

# The Low Cost Embedded Control of the Industrial Hydraulic Pulse System Based on PLC and State Machine Design

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**Abstract** – In the paper we describe the control electronics for an industrial test system based on a low cost PLC. The developed system is a hydraulic pulse system and it generates series of high pressure hydraulic pulses (max. 200bar) and is based on pneumatic-hydraulic circuits. We describe requirements, an overall concept of the embedded control system, user interface, security features and network connectivity. In the description of the software solution we describe implementation of hierarchical ordered program threads (multithreaded program) and main control state machine. At the conclusion, we describe the calibration method of the system and calibration curves, we present the schematic diagram and a photo of a functional prototype of the system.

**Keywords** - PLC programming, hydraulic pulse system, state machine, multithreaded program, ladder logic diagram

## I. INTRODUCTION

Our embedded control system for the hydraulic pulse system is based on the use of modern, low cost programmable controller (PLC)[1]. The modern PLC allows programming of the number of concurrently running separate programs (threads), which are represented as well-known ladder logic or flowchart diagrams. Each thread in our case implements a specific activity (or a task) and individual threads cooperate with each other so that as the result they create a reactive main control state machine [2].

## II. REQUIREMENTS FOR CONTROL OF THE HYDRAULIC PULSE SYSTEM. HYDRAULIC PULSE TRAIN

Our task was to create an embedded system for controlling the generation of hydraulic pulses series. The system controls up to four series defined by up to four adjustable parameters; the number of pulses (N), the maximum hydraulic pressure (p), hydraulic pulse duration (T1) and the duration of the pause (T0). Each series can be described as wagons of a train with some passengers (each WAGON has four passengers: N, p, T1, T2, see Figure 1, wherein WAGONS build so called "hydraulic pulse train". The hydraulic pulse train can cyclically repeat its orbit circle by set number of times (TRAIN SESSION). The number of WAGONS can range from 1 to 4. The embedded control system shall allow the user set the output hydraulic pressure in bar, set

parameters of wagons, the number of wagons and sessions of the train. It must allow systems calibration (the dependence of the output hydraulic pressure to the user's desired input hydraulic pressure) and it must ensure the generation of system and error messages.

## III. HARDWARE SOLUTION

### A. Pneumatic - hydraulic parts

This section describes the diagram in Figure 2 and the photo on Figure 4 below. Input air pressure is regulated by the proportional pneumatic valve. Regulated air is then fed into pneumatic four-way valve circuit and it controls the two-position pneumatic pump. This pneumatic circuit controls the two-direction movement of the hydraulic cylinder with resulting amplified hydraulic pressure at its output [5].

### B. Embedded control system

This section is described by the scheme in Figure 2. It was implemented on a programmable logic controller (PLC) [6] and certain additional modules (analog input - output, user interface LCD display and keypad, USB, RS232 and Ethernet). Input and output logic of the digital signal has levels 0 and 24V, analog outputs are in the range 0-10V, and analog inputs are in the range 0-5V. The used PLC is built on the basis ARM 32 processor and its operating system offers running of several independent program threads simultaneously. The run of each thread is conditional on any particular value, e.g. by the value of the hardware input signal or by the program controlled value of the internal program flag. So parallel programming in the PLC is based on the running separated threads, which can be also identified with the parallel implementation of separate running of independent (for PLC user familiar as) ladder logic or flowchart diagrams.

### C. User interface elements

The user interface consists from keypad, LCD display (4 rows x 20 characters), the manual switch between two basic modes of equipment (MANUAL mode and AUTO mode), the potentiometer for manual adjustment of output hydraulic pressure, the button to start of series hydraulic pulsation (PULSE mode), button to stop of pulses (the RESET button), security (or emergency) button to turn off the power of the appliance (EMERGENCY). The required values for WAGON and TRAIN parameters and the choosing of other equipment modes (e.g. calibration of the system) are entered from the in PLC build keypad.

