Using an n-zone TDI camera for acquisition of multiple images with different illuminations in a single scan

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Abstract

For fast scanning of large surfaces with microscopic resolution or for scanning of roll-fed material, TDI line scan cameras are typically used. TDI cameras sum up the light collected in adjacent lines of the image sensor synchronous to the motion of the object. Therefore TDI cameras have much higher sensitivity than standard line cameras. For many applications in the field of optical inspection more than one image of the object under test are needed with different illumination situations. For this task we need either more than one TDI camera or we have to scan the object several times in different illumination situations. Both solutions are often not entirely satisfying. In this paper we present a solution of this task using a modified TDI sensor consisting of three or more separate TDI zones. With this n-zone TDI camera it is possible to acquire multiple images with different illuminations in a single scan. In a simulation we demonstrate the principle of operation of the camera and the necessary image preprocessing which can be implemented in the frame grabber hardware.

1 Introduction

There are a lot of applications in industrial image processing and optical inspection where the surface of rapidly moving objects has to be scanned. Examples are inspection of large surfaces with microscopic resolution or scanning of continuous (e.g. roll-fed material) or elongate materials. For continuous image acquisition in these cases, line scan cameras are preferred. High line scan rates are necessary to achieve high speed which leads to short exposure times. In many applications one can not provide enough light for these short exposure times. One solution in this case is to use a TDI line scan camera [1]. TDI cameras sum up the light collected in adjacent lines of the image sensor synchronous to the motion of the object. Therefore the line scan rate and the speed of the moving object have to be synchronized. TDI sensor based cameras are mostly built in CCD technology. But CMOS based solutions are also possible [2] [3].

A problem occurs, when it is necessary to acquire two or more images from the same object point under different illuminations. This is the case if different illuminations are needed to uncover different types of defects. One example is the combination of bright field and dark field illuminations. Another example is the inspection of semiconductor material in the visible and the near infrared spectral region. The only solutions in this case is to perform multiple scans one after the other with the appropriate illumination or to use two or more TDI cameras with a spatial displacement. Both solutions are not entirely satisfying because of the effort of adjusting the system for pixel wise matching.

For the automated optical inspection a system is required where different arbitrary illuminations can be used in a single scan in combination with a TDI

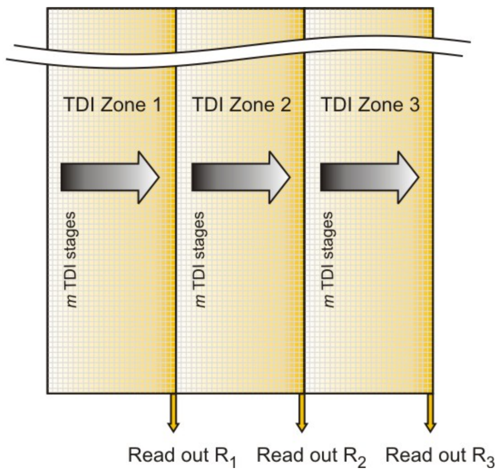

Figure 1: Layout of a 3-zone TDI sensor

sensor. The acquired images have to match pixel wise. This task can be solved with a three-zone (or n-zone for more than three) TDI sensor. The concept can be used with a CCD or a CMOS based sensor. In this paper we present the sensor concept and the necessary preprocessing. In a simulation we show the image generation process.

2 Functional Principle

The TDI sensor consist of three or more independent TDI zones (see figure 1). The zones share the clock signal and operate synchronously. Each zone has m TDI lines which sum up the intensities of the pixels in forward direction. The last column of each zone is read out.

If the sensor consists of three TDI zones also three illuminations I_1, I_2 and I_3 are used. The illuminations are switched after each m clock signals from one illumination to the next. As an example we take TDI zones with $m = 25$ lines and switch to the next illumination every 25 clock signals.

