An Innovative Method to Increase the Resolution of Optical Encoders in Motion Servo Systems

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Abstract - Presently, most high performance motion servo systems rely on optical encoders for position and velocity feedback. Optical encoders with higher resolutions will increase the performance and accuracy of these motion systems. One method to increase the resolution of optical encoders without the need to increase their optical resolution is to use sine-cosine interpolation. There are a few existing methods to accomplish this task. However, all of them have limitations or disadvantages. This paper provides a general overview of these existing methods, highlight their features and limitations. Then, a novel and simple method to realise sine-cosine interpolation of optical encoders is proposed. The proposed method can be implemented by using very few logic gates and comparators. Construction of a 16 times interpolation circuit show that the proposed interpolation circuit can be build with very few components, and its accuracy will not decrease when the travelling speed of the encoder is increased.

I. INTRODUCTION

Most high performance motion control systems rely on optical encoders for position and velocity feedback [1]. Fig. 2 shows the typical configuration of a high performance motion servo system. The optical encoder is the essential feedback element on the servo loop.

For a higher precision servo system, the feedback signal requires a higher resolution. One way to increase the resolution of optical encoders without the need to increase its optical resolution is to use an interpolation method. Presently, there are a few existing methods to perform interpolation of encoder waveforms. These include (i) resistor based look-up table, (ii) processor based ADC conversion, and (iii) processor based ADC conversion with variable resolution.

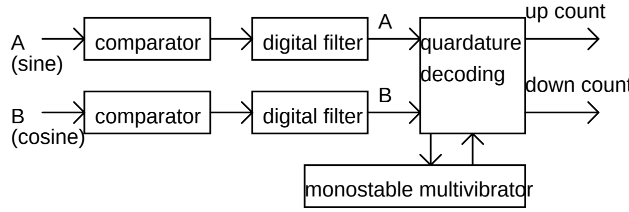

Fig.1 Typical block diagram of a decoder circuit (for optical encoder)

This paper provides a general overview of these existing methods, and highlights their features and disadvantages. Then, the paper proposes an innovative and simple method to perform the interpolation of encoder waveforms. The proposed method is very simple, and it can be realised by using very few components. After that, a 16-fold interpolation circuit is designed and constructed using the proposed method. Results show that the interpolation circuit can achieve a 16-fold resolution increase with no error or decrease in accuracy.

II USING OPTICAL ENCODERS IN MOTION SYSTEMS

Optical encoder is an essential element in motion servo systems. Most industrial encoders output sine-cosine current waveforms (A-B signals) as position information. This signal is then fed to a decoder circuit, which gives up and down count pulses to the motion controller's position counter. Fig. 1 shows the block diagram of such a typical encoding circuit.

