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Improving Incremental Encoder Measurement: Variable Acquisition Window and Quadrature Phase Compensation to Minimize Acquisition Errors

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Abstract—**Motion control is an important task in several areas, such as robotics where the angular position and speed should be acquired, usually with encoders. For slow angular speeds, an error is introduced spoiling the measurement. In this paper there will be proposed two new methodologies, that when combined allow to increase the precision whereas reducing the error, even on transient velocities. The two methodologies Variable Acquisition Window and a Quadrature Phase Compensation are addressed and combined simultaneously. A real implementation of the proposed algorithms is performed on a real hardware, with a DC motor and a low resolution encoder based on hall effect. The results validate the proposed approach since the errors are reduced compared with the standard Quadrature Encoder Reading.**

Index Terms—**Encoder, speed measurement, positioning measurement.**

I. INTRODUCTION

One of the most important areas on motion control is the feedback sensing. The motion control is applied in several areas such robotics, engines, hydraulic or pneumatic cylinders, compressors and pumps, among the others. The feedback can be obtained by measuring positions and speeds on shafts using encoders. Optical encoders have a high precision and it is a technology used some decades ago but nowadays, different approaches have been applied. The most popular encoder type is based on optical technology but it has as disadvantage its price. There are a huge number of models from different manufacturers commercially available to be applied in industry. On the other hand, having in mind the low-cost characteristic, hall effect sensors assume a different method to acquire the measuring of a rotating shaft or wheel. In fact, this methodology is used to measure speed of a wheel with one pulse per revolution placing a magnetic component on the rotary part. Of course, by this way, the accuracy is low but for some applications it is enough.

Another common solution, also using a magnet component, is composed by placing a magnetized cylinder with more than two poles (typical example of 12) coupled to the shaft of a motor and use a hall effect sensor to trigger a circuit with the number of transitions (North-South). Obviously, the commercial optical encoders exhibit an important characteristic that is the direction information. This can be done using two signals shifted by 90 degrees that will allow a digital system to compute the direction. The low cost solutions, based on hall effect sensors, can also use this approach and two hall effect sensors can be applied close to the magnetized cylindrical part coupled to the shaft, giving two channels as the typical encoders). On gearbox motor models, the lower number of pulses that the magnetic approach owns compared by the optical method, can be improved by placing the acquisition system before the gear. That means, that the pulses per revolution will be multiplied by the gearbox ratio. Nevertheless, the quadrature of channels are not so perfect as it happens on the optical encoders, but an algorithm can be used to compensate these offsets and also to increase the precision of the rotary encoders. The same algorithm can be applied to the commercial optical encoders when the angular speed of rotation is low. This way, it will reduce the errors of measuring.

This paper proposes an algorithm set that reduces the measuring errors obtained during the acquisition of quadrature encoders specially at low speeds of rotation. It uses a low resolution encoder based on magnetic hall effect sensors to apply the algorithm and validate the proposed methodology. As an application example, the proposed algorithm uses a low resolution encoder and it is validated at low speeds where the acquisition errors are high.

II. RELATED LITERATURE

Since feedback sensing is one of the most important areas on motion control, linear and rotary position sensors are an essential part of different actuation systems and there are not only numerous variations of the proposed solutions, but also several real-world implementations. These rely on different physics principles, varying from being mechanical, electromagnetic (e.g., resistive, capacitive or magnetic) to optical. Various sensor technologies including interferometers, optical and magnetic encoders have been studied to measure linear or angular displacements [2]. A grating interferometer,

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called the “optical encoder,” is a commonly used tool for precise displacement measurements [1]. Although resolvers are expensive, they have high precision. A resolver outputs signal by energizing the input phase of the resolver with an AC voltage (VAC) to induce output voltage that is converted to a “digital” format using an R/D converter [3]. When using Brushless DC Motors (BLDC) [5] presented a solution that allows to determine the mechanical position using only the standard position sensors in which most BLDC motors are equipped. Based on image based sensor, [8] proposed a Fast and Reliable Alternative to Encoder-Based Measurements of Multiple 2-DOF Rotary-Linear Transformable Objects Using a Network of Image Sensors.

