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A Low Cost Embedded Control System of Step Motor and Its Application

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Abstract: The step motor is a kind of electric actuator that transfers electrical pulses to angular displacement. How to fulfill the control task of step motor by embedded control system is a practical problem since the common computer control system has a higher cost and more redundant than the customized embedded control system. A dual-ARM7 microcontroller embedded structure is developed in this paper to keep the real-time performance, reliability and low cost. One of the ARM controllers is responsible for human-computer interaction, and the other one is dedicated to motion control. Based on this low cost platform an industrial stationary length controller is developed. The two kinds of new velocity profiles are designed and implemented. The application result shows that the embedded control system developed in this paper improves the step motor system performance and achieves low cost purpose.

Keywords: embedded control system, step motor, low cost automation

1. INTRODUCTION

Step motor is a kind of electric actuator that transfers electrical pulses to angular displacement conveniently. It is very suitable for industrial stationary length control. But most medium and small enterprises expect the control system of step motor has a high performance and a low price. Therefore, how to fulfill the control task of step motor by embedded control system is a practical problem since the common computer control system has a higher cost and more redundant than the customized embedded control system for the step motor control.

For the problems mentioned above, a customized embedded control system is developed in this paper. A dual-ARM7 microcontroller embedded structure is used to keep the real-time performance, reliability and low cost. One of the ARM controllers is responsible for human-computer interaction, and the other one is dedicated to motion control. Based on this low cost platform an industrial stationary length controller is developed. The paper briefly introduces the step motor control system based on dual-ARM7 controller at first. Then, some designs details are given. Two kinds of velocity profiles are also designed for the control system to improve the running performance of step motor. Finally, the application result is given to show that the embedded control system developed in this paper improves the step motor system performance and achieves low cost purpose.

2. STRUCTURE OF EMBEDDED CONTROL SYSTEM OF STEP MOTOR

The control system of step motor is an intelligent system which includes control, monitor, display and communication. Figure 1 is the structure of this system.

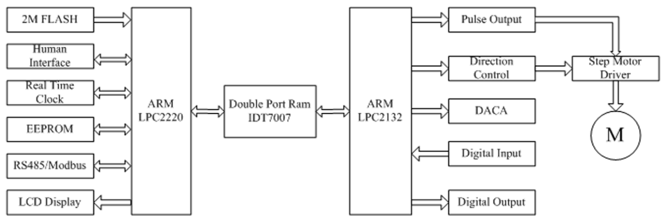

Fig.1 Structure of embedded control system of step motor

2.1 Selection of Embedded Microcontroller

ARM series microcontroller is one of main products of high performance 32 bit RISC microcontrollers. Other similar products mainly have series of PowerPC, 68K, MIPS and so on. With three major characters: lower power, cost-effective and high code density, ARM microcontroller has been recognized as an industry standard in embedded RISC processor field. The main application domain of ARM7 series microcontroller is as follows: industry control, network and modem equipment, mobile telephone and so on.

The hardware platform of pulse output adapts the LPC2132 microcontroller, not the motion control chip, integrated pulse width modulation (PWM) module, LPC2132 has the following characters.

- 16/32-bit ARM7TDMI-S microcontroller in a 64 pin LQFP package.
- 16 KB on-chip Static RAM and 64 KB on-chip Flash Program Memory.
- In-System Programming (ISP) and In-Application Programming (IAP) via on-chip boot-loader software.

- Embedded ICE-RT interface enables breakpoints and watch points. Interrupt service routines can continue to execute whilst the foreground task is debugged with the on-chip real monitor software.

- Embedded Trace Macro cell enables non-intrusive high speed real-time tracing of instruction execution.

- Two 32-bit timers (with 4 capture and 4 compare channels), PWM unit (6 outputs), Real Time Clock and Watchdog.

The motion microcontroller, LPC2132, sends two groups of pulses from pin P1.24 and pin P1.25 respectively (PWM2 channel) to control two step motors. The direction signal is sent by pin P1.8. If P1.8 is in high level, step motor rotates clockwise, or else step motor rotates anticlockwise. LPC2220 has the similar characters with LPC2132.

