

Motion Control IC for X-Y Table based on SoPC Technology

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Summary

The new generation of Field Programmable Gate Arrays (FPGAs) technology enables to be embedded a processor to construct an SoPC (System-on-a-Programmable-Chip) developing environment. Therefore, this study presents a servo control IC for X-Y table using this SoPC technology. In this proposed servo control IC, there are two modules. One module performs the functions of the motion trajectory and two-axis position controller. The other module performs the functions of current vector control of motor drives for two PMSMs (Permanent Magnet Synchronous Motors). The former is implemented by software using Nios II embedded processor due to the need of the complicated control algorithm and low sampling frequency control (motion trajectory & position control: less than 1kHz). The latter is implemented by hardware using PLD (programmable logic device) in FPGA due to the need of high sampling frequency control (current loop: 16kHz, PWM circuit: 4~8MHz) but simple computation. Furthermore, to improve the control accuracy of the table positioning, a full closed-loop control, which the signal of linear encoder is feed-backed for position control, is considered. As this result, the use of SoPC technology can make the servo controller of X-Y table more compact, high performance and cost down.

Key words:

SoPC, FPGA, X-Y Table, NiosII, Motion Control IC.

1. Introduction

Development of a compact and high performance servo controller system for precision X-Y table, CNC machine etc. is a popular research work in literature [1-2]. In position control of X-Y table, there are two methods to be considered, that one is semi closed-loop control and the other is full closed-loop control. The full closed-loop control with feed-backed by a linear encoder as the table position signal had been proven a better position control method than the semi closed-loop control, that a rotary encoder attached to ac motor is feed-backed as the position signal.

For the progress of VLSI technology, the FPGA have been widely investigated due to their programmable hard-wired feature, fast time-to-market, shorter design cycle, embedding processor, low power consumption and higher density for implementing digital system [3-4]. FPGA provides a compromise between the special-purpose ASIC (application specified integrated circuit) hardware and general-purpose processors [5]. Therefore, using an FPGA

to develop a compact, low-cost and high performance servo system for precision machine become an important issue. But in many researches, the FPGA is only used to realize the hardware part of the overall servo control system [6].

Nowadays, SoPC and IP (Intellectual Property) designs can be developed and downloaded into FPGA with an embedded processor to construct an SoPC environment [7-9]. Using SoPC technology, the software and hardware co-design are reprogrammable and can be parallel processing in FPGA to increase the system performance and flexibility. Due to the advantage, a full close-loop control IC for X-Y table based on the SoPC technology is developed and shown in Fig.1. In Fig.1, the scheme of current vector control of two PMSMs can be realized by hardware in programmable logic devices (PLD), and the motion trajectory and position control algorithm for X-Y table can be realized by software using Nios II processor. Therefore, all of the function needed to construct a full closed-loop control for X-Y table can be integrated and realized in an FPGA chip. In this paper, FPGA chip adopts Altera Stratix II EP2S60 [10-11], which has 24,176 ALMs (equivalent 60,440LEs), maximum 718 user I/O pins, 36 DSP blocks, total 2,544,192 RAM bits, and a Nios II embedded processor which has a 32-bit configurable CPU core, 16 M byte Flash memory, 1 M byte SRAM and 16 M byte SDRAM, is used. Therefore, this FPGA chip is very suitable to develop a servo controller system for X-Y table.

2. System Description and Design

The architecture of the proposed SoPC-based motion control IC for X-Y table is shown in Fig. 1, in which the motion trajectory, the position and speed control are implemented by software using Nios II embedded processor and the current vector of motor drives for two PMSMs are implemented by hardware in FPGA chip. The modeling of PMSM, fuzzy control algorithm and design of proposed servo control IC are introduced as follows:

2.1 Mathematical modeling of PMSM

The typical mathematical model of a PMSM is described, in two-axis d-q synchronous rotating reference frame, as follows:

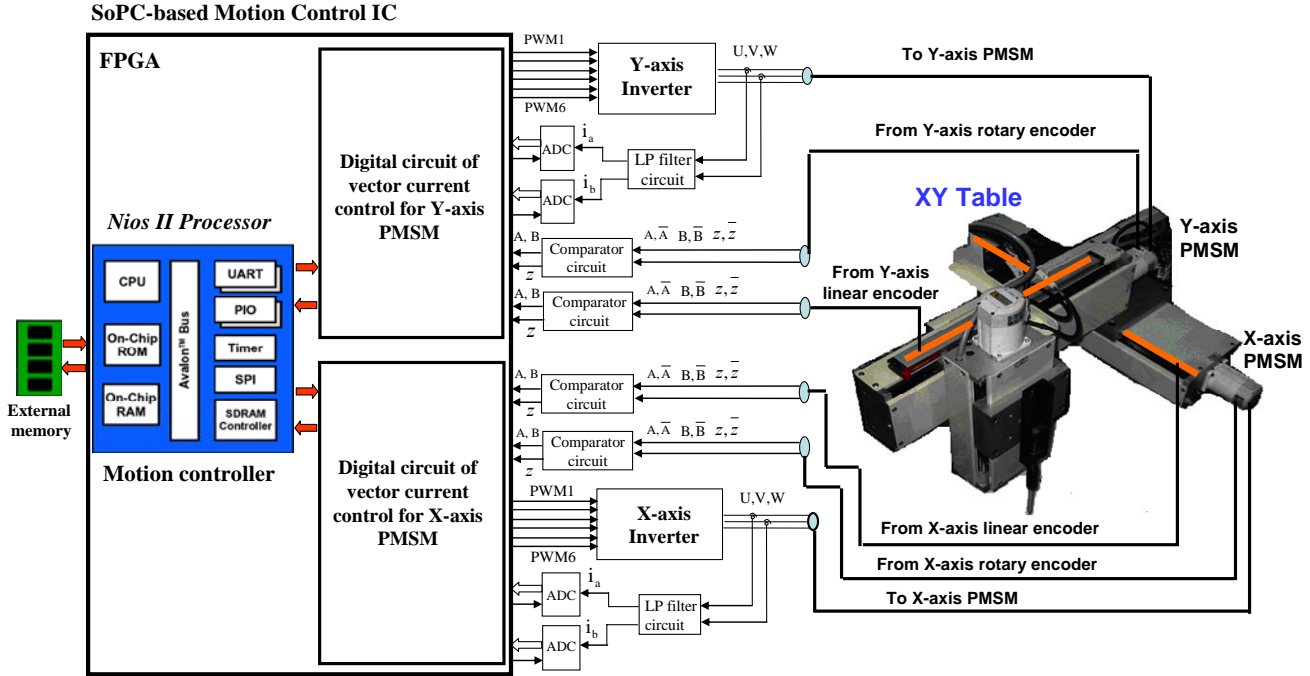


Fig. 1 The architecture of the proposed SoPC-based motion control system for a X-Y table

$$\frac{di_d}{dt} = -\frac{R_s}{L_d}i_d + \omega_e \frac{L_q}{L_d}i_q + \frac{1}{L_d}v_d \quad (1)$$

$$\frac{di_q}{dt} = -\omega_e \frac{L_d}{L_q}i_d - \frac{R_s}{L_q}i_q - \omega_e \frac{\lambda_f}{L_q} + \frac{1}{L_q}v_q \quad (2)$$

where v_d, v_q are the d and q axis voltages; i_d, i_q are the d and q axis currents, R_s is the phase winding resistance; L_d, L_q are the d and q axis inductance; ω_e is the rotating speed of magnet flux; λ_f is the permanent magnet flux linkage.

The current loop control of each PMSM drive in Fig.1 is based on a vector control approach and its detailed description is shown in Fig.2. If the i_d is controlled to 0 in Fig.2, the PMSM will be decoupled, and control a PMSM like a DC motor. After simplification, the modeling of a PMSM can be written as the following equation,

$$T_e = \frac{3P}{4} \lambda_f i_q \triangleq K_t i_q \quad (3)$$

with

$$K_t = \frac{3P}{4} \lambda_f \quad (4)$$

Considering the mechanical load with linear table, the overall dynamic equation of linear table system is obtained by

$$T_e - T_L = J_m \frac{2\pi}{r} \frac{d^2 s_p}{dt^2} + B_m \frac{2\pi}{r} \frac{ds_p}{dt} \quad (5)$$

where T_e is the motor torque, K_t is force constant, J_m is the inertial value, B_m is damping ratio, T_L is the external torque, s_p represents the displacement of x-axis or y-axis table and r is the lead of the screw.

2.2 Coordinate transformation

The coordination transformation of the PMSM in Fig. 2 can be described in synchronous rotating reference frame. The coordination system used in rotating motor includes stationary a-b-c frame, stationary α - β frame and synchronously rotating d-q frame. These transform equations are described as follows, and the \bar{f}_s represents a space vector refer to current, voltage or flux.

□ *Clarke*: stationary a-b-c frame to stationary α - β frame.

