High Speed Processing of Encoder Information by using a Dual-Resolution Approach

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***Abstract*— A novel high-speed, resolution step-up strategy for high precision control system is proposed in this manuscript. Control precision and speed will be limited by the decoder's circuit if an incremental encoder is used as a device providing positioning feedback. A resolution step-up method is designed and proposed in this paper to address this issue. By using data fusion between measurement from original sensor and outputs of proposed circuit, controlled object's speed and accuracy could be improved.**

Keywords-component: data fusion, high precision control, resolution.

I. INTRODUCTION

Generally, high precision and high speed control is required for many industrial applications such as integrated circuits wiring, automatic PCB separator, and high-precision motion control for 3D laser engraving [1]. In the research field, many engineers also studied on quick and accurate control. Lee, Tan, Huang, and Dou proposed an intelligent control of precision linear actuators using a radial-basis function for nonlinear compensation and an iterative learning control scheme [2]. Wang, Yin, Zhu, and Duan also demonstrated a high precision control using a polynomial pole-placement combined with sensitivity function shaping for controlling voice coil motor with air bearing.[3] However, it is difficult to achieve both aims (i.e. precision and speed) at the same time. One of the major reasons is due to processing speed of limitation of decoder.

For a typical linear motion system, in order to achieve high precision motion control, a high precision optical incremental encoder is usually adopted. However, the maximum speed of controlled object (few centimeters per second) is limited when incremental encoder is applied since decoder clock's frequency restricts measurable speed in low value. Digital signal processor (DSP) may be unable to handle the high frequency pulses generated from the incremental encoder when the actuator is moving at high speed. In fact, in many applications, the high resolution incremental encoder is being operated in the case of short stroke movement and operating speed of actuator is not accelerated out of its limitation so that the controlled process will not suffer from the problem mentioned before.

Many engineers use two or more actuators together with separated displacement sensors in order to handle long stroke, high speed, and high precision control. For example, Park and Kim constructed a three-degrees-of-freedom motion system consisting of coarse stage (for initial movement) and fine stage (for high precision fine alignment) to illustrate the possibility of high speed and high precision motion control [4]. Numasato and Tomizuka designed a dual-actuator system which is composed of a voice coil motor and a push–pull-type piezo-electric transducer in order to achieve precise motion control [5]. However, the cost of system mentioned above will be increased since more actuators and sensors are used.

Considering a linear motion system with an incremental encoder for position feedback sensor, when the measured object is accelerated at high speed, the frequency of encoder outputs could be extremely high and DSP might miscount the position pulses. Therefore, this paper proposes a low cost and novel approach (resolution step-up approach) to realized quick and precise motion.

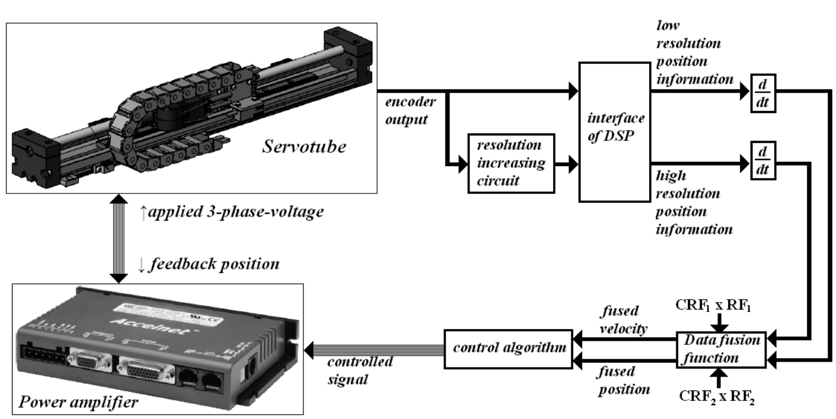

Fig.1 Overview of the system.

