The described method achieves typical linearity deviations below 4.5 μm in the direction along the CCD pixels and 22 μm in the direction perpendicular to the CCD pixels.

In order to measure more than 1DOF, multiple linear CCDs can be used to measure more than 1 or 2DOF. For example, Hooijschuur [24] implemented 3 linear CCDs in a sensor system to measure the planar 3DOF($xy\theta_z$) for contactless wafer precision positioning based on edge detection.

1.4. Thesis objective and goals

As it was mentioned before, the sensors are the main limitations in high precision stages, it is a trade-off between performance and cost. Due to the advancing technology, the demand for high precision stages is increasing. An alternative low-cost sensor system with relatively good performance can be the solution for this increasing demand and to make high precision stages more accessible for different applications.

From the literature research, alternative low-cost sensors systems have been developed to measure the planar 3DOF for precision stages. However, the performance of these sensor systems is limited by the selected sensors. Where a low control bandwidth is one the limitations due to the selected sensor in for example the van Moorsel sensor system. Due to the 2D 8 MP CMOS image sensor (low frame rates) and the image-recognition algorithm, a low sample rate was achieved with the sensor system, resulting in the low control bandwidth. Using a cost-effective linear CCD might be the solution for this problem because this sensor has a maximum of only a few thousand pixels to achieve the same resolution as the 2D image sensor which has millions of pixels. Due to the fewer pixels, the linear CCD can have a higher scan rate and read-out time. This can result in a significantly higher sample rate, which is eventually beneficial for the control bandwidth.

Therefore, this research will primarily focus on a new method to obtain relative 3DOF($xy\theta_z$) position information for planar precision stages with a single 1D CCD. The goal of this thesis is to achieve the same micrometre precision and to increase the sample rate significantly with the new method compared to the van Moorsel sensor system. In addition, the proposed method will be simulated to verify the feasibility of the concept. A sensor system will be developed based on the proposed method and implemented in a demonstrator to gain knowledge about the sensitivity of the different parameters in the sensor system and to demonstrate the possibilities of the sensor system.

1.5. Thesis overview

In Chapter 2 the conceptual design of using a single linear CCD for 3DOF($xy\theta_z$) positioning will be presented for digital microscopy applications. In Chapter 3 the work of this thesis will be presented in a paper form. In Chapter 4 an elaborate discussion of the work is presented, including recommendations for future work. The conclusions are presented in Chapter 5. Additional information can be found in the appendices. Appendix A contains more information about the design of the sensor system. Some additional datasheets can be found in Appendix B.

2

Conceptual design of using a single linear CCD for planar 3DOF positioning

This chapter first presents the application in mind for using a planar 3DOF sensor system. Next, the possibilities and limitations are discussed of using a single linear CCD in the sensor system. The requirements of the sensor system are formulated based on application in mind and to compare with Van Moorsel sensor system. Finally, the conceptual design of the sensor system is presented.

2.1. Application

In digital microscopy, 3DOF($xy\theta_z$) planar precision stages can be used to move the sample. Whether it is required to scan a large sample at high resolution, by stitching images made with the digital microscope or to inspect the region of the interest in real-time. For these applications, a planar precision stage is used to move the sample with micrometre resolution, because the field of view is reduced due to the optical magnification to inspect the sample. It is desired to translate the stage in the x- and y-directions, while the rotation θ_z needs to be locked. Therefore the sensor system should be able to measure the position of the planar 3DOF($xy\theta_z$), where the rotation is also measured to lock the rotation by means of a control loop. For this kind of application, it is not necessary to obtain absolute position information, therefore relative position information is considered in the design.

2.2. Possibilities and limitations of the linear CCD

A linear CCD has only a fraction of the number of pixels compared to a 2D image sensor, where the linear CCD has a maximum of a few thousand pixels, a 2D image sensor generally already have a few million pixels in the 2D array. For example, a linear CCD has 2048 pixels, while the 2D CMOS image sensor of the van Moorsel sensor system has 8 million pixels (3280 x 2464), which has almost a factor 4000 more pixels than the linear CCD. With a linear CCD, significantly high line scan rates can be achieved compared to frame rates of a 2D image sensor. Because of the fewer pixels, the readout time is shorter and less data needs to be processed. This does not directly mean that a linear CCD with 2048 pixels is also a factor 4000 faster than the 2D 8 MP image sensor because there are different methods to read out the data faster, like multiple taps to read pixels in parallel. Taken this in mind, a linear CCD has the advantage that it can achieve significant high line scan rates and less data needs to be processed, which can lead to high sample rates which is beneficial for high bandwidth systems.

The sensor system could still be limited by the hardware and the algorithm which processes the data to obtain the position information. If the algorithm needs a lot of computational power, the hardware can be the limiting factor. Or if the algorithm is not optimized to process the data in an efficient manner, the algorithm can be slow, resulting in low sample rates.

A linear CCD is quite cost-effective (available for $<$ €10), however, it also needs some additional electronics to drive the sensor. It was found that it is possible to create an overall low-cost linear CCD with the additional electronics for only €25 [1,2]. Compared to CCD line camera's sold for the industry with up to 80kHz scan rates, this low-cost project has a relatively slow maximum scan rate of 125 scans/s due to the communication protocol and the CCD clock. By using other hardware, the scan rate can be improved significantly.

2.3. Requirements

The requirements of the sensor system are based on the digital microscope application in mind and the sensor system of Van Moorsel to compare a single linear image sensor with a 2D image sensor for planar 3DOF measurements.

Table 2.1: Requirements of the sensor system

Requirement	
Degrees of freedom	3DOF($xy\theta_z$)
Positioning	Relative
Measurement range translation x and y	30 mm x 30 mm
Measurement range rotation θ_z	≥1°
Precision (3σ) in translation	≤16.0 µm
Precision (3σ) in rotation	≤0.03°
Sample rate	≥16 Hz

2.4. Conceptual design overview

With the microscopy stage application in mind, a conceptual design overview is shown in Figure 2.1. The system consists of three main parts, a planar 3DOF($xy\theta_z$) stage, the microscope and the sensor system. A sample which needs to be observed by the microscope can be placed on top of the planar($xy\theta_z$) stage. The sensor system is placed under the stage, with the printed 2D pattern attached to the bottom of the stage and the linear CCD facing the pattern. The pattern is illuminated by the light sources, where the reflected light of the pattern is focused on the linear CCD by the optics. Using the measured intensity of the reflected light from the pattern, relative planar 3DOF($xy\theta_z$) position information can be obtained with an algorithm. The rotation θ_z is measured to lock the rotation of the stage through a control loop, in order to translate the stage only in the x- and y-directions.

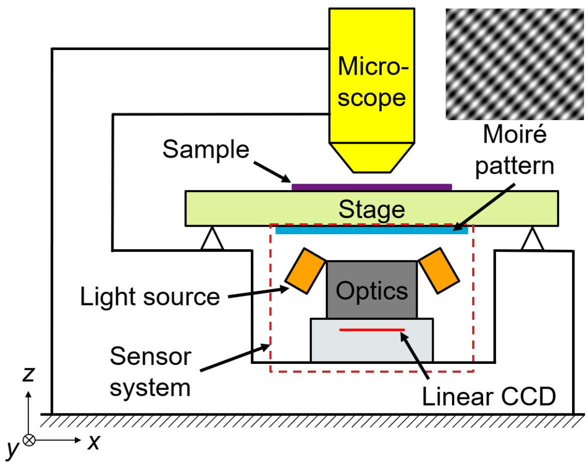


Figure 2.1: Conceptual design sketch for a microscope application. The planar stage can move in 3DOF($xy\theta_z$), mainly in x and y, while θ_z is measured for alignment. It has a sample on top and the Moiré pattern attached to the bottom side of the stage. The sensor system is placed under the stage, where the linear CCD is facing the pattern. Scanning the pattern with the sensor system will give the relative 3DOF position information.

[1] https://hackaday.io/project/9829-linear-ccd-module
[2] https://tcd1304.wordpress.com/

3

Paper: Meausure planar 3DOF($xy\theta_Z$) with one single 1D image sensor from a static 2D pattern

The main results of this thesis are presented in the form of a paper. The paper presents a new methodology for planar 3DOF($xy\theta_z$) measurements with a single 1D image sensor from a static pattern. Which includes the proof of concept, from simulations and experimental results. An additional discussion is presented in Chapter 4.

Measure planar 3DOF($xy\theta_z$) with one single 1D image sensor from a static 2D pattern

Chi Wai Kan

Abstract—**Developing low-cost precision stages with (sub-)micrometre precision are needed for broadening the availability of diagnostics, analysis and manufacturing equipment in the fields of medicine, industry and science. Major contributor in the cost of the positioning system is the sensing solution. Recent studies have proposed using imaging camera modules and QR coded patterns for cost reduction. While such methods allow to realising high translational precision ($\approx$ 1.5 µm) planar 3DOF measurement systems at low cost, such solutions are significantly limited in sampling rate ($\approx$ 170 Hz) due to computational complexity of the necessary image processing. This work proposes a new and simple methodology to use a single linear image sensor as a 3DOF position measuring system by scanning a static 2D Moiré pattern. The proposed methodology allows for achieving significantly higher sampling rates at equivalent precision. The measuring system consists of a stationary CCD line camera, optics and illumination system, and a static 2D Moiré pattern attached to a moving target. First, the basic concept is studied, next the optimal Moiré pattern is studied, and sensitivity of the sensing system to its component properties is studied. Next, the measurement system is implemented in a demonstrator, with the Moiré pattern attached to a motorized linear stage in order to evaluate its performance. The system is first calibrated, then its sensitivity is measured at different conditions, and finally the performance is measured. Our preliminary experiments achieved a precision of 8 µm (3σ) at 20 Hz sampling rate, primarily limited by the algorithm and tuning of the implementation. With further optimisation of the sensor system and implementation of the algorithm on faster hardware will improve the performance significantly compared to previous solutions. This is the first reported methodology for using a single linear image sensor for planar 2DOF and 3DOF position measurement and reported preliminary results demonstrates the potential of such methodology for high-precision high-bandwidth low-cost position measurement applications.**

Index Terms—**linear image sensor, CCD, CMOS, Moiré, 3DOF, planar precision positioning.**

I. Introduction

As technology is advancing, the need for automated high-precision positioning stages is increasing for making research, industry, medical diagnostics with e.g. (electron) microscopes. The stages can be operated manually or by actuators. Cost of the motorized stages increases exponentially with performance, i.e. precision, bandwidth, size and range. While manufacturing and actuation influence the cost, the trade-off between performance and cost is primarily due to the used sensors. Such as linear encoders for stacked stages and laser interferometers for planar stages. Therefore, for wider availability and applications it is important to develop an affordable sensor system for high-precision positioning stages.

Possible solutions include a sensor system based on low-cost optical mouse sensors developed by Mok [1], which has the possibilities to measure the planar 3 degrees of freedom (DOF) with a precision of 9.7 µm (3σ) with a control bandwidth of 10 Hz. Another solution is to use a 2D Position Sensitive Device (PSD) for planar precision measurements by Habib [2], achieving sub-micrometre precision in the translational directions (0.2 µm (3σ)) and 0.15 mrad (3σ) in the θ_z-direction, with a bandwidth up to 60 Hz. Later, Jutte [3] reduced the cost and size of the whole system significantly by using a microcontroller and pulse width modulation based amplifiers. Jutte achieved translational precision of 1.5 µm (3σ) and a control bandwidth of 25 Hz with the significant cost reduction. However, the used 2D PSD is still quite expensive ($\approx$ €750). In 2007 Urbanek et al. [4] used a cheap mass-production camera (2D charge-coupled device (CCD) image sensor) and a coded pattern formed by holes to obtain absolute planar 3DOF position information. They were capable of measuring x and y positions with precision between 0.05-0.7 µm (2σ) depending on the step size, with a sample rate of 4 Hz. Cosandier et al. [5] adapted the system of [4] by using a different coded pattern and imaging processing algorithm to determine the position with a precision of 4.3 µm (x), 2.4 µm (y), 983 µrad (θ_z) (1σ) and a increased sample rate of 10 Hz. Van Moorsel [6] reported a similar concept using an 8 MP camera module (2D complementary metal–oxide–semiconductor (CMOS) image sensor) and a pattern based on QR-like codes to measure position and rotation in-plane (3DOF: $xy\theta_z$). The sensor system was implemented on a ferrofluid-supported planar positioning stage and achieved translational precision of 16 µm (3σ) and 0.5 mrad (3σ) for θ_z, at 16 Hz sampling rate. Later, Florijn [7] improved the system by using a faster camera and a laptop instead of a microcontroller to increase computational power. Florijn achieved a translational precision of 1.5 µm (3σ) and a sampling rate of 94 Hz, applying multi-threading in the software resulted in a sampling rate of 171 Hz. Unfortunately, these imaging solutions are limited by the sensor capabilities and require high computational power for image processing.

Line sensors have been proposed as a simple and cheap way for 1DOF measurements along the pixels by marker tracking [8] or edge detection [9], [10], [11], [12], [13]. Based on edge detection, a 2DOF(xz) position measurement of objects with a circular cross-section and a single linear CCD has been reported by Radil and Fischer [14]. However, no attempts have been reported on using a single linear CCD for planar 2DOF or 3DOF position measurements. In order to measure more than 1DOF, multiple linear CCDs are implemented in the sensor system by Hooijschuur [15].

This work will propose and investigate a new methodology for measuring position in the planar 3DOF($xy\theta_z$) using a single 1D image sensor and a static 2D Moiré pattern. Operating principle of the proposed sensing system is explained in Figure 1. Such a measurement system is expected to achieve equivalent precision to the camera-based systems with a 2D image sensor while being lower in cost and faster in performance. Since a linear image sensor only has one row of pixels, the hardware is simpler and (roughly 1000 times) fewer data to be processed than in 2D image sensors.

In this paper, we will next explain the sensing system in section II. This will cover properties of the linear CCD, analysis and design of the Moiré pattern, necessary auxiliary components of the sensing system and sensitivity analysis. Next, we will introduce the demonstrator and methodology to validate and characterise the proposed sensing system, respectively in sections III and IV. Further, the experimental results are given in section V, discussed in section VI and the work is concluded in section VII.

II. Sensing system

This paper proposes a sensing methodology for measuring translations (xy) and rotations (θ_z) using a single linear image sensor. The proposed sensing system consists of a CCD line scan camera, an appropriate planar printed pattern, its illumination system, optics for the line scan camera, and a computer for processing sensor data. A conceptual design of the sensing system and its application in a typical planar 3DOF positioning application is shown in Figure 1, where translations (xy) and orientation (θ_z) are measured for closed-loop positioning.

Using a linear image sensor with fewer pixels, e.g. 2000 pixels instead of 8 million (2D image sensor), can achieve significantly higher line scan rates and less data needs to be processed by an algorithm compared to the image-recognition algorithm from previously proposed solutions. This can results in a significant improvement in the sample rate at the desired cost.

The linear CCD performs line scans, which measures the intensity of the light reflected from the illuminated pattern on the pixels of the sensor. The measured intensity profile will have a waveform of the 2 sinusoidal gradients (Figure 3(b)). By fitting the data, the sinusoidal functions can be obtained to determine the relative planar 3DOF position information, by comparing them with the previous line scan. However, the sensor system consists of different components which all can influence the performance of the system. It is desired to obtain the most optimal signal out of the linear CCD when scanning the Moiré pattern. A perfect signal of the sinusoidal waveforms without any noise or irregularities is not possible from a line scan. Although it can be reduced significantly if the source of the noise and irregularities are known and can be accounted for.

The main challenge of this research is to obtain relative 3DOF($xy\theta_z$) position information with a single linear image sensor. This consists of two tasks: first pattern design for using it with a single linear image sensor. Secondly, developing and implementing a sensor system to validate the concept. In the following, we will explain the components of the proposed sensing system, their design methodology and the required data processing.

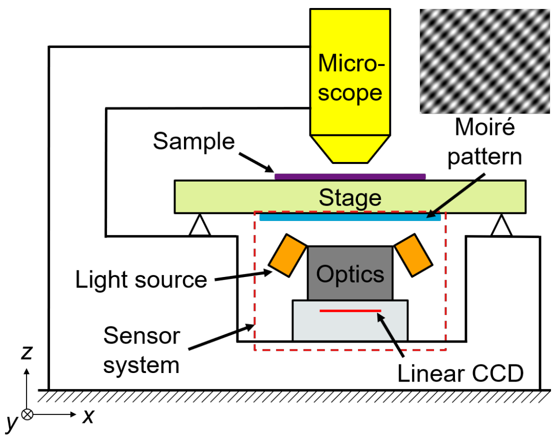


Fig. 1. Conceptual design sketch for a microscope application. The planar stage can move in 3DOF($xy\theta_z$), mainly in x and y, while θ_z is measured for alignment. It has a sample on top and the Moiré pattern attached to the bottom side of the stage. The sensor system is placed under the stage, where the linear CCD is facing the pattern. Scanning the pattern with the sensor system will give the relative 3DOF position information.

A. Line scan camera

The linear image sensor of the line scan camera performs line scans, which measures the intensity of the light reflected from the illuminated pattern on the pixels of the sensor. A (linear) image sensor, e.g. CCD and CMOS, is a photosensor which measures the intensity of the light on the photosensitive surface, the pixels, by the principle of the photoelectric effect [16].

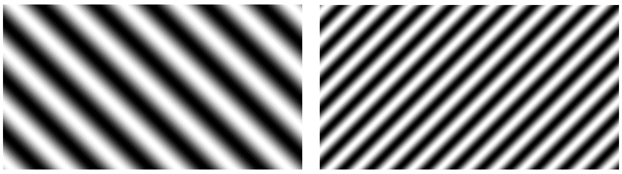
The linear CCD itself has different noise sources which affect the scan performance, which are e.g. quantum efficiency, quantum yield, read noise, shot noise (photon noise), charge transfer efficiency, linearity, dark signal, dark noise and fixed pattern noise. These need to be considered and if possible taken into account during the measurements.

In this work, we use a Thorlabs CCD line camera (LC100) for the validation of the sensor system, operated over a USB connection. The line camera uses a cost-effective Sony ILXB554 linear CCD, which has a total of 2048 pixels (pixel sizes of 14 µm (width) x 52 µm (height) (14 µm pitch), effective pixel length of 28,67 mm). Which is originally intended for barcode hand scanners and optical measurement equipment applications.

B. Moiré pattern design

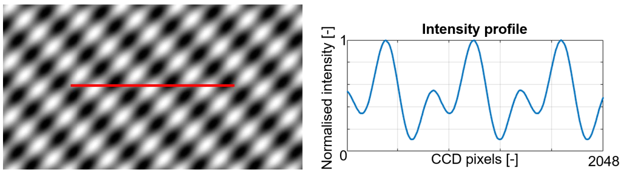
To obtain the relative planar 3DOF position information with a single linear CCD, a smart selection of image pattern is required that contains information on all 3 degrees of freedom. A simple realisation consists of 2 sinusoidal black and white gradients with different spatial frequencies rotated by 90°, to create a Moiré pattern. This resulted in a self-designed 2D Moiré pattern (Figure 3(a)).

The initial 2 sinusoidal patterns (pattern 1 and 2) are formed by sinusoidal functions, where the frequency of pattern 2 is twice the frequency of pattern 1. Also, these patterns have been rotated by 45° in opposite directions to get the final initial



(a) Pattern 1 (b) Pattern 2

Fig. 2. The 2 base patterns which forms the Moiré pattern in Figure 3(a). (a) Pattern 1, a 45° rotated sinusoidal gradient. (b) Pattern 2, a 45° rotated sinusoidal gradient with a frequency of a factor 2 higher than pattern 1.



(a) Designed Moiré pattern (b) Intensity profile of from the line scan in (a)

Fig. 3. (a) Designed Moiré pattern with a red line representing the line scan by the linear CCD as shown in (b). (b) Intensity profile simulation from the line scan in (a) of the Moiré pattern. Each pixel of the linear CCD measures the intensity of the reflected light, resulting in an intensity profile from a line scan. The intensity profile of the pattern is the superposition of the two sinusoidal gradients, which can be clearly seen in the figure.

patterns 1 and 2 (Figure 2), which are the foundations of the realised 2D Moiré pattern. This designed pattern is limited by the range of the rotation θ_z, the directions of the θ_z can be distinguished theoretically for rotations $< \pm 45°$.

