MICROCONTROLLER-BASED ELECTRONIC MODULE FOR CONTROLLING MECHATRONIC SYSTEMS

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Lucrarea prezintă proiectarea şi realizarea unui modul electronic pentru control industrial bazat pe microcontroler RISC pe 16 biţi cu resurse bogate de memorie şi dispozitive periferice. Modulul a fost testat şi s-a elaborat software special pentru o aplicaţie mecatronică clasică – sistemul electrohidraulic de control al poziţiei. Elementul de originalitate al lucrării rezindă în arhitectura modulului electronic, capabil de a deservi şi controla o gamă largă de sisteme industriale. De asemenea, implementarea simplă a algoritmului de reglare PID face posibilă utilizarea modulului în diferite aplicaţii de genul stand de testare a amortizoarelor vagoanelor sau presă hidraulică pentru compactat materiale reciclabile.

The paper presents design and implementation of a single chip electronic module for industrial control based on 16 bit RISC microcontroller with large resources of memory and peripherals. The module was tested and special software was developed for a mechatronic application - an electro hydraulic position control system. The originality aspects of the work come from the unique design of electronic board able to handle a large range of mechatronic systems. Also, the simple implementation of digital PID algorithm makes the module suitable for control of hydraulic applications like railway hydraulic damper test bench or hydraulic presses for recycling materials (chainsaw dust, PETs).

Keywords: microcontroller, position control, PID algorithm, mechatronics

1. Introduction

Industrial processes require rigorous monitoring and control of many parameters. The control systems must be accurate, fast, reliable and inexpensive. Digital control systems offer comparable performance with analog counterparts but are more flexible in communication and data processing and have lower costs ([6]). These costs can be further decreased by using modern system on chip microcontrollers that integrate processing units, memory, timers, communication interfaces, converters and analog peripherals. Designing such control systems requires hardware (design and testing of electronic schematics, CAD/CAM design, and software development (C or assembler), both associated with much

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higher costs than components' costs ([4], [5]). A decrease in development costs can be achieved only using a universal hardware and software platform, adapted to specific issues of controlled process. The paper presents a design for a digital control system that can be easily adapted to control a specific industrial process. There are now three applications, hydraulic press for recycling materials, controlled dryer for fruits and vegetables and hydraulic damper test bench.

2. Hardware structure of electronic module

A mechatronic device combines fine mechanics, electronics and information technology to achieve better performance with lower cost when compared with a mechanical-only device. Hydraulic systems, using hydraulic cylinders as actuators, are typical mechatronic systems. The structure of such a system, intelligent hydraulic axis, is presented in figure 1 and contains electronic servo amplifier, servo-valve, hydraulic cylinder, load and position transducer.

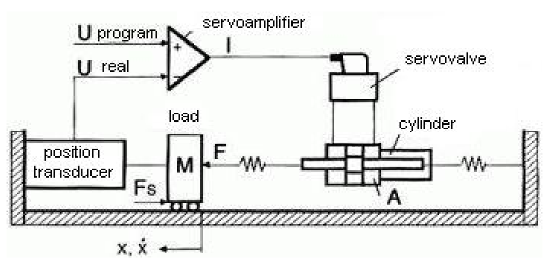

Fig. 1. Structure of a position control system

Common interfaces for sensors, transducers and actuators in electro-hydraulic, electro-pneumatic and electro-mechanic control systems were identified. According to this information, efforts were made to develop a system-on-chip based universal hardware module and software libraries and tools to control it. The structure of such a system is shown in the following figure:

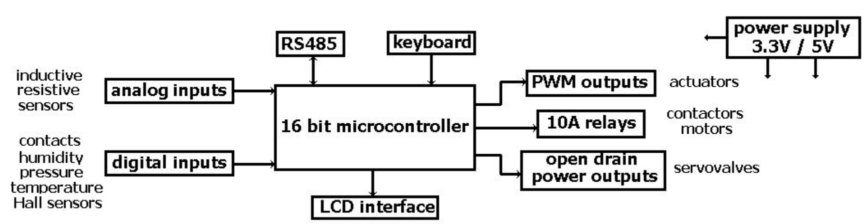

Fig. 2. Proposed structure of microcontroller based module for mechatronic applications.