#### D. Electrical parts of system

Electrical parts of our system are formed by a 24V power supplies, safety relay, electrical and optical relays, switches, terminals and wires and it will be seen in Figure 2 below.

#### E. Safety features

The basis of ensuring the safety operation of high pressure pneumatic - hydraulic system is the use of certified safety relay [7]. The safety relay can in the case of detecting of system errors switched off the power for the whole electrical power part of the equipment (but not for control PLC). Key safety sensors are connected in the series. In the case of detection of problems with any media (hw signals AIR or LIQUID) or detection of mechanical problems (hw signals DISTANCE ERROR or COVER EMERGENCY SWITCH), the series of connected contacts is interrupted, the safety relay responds, set the signal ERROR and witch off the power for hydraulic - pneumatic system in order to automatically reduce the output hydraulic pressure to minimum.

#### F. Network connectivity

Network connectivity of our control system is based on the PLC expansion module for connection to Ethernet LAN [8]. This communication module supports access to all program elements in the PLC multithreaded program (e.g. signals, flags, registers ...) via MODBUS protocol based on the TCP-IP protocol. As part of our PLC system we use also the MODBUS communication modules for both RS232 and USB. For our special purposes, we have developed the communication embedded server – the BUS and protocol converter between CAN bus (the proprietary testbench protocol) and RS232 (MODBUS protocol) (Figure 2). The CAN converter works on the hardware module OLIMEX occupied with 8 bit ATMEL AVR-CAN microcontroller [9]. The developed by protocol and BUS converter allows us to manage and to monitor hydraulic pulses unit even through CAN bus.

### IV. SOFTWARE SOLUTION

#### A. Basic functions

The programming approaches for modern PLC are well described in [3][4]. Modern low cost PLC, which allows running of several program threads gives the possibility to program main control state machine without having to create one long and complicated PLC program (ladder logic diagram or flowchart diagram). Each independent program thread can be initiated by hardware signal(s) (the PLC use 24V logic at input) or by internal programming flag with boolean data type (it can be set by another program thread).

#### B. List of PLC hardware inputs and outputs

Table 1 lists all digital and analog inputs and outputs are used in the project. Signals from the hardware inputs ERROR, WAIT, MANUAL, AUTO, PULSE and RESET are processing in the PLC by individual program threads (see Table 2) grouped in the so called physical layer. Some hardware signal inputs are used for indicating cause of the error in the safety power shutdown of the pneumatic - hydraulic system.

#### C. Physical layer threads

Physical layer threads (Table 2) are initialized by the hardware input signals, it ensures their processing and as a result it sets the outputs program flags. These outputs flags manage transitions between states in the master control state diagram (literally by start or by stop respective threads in the application layer). These programs threads also process of above mentioned inputs hardware signals and set of hardware output signals so as to permit the required settling time or another parameters for particular elements of pneumatic or hydraulic hardware (e.g. delay of relays, setting time of input valve etc.).

#### D. Application layer threads

The start of running of the application layer threads (Table 3) are initiated by changes of program flags received from the physical layer. Some threads from this layer create of individual states in the master control state diagram (Figure 3). In addition, these program threads enable the realization of sub states. For example, thread 2\_State\_Func ensures to call of sub state 6\_State\_Func. This thread ensures by manually set of parameters in the hydraulic pulse train. Next thread underpins subroutine for user input interaction such the 22\_State\_Func. It provides possibility manually input of calibration constants.

#### E. Description of the master control state machine

The main control state machine (Figure 3) is controlled by the program flags and is isolated from the hardware inputs signals. It is not implemented in one separate program thread. We met with reliable functions of high pressure hydraulic pulse system, with reliable answers to user (also confuse) inputs and to error status. We observed the reliable automatically generated ends of each pulsation cycle or hydraulic pulse train.

#### F. Auxiliary functions

Control of pulses sequence according parameters saved in the hydraulic pulse train ensures thread 7\_State\_Func which is called from the state PULSE (3\_State\_Func). The thread 6\_State\_Func ensures the users inputs for controlling of the actual content of hydraulic pulse train and is called from AUTO STATE (2\_State\_Func).