We observe an image point from our object moving from the left of the sensor (see figure 1) to the right. This point enters the sensor on the left side when I_1 is switched on. When the object point is passing the first TDI zone, the object is illuminated by I_1, when it passes the second zone it is illuminated by I_2 and so on. The read out signals R_1, R_2 and R_3 for this point are:

$$\begin{aligned} R_1 &= 25 \cdot I_1 \\ R_2 &= 25 \cdot I_2 \\ R_3 &= 25 \cdot I_3 \end{aligned} \tag{1}$$

Let us now consider a second object point which is one vertical line left of the first image point. When this image point moves over the TDI zone 1, the object is illuminated by I_1 for 24 clock intervals and by I_2 for one clock interval. The same happens for the second TDI zone, where the object point is illuminated by I_2 for 24 clock intervals and by I_3 for one clock interval. After all we get the following results out of our TDI zones:

$$\begin{aligned} R_1 &= 24 \cdot I_1 + 1 \cdot I_2 \\ R_2 &= 24 \cdot I_2 + 1 \cdot I_3 \\ R_3 &= 24 \cdot I_3 + 1 \cdot I_1 \end{aligned} \tag{2}$$

This is a set of 3 linear equations and can be solved for the three unknowns I_1, I_2 and I_3.

Because we have 3 TDI zones with 25 lines each, the acquisition interval is 75 clock intervals. For the first interval the set of equations is (1). The set of equations for the second interval is (2). For each clock interval we have another set of linear equations, which can be solved. After 75 clock intervals the situation recurs.

The only restriction for designing such an image acquisition system is that all sets of linear equations are well-conditioned. To understand this restriction, the sets of linear equations have to be analyzed more in detail. In chapter 3 it is shown that for a setup with 3 TDI zones each set is well-conditioned whereas for a setup with only 2 TDI zones the sets of equations are partly ill-conditioned.

3 Analysis of the set of linear equations

To check whether all sets of equations are all well-conditioned it is sufficient to calculate their condition-number [4].

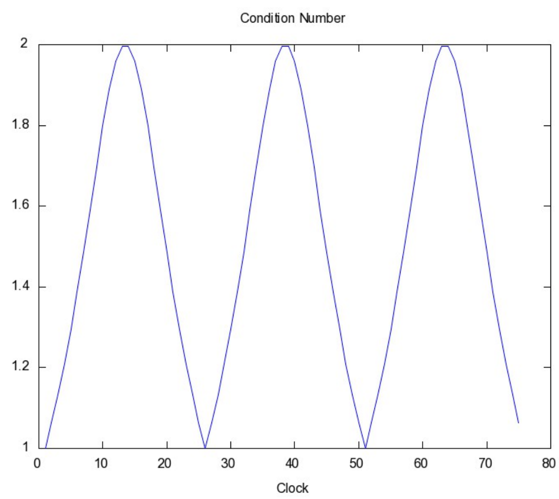

Figure 2: Condition Numbers of a setup with 3 TDI zones

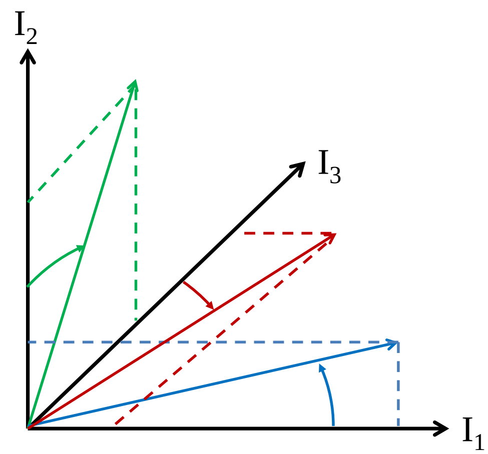

Figure 3: Measurement vectors of 3-zone TDI setup after a few cycles

Setup with 3 TDI zones The sets of linear equations of the first 25 clock intervals with the read out signals $\vec{R}$ and the unknown intensities $\vec{I}$ can be written in matrix form as:

$$\vec{R} = \begin{pmatrix} m-t & t & 0 \\ 0 & m-t & t \\ t & 0 & m-t \end{pmatrix} \cdot \vec{I} \tag{3}$$

where $m = 25$ and $t = 0 \ldots 24$.

