MTF measuring method of TDI camera electronics

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ABSTRACT: The modulation transfer function (MTF) in a camera system is a measurement of how well the system will faithfully reproduce the original scene. The electro-optical camera system consists of optics, an array of pixels, and an electronics which is related to the image signal chain. The system MTF can be cascaded with each element's MTF in the frequency domain. That is to say, the electronics MTF including the detector MTF can be recalculated easily by the acquired system MTF if the well-known test optics is used in the measuring process. A Time-Delay and Integration (TDI) detector can make a signal increase by taking multiple exposures of the same object and adding them. It can be considered the various methods to measure the MTF of the TDI camera system. This paper shows the actual and practical MTF measuring methods for the detector and electronics in the TDI camera. The several methods are described according to the scan direction as well as the TDI stages such as the single line mode and the multiple-lines mode. The measuring is performed in the in the static condition or dynamic condition to get the point spread function (PSF) or the line spread function (LSF). Especially, the dynamic test bench is used to simulate on track velocity to synchronize with TDI read out frequency for the dynamic movement.

KEY WORDS: MTF, Line Spread Function, Point Spread Function, TDI Camera, Camera Electronics

1. INTRODUCTION

A large number of metrics are related to image quality in the electro-optical camera system such as a non-linearity, a modulation transfer function (MTF), a signal to noise ratio (SNR), a resolution. In these, the MTF represents how well the system will faithfully reproduce the original scene as a one of most important performance. A Time Delay and Integration (TDI) camera works like a line-scan camera. But its sensor has multiple rows to take multiple exposures of the same object. Usually, the TDI offers the SNR increases by the square root of the number of the TDI stages. The disadvantage is that the scan velocity must be tightly controlled as the number of the TDI stages increases. If not, the error in scan velocity decrease the MTF[1].

It is more difficult to measure the MTF of the TDI camera than the line-scan camera, especially the along track scan direction, because it has multiple rows but does not have the output port for each row. This paper shows the actual and practical MTF measuring methods for the camera electronics in the TDI camera system. The measuring methods are described according to the scan direction as well as the TDI stages such as the single mode and the multiple-mode. The measuring is performed in the static condition or the dynamic condition to get the point spread function (PSF) or the line spread function (LSF). In particular, the dynamic test bench with the predefined movement profile is used to simulate on track velocity to synchronize with the read out frequency to measure in the along scan direction.

2. SYSTEM MTF AND ELECTRONICS MTF

The MTF is defined to the ratio of output modulation to in modulation normalized to unity at zero spatial frequency. The high MTF is related to the image sharpness. It can be also described as the AC amplitude divided by the DC level. The modulation is represented as follows[1];

$$Modulation = M = \frac{V_{MAX} - V_{MIN}}{V_{MAX} + V_{MIN}} = \frac{AC}{DC} \qquad (1)$$

where V_{MAX} : maximum signal level
V_{MIN} : minimum signal level

The MTF is the modulation ratio at the specified input spatial frequency. Thus, it is described as the magnitude of the Fourier transform of the PSF or the LSF. An object or imaging target can be thought of as the sum of an infinite array of impulses located the target boundaries. That means the object can be decomposed into a series of weighted Dirac delta function[1]. The convolution theorem describes the Fourier transform of the convolution of two functions equals the product of the transform of the two functions. That is, the multiple convolutions are equivalent to multiplication in the frequency domain[2]. The equation (2) describes the system MTF with non-correlated MTFs.

$$MTF_{SYS}(f) = \prod_{i=1}^{N} MTF_i(f) \qquad (2)$$

where MTF_{SYS} is the system MTF
MTF_i is the MTF of subsystem i

An individual lenses within an optical system, in general, are correlated and their MTFs cannot be cascaded. In a real electro-optical camera system, the system MTF can be simply expressed as follows;

$$MTF_{SYS}(f) = MTF_{Optics} \cdot MTF_{Pixel} \qquad (3)$$

where MTF_{Optics} is the optics MTF
MTF_{Pixel} is the electronic MTF including detector

The equation (3) implies that the electronics MTF including the detector MTF can be recalculated easily by the acquired system MTF in the frequency domain if the well-known test optics is used in the measuring process.