2.2 Dual-ARM7 Framework

The control system developed in this paper is composed of two pieces of ARM7 microcontrollers, LPC2220 and LPC2132. The LPC2220 is responsible for the human computer interaction, parameter storage and so on. The LPC2132 concentrates on the motion control according to the velocity profile. This structure selection has two reasons. First, the speed of data transmission of the most widely used monochromatic LCD controller SED1335 is much slower than ARM7 microcontroller. By basic calculation and practical measure, refreshing a screen of 320*240 pixels needs at least about 130ms, therefore it is very difficult to guarantee the real-time ability when the control system has a lot of display task. LCD screen's refreshing speed has become a bottleneck in the system. There are two kinds of solutions to solve the problem: Choose a microcontroller internal integrated the LCD controller or use two pieces of microcontrollers respectively to deal with the display and the motion control. The price of the microcontroller integrated LCD controller is generally expensive. Therefore the second solution is adopted. Now the LPC2132 can specially be responsible for motion control and the real-time ability of the step motor control system is greatly enhanced. The second reason is that the software design difficulty of dual microcontroller system is lower than the one of single controller system.

Different solution is adapted in dual microcontroller or multi microcontroller system according to the practical application. There are mainly the following several kinds of design.

- Two CPUs communicate data through bidirectional buffer, moreover designs several I/O line as the signal of shaking hands.

The hardware is very simple. But it wastes more time to communicate with each other. The protocol between the two microcontrollers makes the software more complex. The two microcontrollers can not access the interface at the same time.

- double port RAM plan

The double port RAM permits data being read and written through the two sets of independent address buses and data buses simultaneously at the same time. The minimum access time of the double port RAM IDT7007 used in the paper is 55ns. Figure 2 shows the hardware structure.

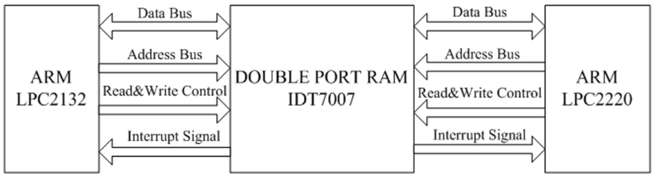

Fig.2 Dual port RAM hardware structure

It is obvious that the exchange of information is more convenient to the later. So the double port RAM plan is adapted.

3. DESIGN OF VELOCITY PROFILE

3.1 Common Velocity Profile

The stationary length control system is used extensively in bag-making industry. The control system's main function is to drive the step motor to cut the material exactly according to a stationary specification. Velocity profile enactment is very important to the running performance of step motor. In the practical application, common velocity profiles include: ladder-shape velocity profile, piecewise linear velocity profile, the index velocity profile and s-shape velocity profile.

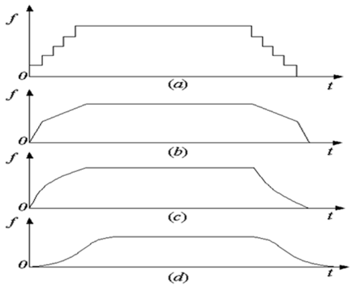

Fig. 3 Common velocity profile of step motor

Figure 3(a) shows the ladder-shape velocity profile. After jumped to a rotational speed every time, step motor is at a constant speed for a period of time. The shortcoming of this method is that step motor does not accelerate/decelerate for the period of time at constant speed, and does not make the best of the constant speed stage. Moreover in the accelerating and decelerating phase in the high frequency band, step motor can lose steps or overshoot when the speed jumps.

Figure 3(b) shows the piecewise linear velocity profile. Step motor holds on at the constant acceleration in every partition of the straight line of the phase. The method has the following advantages: the calculation is very easy and takes less calculation time. The control system is efficient and responds quickly. But the method also has some shortcomings. From the Figure 3(b), it is obvious that there exist some sudden changes of the acceleration at the beginning point, the endpoint and the each point of the intersection between two straight lines. The jump of the acceleration at these points will bring flexible impact. The method is generally used in a simple situation.

Figure 3(c) shows the index velocity profile. The index velocity profile does better in smoothness, motion precision than the piecewise linear velocity profile. But the method is very complex and will take longer calculation time. Moreover sudden change of acceleration or deceleration existing at the beginning point and the endpoint during the course of accelerating will bring flexible impact. The numbers of pulse of the accelerating phase and decelerating phase are theoretically not equal to each other, so it has to be adjusted before practical application. The time of the entire velocity control process is longer than the theoretical calculation.

