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A study on control system of electronic treadmill based on neural network theory

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Abstract. The control system of electronic treadmill is researched on the basis of neural network theory so as to provide theoretic bases for the research and development of new electronic treadmill. Firstly, studies are carried out on the composition of brushless DC motor and its operating principle and neural network as well as PID control to establish mathematical model of motor and confirm the program for single closed loop speed regulation of motor and PID control method based on neural network. Secondly, Secondly, hardware architecture is researched and designed according to the control needs of electronic treadmill. The whole hardware system is divided into main control board and function board with function board researched and designed. In succession, μC/OS-II, the embedded real time operating system is chosen as the target platform for product development and transplanted to the main control board. Finally, tests are made for the control system of the treadmill. It can be seen that, when the performance index of the speed of running belt meets no-load condition, the deviation is lower than 5 % and when meeting load condition, the deviation is lower than 10 %; the deviation of slope regulation is less than 5 %. the deviation of heart rate is less than 5 %.Control system of treadmill designed in the study can meet everything what the design requires.

Key words. Electronic treadmill, neural network theory, μC/OS-II, μC/GUI, PID control method.

1. Introduction

With the development of economy and improvement of living standard, people pay more and more attention to their health [1]. In the present modern life with rapid pace, the chances and places for people to doing physical labor and exercise are lessened, giving rise to the decreasing of the amount of exercise and people's subhealth. Doing exercise on electronic treadmill is unaffected by the limitation of weather and takes up small space, which solve problems about people's unwillingness to expose to bad air, insufficient exercising time and space. In addition, the price of electronic treadmill is acceptable, and general people can afford it. Scientific

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researches show that running is the most effective and scientific aerobic exercise for people to keep health [2], which is vigorously advised in sports and medical filed. From the point view of kinematics, the posture of walking on treadmill are the same as that on ground. As walking on treadmill does not need a posture of stretching, users may feel it is easier to doing exercise on treadmill.

μC/OS-II real time operating system is applied in the control system of electronic treadmill for the first time. On the basis that hardware and software architecture of the control system are confirmed, with with μC/OS-II as the development platform, functions of electronic treadmill are realized on it [3], which provides a new way of thinking for the development of control system of electronic treadmill.

2. Literature review

Treadmill product has been updated for four generations in less than 40 years from the 1980s [4]. The popularity of embedded system overcomes such problems as large size and poor stability of PC terminal. Reference [5] proposes that streaming media technology can be introduced in control system of electronic treadmill. When runners are running, they can choose videos and audios to play. Reference [6] puts forward a adaptive control method that follows the speed of treadmill and can be used in the system of lower limbs rehabilitative robot. According to structure features of lower limbs rehabilitative robot, a force measuring device is adopted to test runner's acting force on treadmill. The acting force is also used to reflect the motion state of runners in real time and control the speed of treadmill. Tests on physical prototype show that this control method works in making treadmill follow and adapt to runner's speed. Reference [7] designs a adjustable speed treadmill based on the principle of computer vision gesture recognition, which collects gestures of runners through camera. Users can control the speed of the treadmill by making gestures in front of camera. References [8, 9] combine virtual reality technology with treadmill to provide a virtual sports ground and interactive entertainment functions for users, thus improving motion perception. In a word, electronic treadmill tends to be digital, intellectual and networked with more improved functions and it also develops more human [10].

3. Methodology

4. Control technologies of electronic treadmill

The brushless DC motor consists of motor body, electronic commutating device and rotor position detecting device [11]. DC motor is made up of stator and rotor. The armature of the general DC motor is mounted on the rotor and the main pole is on the stator, as shown in Fig. 1.

We established a mathematical model for the three-phase and six-state brushless DC motor. The assumed conditions are as follows [12]: the effect of gear slot, commutation process and armature reaction is ignored; three-phase winding is completely