#### G. Input – output calibration of the system

The thread 6\_State\_Func ensures the manual input of calibration constants. The reason for calibration is simple: user works with bar units of pressure but PLC works with an internal representation of pressure in ADU units. The user calibration process is actually implemented within the MANUAL STATE, in the static mode (no pulse condition, manually controlled output hydraulic pressure). The user can obtain by measurements two calibration curves. The first calibration curve is adjustable characteristic between the output hydraulic pressure (measured with portable calibrated hand held hydraulic pressure measurement equipment from WIKA [5]) and the output voltage in ADU (measured via PLC itself) from the sensor output hydraulic pressure ATE PS60 (commercial produced hydraulic pressure sensor used in the cars, the manufacturer is ATE). In our case, we obtained a

linear relationship, which leads to the linear equation (1) derived by regression analysis from the graph of the measured values :

$$P_{WIK A} [bar] = A_{ATE PS60} \times P_{ATE PS60} [ADU] + B_{ATE PS60} \quad (1)$$

the value of the constant  $A_{ATE PS60}$  is 0.1021 [bar / ADU] and the value of the constant  $B_{ATE PS60}$  is 4.8074 [bar].

The second dependence is the static transfer function of the entire pneumatic - hydraulic system and its dependency output hydraulic pressure (in bar, measured by the same equipment [10]) depending on the values of the input voltage (measured in ADU units via PLC itself) for proportional pneumatic valve. Measurement leads to the next linear equation:

$$P_{WIK A} [bar] = A_{SYS} \times P_{SetInputValve} [ADU] + B_{SYS} \quad (2)$$

where the value of the constant  $A_{SYS}$  is 0.053 [bar/ADU] and the value of the constant  $B_{SYS}$  is 0.0626 [bar]. Both linear equations provide four calibration constants, which the user can enter to the control system (thread 6\_State\_Func). The user-entered value hydraulic pressure in bar input is thus obtained at the output as is required.

## V. CONCLUSION

We have created an embedded control system as a control unit for high pressure hydraulic pulse system to able be calibrated, accurate, robust and network connective. This hydraulic pulse unit is a part of the test machine, which can be deployed in the industry for the tests of hydraulic parts. In respect of software architecture, the control system is built on the base low cost PLC architecture and the set of concurrent program threads. Each thread can be identified with one ladder logic or flowchart diagram. The multithreaded PLC program is designed as not one large and opaque linear program, but as the group of mutually communicating PLC programs, which in the final they form one master control state diagram. Our possible contribution is in the introduction of collaborating layers (physical and application layers) at the low cost PLC platform (without need of high-level language programming – also it can be our possible contribution to education). Also we see as important the implementation of the master control state machine with these two layers and own developing of the CAN-MODBUS converter. The price of described networked embedded control system with industrial standard 24V optoelectronic isolated interfaces does not exceed 300 Euro, all control system (PLC + certified safety relay + electrical parts) came to € 1,000.

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Figure 1. Hydraulic pulse train –the schematic of sequence pulse control for hydraulic pulse system represented as train's cyclic sessions

