Trigger on Position

By Kevin McCarthy, Chief Technology Officer

The Basics of "TOP"

In precision motion applications, it is frequently necessary to trigger a device in a way that is synchronized with the position of a moving stage. In this white paper, we will explore this functionality, as well as its implementation in Dover Motion products. The simplest example of such triggering is in point to point motion, when an external device (such as a camera) needs to begin image acquisition as soon as the move is complete, and the stage is maintaining position within the settling window. In a wide range of other applications, however, external device triggers must be produced ***during*** motion, and at very precise positions. In the simplest case, only a single device trigger is required at a single position in each move; in other applications, repetitive device triggers are required at a fixed position spacing during motion. In more advanced cases, repetitive device triggers are required, but with variable position spacing between them. Over the years, a variety of TLAs (Three Letter Abbreviations) have arisen to describe this Trigger On Position capability; these include PCO (Position Compare Output), and PEG (Position Event Generation). In the Dover Motion product family, we refer to this capability as "TOP": Trigger On Position. In a typical example of Trigger On Position, triggers are produced during constant velocity motion, as shown below in Figure 1:

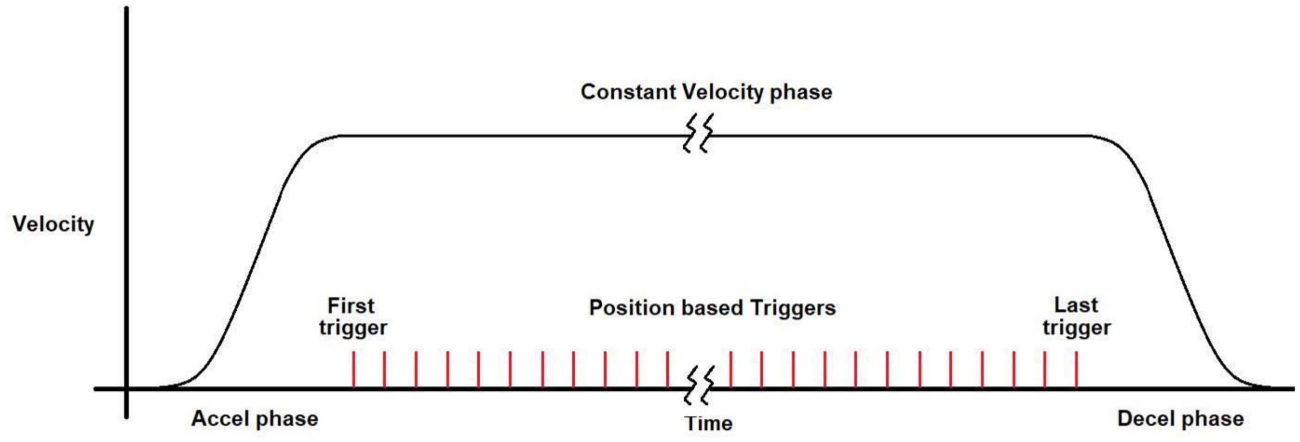

Figure 1: Typical Move Profile with Triggering

In this example, a single axis positioning stage accelerates from rest to a constant velocity. After a short delay in which the stage settles to its constant velocity, the first trigger is issued at the Start position. Successive triggers follow, each separated by a programmed position spacing, until all the triggers have been issued. The stage then decelerates to a rest. Irrespective of the precision of constant velocity motion, the triggers are generated at specific positions of the stage encoder counter, and as a result are precisely positioned relative to the location of the sample.