The two-dimensional system MTF can be assumed separable in two orthogonal axes to obtain two one-dimensional MTFs for convenience.

$$MTF_{SYS}(f_x, f_y) = MTF_{SYS}(f_x) \cdot MTF_{SYS}(f_y) \qquad (4)$$

where $MTF_{SYS}(f_x)$ is the MTF in the x axis
$MTF_{SYS}(f_y)$ is the MTF in the y axis

Electrical filters are causal, one-dimensional, and are considered to operate in the direction of the readout clocking only. In addition, a multiple phase transferring method is needed to the vertical charge movement. These operations may make the difference between the horizontal and the vertical MTF. Practically, the one dimensional MTF can be measured in the cross track and the along track direction separately. The LSF instead of the PSF can be used to get one-dimensional MTF curve. The LSF is the resultant image produced by the imaging system when it is viewing an ideal line.

3. MTF MEASRUING OF SINGLE TDI MODE

The single TDI mode operation is a special case of the TDI camera. The TDI camera works as a simple line-scan camera in this mode. The single mode MTF is useful to predict the electronics MTF and the optical MTF even if it does not cover the MTF of the whole TDI camera operation. Of course, the applicable method to the line-scan camera can be used to the TDI camera as well. Figure 1 shows the basic MTF measuring concept of in the single TDI mode. The point target shall place on the specified pixel to get the MTF exactly and illuminate. After acquisition of pixel value of the illuminated pixel and several adjacent pixels then we can get the PSF and the MTF curve. The static and the dynamic test setup can be used in the both the cross track and the along track direction to measure the MTF.

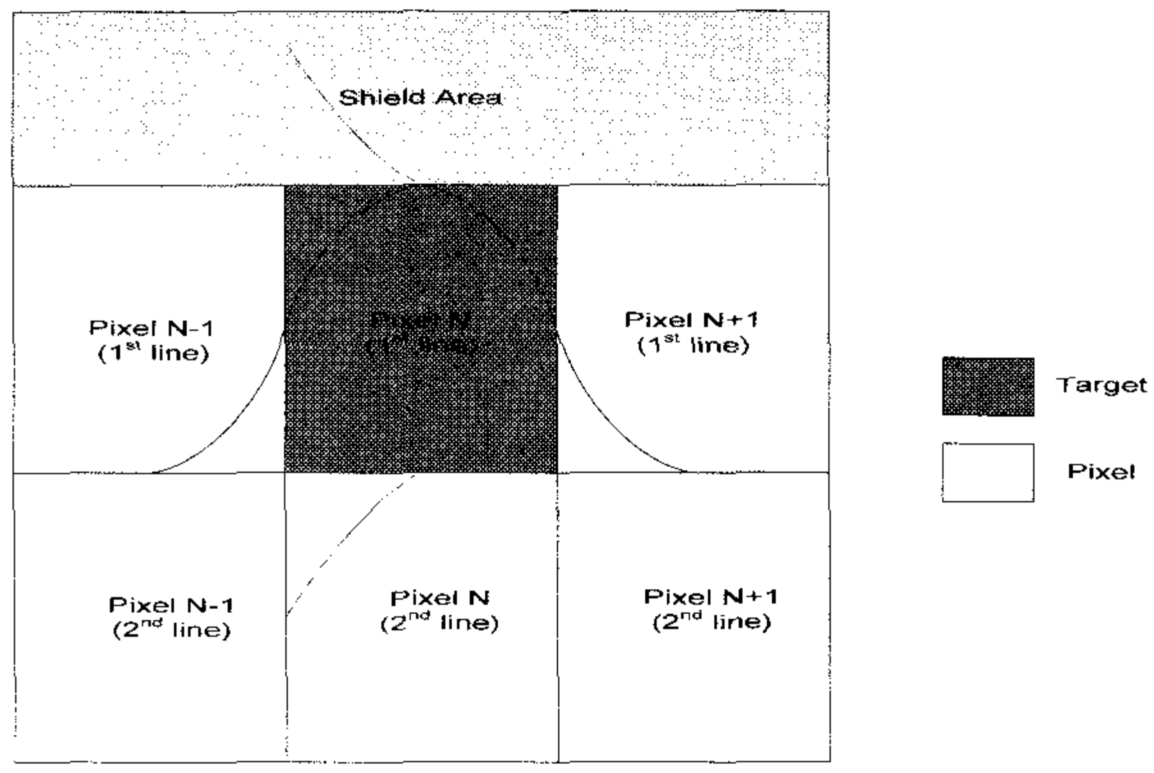

Figure 1. MTF measuring in single TDI mode

3.1 MTF measuring in static setup

It is difficult to illuminate exactly to the specified pixel. The target shall have static movement to overcome this difficulty. The static movement means that the target shall move inside the pixel but, the data is acquired in the static condition. A line target or a knife-edge target can be used to measure the MTF. If the knife-edge target is used, we can get an edge spread function first to get the line spread function. But if the line target is used, the LSF can be achieved directly. All the acquired data shall be mapped to the target's position. Hundreds samples of data can be acquired to minimize noise effect in the static measurement setup.