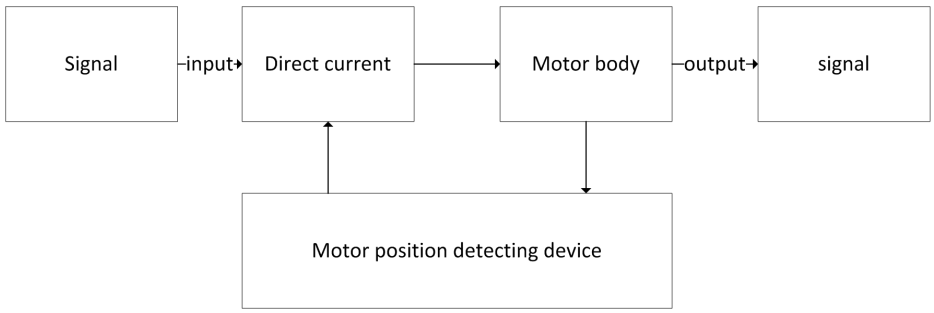

Fig. 1. Schematic diagram of brushless DC motor

symmetrical, the air gap magnetic field has the form of a square wave, and the distribution of stator current and rotor magnetic field is symmetrical; the distribution of armature winding on the surface of stator is uniform and continuous; magnetic circuit is not saturated and eddy currents and hysteresis loss are ignored. The mathematical model of brushless DC motor is composed of voltage, torque and motion equation [13]. When each switch and conduction pressure drop of anti-parallel diode is ignored, the voltage equation can be expressed in the form

$$\begin{bmatrix} u_{\mathrm{a}} \\ u_{\mathrm{b}} \\ u_{\mathrm{c}} \end{bmatrix} = \begin{bmatrix} R_{\mathrm{a}} & 0 & 0 \\ 0 & R_{\mathrm{b}} & 0 \\ 0 & 0 & R_{\mathrm{c}} \end{bmatrix} \cdot \begin{bmatrix} i_{\mathrm{a}} \\ i_{\mathrm{b}} \\ i_{\mathrm{c}} \end{bmatrix} + \\ + \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \cdot \begin{bmatrix} i_{\mathrm{a}} \\ i_{\mathrm{b}} \\ i_{\mathrm{c}} \end{bmatrix} + \begin{bmatrix} e_{\mathrm{a}} \\ e_{\mathrm{b}} \\ e_{\mathrm{c}} \end{bmatrix}, \tag{1}$$

where u_{a}, u_{b} and u_{c} refer to voltages of three-phase stator, R_{a}, R_{b} and R_{c} refer to resistances of three-phase stator winding, i_{a}, i_{b} and i_{c} refer to currents of three-phase stator, and e_{a}, e_{b} and e_{c} refer to induced back electromotive force. Finally, symbol L denotes the inductance of each phase winding and M M refers to mutual inductances of the phase windings.

Current and rotor magnetic field in each phase of winding of the brushless DC motor interact with each other and produce electromagnetic torque

$$\frac{T_{\mathrm{e}}}{\Omega} = \frac{e_{\mathrm{a}} i_{\mathrm{a}} + e_{\mathrm{b}} i_{\mathrm{b}} + e_{\mathrm{c}} i_{\mathrm{c}}}{\Omega}. \tag{2}$$

Here, P denotes the electromagnetic power of the motor and Ω stands for the mechanical angular velocity of rotor.

From (2), the equation of electromagnetic power is

$$P = e_{\mathrm{a}} i_{\mathrm{a}} + e_{\mathrm{b}} i_{\mathrm{b}} + e_{\mathrm{c}} i_{\mathrm{c}} = 2 E_{\mathrm{s}} I_{\mathrm{s}}, \tag{3}$$

where E_{s} is the overall induced back electromotive force of the brushless DC motor and I_{s} is the overall current of the three-phase stator.

From (2), we can also obtain the motion equation in the form

$$J\frac{\mathrm{d}\Omega}{\mathrm{d}t} = T_{\mathrm{e}} - T_{\mathrm{L}} - B\Omega\,, \tag{4}$$

where J refers to rotor inertia, $\mathrm{d}\Omega/\,\mathrm{d}t$ refers to angular acceleration of rotor, B denotes the damping coefficient and T_{i} stands for the load torque.

The PID control principle of K_{P}, K_{I}, and K_{D} consists in self-learning established on the basis of BP neural network: the output state of neural network is in line with three above mentioned parameters of PD controller. By making use of self-learning ability, neural network constantly adjusts weighing factor, and its stable state is consistent with the parameter of PID controller under the optimal control law.

BP neural network has the ability to approximate any nonlinear function whose structure and learning algorithm are simple and clear. It is easy to know P, I, D parameters under the optimal control law by adopting the self-learning property of network. Typical incremental digital PID control algorithm is

$$\Delta u\,(k) = u\,(k) - u\,(k-1) =$$

$$= K_{\mathrm{P}}\Delta e(k) + k_{\mathrm{I}}e(k) + K_{\mathrm{D}}\left[e(k) - 2e(k-1) + e(k-2)\right]\,, \tag{5}$$

where k denotes the index of the step.

4.1. Hardware system of electronic treadmill

The hardware system of electronic treadmill consists of main control board and function board. The main control board is in charge of commanding works of each parts and it functions in controlling the touch screen, playing and recording audios as well as recording motion data of users. It also extends interface to send control signals to function board. Function board mainly works in driving speed motor and lift and drop motor and detecting heart rate.