A Trigger On Position Example: Constant Velocity TDI-CCD Image Scanning

One fairly common application that requires position triggers is constant velocity TDI-CCD ("Time Delay and Integration, Charge Coupled Device) scanning imaging. In this imaging mode, photoelectrons are transferred from row to row, summing their signal along the length of the sensor, until the accumulated signal reaches the "horizontal" output register at the end of the sensor, and is read out. The row to row transfer process requires several "vertical transfers" and, to avoid any image smear, these must be very precisely synchronized with the stage position, as it moves at constant velocity under its optics. See Figure 2:

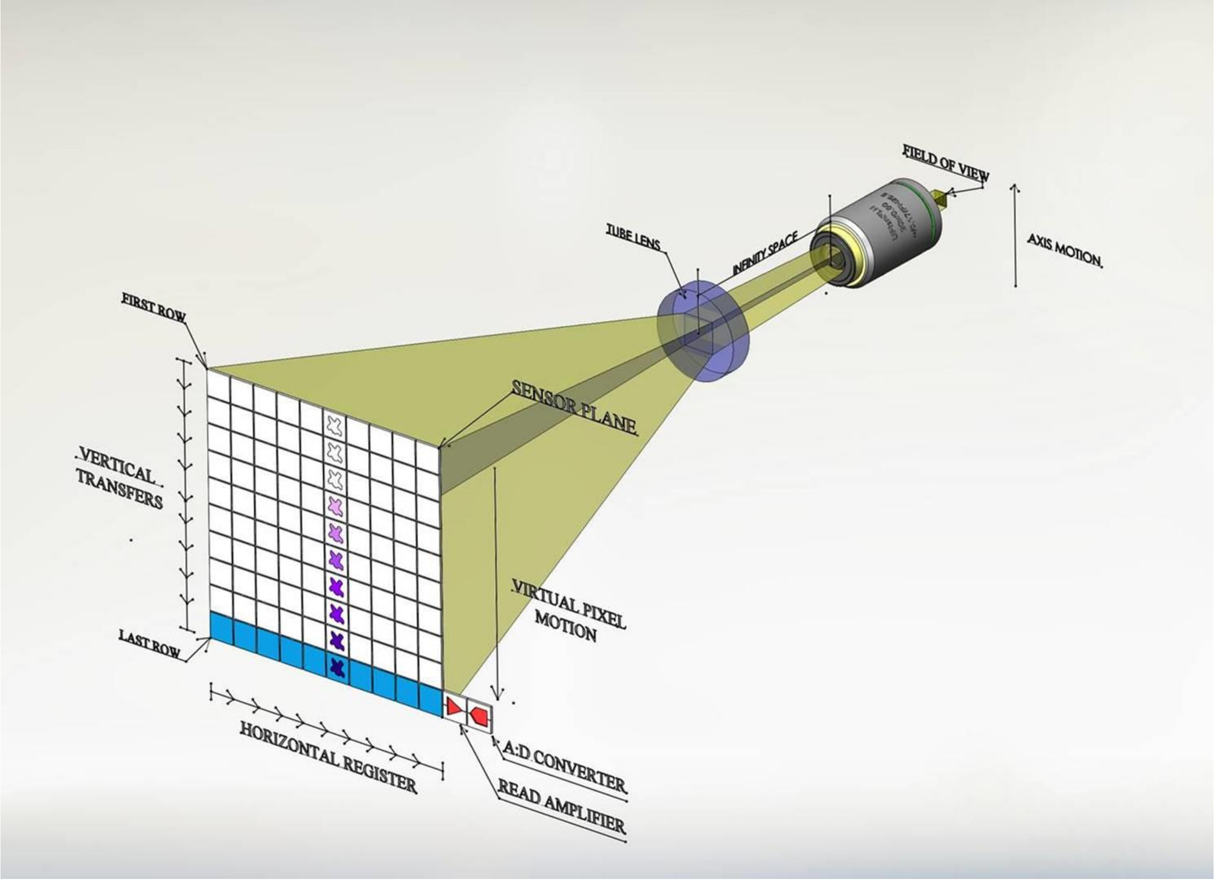

Figure 2

Since the stage is nominally moving at constant velocity during the TDI-CCD image scanning process, one approach to generate the camera's vertical transfer triggers is to use a simple quartz clock or PLL (phase locked loop). However, the assumption of truly constant velocity on the part of the stage is a dangerous one. Quite a number of error sources in the stage, motion controller, and encoder can conspire so as to produce slight variations in constant velocity motion, which will in turn slightly skew the trigger positions relative to the sample, blurring the image. A far better technique is to derive the vertical transfer triggers from the encoder that is being used to close the position loop. Note that any such encoder needs to be linear; the use of a rotary encoder and a leadscrew or ballscrew will result in cyclic leadscrew error that will blur the image. The best encoders for use in TDI-CCD imaging are linear optical devices, with very low encoder cyclic error.

