Why Smart Linear-Position Sensors?

White Paper

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Metal forming and fabrication.

Wood lathes and shape sawing.

Motion simulation and entertainment platforms.

When it comes to linear position feedback for motion control applications, in many respects it has historically been hard to beat tried and true analog sensors. With a variety of output options and user adjustability, these were essentially the “plug-and-play” devices of their day. Taking advantage of their apparent simplicity, controls engineers were **in theory** able to focus on developing their control algorithms without having to worry a great deal on the sensor interface. Theory won out in most instances, but reality also dictated that system noise, signal attenuation, and response dynamics meant that sometimes the controls designer needed to resort to some combination of clever wiring, filtering or feedback “signal massaging” code to overcome such physical limitations.

The other downside to analog sensors is their inability to communicate device properties and health conditions, nor identify or target detailed failure modes either at the sensor or the associated motion axis. Instead, elaborate and often time consuming and therefore costly troubleshooting routines had to be developed to help machine operators and maintenance technicians get to the bottom of shutdown situations. Taking advantage of shrinking yet faster and more powerful microprocessors and DSPs, today’s industrial digital “smart” sensors offer an ever expanding array of functionality and performance enhancements over their “intellectually challenged” predecessors.

One area where the factory automation world has taken advantage of this device-level intelligence is in distributed machine controls through the increasing use of industrial networks. For example, OEMs are designing the newest controls architectures with industrial Ethernet hardware and software as a basis their next generation production machinery. Machine-wide device-level intelligence can be used to optimize the production process while conditions are within normal variations, but they can also be used to help the machine adapt, correct, and even call for help **before** a problem occurs. While industrial networks no doubt have their place in modern factory equipment, they also present a number of challenges for the controls engineer. One challenge is knowing enough to make sound decisions regarding how and when to apply the right industrial network(s) to machine control. While the benefits of reduced cabling and increased diagnostics are attractive, achieving these from the start requires an almost complete revolution in design thinking versus historical machine control methods. One must also realize that there are still many aspects of machine control where the performance of the industrial network is simply not sufficient for the automation process. One example of this is multi-axis synchronized motion control, which often still relies on point-to-point connectivity and deterministic timing to achieve the required level of system dynamic performance.

Besides enabling improvements to process optimization and operational efficiency, another advantage of smart (digital) sensors is the ability to optimize motion control performance and flexibility for specific applications using a COTS product. Today’s microprocessor and customized ASICs enable sensor manufacturers to not only tailor their products for a specific range of applications, they also help users to optimize their feedback and control schemes around these more versatile and capable products.

There are many possible smart sensor configurations, one set being those defined by the IEEE 1541 smart sensor standard. This standard is primarily aimed at component-based embedded sensing products designed for use in finished devices or subsystems. MTS Sensors has developed its new line of Temposonics magnetostrictive sensing products with many of these capabilities in mind, but based on current “open” industry standard interface options. This white paper will detail one example of a product based on one of the newer industry standards that has grown substantially in popularity in recent years. This is in part due to it’s performance and in part because of it’s functionality and flexibility in use. You’ll see how a smarter sensor doesn’t have to be bigger, more complex or more expensive. Besides simplifying your next machine control design, you can save on automation component costs while increasing process performance and productivity and up-time. Too good to be true? Not if you're smart about it.

Synchronous Serial Interface (SSI) is Really Smart (but it wasn't our idea)

The SSI data format was created by Stegmann Inc. (now Sick/Stegmann) as a high speed point-to-point interface for absolute encoders. It is also the basis to other proprietary absolute serial data formats like EnDat and HYPERFACE. Though the use of this interface at the device level requires licensing from Sick/Stegmann, it is now considered an industry standard by most major (and minor) controller and I/O interface manufacturers. User's have also come to appreciate the power and simplicity of this interface because now widely available off-the-shelf hardware can be utilized in practical realization.