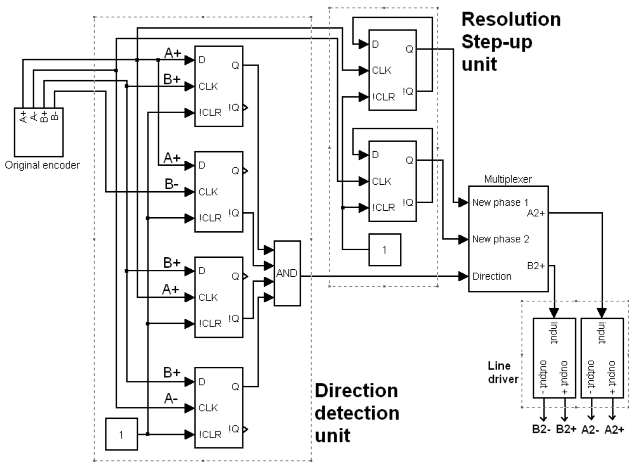

Fig.2 Model of resolution increasing circuit

The maximum velocity of object could be enhanced since the frequency of encoder's outputs could become lower by analog circuit. The disadvantage of this method is that position information will become lower precision. Fusion of high and low resolution information could achieve the quick and precise linear motion control. This approach could be further applied to practical control aspects.

The presenting idea could extend the speed limitation of the controlled object by enhancing the measurable speed of sensor. Also, this method requires one sensor and inexpensive circuitry only. It could reduce the cost of entire system and provide desirable and precise controlled motion.

II. OVERVIEW OF THE PROJECT

The design of proposed method is shown in Fig.1. The position of the mover of servotube is measured by optical linear incremental encoder. Outputs of encoder (phase A and phase B) are processed by "resolution increasing circuit". Note that the "resolution increasing circuit" is achieved by large frequency bandwidth analog circuitry. The equivalent resolution of encoder's outputs could be stepped-up. The original encoder's and circuit's outputs are connected to DSP which converts quadrate signals into position information.

Inside the DSP, both high and low resolution position information is differentiated to provide the velocity information. Note that the subscript 'h' and 'l' meant high resolution and low resolution respectively. Together with confidence/reliability factor (CRF) and resolution factor (RF), the "data fusion function" could combine both velocity information to a trustable fused velocity. "Data fusion function" also converts the fused velocity into fused position by integration.

The fused position and velocity are feedback to "control algorithm". Control signal is calculated and commanding the "power amplifier" to drive the servotube towards the required position quickly and precisely.

III. RESOLUTION INCREASING APPROACH

Fig.2 shows the design of the "resolution increasing circuit" which is targeted to produce a set of high resolution incremental encoded outputs with double resolution of original encoder. The high speed circuit includes "direction detection unit", "resolution step-up unit", multiplexer, and line drivers.

"Resolution step-up unit" consists of two frequency dividers constructed by D-type flip-flops [6]. This unit could double the resolution of output from original encoder. The direction information, however, could not be solely extracted by frequency dividers because "resolution step-up unit" considered one phase of incremental encoder outputs only (phase A as shown in Fig.2). The direction detecting method is simplified from general decoding method of industrial decoder (phase leading-lagging detection) [8]. Direction information modifies outputs from "resolution step-up unit" through "multiplexer" which selects signal for the new phase A and B (A2 and B2 in fig.2).

The simulation of this novel approach was performed by MATLAB and the results are shown in Fig.3. Note that vertical lines shown in first and second figures represent the instant that decoders were receiving tuning direction commands.

Several points should be highlighted regarding to Fig.3. The first valuable observation is that the pulse widths from outputs of "resolution step-up approach" are doubled compared with original incremental encoder outputs. This phenomenon reflects that the proposed idea is feasible and resolution of new circuit's outputs could step up the resolution.