Figure 3(d) shows the s-shape velocity profile. The name of s-shape velocity profile comes from the shape of the velocity curve during the course of acceleration and deceleration. The acceleration phase and deceleration phase are symmetrical. Generally, s-shape velocity profile is divided into 7 phases: accelerating acceleration phase, constant acceleration phase, decelerating acceleration phase, constant velocity phase, accelerating deceleration phase, constant deceleration phase and decelerating deceleration phase. In changing acceleration and deceleration phase, the differential coefficient of acceleration is invariable. In constant acceleration and deceleration phase, the acceleration is invariable. In constant velocity phase, the speed is invariable. Every point of the s-shape velocity profile consecutively changes, so flexible impact is avoided and the system is of excellent velocity smoothness and high motion control precision. But the method is commonly used in high speed or in high precision process for its complexity.

3.2 Realization of Two Kinds of Velocity Profile

3.2.1 Linear Acceleration of Step Motor

It is supposed that step motor starts up at f_1 Hz, accelerates at βstep/s^2 till runs at constant f_s Hz. So consecutive changing step frequency f is expressed as follows:

$$f = g + \beta t \tag{1}$$

where g is a frequency lower than the startup frequency f_1. As shown in Figure 4, the theoretical relation between frequency and time is expressed with real line, the practical one is expressed with broken line.

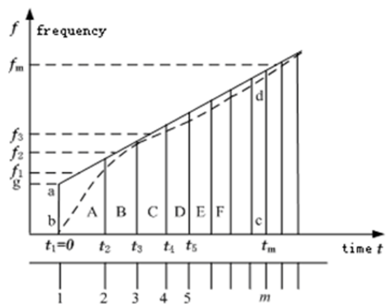

Fig.4 Pulse timing in linear acceleration

The rotational angle is a step angle from the *(m)*th step pulse to *(m+1)*th step pulse. Δt_m is the interval of every two pulses next to each other, namely $\Delta t_m = t_{m+1} - t_m$. The corresponding pulse frequency is $f_m = 1/\Delta t_m$. The frequency is equal to the value of (1) when $t = t_m + \Delta t_m/2$.

Setting $t = \Delta t_1/2$, $f = f_1$, g can be calculated from the equ. (3).

$$f_1 = g + \beta \frac{\Delta t_1}{2} = g + (\beta / 2 f_1) \tag{2}$$

$$g = f_1 - (\beta / 2 f_1) \tag{3}$$

The area surrounded by Point a, b, c and d in Figure 3 can be calculated according to *(m-1)*th step.

$$\{\frac{g + (g + \beta t_m)}{2}\} t_m = (m-1)$$

Based on the equation above, it is easy to get the following quadratic equation.

$$\beta t_m^2 + 2 g t_m - 2(m-1) = 0$$

Therefore the pulse time can be calculated from the equ. (4).

$$t_m = (\sqrt{[g^2 + 2(m-1)\beta]} - g) / \beta \tag{4}$$

The interval of pulse time Δt_m is

$$\begin{aligned} \Delta t_m &= t_{m+1} - t_m \\ &= (\sqrt{g^2 + 2m\beta} - \sqrt{g^2 + 2(m-1)\beta}) / \beta \end{aligned} \tag{5}$$

The *(m)*th step pulse frequency can be given as:

$$\begin{aligned} f_m &= 1 / \Delta t_m \\ &= (\sqrt{g^2 + 2m\beta} + \sqrt{g^2 + 2(m-1)\beta}) / 2 \end{aligned} \tag{6}$$

The value of t_m, Δt_m and f_m can be calculated respectively with the equ. (4), (5), (6) at $m=1, 2, 3\ldots$

Table 1 is a set of pulses of the piecewise linear velocity profile according to the practical technique.

