Drum Position Optical Encoder Driven Level Wind Controller

Introduction

This paper describes the operation of a level wind system for a glider winch that emulates a reversing screw behavior, such as is used in fishing reels, using a recirculating ball screw stage driven by a stepper motor. Such level wind systems have been implemented using such reversing screws driven by a chain or cogged belt from the drum shaft. This approach is an alternative approach to accomplishing this same behavior with uniformly spaced interrupts at a 100 kHz rate. In this approach, the interrupts are generated from an optical encoder that is sensing the drum position, generally at a point further up the drive system to realize higher position resolution and encoder pulse rates than if directly sensing the drum shaft position. First some preliminaries are covered before a block diagram illustrating the processing involved. Then some topics deferred in the main body are addressed. There is also an appendix that contains an involved mathematical analysis needed to determine one of the key parameters for this system.

Preliminaries

Readers are assumed to be familiar with the prototype winch system in development. It will use two (initially one) Siemens 4-pole ac motors controlled by a iFOC controller to control their output torque. The base speed for these motors is around 3,000 RPM but we will use them in some phases of the launch to slightly over 6,000 RPM. The speed of these motors is reduced by a two-stage reduction system that will take the 3,000 RPM motor base speed down to about 500 RPM drum speed for a cable speed of about 20 m/s.

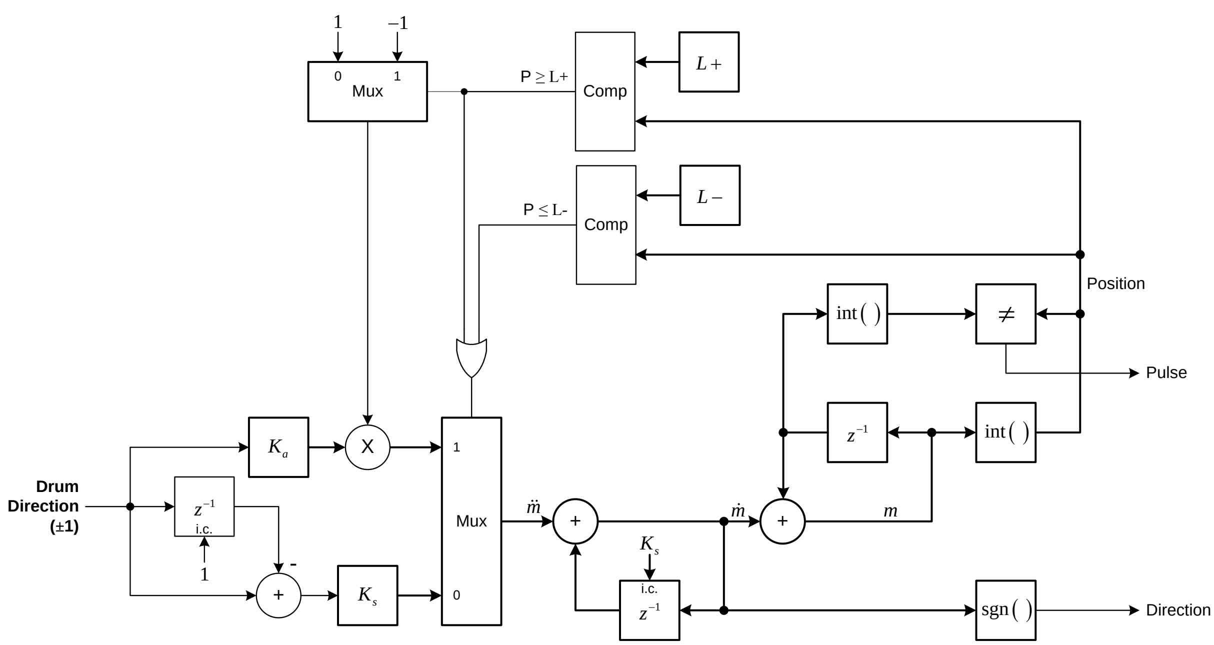
Respecting the 6,000 RPM limit of the encoder on hand, I would propose that the encoder be coupled to the shaft that drives the driveshaft. It will be reduced in speed by about a factor of 1.5:1 from the motor speed. This also reduces the encoder edge rates into what I believe are slightly more favorable ranges. The drive motor speed at 6,000 RPM would be geared to the drum such that the rope speed would be about 40 m/s. This intermediate shaft would be turning about 4,000 RPM here. For this discussion I will assume the encoder I have providing 360 PPR. If only one encoder edge is used to generate interrupts, the interrupt rate near maximum speed would be 24,000 interrupts per second. If 2 edges, 48,000. This rate is less than half that being considered for the time-based approach.