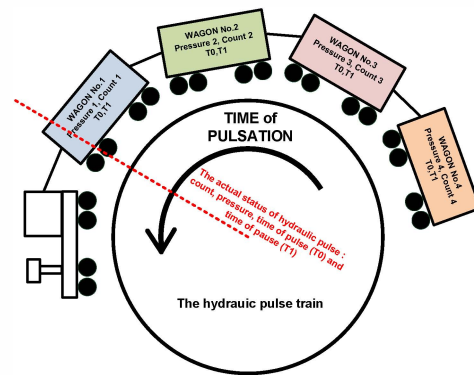


TABLE I. THE LIST OF PLC HARDWARE INPUTS AND OUTPUTS

n.	Name of hardware signal	Signal Direction/ Digital / Analog	Signal is processed in the independent thread	Description of physical signal
1	ERROR	I0-input	Physical layer 4_ERROR	From safety relay
2	MANUAL	I1-input	Physical layer 1_MANUAL	User input, manual control
3	AUTO	I2-input	Physical layer 2_AUTO	User input , pulse gen.
4	PULSE	I3-input	Physical layer 3_PULSE	User input , start of pulsing
5	RESET	I4-input	Physical layer 5_RESET	User input, stop of pulsing
6	AIR_ERROR	I5-input	Application layer 4_State_Func	From pressure air tank switch
7	LIQUID_ERROR	I6-input	Application layer 4_State_Func	From hydraulic tank switch
8	DISTANCE_ERROR	I7-input	Application layer 4_State_Func	From distance contact switch
9	PNEU_PUMP	Q0-output	Application layer 1_State_Func and 3_State_Func	For pneumatic pump control
10	PULSE_RELAY	Q1-output	Application layer 3_State_Func	For pulse control generation
11	HYDR_PRES_SENSOR	AI0-input	All application layers	From hydraulic pressure sensor
12	MANUAL_PRES_SET	AI1-input	Application layer 1_State_Func	From user man. potentiometer
13	PNEUMATIC_VALVE	AU0-output	Application layer 1_State_Func and 3_State_Func	For proportional valve control

TABLE II. THE LIST OF PHYSICAL LAYER THREADS

n.	Name of thread	Signal condition for perform of the thread	Program switches the flag to ON	Conditionally can set also	Description of program thread
1	4_ERROR	Signal ERROR = ON	State_FLAGS_4_ERROR	PNEU_PUMP(OFF) PULSE_RELAY(OFF)	Safety relay output processing
2	0_WAIT	Signal ERROR = ON	State_FLAGS_0_WAIT		Wait state
3	1_MANUAL	Signal MANUAL = ON AND ERROR = OFF	State_FLAGS_1_MAN	State_FLAGS_0_WAIT	User input, manual control mode
4	2_AUTO	Signal AUTO = ON AND ERROR = OFF	State_FLAGS_2_AUTO	State_FLAGS_0_WAIT	User input , pulse generation mode
5	3_PULSE	Signal PULSE = ON AND ERROR = OFF	State_FLAGS_3_PULSE	State_FLAGS_0_WAIT	User input , start of pulsing
6	5_RESET	Signal RESET = ON AND ERROR = OFF	State_FLAGS_2_AUTO	START_BUTT_ON	User input, stop of pulsing

TABLE III. THE LIST OF APPLICATION LAYER THREADS

n.	Name of thread	Flag condition for perform of the thread	Description of program thread, see Figure 3 master control state diagram for hydraulic pulse system
1	0_State_Func	State_FLAGS_0_WAIT = ON AND ERROR = OFF	WAIT STATE, Initialization of calibration constants , zeroing of the ATE pressure sensor
2	1_State_Func	State_FLAGS_1_MANUAL = ON AND ERROR = OFF	MANUAL STATE, manual control of output hydraulic pressure via manual potentiometer
3	2_State_Func	State_FLAGS_2_AUTO = ON AND ERROR = OFF	AUTO STATE, setting of parameters for hydraulic pulse train : WAGON parameters numbers of TRAIN WAGON and number of TRAIN SEASSON, manual calibration constants inputs (sub state: 22_State_Func)
4	3_State_Func	State_FLAGS_3_PULSE = ON AND ERROR = OFF	PULSE STATE, performing of hydraulic pulsation according of parameter settings, after finish of pulsing goes automatic to AUTO MODE ( FLAGS_2_AUTO = ON, FLAGS_3_PULSE = OFF)
5	4_State_Func	State_FLAGS_4_ERROR	ERROR STATE , Safety relay determined, determination of the error source
6	5_State_Func	State_FLAGS_5	Sub state of PULSE STATE, measurement of the maximum of the hydraulic pulse peak during PULSE MODE (during the pause time and during the pulse time )
7	6_State_Func	State_FLAGS_21_QSET	Sub state of AUTO STATE, user setting of parameters for four TRAIN (T0,T1, COUNT, PRESSURE)
8	7_State_Func	State_FLAGS_7	Sub state of PULSE STATE, actual modification of parameters after one TRAIN SESSION