The sensing system needs to observe at least 1 period of pattern 1 and 2 of the Moiré pattern for the algorithm to fit the data properly, more periods are beneficial for the robustness of the fitting algorithm. However, it is a trade-off between the resolution and how much the sensing system can observe, the field of view (FOV). Because scaling the pattern down in order to have a bigger FOV, the resolution of the print needs to be higher. Same goes for using an optical magnification, using an optical magnification > 1 the FOV reduces and the resolution of the print appears to be lower. This can be compensated for by increasing print resolution. For optical magnification < 1, the FOV increases and the resolution of the print appears to be higher. However, the movements of the pattern are also scaled with respect to the optical magnification. For example, when the sensor system has an optical magnification of 0.5, the observed movement of the pattern is a factor 2 smaller. This reduces the resolution of the sensor system by factor 2. Also, the optics can be diffraction-limited when using big optical magnifications.

The designed Moiré pattern needs to be easily manufactured for a low-cost. Therefore it is desired to print the pattern with either a laser or inkjet printer which are widely accessible and cost-effective. This case, increasing the range of the sensor system can be easily achieved by printing the pattern on a larger substrate. The printed pattern requires smooth gradients for an optimal line scan data. Therefore, it is necessary to achieve high-resolution prints, limited by the printers' DPI capabilities and other properties. The substrate where the pattern is printed on needs to be considered as well. White printer paper and white photo paper has been investigated printed on a laser and inkjet printer.

Digital and print resolution can affect the quality of the printed gradients, these gradients need to be as smooth as possible. However, from the printing properties of a laser and inkjet printer, an image is formed by tiny droplets of ink. To create a gradient, these droplets are placed in such a pattern that the printed gradient looks optically smooth from a distance. But taking a closer look, the individual droplets can be seen which formed the gradient. This can directly affect the signal, therefore a high-resolution print is needed. Besides the resolution, the substrate where the pattern will be printed on, needs to have a smooth and uniform surface, any irregularities in the substrate will be seen by the line scan.

C. Simulation analysis for Moiré pattern selection

In order to develop a functional detection method and for validating the choice of detection pattern, we developed a MATLAB tool that simulates the functionality of the proposed sensing system.

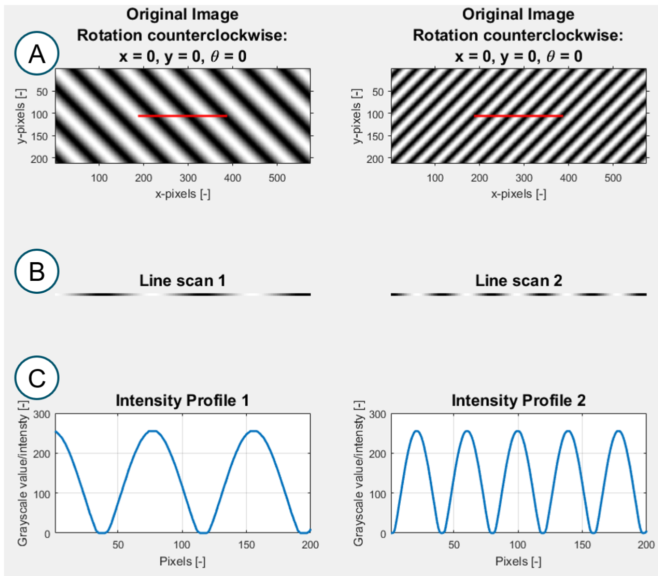


Fig. 4. Overview of the self-developed line scan simulation tool in MATLAB. (A) Imported image of the pattern, red line visualise the scanning area. (B) Grayscale image as seen by the by the line scan. (C) Intensity profile of the line scan.

We first simulate the functioning of a perfect line scan camera above a moving pattern. An image of the pattern is first imported and converted to a grayscale image (Figure 4(A)), a fixed line of red pixels is projected on top of the pattern for visualisation of the image portion seen by the line scan camera. The grayscale image seen by the line scan camera is visualised in Figure 4(B), and its output values of intensity (0 to 255) are shown in Figure 4(C). With this simulation tool, it is possible to move the pattern in each of the planar 3DOF($xy\theta_z$), in order to analyse the intensity profiles of the moving pattern and to develop the data processing method.

D. Fitting algorithm

In order to extract relative position data from the line scan camera output, it is necessary to develop an algorithm that can fit the sensor reading with two sinusoidal signals (see Figure 3(b)) and further determine position and rotation from their frequencies and phase shifts. This algorithm is developed using the MATLAB simulation tool developed in Section II-C.

The workflow of the developed algorithm is described below and visualised in Figure 5:

1) Perform a line scan of the Moiré pattern
2) Obtain line scan data
3) Fit the line scan data to a sum of 2 sinusoidal functions
4) Obtain the frequency and phase of each sinusoidal function, like it is scanning pattern 1 and 2 separately at the same time and location
5) Redo steps 1-4 to perform a second line scan to obtain the coefficients of the sinusoidal functions
6) Compare the frequencies and phases to determine a relative displacement in the 3DOF

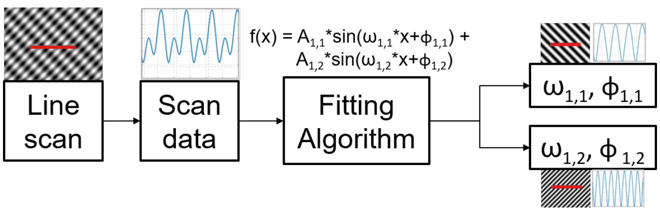


Fig. 5. Workflow of the fitting algorithm, step 1-4.

E. Imaging the pattern

In order to image the pattern, it is necessary to assure illumination of the pattern and projecting its image on the linear CCD. Therefore, it is necessary to choose a suitable lens configuration and tailor a suitable illumination solution.

Lens selection and placement defines the optical magnification of the system. Larger magnifications provides better sensing resolution, while decreasing the field of view. Due to the limited pattern resolution (see Section II-B) and to allow for larger prototyping tolerances (i.e. depth of field) we implemented a magnification of (-)1 in this work. A small aperture is required to increase the depth of field, this is achieved by placing a diaphragm in front of the lens. This in turn, limits the light pass onto the linear CCD. At high scan rates, the short integration time of the pixels further limits the detection of the illumination. Therefore, a bright enough light source is required in order to work near saturation limits of the CCD to obtain a high signal-to-noise ratio (SNR).

Furthermore, an uniform illumination profile is needed. This is especially challenging due to lens vignetting. In order to illuminate the pattern, we first studied a single LED and investigated to use a diffuser to create an uniform illumination profile. The diffuser did not worked out as the intensity of the LED was reduced too much in order to obtain proper data with the sensor system. Then turned to a LED module with 15 LEDs placed in a linear array.

F. Assembled measurement system

The measurement system of the sensor system consists of the CCD line camera, a biconvex lens and a diaphragm for the optics parts and LED(s) for the light source. These are assembled in a 3D printed housing to hold all the components in their place. The configuration of the measurement system can be seen in Figure 6. And the overview of all the components can be seen in Figure 7. The line camera is connected to a laptop by the USB port to power and drive the line camera, but also to obtain the line scan data on the laptop. The LED(s) are powered externally.

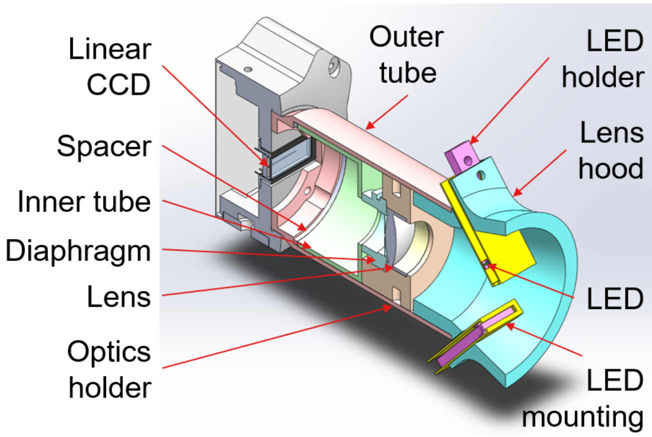


Fig. 6. Cross-section view of the configuration of the measurement system.

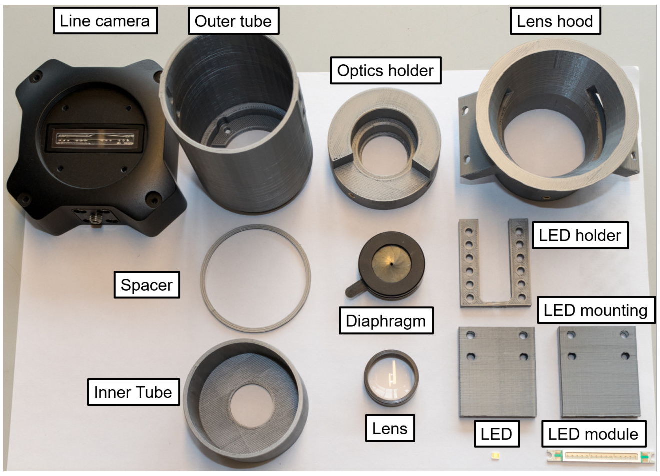


Fig. 7. Overview of the components in the realised measurement system.

III. Demonstrator

A demonstrator (Figure 8) was designed and built (Figure 9) in order to validate the feasibility of the sensing method and how components in the implementation affect its performance.

In the demonstrator set-up, the measurement system containing the line scan camera is stationary in our implementation. It is attached to a frame with the CCD sensor facing downwards, whereas a focus stage is added in order to manually focus on the pattern during preparation. The printed

Moiré pattern is placed directly under the measurement system and the pattern is attached on a mobile stage. During the experiments, we measure each of the 3 DOFs individually. We use a motorized linear stage and turn it by 90° for x and y measurements, and interchanged it with a manual rotation stage to measure the rotation θ_z.

The following stages are used in the demonstrator:

- Manual focus stage: Thorlabs PT1(/M) translation stage (10 μm per Division)
- Motorized linear stage: Thorlabs DDSM100/M (0.5 μm resolution) + TBD001 controller
- Manual rotation stage: Thorlabs CR1/M rotation stage (1.5 mrad resolution)

The motorized linear stage controller is connected to a personal computer (PC) via USB interface, to drive the stage and obtain position information of the internal encoder of the stage. The line scan camera is connected to the same PC via USB interface. Both the line camera and stage are controlled in a MATLAB environment that acquires the data, executes the processing algorithm and stores the data.

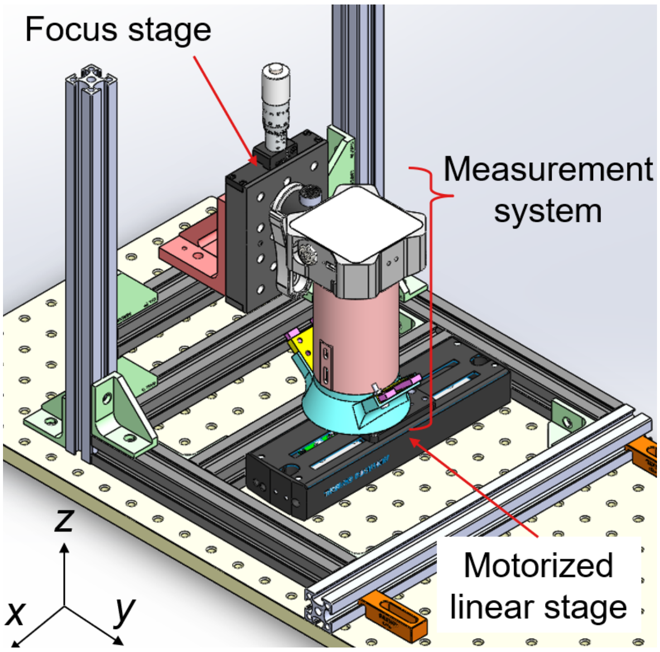


Fig. 8. 3D CAD model of the demonstrator. The sensor system consists of the CCD line camera, 3D printed housing with the optics and LED(s) and the printed Moiré pattern (not shown in the figure). The focus of the sensor system can be adjusted with the focus stage. The linear CCD (pixels along the x-direction) faces the topside of the moving platform of the motorized linear stage, where the pattern is attached on. The linear stage can be rotated with 90° or replaced with a manual rotation stage in order to measure each of the 3DOF($xy\theta_z$) individually.

IV. Validation Methodology

The demonstrator in Section III has been developed in order to demonstrate the functionality of the proposed methodology and to report characteristics of the sensitivity of the different parameters in the sensor system. Validation experiments consist of calibrating the measurement system, making fine-tuning adjustments to the sensor system, and eventually measuring its precision in all 3 DOFs.

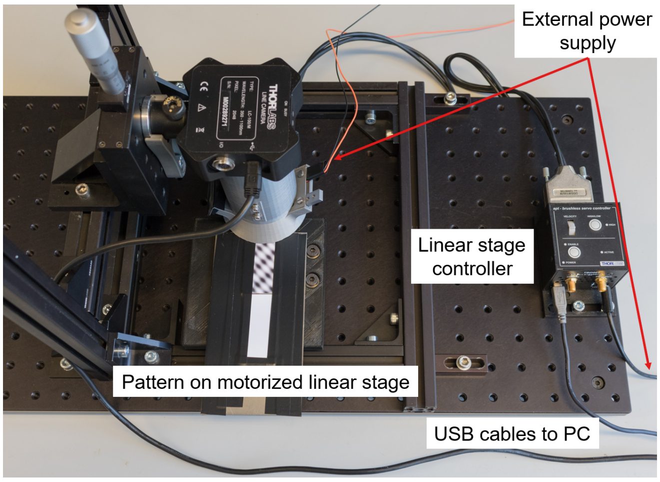


Fig. 9. The realised demonstrator, with the Moiré pattern on the motorized linear stage.

A. Calibration

The sensor system needs to be calibrated before it can be used for the measurements. CCDs exhibit many properties that must be accounted for in setting up the sensor system, whereas most of them are reported by the manufacturer in the documentation. In sensor calibration, we must account for the dark noise (temperature-dependent background noise) and fixed pattern noise (sensitivity variations from pixel to pixel)[16].

The calibrations steps go as follows: (1) first the sensing system needs to be set in focus with the focus stage. (2) Next, the line camera needs to warm up to achieve a steady-state operating temperature to reduce the dark noise variations in the CCD. (3) Next, the intensity profile of the non-uniform illumination and the fixed pattern noise are corrected in a single calibration step. This is done by taking multiple line scans (50) of the white substrate material with no pattern printed on it. A correction factor is determined for every pixel in the line sensor by normalising each pixel's average reading to the maximum reading and take the inverse. After correction, scaling to the white substrate results in an intensity profile reading of approximately 1 for every pixel.

Calibrations for the algorithm needs to be performed for the measurements of the relative displacements when moving the pattern with a stage. For the translational movements, the algorithm needs to be calibrated in order to know how much phase shift is equivalent to a displacement of the pattern. This is done taking multiple line scans at 2 predefined positions and use the encoder position data of the stage as the reference, to obtain a conversion factor for phase shift to displacement. For convenience, the calibration step of the algorithm is included when taking the measurements, the first 100 scans and encoder positions are used by the algorithm to determine the conversion factor of phase shift to translation. For the rotation measurements, the calibrations steps are done in a similar way. However, the algorithm determines the conversion factor based on the phase shift and frequency changes to convert it to rotation.

B. *Tuning the sensor system*

With the demonstrator, the sensitivity of the sensor system can be investigated. Besides focussing the camera on the pattern, it is necessary to implement a sufficiently uniform illumination profile and achieve a pattern print quality that does not limit the measurement resolution.

Pattern illumination depends on the light source, and it is desirable to illuminate the pattern uniformly for even sensitivity over the linear CCD. The uniformity of the illumination on the pattern can be adjusted, by changing the light source from a single LED to a linear array of LEDs (LED module). The illumination profile from the calibration method can be compared and the corrected line scan data will be analysed. Where the focus lies on the noise of the signal due to different illumination uniformity.

The printed pattern has many parameters to create the pattern, which can affect the signal as mentioned in Section II-B. Where the resolution needs to be as high as possible and the substrate needs to have a smooth and uniform surface. Line scan analysis of the printed pattern is performed on 2 different types of printers: laser printer (Xerox AltaLink C8035) and an inkjet printer (HP Envy 5010 All-in-One). Using different substrates, white printer paper and white photo paper (only for inkjet). Effects of the uniformity of the illumination have been studied by using a single LED and a LED module.

As noise and outliers are always present during measurements, some signal conditioning can be applied by the algorithm in order to improve the robustness of the fitting process. This is achieved by using median filtering when processing the data.

C. *Sensor system performance*

The performance of the sensor system is characterised by using the demonstrator described in Section III. The pattern is moved in 1DOF using the translational or rotational stage, and measurements are taken quasi-statically.

The pattern is placed on top of the stage which is programmed to move back and forward between 2 predefined positions, the reference position of the stage is obtained from the internal encoder.

After the calibration of the algorithm (IV-A), the stage is programmed to move back and forward between 2 predefined positions, the position of the stage is obtained from the internal encoder. For every position, the sensor system performs 25 line scans before the stage moves again, with a step size of 20 µm. From these line scan data, the algorithm determines the position of the stage. This position information from the sensor system can be compared to the data of the internal encoder to determine the measurement error. For the θ_z, the manual rotational stage is used instead of the motorized linear stage, with a step size of 1°. The time of 1 sample, from line scan to position information, can be measured during the measurements with the algorithm. From this information, the sample rate of the sensor system can be determined.

V. Results

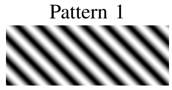
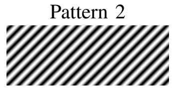
A. *Design and analysis*

The 2D Moiré pattern was designed by combining two individual patterns as described in Section II-B. Simulation of these individual components moving in each of the 3DOF are illustrated in Figure 10 and characterised in Table I. It can be seen that both directions of every DOF can be distinguished and measured, since they correspond to a unique combination of changes in the sine wave frequencies and phase shifts. Therefore, each DOF and direction can be measured and distinguished from each other. This was further confirmed in the simulated measurements on the combined pattern (see Figure 3).

Test-printing the Moiré pattern with the inkjet printer indicated that the substrate significantly influences noisiness of the measurement as seen in Figure 13 and 15. It is clearly seen in Figure 11 that white photo paper performs significantly better than white printer paper.

Uniformity of the illumination has been measured for the single LED and the LED module on white photo paper. The single LED illumination gets 2.2-2.8 times darker towards the edges (see Figure 16), and therefore the applied compensation causes noise as shown in Figure 12. For the LED module this factor is only up to 1.3 (see Figure 17), resulting in a more equal noise level difference over the linear pixel array as seen in Figure 11.

TABLE I
Analysis results from the line scan simulations of the two patterns, where the symbols indicates if the frequency/phase shift is decreasing (-), increasing (+) or remains the same (=) for the given movements of the pattern.

	Pattern 1		Pattern 2	
				
	Frequency	Phase shift	Frequency	Phase shift
Rotation CCW	-	+	+	-
Rotation CW	+	-	-	+
Right	=	-	=	-
Left	=	+	=	+
Up	=	-	=	+
Down	=	+	=	-

B. *Calibration*

Non-uniform illumination and fixed pattern noise were calibrated according to Section IV-A. Results of the printer and photo paper are shown in Figure 13 and 15. Results of the calibration can be found in Figure 14 and 16. These results allow to correct for the fixed pattern noise and non-uniform intensity of the normalised scan data and clearly shows that photo paper affects the illumination profile significantly less than printer paper.

C. *Sensor system performance*

Results of the sensor system performance were characterised for the x-direction (along the pixels of the linear CCD) as described in Section IV-C. Due to time constraints, the

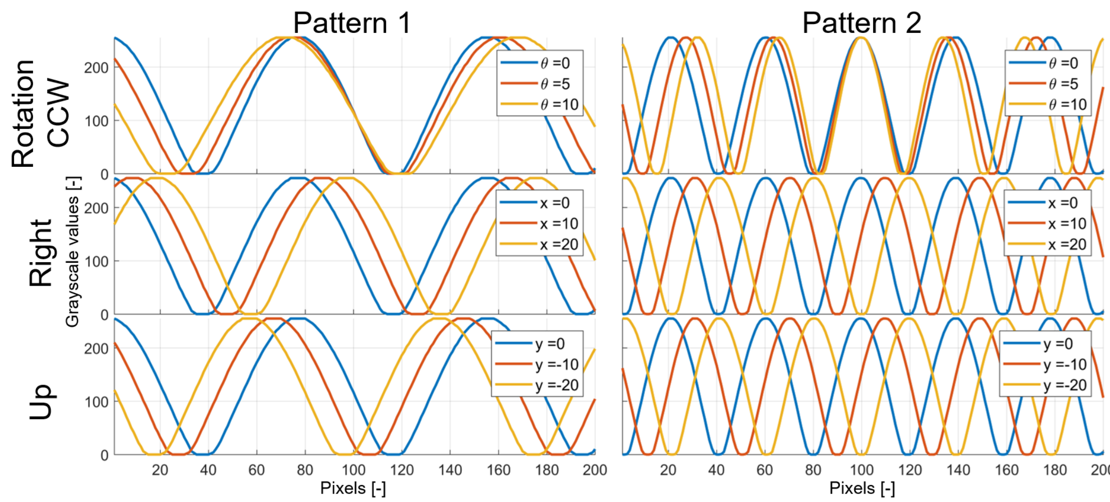


Fig. 10. Simulated intensity profiles of pattern 1 (left) and pattern 2 (right), 3 positions of every DOF in 1 direction can be seen in every figure. Patterns always start in the same initial position $(x, y, \theta_z) = (0, 0, 0)$ (blue lines) and for every position in 1 DOF, the other 2 DOFs are kept at 0. The position and the direction of the movement of the pattern can be found in legend of each figure.