The 2-norm condition number can be calculated analytically and is found to be

$$\kappa = \frac{m}{\sqrt{m^2 - 3mt + 3t^2}} \tag{4}$$

κ is maximal for $t = \frac{m}{2}$ with a value of $\kappa_{max} = 2.0$. This shows that all sets of equations are well-conditioned. In figure 2 the condition number κ of the corresponding sets are plotted for a complete interval of 75 clock cycles.

It is more descriptive to analyze the situation in the three dimensional linear space of the intensities $\vec{I}$. Each vector $\vec{I}$ corresponds to three intensities we want to measure. The read out signals $\vec{R}$ can be seen as measurements of an intensity in a different coordinate system spanned up by the three measurement vectors which are the rows of the matrix in equation (3)

$$\begin{pmatrix} m-t \\ t \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ m-t \\ t \end{pmatrix} \quad \begin{pmatrix} t \\ 0 \\ m-t \end{pmatrix} \tag{5}$$

For $t = 0$ the measurement vectors are collinear to the intensity vectors. This situation after a few clock intervals ($t \approx 5$) is shown in figure 3. The first measurement vector (blue) is moving towards the I_2 axes in the $I_1 - I_2$ plane. The second measurement vector (green) is moving towards the I_3 axes in the $I_2 - I_3$ plane. The third measurement vector (red) is moving towards the I_1 axes in the $I_3 - I_1$ plane. The three measurement vectors are forming a new linear independent coordinate system for each time t. The measurement coordinate system is somehow *rotating* within the coordinate system of the intensity vectors.

Setup with two TDI zones The situation for a setup with only 2 TDI zones is completely different. The set of linear equations for the two read out signals R_1 and R_2 with the two illuminations I_1 and I_2 becomes

$$\vec{R} = \begin{pmatrix} m-t & t \\ t & m-t \end{pmatrix} \cdot \vec{I} \tag{6}$$

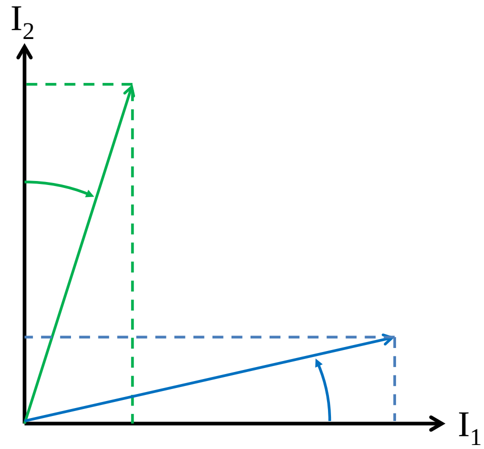

Figure 4: Measurement vectors of 2 TDI setup after a few cycles

At $t = \frac{m}{2}$ the rows of this matrix are identical. The two measurement vectors in the two dimensional linear space of the intensities $\vec{I}$ move in the same plane as shown in figure 4. The condition number of the corresponding matrix increases and goes to infinity at $t = \frac{m}{2}$ where both measurement vectors point to the same direction. The set of linear equations is not invertible any more and the intensities can not be calculated.

Conclusion The restriction for the setup of an n-zone TDI camera is that all sets of linear equations remain well conditioned. This can be checked by calculation of the condition number. It is more intuitive to describe the situation in the linear space of the intensities $\vec{I}$. There we can see more clearly in which situations the set of linear equations is well-conditioned or ill-conditioned. We can conclude

- It is not possible to use a 2 TDI zone setup, because the sets of equations are partly ill-conditioned
- A 3-zone TDI setup leads to well-conditioned sets of equations with condition number of $\kappa_{max} = 2.0$