Figure 2. Schematic diagram of the developed hydraulic system and PLC based control system

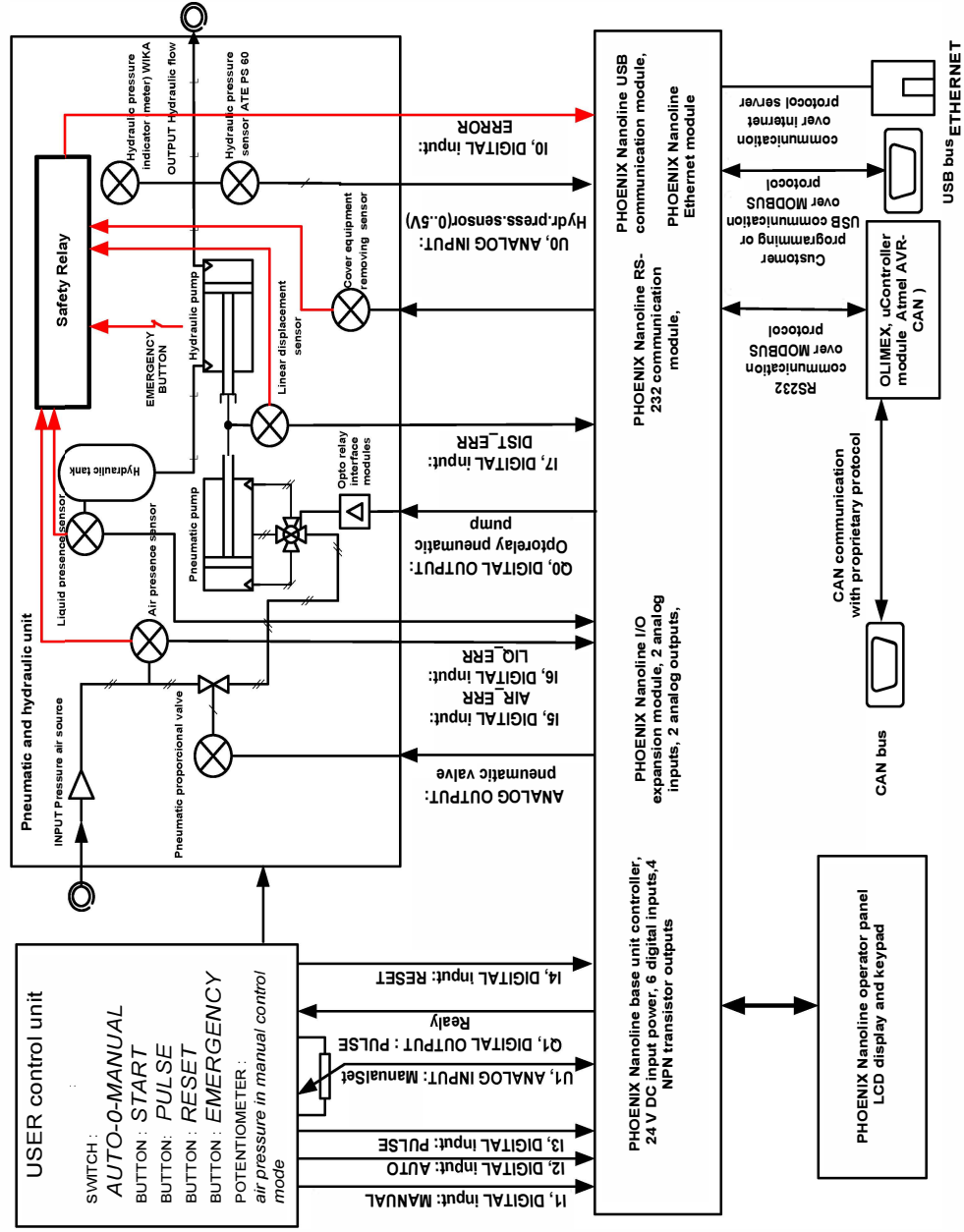


Figure 3. The master control