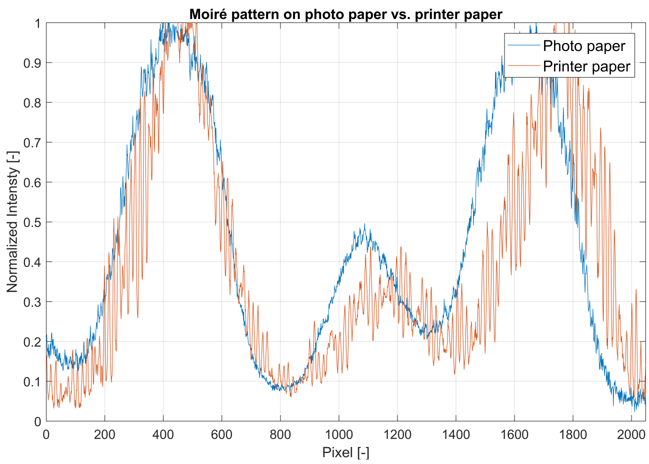


Fig. 11. Line scan of the Moiré pattern printed on white photo paper and white printer paper, printed with the same settings on inkjet printer.

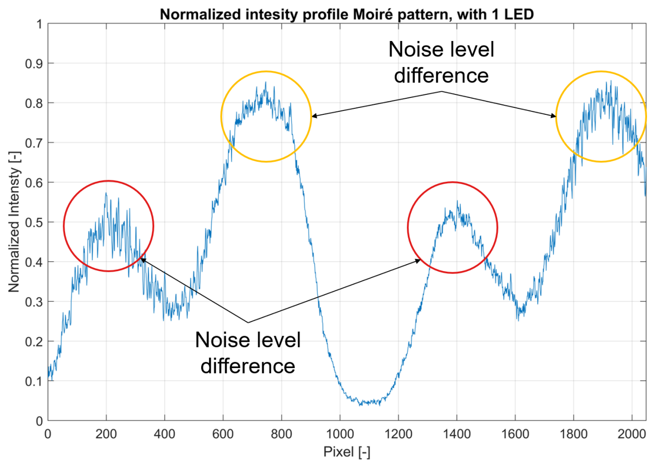


Fig. 12. Line scan of the Moiré pattern printed on white photo paper (inkjet printer), single LED illumination. Noise level differences along the pixel array are highlighted.

measurements were only performed for one DOF. The Moiré pattern, printed with the inkjet printer on white photo paper, has been during the measurements. However, the results are presented by the performance of pattern 1 and 2 (Figure 2) separately. Because the algorithm fits the line scan data of the Moiré pattern to the sum of 2 sinusoidal functions and obtains the coefficients for both sinusoidal functions as described in Section II-D. The algorithm basically separates pattern 1 and 2 from the scanned Moiré pattern, to analyse and determine if the Moiré pattern is moving.

For displacements of 20 µm of the stage with a single LED illumination (Figure 18), the position determined from the fitting algorithm is able to achieve a precision of 13 µm (3σ) (Figure 19), by using only the coefficients of pattern 1 while scanning the Moiré pattern. While using only the coefficients of pattern 2, a precision of 113 µm (3σ) was achieved.

For (sub-pixel) displacements of 10 µm of the stage with the LED module illumination (Figure 20), it was possible to achieve a precision of 8 µm (3σ) (Figure 21), by using only the coefficients of pattern 1 while scanning the Moiré pattern. From the coefficients of pattern 2, a precision of 83 µm (3σ) was achieved.

An average sample rate of 20 Hz has been measured during these measurements. Time for 1 sample is about 50 ms, where the integration time is only 1.54 ms, the fitting process is on average 30 ms and the remaining time is consumed by the algorithm to log the data and to analyse the data to obtain position information.

VI. Discussion

A sensor system and demonstrator has been realised in order to prove and validate the proposed methodology through simulations and experiments.

Feasibility was shown with the simulation results. Simulations showed that it is feasible to obtain planar 3DOF position

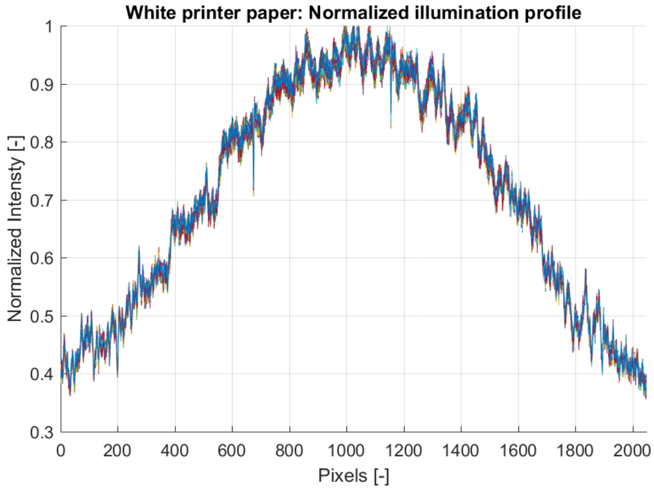


Fig. 13. Normalized illumination profiles of multiple (50) scans of a white printer paper, illuminated with a single LED.

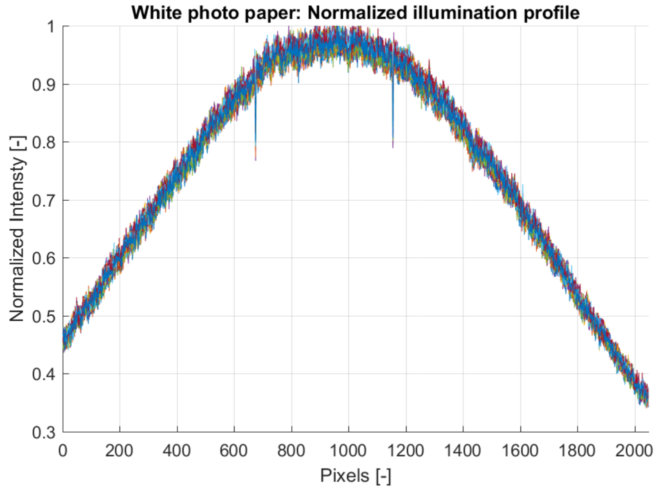


Fig. 15. Normalized illumination profiles of multiple (50) scans of a white photo paper, illuminated with a single LED.

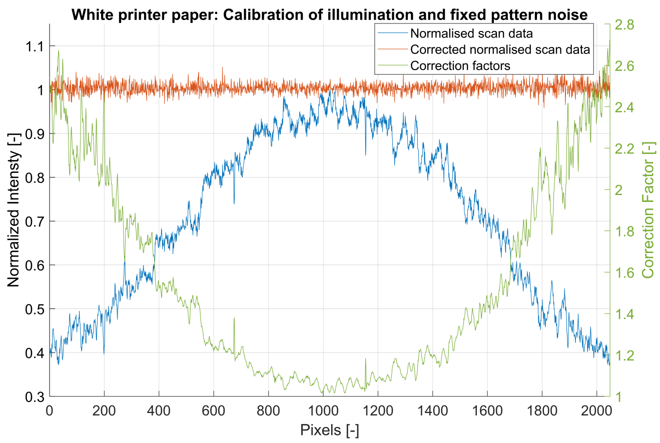


Fig. 14. Calibration results of the non-uniform illumination and fixed pattern noise of a white printer paper illuminated with a single LED. A normalised scan data of a single line scan is corrected by the correction factor per pixel, determined from Figure 13.

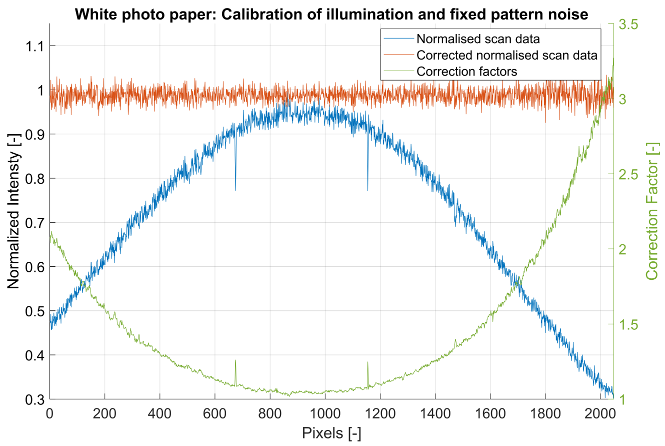


Fig. 16. Calibration results of the non-uniform illumination and fixed pattern noise of a white photo paper illuminated with a single LED. A normalised scan data of a single line scan is corrected by the correction factor per pixel, determined from Figure 15.

information with a single linear image sensor and the designed 2D Moiré pattern has been proven. It was found that the algorithm is capable of fitting the pattern in the planar DOF of the realised sensor system. And able to track the pattern when moving in those directions. Which means that the methodology of using a single linear image sensor can be used to measure the planar 3DOF, with θ_z only for a limited range.

The results of the performance demonstrated the possibilities of the realised sensor system. Quasi-static measurements have been performed in the x-direction (along the CCD pixels), by measuring a predefined motion of the linear stage. This resulted in a precision of 13 µm (3σ) with a non-uniform illumination and the pattern printed on photo paper. By using the LED module, with a more uniform illumination, a precision of 8 µm was achieved. Where the sampling rate of 20 Hz is limited by the algorithm, the fitting process is the bottleneck for the speed of the implemented algorithm.

Factors that affect the sensing performance are investigated during the measurements. Multiple line scans of the pattern have been taken while the pattern is fixed. The noise within the data of the different line scans is not very constant, this results in a deviation of the obtained information from the algorithm, causing position errors. The sensitivity of the sensor system is highly influenced by noise and irregularities in the line scan data because the algorithm is either unable to fit the data or it will cause inaccurate fits. Resulting in significant position errors. The parts of the sensor system which affects the line scan data significantly are the light source and the printed pattern. Parameters of the light source which affects the signal are the intensity and uniformity of the light source. While the printer characteristics and substrate influence the printed pattern significantly.

From the simulations results, the feasibility to obtain planar 3DOF position information with a single linear image sensor and the designed 2D Moiré pattern has been proven. It was found that the algorithm is capable of fitting the pattern in the

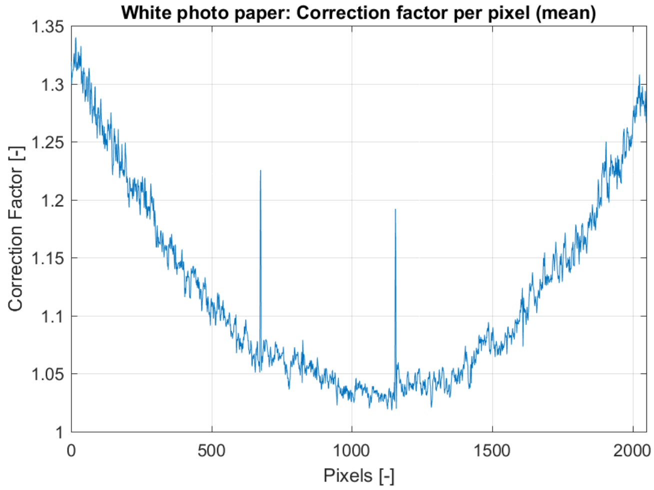


Fig. 17. Correction factors per pixel, averaged over the multiple scans of a white photo paper illuminated with a LED module.

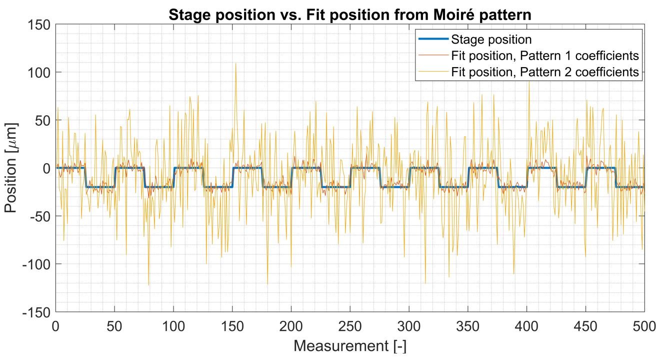


Fig. 18. Measurements of the position from scanning the Moiré pattern in the x-direction on the linear stage. Stage position obtained from stage encoder, fit positions determined from coefficients of pattern 1 and 2 separately. Single LED illumination and step size of 20 µm.

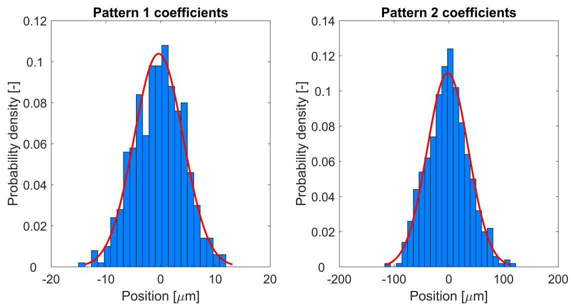


Fig. 19. Positioning precision in the x-direction from scanning the Moiré pattern on the stage. The red line is represents a normal distribution. Precision from coefficients of pattern 1: 13 µm (3σ), pattern 2: 113 µm (3σ). Single LED illumination and step size of 20 µm.

planar DOF of the realised sensor system. And able to track the pattern when moving in those directions. Which means that the methodology of using a single linear CCD can be used to measure the planar 3DOF, with θ_z only for a limited range. However, the measurement results are left out for the y and θ_z, as the noise is too dominant and affects the performance

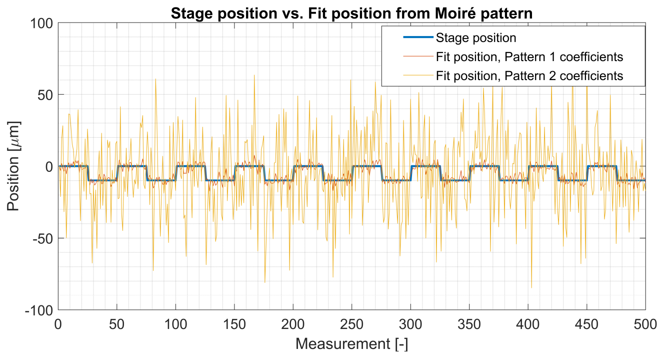


Fig. 20. Measurements of the position from scanning the Moiré pattern in the x-direction on the linear stage. Stage position obtained from stage encoder, fit positions determined from coefficients of pattern 1 and 2 separately. LED module illumination and step size of 10 µm.

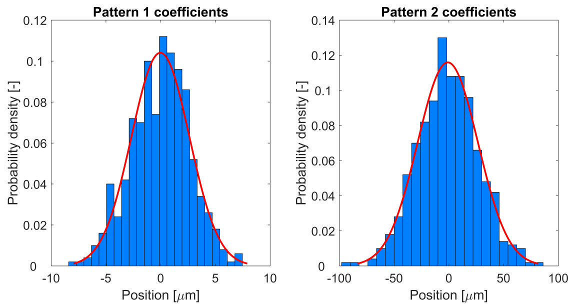


Fig. 21. Positioning precision in the x-direction from scanning the Moiré pattern on the stage. The red line is represents a normal distribution. Precision from coefficients of pattern 1: 8 µm (3σ), pattern 2: 83 µm (3σ). LED module illumination and step size of 10 µm.

significantly.

The resolution of the sensor system can be improved by using a different optical magnification, this improvement is limited by the diffraction limit, the print resolution and quality. Using smaller pixel sizes in the linear image sensor can improve the resolution as well.

For the validation of the sensor system, a relative expensive Thorlabs CCD line camera has been used. While the used linear CCD in the camera, Sony ILXB554, is available for under €10. It is possible to develop a line camera with just a low-cost linear CCD with additional electronics to drive the CCD for only €25.

The speed of the current sensor system is only 20 Hz in sample rate. The fitting process is the most time-consuming part of the algorithm. Optimizing the current algorithm and implementing it on a field-programmable gate array (FPGA), will improve the performance of the sensor system significantly. Or using other methods in the algorithm instead of fitting the data, like Fast Fourier transform (FFT) could improve the sampling rate. Besides the algorithm, the sensor system can be optimized to achieve better precision with improved print quality, optics and illumination.

The feasibility of the proposed methodology to measure relative planar 3DOF($xy\theta_z$) with a single linear image sensor has been successfully shown with the simulations and demonstrate with the realized sensor system implemented in a demonstrator. The current sensor system has the possibility to measure more than the planar 3DOF, out of plane motions z and rotation θ_y can be observed in the current configuration. While θ_x can not be measured with the current sensor system without any adjustments. Using a smart pattern design in combination with an algorithm, absolute position information can be obtained from line scans. These have not been investigated in this paper but are certainly interesting topics for future work.

VII. Conclusions

3DOF($xy\theta_z$) planar precision stages are required in applications like low-cost microscope stages. This research presented a new method to obtain relative 3DOF($xy\theta_z$) position using a single 1D image sensor and a 2D Moiré pattern, and experimentally demonstrated its feasibility.

First, a line scan simulation tool was developed in MATLAB, allowing to analyse effects of different image patterns and position extraction algorithm. Next, analysis of the sensor system was performed in order to optimise the system for a line scan CCD camera. Further, a demonstrator of the sensor system is built and implemented on a positioning stage for demonstration and experimental validation. Measuring each of the 3DOFs individually, the sensitivity of the system to the properties of elements was analysed. The system achieved a precision of 8 µm (3σ) in the x-direction (along the pixels) and a sample rate of 20 Hz. This sampling rate is limited by the way we needed to implement the algorithm for analysing the data and can be significantly increased. Compared to the previous 3DOF measuring systems that consist of a QR-code and a 2D camera, a 1D CCD can achieve similar precision, while having the potential to be cheaper and significantly faster. Therefore, the proposed methodology makes it possible to realise high-bandwidth and high-resolution using line image sensors, to meet the increasing demand for micrometre precision stage applications with the continuously advancing technology. The bandwidth of the system can be increased significantly by using a more efficient algorithm and implementing this in an FPGA. Improvements on the sensor system will be addressed in our future work to realise sub-micron resolution.

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4 Discussion

The objective of this thesis was to obtain relative 3DOF($xy\theta_z$) position information for planar precision stages with a single 1D CCD. With the goal to achieve the same micrometre precision and to increase the sample rate significantly with the new method compared to the van Moorsel sensor system.

4.1. Comparison with the 2D image sensor system

The van Moorsel sensor system achieved a translational precision in x and y of 16 µm (3σ), while the proposed sensor system with a single linear CCD achieved a translational precision of 8 µm (3σ) in the x-direction. The precision in y and θ_z could not be easily measured because the noise was too dominant in the current sensor system, which affects the data too much to obtain accurate measurements in y and θ_z with the algorithm. Due to time constraint, the sensor system could not be optimized further to perform these measurements. However, the output signal, when moving in y and θ_z, behaves like the simulation and the algorithm is able to fit the data, which means that the developed sensor system is able to obtain the planar 3DOF position information from the 2D Moiré pattern with only a single linear CCD.

The van Moorsel sensor system reported a sample rate of 16 Hz, which was mainly limited by the 2D image sensor and the image-recognition algorithm. The realized sensor system in this research achieved a sample rate of about 20 Hz, which is a factor 1.25 faster. Compared to the van Moorsel sensor system, this sensor system is not limited by the scan rate of the used sensor, but mainly by the relatively slow self-developed MATLAB algorithm to fit the line scan data. This algorithm was mainly developed in order to demonstrate the feasibility of obtaining planar 3DOF position information with a single linear CCD from the designed Moiré pattern and not necessarily for speed performances.