Mini 2440 development board, from Friendly ARM, is used as the main control board in the hardware system aiming to save the underlying development time. The development board has abundant resources meeting function needs of the main control board. And external extended port on the development board can be used to control signals for function board. S3C2400 is adopted as the main controller, a microprocessor chip generally applied in handheld devices with low cost, consumption and high performance or other electronic products. Audio circuit is designed for the purpose of playing background musics and related warning tones, which employs solution of embedded audio system based on IIS bus. As a human-computer interaction interface, the touch screen can be used as the display interface, and operates the control system. It shows the current speed, slope, heart rates, distance and calorie consumption and other parameters. Users also can set parameters on it, such as speed and slope. SD card is applied in SD card interface circuit, which is a multifunctional memory card widely used in portable devices based on semiconductor flash memory technology.

Function board includes modules such as speed motor driving, lift and drop

motor driving and heart rate detecting. It functions in adjusting speed and slope and detecting heart rate controlled by control signals from the main control board. The main control board and function board are connected through extended port, where control signals of the main controller and feedback signals of each modules in function board transfer.

Adjusting speed is one of the basic function of treadmill, so speed adjustment is one of the most important part of brushless DC motor in treadmill control system. A special chip for regulating speed is chosen when controlling rotary speed of motor, which simplifies hardware circuit and achieves higher control accuracy. Hand heartbeat detection module TM998 is adopted as heart rate detection device which works by using the ECG principle [14]. Heart beatings produce electrophysiological changes and conduct to body surface. Heart beating signals can be obtained through laying electrodes on skin and measuring potential differences. Arunning asynchronous motor drive with single phase capacitor is used to adjust the running slope. To increase or decrease the running slope can be achieved by controlling the positive inversion of motor. The lift and drop motor is actually a two-phase motor, which produces elliptical rotating magnetic potential in air gap of the motor when it performs, dragging the rotor to rotate. Motor leads to red, white and black lead wires. Wingdings can be switched by using electric relay. The capacity of the actual selected relay is 250 AC/3 A and coil voltage is 12 VDC.

4.2. Software system of electronic treadmill

μC/OS-II is a multitask real time kernel provided by Micrium which can be applied in many microprocessors. Main features of it are: source code is open; it can be transplanted, cured and cut; it has preemption and can manage 64 tasks at most; function call of most μC/OS-II and function time of service are certain; ever task has its stack space. The system provides many kinds of service such as signal quantity, mutual exclusion semaphores, event flag group, message mailboxes and message queue, which is stable and reliable and can be managed in interruption.

μC/OS-II can just read and write processor register through assembler language, codes related with register hardware, thus, is written in assembler language. If μC/OS-II is to be successfully transplanted, the compiler and register need to meet some preconditions. The compiler is required to create reentrant code. Compiler ADS is used in the development, which meets the requirement. Processor ARM9 is adopted and requirements it meets are as follows [15].

1. The processor supports interruption and can produce timer interruption in the frequency range of 10 Hz–100 Hz.

2. CPSR in the core of ARM processor and global interruption disable bit in the register can mange the global interruption. Its state can be changed to enable and disable interruption through the use of C language.

3. The processor supports data storage and hardware stack.

4. Assembler command stmfd in ARM processor can push all registers into the

stack and command ldmfd makes all register pop from the stack.

5. Transplanting can be completed just by revising codes OS_CPU.H, OS_CPU_A.S, OS_CPU_C.C [16] related with the processor.

The task is of three basic characteristics, namely, dynamic, independence and concurrency. When tasks are assigned, comparisons are made among all feasible assignment plans, from which the optimal plan is selected to achieve the expected goal. The method of assigning tasks is as follow[16]: Functions relative with IO device are set as independent tasks, which is a kind of device-relied task. For a function, the assigned key or emergent functions should be realized respectively by an independent task (or ISR) or independent higher priority task(or ISR), and the rest of which can be completed by another task. The two tasks synchronize and exchange information with each other by using the communication mechanism. The emergent and key task should be considered as a emergent task. Data processing function which costs much more time can be combined into a lower priority task. Functions, which are closely connected, triggered by the same event, completed in a certain order and has the same execute cycle, should be integrated into a task so as to conglomerate functions and exempt event and time distribution mechanism and synchronous relay communication.

As a graphic support system in embedded applications, μC/GUI [17] provides GUI for all applications adopting LCD graphic display, has high efficiency and is independent from the processor and LCD controller, which also simplifies the design process of LCD and shortens production time. It can be compatible with single or multiply tasks environment, special operating system or any RTOS with any commercial nature, whose production type is source code of C language.