Tab.1 Pulse interval (linear velocity profile)

M	ΔT(us)	F(Hz)
1	2500.0	400
2	2325.4	430.1
3	2174.5	460.0
4	2041.3	490.0
5	1923.4	519.9
6	1818.4	549.9
7	1724.3	579.9
8	1639.4	610.1
9	1562.3	640.1
10	1492.5	670.0
11	1428.7	699.9
12	1370.5	729.7
……	……	……

3.2.2 S-shape Velocity Profile of Step Motor

1) Feature of Step Motor

Kinetic equation of step motor is given below.

$$Jd^2\theta / dt^2 + \beta d\theta / dt + k\theta + T_z = T_d \quad (7)$$

where J is the sum of rotational inertia of the system, θ is the rotational angle of the rotor, β is the damp coefficient of the rotor, k is the proportional factor according to some functional relation, T_z is the sum of torque of the friction and other resistances and T_d is electromagnetic torque of the step motor.

According to the equation mentioned above and other factors, the practical torque-frequency feature is shown in Figure 5. When the frequency of the drive pulse is low, the torque of step motor becomes large. As the frequency increases, the torque approximately linearly decreases.

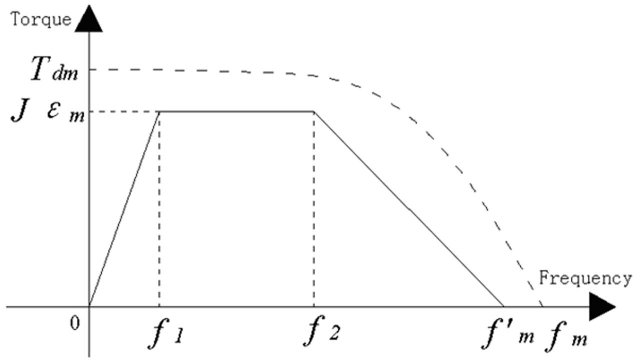

Fig.5 The feature of torque-frequency and the profile of the acceleration of step motor

From (7), the inertial of rotating torque of the system is described as

$$J\varepsilon = Jd^2\theta / dt^2 = T_d - \beta d\theta / dt - k\theta - T_z \quad (8)$$

It is obvious that the inertial rotating torque $J\varepsilon$ should be less than the maxim of electromagnetic torque. In acceleration phase, the acceleration of angle ε should be bigger to enhance the sensibility of the system. But ε should not change suddenly for decreasing the impact.

2) S-shape Velocity Profile

Because the drive frequency f is proportional with the velocity of rotor $d\theta/dt$, the acceleration of angle ε is proportional to f/t. The equation in every phase of the profile of the acceleration is a simple equation.

$$\varepsilon = df / dt = A - Bf \quad (9)$$

where A, B are constants for calculation.

Suppose frequency changes from f_0 to f_1, (9) will be as follows after Laplace transform:

$$F(s) = A / [s(s+B)] + f_0 / (s+B) \quad (10)$$

After Laplace inverse transform,

$$f(t) = f_0 + C(1 - e^{-Bt}) \quad (11)$$

where $C = A / B - f_0$.

From (11), we can find that the constant B determines the changing rule about frequency with t.

$B<0$ is the first phase of the profile, the profile is sunken.

$B=0$ is the second phase of the profile, the profile is straight.

$B>0$ is the third phase of the profile, the profile is bulgy.

But $1/B$ is the constant of time determining the speed of acceleration or deceleration, and it is determined by the drive system. From the analysis above, the velocity profile matching the time-frequency relation of step motor should be shown in Figure 6.

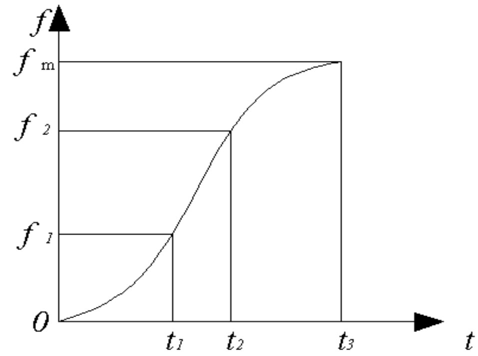

Fig.6 Time-frequency relation of step motor

3) Disperse of S-shape Curve

Because motion of step motor is in stepping drive mode the equ. (11) has to be dispersed.