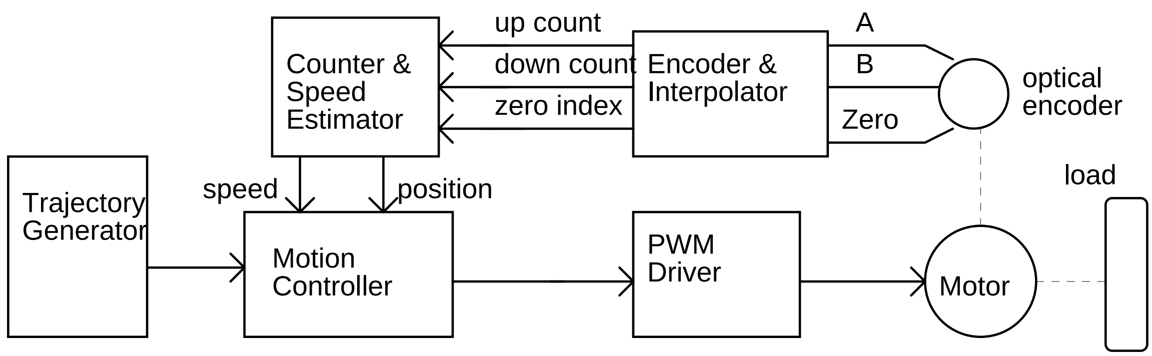

Fig. 2 Block Diagram of a typical high performance motion servo system

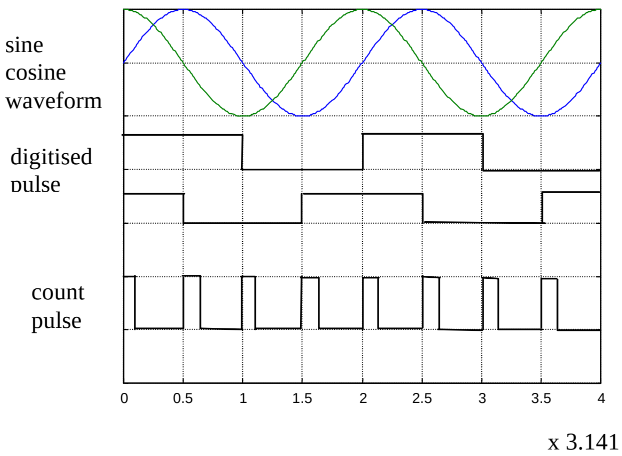

Fig.3 Qudrature decoding of position encoder

In most encoder circuits, a hysteresis comparator and a digital filter is used to filter out the noise, and quadrature decoding is used to obtain the count pulses. Fig. 3 shows the sine cosine waveform outputs of an optical encoder, the A-B signals after the hysteresis comparator circuit, and the output up/down count pulse. The resolution of the up/down count pulse is 4 times the optical encoder's resolution.

Quadrature decoding is the most common method to decode the phase A-B signals into up/down count pulses [2,3]. This has the advantages of simplicity and full digital implementation. However, the count pulse resolution is limited to four times its optical resolution.

III. INTERPOLATION METHODS AND THEIR LIMITATIONS

To increase the resolution of optical encoders more than fourfold, a form of sine-cosine interpolation method has to be employed. Through interpolation, intermediate values of sine cosine waveforms can be found, and, through the detection of these intermediate values, much higher resolution of count pulses output can be achieved. Fig. 4 shows the interpolation of the sine cosine waveform to achieve a 16-fold resolution increase.

Presently, there are 3 commonly used methods to increase the resolution of optical encoders:

1. Use a resistor network to detect the magnitudes of the sine cosine waveforms.
2. Use ADC convertors to acquire the current magnitudes of the sine/cosine waveforms.
3. Use the method similar to 2, but includes a variable resolution scheme to allow faster processing and access.

Method 1: Use a resistor network to find the intermediate positions

The first method is to use analogue comparators to obtain the angle of the magnitude of the phase A and B signals. Since the output of the two signals from the optical encoder has a sine-cosine relation, there is a one-to-one mapping of these signals to the intermediate position values of the optical encoder. Essentially, the locus of the output signal is a circle, when they are plotted on a 2D plane.