Finally, there is a method based on contactless magnetic sensor technology. As well known example, the AS5048A is a 14-bit rotary position sensor for absolute angular measurement and with a PWM output over a full turn of 360°. It measures the absolute position of the magnet’s rotation angle and consists of Hall sensors, analog digital converter and digital signal processing.A comparative analysis of speed measurement and estimation algorithms suitable for low resolution incremental encoder equipped drives has been presented in [9]. The position measurements of optical incremental encoders suffer from quantization errors [10]. Authors [7] mention the improving of resolution and accuracy of incremental type rotary encoders using a phase encoding and code compensation system. So far, [6] used the property that a digital encoder has different levels of uncertainty when it changes state to when it is between quantised levels. It allows lower resolution encoders to be used than would otherwise be necessary. In a servo example, the proposed filter required 4 times less resolution to produce comparable results. The proposed methodology is also particularly useful in estimating low velocities where a standard low resolution encoder would produce erroneous results. Also, [11] presented only a simulation scenario based on Fixed-time (FT) and fixed-position (FP) methods to estimate velocity and acceleration. Based on these approached around the community, authors are addressing a new approach to get even better results, in a real scenario.

III. METHODOLOGY

It is well-known the encoder procedure to obtain the displacement. It can be observed as a state machine with two bits that possesses four states (00, 01, 11 and 10). The transition between previous and actual state allows to perceive the displacement that was performed. Figure 1 presents the transitions for each state. It is true that this decoding is usually codded with several comparisons (example with if) that is executed for thousand of times per second (depending on the maximum speed), that imply a time consuming procedure. Especially, for high speeds, the microcontroller should be able to measure all the transitions, and if it fails wrong measures could be introduced. A different approach can be applied to speed up the measurement by introducing a look-up-table. An array of 16 positions, considering the 4 bits (two represent the actual state, and other two represent the previous state), is used as a pointer to the ($encodertable[16]$) array ensuring that it can be previously calculated the transition state. The next Algorithm summarizes this approach.

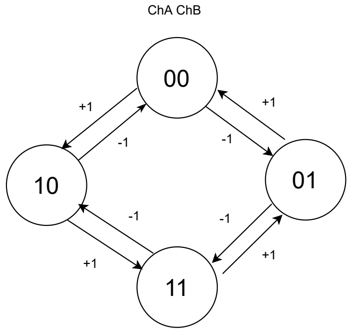

Fig. 1: State machine of the encoder output: usual approach

Algorithm 1 Encoder State transitions computation based on a Look-Up-Table

```
Result: Displacement of encoder: encoder_pos
  encodertable[16] ≡ $\{0, 1, -1, 0, -1, 0, 0, 1, 1, 0, 0, -1, 0, -1, 1, 0\}$
  $next\_state = Read(ENCA) << 1$
  $next\_state\ | = Read(ENCB)$
  $table\_pointer = (encoder1\_state << 2)|next\_state$
  $encoder\_pos+ = encodertable[table\_pointer]$
  $encoder\_state = next\_state$
```

But, although the speed-up approach previously presented, for low rotational speeds, the error introduced is high [4]. To reduce this error, this paper presents two different methods that will be addressed, as detailed in next subsections. They can be applied simultaneously reducing the error. While the a) SQER is the Standard Quadrature Encoder Reading, the b) VAW - Variable Acquisition Window and c) QPR - Quadrature Phase Compensation are proposed and tested. Results will allow to validate the methodology.

A. Variable acquisition window

The VAW - Variable Acquisition Window, occurs since the reading times are not synchronized with the control sampling period. In fact, there are two sampling periods: a faster one to read the transitions of the encoder (i.e. 40 kHz), and a second one slower to measure the encoder speeds (100 Hz). Figure 2 presents a time diagram where this problem is described. In order to synchronize the sampling period (T) with the encoder transitions, the time of the last transition that occurred on the previous acquisition window, and the time of the last transition on the current acquisition window are stored. The number of transitions inside these two moments divided by t' is a better estimator of the angular speed, as further presented on the results discussion section.

