A method for designing the brushless direct current system using FPGA based on fuzzy set similarity algorithm

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Abstract
In this paper, we prompt a new method for designing the brushless direct current system using FPGA based on the fuzzy set similarity to ideal solution. The most demanding design constrain is size. It is important for the robot hand to improve its dexterity and structure compactness by reducing occupying space of its driving system. At the first time, it utilizes particle swarm optimization method in the field of the colony intelligence into the optimization of the FPGA based system, so as to recommend a full set of methods to optimize the FPGA based system based on the fuzzy set similarity to ideal solution. The experiment shows that the new brushless direct current system using FPGA based on fuzzy set Similarity algorithm can achieve better performance and meet the requirements of engineering.
Key words: BRUSHLESS DIRECT CURRENT SYSTEM, FUZZY SET, SIMILARITY ALGORITHM.

Introduction

With the increasing capacity and power processing of FPGA, logic resources in a single FPGA chip have exceeded 4 million gates. Because of the rapid development and parallel computing features of FPGA, it is used more and more in many solutions, especially in high-definition image processing and highly parallel big data computing. Traditionally, FPGA is design to be a coprocessor with fixed feature .There is not fully utilize the max advantages of FPGA-Field Programmable.

With the continuous progress of the field programmable gate array (FPGA) technology, AC servo drive technology based on FPGA gets more and more attention gradually by high running speed, flexible interface, good portability, et al. Based on analysis of the research literature, the thesis focuses on the hardware design method of the current loop control of ac servo system based on FPGA, aiming to improve the current loop control performance of the servo system which restricts the response of the servo system seriously. Brushless DC motor (BLDCM), in which electrical commentator is used instead of mechanical, has not only the same governing performance as traditional DC motor, but also the good characteristics of AC Motor. Besides, the machines have high power density and small volume. Brushless DC motors have been widely used in many areas, especially in high performance servo and drive areas, such as the spacecraft pose control and robot. In these scenarios, not only a small volume but also the parallel controls of multiple motors are required. The motor controllers based on the digital processor like MCU or DSP are usually implemented in software. As a result, the problems of slow response speed and low reliability are existed, and the controller performances are difficult to meet demands. The FPGA (Field Programmable Gate Array) may realize the complex control function on a piece of system chip. The volume of control system has been cut down greatly. This kind of control system presents a good application prospect in the industrial and civil territory even in the servo domain.

Because of the development of microprocessor technology, power electronics, motor manufacturing technology and modern control theory, the application of AC servo system has replaced DC servo system, used more and more widely. BLDC are increasingly being used in AC servo system because of its superior performance. At the same time as the development of semiconductor technology, the production process of FPGA promotion rapidly, density and performance are improved too. On this basis, this article give up the traditional DSP program, use FPGA as the vector control platform of BLDC, design the vector control system based FPGA.

The background and structure of the driving system

It is important for the robot hand to improve its dexterity and structure compactness by reducing occupying space of its driving system. The traditional drive electronics for 3-phase BLDC motor often occupy a surprising amount of space, and complex circuitry is needed to drive the power MOSFETs. The Si9979 is a monolithic BLDC motor controller which is housed in a 7-mm SQFP package. It allows of easy implementation of an all-n-channel three-phase bridge and simplifies both motor and electronics package. The Si9979 provides several useful functions for motor control such as control inputs, commutation logic, gate drive outputs, and protection circuitry. All of the control input signals, such as PWM, direction and braking, are TTL compatible with internal pull-up. The basic commutation signals are generated from the code provided by the commutation sensors connected to BLDC motor [1].

The 6 low and high-side gate outputs which are synthesized in Si9979 can drive 6 MOSFETs, the low-side gate output can drive the low-side MOSFET directly and the high-side gate outputs drive the high-side MOSFET through a floating circuit. The protection circuitry provides current limit, cross-conduction protection, under voltage lockout and FAULT output that can indicate when under-voltage, over-current, disable, or invalid sensor shutdown has occurred.