Figure 2 shows the cross track MTF measuring method in the static setup. The line target can be used for measuring the MTF in the specified pixel. The target shall be moved from the adjacent pixel or 2-3 pixels before. We can get the value of pixel and the position of target. Using these data we can get the LSF and the MTF curve.

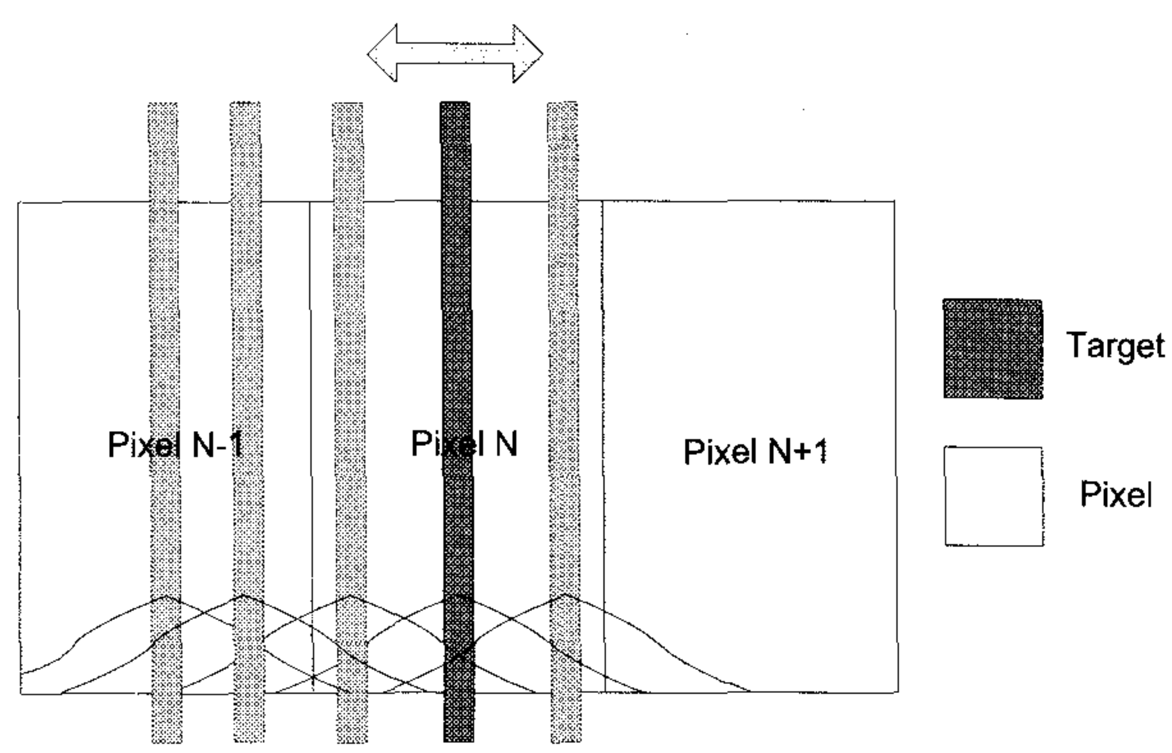

Figure 2. Cross track MTF measuring method in the single TDI mode using static movement.

The TDI camera actually works, in the along track direction, under the dynamic condition. However, the measurement in the static movement can replace that of the dynamic condition because the difference is very small. Figure 3 shows the vertical MTF measuring method in the static condition. The line target can be moved along the scan direction. Using the acquired pixel data and the target's position data we can get the LSF and the MTF as well.