The major advantages of this interface for servo-control engineers include:

- Absolute position feedback
- Extremely high resolution and therefore range – Up to 26 bits
- Fast serial data communication – Up to 1 Mbaud
- Synchronization to precise clocking signals from the host

Absolute position feedback format is preferred in many applications over the alternative "incremental" approach – one that tells only how far something has moved from its previous location. This is because if power to the incremental sensor is for some reason lost during operation, the controller will not know where the measured part is. Even if the machine controller has the ability to remember the last position, there is no guarantee that everything is where it is supposed to be. Thus, unless an absolute position sensor is used – one that will immediately provide the absolute position upon machine restart – some type of "re-homing" routine will be required to regain the actual position. This can result in lost productivity due to damaged parts or machinery or the need to reset machine conditions to avoid such damage.

To illustrate the value of the resolution capability from this type of interface, we can look at a couple of practical application examples. Temposonics R-Series SSI magnetostrictive sensors are capable of resolving position repeatably to as low as 1 micron (0.00004 inch). At this resolution, even 24 bits of position data equate to 33 plus meters! This enables high precision **absolute** positioning for long travel applications such as those found on large injection molding equipment, motion simulators and machining centers (up to 5 meters) within a single sensing device. Imagine the difficulty in being able to accomplish this type of performance and range of use with an analog output sensor.

What is equally impressive about the SSI interface is that one does not have to trade feedback response performance for position resolution. The SSI communication format is shown in Figure 1, which illustrates how the clock signal prompts the sensor to deliver absolute position information. One bit of data is returned for each clock pulse transition. With a maximum clock frequency of 1.5 MHz, this means even 26 bits of absolute position data can be delivered with negligible transport delay. As is true with all serial communication realizations, the applicable clock frequency decreases with cable run length (down to 400 kHz for 50 m) for this standard RS-485 hardware interface. Even in this extreme situation, however, 26 bits of data can be delivered in a span of only 65 microseconds.

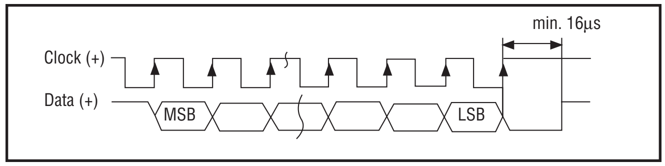

Figure 1: *SSI Data vs clock signal timing.*

Minimization of transmission delay and providing data synchronized to the motion controller creates an ideal situation for absolute serial feedback in high speed servocontrols applications (see next section). In particular, synchronized position feedback enables controllers to generate more accurate velocity estimates, which are crucial for high performance servocontrol.

Adding the "Smarts"

A fast growing number of customers in North America are taking advantage of the SSI interface attributes listed above, but that's just the beginning. Using the smart sensor platform, MTS Sensors and other position sensor suppliers have added a number of enhancements to the basic concept in order to squeeze the highest level of performance and functionality out of these products.

Feedback Data Synchronization

There are two characteristics of the feedback related signals that will limit the controller's ability to increase dynamic performance – time delays and controller sample (also referred to as "cycle") time variability. Digital controllers typically operate at what is known as a fixed cycle time to maintain control algorithm simplicity and closed-loop stability. In an ideal world, there would be no delay between the time a motion change takes place and when the associated feedback signal was delivered to the controller. Similarly, the ideal control system would read and react to the feedback signal instantly without delay or uncertainty. While this may be essentially true for slower process control systems, for higher speed motion control systems this is not the case. Figure 2 illustrates an exaggerated view of these issues.