The whole driving system consists of three parts, Si9979 circuitry, FPGA data acquiring and communication circuitry, DSP data processing and control circuitry. During the design of robot hand the analog signals derived from BLDC motors and other devices are required to be converted to serial data near signal sources, so analog/digital inverters, 16-bit AD7888 with 8 channels, are employed. In such a way, we can achieve digital control that can make motor easy and improve the stability of BLDC motor's driving system. In this paper, we'll mainly introduce the Si9979 driving circuitry and its peripheral circuitry. The whole structure of the driving system of BLDC motor is shown in Figure 1.

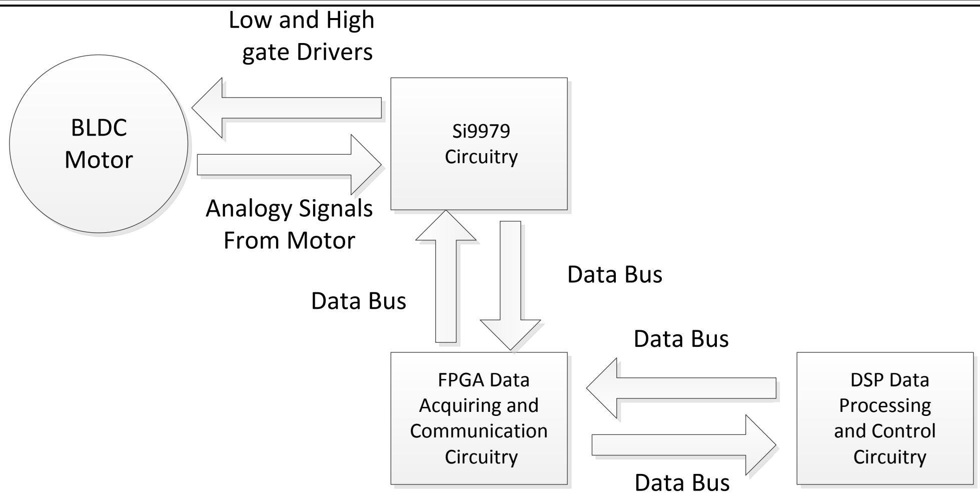


Figure 1. The frame of BLDC motor's driving system

Motor control is by no means a trivial consideration, a host of parameters-commutation, speed, acceleration; deceleration and torque must be taken into account when designing a motor control system. According to the motion transmission system of the robot hand, the rotational outputs of BLDC motor have a fixed rate with that of finger's joints. The velocity ratting is defined by gear system. During robot hand grasping some work-piece or contacting with its environment, force/torque control is needed to implement the task precisely. The force/torque information derived from force/torque sensors is processed and converted to digital signals on sensory circuit board. Utilizing the digital signals, the DSP data processing and control circuitry adopts such an algorithm to realize the force/torque and position control of robot hand. The DSP controller's output is by the means of PWM to control BLDC motor [2].

Figure 2 shows the functionality of a single Si9979 circuitry. All of the electronic components of three Si9979 circuitries are integrated on a 35X65-mm PCB (Printed Circuit Board). The board is connected to the motor modules of one finger, which is actuated by three BLDC motors. The structure can decrease the whole size and improve dexterity of robot hand [3].