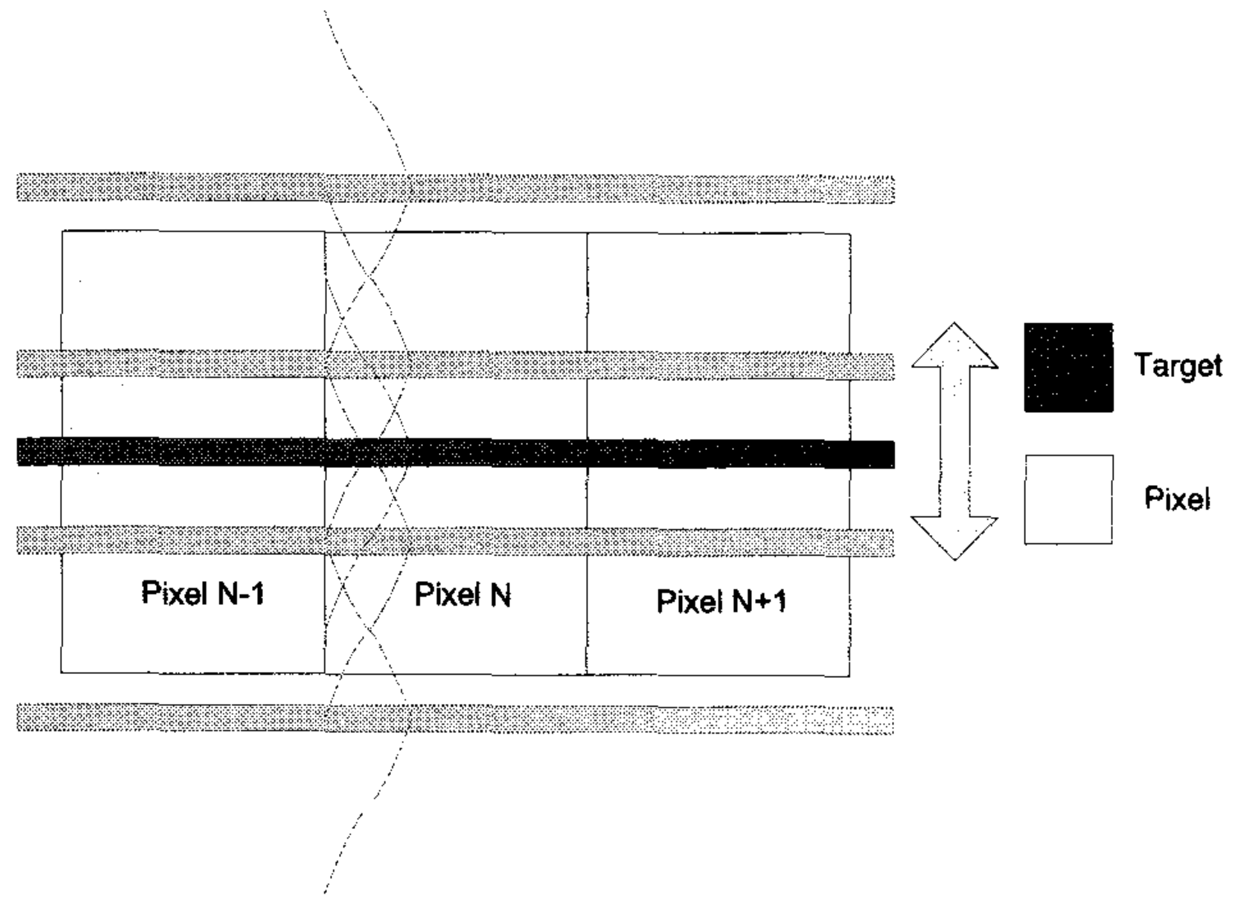

Figure 3. Along track MTF measuring method in the single TDI mode using static movement.

3.2 MTF measuring in dynamic setup

The dynamic movement gives the more realistic MTF curve. It is needed to move the target with vertical synchronization to get the MTF in the along track direction in particular. If not, it affects the MTF results. However, if we use a tilted rectangular target, we can overcome this weakness. This may be useful to get the MTF curve without the accurate linear stage or with a simple test setup.

Figure 4 and Figure 5 shows the concept of measuring the MTF using tilted rectangular target for both directions respectively. An edge spread function can be acquired first. And then the LSF and the MTF curve can be calculated using the acquired edge spread function. It is needed the prediction and calculation using target shape and its tilt-angle to get the more accurate target movement.