However, the magnitude of the signals decrease as the speed

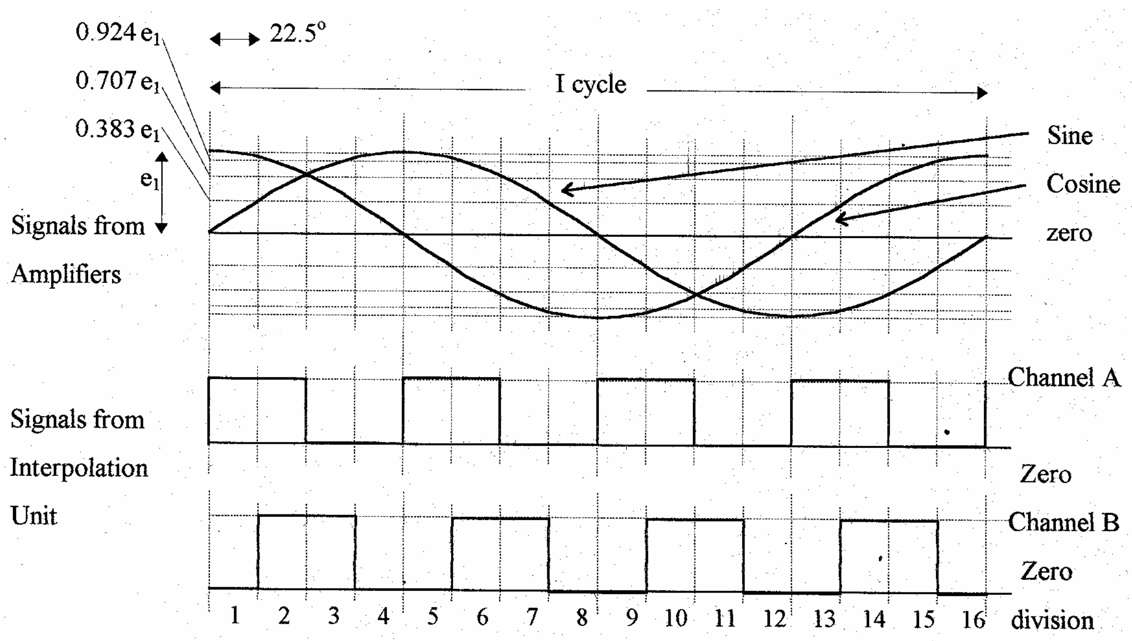

Fig.4 16 fold resolution increase with sine cosine interpolatio

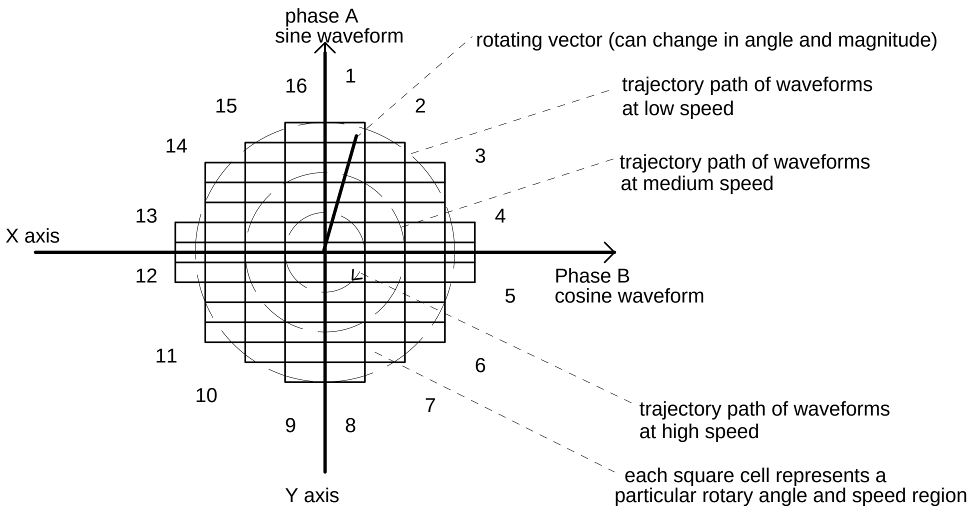

Fig. 5 Mapping the rotating angle by bounded regions

of the optical encoder is increased. A circular locus can only be created when the speed is low. In most practical situations, infinite numbers of circular loci are created as the encoder moves at different speeds. Therefore, to obtain the intermediate values by tracking the values of the sine cosine signals can only work when the moving speed of the encoder is slow.

For high performance motion systems, it is necessary to track the values on the whole 2D circular plane. A 2D lookup table based on a large resistor network and analogue comparators is needed. Fig. 5 shows the 2D lookup table for such an interpolation method. The 2D plane is divided into 72 cells, a 16-fold resolution increase can be achieved for low speeds, but the resolution is much lower for higher speeds.

This method has the advantage of employing straightforward circuit, with no software programming. However, it has a few disadvantages:

1. Difficult to construct a precise resistor network.
2. A large number of comparators are needed.
3. Resolution decreases at higher speed.