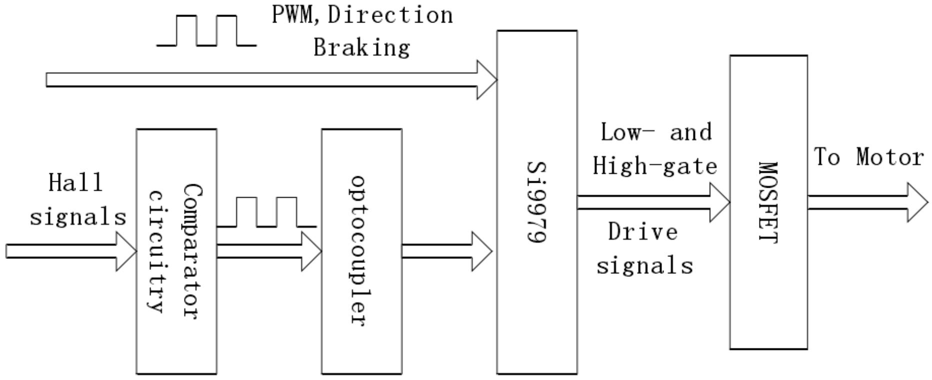


Figure 2. The functionality of Si9979 circuitry

Commercial BLDC motors of Micro MO Electronics are chosen to actuate robot hand. The motor uses Hall Effect Switches with open collector outputs. Housed in motor in such a way, the three linear hall sensors can detect position of the motor's rotator. The hall signals can generate basic commutation logic for BLDC motor to realize contactless commutation. In Si9979, there are digital logic electronics to generate BLDC motor's communication logic, therefore the hall signals must be converted to square wave compatible with TTL before connected to Si9979. A comparator circuitry based on LMV339, low voltage versions of quad comparator of National Semiconductor, can achieve the functionality, as shown in Figure 2. Two of the three hall signals can be used to compute velocity of the motor's rotator, and the velocity has a fixed relationship with that of the finger's joint. In order to reduce power dissipation of the whole driving system, 3.3-

V power supply is applied. To ensure a reliable design, optimal coupler circuitry must be used to protect interference between Si9979 and its input signals. There are about six digital input signals with different frequency from BLDC motor and DSP controller, so three optimal couplers with different speed, dual channel package from Agilent Technology, are chosen.

Each phase of BLDC motor is driven by a pair of N-channel MOSFETs, six these MOSFETs are selected to power electronics for three-phase BLDC motor. FDC6561AN, a dual N-channel logic level MOSFET from Fairchild Semiconductor, is well suited for all applications where small size is desirable. It is produced using Fairchild Semiconductor's advanced Power Trench process that has been especially tailored to minimize the on-state resistance and yet maintain low gate charge for superior switching performance. The low-side MOSFET of the power electronics can be directly driven by three low-side gate outputs which are pulled up to VDD inside Si9979, and three high-side gate outputs of Si9979 drive the high-side MOSFET through a floating circuit powered from a combination bootstrap/charge pump supply. The bootstrap capacitor is charged to VDD whenever the low-side MOSFET is turned on. After the low-side MOSFET is turned off, the bootstrap are kept charge by charge pump and used to turn on the high-side MOSFET. Dual channel package from Agilent Technology are chosen.

Snubber network

Si9979 integrates some functions to protect BLDC motor from wrong motion and the circuitry from damage. The protection features include cross-conduction protection, current limitation and under-voltage lockout. And Si9979 also has FAULT output to indicate when under-voltage, over-current, disable or invalid sensor shutdown has happened. The Si9979's low- and high-side gate outputs change switching states of power electronics. To protect the device against simultaneous conduction in both arms of the bridge resulting in a rail to rail short circuit, the drive signals of the complementary MOSFETs must have time interval, which is called "dead time". To prevent shoot-through current conduction in the complementary MOSFETs, each half-bridge has break-before-make circuitry. It delays the MOSFET turn on for 250 ns from the turn off of the opposite MOSFET [4-5].

Si9979 has internal circuitry to monitor the voltage level on VDD and high-side supplies [6], which can ensure that there is sufficient voltage to turn on the MOSFETs. Because the low-side gate is powered by VDD, it means that VDD must be decoupled with a 1-uF capacitor to prevent VDD dropping to the level of under-voltage. It's also important for motor to design a perfect current limiting circuitry to limit the current flowing motor's armature. If the current in the armature continues to be larger than that of motor can endure, temperature of the motor will rise to such a high level that can even damage the motor permanently. A current sensing resistor is selected to measure the current. When over-current condition happens, the current limiting circuitry triggers the one-shot and turns off the active MOSFETs for a period defined by the R-C network. The value of the resistor is a function of the driven motor's ratting current.