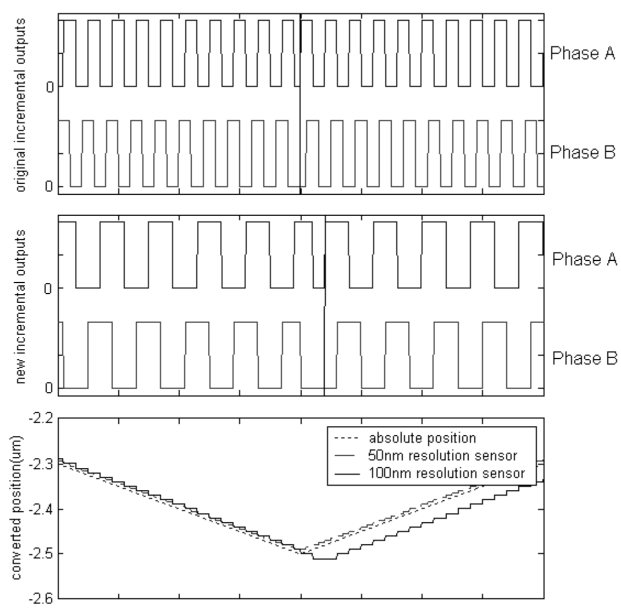

Fig.3 Simulation results of resolution step-up approach
First figure: original incremental outputs.
Second figure: incremental outputs from "Resolution increasing circuit".
Third figure: converted displacement from original encoder, "Resolution increasing circuit", and the actual position.

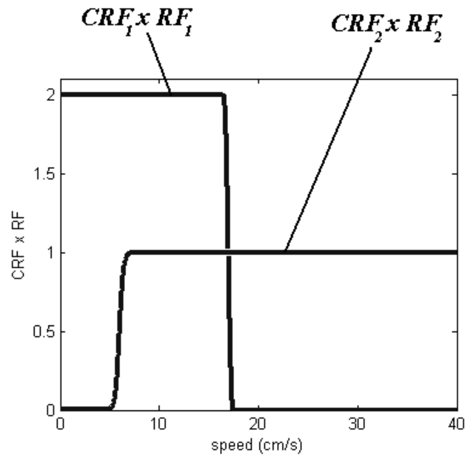

Fig.4 CRF×RF of 50nm sensor and new approach output

Another observation is related to the turning point. The converted displacement from higher resolution sensor suffered from time delay problem. This time delay is caused simplified logic decision in direction detection method. Turning point delay problem will be solved by "position fusion" and it will be discussed later.

The final important observation is related to velocity information. Estimated velocity from "resolution increasing circuit" should be accurate since the slope of displacement measured by 100nm is equal to slope of absolute position except the information nearly to the turning point.

IV. DATA FUSION FUNCTION

Limitation of measurable velocity of incremental encoder could be caused by clock's frequency of decoder in DSP. The relationship between clock's frequency and encoder velocity is shown below

$$\left(\frac{encoder\ \ velocity\ \ (m/s)}{resolution\ \ (\mu m)}\right)\times 4 = clock\ \ frequency\ \ (MHz) \qquad (1)$$

For general decoder integrated circuit, such as HCTL-2016, the maximum clock frequency is 14MHz. If the incremental encoder could provide resolution down to 50nm, maximum measurable velocity would be limited to 0.175m/s. When the measured object is driven beyond this critical speed, the measured position will become inaccurate.

This maximum speed of controlled object could be enhanced by using signals from "resolution step-up approach". Since the resolution is stepped-up, the maximum speed is doubled. In the other words, the response of controlled object could be faster.

