# Automatic Defect Recognition in Magnetic Particle Inspection Applications

A Paper By

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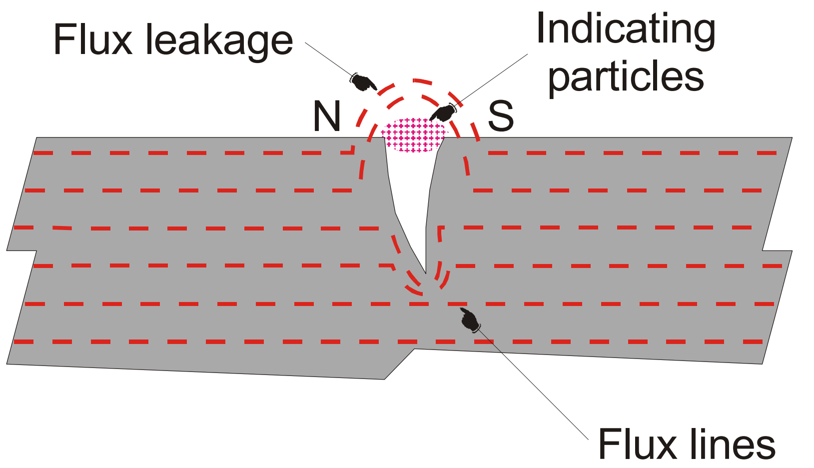
# Table of Contents

# 1 Introduction

The purpose of this paper is to provide a detailed technical account of the parameters that should be considered when implementing automatic defect recognition systems on MPI equipment.

# 2 Basic Principles of Magnetic Particle Inspection

Magnetic Particle Inspection (MPI) is used to highlight defects that are not necessarily visible to the human eye. The process involves the magnetising a component during which time ferromagnetic particles - either suspended in a fluid or in a powder form - are applied. If a defect exists in the component the particles will be attracted by the magnetic poles, which are present on each side of the defect, where the flux leaks in to the air.




Usually particles are suspended in a fluid - commonly treated water - which provides mobility to the particles in migrating to the crack edges, thus the particles are aligned along the crack. The contrast between the component surface - background - and the particles along the crack is high; therefore the human eye easily sees the defects. Maximum contrast is achieved by the use of particles coated with a material, which fluoresces when illuminated by ultraviolet radiation (black light). Thus the effect is that it is not necessary to closely inspect the component since the bright defect indications attract the eye of the viewer, particularly if the inspection is carried out in a darkened environment.

# 3 Background of Machine Vision

For nearly two decades, machine vision has been applied to a wide range of challenges. These challenges all hinged on the desire to improve quality and productivity whilst lowering costs. While machine vision has come a long way, it also continues to experience “Growing pains”, many of which are impossible to eliminate even today’s technological advances occurring daily.

The simple explanation for the developmental costs of automatic machine vision systems is the lack of a clear understanding of technology’s inability to replicate nature in regard to the Human brain’s ability to process information subjectively, which it receives from the photo receptors in the eye via the optic nerve. Technology, even with the advances in robotics, logic controllers, and artificial intelligence, simply cannot be as reliable as the Human being’s ability to reason.

This is due to the amazing power of the Human brain. Once it is realised and appreciated that while machine vision will never be better than the ability to scrutinise, inspect and reason as the human brain does, only then can we realise what machine vision can do, and what an excellent tool it could be when used in the Non-destructive Testing industry.

It is theorised that the human inspector is, at best 80% effective. This means that the human inspector with the ability to reason will still miss at least 20 opportunities to detect a defective piece out of 100 samples presented. Machine vision on the other hand has been proven to be successful 95%-99% in detection of defects, which it has been programmed to detect, but nothing more. While the machine vision system will be successful in detecting 15-19 defects the human will miss per 100 parts, all the time, the machine vision system will also, depending on the programming, detect false positive rejectable components. This means that the machine vision will detect nearly all defects it has been programmed to detect, but because of its inherent lack of reason, it will also signal rejectable status of otherwise acceptable components. A human inspector would most likely not have rejected these false positives provided the reasoning and scrutiny necessary for a proper inspection were in fact utilised. These false positives are a “necessary evil” for a machine vision installation in that in order to guarantee the detection of all actual rejectable defects, it is necessary to over scrutinise the component under test, which causes the occasional false positive response.