In applications that involve fast switching of inductive load like BLDC motor, the voltage transients that are generated in the applications must be taken into account. To insure a reliable design, the voltage transients must be limited to a level that is within the safe operating conditions of the selected switching devices-MOSFETs. The voltage transients may occur as results of the mismatch of switching times between the power transistors and their intrinsic diodes, and the parasitic inductance in the wiring or printed circuit board layout can also contribute to the transients. For an inductive load driven by power electronics, switching the MOSFET bridge will result in a change of direction of current flow in motor's armature, which leads to produce voltage transients due to the collapsing magnetic field inducing a counter-EMF (electromotive force) in the inductor. The resulting voltage across the inductance meets the following equation:

$$V = L\left(\frac{di}{dt}\right) \qquad (1)$$

So it is easy to make a conclusion that large voltage transients will be generated even small parasitic inductance when large current changes its direction rapidly. The voltage transients will destroy the stability of motor's driven power supply, which decides the performance of BLDC motor. And the more badly thing is that the voltage transients will damage the MOSFET when the operating conditions exceed the safe operating area of the power transistor. It is necessary to design a critical or over-damped response snubber structure for each phase of the driven motor. An R-C snubber network is developed to limit the rate of change of the voltage across the motor, as shown in Figure 3.

The rate change of the voltage on the output is dominated by the capacitor while the resistor is used primarily to limit the peak current flowing through the MOSFET when it turns on. To ensure effectively of the snubber network, the values of the resistors and capacitors must be selected carefully. In the design, the maximum resistor and capacitor is given by the following equations:

$$R_{\max} = \frac{V_{s\min}}{I_{peak}} \quad (2)$$

$$C = I_{peak}\left(\frac{dt}{dv}\right) = I_{peak}\left(\frac{T_{r\max}}{V_{s\max}}\right) \quad (3)$$

Where $V_{s\min}$ is noted as minimum supply voltage; $V_{s\max}$ is noted as maximum supply voltage; I_{peak} is denoted as peak motor current; $T_{r\max}$ is denoted as the turn-on time of the intrinsic drain to source diode.

To reduce the interference to the power supply from parasitic inductance, a food high frequency capacitor with an electrolytic capacitor is placed between the power supply and the ground, as shown in Figure 3.