Regarding to data fusion problem, the method used in [8] is studied and being adopted in this project. The fusion method is based on the equation as shown below:

$$Fused\ \ Data = \frac{CRF_1 \times RF_1 \times Data_1 + CRF_2 \times RF_2 \times Data_2}{CRF_1 \times RF_1 + CRF_2 \times RF_2} \qquad (2)$$

where *CRF* is confidence/reliability factor and *RF* is resolution factor. Data in (2) are calculated velocity information from original incremental encoder and resolution increasing circuit. Note that *CRF* is reflecting confidence of sensor in different situations and it could be obtained from datasheet or experimental verification. *RF* is a variable related to the resolution of sensor. Function of *RF* is reshaping the *CRF* so that the fused data could be more trustable in the sense of accuracy

In presenting approach, data come from same sensor and thus CRF are only related to the decoding method and velocity of moving object. Fig.4 shows the relationship between *CRF×RF* and velocity (*CRF×RF* is function of velocity). This could be obtained by other rough velocity sensor or sensorless method such as using back electro-motive force to estimate the rough velocity value of mover of servotube

Data fusion function is implemented by signal processing shown in Fig.5. Fused position and fused velocity are going to serve as feedback signals in control loop. For low velocity, outputs of lower resolution sensor have to be used to give precise measurement. When the speed of the object is high, higher resolution sensor should be chosen. Between the transition region, each sensor will be assigned a weighting factor and fusion process is based on the CRF and RF of the data. Demonstration of fusion process and results are shown in Fig.6. Note that Zone A and Zone B in second figure of Fig.6 could indicate the velocity region that using outputs of original encoder and "resolution increasing circuit" respectively.

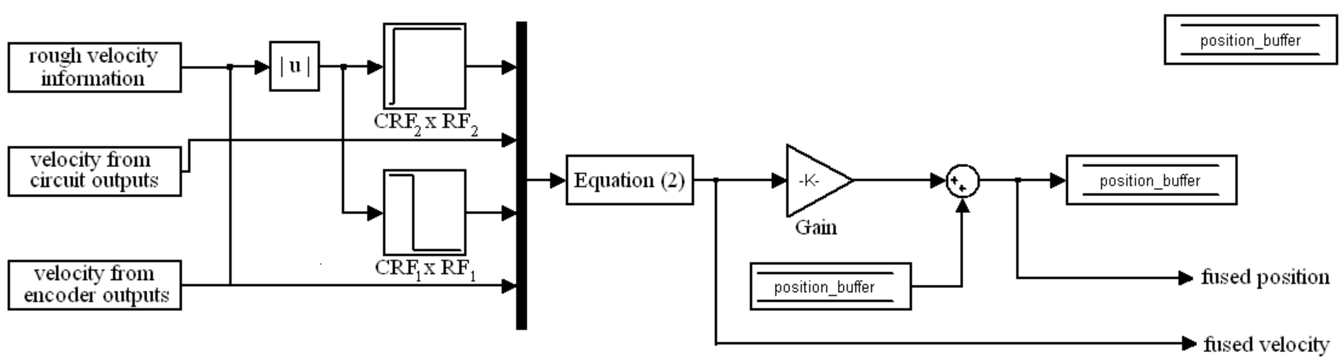

Fig.5 Data fusion function block diagram

V. CONTROLLER PARAMETER CALCULATION

Low resolution sensor could enhance the possibility of precision control. However, using precise sensor causes the problem of limitation speed due to processing speed of decoder. The controlled object speed could be improved by proposed fusion method and the idea is shown in Fig.7.

Controlled object is classified into different situations. For large error or high speed situation, controller should drive the object in maximum velocity towards the set-point value (achieved by high speed control algorithm). When the error is small and low velocity, the object will be driven in high precision manner (achieved by precision control algorithm). Commanded velocity sent to driver is combined from two algorithms' outputs so that the mover of the servotube could be forced towards required position quickly and precisely.

VI. EXPERIMENTAL SETUP AND RESULT

Experiment was conducted to verify the proposed strategy. The experimental setup is shown in Fig.8. This setup was based on the approach mention in Fig.1. The linear motor is servotube (Copley Control Crop., SM1104, SERVOTUBE MODULE) with 825mm travelling range. This motor was driven by the power amplifier produced by same company (Copley Control Crop., Accelnet Panel ADP-90-18-S, DIGITAL SERVO DRIVE for BRUSHLESS/BRUSH MOTORS). The servotube embedded an analog Hall Effect positioning sensor. This sensor provided position information for power amplifier and rough velocity estimation for this novel approach. Another positioning sensor (Renishaw, linear optical incremental encoder, resolution=50nm, RGH24H30D30A) was installed on the mover of servotube.