4.2. Limitations of the sensor system

The performance of the developed sensor system is mainly limited by the relative slow MATLAB algorithm. Fitting the data is the most time-consuming process to obtain position information from a line scan in the algorithm. MATLAB might not be the most optimal method in terms of speed to do this, but it is a great program to analyse data, as the purpose of this research is primarily focused on the methodology to obtain 3DOF position information form a single line scan.

The resolution of the sensor system can be improved by using an optical magnification > 1. However, the noise and irregularities in the pattern will be amplified as well in the line scan data. The resolution of the printed pattern needs to be significantly higher and the material needs to be uniform as possible. Other manufacturing techniques might be needed to obtain an optimal pattern. Also, the illumination plays a role, this needs to be uniform as possible to get rid of differences in noise levels along the pixels of the linear CCD. The resolution of the sensor system can be optically limited by the wave nature of light due to the diffraction limit.

The pixel size of the CCD are relatively large compared to other available linear CCDs. By using a CCD with smaller pixel sizes, the resolution of the sensor can be improved significantly. However, there is a downside by using smaller pixel sizes, as this results in strong sensor noise. This can affect the performance of the fitting algorithm negatively. So it is a trade-off between sensor resolution and the noise induced by the sensor.

The designed Moiré pattern in combination with the linear CCD can only be used for relative position information. This is in most application, not a real issue, however, it does have some additional value if absolute position information can be implemented in the sensor system. Also, the rotational range is limited to $< \pm 45°$ theoretically, as the direction of the rotation in θ_z can not be distinguished anymore due to the symmetry of the pattern at an angle $45°$.

The sensor system is not insensitive to out of plane motions in the z-direction and rotation around the y-axis, θ_y. These are not considered by the algorithm, however, they can appear as a displacement in the planar 3DOF when fitting the data with the algorithm, causing position errors. This is neglected in the demonstrator as the measurements were taken only in DOF for each measurement. But it can be a problem when using a planar stage with ferrofluid bearing, were the height of the mover of the stage changes due to the trail formation of the ferrofluid when moving [2].

4.3. Recommendations and future work

4.3.1. Recommendations

Optimisation of the current sensor system

Optimise the current sensor system by reducing the noise and irregularities observed by the sensor system to increase the resolution. The significant noise sources are caused by the resolution of the printed pattern and the reflected illumination uniformity of the pattern on the pixels of the CCD. The irregularities observed in the signal are mainly caused by the material properties of the substrate which the pattern is printed on. Obtaining high-resolution prints of the pattern on a substrate which has a homogeneous surface without any flaws can reduce the noise and irregularities. Other alternatives to create the pattern can be investigated as well to achieve this, such as analog film and etching. The uniformity of the reflected light on the pixels can be achieved by adapting the light source or by using an optical filter to compensate the non-uniformity.

Alternative for the relative expensive Thorlabs LC100 CCD line camera

An alternative CCD line camera for the LC100 is a USB Line Camera form COPTONIX[1]. This is also a plug-and-play type of line camera with the same Sony ILX554B linear CCD as the LC100, without a housing like the LC100. And some other software to perform line scans and to change the settings. The price is only €250 instead of the €1250 for the LC100. From the specifications, only the maximum scan rate is lower compared to the LC100, which is 364 scans/s instead of 900 scans/s. The COPTONIX line camera consists of two circuit boards, the main circuit board and the sensor circuit board. The main circuit board supports different sensor boards, so it is also easily possible to change the sensor board, with other linear CCD or CMOS sensors with different amount of pixels, pixel sizes and characteristics.

Low-cost

As mentioned in Section 2.2 a low-cost CCD with additional electronics has already been developed for only €25. Where the maximum scan rate (125 Hz) is dependent on both the communication protocol and the CCD clock. Which means that a low-cost sensor system is certainly possible to realise by using a low-cost linear CCD and additional electronics to drive the CCD.

Imaging

Obtain images with the line camera, the output signal is now only an intensity profile of the pattern. It should be possible to convert this intensity profile to an actual image just like a camera by programming. To observe what the line camera actually sees and to visually check if the pattern is in focus.

Increase sample rate

To obtain significantly higher sample rates with the linear CCD, the hardware and software need to be improved. This can be achieved by optimizing the algorithm, programming in C/C++ for speed or Julia (scripting language like MATLAB and Python, but with the speed of C/C++) and implementation in hardware like a field-programmable gate array (FPGA). Or using other methods instead of fitting

[1] `https://www.coptonix.com/_en/html/usblinecamera.html`

the data, like Fast Fourier Transform (FFT) to obtain the frequency and phase shift of the sinusoidal functions.

4.3.2. Future work

Absolute position information

This sensor system is able to measure relative position information, but absolute position information does have an added value for other applications. So a pattern which contains absolute position information and an algorithm which can obtain the information from line scanning the pattern could be developed to make this sensor system compatible for more applications. This can be achieved with for example adding markers in the pattern, which can be decoded by the algorithm to obtain absolute position information.

Possibilities to obtain more than 3DOF

The sensor system is not insensitive to 2 other DOF as mentioned in Section 4.2. However, this does not have to be a limitation of the sensor system. Because the sensor system has the possibility to measure more than the planar 3DOF, with the current system it is theoretically possible to obtain information about the height z and the rotation about the y-axis, θ_y. In order to measure the rotation about the x-axis, θ_x, adjustment to the current sensor system is needed to make the sensor system sensitive for θ_x and the other DOFs. Investigating the possibilities in obtaining the 6DOF position information with a single linear CCD can result in an alternative low-cost sensor system for a wider field of applications in the future.

5
Conclusion

This research presents a new methodology to obtain relative 3DOF($xy\theta_z$) position data for planar precision stages with a single 1D CCD and a self-designed static 2D Moiré pattern. The developed sensor system consists of a CCD line camera, optics, light source and a printed 2D Moiré pattern. Which achieved a precision of 8 µm (3σ) in the x-direction (along the pixels of the CCD) and a sample rate of 20 Hz. Where the sample rate is limited by the algorithm.

3DOF($xy\theta_z$) planar precision stages can be used in applications like microscope stages to move the sample. It is desired to translate the stage in the x- and y-directions, while the rotation θ_z needs to be locked. Therefore the sensor system should be able to measure the position of the planar 3DOF, where the rotation is also measured to lock the rotation by means of a control loop.

One of the previously developed sensor system at the MSD group at the TU Delft which is able to measure planar 3DOF position information at a low-cost is the van Moorsel sensor system. Which uses a 2D image sensor and a pattern of QR-like codes. It achieved a translational precision of 16 µm and a sample rate of 16 Hz. Where a higher sample rate is beneficial for the control bandwidth. The sample rate of the van Moorsel sensor system is limited by the 8 MP 2D image sensor and the image-recognition software, due to the many pixels and the time to process all the data from the pixels.

Hence, this research has investigated if it is feasible to achieve the same precision but at a lower cost and a significantly higher sample rate with a linear CCD compared to the van Moorsel sensor system. The idea is that a linear CCD with fewer pixels, e.g. 2000 pixels instead of 8 million, can solve the limitations of the van Moorsel sensor system. Due to the fewer pixels, a cost-effective linear CCD can achieve significantly higher line scan rates and less data needs to be processed by the algorithm, which can result in a significant improvement of the sample rate.

The main challenge of this research is to obtain relative 3DOF($xy\theta_z$) position information with a single linear CCD. With the goal to achieve the same precision and to increase the sample rate significantly by using a single 1D CCD compared to the 2D image sensor of the van Moorsel sensor system. Therefore, a pattern has been designed first and simulated to show the feasibility to obtain relative planar 3DOF position information with a single linear CCD. Next, a sensor system has been developed and implemented in a demonstrator in order to gain knowledge about the sensitivity of the different parameters in the sensor system and to demonstrate the possibilities of the sensor system.

Pattern design and simulation

To obtain the relative 3DOF($xy\theta_z$) position information with a single linear CCD sensor, a pattern has to be designed which contains this information if the sensor is line-scanning the pattern. This resulted in a self-designed 2D Moiré pattern (Figure 5.1), which consists of 2 sinusoidal black and white gradients with different spatial frequencies, rotated by 90°. The idea is that the linear CCD performs line scans, which measures the intensity of the light reflected from the illuminated pattern on the pixels of the sensor. The measured intensity profile will have a waveform of the 2 sinusoidal gradients (Figure 5.2). By fitting the data with an algorithm, spatial averaging can be applied and the coefficients of the sinusoidal functions can be obtained from the data. The frequency and phase information of the 2 sinusoidal functions from the fit can be used to determine the relative 3DOF position information, by comparing them with the previous line scan. This 2D Moiré pattern has been analysed with a self-developed line scan simulation tool in MATLAB. It can be concluded that the methodology of using a single linear CCD with a self-designed 2D Moiré pattern together with an algorithm to obtain relative planar 3DOF position information, has been demonstrated and proven with the simulations.

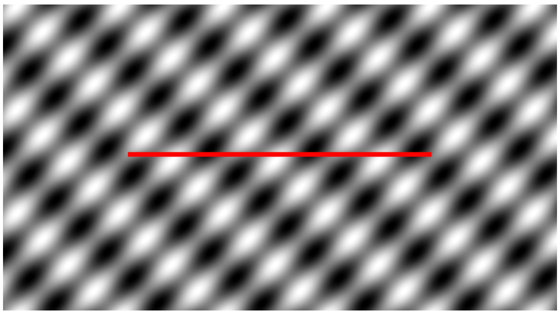


Figure 5.1: The designed Moiré pattern with a red line representing the line scan by the linear CCD as shown in Figure 5.2. The Moiré pattern consists of two overlapping sinusoidal black and white gradients, with each a different spatial frequency.

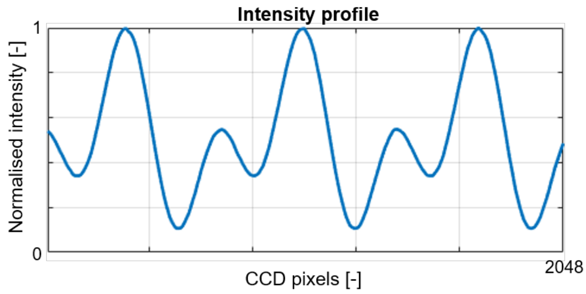


Figure 5.2: Intensity profile simulation from the line scan in Figure 5.1 of the designed Moiré pattern. Each pixel of the linear CCD measures the intensity of the reflected light, resulting in an intensity profile from a line scan. The intensity profile of the pattern is the superposition of the two sinusoidal gradients, which can be clearly seen in the figure.

Demonstrator

A sensor system has been developed and implemented in a demonstrator in order to gain knowledge about the sensitivity of the different parameters in the sensor system and to demonstrate the possibilities of the sensor system. The sensor system consists of a CCD line camera, optics, light source and a printed 2D Moiré pattern. This has been implemented in a demonstrator where the planar 3DOF can be measured individually by using a motorized linear stage or a rotational stage.

From the demonstrator, it can be concluded that the sensitivity of the sensor system is highly influenced by noise and irregularities in the line scan data because the algorithm is either unable to fit the data or it will cause inaccurate fits. Resulting in significant position errors. The parts of the sensor system which affects the line scan data significantly are the light source and the pattern. Parameters of the light source which affects the signal are the intensity and uniformity of the light source. The other part which has a significant effect on the output signal is the printed pattern, which has a lot of different parameters. Parameters like digital resolution, printer type, printer setting, print resolution and material properties of the substrate can all influence the output signal of the line scan.

The realized sensor system has demonstrated that it is possible to achieve a precision of 8 μm (3σ) in the x-direction (along the pixels) and a sample rate of 20 Hz with the algorithm. The sensor system is not limited by the linear CCD, but by the algorithm. Due to time constraint, the other planar DOF could not be measured accurately without optimizing the system further. But preliminary results showed that the output signal of the linear CCD does behave like the simulations when moving the Moiré pattern in y and θ_z. The fitting algorithm is also able to fit the data when moving the pattern.

The algorithm uses toolbox functions in MATLAB to fit the data and to process it further to obtain relative position information in the end. Where the fitting process is the most time-consuming part of the algorithm. This might not be the most optimal and fastest way to fit and process the data, but it has been done in order to analyse the data easily for the validation of the sensor system. Optimizing the algorithm and implementing it on an FPGA, will improve the performance of the sensor system significantly.

For the validation of the sensor system, a relative expensive CCD line camera has been used, but the idea is to reduce the cost by using a cost-effective linear CCD and additional electronics to drive the sensor in order realise a cost-effective planar 3DOF sensor system. The proposed methodology is not only limited for linear CCDs, but linear image sensors such as a linear CMOS sensor can be implemented in the sensor system instead of the CCD.

Summarizing, this thesis has proven and demonstrated that it is feasible to obtain relative 3DOF($xy\theta_z$) position information for planar precision stages with a single 1D CCD and a static 2D Moiré pattern. A line scan simulation tool has been developed to analyse 2D patterns and an algorithm has been written to obtain 3DOF($xy\theta_z$) position information from the designed 2D Moiré pattern. A sensor system has been developed and implemented in a demonstrator in order to gain knowledge about the sensitivity of the different parameters in the sensor system and demonstrated the possibilities of the sensor system. Compared to the 2D image sensor used in the van Moorsel sensor system, a 1D CCD can achieve the same precision, while it has the potential to be cheaper and significantly faster. Making it possible to create an overall low-cost alternative 3DOF positioning sensor system, where the demand for micrometre precision stage applications is increasing with the continuously advancing technology.

A

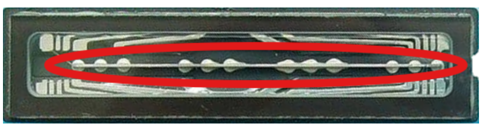
Detailed sensor system design

In this appendix the detailed sensor system is presented.

A.1. CCD line camera

A relative expensive 2048 pixels Thorlabs CCD line camera, the Thorlabs LC100 Smart Line Camera (Figure A.1(a)), has been selected for the validation of the concept. Where the line camera has features like a USB 2.0 interface so it can be directly used when connected to a computer with the provided software (SPLICCO), so it could be used for easy and fast analysing of the scans. However, during the research, it seems that the SPLICCO software is quite limited and could only be used for visual analysis while it is scanning. Or the data can only be recorded with timed sequential scans with a minimum interval of 1 second or a fast sequential scan of maximum 1000 scans can be made. So the data is only available after all the scans are performed, which is not very useful if data is directly needed for feedback in a control loop for the application in mind. Also, the analog output pin can only be used for 1 selected pixel instead of the whole linear array of pixels. The line camera also comes with additional driver packages so you can write your own application with the provided functions. This is done with MATLAB in this thesis, in order to adjust the settings, drive the CCD, obtain the digital output data of the whole pixel array and for further processing and analysing of the data.

(a) Thorlabs LC100 Line Camera



(b) The Sony ILX544B linear CCD, the highlighted silver coloured line are the 2048 pixels.

Figure A.1: On the left A.1(a) the Thorlabs LC100 Line camera can be found, with on the right A.1(b) a more detailed picture can be found of the Sony CCD used in the LC100.

The line camera uses the Sony ILXB554 linear CCD (Figure A.1(b)), which has a total of 2048 pixels. With pixel sizes of 14 µm (width) x 52 µm (height) (14 µm pitch), resulting in 28,67 mm total length of the linear pixels. This linear CCD is originally intended for barcode hand scanners and optical measurement equipment applications. The specifications of the LC100 with the ILXB554 linear CCD are shown in Table A.1. More relevant information can be found in the data sheets (Appendix B.1 and B.2).

Table A.1: Thorlabs CCD Line Camera: LC100 specifications

LC100 Specifications	
Number of effective pixels	2048 pixels
Pixel size (W x H)	14 µm x 56 µm (14 µm pitch)
Total effective pixel length	28.672 mm
Integration time	1.054 ms - 50 s
Scan rate internal trigger	Max 900 scans/s
External scan rate	Max 450 scans/s
Detector range	350 - 1100 nm
Interface	Hi-Speed USB2.0 (480 Mbit/s)

A.2. Pattern design

The idea of the concept is that the linear CCD looks at a pattern to obtain position information. This is based on the received reflected intensity of the light from the pattern on the pixels of the CCD. It is required to obtain relative planar 3DOF information, so each DOF and direction needs to be individually distinguished from the other DOFs. With the application in mind (Section 2.1, the rotation θ_z is only measured to lock the rotation by means of a control loop. This means that only small rotations need to be measured in order to achieve this. To design such a pattern, first the basics of a single DOF pattern design will be discussed, then a 2DOF pattern design and eventually a 3DOF pattern design. In all these cases it is assumed that the sensor is fixed and the pattern can translate in x and y, and rotate around z separately (centre of rotation is in the centre of the linear pixel array). The simulated intensity profile of the pattern is added for a visualisation of a line scan of the pattern, more information about the line scan simulation tool can be found in Section A.3.

A.2.1. 1DOF pattern

A pattern for 1DOF measurement is basically like tracking a marker of high contrast like the one discussed in 1.3.1 from Yoon et al. [16]. So a white marker on a black ground like the pattern in Figure A.2. If this pattern is scanned with a linear CCD as the red line in the figure, the intensity profile of the scan is only changing for translations of the pattern along the pixels in the x-direction. The intensity profile will translate in parallel with the pattern to the left or right. The intensity profile will not change if the pattern is only translating in the y-direction. Rotating the pattern around the z-axis will only be slightly visible for very big rotations and can be neglected. So this pattern is insensitive to rotation θ_z and translation in y and can only be used for 1DOF measurements along the pixels of the linear CCD in the x-direction.

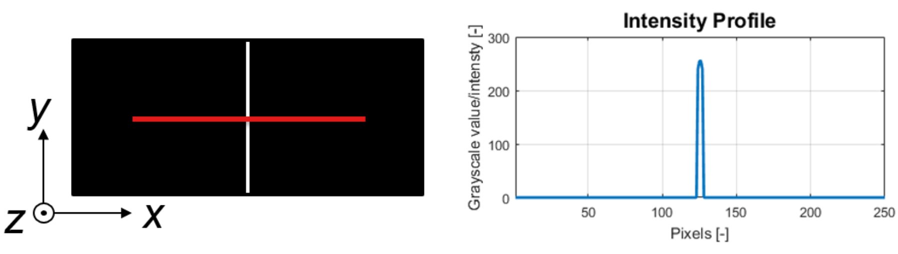


Figure A.2: 1DOF pattern, only for the x-direction.

A.2.2. 2DOF pattern

A 2DOF pattern can be something like a normal linear black and white barcode, like the one in Figure A.3. The translation along the pixels can be obtained just like with a single marker for the 1DOF pattern, but now there are basically more markers which are also wider. This pattern can be used to obtain information from large rotations. If the pattern rotates, the black and white bars will appear wider in the line scan of the sensor, using trigonometric functions the rotation can be retrieved. The main difference with the 1DOF pattern is that the bars are wider than the single marker, which makes this pattern also sensitive to large rotations of θ_z besides the translations in the x-direction. Although this pattern can be used for large rotations, it can not distinguish the directions of the rotations because the pattern is symmetric along the x- and y-axis in the middle of the pattern. And again this pattern can not be used for measurements in the y-directions.

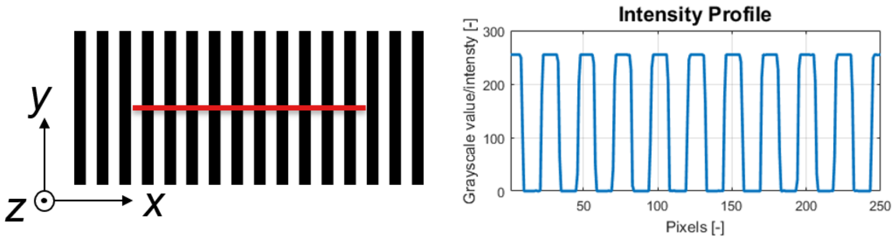


Figure A.3: 2DOF pattern, only for the x-direction and large rotations of θ_z.

A.2.3. 3DOF pattern

From the 2DOF pattern, a possible 3DOF pattern is a rotated barcode (45°) (Figure A.4), the same principle like the normal linear black and white barcode for x and θ_z (Figure A.3. It is now possible to obtain information about y. Because if the pattern moves in the y-direction, the black and white bars appear to be translating along the pixels. However, this is just like when the pattern moves in the x-direction. The pattern can not distinguish a translation in the x- or y-direction with such a pattern.