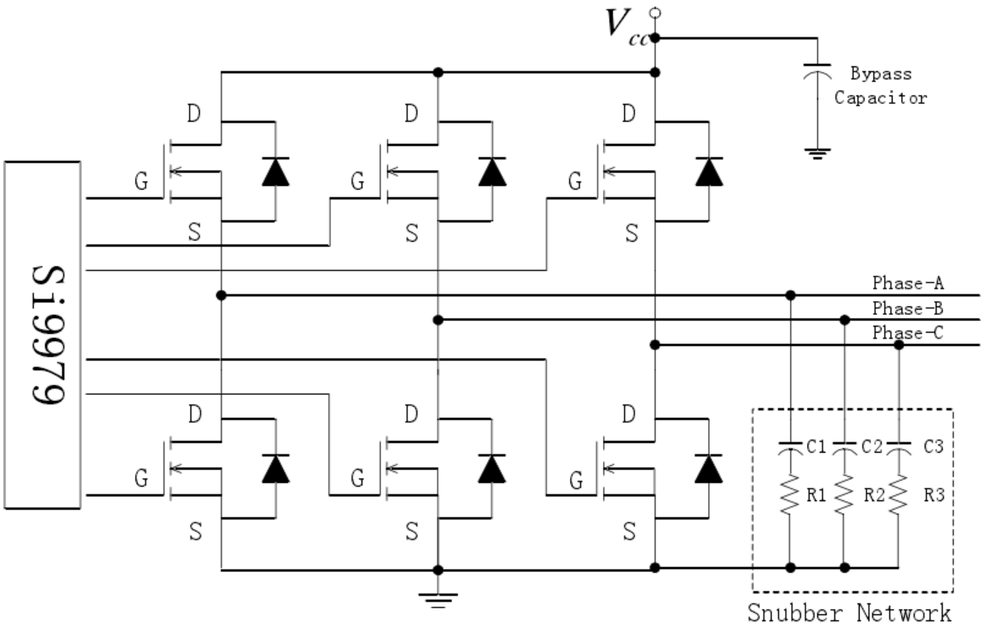


Figure 3. The power electronics with snubber network

The algorithm of fuzzy set similarity to ideal solution

Technique for Order Preference by Similarity to Ideal Solution (SIS) method is also one of those useful multi-criteria decision making method for surveying issues in real world for the first time. This method was also suggested by Jahanshahlo et al. They described it as: Let A_1, A_2 ,…, A_m be m alternatives, which are supposed to be ranked by k decision makers based on n criteria (C_1, C_2,…, C_n). Let X_{ij} be the rating score of A_i associated with j^{th} criteria and is defined as $x_{ij} \in [x_{ij}^l, x_{ij}^u]$. Weights of criteria are defined as $w_1, w_2, \ldots, w_n$, where w_j is the weight of C_j. We can define an MADM problem with interval numbers briefly in a decision making matrix.

In SIS method with interval numbers we have to normalize decision making matrix as we show it below:

$$\tilde{a}_{ij}^l = \frac{x_{ij}^l}{\sqrt{\Sigma_{j=1}^m\left[\left(x_{ij}^l\right)^2 + \left(x_{ij}^u\right)^2\right]}}, i = 1, 2, ..., n, \ j = 1, 2, ..., m \quad (4)$$

$$\tilde{a}_{ij}^u = \frac{x_{ij}^u}{\sqrt{\Sigma_{j=1}^m\left[\left(x_{ij}^l\right)^2 + \left(x_{ij}^u\right)^2\right]}}, i = 1, 2, ..., n, \ j = 1, 2, ..., m \quad (5)$$

Now $[x_{ij}^l, x_{ij}^u]$ are normalized and the calculated domain $[a_{ij}^l, a_{ij}^u]$ belongs to [0,1].

Because of the differences in importance of each criterion, in the next step we will calculate weighted normalized decision matrix with interval numbers as below:

$$\tilde{v}_{ij}^{l} = w_j \tilde{a}_{ij}^{l}, i = 1, 2, ..., n, \; j = 1, 2, ..., m \quad (6)$$

$$\tilde{v}_{ij}^{u} = w_j \tilde{a}_{ij}^{u}, i = 1, 2, ..., n, \; j = 1, 2, ..., m \quad (7)$$

Where w_i is the weight of the i^{th} criterion and $\sum w_i = 1$.

Fuzzy set is an extended form of classic set introduced by Zadeh. In a classic set, each element has two values. In other words, an element either belongs to a set or not. If an element becomes a member of set A, its related value is equal to 1, and zero, otherwise. However, fuzzy theory is attributing a number between [0, 1] to each x from X.

A Convex Fuzzy Set: The “A” fuzzy set is convex if and only if for each $x_1, x_2 \in X$ and each $\lambda \in [0,1]$, we have

$$\mu_A\left[\lambda x_1 + (1-\lambda)x_2\right] \geq \min\left[\mu_A\left(x_1\right), \mu_A\left(x_2\right)\right] \quad (8)$$

For real-world applications, we utilize some fuzzy and vague statements rather than some crisp terms. Very low, low, middle, high and very high are some examples of linguistic terms. Fuzzy numbers can stand for these linguistic terms in a mathematical model. In this paper, the importance weights of the ratings of qualitative criteria are considered as linguistic variables. In this paper, the decision-makers use the linguistic variables that are shown in Table 1 to evaluate the ratings of alternatives with respect to qualitative criteria.

In this article, we select a supplier that has the low amount of risk in relationship with the company. This problem can be defined as a group MADM (GMADM) problem. We consider some steps for modeling these cases as below:

a) A set of k decision maker that is defined by $D = \{D_1, D_2, ..., D_k\}$;

b) A set of m supplier (alternative) that we call it $A = \{A_1, A_2, ..., A_m\}$;

c) A set of n criteria that we evaluate suppliers by those criteria and call it $C = \{C_1, C_2, ..., C_n\}$;

d) A set of performance rate of supplier, $A_i\left(i = 1, 2, ..., m\right)$ in association with criteria $\left(C_j, \; j = 1, 2, ..., n\right)$ that we show it as $X = \left\{x_{ij}, i = 1, 2, ..., m, \; j = 1, 2, ..., n\right\}$.

