

Design, Modelling and Testing of Mechatronic System Controlled with System-on-Chip Device

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Abstract: Mechatronic systems combine 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. Efforts were made to develop a universal electronic module for controlling mechatronic devices and a test mechatronic system to validate this module was design and implemented. The paper presents design, simulation, implementation and testing of a mechatronic system controlled by a single chip electronic module 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. 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).

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. 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 higher costs than components' costs. 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

The structure of a hydraulic-based mechatronic system, intelligent hydraulic axis, consists of electronic servo amplifier, servo-valve, hydraulic cylinder, load and position transducer (figure1).

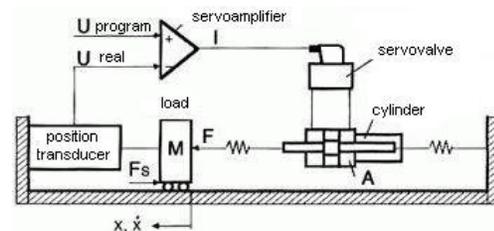


Fig. 1. Structure of a position control system.

This structure offers the advantages of hydraulics—high power density, simple transmission of power, ruggedness and long service life—with the flexibility of electronics. Integrated electronics automatically compensate the non-linearity of the

hydraulic system so positioning precision can reach the micrometers range.

Common interfaces for sensors, transducers and actuators in electro-hydraulic, electro-pneumatic and electro-mechanic control systems were identified and 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 figure 2:

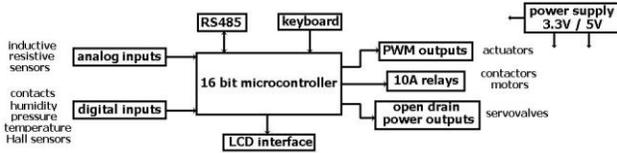


Fig. 2. Structure of a microcontroller based module for mechatronic applications.

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).

Keyboard interface has pull-up resistances and key connected to ground. To avoid picking noise, lower pull-up resistance value is used compared with microcontroller datasheet (1K instead of 100K). 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. Digital output lines can drive integrated sensors like humidity, temperature or pressure, Hall sensors for proximity detection or can extend number of control relays in conjunction with an extra relay board.

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. 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. The entire board is shown in figure 3:

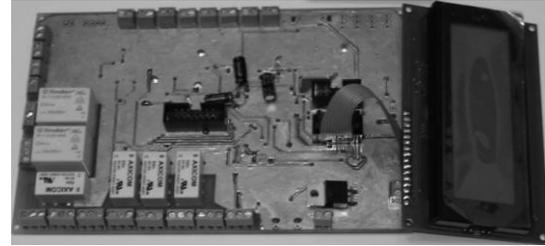


Fig. 3. Universal module for mechatronic systems.

The printed circuit board is a 2-layer design with separate planes for analog and digital ground (figure 3) to reduce noise level.

3. DIGITAL CONTROL ALGORITHM

Typical closed loop control system contains controller, actuator, controlled process and sensors. Sensors and actuators can be considered with linear behavior and neglected so closed loop can be described by the structure 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.

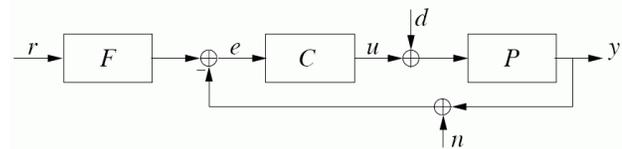


Fig. 4. Typical closed-loop control system.

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. PID control law in continuous time form is described by equation 1 ([4]).

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

Digital implementation of PID control laws requires discretization. Control variable can be directly calculated, as shown in discrete time control law called positional algorithm ([4]):

$$u(t_k) = K_p \left(e(t_k) + \frac{\Delta t}{T_i} \sum_{i=1}^k e(t_i) + \frac{T_d}{\Delta t} (e(t_k) - e(t_{k-1})) \right) \quad (2)$$

Incremental algorithm or speed form ([4]) can be obtained by expressing control variable at tk moment as function of its value in previous moment

$$u(t_k) - u(t_{k-1}) = K_1 e(t_k) + K_2 e(t_{k-1}) + K_3 e(t_{k-2}) \quad (3)$$

where K_i parameters are:

$$K_1 = K_p \left(1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t} \right) \quad (4)$$

$$K_2 = -K_p \left(1 + \frac{2T_d}{\Delta t} \right) \quad (5)$$

$$K_3 = K_p \frac{T_d}{\Delta t} \quad (6)$$

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) written in C language grouped in libraries for different peripherals and sensors and a universal main.c module that uses all these library functions ([1]). 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 a configuration file.