Machine vision however is an attractive idea because it is able work around the clock without the need for breaks and interruptions which human inspectors encounter. Machine vision systems perform their jobs 100% of the time with up to 99% accuracy in actually locating rejectable components at much faster rates than possible with a human inspector and with absolute consistency.

It is assumed that in most any high production application requiring Non-Destructive Testing to be performed will benefit greatly in regard to reduced product liability, increased production, and a high degree of confidence that while a very small number of acceptable components will be rejected because of machine vision's lack of reasoning ability, that all of the rejectable components would have been identified. Quality Control and Quality Assurance managers agree that a very small number of acceptable parts being falsely rejected are an acceptable trade when it results in the elimination, or near elimination of rejectable defect indications being missed by the human inspector.

There are several variables, which will play a role in the machine vision installation for MPI. The following list represents the main concerns to be addressed with an MPI machine vision system:

- Brightness of indication
- Size of indication
- Surface area to be inspected
- Surface condition
- Inspection speed
- Direction of defect indication
- Accept/reject criteria
- Lighting
- Magnetic particle inking suspension used
- Contrast between Defect and background
- Camera type used
- Shutter speed
- Spectral sensitivity
- Method of obtaining image
- Method of processing image
- Processing ability and speed of CPU

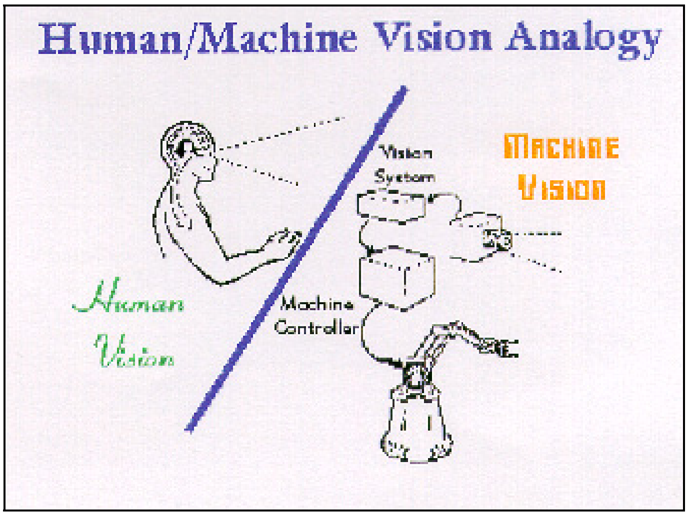
While there are surely other application specific variables involved with machine vision systems, the above list represents the common concerns needing addressed. The most crucial of these, as it relates to nearly each of the other variables is the inking material used for the formation of the MPI defect indication.

As discussed previously, the human eye is second to no machine vision system when inspecting one component thoroughly and effectively if given the time to perform the inspection with great subjective scrutiny. This human advantage is due not only to the ability to reason and process the information received from the eyes, but indeed by the very way in which the human eye sees.

It is theorised that the human eye possesses over 100,000,000 individual discrete light sensing elements. It is in fact the ability to sense the reflected light from off of objects, which allows the human to see.

This reflected light is the means by which we see, and in fact, without light the human being does not see objects. In fact, human vision is very much like machine vision in that it is processing reflective light from objects, which creates the images of these objects that we consider sight. The best vision systems of the past few years used on the order of 250,000 light sensing elements, or pixels. Today there are some cameras that offer up to 16,000,000 pixels, which seem to be quite an improvement, but still a fraction of what the human eye is capable of using to see. Beyond this, we tend to expect the machine vision systems to duplicate the inspection via the same process the human inspector uses.

## 4 Human Vision vs Machine Vision




As a model we can consider the human vision system comprising the eye(s), the optic nerve, and the brain. The eye forms an optical image with its lens and senses this optical image with the retina. The optic nerve transmits the image information to part of the brain, which analyses and extracts the image information. Another part of the brain uses this information to control the body's muscles.

A model of machine vision is quite similar to the simplistic model of the human vision system. A camera with a lens forms the optical image onto an image sensor; a video signal then travels through a cable to a computer that analyses the image information to extract the necessary information. This information is then sent to a controller, which operates some machinery.

These are very simple models, both of machine vision and especially of human vision, but they are sufficient as a beginning point.