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (6)$$

□ *Modified Clarke*⁻¹: stationary α - β frame to stationary a-b-c frame.

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_\beta \\ f_\alpha \end{bmatrix} \quad (7)$$

□ *Park*: stationary α - β frame to rotating d-q frame.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos \theta_e & \sin \theta_e \\ -\sin \theta_e & \cos \theta_e \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \quad (8)$$

□ $Park^{-1}$: rotating d-q frame to stationary α - β frame.

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta_e & -\sin \theta_e \\ \sin \theta_e & \cos \theta_e \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \quad (9)$$

Current vector control for each axis of X-Y table Which is Implemented by hardware (PLD) in FPGA

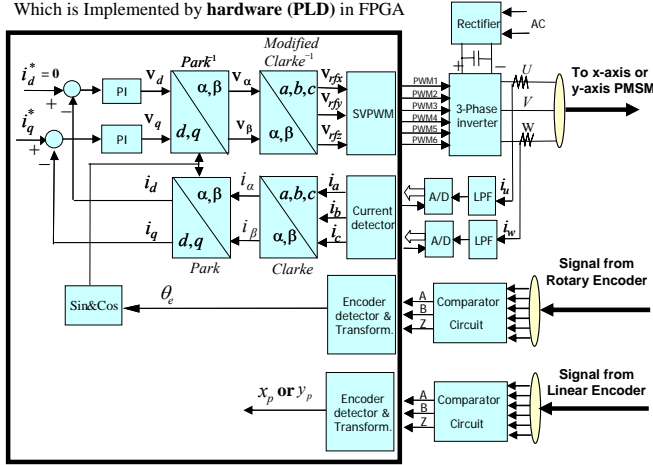


Fig.2 Block diagram of current vector control at each axis of X-Y table

2.3 Fuzzy controller for position control loop

The internal block diagram of motion controller for X-Y table in Fig.1 is shown in Fig.3. The motion controller, which is implemented by software in Nios II embedded processor, performs the function of the motion trajectory, two-axis' position and speed controller, etc.

FPGA-based servo control IC for X-Y Table

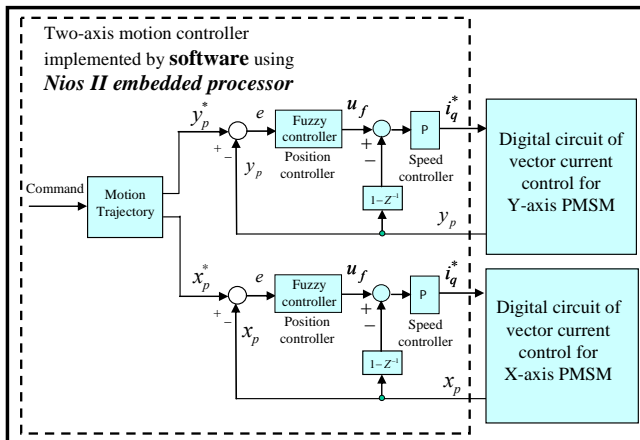


Fig.3 Block diagram of position control and trajectory computation in Nios II Processor

Each position controllers in Fig. 3 adopts fuzzy controller, which includes fuzzification, fuzzy rules, inference mechanism and defuzzification. At first, the position error and its error change, e , Δe are defined by

$$e(n) = x_p^*(n) - x_p(n) \quad (10)$$

$$\Delta e(n) = e(n) - e(n-1) \quad (11)$$

and $K_e * e$, $K_{de} * \Delta e$ and u_f are the input and output variable of fuzzy controller, respectively. Then, the design procedure of the fuzzy controller is as follows:

□ Define the linguistic value as $\{A_1, A_2, E\}$, they are symmetrical triangular membership function:

$$\xi_m(x_i, \bar{x}_i^m, w_i^m) = \begin{cases} 0 & x_i \leq \bar{x}_i^m - w_i^m / 2 \\ \frac{x_i - \bar{x}_i^m + w_i^m / 2}{w_i^m / 2} & \bar{x}_i^m - w_i^m / 2 < x_i < \bar{x}_i^m \\ w_i^m / 2 & \bar{x}_i^m < x_i < \bar{x}_i^m + w_i^m / 2 \\ \frac{\bar{x}_i^m + w_i^m / 2 - x_i}{w_i^m / 2} & \\ 0 & x_i \geq \bar{x}_i^m + w_i^m / 2 \end{cases} \quad (12)$$

where x_i is input value, $\xi_m(\bullet)$ is output value, \bar{x}_i^m and w_i^m are mean value and width of the triangular function, respectively.