Action	Size (bytes)	Interrupt time	Main loop time
Serial communication	2000	50 μ s	200 μ s
Temperature measurement	500	10 μ s	100 μ s
Keyboard	500	5 μ s	10 μ s
PID control	1000	70 μ s	500 μ s
LCD display	1000	-	10 ms
Displacement measurement	500	30 μ s	50 μ s
Other tasks	2500	10 μ s	200 μ s
Total	8000	175 μ s	...

Tab. 1. Memory requirements and timings.

Firmware is written using interrupt-driving techniques and benefits from orthogonal RISC architecture of microcontroller. Communication protocol is a simple serial frame protocol implemented in two sets of libraries, one for microcontroller, and one for Windows software. PID control was implemented with positional algorithm (equation 7) with parameters described in equations 8, sampling time is 1 millisecond:

$$u(t_k) = K_p e(t_k) + K_i \sum_{i=1}^k e(t_i) + K_D (e(t_k) - e(t_{k-1})) \quad (7)$$

$$P = K_p \quad I = K_p \frac{\Delta t}{T_i} \quad D = K_p \frac{T_d}{\Delta t} \quad (8)$$

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 ([2]). 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 - slower, large events are divided and placed in available time windows between faster processes (communication and PID).

5. SYSTEM MODELING AND SIMULATION

A system model using standard mechanical and fluid flow equations was taken from hydraulics reference literature ([5]). This model was

implemented in Matlab Simulink by creating simulation schematics for position control system and its most complex component, the servovalve (figures 5-7).

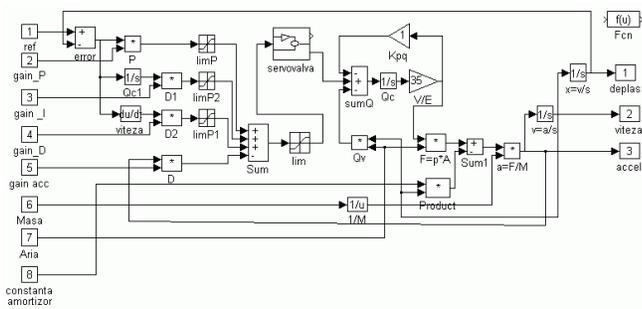


Fig. 5. Simulation schematics for position control system.

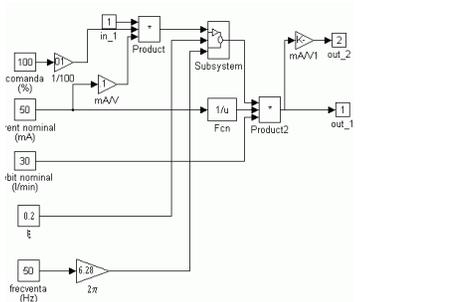


Fig. 6. Simulation schematics for a servovalve.

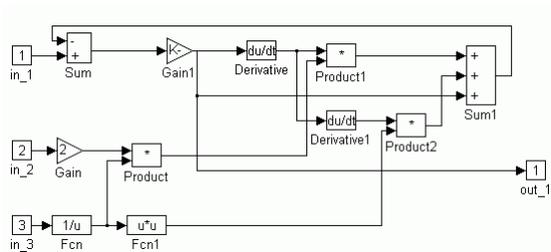


Fig. 7. Simulation schematics for subsystem of servovalve.

Resulted model was simulated and a set of results for different values of parameters of digital controller was obtained. Figures 8-14 show system response to rectangular signal for different P, I, D (time in seconds, displacement in meters).

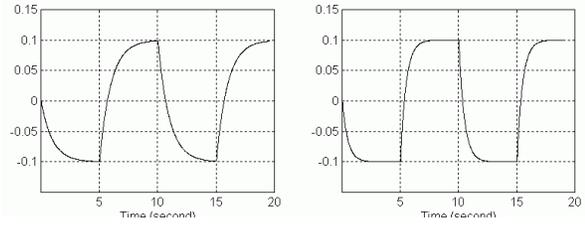


Fig. 8. Simulation for parameters P=1 / P=2.