The outputs of incremental encoder were connected to the analog circuit which was responsible for resolution stepping-up. This circuit was composed of "Direction detection unit" and "Resolution step-up unit" and they were constructed by D-type flip-flops (SN74F74, Dual positive-edge-triggered D-Type flip-flop with clear and preset) and multiplexer (SN54HC153, dual 4-line to 1-line data selection/multiplexers) as shown in Fig.2. Outputs of this circuit were two square wave serving as new phase A and B of encoder (with 100nm resolution). Original encoder output and circuit output connected to the DSP (dSPACE board DS1104, connected to personal computer). DSP is responsible for several functions including velocity calculation, data fusion function, and control algorithm.

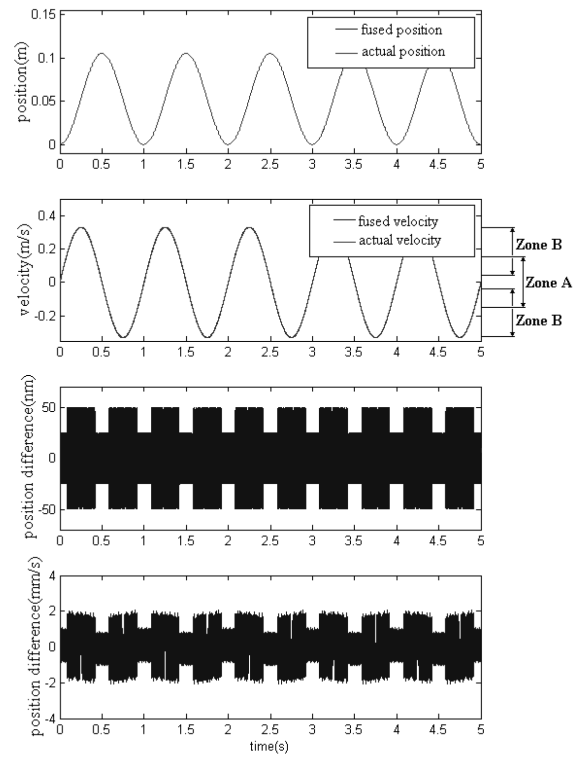

Fig.6 Data fusion function simulation

Note that the DSP and optical incremental encoder used could provide 0.36 m/s maximum measurable velocity since DSP incremental decoder clock frequency is about 29 MHz which is much higher than general decoder. Artificial position cutoff, however, was applied to position information from encoder when the speed was higher than 0.175mm/s. The aim of creating this cutoff was demonstrating the situation of using inexpensive decoder with clock frequency 14MHz, such as HCTL-2016. Note that the original position and velocity information from incremental encoder was kept and absolute position and velocity since it was the most reliable sensor in experimental setup

The experimental fusion results are shown in Fig.9 and the servotube controlled performance is shown in Fig.10.