There is much that is not understood about the workings of human vision and one can only marvel at how incredibly well the human vision system works. With the best technology and the most powerful computers, it is still not practical for any artificial vision system to guide a car, through traffic, looking for street signs and avoiding sudden dangers. However, even in this example, research is pushing forward.

Human vision is still an unsolved mystery. Analysing the human vision system we find that its apparent speed would not allow humans to see the ball in most sports. We find that human visual acuity is too coarse to explain how inspectors can grade surface finish on a finely machined part. Yet both activities are very common.

Human vision provides a natural starting point for development of machine vision. Most machine vision equipment has an architecture that is modelled, to some degree, after human vision. In a person the eye senses an image, information from the image is extracted by one part of the brain, and another part of the brain accepts the processed information and commands the muscles to make certain movements. In a machine vision system, camera or other image sensor replaces the eye, a processor, specially constructed and programmed to analyse image information, processes the camera's output, and a machine controller accepts the output of the image analyser and directs the associated mechanisms in performing the work.

As noted above, no vision system is presently capable of reliably guiding a car through traffic. Yet the human vision system does this relatively well. Fortunately most visual tasks in manufacturing are simple when compared to the requirements for driving a car. It is in performing these simple visual tasks that machine vision excels and unshackles the worker.

If machine vision were limited to only emulating human capabilities, no one would have ever tried, and succeeded, to make measurements with machine vision; the unaided human eye is an unreliable rule. Machine vision would be limited to working only with visible light, instead of also exploiting the potential of infrared, x-ray imaging and ultraviolet inspection.

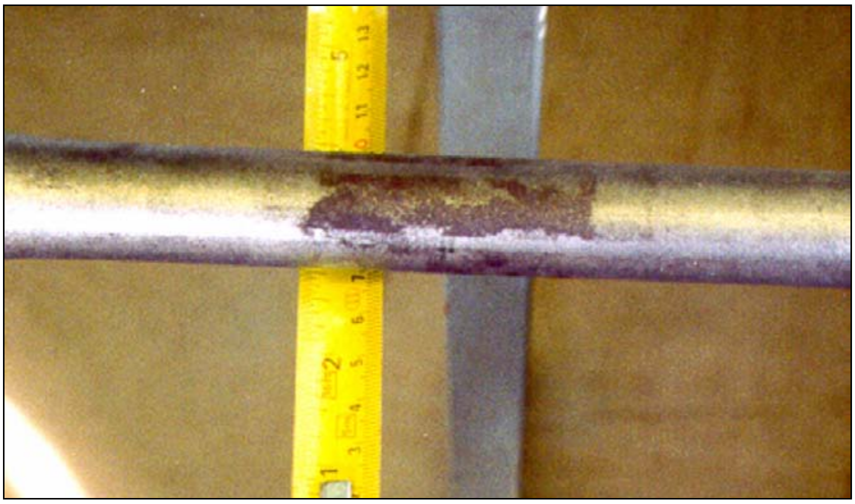
# 5 Human Viewing of MPI Indications

The human eye only responds to visible light, that is light that falls in the visible light spectrum, from Red with a wavelength of 700 nanometres ($700 \times 10^{-9}$ of a metre) to Violet with a wavelength of 400 nanometres ($400 \times 10^{-9}$ of a metre). The eye also has the highest sensitivity to light that has a wavelength of 555 nanometres ($555 \times 10^{-9}$ of a metre) which is in the Yellow / Green region of the light spectrum.

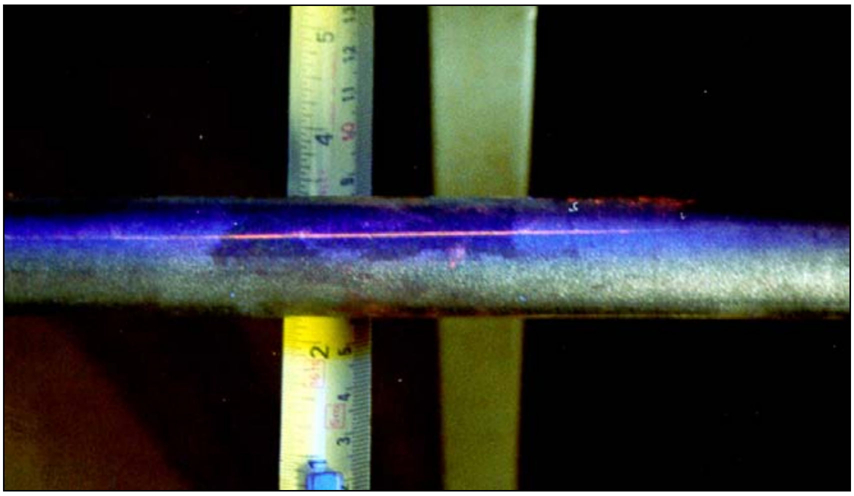
In general the fluorescent coating on a magnetic particle is also in the Yellow / Green region of the light spectrum. However, the actual colour is dependent on the particle manufacturer, for example Ely Chemical Co. supply particles which fluoresces a colour closer to Yellow rather than Green whereas Magnaflux products fluoresces closer Green rather than Yellow.