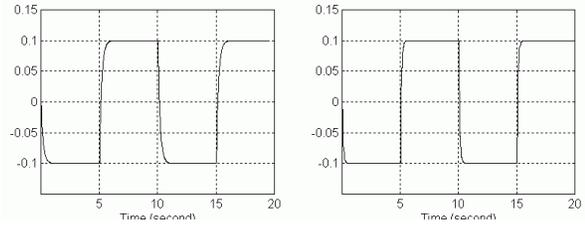


Fig. 9. Simulation for parameters P=5 / P=10.

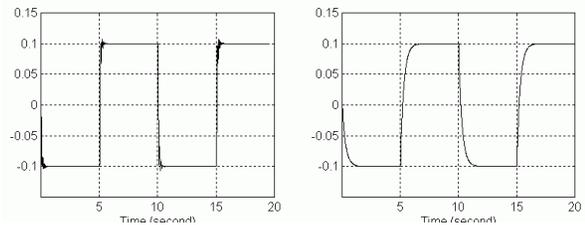


Fig. 10. Simulation for parameters P=15 / P=5, D=0.5.

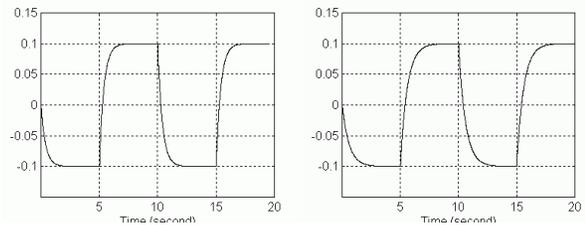


Fig. 11. Simulation for parameters P=5, D=1 / P=5, D=2.

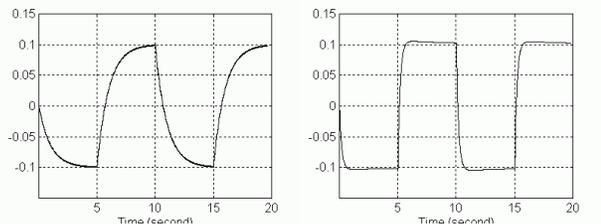


Fig. 12. Simulation for parameters P=5, D=4 / P=5, I=1.

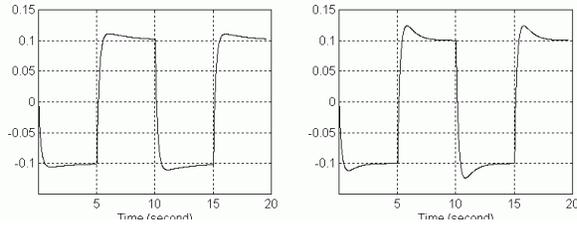


Fig. 13. Simulation for parameters $P=5, I=2 / P=5, I=5$.

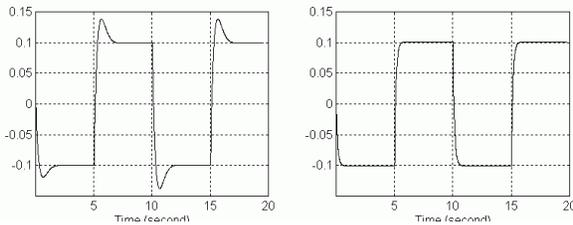


Fig. 14. Simulation for param. $P=5, I=10 / P=15, I=1, D=1$.

System behavior is typical for a PID-algorithm controlled process. The system becomes unstable and begins to oscillate for higher gains ($P>10$).

6. SYSTEM TESTING

Test for integrated electronic module for mechatronic systems are performed on a hydraulic damper test bench (figure 15) that contains pump unit, linear actuator (hydraulic cylinder) with attached displacement and force transducer. The test bench implements a position control system and is computer controlled with a software instrumentation application written in TestPoint environment.



Fig. 15. Measurement equipment setup and test bench.

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. TestPoint instrumentation software observes 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. Detailed view of application panel is shown in fig.16.

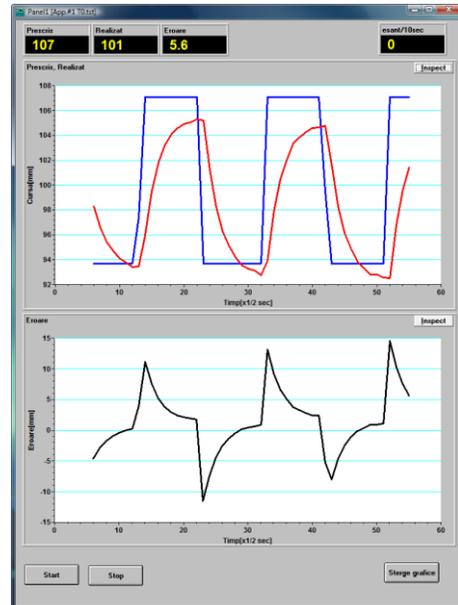


Fig. 16. Detail view of application window. System response with proportional gain $P=1$.