VII. DISCUSSION

A. Data fusion function

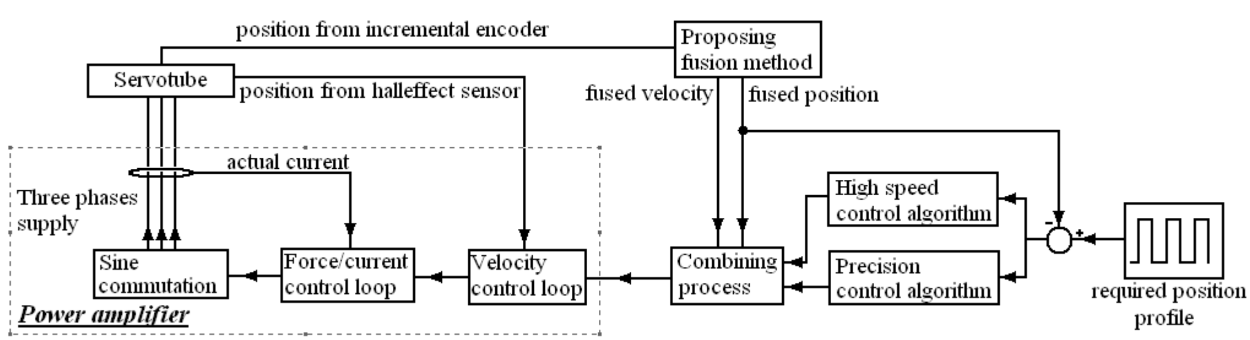

Fig.7 Control strategy for servotube

The data fusion of position and velocity results are shown in Fig.9. It is reminded that the CRF×RF is function of velocity. The second figure of Fig.9 contains three lines which are position information converted from incremental encoder's outputs, resolution increasing circuit output, and "data fusion function". The differences between all position information are very small. In order to compare the performance of encoder converted position and fused position, the difference between them is shown in fourth figure of Fig.9. Similarly, velocity information and its error are shown in third and fifth figure in of Fig.9.

Regarding to the position difference shown in Fig.9, there are several observation. Note that similar observations are appearing in velocity difference.

- Position difference is zero when speed is lower than 0.02 m/s because the fused position uses the information from encoder only.
- The position difference has a fundamental frequency variation which is equal to frequency driving frequency (1 Hz). This variation should be resulted from time delay of fusion process. Supposing that the fused position suffers from small time delay compared with original position form incremental encoder, the difference between them will be similar to $x(t)-x(t-\Delta t) = v\times\Delta t$, and it is proportional to velocity. Referring to the position difference curve, the shape is similar to velocity curve and this could prove the time delay assumption.
- If the fundamental frequency component of position difference could be removed, it could be noticed that the outline of the curve is similar to simulation result and its maximum deviation is equal to simulation result (100nm).

Overall, the fusion process could capture the actual position and velocity with high precision and improved velocity limitation.

B. *Speed improvement for precision control.*

To compare the performance of using original encoder's output and proposed data fusion method, the control loop shown in Fig.7 is constructed and the results are shown in Fig. 10. For case A, using fused position, the speed limitation was 175mm/s. For case B, using original encoder's output only, the maximum speed was 350mm/s. The control algorithms used in both cases are same expect the maximum travelling speed of servotube is different. Note that the last figure of Fig. 10 is the magnifying version second figure.

Referring to the rising time of both cases, step response of case A is shorter than case B and this is the advantage of using fused position information. In addition, if the settling times of both cases are compared, case A could reduce the position error quicker and its steady state error is smaller than case B. Therefore, the operating speed could be improved compared with the case B.

In this experiment, the maximum speed is limited in 350mm/s. In fact, this could be further improved by inserting