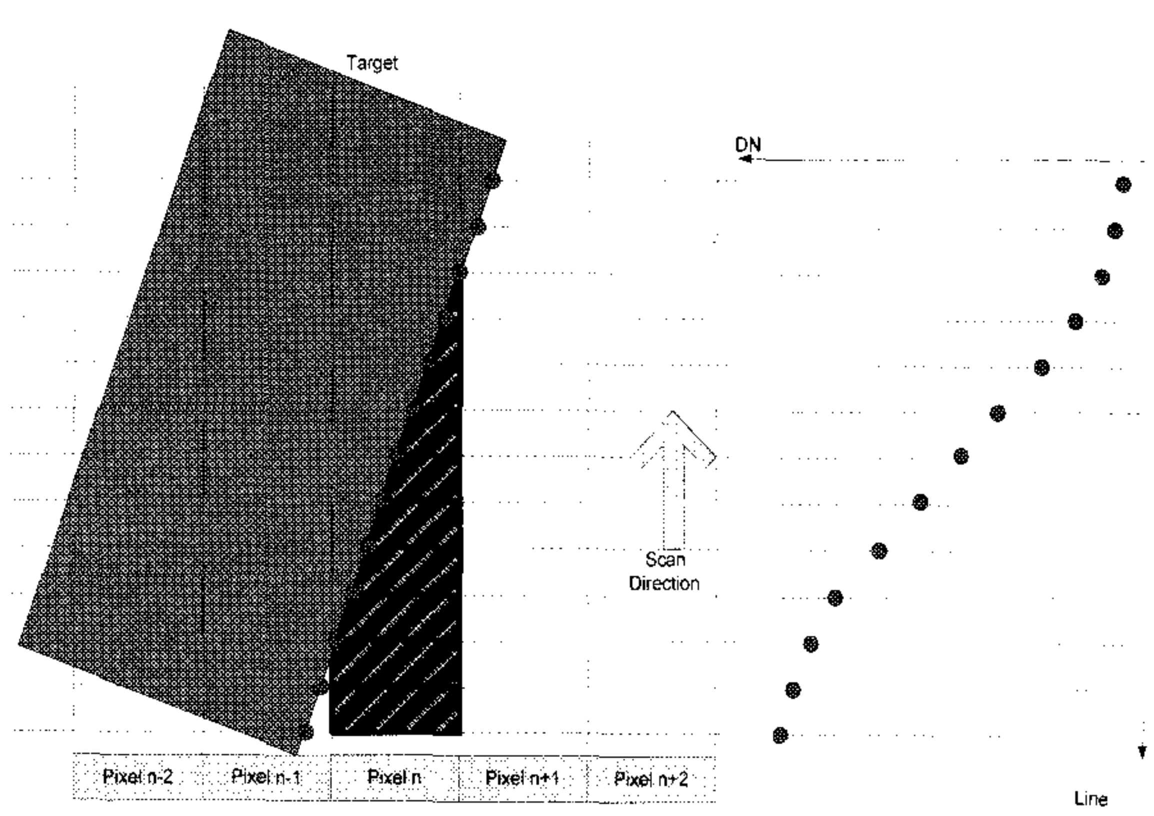

Figure 4. Cross track MTF measuring method in the single TDI mode using dynamic movement.