The heart of module is a 16 bit advanced RISC system on chip microcontroller with large memory resources (2Kbytes RAM, 60 Kbytes flash program memory) and integrated peripherals (direct memory access controller, 12 bit analog to digital and digital to analog converters, timer/counters with capture/compare inputs and PWM outputs, synchronous and asynchronous serial communication interfaces and watchdog timer).

RS485 subsystem is implemented using a low pin-count driver that converts TTL or CMOS levels into RS422/485 levels. 120 ohm termination resistance is placed near RS485 connector and can be disabled with a jumper.

The 8 analog inputs can read unipolar signals in 0-5 Volt range with up to 10 bit accuracy. They can read also 4-20 mA current loops from different industrial sensors (force, pressure etc.) but can be transformed also in digital inputs or outputs by changing or removing associate resistors.

The interface for inductive displacement transducer consists of two operational amplifiers in voltage follower configurations that drive transducer windings; excitation frequency is in 1...10 kHz range; middle point voltage of windings offers displacement information.

Analog outputs are implemented with PWM outputs and low pass filters realized with low power rail to rail operational amplifiers. They are able to generate signals with frequencies up to 100 Hz and voltages in 0...5V range.

Digital lines can drive integrated sensors like humidity, temperature or pressure. They can read also Hall sensors for proximity detection or can extend number of control relays in conjunction with an extra relay board.

Keyboard interface is simple, with pull-up resistance and key connected to ground. To avoid picking noise, lower pull-up resistance value is used compared with microcontroller datasheet (1K instead of 100K).

Electromagnet output for hydraulic servo valve is a full H bridge implemented with FET transistors. It can drive electromagnets with up to 100 mA and has PWM control.

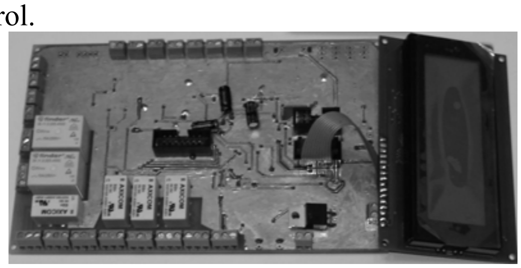

Fig. 3. Universal electronic module for control of mechatronic systems.

The printed circuit board is 2 layer board with separate planes for analog and digital ground (figure 3) to reduce noise level. All relays have contacts for 230V operation with copper traces away from low voltage signals.

3. PID Control algorithm

PID controller (regulator) represents a widely spread solution in industrial automation. It offers both simplicity and high performance for a large range of industrial processes and became de-facto standard for industrial control. Sometimes is also building block in more complex control systems that offer superior performances compared to standard control.

Typical closed loop control system contains controller, actuator, controlled process and sensors. From controller perspective, sensors and actuators are neglected (considered with linear behavior) so closed loop structure is like the one presented in figure 4, where C is controller, P process, F input filter, r reference signal, y controlled process variable, e = r-y control error term, u control variable, d load disturbance and n measurement noise.

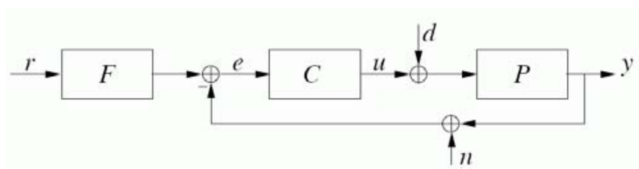

Fig. 4. Typical closed loop control system.

Transfer function for PID control law can be expressed as ideal (equation 1), series (equation 2) or parallel (equation 3) form ([6]):

$$H_i(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

$$H_s(s) = K_p^{'}\left(1 + \frac{1}{T_i^{'} s}\right)\left(T_d^{'} s + 1\right) = K_p^{'}\left(\frac{T_i^{'} s + 1}{T_i^{'} s}\right)\left(T_d^{'} s + 1\right) \tag{2}$$

$$H_p(s) = K_p + \frac{K_i}{s} + K_d S \tag{3}$$

PID control combines 3 actions – proportional, integrative and derivative

Presented closed loop control system was in continuous time. Use of modern microprocessors and microcontrollers require digital control, with architecture shown in figure 5:

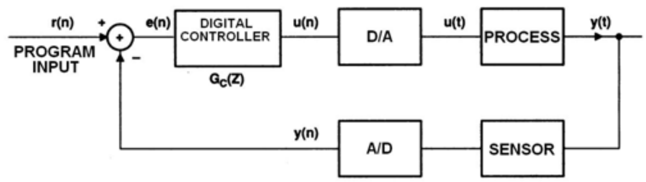

Fig. 5. Structure of a digital control system.