For our 2X working level wind factor, it was previously established that the sweep speed would be about 100 mm/s for a cable speed of 20 m/s. For a 40 m/s maximum rope speed, this would be about 200 mm/s. One rotation of the stepper moves the level wind 20 mm. I will assume we are using the 2000 microsteps per stepper revolution driver settings. (Going forward, I will use steps and microsteps synonymously.) At this setting, one step corresponds to 10 um of level wind motion. The number of steps per second for 200 mm/s then is about 20,000 steps per second. A requirement is the number of steps per interrupt must be no greater than one as the ISR can only issue at most 1 step command per interrupt. This requires the maximum step rate be less than the corresponding maximum interrupt rate. That is just satisfied for 1 edge and well satisfied by 2 edge operation. If the level wind factor needs to be increased above the current 2X baseline very much, this requirement could be violated for 1 edge. There is also some reduction in jitter realized by using a higher interrupt rate. So for the discussion to follow I will assume we get interrupts based on 2 edge encoder processing. It should be very easy to change this during testing if we want to explore 1 edge (or 4 edge) processing.

With this choice, roughly the ratio of microsteps per encoder step is around 20,000/48,000 or about 5/12 or 0.417 steps per encoder edge/interrupt during the sweep period. (Super precision here is not needed.) The reversals take place over a relatively short distance. A typical value might be 2.5 mm. 2.5 mm corresponds to 250 microsteps. For comparison, the drum width is planned to be 165 mm. That distance corresponds to 16,500 microsteps. This concludes the preliminaries that needed to be covered. One of the integrators employed holds the current level wind system position in integral microsteps plus a fairly fine fractional component. The integral component must support the number of microsteps across the operating range so the 16,500 value here says it could possibly be supported by a 14-bit value. But the range may not be well centered so 15 bits would be better. Since this is so close to 16 bits and the processors we are using are generally 32 bit, the starting plan is to use the upper half of the 32-bit register for the integral component and the lower half for the fractional component.

Main Body

Below is a block diagram for the processing required by this encoder triggered interrupt approach.



This discussion will initially assume no abnormal conditions, e.g., loss of synchronization, and defers addressing indexing until the normal operational mode is covered. I am depicting this using z^{-1} elements which in DSP processing normally represent a unit sample delay at a fixed rate. Here they represent a one interrupt delay but the interrupt rate can vary from zero to the maximum rates discussed above.

The rightmost digital integrator's register hold the current level wind system position in integral microsteps plus a fairly fine fractional component. The integral component must support the number of microsteps across the operating range so the 16,500 value developed above says it could possibly be supported by a 14-bit value. But the range may not be well centered so 15 bits would be better. Since this is so close to 16 bits and the processors we are using are generally 32 bit, the starting plan is to use the upper half of the 32-bit register for the integral component and the lower half for the fractional component. The preceding integrator really only needs to hold a fractional component and could only be 16 bits. If there is any benefit to making it this size that is an option but most likely it will be 32 bits also.