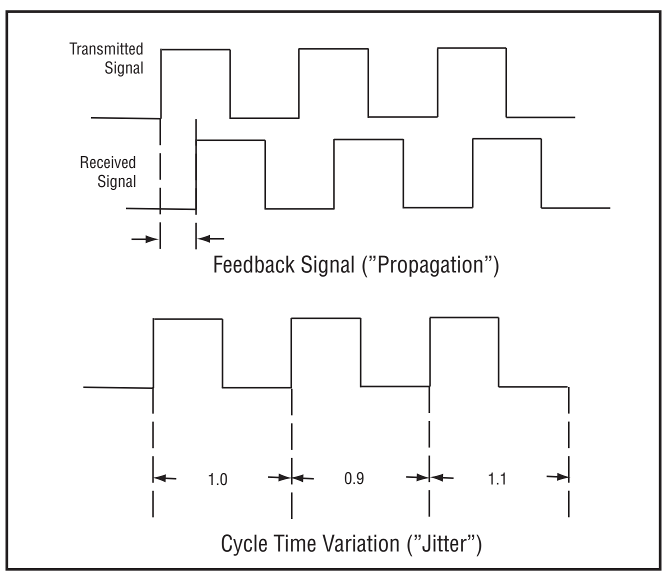

Figure 2. *Source of dynamic feedback error.*

In the presence of negligible cycle time jitter, feedback delays destabilize a closed-loop system resulting in lower controller gains and reduced system bandwidth and accuracy. Cycle time variation can have a similar, but less predictable effect. Significant, typically unpredictable, variations in the cycle time will make the resulting control system less predictable, stable and accurate. Consider the situation where velocity estimation is used to augment a position control loop. In most cases, this estimate is derived by simply dividing the change in position feedback from the last to current position by the feedback update rate. However, any variation in the feedback cycle time will show up as additional noise in the velocity estimate. Even with a highly stable clock cycle time, the inherent variability resulting from variations in the sensors internal cycle time will create a similar result.

By it's fundamental design, the SSI interface minimizes the cycle time variability and propagation delay through the use of accurate, high frequency clocking signals. There will be controller and actuator delays before the control system can finally take the desired action on the plant, but for this discussion, we will only focus on the sensing side of the equation. Given all of these external factors, it is up to the sensor manufacturer to minimize the sensing delay and maximize the sensor response.

Magnetostrictive Position Sensing and True Feedback Synchronization

Like most feedback devices, magnetostrictive position sensors include a measurement delay component. What is somewhat unique about this technology is that because it is essentially a time based measurement, the update rate is dependent largely on the sensor stroke length. Very simply, the minimum measurement time for a given magnetostrictive sensor is approximately the sensor length multiplied by the sonic wave travel speed (speed of sound) in the sensor waveguide material.

In a magnetostrictive position sensor, a sonic strain pulse is induced in a specially designed waveguide by the momentary interaction of two magnetic fields (See Figure 3). One field comes from a movable permanent magnet, which passes along the outside of the waveguide housing, the other field comes from a current or "interrogation" pulse applied to the conductive waveguide. The interaction of the two magnetic fields produces a strain pulse, which travels at sonic speed along the waveguide until the pulse is detected at the head of the sensor. The position of the magnet is determined with high precision by measuring the elapsed time between the application of the interrogation pulse and the arrival of the resulting strain pulse. Consequently, accurate non-contact position is achieved with absolutely no wear to the sensing components.

Most magnetostrictive position sensors provide their outputs at this fastest internal "update rate" or cycle time allowed due to the physical limitations of this technology – the stroke length of the given

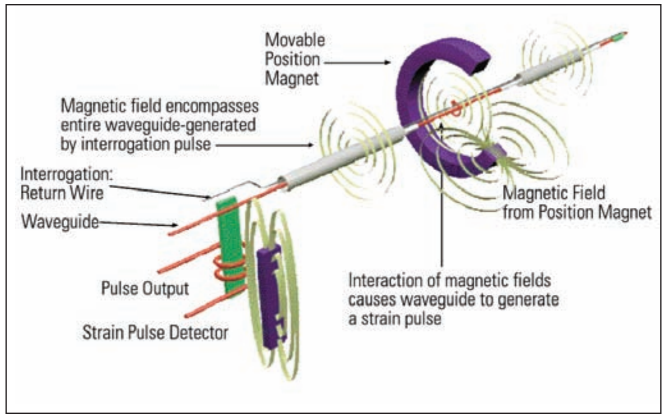

Figure 3: *Magnetostrictive position measurement.*

sensor divided by the sonic wave speed. Thus while each sensor supplies it's "latest" data per request from the SSI interface in synch with controller's clock, the actual time the position data was generated is not necessarily synchronized to this **external** clock. Further, since the data clock interval is most likely not the same as the internal sensor feedback cycle time, the degree of true synchronization will vary from cycle to cycle (See Figure 4).

Historically, this update rate limitation and internal data timing has not been an issue for most machine motion control applications since the shorter stroke sensor internal update rates are sufficiently high compared with the controller cycle time ($T_C >> T_S$). However, as the number of electromechanical axes increases along with the need for faster machine operation and therefore data rates, the advantages of magnetostrictive position sensing may appear to be somewhat overshadowed by this dynamic feedback response limitation. Fortunately, using today's "smarter" smart sensors, there are some clever ways to overcome this apparent limitation that actually highlight further advantages of magnetostrictive position sensing.