In an example of constant velocity TDI-CCD imaging, the sensor array is 2,000 columns wide by 250 rows deep, the pixel size is 4 x 4 microns, and the optical magnification is 20X. During any given imaging scan, a swath 400 µm wide (2,000 x 4 um / 20X) will be acquired, and each sensor pixel corresponds to 0.2 µm resolution at the sample plane (4 µm sensor pixel size / 20X magnification). At a scan velocity of 20 mm/s, the triggers to initiate vertical transfers at the sensor will be spaced every 0.2 µm (200 nm) at the sample, and will occur for the length of the scan at a frequency of 100 kHz (20 mm/s divided by 200 nm pitch). Typically, the scanning stage will start moving outside of the active sample area, accelerate up to the scan velocity, and image along the sample at constant velocity, acquiring an image swath 400 µm wide in this example. At the end of the sample, imaging stops, the stage decelerates to a stop, an orthogonal axis indexes over by 400 µm to a new image swath on the sample, and imaging resumes in the opposite direction. This “serpentine scan” then continues, until the full sample area has been imaged.

Since the triggers to perform sensor vertical transfers in the above TDI-CCD imaging example are based on the stage position, they will be generated at precisely the right location, irrespective of the stage’s constant velocity precision. One might ask why constant velocity even matters in this case, but it does. Were the stage to slow down and speed up during the scan, the vertical transfers still take place at precisely the right locations, but the amount of light falling on the virtual pixel will vary, increasing when the stage slows down, and decreasing when it speeds up. The resulting image will still have all of its targeted resolution, but the intensity of the image will be modulated by any velocity variations, resulting in misleading data. If the stage velocity varied sinusoidally, an image of a uniform grey sample will show a corresponding sinusoidal variation in intensity. This is why the stage velocity must normally be controlled very precisely. There is one trick, however, that can relax stage constant velocity requirements; this is addressed in a different Dover Motion white paper, “CCD and CMOS Imaging”.

Quadrature Divide-by-n triggers

In many cases, the resolution of the stage’s linear encoder will be far finer than the optical resolution of an imaging system, and this will require that we “divide down” the encoder signals to generate the camera’s required trigger position signal. In the above TDI imaging example, camera triggers are required every 200 nm. If the 4X quadrature (counting both rising and falling edges of encoder channels A and B) resolution of the linear encoder is 10 nm, then a Trigger On Position signal will be required every 20 encoder counts (20 counts * 10 nm/count = 200 nm). Such a “divide -by-n” function is required, and many of Dover Motion’s controllers support it.

Optical Unit to Unit Variation, and the Limitations of Typical Encoder-based Triggers

As it happens, optical components such as objectives and tube lenses typically exhibit substantial unit to unit variations in key parameters such as magnification. As an example, the DIN standard for objectives specifies that their magnification must fall within a surprisingly large +/- 5% range. This means that a nominally 20X objective could actually be anywhere from 19X to 21X. In TDI-CCD scanning imaging, it is essential that the triggers for the vertical transfers be precisely synchronized with the sample motion, and this means that the trigger spacing must equal the pixel size divided by the magnification. As the magnification varies from unit to unit, so must the trigger spacing, but in the previous example, divide-by-n based triggers lack the resolution to do so. In that example, an objective with an accurate magnification of 20.0X requires a trigger spacing of 200 nm, or twenty 10 nm encoder counts. But if the objective in the next instrument built has a magnification of 20.57X, then the required distance between successive triggers is 194.46 nm. That poses a problem when the resolution of the linear encoder is 10 nm; the two closest choices are to either produce a trigger every nineteen counts (190 nm; error 4.46 nm per trigger), or every twenty counts (200 nm; error 5.54 nm per trigger). An error of about 5 nm may seem very small, but with triggers being produced at 100 kHz, each off by 5 nm, the error will rapidly accumulate, and will result in a badly smeared image. This is a problem!