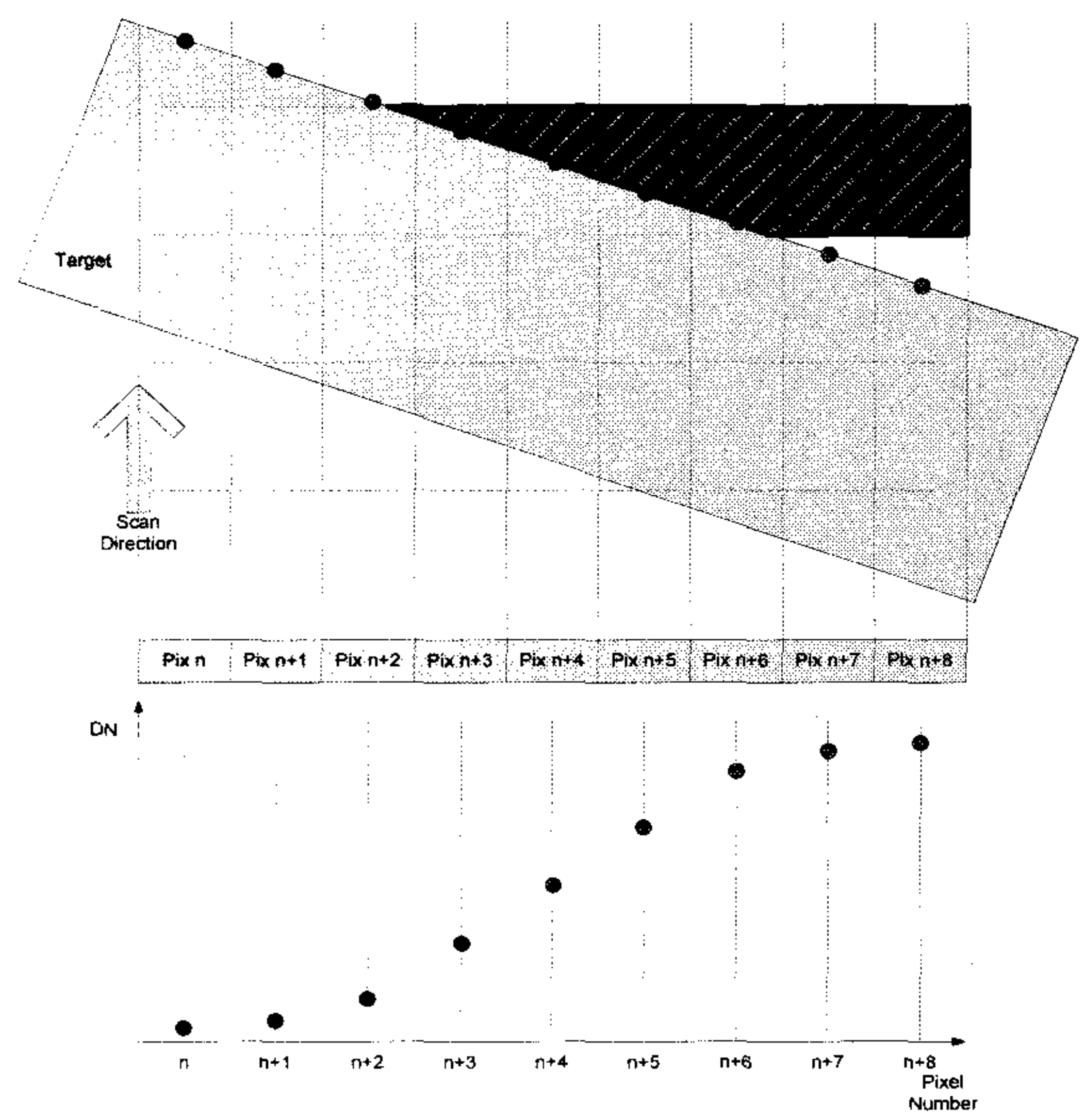

Figure 5. Along track MTF measuring method in the single TDI mode using dynamic movement.

4. MTF MEASRUING OF MULTIPLE TDI MODE

Generally, the multiple-TDI stage gives the SNR increase by square root of the number of the TDI stages. But the system error in the scan velocity and the sensor alignment can dramatically decrease the MTF. The multiple-TDI MTF is related to the TDI charge transfer, the line-frequency accuracy and the all pixels' characteristics on the TDI direction as well as the optical MTF.

Some methods can be considered to get the MTF in the multiple-TDI mode. It is not easier to measure than a single TDI mode. Especially the static method cannot be used for the along track direction if the special calibration mode such as a frame mode does not exist in the system. If the system provides the frame mode for calibration, each pixel's MTF can be achieved easily by the free sub-pixel movement.

For along track direction, the special test setup such as the dynamic test bench is needed to synchronize the target movement and the system read-out frequency. Also accurate linear stage is needed to keep step with the line frequency.

4.1 MTF measuring in the cross track direction

The static movement can be used to get the MTF curve in the cross direction. The measuring method is almost same to the single TDI mode except the line-target covers all TDI lines. Figure 6 shows the MTF measuring concept. The target shall be moved from the adjacent pixel or before. The LSF curve and the MTF curve can be achieved by the acquired pixel data and the target's position data as well.