Along with each encoder edge interrupt, a binary indication of the direction of drum travel is required. Drum travel in the positive direction will be considered that which pulls in cable but that will not be important in this discussion. The drum direction will be a binary value but with values +1 for a forward/positive direction and -1 for travel in the reverse/negative direction. In the drawing, the lighter/finer lines and blocks are associated with binary (not necessarily 0 and 1 as just indicated) values and operations. The heavier lines represent numerical values represented with more than 1 bit.

There are 3 regions the level wind may be in. Most of the time the level wind rollers will be sweeping across the face of the drum at a speed proportional to the drum speed. That can be in either direction. When the sweep gets near an inner drum flange, the travel direction must reverse and the rollers start sweeping in the opposite direction. Most of the time the drum speed will be approximately constant during this reversal action (and even across a sweep). In this case, the scheme to be described will reverse the direction of travel over a short, fixed distance at a constant acceleration rate. As will be discussed, this reversal distance is constant independent of the drum speed or even if it varies significantly during the reversal period. The acceleration magnitude will increase (quadratically) with higher drum speeds (magnitudes). This is essentially the same behavior as that of a reversing screw mechanism as used in fishing reels. This system will even work just as such a reversing screw fishing reel if the drum is operating near zero speed and between positive and negative velocities, e.g., if the drum were held by hand and moved back and forth.

Two parameters determine when to start the reversal, one for each side of the drum. The first parameter is L+ and it defines the level wind position (in integral microsteps) where the reversal action begins for the positive side of the drum. (The side that is in the direction of positive level wind travel.) L- similarly indicates the start of the reversal region going in the negative direction. There are two comparators employed to determine which region the level wind is current in. One compares the current integral position to L+ and the other to L-. The comparator output for the comparison against L+ is true if P(osition) ≥ L+. This signifies the level wind is in the positive reversal region. Similarly, the one comparing against L- outputs true if P ≤ L- when in the negative reversal region. These are ORed together to signify that the level wind is in either of the reversal regions. When in either of these regions, the lower multiplexor selects its upper input. When in the sweep region, its lower input is used.

First the normal sweeping behavior is discussed. This is when the lower input signal is selected by the lower mux. Assume the drum is and has been drawing in rope at some reasonable and fixed speed. Then the drum direction will and has been for a while positive and its signal line is and has been at a value of +1 for some time (at least one prior interrupt). The digital differentiator on that channel will be outputting a value of 0 as the direction has not changed recently. So the value output from the mux will be 0. This value is the velocity increment $\ddot{m}$ input into the velocity integrator so its value will not be changing. (I refer to the first integrator as the velocity integrator. But technically that is a misnomer. Velocity is the rate of change of position with respect to time. Here it is not with respect to time but to encoder edges. If the drum speed is constant, the encoder edge rate is constant and this is indeed proportion to sweep velocity so I use this simple nomenclature. Similarly, its input, $\ddot{m}$, is not technically an acceleration unless the drum speed is constant. In both such cases, these are only proportional to velocity and acceleration scaled by the current edge rate.) To be explained later, the velocity output value $\dot{m}$ is and has been a positive value K_s, *s* for sweep. This parameter is the number of microsteps per encoder edge value developed above expressed as a signed 32-bit integer with the binary point just above the 16th lsb. So, its value would be about $5/7*2^{16}$ = 27,307. (Some further restrictions on actual allowable values will be added shortly but they are not relevant here.) Every time there is another interrupt, this value increments the position integrator. The position integrator employs a 32-bit signed register with the same binary point location. Every 2 or 3 interrupts, the fractional part will overflow and increase the integer Position value by 1. When such an overflow occurs, a stepper micropulse is generated. This is effected in the block diagram by looking for a change in the integral Position value between the current Position output, m, and its previous output. (For travel in the negative direction this function also detects a borrow action associated with a decrease in the integral Position value.) The positive sign of the velocity input $\dot{m}$ indicates to the stepper driver the direction this step should be in. Discussion of setup requirements for the Direction signal is deferred until later. This continues so long as the drum turns in the positive direction and the level wind does not enter the positive reversal region. If the drum speed increases/decreases, the interrupt speed increases/decreases proportionally, and the sweep speed increases/decreases proportionally with the scale factor set by K_s. This includes the drum slowing to a complete stop. Then the encoder interrupts stop and the level wind stops.