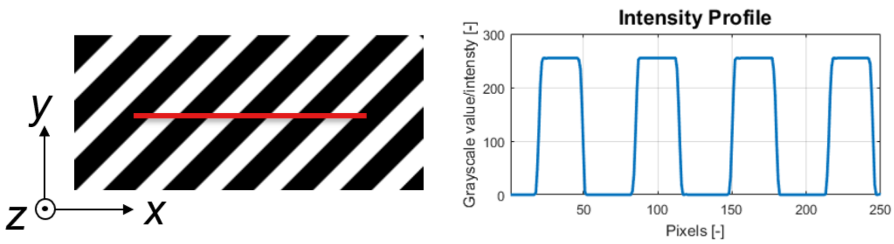


Figure A.4: 3DOF pattern, x, y and θ_z, however x and y translations can not be distinguished from each other.

A rotated checkered pattern as shown in Figure A.5 is able to get 3DOF information. However, due to symmetry (in the x- and y-axis) in the pattern, the directions in y can not be distinguished from each other, this is also valid for the rotation θ_z.

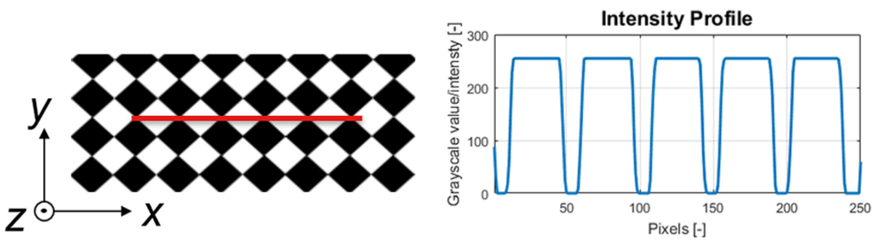


Figure A.5: 3DOF checkered pattern, x, y and θ_z, the direction of y and θ_z can not be distinguished.

An alternative for a 3DOF pattern is a pattern with multiple sections, each section has its own function. Like one section for the x, another section for the y and the rotation can be obtained from the changing widths. This can result in something like a combination of the discussed patterns in this section as seen in Figure A.6. The straight vertical bars can be used for the x-direction, the rotated bars can be used for y-direction. Rotation can be obtained from the width of the bars (constant width is no rotation). The limitation of such a pattern is that an algorithm needs to distinguish the different sections and at least 3 sections need to be always in the field of view of the sensor. If a significant large pattern is needed for a larger range of motion of the stage, this needs to be taken into consideration.

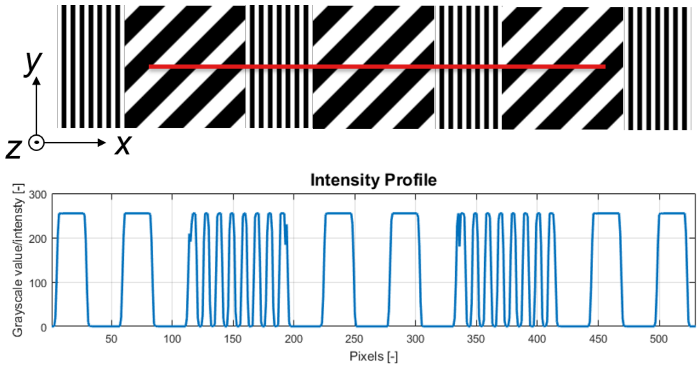


Figure A.6: Alternative 3DOF pattern, x, y and θ_z, multiple sections.

A.2.4. Sinusoidal gradient pattern

Pattern with a sinusoidal gradient (example in Figure A.7) can be used with spatial averaging, as the whole signal will be used. By having a sinusoidal black and white pattern, the signal from the line scan will be sinusoidal as well. By fitting the data, the sinusoidal function with its coefficients can be obtained. So amplitude, frequency and phase can be obtained from the fit. By using the whole signal for the fit, means that outliers in the line scan data caused by e.g. dust particles, contamination or pixel defects will be averaged out, also known as spatial averaging. If a discrete pattern will be used, like the patterns mentioned above, the outliers can have a more significant impact on the position information.

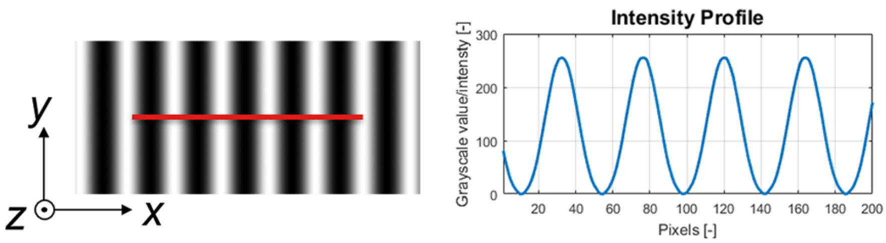


Figure A.7: Sinusoidal pattern for 2 DOF.

A.2.5. Creating Moiré pattern

When looking at the 3DOF pattern with the rotated barcode, a similar pattern can be made with the sinusoidal gradients instead of only pure black and white (Figure A.8. If this pattern will be scanned, the output will be sinusoidal and can be fitted with an algorithm. If another rotated sinusoidal pattern is added but rotated with 45° in the other directions, a Moiré pattern is created. The output of this signal will be the superposition of the two sinusoidal patterns and looks similar to the checkered pattern in Figure A.5. However, this pattern is symmetric on the x-axis and the y-axis. Because of this symmetry the y- and θ_z-directions can not be distinguished.

To create a non-symmetric pattern on the x-axis and the y-axis, one of the sinusoidal patterns can be adjusted. The spatial frequency in one of the sinusoidal pattern needs to be different from the other

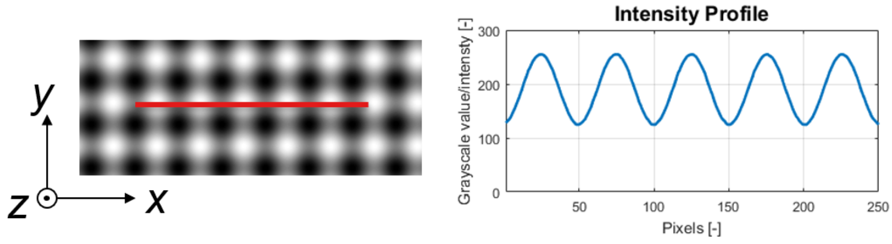


Figure A.8: A 3DOF Moiré pattern similar to Figure A.5, the y- and θ_z-directions can not be distinguished.

one. A frequency with a factor two has been chosen for the other pattern (pattern 2 Figure A.9), so the two frequencies can be observed easily. The created pattern from these new sinusoidal gradients results in a non-symmetric pattern on the x-axis and the y-axis (Figure A.9). However, the pattern is symmetric at an angle of $\pm 45°$ from the x-axis. This means that the pattern can be rotated up to this angle before the direction of the rotation can not be distinguished anymore. The y-directions are now also distinguishable from the non-symmetric pattern on the x-axis and the y-axis. This means that this pattern contains the information for a linear CCD to obtain relative 3DOF position information. Where the directions of 3DOF can also be distinguished, but the rotations should be $< 45°$. This rotation $< 45°$ is more than enough for the application in mind, where the rotation is only measured to lock the rotation of the stage by a control loop.

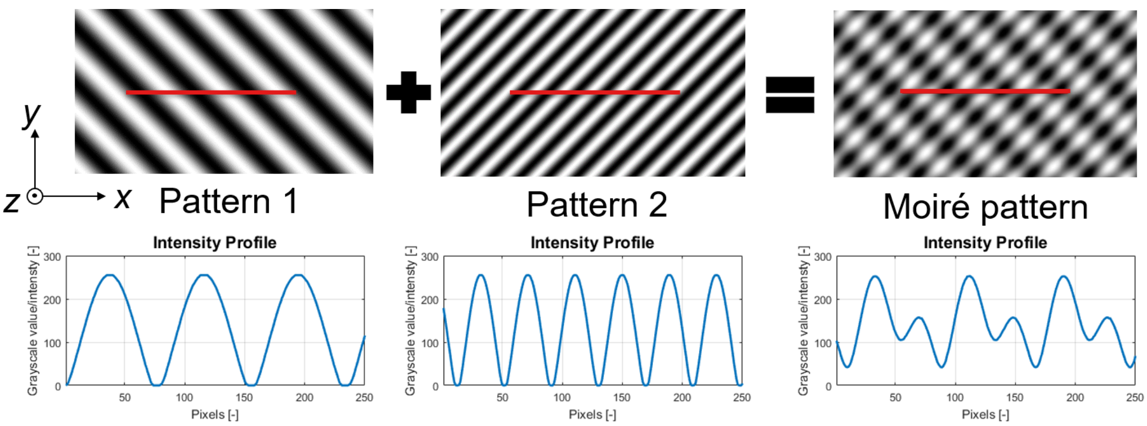


Figure A.9: A 3DOF Moiré pattern, which can distinguish the 3DOF from each other and their directions. The range of θ_z is limited to <45°.

A.3. Line scan simulation and algorithm

In order to analyse the designed pattern, a line scan simulation tool has been developed in MATLAB. This self-designed simulation tool needs to simulate how the output signal of a linear CCD looks like if it is line scanning a pattern. Furthermore, the output signal, the intensity profile, can be used to test an algorithm to obtain more information from the signal. This can be used to demonstrate if it is feasible to obtain 3DOF with a single linear CCD and the designed pattern.

The simulation tool can be seen in Figure A.10. It measures the intensity per pixel, in this case a horizontal line which represents the pixels of the linear CCD, of a digital image converted to a grayscale image of the designed pattern (Figure A.10(A)). A representation of what this line observes from the pattern has been shown visually in Figure A.10(B)). The intensity measurement of the line scan is shown in an intensity profile A.10(C) in grayscale values. Where pure white has the maximal value of 255 and pure black is 0. And the gradient from black to white has a value between the pure black and white.

In order to determine if the designed pattern can be used for planar 3DOF position measurements, either the line scan has to move or the pattern. From the application in mind, it is chosen to make the

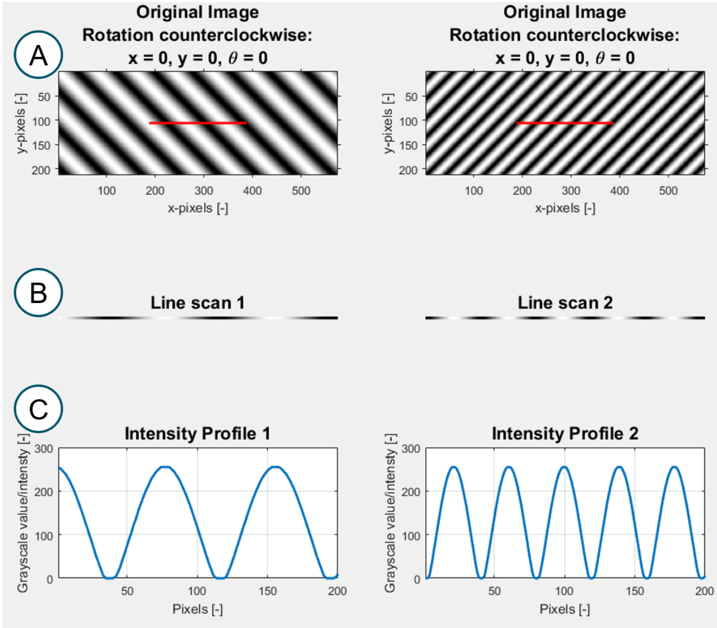


Figure A.10: Overview of the self-developed line scan simulation tool in MATLAB. (A) Imported image of the pattern, red line visualise the scanning area. (B) Grayscale image as seen by the by the line scan. (C) Intensity profile of the line scan.

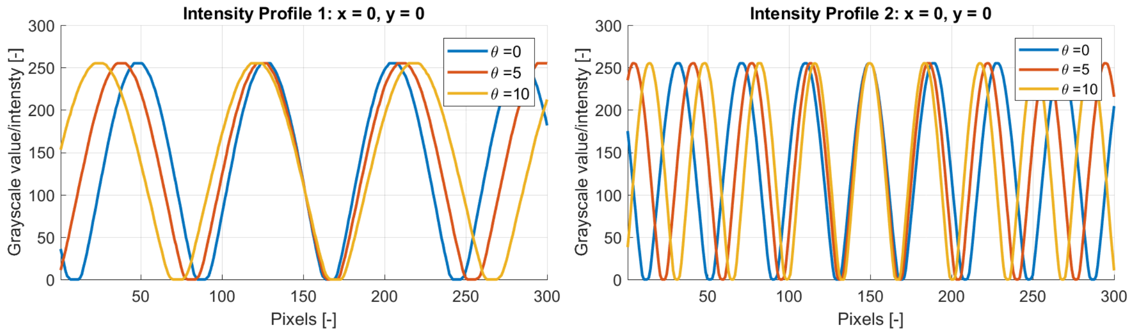
line scan fixed and the pattern movable in the planar 3DOF, like it is attached to the planar stage. The pattern is able to translate in x- and y-directions and it can rotate around the z-axis. By performing line scans, while the pattern moves in one of the DOFs, each DOF can be analysed individually. This has been done visually by looking how the intensity profile behaves when the pattern moves.

For the designed Moiré pattern, which is basically a superposition of two different sinusoidal gradients, the intensity profiles of both gradients can be analysed simultaneously instead of the Moiré pattern itself. Making it easier to analyse the intensity profile. As mentioned in Section A.2.5 the intensity profile is sinusoidal, where the frequencies and phases of the intensity profile can be used to obtain 3DOF position information and to distinguish the 3DOF movements.

The pattern moves in one DOF, in both directions (negative and positive direction). Before each movement, a line scan is performed. So each DOF can be analysed and to check if the directions of the movements can also be distinguished from each other.

The unit of the translational movement is in pixels of the pattern and the rotation angle is in degrees. The intensity profile results of the line scan simulations of the patterns can be found in Figure A.11-A.16, where each DOF is simulated individually in both directions. Each time the pattern starts in its initial position $(x, y, \theta_z) = (0, 0, 0)$ and moves in 1 direction. For example, if the pattern moves counterclockwise (CCW), x and y while remain 0, while θ_z increases. To visualise the movements, the initial position of the pattern and two incremental steps has been plotted into the same figure. For the rotation θ_z, the incremental step size is 5° and for the translations, it is 10 pixels. The blue line in all the intensity profiles is the initial start position of the pattern, the red line is the first incremental step and the yellow line is the second step.

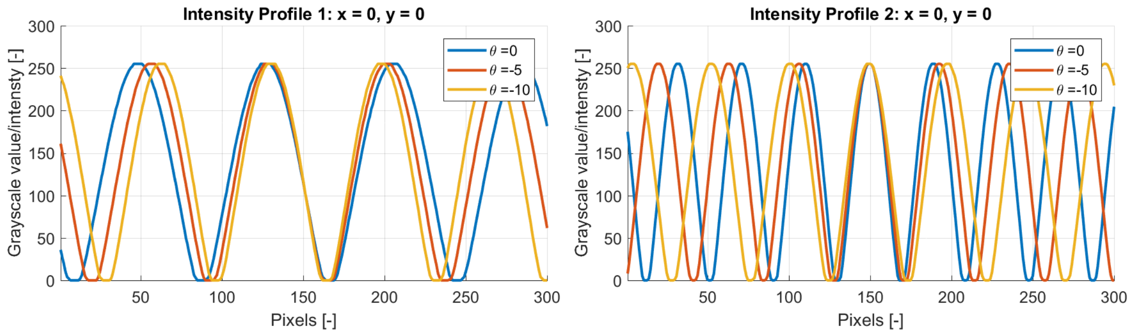
A.3.1. Simulation results



(a) Line scan simulation of pattern 1: CCW

(b) Line scan simulation of pattern 2: CCW

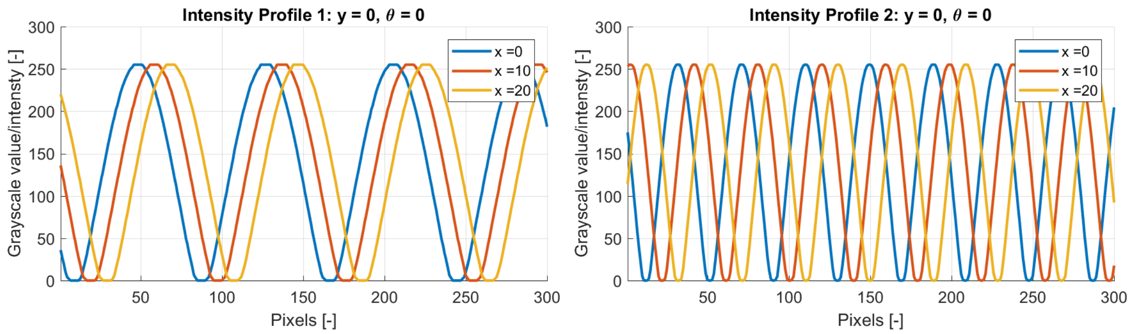
Figure A.11: Intensity profiles of line scan simulations, pattern is rotating counter-clockwise (CCW).



(a) Line scan simulation of pattern 1: CW

(b) Line scan simulation of pattern 2: CW

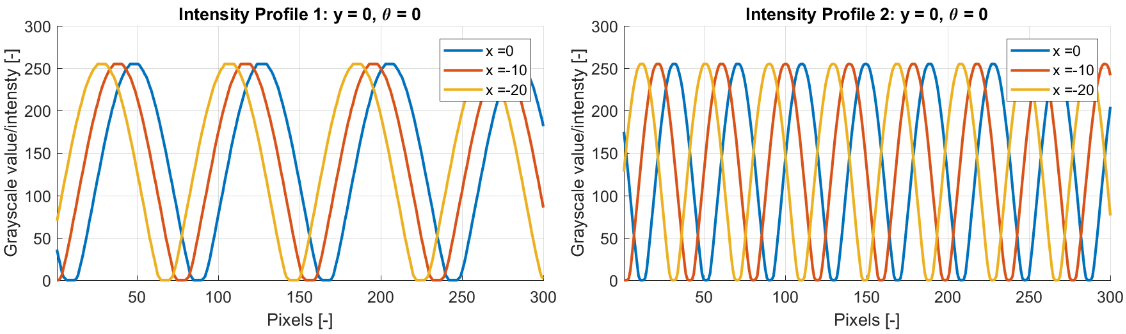
Figure A.12: Intensity profiles of line scan simulations, pattern is rotating clockwise (CW).



(a) Line scan simulation of pattern 1: Right (+x)

(b) Line scan simulation of pattern 2: Right (+x)

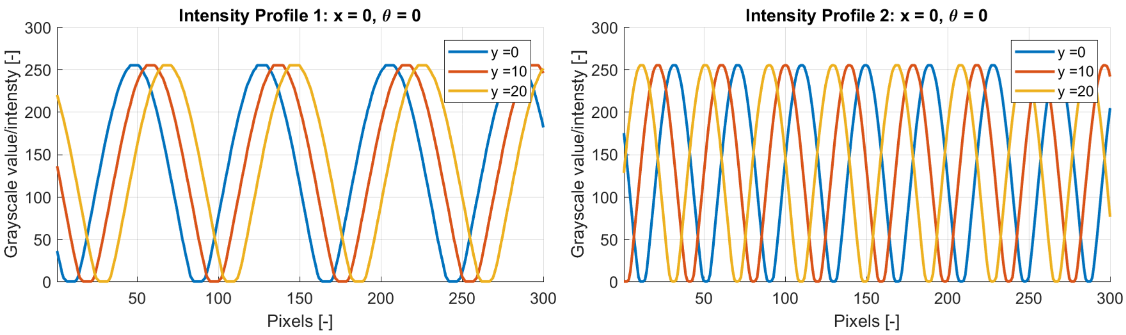
Figure A.13: Intensity profiles of line scan simulations, pattern is translating to the right in the positive x-direction.



(a) Line scan simulation of pattern 1: Left (-x)

(b) Line scan simulation of pattern 2: Right (-x)

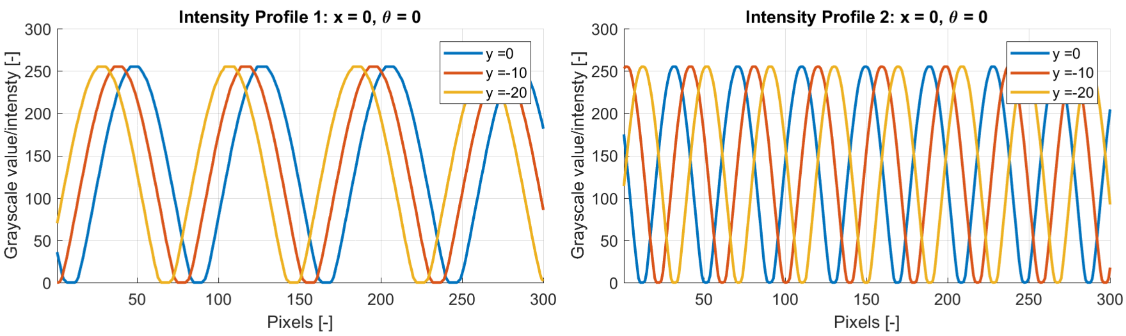
Figure A.14: Intensity profiles of line scan simulations, pattern is translating to the left in the negative x-direction.