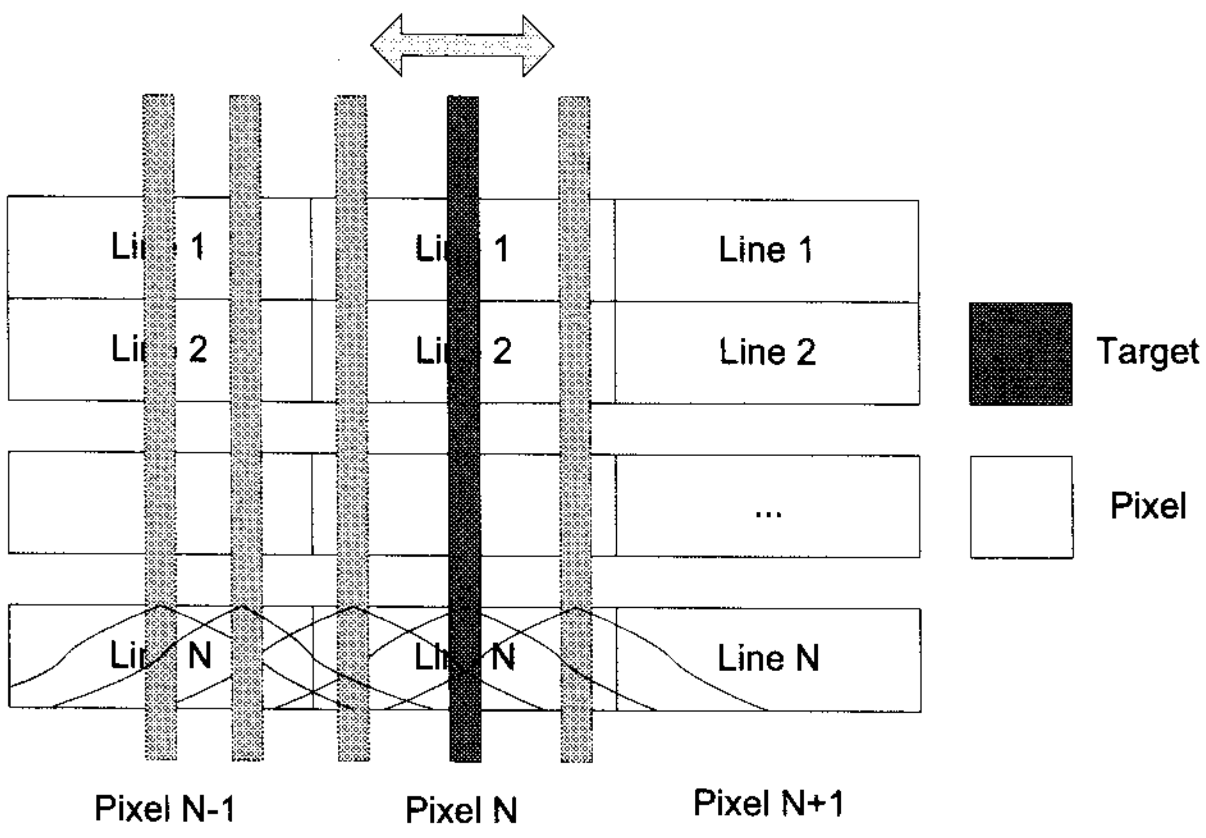

Figure 6. Cross track MTF measuring method in the multiple TDI mode.

4.2 MTF measuring in the along track direction

The multiple TDI MTF in the along track direction can be achieved using the target's dynamic movement. The special test setup such as the dynamic test bench is needed to synchronize the target movement. The dynamic test bench simulates the on-track velocity in synchronization with TDI read-out frequency. That means the test set-up can record exact target's position and velocity in synchronization with camera read operation. Also the accurate linear stage is needed to keep step with the line frequency. This velocity error may make the MTF measurement error. Figure 7 shows the dynamic test bench to measure the along track MTF. Test setup shall have a predefined movement profile. The camera works in step with this profile as well. The camera shall provide the synchronization signal to the test setup. The position and the velocity of the linear stage shall be stored in the controller. The electronics MTF can be calculated using the acquired system MTF and the known optics MTF.