Digital implementation of presented control laws requires discretization. Starting from continuous time form law:

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \tag{4}$$

If sampling time is Δt integrative term can be estimated with rectangular approximation (Riemann):

$$\int_0^{t_k} e(\tau)d\tau = \sum_{i=1}^{k} e(t_i)\Delta t \tag{5}$$

Derivative term can also be described with finite differences:

$$\frac{de(t_k)}{dt} = \frac{e(t_k) - e(t_k - 1)}{\Delta t} \tag{6}$$

Control variable can be directly calculated, as shown in discrete time control law called positional algorithm ([6]):

$$u(t_k) = K_p\left(e(t_k) + \frac{\Delta t}{T_i}\sum_{i=1}^{k} e(t_i) + \frac{T_d}{\Delta t}\left(e(t_k) - e(t_{k-1})\right)\right) \tag{7}$$

Incremental algorithm or speed form ([6]) can be obtained by expressing control variable at tk moment as function of its value in previous moment, according to equation (8) using (9) notations:

$$\begin{aligned} u(t_k) &= u(t_{k-1}) + K_p\left[\left(1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t}\right)e(t_k) + \left(-1 - \frac{2T_d}{\Delta t}\right)e(t_{k-1}) + \frac{T_d}{\Delta t}e(t_{k-2})\right] \\ u(t_k) - u(t_{k-1}) &= K_1 e(t_k) + K_2 e(t_{k-1}) + K_3 e(t_{k-2}) \end{aligned} \tag{8}$$

$$K_1 = K_p\left(1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t}\right)$$
$$K_2 = -K_p\left(1 + \frac{2T_d}{\Delta t}\right) \quad (9)$$
$$K_3 = K_p \frac{T_d}{\Delta t}$$

Both digital forms for PID algorithm can be easily implemented on modern 8/16 bit microcontrollers. Each new sample require a small number of arithmetic operations and also small RAM memory footprint for variables - 4 floats for positional algorithm (u(tk), e(tk), e(tk-1) and actual error sum) or 5 floats for speed algorithm (u(tk), u(tk-1), e(tk), e(tk-1), e(tk-2)).

4. Software implementation

Software solution consists of a set of software functions (Table 1) grouped in libraries for different peripherals and sensors and a universal main.c module that uses all these library functions. This firmware is written in C language. Depending of application, design engineer can disable or enable some functions (by commenting their calls) or can assign signals to different connectors, cables and sensors. This is done by changing some parameters in configuration file. Added functionality can be later used without fear of errors, because it was already tested.

Table 1

Code memory requirements and timings

Action	Code size	Interrupt time	Main loop time
RS485 Communication	2000 bytes	50 μs	200 μs
Temperature and humidity measurement	500 bytes	10 μs	100 μs
Keyboard	500 bytes	5 μs	10 μs
PID control	1000 bytes	70 μs	500 μs
LCD display	1000 bytes	-	10 ms
Displacement measurement	500 bytes	30 μs	50 μs
Other tasks	2500 bytes	10 μs	200 μs
Total	8000 bytes	175 μs	…

Firmware is written using interrupt-driving techniques and benefits from orthogonal RISC architecture of microcontroller. Communication protocol is a simple serial frame protocol, with escape characters and cyclic redundancy check (CRC16). Its implementation consists of two sets of libraries, one for microcontroller, and the other for PC Windows software. PID control was implemented with a modified form of positional algorithm (equation 10) with parameters described in equations 11, sampling time is 1 milisecond:

$$u(t_k) = K_p e(t_k) + K_I \sum_{i=1}^{k} e(t_i) + K_D \left(e(t_k) - e(t_{k-1}) \right) \qquad (10)$$

$$P = K_p$$
$$I = K_p \frac{\Delta t}{T_I} \qquad (11)$$
$$D = K_p \frac{T_d}{\Delta t}$$

Firmware is real time software. To work properly, it reacts to an event before its next occurrence. This rule must be respected for all events. Problems are issued for fastest events, serial communication and PID processing. They are triggered every millisecond. System runs without losing events with an efficient scheduling of main loop tasks - slower, large events are divided and placed in available time windows between faster processes (communication and PID).