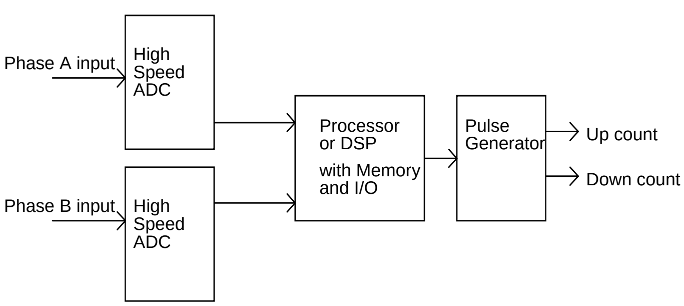

Fig. 6 Block diagram of a processor based interpolation unit

Method 2: Use a two channel data acquisition circuit

This is the most common interpolation method used in motion control systems. Rather than building a large resistor network with a large number of comparators, the interpolation process can be implemented by a high speed data acquisition circuit. Fig. 6 shows the block diagram of such a data acquisition system. Such an approach has the advantages of high flexibility and large resolution increase. In some cases, resolution increase of up to ×1024 can be achieved.

However, it has a few disadvantages:

1. Complex circuit and expensive component cost due the ADCs and computing unit.
2. Only suitable for low speed operation, due to the speed limitation of the computing unit and the data acquisition circuit.

The higher the resolution, the higher will be the pulse output rate, and the higher will be the computing requirement. Under this configuration, it is very expensive to implement a high speed and high-resolution interpolation decoder.

Method 3: Variable resolution data acquisition circuit

For most applications, high resolution is not required for high-speed motions, but when the system's speed is very low or coming to a stop, high resolution is required. The previous method has the advantage of high resolution, but it cannot travel at very high speed. To overcome this problem, many systems use a variable resolution scheme. When the speed is too fast for the computing unit to handle, its resolution decreases to reduce the computing burden. However, this method has the disadvantages of complex hardware (to accommodate the flexible resolution scheme) and the problem of a "glitch" during resolution change.

IV A NOVEL METHOD TO PERFORM SINE-COSINE INTERPOLATION

In this paper, a simple and innovative method to obtain the vector angle of the sine cosine waveform is proposed. The proposed method uses very few components to accomplish the sine-cosine interpolation task. The method does not need to use an expensive resistor network, computing devices, or data acquisition units.

The method takes advantage of the fact that both sine and cosine waveforms decrease by the same ratio when the vector rotating speed is increased, and the shape of the circular locus and the vector angle remains the same. Therefore, instead of comparing the waveforms to reference voltages, the two waveforms can be compared with each other to find out the angle of the rotating vector, and deduce the immediate position values. The problem of signal variation can be effectively eliminated.

To demonstrate the design process of the proposed method, a 16-fold interpolation unit is used as a design example. The interpolation unit divides the sine-cosine cycle into 16 sections, with an angular distance of 22.5° for each section.

The sectioning process can be represented conceptually as shown in Fig. 7. In this figure, 8 boundary lines (L0-L7) are used to divide the 16 sectors (S0-S15). The following table can express the boundary conditions of L0-L7:

L0: Y=0	*L1: X=0.414Y*	*L2: Y=X*	*L3: Y=0.414X*
L4: X=0	*L5: Y=-0.414X*	*L6: Y=-X*	*L7: X=-0.414Y*

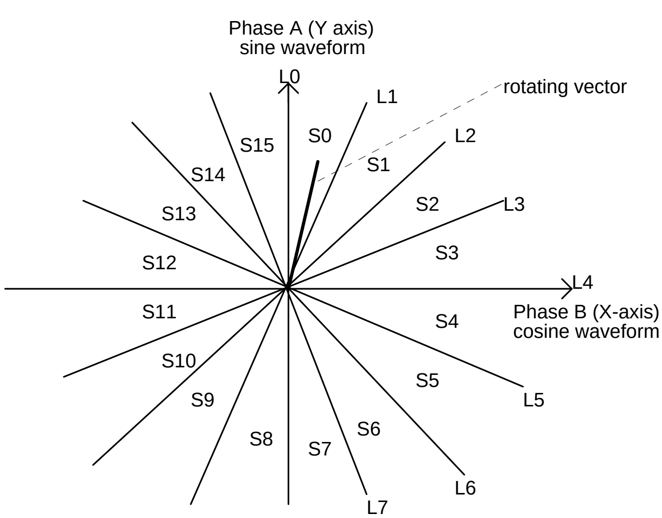

Fig. 7 Conceptual representation of a x16 interpolation unit

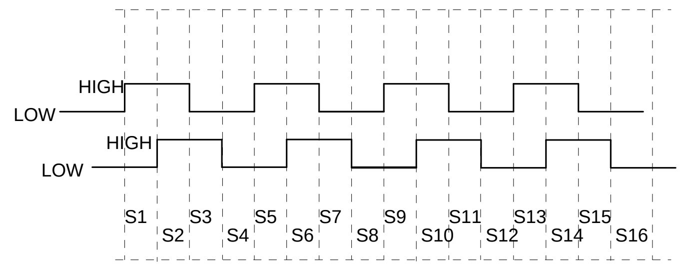

Fig.8 The quadrature output waveform of the 16-fold interpolation unit

By setting the conditions for each of the sector (e.g. S0 ⇒ Y>0 and X<0.414Y) all 16 sectors can be identified. The position of the optical encoder can be represented by a rotating vector in Fig. 7. In this way the change of signal amplitude will merely change the magnitude of the rotating vector; the angle of the rotating vector remains the same. By testing boundary conditions of the rotating vector, one can find out which sector the rotating vector resides.

Since the interpolation unit is designed to be interfaced with conventional quadrature decoding unit, the interpolation unit should output 90° phase-shifted A-B digital pulse-trains, as shown in Fig. 8. The figure shows that for channel A, output is high at S1, S2, S5, S6, S9, S10, S13, and S14. For channel B, output is high at S2, S3, S6, S7, S10, S11, S14, and S15. These output criteria can be matched with the boundary conditions of Fig. 7, to form a table shown in Fig. 9 below.

Output	Input	Output Sector
Channel A	(x>0) & (y>x)	S1,S2 high
	(y<0) & (-y<x)	S5,S6 high
	(y<0) & (y<x)	S9,S10 high
	(y>0) & (-y>x)	S13,S14 high
Channel B	(0.414y<x) & (y>0.414x)	S2,S3 high
	(-y>0.414x) & (-0.414y<x)	S6,S7 high
	(0.414y>x) & (y<0.414x)	S10,S11 high
	(-y<0.414x) & (-0.414y>x)	S14,S15 high

Fig.9 Matching the output to the boundary conditions

Once this is obtained, the 16 sectors can be translated into A-B pulse-trains (with ×4 resolution increase), which in turn can be translated into up/down count pulses (with ×16 resolution increase) using standard logic hardware or ASIC implementation.

Under the proposed method, sine-cosine interpolation units with higher resolution increases can be designed in a similar manner.

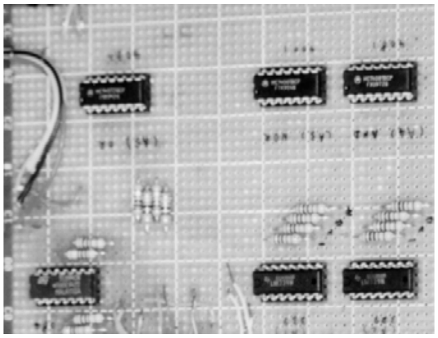

Fig.10 The interpolation hardware

V IMPLEMENTATION OF THE SINE-COSINE INTERPOLATION UNIT

The 16-fold interpolation unit is realised by simple logic gates and comparators, as shown in Fig. 10. Even using SSI components such as LM339 comparators and 74XX logic devices, the component count is still very low. Fig. 11 is the block diagram of the proposed 16-fold interpolation circuit.

VI RESULTS

The interpolation unit has been fabricated and tested with two types of optical encoders:

1. A very low-cost rotary optical encoder manufactured by Sansei Electric Corp. Model no is OME-100-2. Resolution is 100 cycle/rev.
2. A high grade linear optical encoder manufactured by Heidenhain. Model no. is LS176. Resolution is 5μm per cycle.