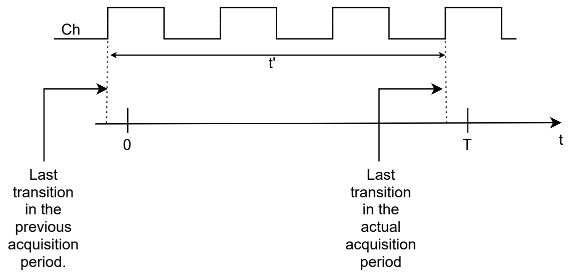

Fig. 2: Variable acquisition window. T is the reading period and t' is the time between states.

B. Quadrature recovery

One of the common problems of encoders is the disequilibrium between states. According to Figure 3, it is possible to notice that each one of the four states has different times.

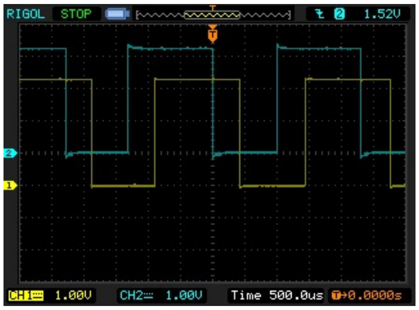

Fig. 3: Oscilloscope signals: quadrature encoder ChA and ChB for cyan and yellow lines.

That means, as presented in Figure 4, the values Δ1, Δ2, Δ3 and Δ4 are not equal. This problem can be reduced by creating an adaptive algorithm for each encoder. That means the algorithm will learn the deviation for each state and the output will be calculated according to the time gain of each sate. Obviously, the sum of Δ1, Δ2, Δ3 and Δ4 is equal to 360 degrees. Next subsection will address the calibration method.

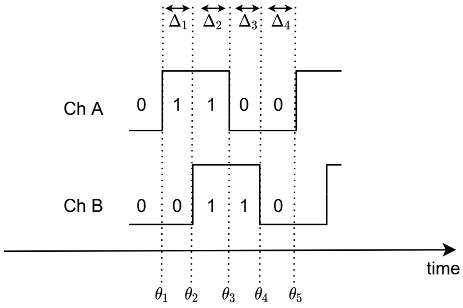

Fig. 4: Measuring the quadrature deviation for a typical encoder. Δ determines the time in each state and θ the angles at each state transition. The θ_5 is the θ_1 for the next iteration.

A complete state machine for the QPR including VAW is presented in Figure 5.

Taking into account two assumptions:

- θ_i Is the angle associated with the transitions on ChA and ChB;
- Last position is codded in X bit (Figure 5).

So, variable (X) will be introduced in the state and three bits will be required to define each state and a total of eight states will exist. In fact, for the same direction of movement, the state machine will appear the one on Figure 1.

By using this methodology, the transition between different states with the same direction (X) does not introduce error.

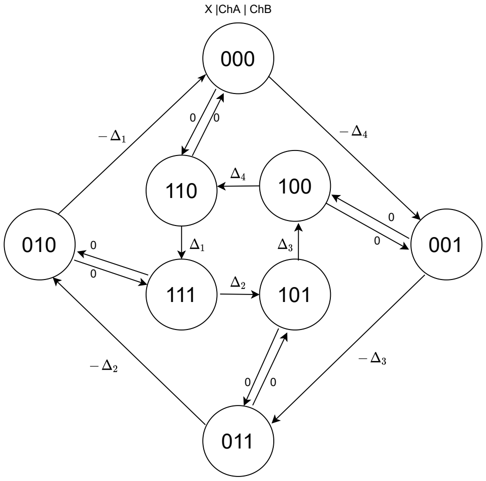

Fig. 5: State machine with QPR (including VAW).