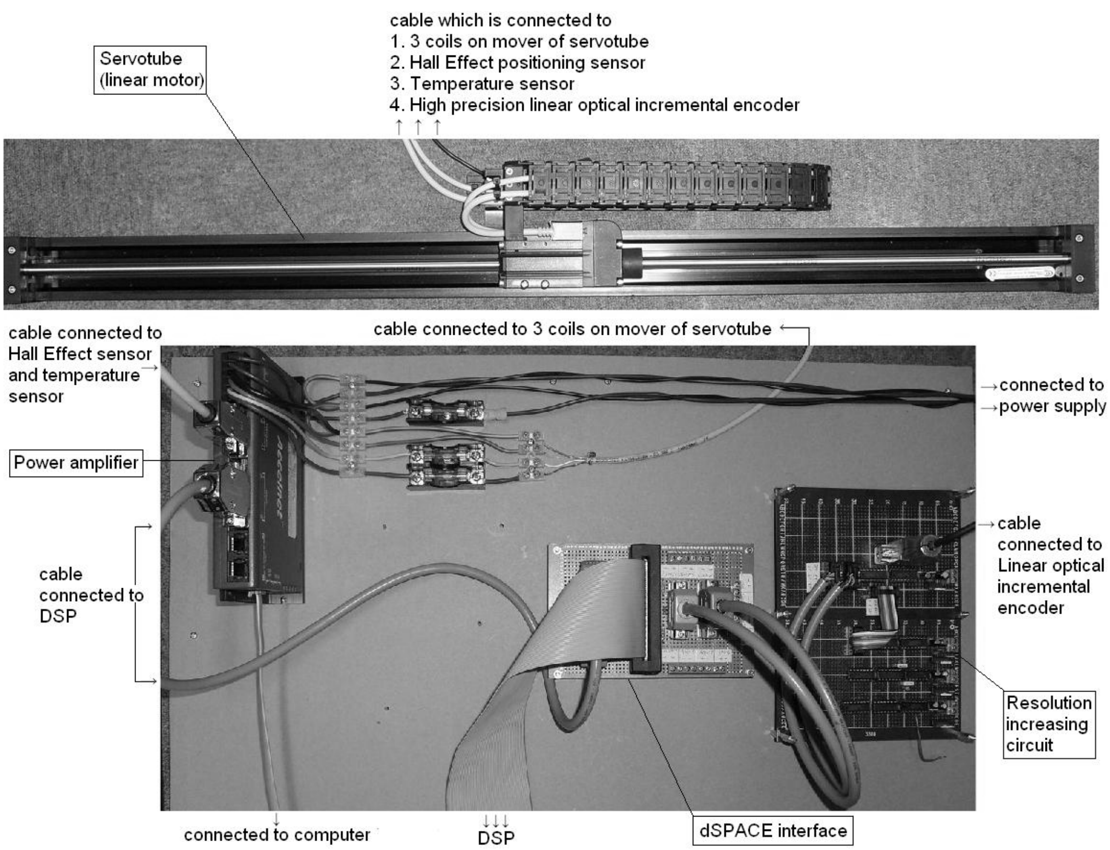

Fig.8 Snapshot of experimental setup

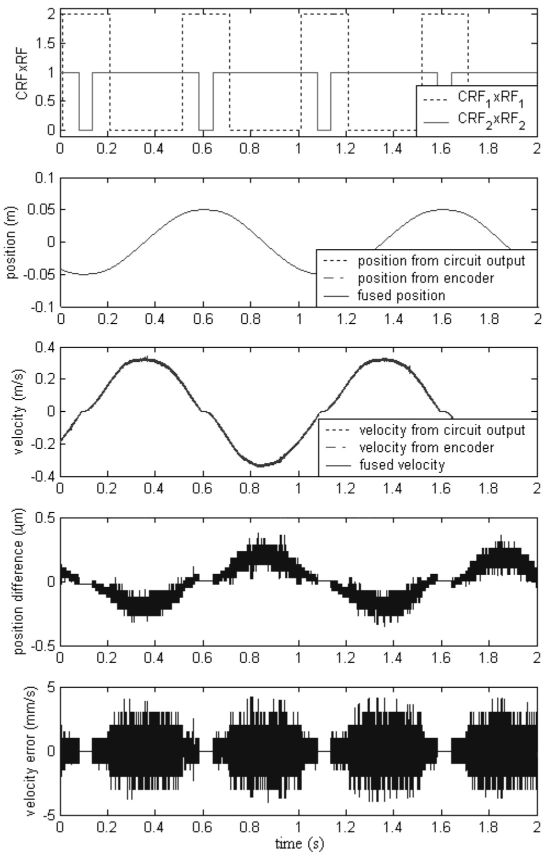

Fig.9 Data fusion function experimental result

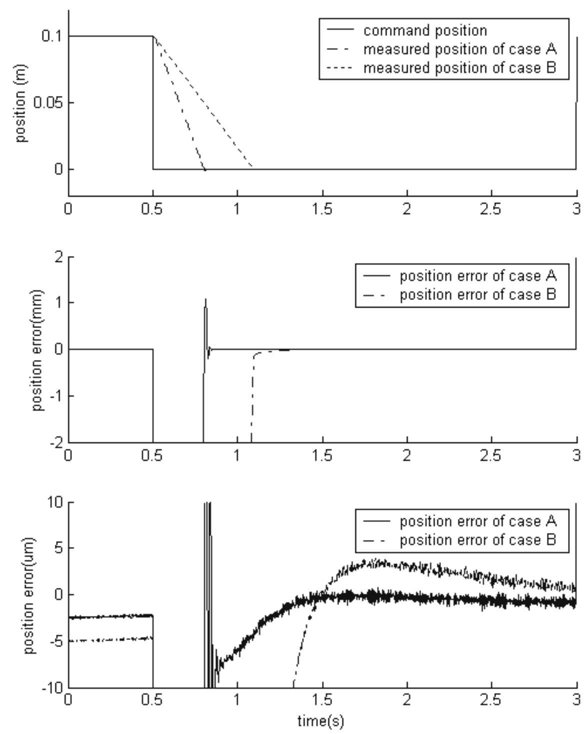

Fig.10 Experimental results of using A) fused position information, and B) output position of original encoder as feedback position.

one or two more resolution increasing circuits. Only one circuit is used because the aim of this project is demonstrating the possibility of speed improvement idea for precision control.

VIII. CONCLUSION

A novel measurable speed improvement for high precision sensor is proposed and demonstrated by using “resolution increasing circuit”. This improvement enhances the maximum speed of the system and, therefore, high speed and high precision linear motion control is becoming possible. In this manuscript, the control strategy for high speed and precision control and its performance are also demonstrated. The control speed could be double in real situation since the resolution of incremental encoder’s output is stepped-up.

In addition the maximum speed could be further improved to higher value if more resolution increasing circuit is used.

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Reference

[1] “Motion Control Application Stories-Versatile Form Factors to Meet Diverse Applications”, eAdvantech, www.csi.net.pl/download/MotionControlApplicationStory.pdf, extracted on 29 Sept 2009