The Ultraviolet lamp used to view an MPI indication does not emit light across the whole ultraviolet light spectrum, the light output is limited to UV-A which has a wavelength of 400 nanometres ($400 \times 10^{-9}$ of a metre) to 365 nanometres ($375 \times 10^{-9}$ of a metre). Hence light output from a blacklight ranges from Violet in the visible spectrum to invisible Ultraviolet; this is the reason that the blacklight appears Violet when looked at by the human eye.

When viewing an MPI indication illuminated by a blacklight, the human eye filters out any reflected ultraviolet light, and only sees the visible Violet glow on the component, which is emitted by the blacklight.  A defect which fluoresces in the Yellow / Green region of the light spectrum will stand out against the surface of the component and the Violet glow from the blacklight.
Illustrations of a component with a crack in are shown below, both before the MPI process and after under ultraviolet light conditions.



Component prior to MPI process



Ultraviolet image of component after MPI

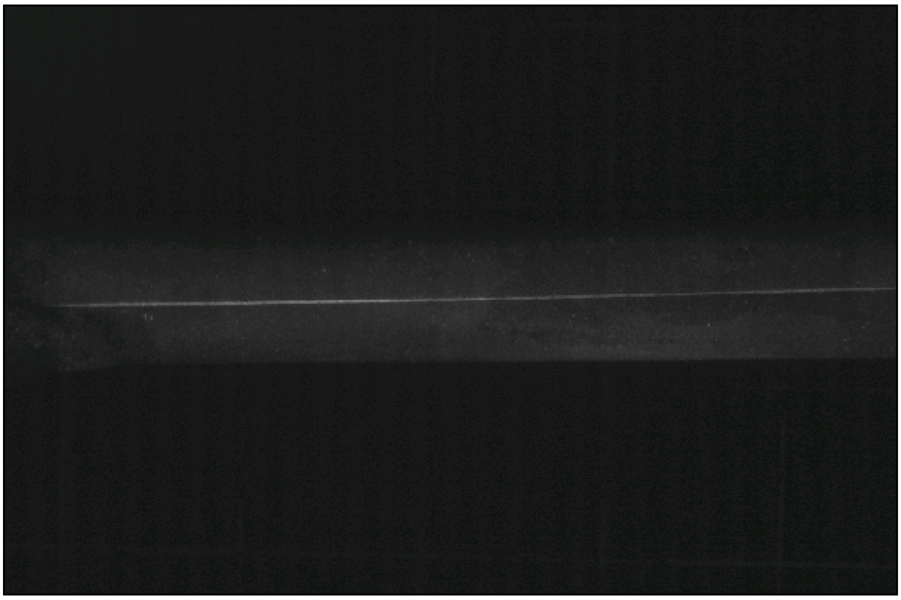
# 6 Camera Viewing of MPI Indications

A CCD camera not only responds to visible light but also responds to invisible light, that is light that falls in the spectrum, from Infrared with a wavelength of 1 millimetre ($1 \times 10^{-3}$ of a metre) to Ultraviolet with a wavelength of 10 nanometres($10 \times 10^{-9}$ of a metre). This response is a much wider range than the limited response of the human eye.

When viewing an MPI indication, which is illuminated by ultraviolet light, the camera's wide light spectrum response becomes a big problem. The camera would be sensitive to the reflected ultraviolet light energy, which actually saturates any image that the camera sees.
Therefore, it would not be possible to discriminate the defect indication which is in the Yellow / Green region of the light spectrum from the ultraviolet refection in the Ultraviolet region of the light spectrum. It is therefore necessary to use optical filters so that the human eye light spectrum response may be mimicked.