Now considered is when the drum speed drops to zero and then continues to decrease—meaning the drum is now rotating in the negative direction. When the drum first starts turning backward, the Drum direction input goes to -1. The first time this happens, the current value drum direction value into the differentiator is -1 and the value in the delay element is +1. But this delayed value is subtracted from the current value resulting in a value of -2. This is multiplied by the scaling factor K_s resulting in the value out of the multiplexor being $-2K_s$. This is added to the previous value, K_s, in the integrator so the velocity value $\dot{m}$ changes from K_s to $-K_s$. This negative value is integrated by the position integrator resulting in its value decreasing. When such a subtraction result in the integral position value decreasing (by 1), the carry/borrow detector generates a stepper pulse command. The Direction value is the sign of the velocity output, now negative, so the stepper moves in the negative direction. On the next interrupt with the drum velocity still negative, the current and prior Drum Direction values are both -1 and so the input differentiator produces a 0 output and the velocity value remains $-K_s$. This value remains fixed indefinitely as long as the drum direction remains negative. Should the velocity return to 0 and go positive, on that transition the differentiator will output a value $2K_s$ and the velocity integrator value will toggle back to K_s. So the only two values the velocity output can take on are $\pm K_s$ so long as the level wind remains in the sweep region. As previously noted, if the drum were moved back and forth by hand through zero, the level wind would move back and forth proportionally with the drum deflections. This concludes the description of operation in the sweep region.

Now the reversal behavior is addressed. Assume the drum is traveling in the forward direction at a constant speed. Eventually, the stepper position will increase to and become equal to L+. When this happens, the lower mux switches to the upper input. The level wind is now in the positive reversal region with the upper comparator asserting true. That gates the -1 value through the upper mux. The drum direction is still +1 and that is multiplied times K_a, a positive parameter--the *a* is for acceleration.

This parameter determines the acceleration (actually deceleration) magnitude during a reversal. This parameter is much smaller than K_s. The number of encoder interrupts between L+ and the farthest travel point is now shown to be K_s / K_a, call this ratio N_r. Not certain yet this is actually required but for now, assume K_s is an exact multiple of K_a so that N_r is an integer. Returning to the description of the behavior during the reversal, since the drum's direction of travel is positive, the value into the multiplier is $+K_a$. The value out of the upper mux was -1 so the value into the lower mux and gated through to become the acceleration increment $\ddot{m}$ is $-K_a$. This reduces the value of the velocity value slightly below K_s. On subsequent interrupts, this value continues to drop linearly, with interrupt edges, until it reaches 0. This will occur N_r interrupts after the reversal begins. Remember the drum speed is assumed to remain relatively constant during this reversal so the rate of encoder edge interrupts remains essentially constant. But the decreasing value of $\dot{m}$, the velocity input, results in the rate (again with respect to encoder interrupts) of the stepper pulses dropping until the stepper velocity value reaches 0. At this time, the level wind will have reached zero speed and the level wind position is at its greatest value. That value will be determined shortly. But the drum direction input remains +1 and the level wind position is still greater than $L+$ so the velocity increment value $\ddot{m}$ remains $-K_a$. The encoder interrupts keep occurring at the same rate so the velocity output of the first integrator continues to fall linearly but now the Direction output has gone negative so step pulse commands, at an ever increasing rate, are now in the reverse direction. The Position value now begins to fall and the stepper rate continue to increase until the velocity value $\dot{m}$ reaches $-K_s$. By symmetry, the distance traveled in the positive direction as $\dot{m}$ fell to zero will now have been traversed in the negative direction so the Position value will once again reach $L+$ but now traveling in the reverse direction at speed $-K_s$. The upper comparator will deassert and the system is now in the sweep region traveling at speed $-K_s$. When that sweep reaches position $L-$ the dual reversal process ensues. Here the drum travel direction is still positive but the upper mux will be passing the +1 value so the acceleration $\ddot{m}$ employed for the reversal will be $+K_a$. The velocity input $\dot{m}$ on entry was $-K_s$ so it will increase linearly reaching zero N_r interrupts later when the travel in the negative direction is at its extrema value and then become positive finally reaching $+K_s$ as the level wind exits the negative side reversal region and is now sweeping forward again. Should the drum be rotating in the negative direction, the behavior is the same except the directions are reversed. It is the product of the drum direction and the upper multiplexor output that selects the correct sign for the acceleration value $\ddot{m}$ for all situations.