□ Derive M fuzzy control rules from the dynamic response characteristics [12], as follows

IF e is A_1^m and Δe is A_2^m THEN u_f is E^m , $m=1, \dots, M$ (13)

□ Construct the fuzzy system with $u_f(x|\theta)$ from those M rules using the singleton fuzzifier, product-inference rule, and central average defuzzifier method. Therefore, the fuzzy control rule in (13) can be replaced by the following expression:

$$u_f(x|\theta) = \frac{\sum_{m=1}^M c_m [\prod_{i=1}^2 \xi_m(x_i, \bar{x}_i^m, w_i^m)]}{\sum_{m=1}^M [\prod_{i=1}^2 \xi_m(x_i, \bar{x}_i^m, w_i^m)]} \Delta = \frac{\sum_{m=1}^M c_m \mu_m}{\sum_{m=1}^M \mu_m} \quad (14)$$

where c_1, c_2, \dots, c_m denote the center of the output membership function.

2.4 Point-to-point motion control

In Fig.3, the point-to-point motion control algorithm is used as the motion trajectory control for X-Y table. In this scheme, a trapezoidal velocity profile by constant acceleration and deceleration is considered, and the overall displacement $\Delta s = [\Delta x_p, \Delta y_p]$ (mm), the maximum velocity $[W_1, W_2]$ (mm/s), the acceleration and deceleration period T_{acc} , and the sampling interval t_d are the input parameters of the scheme. Therefore, based on the velocity profile, the command of instantaneous position, $s^* = [x_p^*, y_p^*]$ at each sampling interval in Fig.3 can be determined by the following procedure.

Step 1: Computation of the overall running time. First, compute the running time without considering acceleration/deceleration:

$$T_1 = \max(\Delta x_p / w_1, \Delta y_p / w_2) \quad (15)$$

This T_1 must exceed acceleration time T_{acc} . Next, the acceleration/deceleration design is considered, and the overall running time is

$$T_o = \max(T_1, T_{acc}) + T_{acc} \quad (16)$$

Step 2: Adjustment of the overall running time to meet the condition of multiple of the sampling interval.

$$N' = \lceil T_{acc} / t_d \rceil \text{ and } N = \lceil T_o / t_d \rceil \quad (17)$$

where N is the interpolation number and $\lceil \cdot \rceil$ represents the Gauss function. Therefore,

$$T'_{acc} = N' * t_d \text{ and } T'_o = N * t_d \quad (18)$$

Step 3: Modification of the maximum velocity

$$W' = [W'_1, W'_2] = [\Delta x_p, \Delta y_p] / (T'_o - T'_{acc}) \quad (19)$$

Step 4: Calculation of the acceleration/deceleration

$$A = W' / T'_{acc} \quad (20)$$

Step 5: Calculation of the position command, namely $s_p^* = [x_p^*, y_p^*]$, at the mid-position

(a) Acceleration region:

$$s_p^* = s_{r0} + \frac{1}{2} * A * t^2 \quad (21)$$

where $t = n * t_d$, $0 < n \leq N'$, and s_{r0} is the initial position.

(b) Constant speed region:

$$s_p^* = s_{r1} + W' * t \quad (22)$$

where $t = n * t_d$, $0 < n \leq NI$ and s_{r1} is the final position in the acceleration region and $NI = N - 2 * N'$.

(c) Deceleration region:

$$s_p^* = s_{r2} + (W' * t - \frac{1}{2} * A * t^2) \quad (23)$$

where $t = n * t_d$, $0 < n \leq N'$ and s_{r2} is the final position in the constant speed region.

2.5 Design of SoPC-based motion control IC for X-Y table

The internal architecture of the proposed SoPC-based motion control IC for X-Y table is shown in Fig. 4. The FPGA uses Stratix II EP2S60, which has 24,176 ALMs (equivalent 60,440LEs), maximum 718 user I/O pins, 36 DSP blocks, total 2,544,192 RAM bits, and a Nios II embedded processor which has a 32-bit configurable CPU core, 16 M byte Flash memory, 1 M byte SRAM and 16 M byte SDRAM. A custom software development kit (SDK) consists of a compiled library of software routines for the SoPC design, a Make-file for rebuilding the library, and C header files containing structures for each peripheral. In