The Algorithm presented on Listing 1 can be used to implement the described state machine, according to different rotation movements.

```
Displacement_of_encoder: encoder_odo
enc_delta[32] = [
//AB
// 00   01   10   11
    0, -1,  0,  0,   // 00
    0,  0,  0, -1,   // 01
   -1,  0,  0,  0,   // 10
    0,  0, -1,  0,   // 11
    0,  0,  1,  0,   // 00
    1,  0,  0,  0,   // 01
    0,  0,  0,  1,   // 10
    0,  1,  0,  0    // 11
]

enc_next_state[32] = [
//AB
//00      01      10      11
  0b000, 0b001, 0b110, 0b000,
  0b100, 0b100, 0b001, 0b011,
  0b000, 0b010, 0b010, 0b111,
  0b011, 0b101, 0b010, 0b011,
  0b100, 0b001, 0b110, 0b100,
  0b100, 0b101, 0b101, 0b011,
  0b000, 0b110, 0b110, 0b111,
  0b111, 0b101, 0b010, 0b111
]

function table_delta(deltas[4], i)
  return deltas[i - 1] * 100  // 0-based correction
```

```
procedure fill_enc_deltas(deltas[4])
  enc_delta[1]  = -table_delta(deltas, 4)
  enc_delta[7]  = -table_delta(deltas, 3)
  enc_delta[8]  = -table_delta(deltas, 1)
  enc_delta[14] = -table_delta(deltas, 2)
  enc_delta[18] = table\delta(deltas, 4)
  enc_delta[20] = table\delta(deltas, 3)
  enc_delta[27] = table\delta(deltas, 1)
  enc_delta[29] = table\delta(deltas, 2)

procedure timer_interrupt()
  encoder_table =
  [0, 1, -1, 0,  -1, 0, 0, 1,  1, 0, 0, -1,  0, -1,
    1, 0]
  AB = (digitalRead(encoder0_A_pin) << 1) |
    digitalRead(encoder0_B_pin)
  delta = encoder_table[encoder_state | AB]
  encoder_odo += delta
  encoder_state = AB << 2
  if (delta) then
    enc_int.tact = enc_int.tc
    if (enc_int.ti == -1) then
      enc_int.ti = enc_int.tc
  enc_int.tc++
```

Listing 1: Encoder State for QPR and VAW

C. QPR parameters calibration

As previously described, the algorithm should learn and adapt the disequilibrium for the different states. A the beginning, the motor turns while $pc\_calib[AB]$ array is populated with the calibration, as detailed in Algorithm 2. This can be done since each state AB will increment the $pc\_calib[AB]$ array while it does not reach MAXPHASEMEASURES constant (assuming a calibration period of 0.5 seconds). At the end, it is possible to get the percentage of each state that will weight the movement.

Algorithm 2 QPR Calibration

```
Result: pc_calib[AB]
CONST MAXPHASEMEASURES = 20000

if pc_calibrate == cs_calibrating then
    pc_calib[AB]++
    if pc_calib[AB] $\geq MAXPHASEMEASURES$ then
        pc_calibrate = cs_process
    end
end
```

IV. SYSTEM ARCHITECTURE

In order to experiment and validate the proposed algorithm that enhances the accuracy of an encoder, an apparatus should be developed to couple all the necessary parts and it is used as testbed for the algoritjm validation. It uses an ESP32 microcontroller from Espressif Systems. Beyond it has a 32 bit architecture, it has dedicated hardware to measure a quadrature encoder, has PWM output and communication to provide information to a computer regarding the acquisition. The main mechanical parts are represented as shown by Figure 6.

As it can be observed, there are two Hall sensors (Hall A and Hall B) placed accordingly to provide quadrature signals.

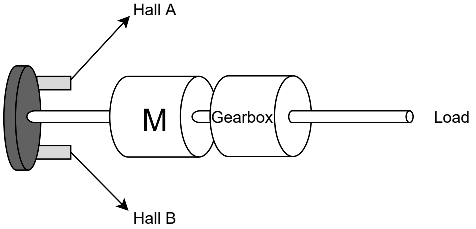

Fig. 6: Mechanical model of the test bed.

This approach can provide 44 states/revolution (11 magnetic poles) The motor used for the tests was the JGY-371 that owns a worm gear with a reduction of 1:380. The output shaft after reduction has a nominal speed of 20 rpm and a torque of 1150 g.cm. The DC motor is connected to a Dual BTS7960H Half-Bridge Configuration that receives the control signals from the microcontroller, as depicted on Figure 7.

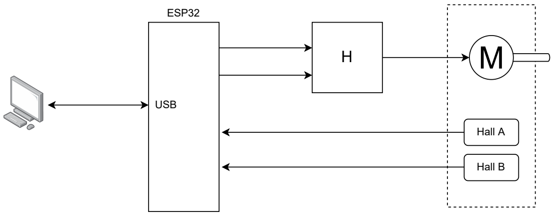

Fig. 7: Electric schematic for the test bed

The final test bed is presented in Figure 8 composed by a base with the electronics and the motor holder that was designed and 3D printed.