Enter Dover Motion's "DFI": Deep Fractional Interpolation

Most linear encoders have fixed internal or external interpolators, and accordingly provide only a single resolution, which cannot be changed. Dover Motion's Precision Encoder (subsequently, the "Dover Encoder"), available as both an external device on standard stages, and as a built-in, chrome-on-glass encoder on our new line of SmartStage crossed roller positioners (see below), can be user-programmed to an enormous number of individual quadrature resolutions. The Dover Encoder's finest resolution is 1.25 nanometers, and its incredible resolution range is exactly what it takes to address the issues posed by optical unit variation. For example, in the above TDI-CCD scanning imaging example, the vertical transfer triggers are required every 200 nm. Due to optical unit to unit variation, that means the position triggers are required with a separation of between 19 and 21 ten nanometer counts. But the Dover Encoder is not limited to 10 nm counts. In fact, it offers a remarkable 32,824 different resolutions between 9 and 11 nanometers! That amounts to a resolution setting granularity of 61 picometers, which to put things in perspective, is one-fifth of the Van der Waals diameter of a single aluminum atom! This allows TDI-CCD scanning imaging users to quickly image a precision chrome on glass artifact with lines at known distances apart, and quickly deduce the actual optical magnification in each production instrument. A simple program that we provide then calculates the best resolution to generate triggers at precisely the right separation, using integer division of a new custom encoder resolution. The result is diffraction-limited imaging across the entire imaging swath, with complete elimination of image smearing due to accumulating position mismatch between successive TDI-CCD vertical transfers along the depth of the sensor.

Figure 3: SmartStage XY with TOP built-in

Note that there is a division of labor required to produce the precise triggers required for TDI-CCD scanning imaging. The job of the Dover Encoder is to provide digital quadrature signals at just the right resolution to eliminate any image smear during the scan. Once the user measures a known artifact to determine the precise optical magnification for a given production instrument, our spreadsheet calculates the optimum resolution to eliminate any accumulating residual during the scan and downloads this new custom resolution to the Dover Encoder using a dedicated cable. This value is stored there in non-volatile memory, although it can be updated whenever needed by downloading a new resolution value. Once the Dover Encoder is programmed with its custom resolution, its job is done. The job of using the encoder signals to generate triggers on position at a specific spacing then falls to the motion controller. Both the standalone Dover Motion Controller Module (DMCM), and our new line of SmartStage™ linear positioners, with their built-in encoder interpolator and motion controller, are capable of generating precisely spaced triggers by performing divide-by-n processing of the incoming quadrature encoder signals.

The Importance of Eliminating Encoder Cyclic Error

The highest performance constant velocity scanning stages all use direct-drive motors, with position feedback provided by linear optical encoders. Such encoders produce sine and cosine position signals and are available with sine wave periods ranging from 250 nanometers to 100 microns. Specialized interpolation circuitry can subdivide these signals to sub-nanometer levels, but all too often, remnants of the original sinusoidal period remain as repeating (cyclic) errors. When displayed on an oscilloscope with the sine signal along the X axis, and the cosine signal along the Y axis, a “Lissajous circle” results, and inspection of this waveform can be very helpful when diagnosing cyclic error. The most common cause of encoder cyclic error is a DC offset of the measured sine wave relative to that of its reference; this produces a cyclic error at the fundamental period of the sine wave. A variation in gain between the sine and cosine channels produces an inclined oval instead of a circle, with the resulting cyclic error at one half the period of the sine wave (i.e., every 10 um for a 20 um period linear encoder). Slight saturation of both signals puts four "corners" on the Lissajous circle, and will produce cyclic error at 4X the fundamental frequency (one quarter the period, or every 5 um for a 20 um period linear encoder). When constant velocity motion is commanded, any encoder cyclic error "prints thru" into the motion; if a laser interferometer is used to acquire position vs. time data, and the resulting slope-corrected position error is plotted, the encoder cyclic error will manifest as a variety of superimposed sine waves. The best way to look at this is to perform an FFT (Fast Fourier Transform) on the data. This typically reveals a number of different frequencies, ranging from the fundamental first order (whose frequency will be the constant velocity divided by the encoder period), through the second, third, and higher orders. Normally, no harmonics beyond the eighth order (at one eighth the spatial period of the encoder) are observed.