this control IC, it has two modules. One module performs the functions of the motion trajectory and two-axis position servo control. The other module performs the functions of vector control of two PMSMs. Module 1 in Fig.4 is Nios II embedded processor used to implement the complicated control algorithm by software. The flow charts of interrupt service routine (ISR) for motion control are plotted and shown in Fig.5. The module 2 in Fig.4 includes two set of circuits of current vector control which is implemented by hardware in FPGA due to the need of high-speed processing but simple computation. Each circuits of vector control includes two PI controllers, coordinate transformation of Clarke, Park, inverse Park, modified inverse Clarke and circuits of SVPWM, QEP and ADC conversion control. Figure 6 shows the digital circuit of PI controller which includes 3 adders, 2 multipliers, 2 D-type flip-flops and 3 max value limiters. Figures 7 to 8 are the circuits of modified $Clark^{-1}$ and $Park^{-1}$ transformation, respectively. The block diagram of SVPWM circuit is shown in Fig. 9. SVPWM circuit is designed with 12 kHz frequency and 1μs dead-band. The overall circuits included a Nios II embedded processor IP (10%) and two current vector control circuits (15%) in Fig. 4, use 25% utility of Stratix II EP2S60.

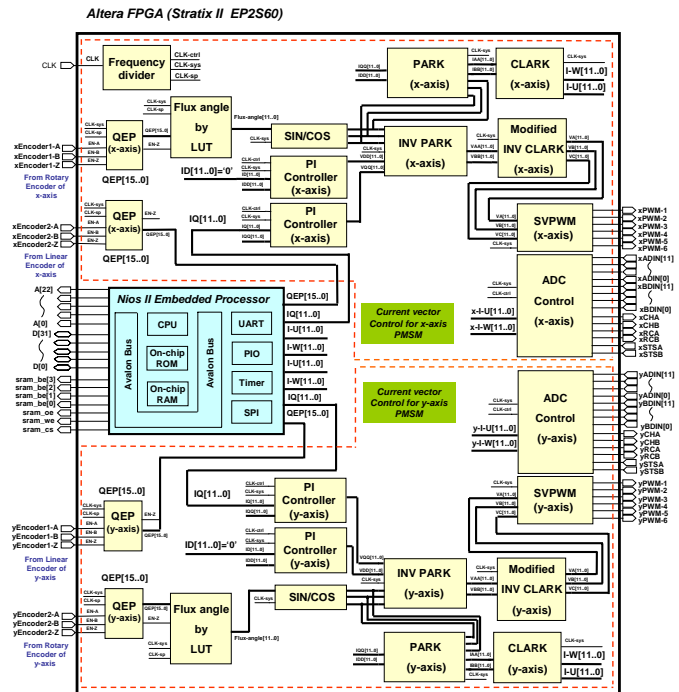


Fig. 4 The block diagram of internal circuit of SoPC-based motion control IC

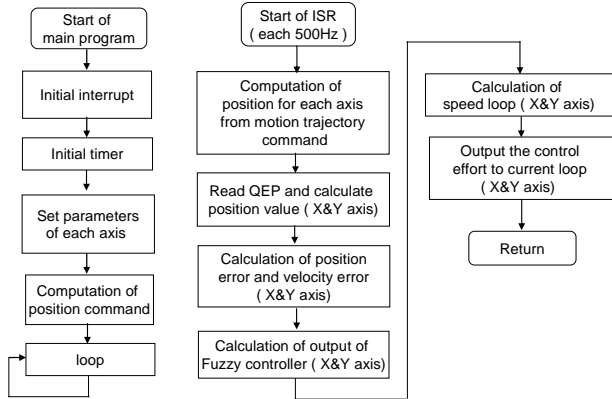


Fig. 5 Flow chart of main and ISR program in Nios II processor

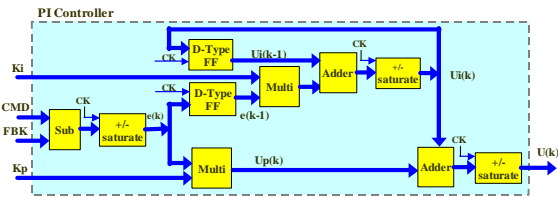


Fig. 6 Digital circuit of the PI controller

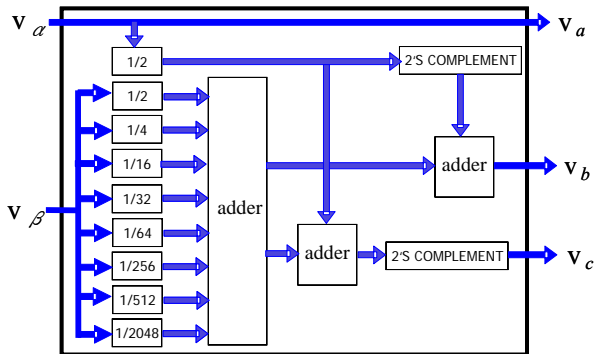


Fig. 7 The designed circuit of the modified $Clarke^{-1}$ formulation

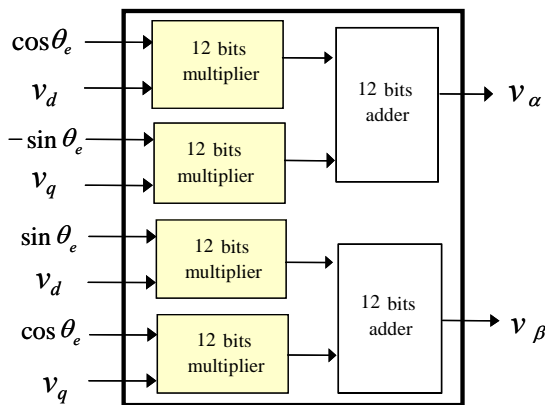


Fig. 8 The designed circuit of the $Park^{-1}$ formulation

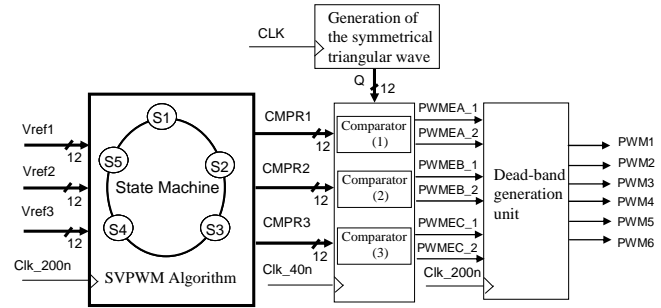


Fig. 9 Block diagram of the SVPWM circuit

3. Experiments and results

The overall proposed experimental system is depicted in Fig. 1. This system include an FPGA experimental board, two sets of voltage source IGBT inverter and an X-Y table which is driven by two PMSMs and two ball-screws. The power, rating, voltage, current and rating speed of each PMSM are 200W, 92V, 1.6A and 3000rpm, respectively. A 2500 ppr rotary encoder attached to PMSM is used to the sensor of motor's electrical angle. Two linear encoders with 5µm resolution are mounted on the x- and y-table as position sensor, respectively. Each ball-screw has 5mm lead. The inverter has 6 sets of IGBT type power transistors. The