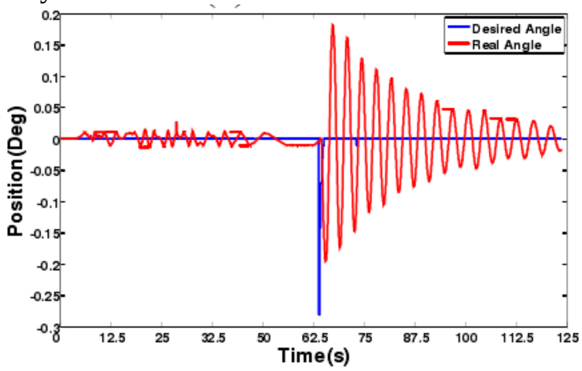
Consider a situation where there are k decision makers in a group and each decision maker D_k and $k = 1, 2, ..., k$ evaluates suppliers based on fuzzy numbers $\mu_{\tilde{A}}\left(x\right)$ that has a membership degree $\mu_{\tilde{A}}\left(x\right)$. After choosing adequate linguistic terms for ranking suppliers and translating them to fuzzy numbers, we utilized α-cut method to alternate these fuzzy numbers by interval numbers instead of defuzzification for prioritizing alternatives and then we used a SIS method to rank interval numbers for ranking suppliers.

The Experiment and data analysis

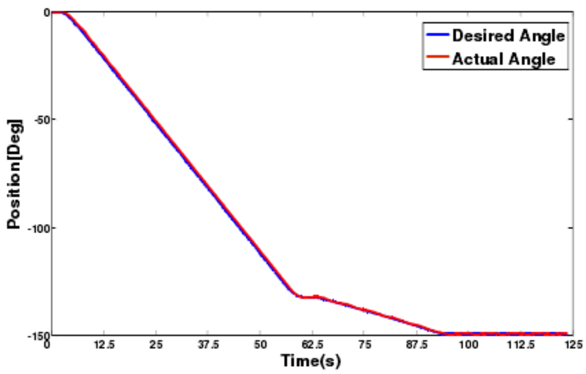
In order to control the robot hand precisely, some useful signals must be acquired to achieve some advanced control algorithm. The signals are the positions of the finger's joints, and the force/torque information during the hand grasping some work pieces or contacting with its environment, etc. In the whole electronic system of the hand, the analog signals from sensor systems are converted to serial digital signals through A/D inverters-AD7888. The FPGA circuitry acquires the serial signals and communicates with the DSP circuitry through serial data bus for data transmission; it can also transmit the command instructions from DSP circuitry to the motor drive circuitry based on Si9979 to actuate the BLDC motors. The FPGA can achieve the above functions through configuring it for the specific functionality required using Altera's compiling software. The DSP circuitry converts the serial data to parallel data to construct close-loop control system; the outputs of the controller decide the performance of the driven BLDC motors and even the whole robot hand.

The functional and performance test of the space robot system is HIL (Hardware in the Loop) system. Tests were carried out under the conditions that the space robot captures a known object at the initial state and that the gripper of the space robot moves along a straight path from the initial position to the target position and then the gripper captures the free-flying target by hand-eye. The space robot system makes extremely strict requirements for real-time response of control system, and it has to realize communication with 6 joints and gripper through CAN bus, trajectory plan in Cartesian coordinate, control arithmetic, inverse dynamics calculation and vision severing arithmetic in a control cycle. In this task, the control performance is: (a) Control period of joint servo system is 25ms. (b) Control period of visual severing system is 250ms. (c) The drift motion of the target after the capture is within 4mm position error.