As we have seen, use of the SSI interface serves to minimize the signal delay and timing variability between the sensor and controller. What is not typically controlled in many sensors is the timing between the clock signal and the actual internal sensor measurement cycle. In order to overcome this, MTS Sensors developed a proprietary algorithm to not only guarantee true measurement synchronization but at the same time minimize any propagation delay relative to the controller loop rate.

First, the sensor quickly determines the clock cycle timing – typically after one stable cycle period. Once this is known and determined to be repeatable to specified limits, the sensor knows exactly when data will be required. Also, knowing the time required to produce and deliver the data, the sensor cleverly sets the internal sensor measurement start time such that data delivery occurs precisely at

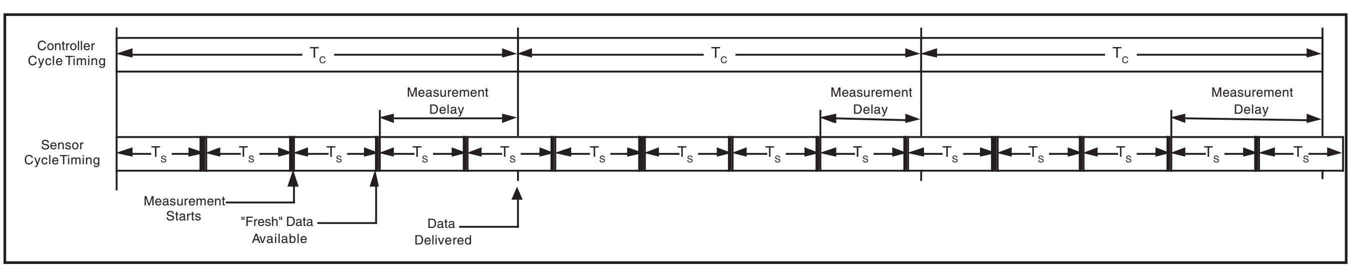

Figure 4: *Feedback timing for measurement update times not synchronized to controller cycle time.*

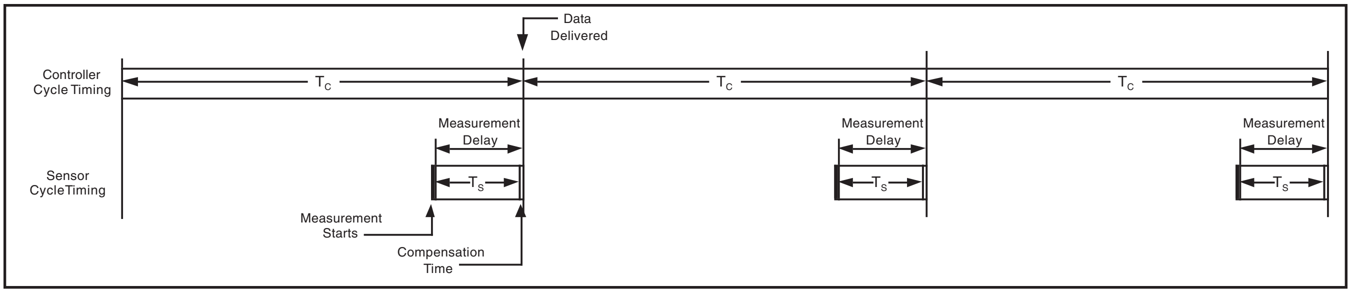

Figure 5: *Feedback timing for measurement update times synchronized to controller cycle time.*

the time it is requested (see Figure 5). This ensures that the "freshest" data available is delivered with minimal delay and minimal variability.

Now, if the control algorithm requires a velocity estimate, this can be generated quickly with minimal noise, making it much more valuable as a higher order variable to the control algorithm. Additionally, when multiple axes must be synchronized where magnetostrictive position sensors with varying stroke lengths are used, the internal signal synchronization scheme can be utilized to ensure that axis-to-axis synchronization is optimized. For example, this capability has enabled higher bandwidth applications with multiple synchronized axes such as curve shape sawing machinery (with up to 21 axes) and high fidelity flight simulator and entertainment simulation equipment.