collector-emitter voltage of the IGBT is rating 600V, the gate-emitter voltage is rating ±12V, and the collector current in DC is rating 25A and in short time (1ms) is 50A. The photo-IC, Toshiba TLP250, is used for gate driving circuit of IGBT. Input signals of the inverter are PWM signals from FPGA chip. The FPGA-Altera Stratix II EP2S60 in Fig.1 is used to develop a full digital motion controller for X-Y table, which the motion trajectory and two-axis position servo control are implemented by software using Nios II processor, and the two axis current vector controller are implemental by hardware using programmable logic devices in FPGA. In our proposal system, the PWM switching frequency of inverter is designed with 12k Hz, dead-band is 1µs, and the control sampling frequency is 500Hz. The motion control algorithms are coded by C language. The computation time of Nios II processor for executing two-axis position/speed control loop and a motion trajectory algorithm is about 1.5ms.

In experiment, the position step response and the motion trajectory control are used to evaluate the dynamic performance of the proposed system. In the experiment of the step response, the results of X-axis and Y-axis table under 5 mm amplitude square wave command are shown in Fig.10 and Fig.11, respectively. The rising time and steady-state value in Fig.10 are 150ms and 0mm, and in Fig.11 are 120ms and 0mm. It reveals that the mass carried in X-axis

table is heavier than those in Y-axis table. To test the tracking performance of a point-to-point motion control for X-axis and Y-axis, the total displacement command is designed with moving from 0 mm to 50 mm position. In addition, the acceleration and deceleration velocity profile is considered. The trajectory tracking results in every axis corresponding with the aforementioned input commands are shown in Fig.12 and Fig.13. It can be seen that no matter what in position or the velocity trajectory, the motion of X-Y table can give a perfect tracking with target in X axis and Y axis. In the experiment of the two-axis (X and Y axis) simultaneous motion control, the tracking performances about circular trajectory are evaluated and those results are shown in Fig.14. In Fig.14, the motion trajectory of X-Y table is circle with center (5, 5) cm, radius 5cm and its tracking errors are between 0.5 ~0.6 mm. Fig. 14 show good tracking responses in motion control of the X-Y table. Therefore, from the experimental results of Figs.10~14 demonstrate that the proposed motion control IC for X-Y table based on SoPC technology is effectiveness and correctness.