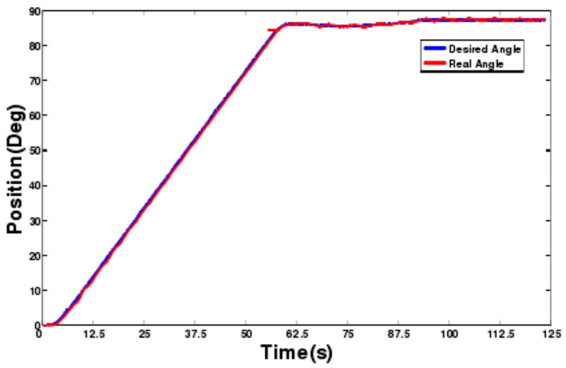
The proposed BLDC driving system is applied to the space robot system, and the position control results of 6 joints of the space robot system are shown in Fig. 4. It can be seen in Fig. 4 that most robot arm links approaches their desired values. The control precision and control error can meet system's real-time demands.



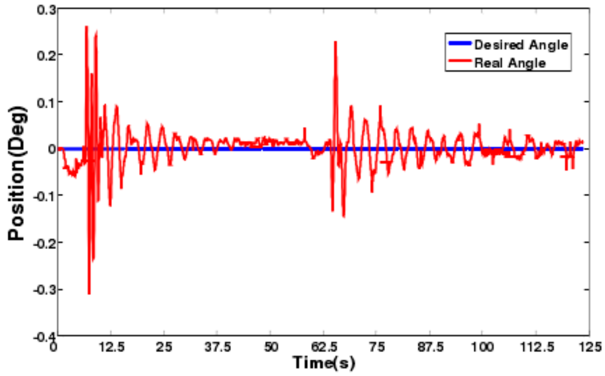
(a) Joint 1



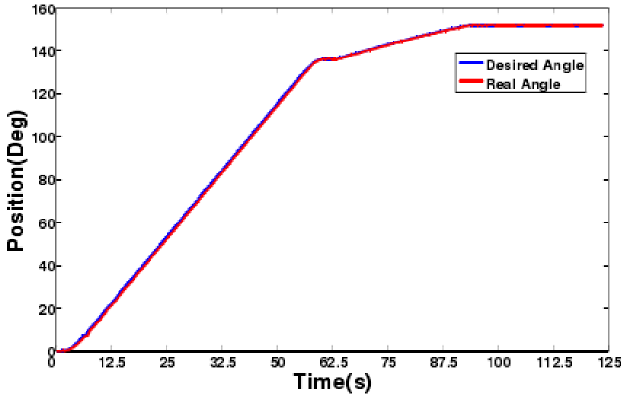
(b) Joint 2



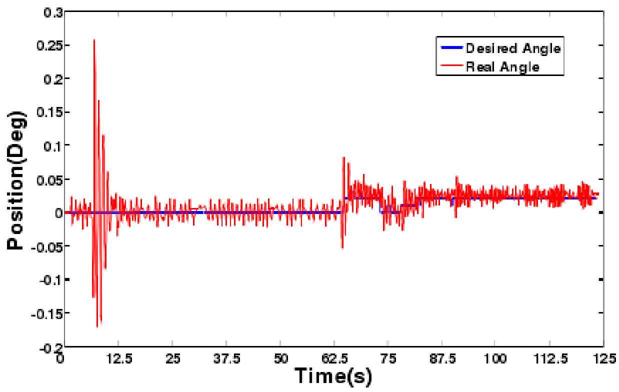
(c) Joint 3



(d) Joint 4



(e) Joint 5



(f) Joint 6

Figure 4. The Position Control Result of 6 Joints

Conclusion

The whole motor drive system consists of three parts: Si9979 circuitry, FPGA data acquiring and communication circuitry, and DSP data processing and control circuitry. The paper mainly describes the drive system based on Si9979. The Si9979 circuitry integrates Si9979 controller with comparator optimal coupler and power electronics. Si9979 integrates some protection functions, e.g. current limiting and under-voltage lockout, to protect BLDG motor from wrong motion and the circuitry from damage. To insure reliable performance of the Si9979 drive circuitry, a R-C snubber network is designed to control the voltage transients in the fast switching applications. With the snubber network, the voltage across the output of the MOSFET bridge can be limited within the maximum rating. At last, the FPGA and DSP circuitry that can finally realize the motor control are introduced briefly.

Acknowledgements

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