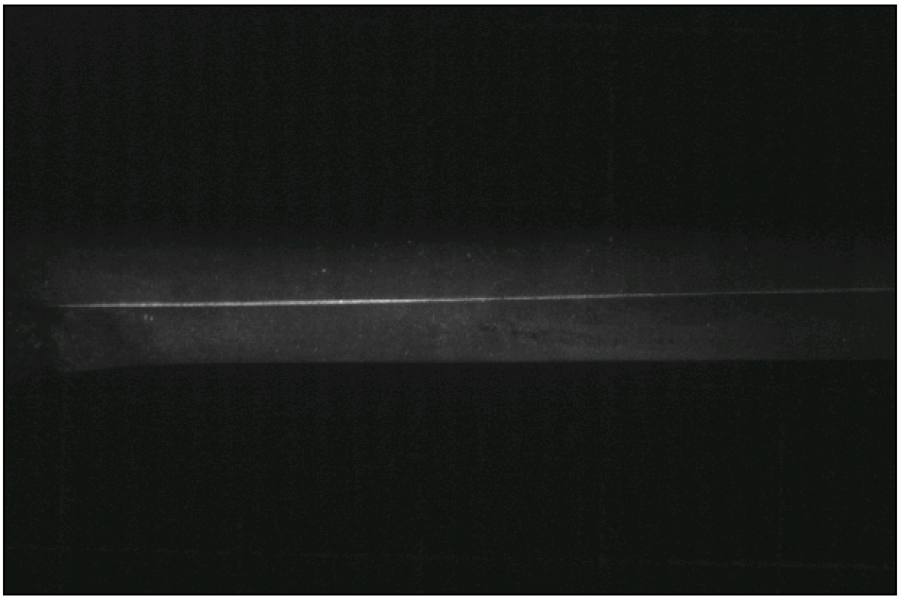
An optical filter placed in front of the camera lens would preferentially transmit light of their own wavelength and hold back light of other wavelengths. Therefore the use of both Ultraviolet and Infrared absorbing filters screen out the non-visible light of the light spectrum and only allow the visible light through to the camera lens. Using these filters, it is possible to resolve the defect indication which fluoresces Yellow / Green.

An example image of a component is shown below of a component which has a longitudinal defect running along its length, identified by the light line running across the image. It was captured from a standard CCD imaging camera; using both an Ultraviolet and Infrared absorbing filter. It is obvious from the image that the contrast of the defect indication against the background surface of the component is not as good as seen by the human eye.



The camera has a linear response to the visible light spectrum, since the invisible light has been filtered out, whereas the human eye has a non-linear response, centred in the Yellow / Green region of the light spectrum.

It is possible to add additional filtration which will only allow the Yellow / Green light to pass through to the camera lens, further enhancing the contrast of the defect to background. An example, using the same component illuminated in the same way, was captured from a CCD imaging camera using Ultraviolet and Infrared absorbing filters along with a Yellow-Green filter and is shown below.



The use of the Yellow-Green filter has the effect of increasing the apparent brightness of the MPI indication, essentially increasing the defect to background contrast ratio, making the defect more obvious.

Both of the previous images were captured using a CCD imaging camera, which has a resolution of 768 by 512 pixels, and using a 25 mm lens set at f2.8. The filters used were, a Hoya Ultraviolet cut filter, and a Hoya Infrared cut filter and a Hoya Yellow-Green XO filter. The blacklight used to illuminate the component was a Labino Flood lamp, its position set to give a surface Ultraviolet intensity of 2000 microwatts per centimetre squared.

# 7 Particle Selection to Enhance Defect Contrast

Both of the images so far shown used a particle manufactured by Ely Chemical Co., which is a particle that exhibits low background characteristics and fluoresces a colour closer to Yellow rather than Green. This particle was initially selected because of its low background characteristics that are essential to aid the contrast of the captured image. If a high background particle is used it would be necessary to process the captured image to remove the random spots of the background.

Semiconductor CCD cameras are generally most sensitive to light that has a wavelength of 700 nanometres ($700 \times 10^{-9}$ of a metre), that is visible Red light. It was therefore thought necessary to investigate the use of a particle that fluoresces Red or Orange rather than the more usual Yellow / Green. Manufacturers of the Red particle are not as easy to find, however, Circle Systems Inc. manufacture a product that was thought to be suitable, the product being MI-Glow 502.