5. Tests and results

Test for integrated electronic module for mechatronic systems are performed on a hydraulic damper test bench that contains pump unit, linear actuator (hydraulic cylinder) with attached displacement and force transducer. The test bench implements a position control system. This test bench is computer controlled with a software instrumentation application written in TestPoint environment. A picture of stand is shown in following figures:

Fig. 6. Measurement equipment setup and test bench with hydraulic damper as load.

Dynamic behavior of the system is found by applying rectangular signal on its input, prescribed position and observing its output, real position of cylinder rod. For slow hydraulic systems like position system, a 0.1Hz rectangular signal is used. A data logging application was implemented in TestPoint instrumentation software to observe signals, prescribed and real position, and their difference (error signal). All these values are represented in millimeters, time scale has 0.5 seconds per division. A detailed view of application panel is shown in figure 6.

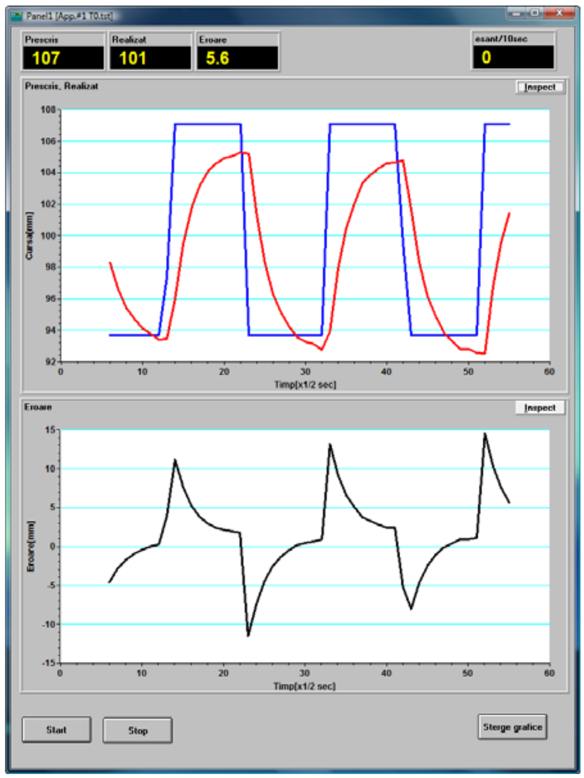

Fig. 7. Detail view of application window, for system response with proportional gain P=1

A first series of tests were performed with proportional gain only, no integrative or derivative action. Results are shown in figures 8 and 9; at low gains steady state error is large, at high gains (10, 15) overshoot is present. Integrative action cancels steady state error but introduces large overshoot, as shown in figure 10. Derivative action produces bad system response, as shown in figure 11. For presented hydraulic system best response was obtained for P only controller (P=5-10), but this parameter is system dependent.

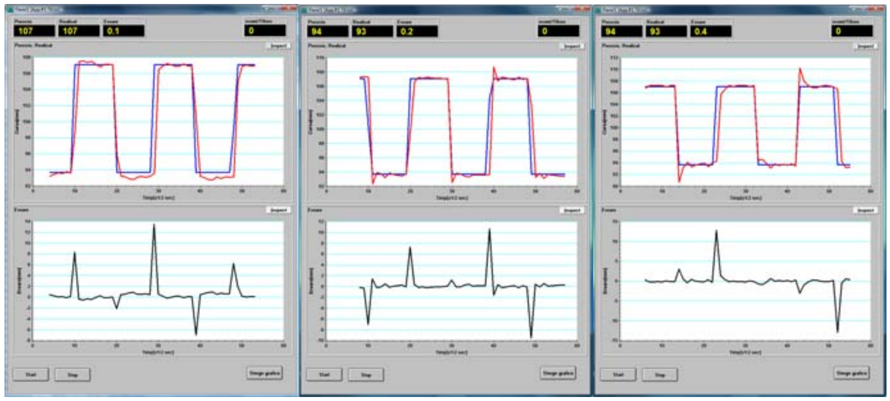

Fig. 8. System response for proportional gain only P=5, P=10, P=15.