Better Immunity to Extreme Environmental Conditions

A smarter sensor design isn't just about optimizing sensing precision and dynamic performance. In many manufacturing environments, product durability and reliability under harsh conditions, is just as important. There is no glory for the world's most productive machine if it doesn't run nearly 100% of the time. Therefore, when it comes to dealing with extreme environmental conditions, smarter sensors should be expected to out outperform their analog cousins. Customers do not want to compromise or take chances when hundreds of dollars per minute of their customer's product can be affected by a machine down situation.

A typical SSI sensor hardware and serial interface structure is shown in Figure 6. Use of the opto-couplers and RS-485 +/- signal connections means that susceptibility to system noise, even over long cable runs, is low. This is particularly important today where larger, high powered motors and drives are more often utilized on higher productivity machinery. Temposonics R-Series SSI sensors take this a step further by adding a double layer of electromagnetic shielding along with electronic filtering to create the industry's highest level of EMI protection. Add to that over-voltage to 36 Vdc and polarity protection for all conductors to 30 Vdc, along with 15 g vibration and 100 g shock isolation and you've got a nearly "bulletproof" industrial sensor.

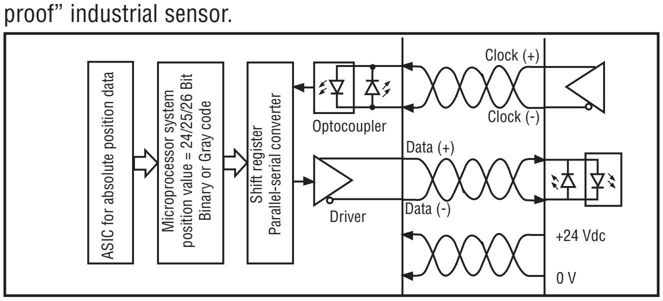

Figure 6: *SSI sensor structure.*

Besides the hardware smarts, there are a number of standard proprietary and some custom features that can be added to the smart sensor's firmware that enable the sensor to detect and appropriately react to extreme conditions. For example, based on behavior of the real-time measurement response, one method predicts when the next magnetostrictive return signal should trigger the stopping of the clock. Another method utilizes the actual measurement history, and in combination both methods are used to determine the validity of the sensor data. If an invalid data point is found – usually caused by an extreme (out of spec) shock or EMI spike – the sensor can provide a repeat of the last valid data point or a fault output value, depending on the system requirements. If the events that cause the data error are rare, the sensor can be programmed to "ignore" such events for a desired brief period. If they are persistent, then the sensor can send the desired fault signal back to the controller to facilitate the necessary shutdown sequence.

Two applications where these capabilities have been successfully applied are on die casting machinery and dynamic test rig equipment. In the die casting application, extremely high shock levels can be present near the position sensor as hydraulic ram compresses the metal to fill the die cavity. Fortunately, this shock disturbance is very brief and occurs only near the ram's full extend position. Thus the smart SSI sensor can basically ignore the obvious erroneous data produced by the shock for that instant of time and still continue to produce valid data to satisfy the motion control requirements of the die casting process. The dynamic test rig can also produce occasional extreme vibration disturbances, but because they are often a function of the test subject, they are unpredictable and can be more persistent than the in the die cast application. Here, because the motion profile is typically smoother and more predictable, the so-called "error skip" window can be widened to sufficiently enable the sensor to ignore brief periods of resonance disturbance response, yet also trigger a shutdown fault signal in the event of a violent part failure.

Better Communication and Flexibility

Any discussion about smart sensors would not be complete without discussing the potentially vast added sensor functionality and information sharing afforded by such products – without necessarily having to complicate the hardware design. The fact that SSI was designed as a high speed absolute serial interface – for the fastest pure data transmission possible – makes field adjustment and transferring non-measurement sensor information for such products a challenge. Having said this, it would be a mistake not to find a way to provide at least the most basic field programmability and diagnostics for the SSI sensor. Besides the obvious benefits of diagnostic sensor feedback such as those discussed above, field adjustability enables customers to reconfigure the same product for a variety of applications. It also can save customers valuable time and the cost of having to factory reprogram incorrectly specified product.