Uncorrected encoder cyclical error directly impacts the accuracy of Trigger On Position signals. If the TOP application calls for equally spaced triggers, close inspection will reveal that the trigger positions wander around their nominal positions in a complex manner, due to multiple harmonic orders of encoder cyclic error. In an application where trigger position matters (essentially all of them, according to our customers), encoder cyclic error can be a deal-killer. Fortunately, at Dover Motion, we have managed to eliminate encoder cyclic error, driving it down below the noise floor. We start by choosing a high-precision, chrome on glass, linear optical encoder scale, rather than some rolled or laser written steel tape. We then employ the latest in optics, interpolation electronics, and advanced math to identify and eliminate up to the first eight orders of encoder cyclic error. The result, implemented in our DOF-5, SmartStage™ linear positioners, and other Dover Motion stages with our DMCM motion controller, is essentially perfect Trigger On Position signals.

Command syntax for Dover Motion Trigger On Position

The same C language call is used to generate Trigger On Position signals in both the DMCM (Dover Motion Control Module), and our new line of SmartStage™ crossed roller linear positioners, which feature a built-in, high-performance servo drive and control. This C language call is:

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Trigger_on_Position(Trigger_Start, Trigger_Separation, Trigger_Number)
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The first trigger is issued at the absolute position Trigger_Start. Successive triggers are issued every Trigger_Separation counts, until a total of Trigger_Number signals are issued.

Table Based Trigger On Position

In the above case of TDI-CCD scanning imaging, as well as for many other applications, position based triggers are required at precisely uniform position separation. However, there are other applications where precise, position-based triggers are required at non-uniform spacing. For example, a laser could be used to sever links in bad memory cells, where a map of bad cell locations is provided ahead of time.

Another reason to use non-uniform position triggers is to improve throughput in applications where there is a latency between the issuance of the trigger, and its effect on the sample. Suppose, for example, that position-based triggers are used to launch microscopic liquid droplets across a small gap between the droplet eject tip and the sample. If the goal is to place the droplets at precisely equal spacing on the sample, one approach is to wait until the stage has accelerated up to and settled at a constant velocity, and only fire off droplets while at constant velocity, using equally spaced triggers on position. The downside is that this method wastes time at the end of each scan line for acceleration and deceleration, as well as the time to settle to constant velocity. Far higher throughput can be achieved using a triangular velocity profile (perhaps with some S-curve) and firing droplets during the entire motion profile. In this case, because of the fixed time of flight of droplets between the eject tip and the planar sample, the positions at which droplets are ejected will vary as a function of velocity. When the stage is moving faster, the position delta between successive droplet ejections will need to be shortened to ensure that the droplets arrive at the sample at equal spacing. This can all be calculated ahead of time, building a Trigger On Position table, which can be downloaded into either the Dover Motion Controller Module, or our new line of SmartStage crossed roller linear positioners, which feature built-in servo drive and control. Note that the Trigger On Position table in the above example will likely include symmetric but reversed offsets for the individual droplet firing trigger positions during motion in the reverse direction. Both our DMCM and SmartStage positioners support table-based triggers at speeds of up to 10 kHz, and with table depths of up to 8,000 points.

In conclusion, Dover Motion's SmartStage™ linear positioners provide built-in advanced Trigger On Position capabilities, allowing users to flexibly generate highly precise triggers at both periodic and table-based positions, and with exceptionally fine resolution. They are the perfect choice for demanding TDI-CCD imaging, as well as other applications requiring precise, position-based trigger generation during motion.

ABOUT THE AUTHOR...

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