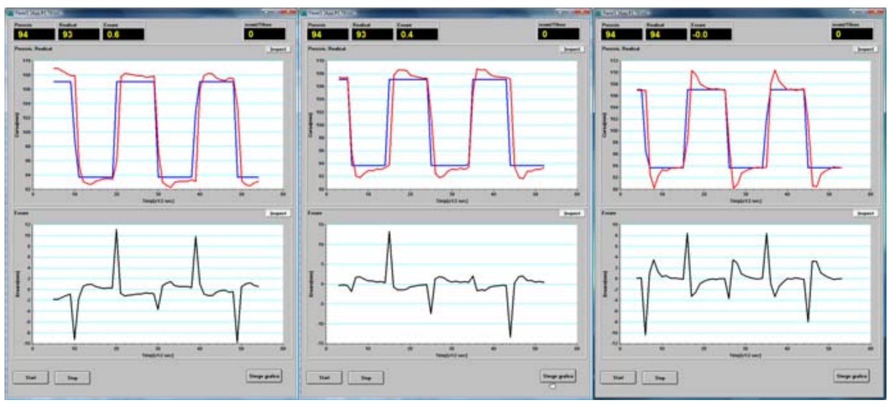

Fig. 9. Results for proportional gain P=5 and integrative parameter I=0.001, 0.002 and 0.005.

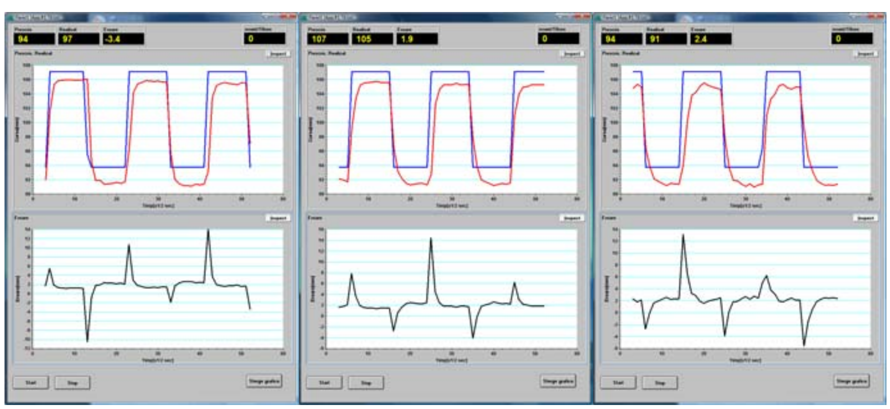

Fig. 10. Results for proportional gain P=5 and derivative parameter D=0.5, 1 and 1.5.

Test results have proven that digital control implemented with universal electronic module for mechatronic systems has expected behavior. Anyway, for other systems all tree control actions (Proportional, Integrative, and Derivative) can be used, their coefficient values can be downloaded into controller using existing serial communication line.

6. Conclusions

Mechatronic devices can be handled with modern system on chip devices obtaining similar performances with analog controllers but at lower costs. The advantages of digital control become obvious for certain mechatronic applications with slow movement but requiring higher precision like hydraulic axis.

Modern 16 bit microcontrollers integrate all peripherals required for industrial control and allow the implementation of complex control algorithms as well as sensor data processing in a single chip solution thus offering small size and low cost.

Presented work is a part of a mechatronic project for low-cost position control systems. Replacement of analog modules with digital electronics brings more options and greater flexibility to system designer and offers same performance level.

The originality aspects of the work come from the unique design of electronic board able to handle a large range of mechatronic systems. Also, the simple implementation of digital PID algorithm makes the module suitable for control of hydraulic applications like presses for recycling materials (chainsaw dust, PETs) or fruit and vegetables dryers.

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