Step motor control system sends the *(N)*th pulse at the time t.

$$N(t) = \int_0^t f(t)dt = \int_0^t f_0 + C(1 - e^{-Bt})dt$$
$$= (f_0 + C) - C / B(1 - e^{-Bt}) \quad (12)$$

The equ. (12) is a transcendental equation. Control system sends the *(N)*th pulse at the time t and it can be solved by Newton iterative method. The formula is as follows.

$$t_{k+1} = t_k - [(f_0 + C)t_k - C / B(1 - \exp(-Bt_k))$$
$$- N]/[f_0 + C(1 - \exp(-Bt_k))] \quad (13)$$

Precise results of $t(N)$ will be achieved after having been iterated for a few times. And then, every $f(N)$ corresponding with N can be worked out from (11) and $T(N)$ can be worked out by reciprocal of $f(N)$.

Table 2 is a set of pulses of s-shape velocity profile according to the practical technique.

Table 2. Pulse interval of S-shape profile

N	ΔT(us)	F(Hz)
1	2500.0	400
2	2410.4	414.9
3	2326.5	429.8
4	2247.3	445.0
5	2174.0	460.0
6	2105.3	475.0
7	2041.3	489.9
8	1980.3	505.0
9	1923.5	519.9
10	1869.7	534.8
11	1818.3	550.0
12	1770.4	564.8
13	1724.5	579.9
……	……	……

3.3 Comparison of Two Kinds of Velocity Profile in Industrial Stationary Length Control

Table 3 is the comparison of the productive efficiency of the bag making between the two kinds of velocity profile proposed in this paper, where *L* (mm) is the request length of bag, *P* is the velocity profile type and the data in the table are the output of the bag every minute. From the comparison, we can draw a conclusion that the control system adapted S-shape velocity profile has a higher productive efficiency than the piecewise linear velocity profile in the same condition of the length and the time of bag making.

Table 3. The comparison of the productive efficiency of the bag making between two velocity profiles

P \ L	10*mm*	50*mm*	500*mm*
Piecewise linear	620	220	70
S-shape	675	228	76

4. CONCLUSION

A low cost embedded control system based on dual-ARM7 microcontroller is developed and the two kinds of velocity profiles are proposed for industrial stationary length control in this paper. The embedded control system meets the application requirement completely. From the practical application results, it can be drawn a conclusion that S-shape velocity profile can effectively avoid step motor’s out-of-step and overshooting, enhance the efficiency and reduce the flexible impact. From economical point, the application of embedded control technology based on dual-ARM7 microcontroller meets the requirement of low cost for the medium and small enterprises.

REFERENCES

Wang Hongyu (1990). Basic techniques of step motor. Tongji University Publishing Company, Shanghai.

Jae Wook Jeon(1996). A generalized approach for the acceleration and deceleration of CNC machine tools. Industrial Electronics, Control and Instrumentation, Proceedings of the 1996 IEEE IECON 22nd International Conference, Vol.2, pp. 1283-1288

Jae Wook Jeon(2000). A generalized approach for the acceleration and deceleration of industrial robots and CNC machine tools. Industrial Electronics, IEEE Transactions on. Vol.47, pp. 133-139

Chen Aiguo, Huang Wenling and Yanghong (2003). Study on acceleration and deceleration curve of step motor. In: Development and innovation of machine and electrical product, Vol.48, No.2, Beijing.

Jacob Levman, Gul Khan, Javad Alirezaie(2004). Hardware-software co-synthesis of bus architecture embedded devices. Electrical and Computer Engineering, 2004. Canadian Conference on. Vol.1, pp.69-72

Philips (2005). LPC213x User Manual Rev.01. Philips Semiconductors.

Philips (2005). LPC2220 User Manual Rev.01. Philips Semiconductors.

Cui Jing, Chu ZhongYi(2005). An Improved Approach for the Acceleration and Deceleration of Industrial Robots and CNC Machine Tools. Industrial Technology, 2005. JCIT 2005. IEEE International Conference. pp. 1269-1273

Ngoc Quy Le, Jung UK Cho, Jae Wook Jeon(2006). Application of Velocity Profile Generation and Closed-Loop Control in Step Motor Control System. SICE-ICASE, 2006. International Joint Conference. pp. 3593-3598