The remaining question is what is the distance traveled during the reversal period? More precisely, how much does the position value change from reaching $L+$ or $L-$ until the velocity reaches zero. This value has been determined by analysis, included as an Appendix, to be

$$\Delta P = \frac{N_r - 1}{2} K_s$$

(This is closely related to the distance traveled by an object under constant acceleration being $0.5At^2$. The ½ factor comes from this being the area under the triangle associated with the linearly increasing (or decreasing) velocity.) ΔP is properly in units of steps. So this distance is fixed regardless of drum speed and proportional to K_s which determines the level wind factor. Previous analysis shows the actual acceleration employed here increases quadratically with increasing drum, hence sweep, speeds. With a little algebra, we can choose K_a to set this distance as given by

$$K_a = \frac{K_s^2}{2\left(\Delta P + K_s\right)} \approx \frac{K_s^2}{2\,\Delta P} \qquad N_r \gg 1$$

N_r, the number of interrupts required to take the stepper "velocity" to zero is given by

$$N_r = 2\left(\frac{\Delta P}{K_s} + 1\right) \approx 2\frac{\Delta P}{K_s} \qquad \frac{\Delta P}{K_s} \gg 1$$

Note that the reversing period, in interrupts is actually $2\,N_r + 1$ as N_r interrupts only get the velocity to 0, then another N_r interrupts are needed to get the speed back up to the reverse sweep speed.

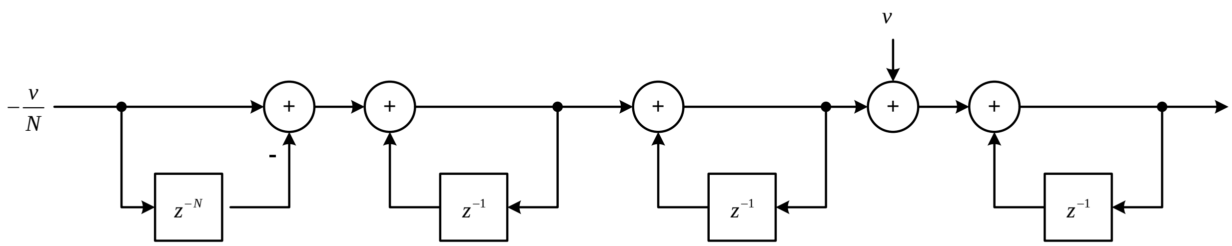
Just to emphasize, these computations are not done in real time during the interrupts. They will selected and adjusted during field trials and will likely be hard coded. (It is possible there may be some way to set $L+$ and $L-$ for adjusting the level wind travel in the field for maintenance and allowing K_s and K_a to be similarly adjusted would be simple to add.)