[2] T.H. Lee, K.K. Tan, S.N. Huang, H.F. Dou, "Intelligent control of precision linear actuators", Engineering Applications of Artifcial Intelligence 13 (2000), pp.671-684, Elsevier Science Ltd

[3] J.F.Wang, W.S.Yin, Y.Zhu, G.H. Duan,"Identification & Super-Precision Control of a Linear Stage driven by a Voice Coil motor", Conference on Robotics, Automation and Mechatronics 2004, pp.192-196, 1-3 Dec 2004

[4] Y.Park, H.Kim,"Precision Motion Control of a Three Degrees of Freedom Hybrid Stage With Dual Actuators",Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation, pp.1458-1465 August5-8, 2007, Harbin, China

[5] H.Numasato, M.Tomizuka, "Settling Control and Performance of a Dual-Actuator System for Hard Disk Drives", IEEE/ASME TRANSACTIONS ON MECHATRONICS, pp.431-438 , VOL. 8, NO. 4, DEC 2003

[6] "Electronics Tutorial about Frequency Dividers", http://www.electronics-tutorials.ws/counter/count_1.htm, Electronics-Tutorial.ws, extracted on 29 Sept 2009

[7] A.Moore, "Understanding Quadrature Encoding-Dealing with Ambiguity", http://prototalk.net/forums/showthread.php?t=78, proto-talk.net Article, extracted on 29 Sept 2009

[8] A.Mahajan, K.H.Wang, P.K.Ray, "Multisensor Integration and Fusion Model that Uses a Fuzzy Inference System",IEEE/ASME TRANS on mechatronics, pp.188-196, Vol. 6, No. 2, June 2001