(a) Line scan simulation of pattern 1: Up (+y)

(b) Line scan simulation of pattern 2: Up (+y)

Figure A.15: Intensity profiles of line scan simulations, pattern is translating upwards in the positive y-direction.



(a) Line scan simulation of pattern 1: Down (-y)

(b) Line scan simulation of pattern 2: Down (-y)

Figure A.16: Intensity profiles of line scan simulations, pattern is translating downwards in the negative y-direction.

A.3.2. Simulation analysis

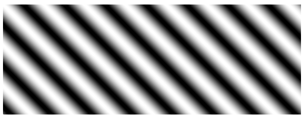
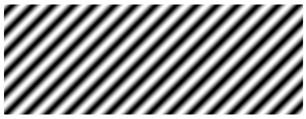
Table A.2 shows the analysis of the simulated intensity profiles of the patterns moving in each of the 3DOF. For each movement and direction, the changes in frequency and phase shift were analysed for both patterns. Looking at the CCW rotation (Figure A.11), both the frequencies and phases are changing. For pattern 1, the frequency decreases for a bigger CCW rotation angle and the phase shift increases. For pattern 2, this is exactly the opposite, frequency increases and phase shift decreases. Now looking at the CW rotation (Figure A.12), the opposite happens with respect to the CCW rotations. So the rotation can be distinguished in both directions.

Translating the pattern along with the line scan (x-direction), to the right and left results only in phase shifts, while the frequency remains constant (Figure A.14 and A.13). If the patterns are only translated to the right, the intensity profiles should also only translate to the right, which would result in a decreasing phase. This is indeed the case, both patterns showed a decreasing phase while the frequency remains constant. For the translation to the left, the opposite is happening. This means that the translations to the right and left can be distinguished from each other, but also from the rotations.

Finally, translating up and downwards (y-direction) results in constant frequencies and changing phase shifts (Figure A.15 and A.16). However, the phase shifts of both patterns are not decreasing or increasing. If the patterns translate upwards, the phase shift of pattern 1 decreases, while the phase shift of pattern 2 increases. For a downwards translation of the patterns, the opposite can be observed for the phase shifts. This means that the up and downwards translations can also be distinguished from each other, but also from the translations in the x-direction and the rotations.

From these results, it can be concluded that if these 2 patterns are used to create the Moiré pattern, it is feasible to obtain relative 3DOF position information with a single linear CCD. Because if the patterns 1 and 2 are overlapping each other to create the Moiré pattern, a superposition of the two intensity profiles will be the result of a line scan. If the intensity profiles from pattern 1 and 2, could be extracted from the intensity profile of the Moiré pattern, the frequencies and phase shifts can be analysed for each movement and direction of the 3DOF, like it has been done with pattern 1 and 2.

Table A.2: Analysis results from the line scan simulations of the two patterns, where the symbols indicates if the frequency/phase shift is decreasing (-), increasing (+) or remains the same (=) for the given movements of the pattern.

	Pattern 1		Pattern 2	
				
	Frequency	Phase shift	Frequency	Phase shift
Rotation CCW	-	+	+	-
Rotation CW	+	-	-	+
Right	=	-	=	-
Left	=	+	=	+
Up	=	-	=	+
Down	=	+	=	-

A.3.3. Algorithm in simulation

The algorithm to fit the data of the output signal of the line scan can already be designed and it can be tested with the simulation output. This is done in MATLAB with the fitting toolbox. The basic principle of the algorithm is described below and shown in Figure A.17:

1. Perform line scan of the Moiré pattern.

2. Obtain line scan data.

3. Fit the output signal of the line scan, the algorithm fits the data to the sum of two sinusoidal functions. A single sinusoidal function can be found in Equation (A.1).

$$f_{i,j}(x) = A_{i,j}\sin(\omega_{i,j}x + \phi_{i,j}) \tag{A.1}$$

   Where A is the amplitude, ω the frequency, ϕ the phase and x is the pixel number of the linear CCD. The index i represent the line scan number and j denotes the individual sinusoidal function. From the sum of two of these sinusoidal functions (Equation (A.1)), the function to fit the data of the designed Moiré pattern can be created as shown in Equation (A.2).

$$f_i(x) = A_{i,1}\sin(\omega_{i,1}x + \phi_{i,1}) + A_{i,2}\sin(\omega_{i,2}x + \phi_{i,2}) \tag{A.2}$$

4. Obtain frequencies and phases of the individual sinusoidal functions. The output of the fit are, among others, the plot of the fit and the coefficients of the two sinusoidal functions, which are the amplitudes $A_{i,j}$, frequencies $\omega_{i,j}$ and phases $\phi_{i,j}$. With these coefficients, the separate sinusoidal functions can be plotted from Equation (A.1), for a visual check. Note that the fit basically separates pattern 1 and 2, which formed the Moiré pattern. To determine the 3DOF position information, only the frequencies and phases are needed.

5. Redo step 1-4 to obtain coefficients of the next line scan of the Moiré pattern. Because with the designed pattern only relative position information can be obtained. So another scan is needed to compare the data for the position information.

6. Check the differences in frequencies and phases of the two line scans. According to Table A.2, it can be determined if there is a relative displacement between the line scans of the pattern.

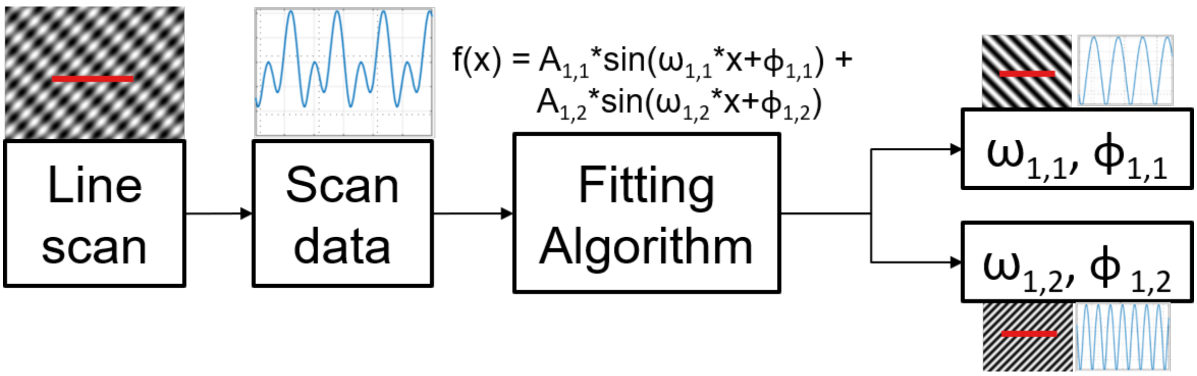


Figure A.17: Work flow of the fitting algorithm for 1 line scan, steps 1-4.

The results of fitting a simulated line scan of the Moiré pattern can be found in Figure A.18. It can be observed that the algorithm is able to fit the data as described. The coefficients from pattern 1 and 2 of the Moiré pattern can be used to plot the fitted intensity profiles of the 2 patterns. By moving the pattern like in Section A.3, the same analysis can be performed on the 2 patterns, but now with the fitted data from the Moiré pattern. It could be observed that the fitted data does behave exactly like in Section A.3.2.

From these results, it can be concluded that the designed Moiré pattern with the fitting algorithm is able to determine 3DOF position information with a single linear CCD.

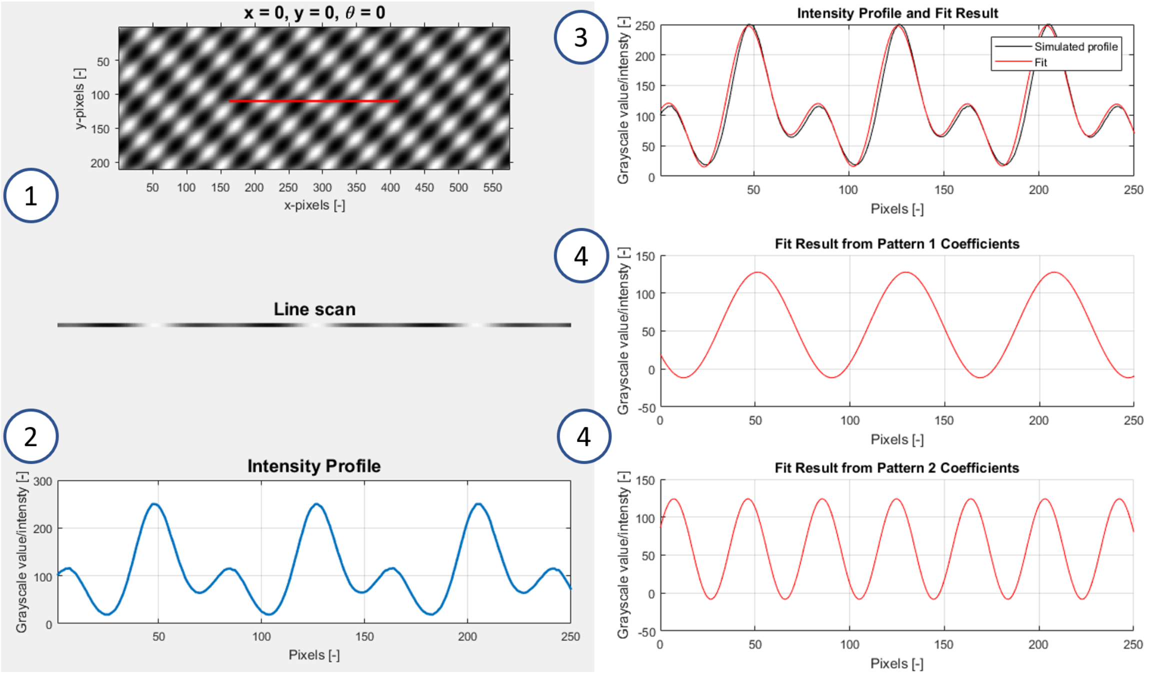


Figure A.18: Fitting results of a simulated line scan of the Moiré pattern, steps 1-4. (1) Perform line scan. (2) Obtain line scan data. (3) Fit the line scan data to the sum of 2 sinusoidal functions. (4) Obtain the the coefficients of pattern 1 and 2 from the fit.

A.4. Printing of the pattern

The designed Moiré pattern needs to be easily manufactured for a low-cost. Therefore it is desired to print the pattern with either a laser or inkjet printer which are widely accessible and cost-effective. This case, increasing the range of the sensor system can be easily achieved by printing the pattern on a larger substrate.

A.4.1. Digital resolution

The Moiré pattern is made with MATLAB and when saving the pattern from MATLAB to an image file, the standard resolution of the output file is 96 dots per inch (DPI) for a lossless Tagged Information File Format, also known as TIFF. This is a relatively low resolution for an image file, especially if the gradients of the pattern are used for micrometre positioning. And knowing the maximum resolution of 1200 (H) x 2400 (W) DPI for the available laser printer (Xerox AltaLink C8035) and the 1200 (H) x 4800 (W) DPI for the inkjet printer (HP Envy 5010 All-in-One). The resolution should be at least 4800 DPI, such that the print resolution is not limited by the digital pattern. In order to improve the resolution of the exported Moiré pattern from MATLAB, a function from the MATLAB File Exchange was used, the "*export_fig*" [1]. The *export_fig* is created by Oliver Woodford and maintained by Yair Altman since January 2015. With this function it possible to create a digital image of the Moiré pattern with a resolution of 4800 DPI.

A.4.2. Printing the pattern

In order to print the digital image of the pattern on to a substrate, the digital image is first imported into Photoshop to re-position the pattern, but also to access some more settings for the printer. To print the file from Photoshop, it can be chosen to let Photoshop handle the colours or the printer itself. Also, the 2D Moiré pattern is basically a combination of sinusoidal black and white gradients, where the printer will only print the black parts on a white paper. However, there are several settings to print the gradients, it can be chosen to print only with black ink, grayscale or CMYK (cyan, magenta, yellow and key (black)). Depending on the optical magnification of the sensor system and the print resolution these print settings can influence the printed 2D Moiré pattern and therefore the output signal of the line scan.

[1] `https://www.mathworks.com/matlabcentral/fileexchange/23629-export_fig`

A.4.3. Print material

Printing the pattern on a normal A4 plain white printer paper would be the cost-effective option as the print material. A plain white printer paper sheet works great for printing text on paper but is not the optimal material to print high-resolution images on it. Due to the properties of the printer paper, which is uncoated, the ink gets absorbed by the paper but also spreads the ink if high saturation images are printed. A photo paper, which is coated, is made to reduce the spread of the ink droplets, making it possible to achieve higher print resolutions. Also, a normal A4 plain white printer paper is made of pulp, e.g. wood fibres, the density of the fibres is not homogeneously spread over the paper. This can be seen when the paper is held against a light source, patches of clustered fibres can be observed as darker spots while there are also some brighter spots, these contain fewer fibres. This also results in some small height variations over the surface of the paper. This can affect the quality of the print and what the linear CCD will observe.

Photo paper is a more homogeneous material, the fibres can not be seen as like the plain printer paper. However, some small height variations are also present on the surface of the photo paper. Concluding, it would be great if a normal A4 plain white printer paper could be used to print the pattern on. But the resolution of a plain printer paper is not as good photo paper. And a high-resolution print is needed to print the pattern with smooth gradients.

From the visual inspection, the quality of the print is significantly better when printing with an inkjet printer compared to the laser printer. This was printed with the same settings on printer paper. And using photo paper in combination with the inkjet printer resulted in smoother gradients compared to the printer paper. The best print quality was obtained with the inkjet printer, using photo paper, grayscale print setting and 4800DPI.

A.5. Optics

A digital camera without any optics can not capture an image of an object, because the image sensor is exposed to light from all directions and gets saturated very quickly resulting in a white image. Optics are needed in order to create an optical image from an object on the image plane and a housing for the optics is needed to block the stray light. In this sensor system, the object is the pattern and the image plane are the pixels of the linear CCD. Where pixels of the linear CCD gives an intensity profile of the optical image, the reflected light of the illuminated pattern. This can already be achieved with a simple pinhole, where a small hole can be used to create an optical image. However, a pinhole is quite limited and often results in very dark images, which means a significantly longer exposure time is needed to obtain a brighter image on the linear CCD. An optical element like a single biconvex lens can be used to acquire a better image, which can also be used to scale the image optically, also known as optical magnification.

It is desired to achieve a sharp optical image of the pattern on the pixels of the linear CCD, in order to obtain an accurate intensity profile of the line scan of the pattern. This requires a certain field of view, dependent on the size of the printed pattern and the optical magnification. The depth of field, the focus range needs to be increased so the pattern can be set in focus easily and to cope with the manufacturing tolerances of the sensor system.

A.5.1. Lens

An optical image of a certain region of interest is needed from the pattern to create an intensity profile which can be used by the algorithm fit the data of the two sinusoidal gradients. For a more robust fitting of the algorithm and better spatial averaging, the intensity profile should contain as much as possible of the periods of the gradients. At least one period of both sinusoidal functions need to be observed in order to fit the data properly with the algorithm. The sensor size of the linear CCD (28.7 mm) is relatively large, which means that for an optical magnification of 1, the scanned region of the pattern is 28.7 mm long. The optical magnification can be calculated from the thin lens formula, also known as the Gaussian lens formula [25],

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f} \tag{A.3}$$

Where S_1 the is distance between the object and the lens, S_2 is the distance between the image plane (sensor) and f is the focal length of the lens.

The optical magnification M can be determined from the relation between S_1 and S_2, but also from the object height (h_o) and the image size (h_i):

$$M = -\frac{S_2}{S_1} = \frac{h_i}{h_o} \tag{A.4}$$

Following the sign convention used in [25] the minus sign represent the image location at the opposite side of the optical axis as the location of the object. This means that for real images, the M is negative and the image is inverted.

A lens with focal length of 30 mm has been selected, to have a relative compact optical configuration. Using smaller focal lengths can significantly increase the distortion caused by the lens. The schematic of the lens with the CCD can be seen in Figure A.19

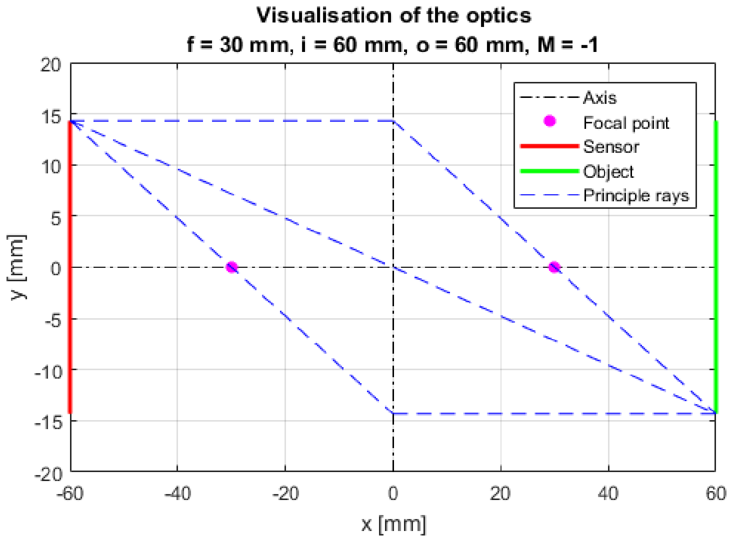


Figure A.19: Schematic of using a lens with focal length of 30 mm and a optical magnification of (-)1.

A.5.2. Depth of field

In order to create a sharp optical image on the pixels of the sensor, the pattern should be in focus. In reality, an image appears to be acceptably sharp for a certain range, this is the known as the depth of field. This is the distance between the nearest and farthest objects which appears to be acceptably sharp. Acceptably sharp is defined by the circle of confusion [26].

The depth of field can be calculated with Equation A.5, if the circle of confusion is small relative to the aperture:

$$T = \frac{2u^2NC}{f^2} \tag{A.5}$$

where T is the depth of field, u is the distance to the in-focus plane, N is the F-number of the lens, C is the circle of confusion and f is the focal length of the lens.

For a circle of confusion of 10 µm (should be smaller than the pixel size of the sensor) a depth of field of 1.2mm is calculated with Equation (A.5). This is large enough in order to get the pattern easily in focus in the demonstrator, to cope with the possible misalignment of the components in the sensor system and the height variation caused by the stage. In future application of the sensor system, in for example a ferrofluid bearing stage, this height variation is caused by the trail formation of the ferrofluid when moving the stage [2].

From the requirements, a single biconvex lens with an adjustable diaphragm has been selected for the optics of the sensor system. The biconvex lens has a focal length of 30 mm and the diaphragm has an aperture diameter of 1.2 mm. A magnification of (-)1 has been selected because the sensor size is already relatively large with 28.7 mm, which can observe more than one period of both sinusoidal gradients of Moiré pattern. Also, the resolution of the printed pattern was not the optimal quality of smooth gradients, which would be more visible in the intensity profile of a line scan and affects the performance of the fitting algorithm. So a larger magnification is not beneficial for the resolution of the current state of the sensor system. Also, the resolution of optical systems is physically limited, besides other factors which can affect the optical resolution such as imperfection in lenses or misalignment of the optics. This physical limit is known as the (Abbe) diffraction limit. And should be considered when improving the resolution of the sensor system.

A.6. Light source

In order to use the linear CCD for position measurements, a light source is needed to reflect light from the pattern to the sensor. The linear CCD sensor needs photons in order to convert it to an output signal, the intensity of the light. This is achieved with a light source, in this case, the light source needs to illuminate the pattern and the intensity of reflected light is measured by the linear CCD sensor.

It is required to illuminate the region of interest (line scanning area on the pattern) with uniform illumination. High intensity is needed to have a good signal-to-noise ratio. However, this intensity must be below the saturation level of the CCD. The wavelength of the light source must be in the range of CCD specifications, where it is desired to choose for the optimal spectral sensitivity of the CCD.

A.6.1. LED vs. Laser

The sensor system should be compact and easy to handle, so the focus is more on LEDs or lasers. Lasers are very bright and need to be handled with safety. Also they can be very expensive depending on the requirements for the applications. They create a single light spot, or in case of a line, some mechanical system is needed to create a line with a laser. These were investigated, but the intensity is too bright for the CCD, resulting in saturation of the CCD and even the blooming effect (electron overflow to adjacent pixels) [13] could be observed when shining a low-power laser pointer on a few pixels of the CCD.