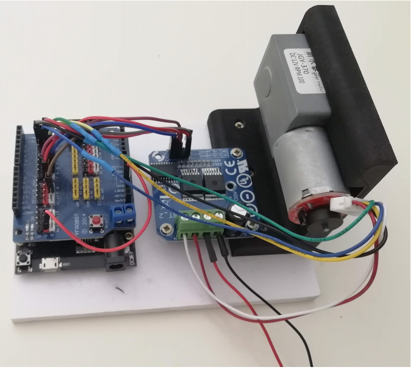

Fig. 8: Real test bed for the validation of the proposed algorithm

V. RESULTS AND DISCUSSION

This section will detail the results obtained for two kind of tests: constant speed, and step input voltage (falling and rising). The first subsection will detail the test and the second one will present and discuss the Measuring and estimation errors. The three methodologies SQER (Standard Quadrature Encoder Reading), VAW (Variable Acquisition Window) and QPR (Quadrature Phase Compensation) will be evaluated and compared. Later, a quantitative analysis for different speeds will be stressed in this paper.

A. Steady-state

In this subsection, a constant speed case is presented. The motor is supplied with a constant voltage and the encoder is read. Figure 9 presents the constant speed reading for each proposed methodology. The red line is the standard reading (SQER), the blue is the VAW and the dark green is the QPR (with the VAW).

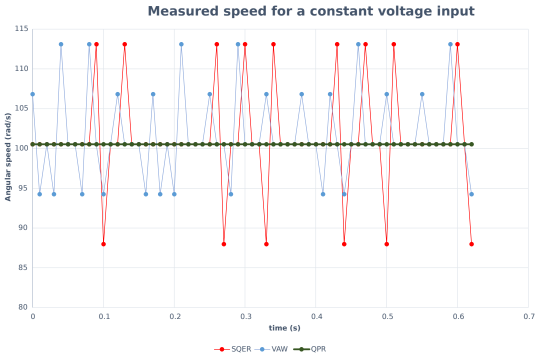

Fig. 9: Constant speed. The red line is the standard reading (SQER), the blue is the VAW and the dark green is the QPR (including the VAW).

It is notorious that the QPR proposed methodology is the one that fits better the constant speed of the shaft without introducing error. Later, a quantitative analysis for different speeds will be stressed in this paper.

B. Transitory response

In this section the test will be carried out with a step at the supply of the motor. By this way it is possible to analyze the transitory response for the different algorithms. Two tests were implemented: a step voltage input (to zero) and a step voltage input (from zero), as presented in Figures 10 and 11, respectively.

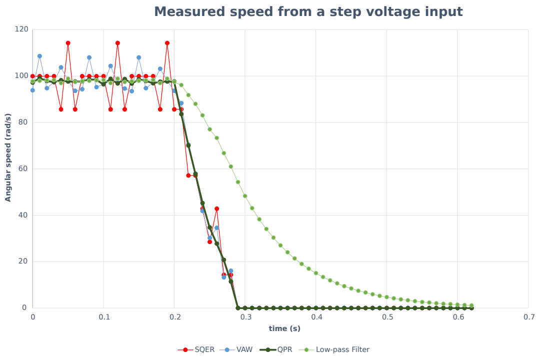

Fig. 10: Measured speed from a step voltage input (to zero). The red line is the standard reading (SQER), the blue is the VAW, the dark green is the QPR (including the VAW) and light green is a low pass filter of SQER signal.

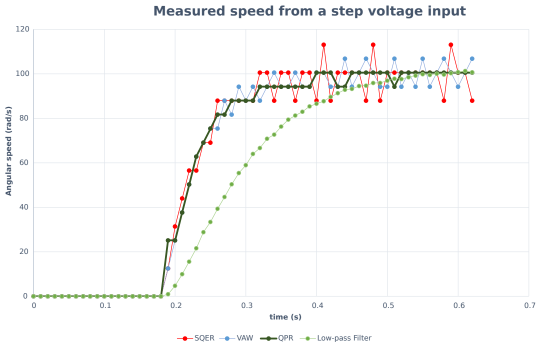

Fig. 11: Measured speed from a step voltage input (from zero). The red line is the standard reading (SQER), the blue is the VAW, the dark green is the QPR (including the VAW) and light green is a low pass filter of SQER signal.