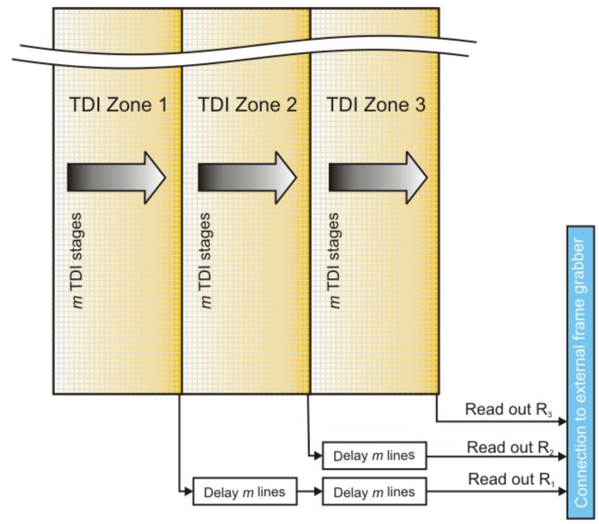

Figure 5: Function of the 3-zone TDI camera in the simulation

4 Simulation of the data flow

For proof of the camera concept and for visualization of the data flow, a simulation is performed. In the simulation a 3-zones TDI monochrome camera is used. The TDI camera has internal delays operating as FIFO registers to synchronize the three output channels (see figure 5). The three output channels are connected to an external frame grabber.

Although the camera is a monochrome camera, a color picture is used as a test image (see figure 6).

The three illuminations used in our simulation setup are colored in $I_1 = red$, $I_2 = green$ and $I_3 = blue$ and are controlled by the GPIO of the frame grabber board. During the first 25 clock intervals the red illumination is on, then the green follows. Because of the colored illumination only the corresponding color channel is imaged. The resulting read out channels are shown in fig. 7 - 9. One can clearly observe the color mixing in the color strips in the upper part of the test image.

After recording the three read out channels in the frame grabber board the preprocessing can be performed. As described in chapter 2 and 3 we have to solve a set of three linear equations for each pixel.

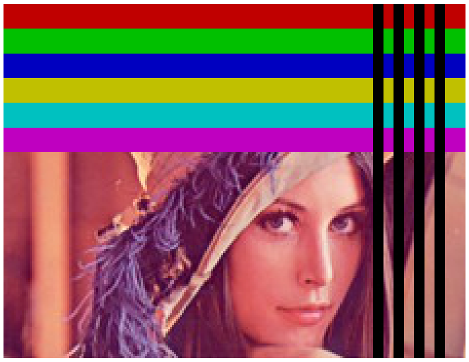

Figure 6: Color Test Image (172x225 Pixel)

Figure 7: Read Out Channel 1

Figure 8: Read Out Channel 2

Figure 9: Read Out Channel 3

Figure 10: Red Color Channel

This is done by simple matrix multiplication of the read out values using the inverse of the linear operator. For each of the 75 clock intervals the matrices are precomputed and stored in the frame grabber. All calculations are performed in integer arithmetic. As a result we get the three color channels separately. To show the results, the red color channel is shown in fig. 10 where you can observe the correct color reconstruction in the color strips at the top of the image. The red strip as well as the yellow and magenta strips show the red color portion.

The combined color image result is shown in fig 11. All pixels are reconstructed correctly for column number 75 and larger column numbers. It is obvious that for smaller column numbers on the left part of the image information is missing, because the pixels are imaged less than 75 times. This is the normal

Figure 11: Result Color Image (172x225 Pixel)

start-up behavior of TDI cameras.

The TDI imager as shown in figure 5 is very much idealized. In practice, there must be a gap between the imaging pixels because there needs to be a non-imaging shift register to move the charge to the output node, plus the bus for clocking such a structure. This gap would be on the order of 10 pixels. A more realistic imager is shown in figure 12. Now the illuminations are switched every 35 clock intervals instead of every 25 intervals. For the first 10 clock intervals the set of linear equations is the same (equation set (1)). Then mixing is started with equation (2).