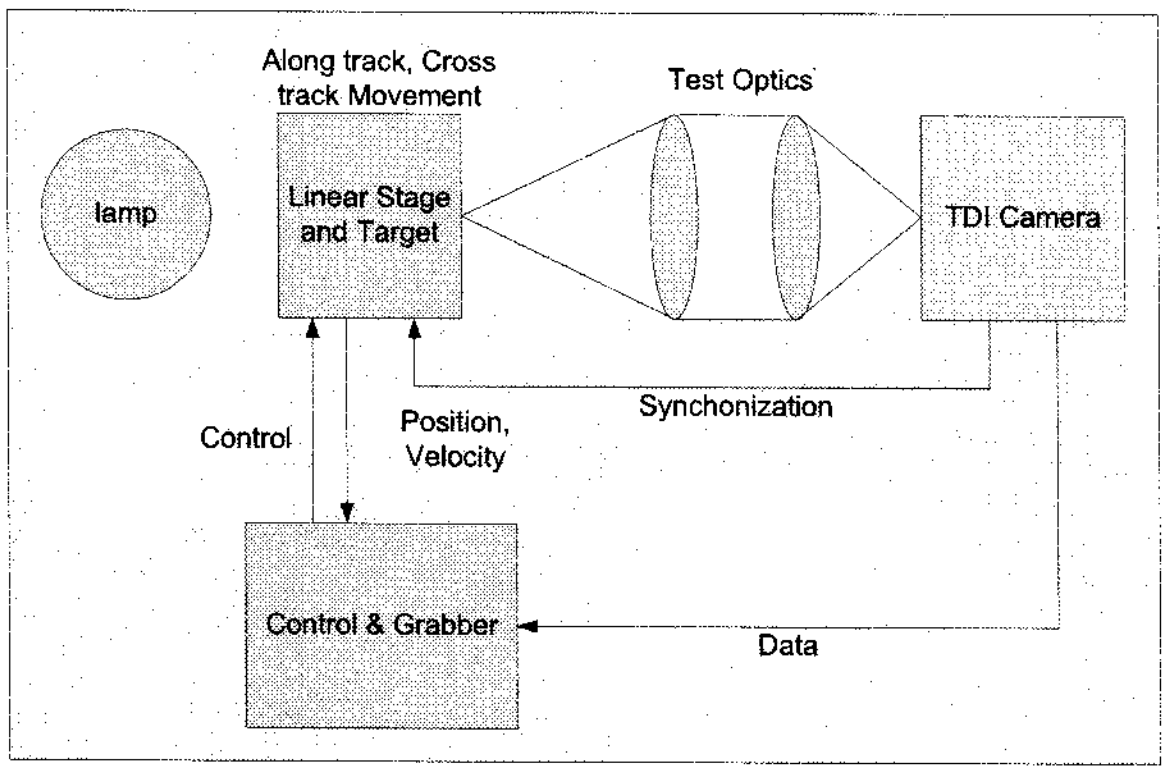

Figure 7. Dynamic test bench.

Figure 8 shows the MTF measuring concept in the along track direction. The test setup shall give the target's position, which is exactly synchronized with the TDI read-out frequency. The mapping table can be built using the acquired pixel data and the target's position data. This table helps to make the LSF and the MTF curves.

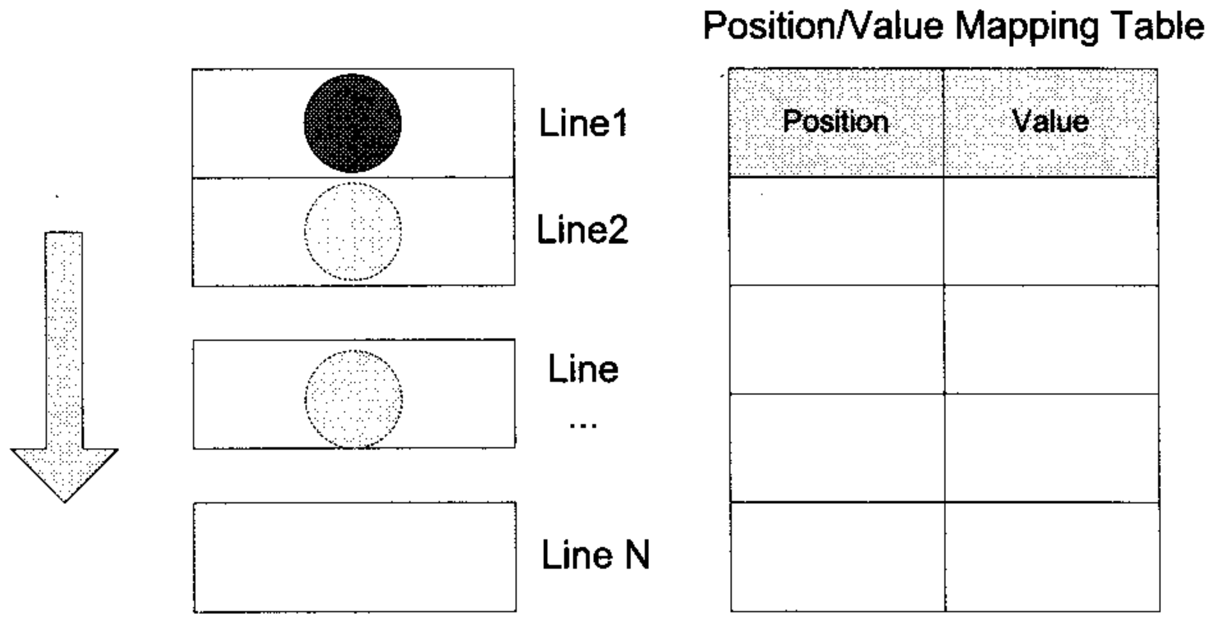

Figure 8. Along track MTF measuring method in the multiple TDI mode.

5. CONCLUSION

The MTF is a one of most important performance metric which is related to the image sharpness in the camera system. As the object is decomposed into a series of weighted Dirac delta function, the system MTF can be cascaded with each element's MTF in the frequency domain. That is to say, the electronics MTF can be calculated easily by the acquired system MTF if the well-known test optics is used. This paper shows the actual and practical MTF measuring methods for the TDI camera electronics. The several methods are described according to the scan direction and the number of TDI stages. The measuring to get the PSF or the LSF can be performed in the static or the dynamic test setup accordingly. The MTF in the single TDI mode can be achieved simply through static movement. But, it is more difficult in the multiple-TDI mode, especially in the along track direction. The dynamic test bench with the predefined movement profile is introduced to simulate on track velocity to synchronize with TDI read out frequency for the multiple TDI stages in this paper.

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