In fact, it can be thought that a low pass filter will reduce the error. It is true for the constant speed but for the transitory response it will introduce a delay, that several times is a problem in a position controller. Thus, in Figures 10 and 11 it is included a low pass filter of the SQER signal with the same average error of the proposed QPR. It is true that the QPR algorithm delivers a fast reading (as the SQER) and low average error (noise) as the low pass filter. By this way, the QPR proposed algorithm promises to be the selected one.

C. Measuring and estimation Errors

In this subsection, nine different speeds were introduced on the encoder (105.4, 170.7, 235.0, 299.9, 365.5, 431.0, 496.8, 589.1 and 649.5 rad/s) using a stabilized voltage applied to the motor (increasing of 10% steps of supply voltage). By this way, it allows measuring the error and its standard deviation for each SQER, VAW and QRP processing methodology.

It will be presented the histogram for each comparison. Eight experiments were done for each case. Figure 12 presents the histogram of the average error for each one of the nine different speeds.

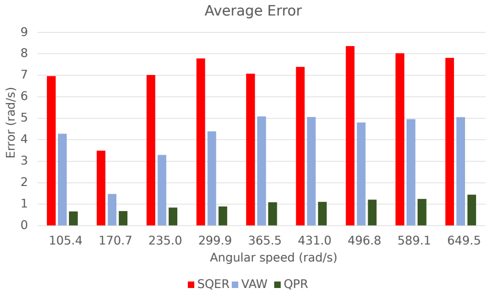

Fig. 12: Average of error for different speeds. The red line is the standard reading (SQER), the blue is the VAW and the dark green is the QPR (with the VAW).

As result, an average error of 7.1 rad/s is obtained for the SQER, 4.27 rad/s for the VAW and 1.0 rad/s for the QPR.

Figure 13 presents the histogram of the relative average error for each one of the nine different speeds. In this case an average of relative error of 15.4% is obtained for the SQER, 9.0 % for the VAW and 2.0% for the QPR.

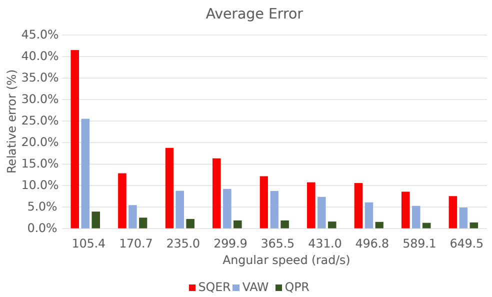

Fig. 13: Relative average of error for different speeds. The red line is the standard reading (SQER), the blue is the VAW and the dark green is the QPR (with the VAW).

Finally, the standard deviation is presented for these tests, as depicted in Figure 14. In such case, it is observed an average of 42.9% for the SQER standard deviation, 20.3 % for the standard deviation of VAW and 6.1% for the standard deviation of the QPR methodology.

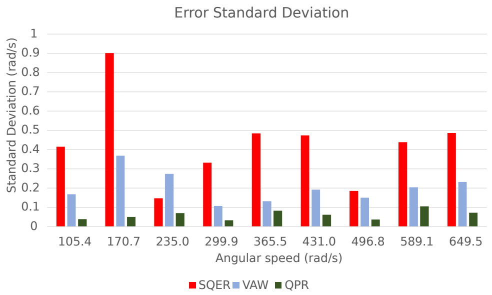

Fig. 14: Standard Deviation of error. The red line is the standard reading (SQER), the blue is the VAW and the dark green is the QPR (with the VAW).

D. Discussion

As a final remark, Table I presents a summary of the error and the standard deviation for each methodology of reading.

Average\Method	**SQER**	**VAW**	**QPR+VAW**
Error (rad/s)	7.1	4.27	1.0
Relative Error (%)	15.4	9.0	2.0
Standard Deviation (rad/s)	42.9	20.3	6.1

TABLE I: Statistics of speed measuring for the proposed methodologies

As it can be seen, the proposed QPR+VAW approach presents a reduced error of about 7 times smaller than the common acquisition. It is obvious that the proposed approach of QPR+VAW is an excellent algorithm for low speeds measurement (Figure 13).