Temposonics R-Series SSI sensors include the following factory and field configurable parameters:

- Position Resolution – 1, 2, 5, 10, etc. micron
- Data Length – 24, 25 or 26 bits
- Data Coding – Binary or Grey
- Measurement Direction – Forward or reverse acting
- Measurement Mode – Internally synchronous or asynchronous data

In addition, one or more of the following status and diagnostics may be provided by the sensor via visual LEDs and / or serial data:

- Normal function
- Magnet not detected or incorrect number of magnets
- Interrogation clock or synchronization error

Unfortunately, because the SSI data format standard is restricted to essentially raw data, beyond the internal error checking and handling indicated in the earlier section, there are not many options for passing such important information across the RS-485 interface during normal operation. One option used in the past was to report a pre-specified out-of-range output data value (say 000000 or FFFFFF hex) after a magnet error occurred. This was not the preferred method because of the invalid data point, but was in many cases necessary to report the error condition. A more recent method takes advantage of the 25th bit as a status variable, where the high value represents the error and the 26th bit is a parity bit. The other 24 bits are pure data. This is a vast improvement over the previous method since normal data delivery is not interrupted by the generation of the error. This simple example shows how a little bit of creativity and some minor firmware changes can enhance the sensor functionality without violating a well established industry standard data format.

In order to facilitate field programming of the parameters listed above, the Temposonics R-Series SSI sensor was designed to operate in two separate modes – one for standard data transmission and one to facilitate “off-line” serial communication between the sensor and another serial interface like the RS-232 port of a PC. Communication between the PC and sensor is accomplished using only a RS-232 to RS-485 converter and software resident the PC. The sensor switches to programming mode after it receives a unique clocking signal code and returns to normal operation after a second specific code is received.

Programming of the sensor configuration settings is accomplished using a very simple program illustrated in Figure 7. The software also includes diagnostic and troubleshooting tools so that customers can communicate sensor conditions to applications engineering and field service support personnel if necessary.

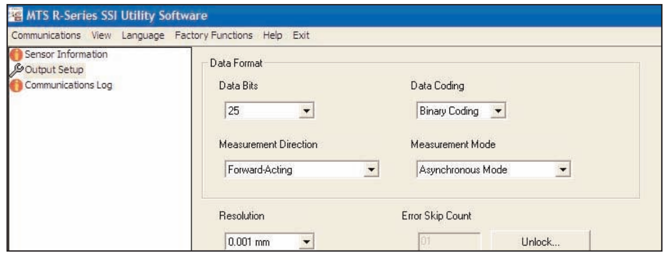

Figure 7: *MTS R-Series SSI utility software - output data format programming.*

What’s next in smart magnetostrictive sensors

While we’ve covered a great deal of capabilities associated with the highly intelligent SSI position sensor, there are plenty of other’s to talk about. For example, further improvements to the microprocessor speed and memory have enabled the use of internal non-linearity correction algorithms within the same sensor envelope. What this means for customers is a factor of 3 to 4 improvement in absolute position accuracy, with negligible impact on the sensor response. This will make the proven durable and lower cost magnetostrictive position sensing technology an attractive option for the machine tool industry where higher precision is essential.

Another improvement that has already been applied to other products like the industrial Ethernet sensors include proprietary internal predictive sensing algorithms. This capability enables us to overcome the physical sonic wave speed limitation that is fundamental to magnetostrictive position sensing. Now, these sensors can provide the desired rate of measurement cycle data regardless of the sensor stroke. This improvement will make smart magnetostrictive position sensors a better choice for highly dynamic electromechanically actuated servosystems, particularly those used in long stroke applications like router tables and laser, plasma, and water jet cutting machinery.

As MTS Sensors has already demonstrated with our Temposonics R-Series line of smart sensors is that more functionality and data formats like CANOpen, DeviceNet, Profibus and EtherCAT can be added to the existing technology with a minimal cost impact to the customer. Not far down the road, we expect to see magnetostrictive sensors adopting more of the high speed incremental, serial and network interface options like quadrature, Endat, Ethernet Powerlink, Profinet and others as the automation industry’s needs continue to grow.

Is it time to jump on the smart sensor bandwagon? Instead of asking the question, “why should I be using smart digital sensors?”, the more important question might be “why not?”

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