A first series of tests were performed with proportional gain only, no integrative or derivative action. Results are shown in figures 17 and 18; 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 19. Derivative action produces bad system response, as shown in figure 20.

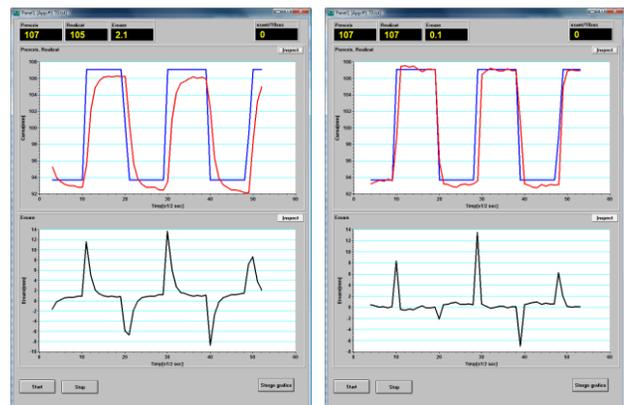


Fig. 17. Response for parameters $P=2 / P=5$.

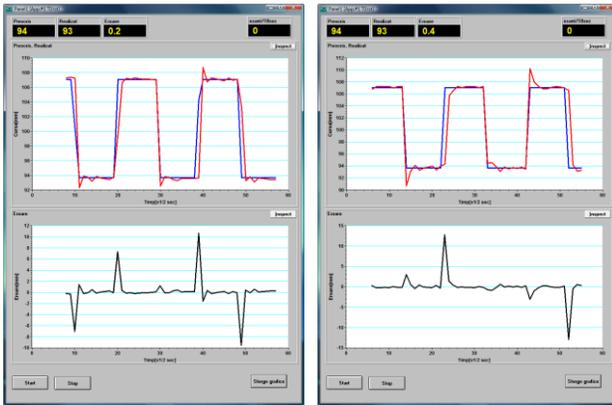


Fig. 18. Response for parameters $P=10 / P=15$.

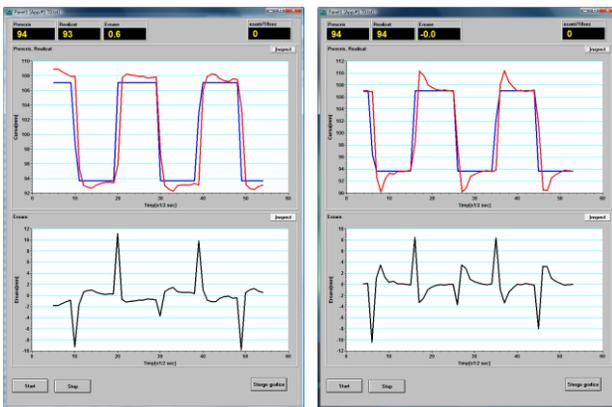


Fig. 19. Response for $P=5, I=0.001 / P=5, I=0.005$.

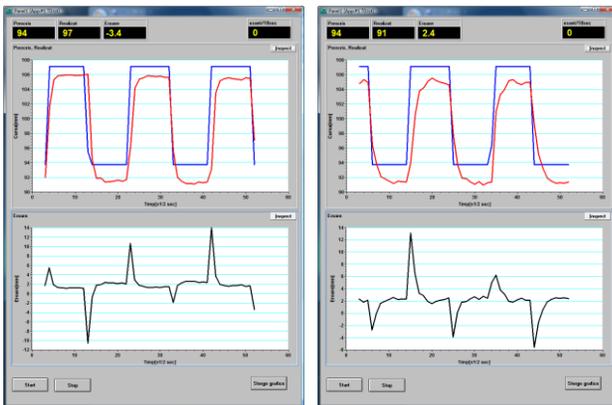


Fig. 20. Response for parameters $P=5 D=0.5 / P=5 D=1.5$.

For presented hydraulic system best response was obtained for P only controller $P=5-10$.

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

7. CONCLUSIONS

16 bit microcontrollers 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. Replacing analog modules with digital electronics offers to system designer same performance level but greater flexibility.

Modeling and simulation of simple mechatronic systems using standard software offer comparable results with real measurements and represent a useful tool for system designer.

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