The use of the Red particle from Circle Systems Inc. made it necessary to use a Red filter, in place of the Yellow-Green filter previously used. It was found that this Red particle appeared to have a greater brightness to the human eye over the Yellow / Green particle used previously, which is surprising, since the human eye is more sensitive to Yellow / Green rather than Red.

With the Red filter in place, only Red light is allowed to pass through to the camera lens, further enhancing the contrast of the defect to background. The CCD imaging camera using both the Ultraviolet and Infrared absorbing filters as before along with the new Red filter captured a sample image, once again using the same component, illuminated in the same way. This image is shown below.

In order to capture this image it was necessary to change the setting of the lens by one stop, to f 4.0. This change effectively means that the image captured is at least twice the brightness of the images captured using the Yellow / Green particle. If the image is examined closely it is possible to see that the image brightness is higher than the previous images

From this the only conclusion can be, that it is advisable that a Red or Red / Orange particle is used when trying to view the defect indications by a CCD camera, rather that the more conventional Yellow / Green particle.

# 8 Camera Selection to Enhance Sensitivity

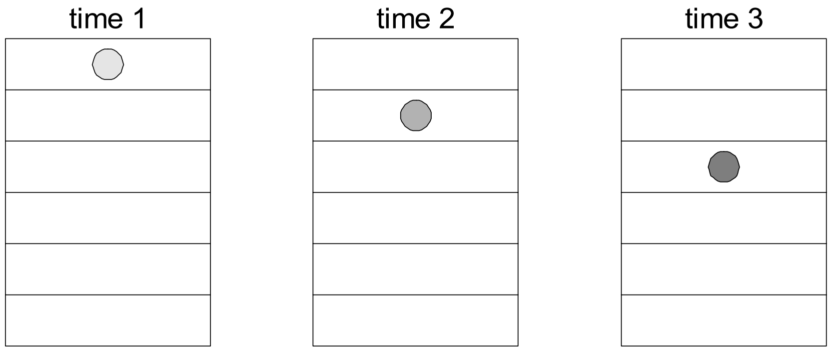
All the images shown were captured using a CCD imaging camera with a resolution of 768 by 512 pixels and a 25 mm lens. This camera is ideally suited to capturing images from a static component that is a component that is not moving. If however, it is required to capture images from a moving component, it would be necessary to use a shutter on the camera, and then even so, the system update rate would be limited to no more than 30 frames per second, which incidentally is the same rate as used in conventional home video cameras.

It is however possible to have a CCD camera system that runs at much higher update rates provided a different type of camera is used; this type of camera is a line scan camera. As its name suggests it is a camera that rather than having a rectangular array of light sensing elements (such as 768 by 512, as in the imaging camera used in the previous experiments) has a single line of sensing elements (typically 512 by 1 or 1024 by 1).

The main advantage of this type of camera is, the fact that the image capture is synchronised to the speed of movement of the component being viewed and at much higher update rates when compared to the imaging camera. However, there is one significant draw back with this type of camera, the fact that the sensitivity of the camera is less than an imaging CCD camera, typically a factor of 20 less sensitive. This fact essentially means that this type of camera is not suitable for viewing MPI defect indications, because of the limited light intensity emitted from the indication.

To overcome the limitation of the conventional line scan camera, a new architecture called Time Delay and Integration (TDI) was developed. A typical TDI line scan camera has an 80 times increase in sensitivity over the conventional line scan camera and 4 times over a standard imaging camera.

A TDI line scan camera is based on the concept of taking multiple exposures of the same object. The object must be in motion since the exposures are taken at differing points in time corresponding to different spatial locations, as illustrated in the diagram on the next page. This illustration shows a small circular defect on a component that is moving through different exposures (stages) of the TDI array. As the defect passes through more and more stages, the signal registered by the sensor is increasing in direct proportion to the number of stages. In effect, the integration time available to collect photons has been increased by using the TDI method.




Signal strength of the circular defect
increases as it passes through each stage

Another way to think of TDI is to consider a car passing another car on a highway. If the first car is passing a stationary car, its closing speed is very fast. If however, the other car is moving at the same speed, that is it is not passing but rather keeping pace, the ability of the driver to see the other car and note detail is greatly enhanced because the driver has multiple opportunities to view the other car. If the car had passed a stationary car the drivers' time to view (effective integration time) would have been much shorter.

A typical TDI Line scan camera is shown below