It has been found that the low cost rotary encoder gives satisfactory performance at 16-fold resolution increase with the proposed method. The maximum error is <10%. Measurement of maximum error is obtained by rotating the encoder at uniform speed, and by inspecting the uniformity of the captured pulse output. Fig. 12 is the sine cosine output from the optical encoder, and Fig. 13 is the pulse output from the interpolation unit.

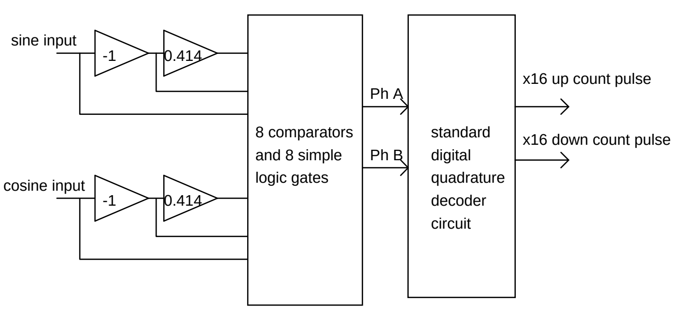

Fig. 11 Hardware block diagram of the x16 interpolation unit

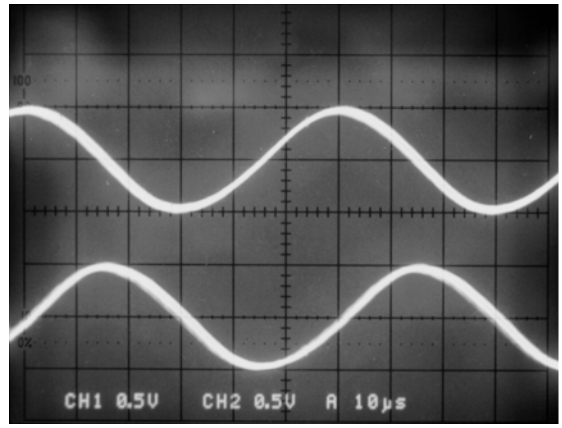

Fig.12 Output of the rotary optical encoder

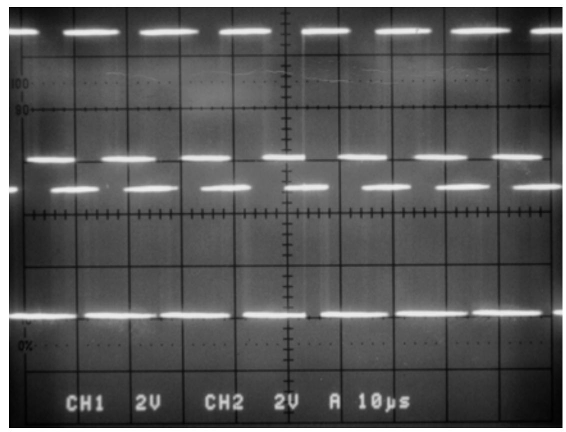

Fig. 13 Output of the 16-fold interpolation unit

By closely inspecting the waveforms, it was found that the interpolation unit did not create the error. The error was due to the output of the rotary encoder. The output was not a pure sine wave; therefore the output pulses from the interpolator were not uniform.

The next step was to connect a high-grade linear optical encoder to perform the interpolation unit. In this case the error was virtually zero (undetectable), even at very high speed.

VII CONCLUSION

This paper proposes a novel and simple method of increasing the resolution of optical encoders in servo motion systems. By comparing the magnitudes of the sine-cosine waveforms, the angle of the rotating vector can be obtained in a very simple manner. In this paper, a 16-fold interpolation unit has been designed and implemented, using the proposed method. Implementation results show that the resulting circuit is very simple, and its output produces error free up/down count pulses, with no decrease in accuracy. The proposed method is an effective and economical way to increase the resolution of optical encoders.

VIII REFERENCES

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IX APPENDIX

Below is the full circuit diagram of the 16-fold interpolation unit.