μC/GUI can be applied in S3C2440, but a series of configurations need to be carried out on it before use. μC/GUI is transplanted to modify head documents GUIConf.h, GUITouch Conf.h and LCDConf.h in the content of\Config and C documents GUI_X_u COS.candLCDWin.cin the content of GUI\LCDDriver.

5. Result analysis and discussion

5.1. Hardware debugging

Problems appearing in the process of hardware debugging are mainly from motor driver chip LB11820M. Because of deficient knowledge about features of LB11820M, the allowed voltage range of monitoring end LVS protecting low voltage is ignored. The working voltage inserted in LVS end is less than 3.6 V and as a result, the motor halts when it is started for a while. After related analyses and investigations, the problems is found out and settled down by changing voltage regulator tube in the LVS end.

5.2. Software debugging

After hardware debugging is accomplished, software debugging is to be carried out. The most critical drivers are: driver of speed motor, lift and drop motor and heart rate detection. Speed motor is the brushless DS motor, whose operating condition can be evaluated through its input driving waveform and input of correspondent Hall senor. Driving module of lift and drop motor is tested. When control command is signaled to control running slope from control board, the electric relay can correctly pull and disconnect operation according to operation demand. Two electrodes of heart rate module are respectively held by hands and oscilloscope is connected to the output end of TM998 in order to observe output pulse waveform.

5.3. Tests on performance of the complete motor

The system works at the speed of 1 km/h when it begins to operate. Step speed regulation is tested at first at the increasing speed from 1 km/h to 20 km/h and later decreasing speed back to 1 km/h. It can be observed that the speed of running belt is changing with changing demands from main board. Speed direct shortcut is, in the following, tested. Low, middle and fast speed shortcut is pressed in order and another same test is carried out in a converse order. It is observed that the speed of running belt is slowly changing to the set speed. Table 1 shows the record of tests on the speed of treadmill.

Table 3. Record of speed test

Set speed (km/h)	Sped of running belt (no-load, km/h)	No-load deviation	Speed of running belt (load, 100 kg, km/h)	Load deviation
1.0	0.99	−1.0 %	0.95	−5.0 %
3.0	2.88	−4.0 %	2.90	−3.3 %
6.0	5.78	−3.7 %	5.73	−4.5 %
9.0	8.65	−3.9 %	8.51	−5.4 %
12.0	11.48	−4.3 %	11.39	−5.1 %
15.0	14.33	−4.5 %	14.24	−5.1 %
18.0	17.28	−4.0 %	17.16	−4.7 %
20.0	19.19	−4.1 %	19.06	−4.7 %

From Table 1, it can be seen that when the performance index of the speed of running belt meets no-load condition, the deviation is lower than 5 % and when meeting load condition, the deviation is lower than 10 %. In the testing process, if speed changes suddenly, the motor should be stopped and checked. From what are tested, it is known that both hardware and software of the speed motor are correct.

The range of slope regulation is $0° - 26°$ and uniform quantization is 0–13, namely 14 grades with 2 degrees in each grade. The slope can be adjusted in grades and grades are 3, 6, 9 and 11. When the system is restarted, the running slope is always set to grade 0. When the slope adjustment is tested in grades, it is adjusted from grade 0 to 13 and back to grade 0. It can be seen that the slope changes according to changing demands. When the test is made on slope shortcut, direct shortcuts are pressed from the low to the high and in the converse order, and the running slope is slowly changing to the set one. Test record of typical slope is shown in Table 2.

Table 2. Record of slope test

Grade	Set slope (°)	Slope measurement (°)	Deviation
0	0	0	0 %
3	6	5.9	−1.6 %
6	12	11.7	−2.5 %
9	18	17.4	−3.3 %
11	22	21.5	−2.3 %
13	26	25.6	−1.5 %

The test on heart rate is conducted as heart rate monitor is the reference standard. Metal electrode is held by two hands, and heart rate display window in the touch screen shows the current value of heart rate. When indication of heart rate monitor is up to the value needing to be recorded, value displayed in the heart rate display window of the touch screen is read.

Table 3. Record of heart rate test

Heart rate reading	Show value	Deviation
80	82	+2.5 %
100	103	+3.0 %
120	117	−2.5 %
140	137	−2.1 %

Table 3 indicates that the deviation of heart rate is less than 5 %.

6. Conclusion

According to the current development situation of electronic treadmill combining with multi-disciplinary knowledge and technologies and the trend of digital intelligence, for the first time, μC/OS-II system is introduced in software system of electronic treadmill control system, which is considered as a new attempt.It turns out that, when the performance index of the speed of running belt meets no-load condition, the deviation is lower than 5 % and when meeting load condition, the deviation is lower than 10 %; the deviation of slope regulation is less than 5 %. the

deviation of heart rate is less than 5 %. Control system of treadmill designed in the study can meet everything what the design requires.