VI. CONCLUSION AND FUTURE WORK

When slow angular speeds are measured by an encoder, an error is introduced spoiling the measurement. This paper presented two algorithms that when combined, allow to reduce the error while increasing the precision of measurement. A real implementation of the proposed algorithms are assembled on a real hardware prototype with a DC motor and a low resolution encoder based on hall-effect. This real approach allowed to compare the standard Quadrature Encoder Reading with the proposed algorithms Variable Acquisition Window and Quadrature Phase Compensation. Results value and validate the proposed algorithms reducing to seven times smaller than the common acquisition. The improved speed estimation at low speeds has the limitation that needs, at least, one state transition per sampling period. As future work, considering multi period measures could extend the improvements to even lower speeds. Also, the integration of the algorithm with more low cost encoders to stress its robustness can be addressed.

ACKNOWLEDGMENT

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REFERENCES

[1] Hu, Pc., Chang, D., Tan, Jb. et al. Displacement measuring grating interferometer: a review. Frontiers Inf Technol Electronic Eng 20, 631–654 (2019). https://doi.org/10.1631/FITEE.1800708.

[2] N. Arora, L. Petit, M. U. Khan, F. Lamarque and C. Prelle, "Signal processing of a high resolution and long-range displacement sensor," SENSORS, 2012 IEEE, 2012, pp. 1-4, doi: 10.1109/ICSENS.2012.6411266.

[3] Attaianese, C.; Tomasso, G. Position measurement in industrial drives by means of low-cost resolver-to-digital converter. IEEE Trans. Instrum. Meas. 2007, 56, 2155–2159.

[4] .R. Petrella, M. Tursini, L. Peretti and M. Zigliotto, "Speed measurement algorithms for low-resolution incremental encoder equipped drives: a comparative analysis," 2007 International Aegean Conference on Electrical Machines and Power Electronics, 2007, pp. 780-787, doi: 10.1109/ACEMP.2007.4510610.

[5] Kolano, K. Determining the Position of the Brushless DC Motor Rotor. Energies 2020, 13, 1607.

[6] Daniel Luong-Van, Jayantha Katupitiya, An Adaptive Kalman Filter with Quadrature Encoder Quantisation Compensation, IFAC Proceedings Volumes, Volume 37, Issue 14, 2004, Pages 109-114, ISSN 1474-6670, doi:10.1016/S1474-6670(17)31089-3.

[7] N. Hagiwara, Y. Suzuki and H. Murase, "A method of improving the resolution and accuracy of rotary encoders using a code compensation technique," in IEEE Transactions on Instrumentation and Measurement, vol. 41, no. 1, pp. 98-101, Feb. 1992, doi: 10.1109/19.126640.

[8] Bošnak, M.; Klančar, G. Fast and Reliable Alternative to Encoder-Based Measurements of Multiple 2-DOF Rotary-Linear Transformable Objects Using a Network of Image Sensors with Application to Table Football. Sensors 2020, 20, 3552. https://doi.org/10.3390/s20123552

[9] R. Petrella, M. Tursini, L. Peretti and M. Zigliotto, "Speed measurement algorithms for low-resolution incremental encoder equipped drives: a comparative analysis," 2007 International Aegean Conference on Electrical Machines and Power Electronics, 2007, pp. 780-787, doi: 10.1109/ACEMP.2007.4510607.

[10] R.J.E. Merry, M.J.G. van de Molengraft, M. Steinbuch, Velocity and Acceleration Estimation for Optical Incremental Encoders, IFAC Proceedings Volumes, Volume 41, Issue 2, 2008, Pages 7570-7575, ISSN 1474-6670, ISBN 9783902661005, doi:10.3182/20080706-5-KR-1001.01280.

[11] O. Baser, E. Kilic, E. I. Konukseven and M. Dolen, "A hybrid method to estimate velocity and acceleration using low-resolution optical incremental encoders," ICSES 2010 International Conference on Signals and Electronic Circuits, 2010, pp. 57-60.