4. Conclusion

This study presents a motion control IC for X-Y table based on novel SoPC technology. A Nios II embedded processor is integrated into an FPGA chip. In the proposed motion control IC, the Nios II embedded processor is adopted to develop the function of the motion trajectory and fuzzy controller by software. Other functions, such as the two-axis current vector control, are designed by hardware in FPGA. Therefore, the motion control IC can integrate and realize a fully digital motion controller of X-Y table in an FPGA chip. Experimental results successfully validated the step response, point-to-point path tracking and circular trajectory tracking, revealing that the proposed software/hardware co-design method with parallel processing performance well in the servo system of X-Y table.

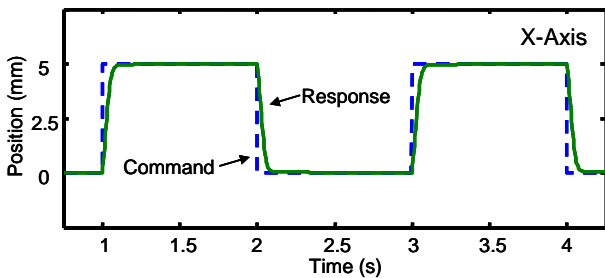


Fig. 10 Step response for X-axis table

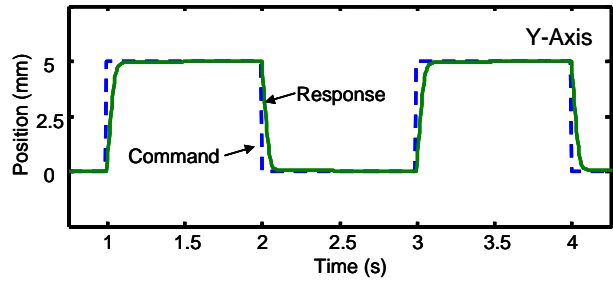


Fig. 11. Step response for Y-axis table

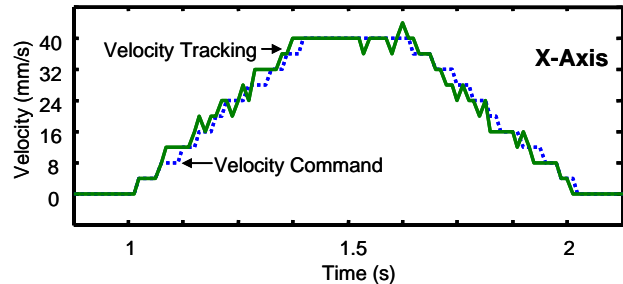
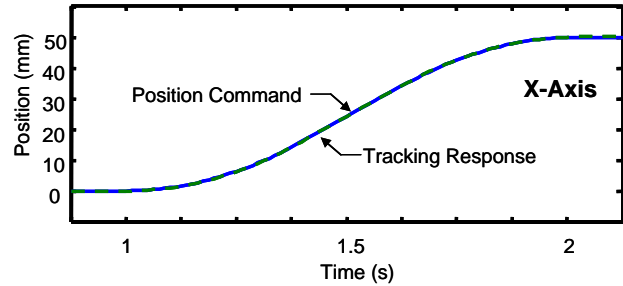


Fig. 12 Position and its velocity profile tracking response of X-axis table

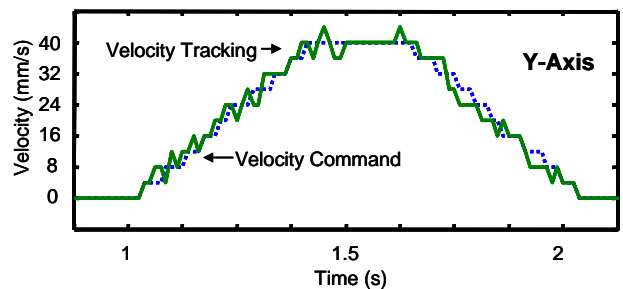
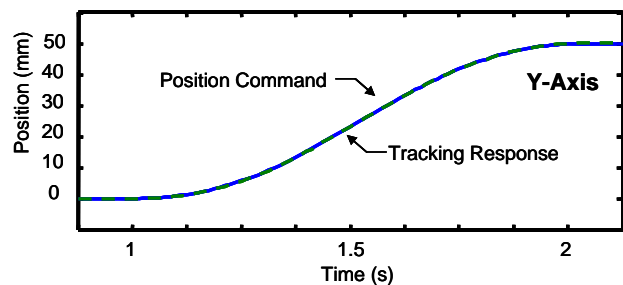