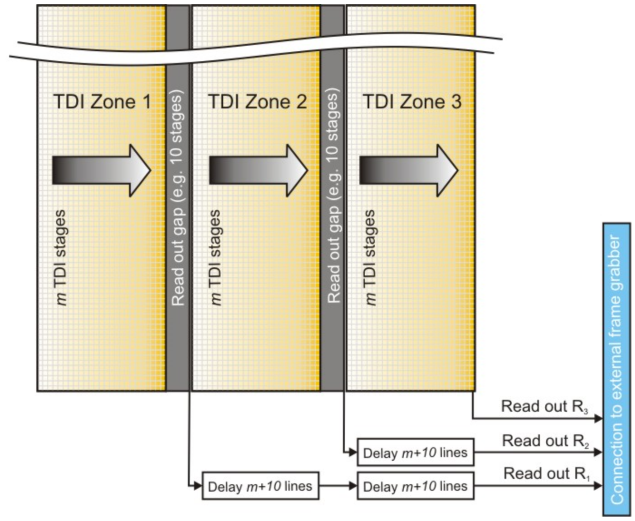

Figure 12: 3-zone TDI camera with read out gap

5 Fields of Application

The fields of application can be described by the distinctive features of the illuminations. They can differ in wavelength, direction, polarization and intensity.

Wavelength In chapter 4 a monochrome 3-zone TDI setup is used to acquire a color image by a red, green and a blue illumination. If a modern CCD sensor with enhanced near infrared sensitivity is used, we can modify this setup by using a 4-zone TDI camera and add a fourth illumination in the near infrared region. This can be useful to inspect semiconductors which become transparent in the near infrared or for detection of organic material.

It is not necessary to use the same illumination duration for all illuminations. If a 3-zone TDI setup is used for color imaging we are often in the situation that the sensitivity in the red channel is higher than in the green channel than in the blue channel when we use the same illumination time (25-25-25). In this case we can use longer illumination in the blue channel and reduce the red illumination (20-25-30) and the set of linear equation changes. Such changes also lead to higher condition numbers. It has to be ensured that the sets remain well-conditioned. For example a change to illumination times (10-15-50) would lead to this set of equations for $t = 0$:

$$\vec{R} = \begin{pmatrix} 10 & 15 & 0 \\ 0 & 0 & 25 \\ 0 & 0 & 25 \end{pmatrix} \cdot \vec{I} \qquad (7)$$

This set is ill-conditioned. This can be seen easily in figure 3. For the first clock interval the first measurement vector is in the $I_1 - I_2$ plane and the other two of the measurement vectors are collinear to I_3. These three measurement vectors are not forming a linear independent three dimensional coordinate system.

It is also possible to acquire only two images with a 3-zone TDI sensor. For example one white illumination provides the gray scale image in the visible spectral domain and a second illumination in the near infrared provides a second image. To acquire two images with a 3-zone TDI camera only the set of linear equation changes. Instead of using the inverse of the linear operator, the Moore-Penrose pseudoinverse is used in this case. No changes in the camera are necessary.

Direction A well known application where different illumination directions are used is the combination of bright field and dark field illumination. This can be realized also with a 3-zone TDI camera. Often the bright field illumination leads to much brighter images than the dark field illumination. This can be compensated by using a longer illumination time for the dark field illumination. If the same setup is used as for three color imaging, the bright field illumination can be I_1 and the dark field illumination can be I_2 and I_3.

Intensity and High Dynamic Range (HDR) Imaging The first approach of using n-zone TDI cameras for HDR imaging is to use illuminations with different intensities. However this approach does not work if one of the readout channels is saturated, which is normally the case. In this case the set of equations is not linear any more and can not be solved.

6 Conclusions

In this paper the idea using a monochrome n-zone TDI camera for the acquisition of multiple images with different arbitrary illuminations in a single scan was presented. Although images are acquired with a high clock frequency, the switching of the illuminations is done at a much lower frequency which makes the implementation more simple.

A variety of possible applications have been shown in chapter 5. The examples show that most applications can be realized with a 3-zone TDI sensor.

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