LEDs are very low-cost in general, safe to use, energy-efficient and also available with high intensities. Multiple LEDs can be placed in an array to get a more uniform illuminated region. There are different types of LEDs, a conventional LED might not be bright enough to use it in the sensor system. Because a high-intensity light source is needed to achieve a good contrast of the pattern, but also to achieve the maximum scan rate of 900 scans/s. The intensity of the light is related to the scan rate by the integration time of the sensor. This is the exposure time of the pixels to the light source. If the intensity of the light is very low and the exposure time is set to the minimum of 1.54 ms, the pixels will only capture a very small amount of photons, resulting in an output signal of almost zero. On the other hand, if the intensity of the light is too high, saturation can occur or even blooming.

A.6.2. Illumination profile

In the case of the sensor system, a light source illuminates the pattern, the light reflects from the pattern through the optics to the linear CCD. The intensity of the light from the light source has been reduced before the light has reached the linear CCD. A single bright white SMD LED (L130-5090003000X26) has been used first, to check how the sensor system behaves. And to investigate how a non-uniform illumination on the region of interest affects the output signal of the linear CCD. A more uniform illumination source can be realized by using multiple LEDs in a linear array. The idea was to use multiple single bright SMD LEDs to create such an array. However, there were also bright LED modules available, where multiple tiny LEDs are put in a linear array in one component. These LED modules (KAS-4805SYLS/5) has been selected instead of creating a linear array of LEDs, as they are easy to use in the sensor system. This LED module has 15 tiny LEDs in a linear array. When creating an own linear array of LEDs, the production can cause many variations in for example the placement of the SMD LEDs. So the illumination profile is not as smooth as the LED modules. However, there is more freedom when creating an own linear LED array, not only on the SMD LED components but also on the illumination profile. If the brightness of the LEDs can be tuned individually, the illumination profile can be changed as well. This can be interesting if the optics are causing vignetting, where the illumination is changed by the optics, causing the illumination to be higher at the centre of the optics and darker towards the sides. And if the vignetting affects the signal significantly, tuning the light source is one of the options to achieve a more uniform intensity profile on the linear CCD.

A uniform illuminated region of interest can also be achieved with a diffused light source. This can be achieved by e.g. reflecting the light of a white surface or putting a translucent material between the light source and the pattern, which diffuses the light and a ”softer” (more uniform) illumination can be achieved on the surface the pattern. Translucent materials can be for example frosted glass, milk glass, ground glass, opal and silk sheet. But also a sheet of white paper in front of a light source can be used to obtain a diffused illumination. However, the intensity of the light will be reduced through diffusion, which can be a problem. Otherwise, a brighter light source is needed or more light sources to illuminate the region of interest. This was investigated shortly, but the intensity of the illumination was reduced significantly to obtain proper scan data, even with longer exposures of the CCD. Increasing the intensity of the LED resulted in a high temperature in LED and wires. Causing the 3D-printed components (PLA) which hold the LED, to deform plastically due to the heat generation of the LED.

B

Datasheets

B.1. Thorlabs LC100 Smart Line Camera (Manual pages)

7 Appendix

7.1 Technical Data

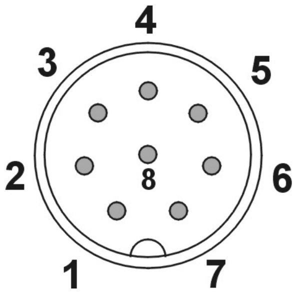
	LC100
Sensor Specifications	
Detector Range (CCD Chip)	350 - 1100 nm
CCD Pixel Size	14 µm x 56 µm (14 µm pitch)
CCD Sensitivity	240 V / (lx · s)
CCD Dynamic Range 1)	333
CCD Pixel Number	2048
Integration Time	1.054 ms − 50 s
Scan Rate Internal Trigger 2)	Max 900 scans/s
S/N Ratio 3)	≤2000 : 1
External Trigger	
Trigger Input	BNC
Trigger Signal	TTL 5 V and 3.3 V
Trigger Frequency, Scan Rate 2)	Max 450 Hz, 450 Scans/s
Trigger Pulse Length	Min 50 ns
Trigger Delay	4.5 µs
Number of GPIOs	5
GPIO Type	3.3 V TTL
Region of Interests	16
Analog Output	Programmable 0 - 4 V
General Specs	
Interface	Hi-Speed USB2.0 (480 Mbit/s)
Dimensions (L x W x H)	80 mm x 80 mm x 33 mm (3.13" x 3.13" x 1.30")
Weight	<0.4 kg
Operating Temperature Range 4)	0 to 40 °C
Storage Temperature Range	-40 to 70 °C

All technical data are valid at 23 ± 5°C and 45 ± 15% rel. humidity (non condensing)

1) ratio of saturation voltage to dark current voltage
2) 1.055 ms integration time
3) with 10x averaging, depending on integration time; for single shot use CCD dynamic range
4) non-condensing

SPLICCO

7.1.1 GPIO port connector



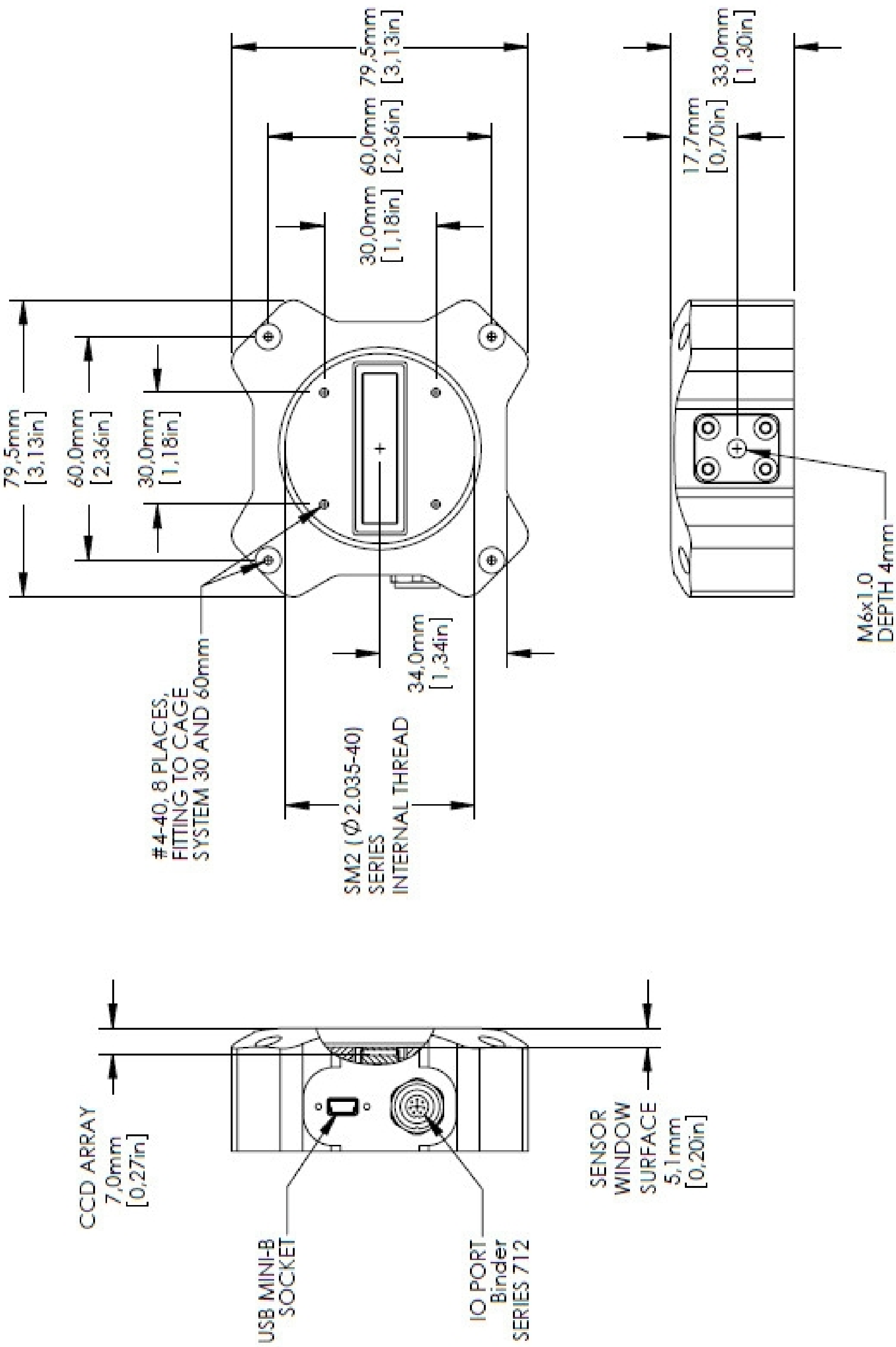
Pin #	Description
1	Trigger Input, LL TTL (max. 3.3V; 0 - 0.4V = LOW, 2.4 - 3.3 V = HIGH)
2	Common GND (Trigger and GPIO)
3	Analog Output, *0 - 4V DC in 4096 increments*, max. current 16mA
4 -8	GPIO ports 1-5, LL TTL

CAB-LC100 Trigger cable
DIN 47100 color code

Pin #	Color	Description
1	BNC plug	Trigger In
2	BNC shield, brown	Trigger Ground
3	green	Analog Out
4	yellow	GPIO1
5	gray	GPIO2
6	pink	GPIO3
7	blue	GPIO4
8	red	GPIO5
	white	n.c. (unused)

 © 2012 Thorlabs

7.2 Dimensions



B.2. Linear CCD: Sony ILX554B

SONY

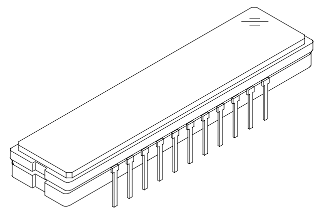
ILX554B

2048-pixel CCD Linear Sensor (B/W) for Single 5V Power Supply Bar-code Reader

Description

The ILX554B is a rectangular reduction type CCD linear image sensor designed for bar code POS hand scanner and optical measuring equipment use. A built-in timing generator and clock-drivers ensure single 5V power supply for easy use.

22 pin DIP (Cer-DIP)



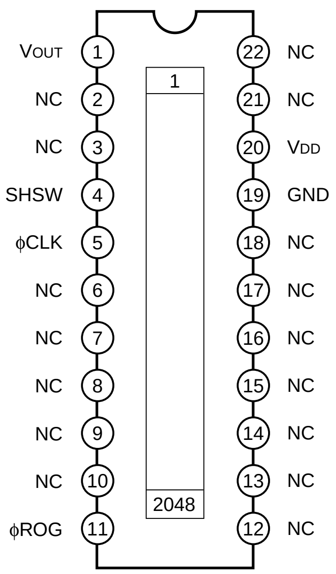
Features

- Number of effective pixels: 2048 pixels
- Pixel size: 14µm × 56µm (14µm pitch)
- Single 5V power supply
- Ultra-high sensitivity
- Built-in timing generator and clock-drivers
- Built-in sample-and-hold circuit
- Maximum clock frequency: 2MHz

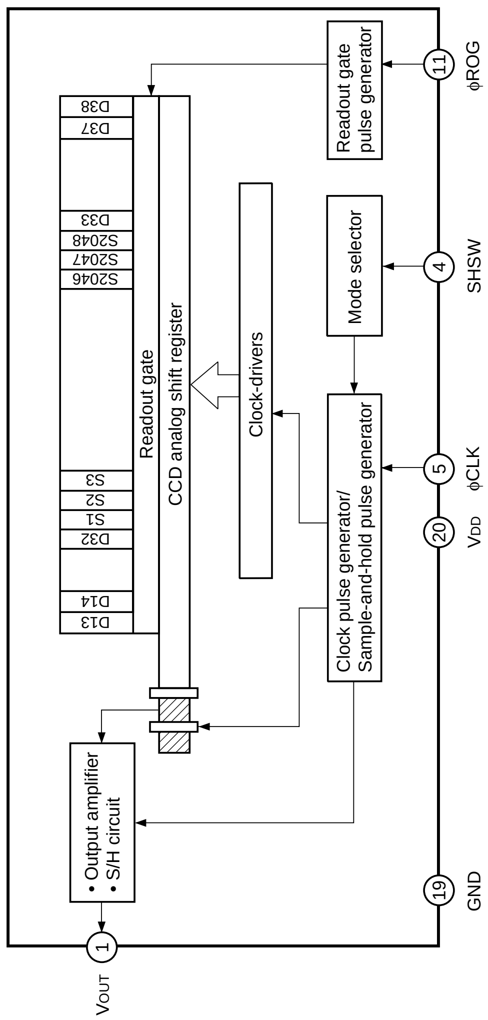
Absolute Maximum Ratings

• Supply voltage	V_{DD}	6	V
• Operating temperature		–10 to +60	°C
• Storage temperature		–30 to +80	°C

Pin Configuration (Top View)



Block Diagram



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Pin Description

Pin No.	Symbol	Description	Pin No.	Symbol	Description
1	V_{OUT}	Signal output	12	NC	NC
2	NC	NC	13	NC	NC
3	NC	NC	14	NC	NC
4	SHSW	Switch (with S/H or without S/H)	15	NC	NC
5	ϕCLK	Clock pulse input	16	NC	NC
6	NC	NC	17	NC	NC
7	NC	NC	18	NC	NC
8	NC	NC	19	GND	GND
9	NC	NC	20	V_{DD}	5V power supply
10	NC	NC	21	NC	NC
11	ϕROG	Readout gate pulse input	22	NC	NC

Mode Description

Mode in use	Pin 4 (SHSW)
With S/H	GND
Without S/H	V_{DD}

Recommended Supply voltage

Item	Min.	Typ.	Max.	Unit
V_{DD}	4.5	5.0	5.5	V

Input Clock voltage Condition*1

Item	Min.	Typ.	Max.	Unit
V_{IH}	4.5	5.0	V_{DD}	V
V_{IL}	0	—	0.5	V

*1 This is applied to the all pulses applied externally. (ϕCLK, ϕROG)

Clock Characteristics

Item	Symbol	Min.	Typ.	Max.	Unit
Input capacity of ϕCLK	$C_{\phi CLK}$	—	10	—	pF
Input capacity of ϕROG	$C_{\phi ROG}$	—	10	—	pF

Electro-optical Characteristics

(Ta = 25°C, V_{DD} = 5V, Clock frequency: 1MHz, Light source = 3200K,
IR cut filter: CM-500S (t = 1.0mm), Without S/H mode)

Item	Symbol	Min.	Typ.	Max.	Unit	Remarks
Sensitivity 1	R1	180	240	300	V/(lx · s)	Note 1
Sensitivity 2	R2	—	3500	—	V/(lx · s)	Note 2
Sensitivity nonuniformity	PRNU	—	5.0	10.0	%	Note 3
Saturation output voltage	V_{SAT}	0.8	1.0	—	V	—
Dark voltage average	V_{DRK}	—	3.0	6.0	mV	Note 4
Dark signal nonuniformity	DSNU	—	6.0	12.0	mV	Note 4
Image lag	IL	—	1	—	%	Note 5
Dynamic range	DR	—	333	—	—	Note 6
Saturation exposure	SE	—	0.004	—	lx · s	Note 7
5V current consumption	I_{VDD}	—	5.0	10	mA	—
Total transfer efficiency	TTE	92	98.0	—	%	—
Output impedance	Z_O	—	250	—	Ω	—
Offset level	V_{OS}	—	2.85	—	V	Note 8

Note)

1. For the sensitivity test light is applied with a uniform intensity of illumination.
2. Light sourse: LED λ = 660nm
3. PRNU is defined as indicated below. Ray incidence conditions are the same as for Note 1.

$$PRNU = \frac{(V_{MAX} - V_{MIN})/2}{V_{AVE}} \times 100\ [\%]$$

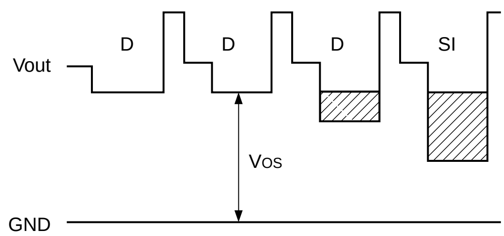
The maximum output of all the valid pixels is set to V_{MAX}, the minimum output to V_{MIN} and the average output to V_{AVE}.

4. Integration time is 10ms.
5. Typical value is used for clock pulse and readout pulse. V_{OUT} = 500mV.
6. $$DR = \frac{V_{SAT}}{V_{DRK}}$$

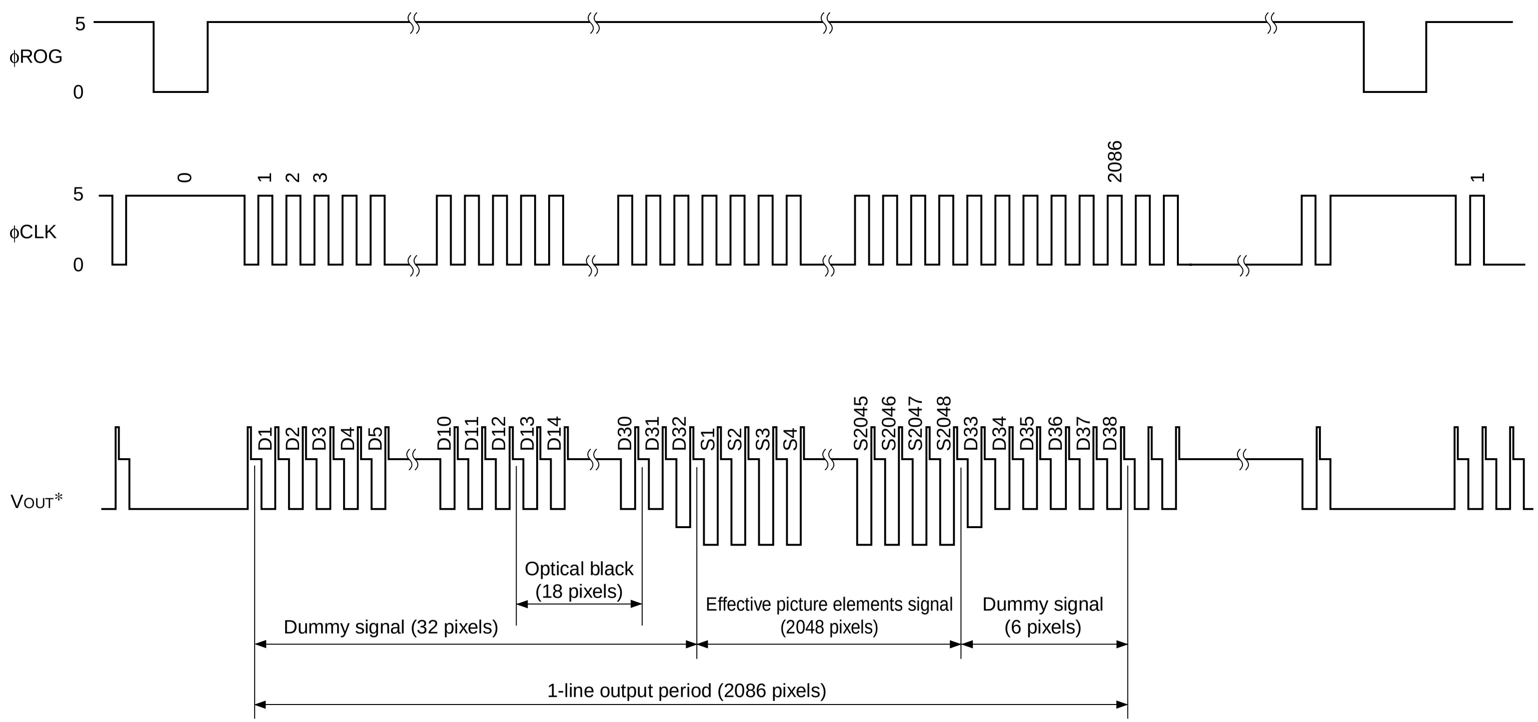
   When optical integration time is shorter, the dynamic range sets wider because dark voltage is in proportion to optical integration time.