Fig. 13 Position and its velocity profile tracking response of Y-axis table

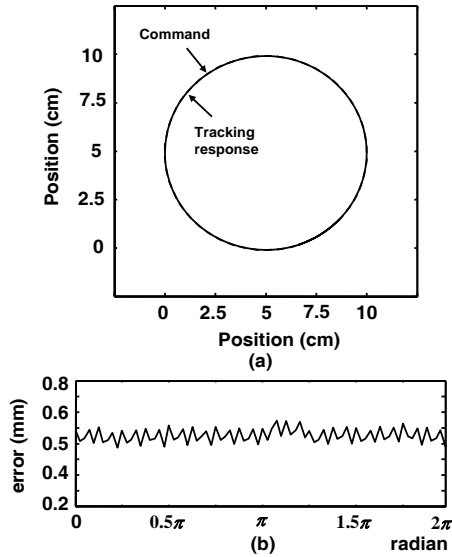


Fig. 14 Circular motion tracking of X-Y table

Acknowledgments

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References

- [1] E. C. Park, H. Lim, and C. H. Choi, "Position control of X-Y table at velocity reversal using presliding friction characteristics," *IEEE Trans. Control Systems Technology*, vol. 11, no. 1, pp. 24-31, 2003.
- [2] D. Hanafi, M. Tordon, and J. Katupitiya, "An active axis control system for a conventional CNC machine," in *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 1188-1193, 2003.
- [3] C. G. Julio, L. H. Hoang, "A VHDL-based Methodology to Develop High Performance Servo Drivers," in *Proceedings of IEEE Industry Application Conference*, pp. 1505-1512, 2000.
- [4] X. Shao and D. Sun, "A FPGA-based Motion Control IC Design," in *Proceedings of the IEEE International Conference on Industrial Technology*, 2005, pp.131-136.
- [5] R. Wei, X.H. Gao, M.H. Jin, Y.W. Liu, H.Liu, N. Seitz, R. Gruber and G. Hirzinger, "FPGA based Hardware Architecture for HIT/DLR Hand," in *Proceeding of the IEEE/RSJ International Conference on intelligent Robots and System*, 2005, pp. 523~528.
- [6] Y.Y. Tzou and T.S. Kuo, "Design and Implementation of an FPGA-based motor control IC for permanent magnet AC motors," in *Proceedings of the International Conference on Industrial Electronics, Control and Instrumentation*, 1997, pp. 943~947.
- [7] Y.S. Kung, P.G. Huang and C.W. Chen, "Development of a SOPC for PMSM Drives," MWSCAS 2004, the 47th IEEE International Midwest Symposium on Circuits and Systems, vol. II, pp. II-329~II-332, 2004.
- [8] Y.S. Kung, M.H. Tsai and C.S. Chen, "FPGA-based Servo Control IC for PMLSM Drives with Adaptive Fuzzy Control," *IEEE ICIEA'06*, in *Proceedings of the IEEE*

International Conference on Industrial Electronics and Applications, pp. 731~736, 2006.

- [9] Y.S. Kung and G.S. Shu, "Design and Implementation of a Control IC for Vertical Articulated Robot Arm using SOPC Technology," in *Proceedings of IEEE International Conference on Mechatronics*, pp. 532~536, 2005.
- [10] www.altera.com.
- [11] Altera, Nios II Development Kit, Stratix Edition – Getting Started user Guide, 2005.
- [12] C.M. Liaw and Y.S. Kung, "Fuzzy Control with Reference Model-Following Response," *Fuzzy Theory Systems: Techniques and Applications*, vol.1, pp. 129-158, 1999.1



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servo control system developing with DSP chip with the industrial company.

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Ting-Yu Tai was born in Tainan, Taiwan, R.O.C., in 1980. He received the B.S. degree from Southern Taiwan University of Technology, Tainan, Taiwan, in 2004, and the M.S. degree from Southern Taiwan University, Tainan, Taiwan, in 2007, both in electrical engineering. His research interests are permanent magnet synchronous motor servo control system, intelligent control, FPGA-based control system,