References

[1] E. Gilberthorpe, E. Papyrakis: *The extractive industries and development: The resource curse at the micro, meso and macro levels.* The Extractive Industries and Society *2* (2015), No. 2, 381–390.

[2] K. J. Reid, K. G. Baron, B. Lu, E. Naylor, L. Wolfe, P. C. Zee: *Aerobic exercise improves self-reported sleep and quality of life in older adults with insomnia.* Sleep Med *11* (2010), No. 9, 934–940.

[3] K. Soga, T. Shishido, R. Nagatomi: *Executive function during and after acute moderate aerobic exercise in adolescents.* Psychology of Sport and Exercise *16* (2015), No. 3, 7–17.

[4] J. J. Daly, J. Zimbelman, K. L. Roenigk, J. P. McCabe, J. M. Rogers, K. Butler, R. Burdsall, J. P. Holcomb, E. B. Marsolais, R. L. Ruff: *Recovery of coordinated gait: Randomized controlled stroke trial of functional electrical stimulation (FES) versus no FES, with weight-supported treadmill and over-ground training.* Neurorehabil Neural Repair *25* (2011), No. 7, 588–596.

[5] R. Stojanovic, S. Knezevic, D. Karadaglic, G. Devedzic: *Optimization and implementation of the wavelet based algorithms for embedded biomedical signal processing.* Computer Science and Information Systems *10* (2013), No. 1, 503–523.

[6] W. Cui, F. Li: *An adaptive speed control method for running machine in lower extremity rehabilitation robot system.* Modern Manufacturing Engineering (2013) No. 9, 30–34.

[7] L.V̇. Nguyen-Dinh, A. Calatroni, G. Tröster: *Robust online gesture recognition with crowdsourced annotations.* Journal of Machine Learning Research *15* (2015), No. 1, 3187–3220.

[8] T. Ning, H. B. Ma, L. Huo, F. Zhao: *Virtual environment interactive system of treadmill.* Proc. IEEE Fourth International Conference on Information and Computing, 25–27 April 2011, Phuket Island, Thailand, *240*, No. 5, 933–939.

[9] H. Hu, Y. Cui, B. X. Huang: *Game system of treadmill based on video capture.* Proc. IEEE/ACM IC Cyber, Physical and Social Computing & Computing and Communications (CPSCom), 18–20 Dec. 2010, Hangzhou, China, 836–839.

[10] A. J. Stevenson, S. S. Geertsen, T. Sinkjr, J. B. Nielsen, N. Mrachacz-Kersting: *Interlimb communication following unexpected changes in treadmill velocity during human walking.* Journal of Neurophysiology *113*, (2015), No. 9, 3151–3158.

[11] J. H. Park, J. H. Chang, G. H. Jang: *Development of the starting algorithm of a brushless DC motor using the inductance variation.* J. Korean Society for Precision Engineering *17* (2000), No. 8, 157–164.

[12] S. Song, Y. Xu, H. Tian, X. Gong: *Design and simulation of dual rotor permanent magnet brushless DC motor.* Proc. IEEE International Conference on Electrical Machines and Systems (ICEMS), 22-25 Oct. 2014, Hangzhou, China, 1591–1595.

[13] C. S. R. Reddy, M. S. Kalavathi: *Improved performance of a novel SMC-fuzzy controller for DTC brushless DC motor drive for precise speed regulation.* Proc. IEEE Ninth International Conference on Power Electronics and Drive Systems, 5–8 Dec. 2011, Singapore, 873–880.

[14] X. X. Cao, S. Q. Zhu, Z. P. Cui: *Control system of intelligent treadmill based on sensor application technology.* Transducer and Microsystem Technologies *2* (2011), 97–100.

[15] G. Sun, F. S. Name, B. Sheng: *Performance test of an embedded real-time operating system based on a new high-security network computer.* IJ Digital Content Technology and its Applications *4* (2010), No. 8, 252–259.

[16] L. Yuan, G. Zhang, H. Gao: *Implementation of a multifunction black-box for tower crane based on ARM and μC/OS-II*. Proc. IEEE World Congress on Intelligent Control and Automation (WCICA), 25–27 June 2008, Chongqing, China, 7681–7685.

[17] Y. Liu, X. J. Wang, X.,W. Kong, C. C. Zhou: *Touch screen display design based on UCGUI*. Chinese Journal of Liquid Crystals and Displays *5* (2014), 739–744.

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