state diagram for hydraulic pulse system

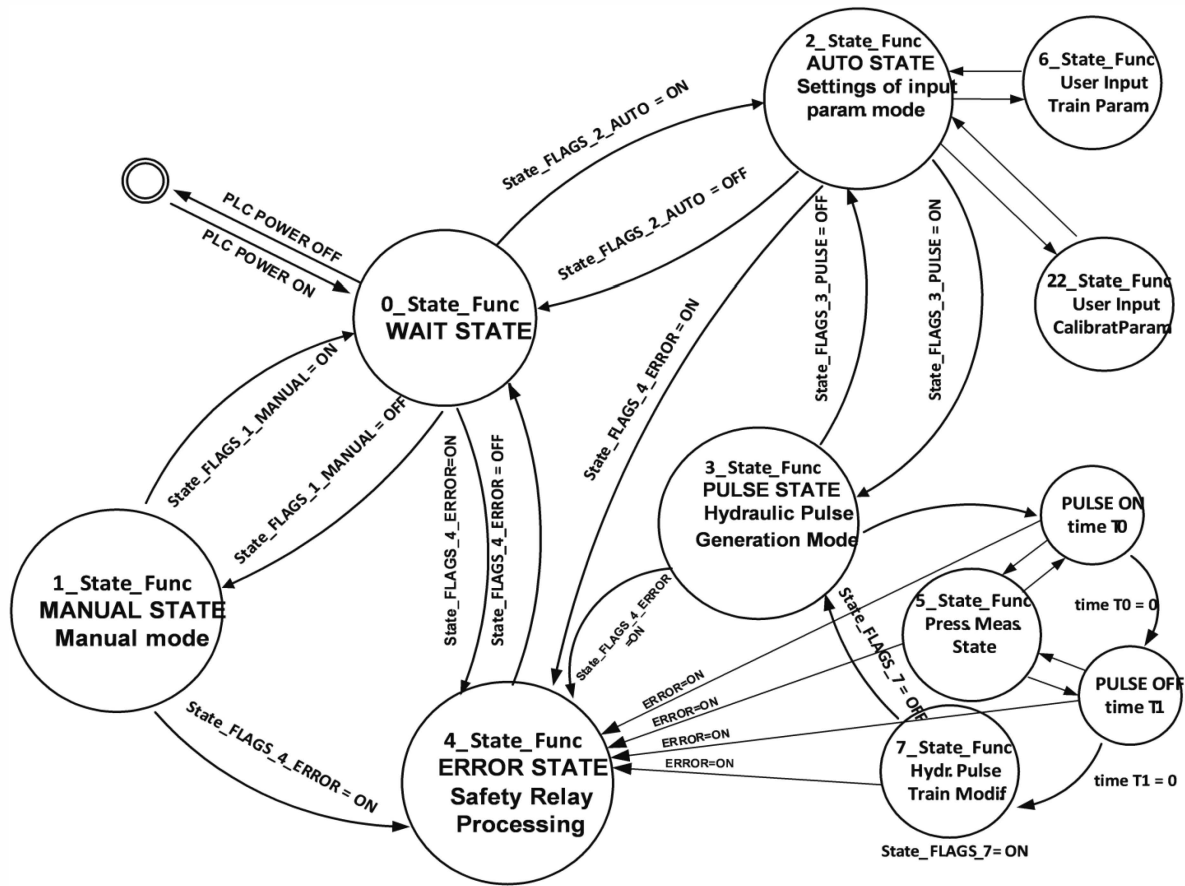


Figure 4. The photo of the functional prototype of the hydraulic pulse system