What is a typical value for this parameter? As noted in the preliminaries, a typical value for ΔP is 2.5 mm. But ΔP here is in unit of microsteps and since a microsteos is 10 um, ΔP here is about 250. So K_a is about 3.47E-4 as compared to about 0.417 for K_s. So N_r, the ratio of these, is about 1,200 indicating the reversal period in interrupts would span about 2,400 encoder interrupts. In terms of the 32-bit increment value for the integrators, the value used for K_a would be about 23 as compared to 21,800 for the value used for K_s. This is pretty coarse but a lot of accuracy is not needed here. This just goes to the distance in steps from $L+$ to the farthest point traveled during the reversal. In practice this reversal distance will be determined by trial and error in the field as will be $L+$ and $L-$. If we wanted finer resolution, we could shift the binary point up one, possibly 2, bits but this might complicate separating the fractional and integer parts of the position integrator for determining when to emit a pulse. If it remains a requirement that K_s must be an integer multiple of K_a, that would require here that K_s must be a multiple of 23. But the fractional change in K_s around its nominal value of 21,800 is minuscule, about 0.1%. We are debating whether the level wind factor should be 2 or 3.

Deferred Topics

Establishing Initial conditions
Operation when drum is not rotating.
Why must Ka and Ks be integrally related
Indexing
Recovery from synchronization losses
Stepper Pulse Jitter
Direction Setup

Appendix



$$
\begin{aligned}
F(z) &= v\left[\frac{z}{(z-1)}\frac{1}{\left(1-z^{-1}\right)} - \frac{1-z^{-N}}{N}\frac{1}{\left(1-z^{-1}\right)^3}\right] \\
&= v\left[\frac{1}{1-z^{-1}}\frac{1}{1-z^{-1}} - \frac{1-z^{-N}}{N}\frac{1}{\left(1-z^{-1}\right)^3}\right] \\
&= v\left[\frac{1-z^{-1}}{\left(1-z^{-1}\right)^3} - \frac{1-z^{-N}}{N}\frac{1}{\left(1-z^{-1}\right)^3}\right] \\
&= v\left[\frac{1-z^{-1}-\frac{1}{N}\left(1-z^{-N}\right)}{\left(1-z^{-1}\right)^3}\right]
\end{aligned}
$$

$$
\begin{aligned}
\lim_{k\to\infty} f(k) &= \lim_{k\to 1}(z-1)F(z) \\
&= v\lim_{k\to 1}(z-1)\frac{z^{-1}}{z^{-1}}\left[\frac{1-z^{-1}-\frac{1}{N}\left(1-z^{-N}\right)}{\left(1-z^{-1}\right)^{3}}\right] \\
&= v\lim_{k\to 1}\frac{\left(1-z^{-1}\right)}{z^{-1}}\left[\frac{1-z^{-1}-\frac{1}{N}\left(1-z^{-N}\right)}{\left(1-z^{-1}\right)^{3}}\right] \\
&= v\lim_{k\to 1}\left[\frac{1-z^{-1}-\frac{1}{N}\left(1-z^{-N}\right)}{z^{-1}\left(1-z^{-1}\right)^{2}}\right] \\
&= v\lim_{k\to 1}\left[\frac{1-z^{-1}-\frac{1}{N}\left(1-z^{-N}\right)}{\left(1-z^{-1}\right)^{2}}\right] \\
&= v\lim_{k\to 1}\left[\frac{z^{-2}-\frac{1}{N}\left(N\,z^{-(N+1)}\right)}{2\left(1-z^{-1}\right)z^{-2}}\right] \\
&= v\lim_{k\to 1}\left[\frac{z^{-2}-z^{-(N+1)}}{2\left(1-z^{-1}\right)z^{-2}}\,\frac{z^{2}}{z^{2}}\right] = v\lim_{k\to 1}\left[\frac{1-z^{-(N-1)}}{2\left(1-z^{-1}\right)}\right] \\
&= \frac{v}{2}\lim_{k\to 1}\left[\frac{(N-1)\,z^{-N}}{z^{-2}}\right] \\
&= \frac{(N-1)}{2}v
\end{aligned}
$$