7. $$SE = \frac{V_{SAT}}{R1}$$

8. V_{OS} is defined as indicated below.



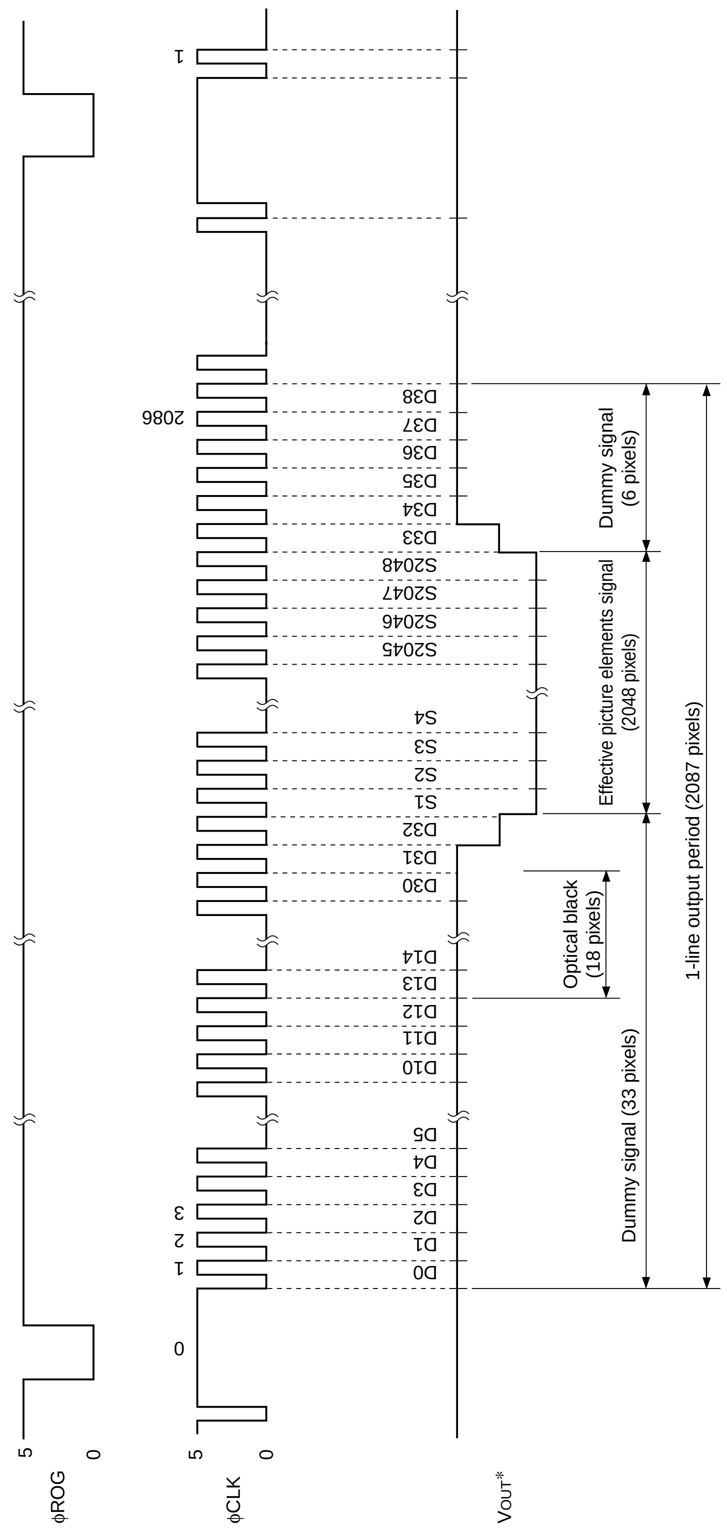
Clock Timing Diagram (without S/H mode)



* Without S/H mode (Pin 4 → VDD)

Note) 2088 or more clock pulse are required.

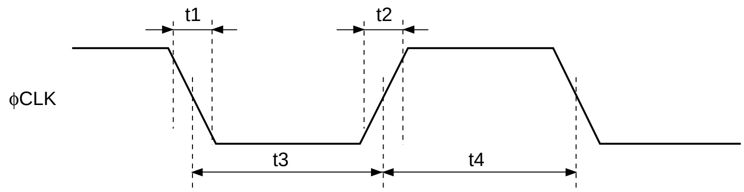
Clock Timing Diagram (with S/H mode)



* With S/H mode (Pin 4 → GND)

Note) 2088 or more clock pulse are required.

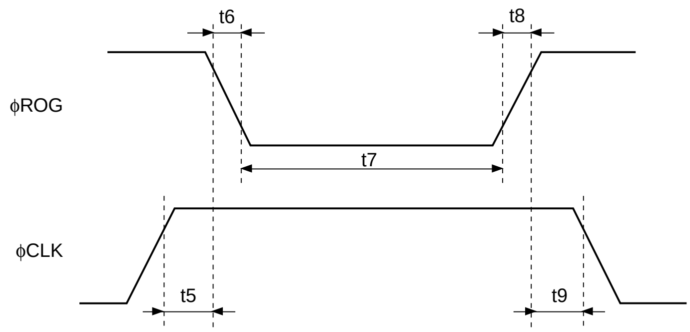
ϕCLK Timing (For all modes)



Item	Symbol	Min.	Typ.	Max.	Unit
ϕCLK pulse rise/fall time	t1, t2	0	10	100	ns
ϕCLK pulse duty*1	—	40	50	60	%

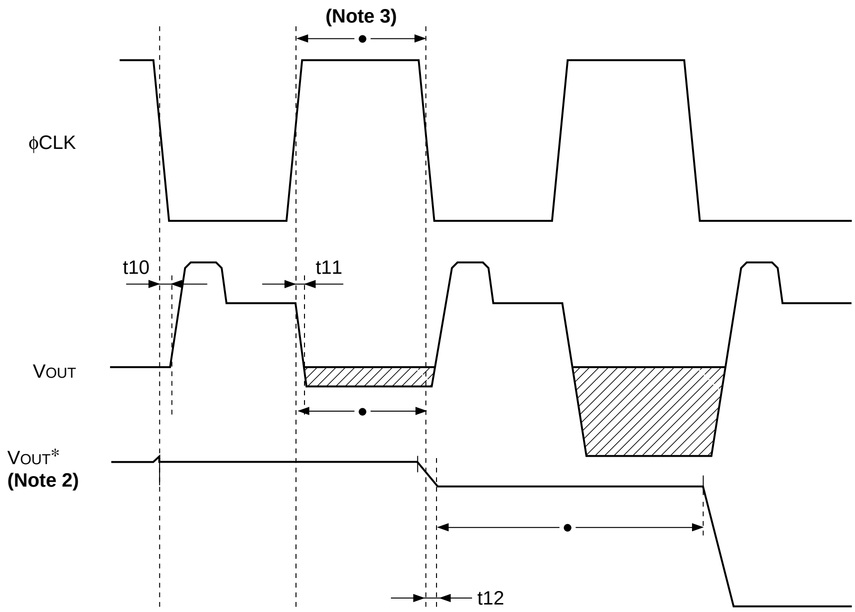
*1 100 × t4 / (t3 + t4)

ϕROG, ϕCLK Timing



Item	Symbol	Min.	Typ.	Max.	Unit
ϕROG, ϕCLK pulse timing 1	t5	0	3000	—	ns
ϕROG, ϕCLK pulse timing 2	t9	1000	3000	—	ns
ϕROG pulse rise/fall time	t6, t8	0	10	—	ns
ϕROG pulse period	t7	1000	5000	—	ns

ϕCLK, VOUT Timing (Note 1)

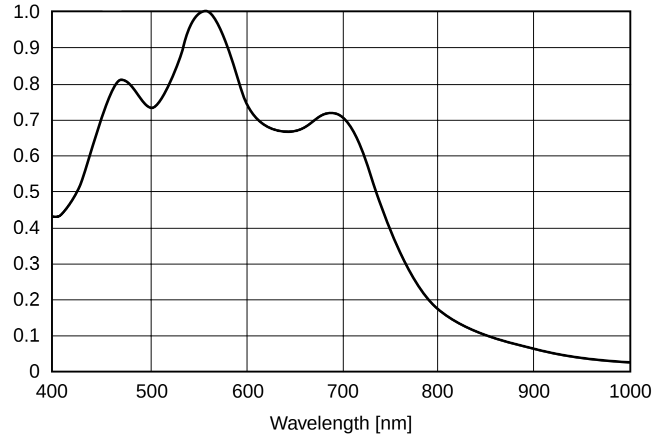


Item	Symbol	Min.	Typ.	Max.	Unit
ϕCLK-VOUT 1	t10	20	100	250	ns
ϕCLK-VOUT 2	t11	55	210	410	ns
ϕCLK-VOUT* (with S/H) 3	t12	20	150	250	ns

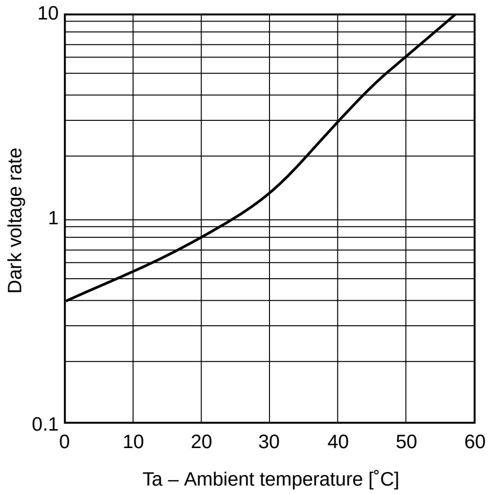
Note 1) fck = 1MHz, ϕCLK pulse duty = 50%, ϕCLK pulse rise/fall time = 10ns
Note 2) Output waveform when internal S/H is in use.
Note 3) • indicates the correspondence of clock pulse and data period.

Example of Representative Characteristics

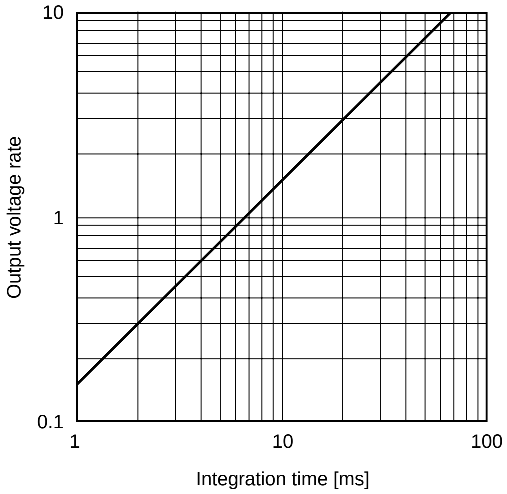
Spectral sensitivity (Typ.) (Ta = 25˚C)



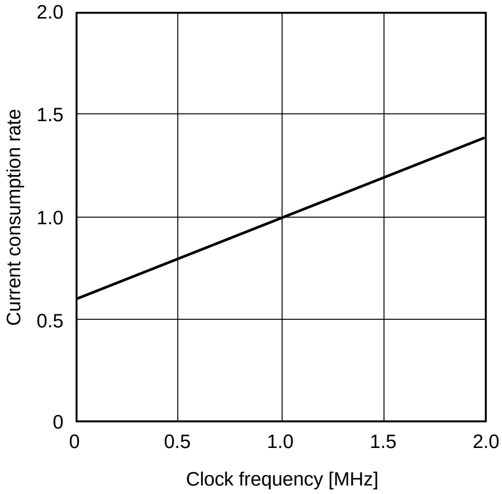
Dark voltage rate vs. Ambient temperature (Typ.)



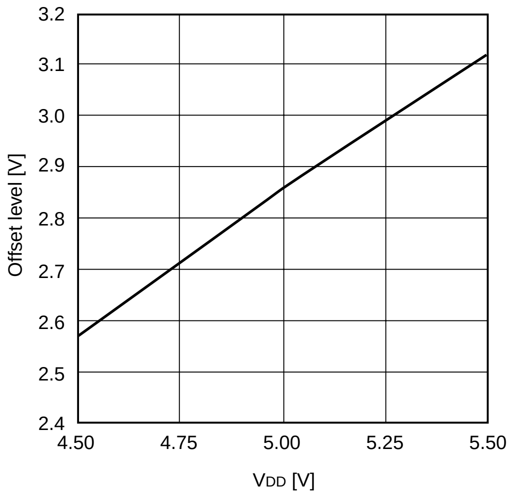
Output voltage rate vs. Integration time (Typ.)



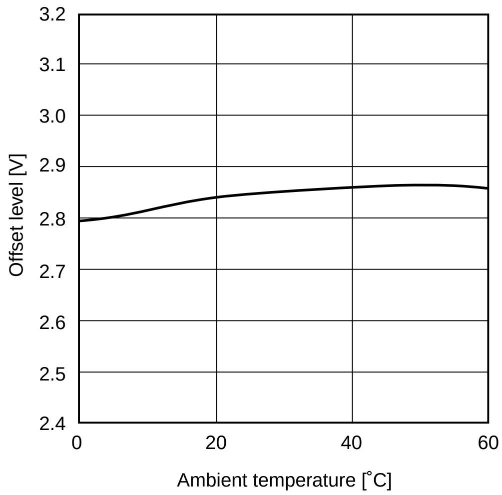
Current consumption rate vs. Clock frequency (Typ.)



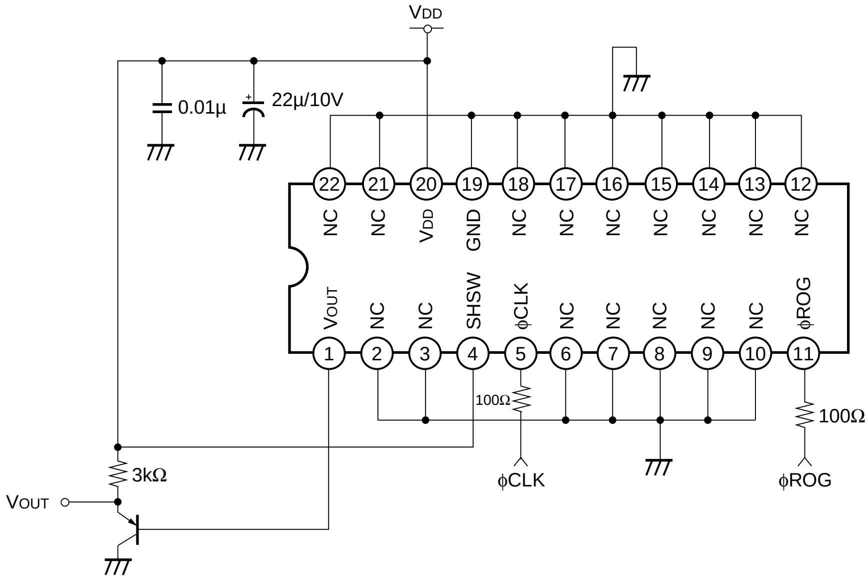
Offset level vs. VDD (Typ.)



Offset level vs. Ambient temperature (Typ.)



Application Circuit (Without S/H mode) Note)



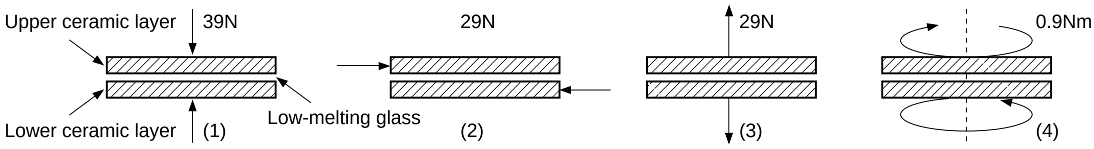
Note) This circuit diagram is the case when internal S/H mode is not used.

Application circuits shown are typical examples illustrating the operation of the devices. Sony cannot assume responsibility for any problems arising out of the use of these circuits or for any infringement of third party patent and other right due to same.

Notes on Handling

1) Static charge prevention
   CCD image sensors are easily damaged by static discharge. Before handling, be sure to take the following protective measures.
   a) Either handle bare handed or use non-chargeable gloves, clothes or material. Also use conductive shoes.
   b) When handling directly use an eath band.
   c) Install a conductive mat on the floor or working table to prevent the generation of static electricity.
   d) Ionized air is recommended for discharge when handling CCD image sensors.
   e) For the shipment of mounted substrates use cartons treated for the prevention of static charges.

2) Notes on handling CCD Cer-DIP package
   The following points should be observed when handling and installing this package.
   a) (1) Compressive strength: 39N/surface
      (Do not apply any load more than 0.7mm inside the outer perimeter of the glass portion.)
      (2) Shearing strength: 29N/surface
      (3) Tensile strength: 29N/surface
      (4) Torsional strength: 0.9Nm



   b) In addition, if a load is applied to the entire surface by a hard component, bending stress may be generated and the package may fracture, etc., depending on the flatness of the ceramic portion. Therefore, for installation, either use an elastic load, such as a spring plate, or an adhesive.
   c) Be aware that any of the following can cause the glass to crack because the upper and lower ceramic layers are shielded by low-melting glass.
      (1) Applying repetitive bending stress to the external leads.
      (2) Applying heat to the external leads for an extended period of time with a soldering iron.
      (3) Rapid cooling or heating.
      (4) Applying a load or impact to a limited portion of the low-melting glass with a small-tipped tool such as tweezers.
      (5) Prying the upper or lower ceramic layers away at a support point of the low-melting glass.
      Note that the preceding notes should also be observed when removing a component from a board after it has already been soldered.

3) Soldering
   a) Make sure the package temperature does not exceed 80°C.
   b) Solder dipping in a mounting furnace causes demage to the glass abd other defects. Use a grounded 30W soldering iron and solder each pin in less than 2 seconds. For repairs and remount, cool sufficiently.
   c) To dismount image sensors, do not use a solder suction equipment. When using an electric desoldering tool, ground the controller. For the control system, use a zero cross type.

4) Dust and dirt protection
   a) Operate in clean environments.
   b) Do not either touch glass plates by hand or have any object come in contact with glass surfaces. Should dirt stick to a glass surface blow it off with an air blower. (For dirt stuck through static electricity, ionized air is recommended.)
   c) Clean with a cotton bud and ethyl alcohol if the glass surface is grease stained. Be careful not to scratch the glass.
   d) Keep in case to protect from dust and dirt. To prevent dew condensation, preheat or precool when moving to a room with great temperature differences.

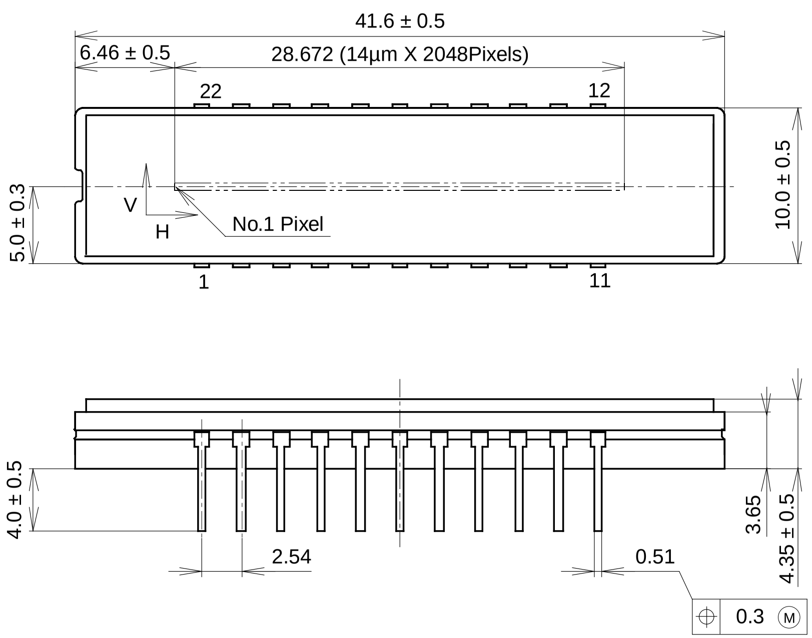
5) Exposure to high temperature or humidity will affect the characteristics. Accordingly avoid storage or usage in such conditions.

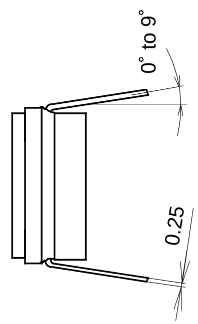
6) CCD image sensors are precise optical equipment that should not be subject to mechanical shocks.

7) Normal output signal is not obtained immediately after device switch on. Use the output signal added 22500 pulses or above to ϕCLK clock pulse.

Package Outline Unit: mm

22 pin DIP (400mil)





1. The height from the bottom to the sensor surface is 2.45 ± 0.3mm.
2. The thickness of the cover glass is 0.7mm, and the refractive index is 1.5.

PACKAGE STRUCTURE

PACKAGE MATERIAL	Cer-DIP
LEAD TREATMENT	TIN PLATING
LEAD MATERIAL	42 ALLOY
PACKAGE MASS	5.20g
DRAWING NUMBER	LS-A20(E)

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