

Discrete sliding mode control realised with MicroLogix 1400 and S7-1200 Siemens in industrial environment

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Abstract - This paper shows the possibility of realizing robust control in the form of Discrete Sliding Mode Control (DTSMC) using MicroLogix 1400 and S7-1200 series PLC controllers. Both series of PLC controllers are primarily intended for less demanding applications and can only control industrial processes using PID instructions. Examples are given for processes that can be identified by first or second order models with or without delay (FOPDT), (SOPDT). Model identified in this way is translated into a model in the form of a differential equation in state space, and then, using Euler's method, it is translated into a discrete time system described by the model with and without disturbance based on a properly selected period of discretization. Based on the model in the state space, and the selection of the appropriate digital sliding mode controller (SMC), the control system is implemented using commands from the instruction set of PLC. The periodicity of the execution of the control law is made possible by the use of interrupt routines from PLC, which are executed with a period corresponding to the discretization period. With this, the field of application of the mentioned series of PLC controllers has been extended to the regulation of non-linear processes using SMC controllers.

Keywords - MicroLogix 1400, Euler Approximation, Non-linearity process, Discrete Sliding Mode Control.

I. INTRODUCTION

Allen Bradley MicroLogix 1400 (ML1400) [1-4] and Siemens S7 1200 (S7-1200) [5, 6] PLC controllers are intended for control smaller industrial applications. They are equipped with instructions for controlling sequential and processes that are regulated using PID control laws [1, 5]. In ML 1400, 1-DOF (One Degree of Freedom) PID instruction is implemented, while in S7-1200, PID instruction is implemented in 2-DOF (Two Degree of Freedom), which makes it more advanced in terms of tracking performance and disturbance rejection.

The number of PID instructions for ML1400 and S7-1200 PLC series usually ranges from 2 to 16, and on the physical side it is limited based on the maximum number of analog inputs and outputs and in terms of the maximum number of installed analog modules [1, 2, 5, 6] and instruction execution time. PID control [7, 8] is primarily intended for linear systems or systems that can be

considered linear, i.e., linearized and with the requirement to operate near the operating point.

The paper presents the implementation of robust control in the form of an extension to variable structure controllers (VSC) [9, 10] for processes that can be identified by models with the transfer function of the first (FOPDT) and second order (SOPDT) [7] with limitations in terms of delay time and neglecting poles with less impact on the system. The variable structure controller (VSC) belongs to the class of nonlinear discontinuous control laws and as such is primarily used in nonlinear systems. Modeling and creating control algorithms is not a trivial task, but considering that SMC is characterized by good features in terms of robustness to disturbances, it makes it attractive for use in applications developed for small and medium-sized PLC controllers. The main limitation in the implementation of SMC control using a microprocessor or microcontroller, is reflected in the occurrence of unwanted quasi-sliding movement [10] near the sliding surface, which is manifested by a high-frequency control signal that reduces the life cycle of control components. This limitation has recently been overcome by suitably chosen control laws and the use of solid state relays (SSRs) instead of relays with mechanical contacts.

With this work, an attempt was made to expand the area of application of the ML1400 and S7-1200 PLC to the regulation of non-linear processes with a single input and output (SISO) that can be reduced to the previously mentioned models.

This paper is organized as follows. In part 2, the modeled problem formulation and the DTSMC problem formulation and control laws are described. The implementation of DTSMC with PLC is presented in Sec. 3. Conclusions are presented in Sec. 4.

II. PROCESS MODEL AND DESIGN DTSMC CONTROLLER

The process model is identified by simple graphical methods as a first-order system with delay (1) (FOPDT) or as a second-order system with delay (2) (SOPDT) [7]. The transfer functions (1) and (2) can be well approximated by developing an exponential function in the Taylor series for small τ , $|\tau| < 1$, where in the case of identification with model (2) it is assumed that T_l is the dominant time constant, on the basis of which model (4) is obtained. The

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goal of this approximation is to replace the real transferable function with a simpler one, all with the aim of simplifying the implementation of the control:

$$W(s) = k_p \frac{e^{-\tau s}}{T_1 s + 1} \quad (1)$$

$$W(s) = k_p \frac{e^{-\tau s}}{(T_1 s + 1)(T_2 s + 1)} \quad (2)$$

Model (4) simplifies the analysis and design of the variable structure controller:

$$e^{-\tau s} \approx 1 - \tau s \approx \frac{1}{1 + \tau s} \quad (3)$$

$$W(s) = k_p \frac{1}{(T_1 s + 1)(\tau s + 1)} \quad (4)$$

Based on equation (4), the process model (5) was derived, and translated into the canonical form (6), by applying the $x_1 = x$, $\dot{x}_1 = x_2$:

$$\ddot{x}_1 \tau + (T_1 + \tau) \dot{x}_1 + x_1 = k_p u(t) \quad (5)$$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -a_0 x_1 - a_1 x_2 + b u \end{aligned} \quad (6)$$

System (6) after discretization using the Euler forward approximation (7) was translated into the discrete domain (8), where T_s is the discretization period, which enables the realization of the model in the PLC controller:

$$\dot{x}(t) \approx \frac{x_{k+1} - x_k}{T_s} \quad (7)$$

$$x_{k+1} = A x_k + B u_k \quad (8)$$

The obtained model (8) is taken as the nominal model, $x \in R^2$ is the state coordinate vector, and $u \in R^1$ control, without diminishing the generality, equation (9) presents the real model as deviation from nominal, $d \in R^1$ is disturbance.

$$x_{k+1} = A x_k + B u_k + E d_k \quad (9)$$

For model (9), a discrete control law (DTSMC) was implemented in the form:

$$u_k = u_k^{eq} + u_s \quad (10)$$

where u_k^{eq} is equivalent part of control (10):

$$u_k^{eq} = -(c^T B)(c^T A x_k - s_k) \quad (11)$$

and u_k^s switching part of control (10):

$$u_k^s = -(c^T B)k \operatorname{sgn}(s_k) \quad (12)$$

where is the sliding surface s_k given as:

$$s_k = c^T x_k \quad (13)$$

In the beginning, it was said that the DTSMC controller of the second order is realized, so the parameters are vectors $c^T = [c_1 \ c_2]$ determined based on the conditions of the system of equations (11) so that the system (9) without disturbances and when applying equivalent control (11) is stable:

$$\begin{aligned} c^T x_k &= 0 \\ x_{k+1} &= (A - B(c^T B)^{-1} c^T (A - I)) x_k \end{aligned} \quad (14)$$

The choice of the dynamics parameter of the switching part of the control comes down to determining the parameter k so it is (15) [11]:

$$k > |c^T E w_k|_{\max} \quad (15)$$

III. REALIZATION OF DTSMC CONTROL USING A SELECTED PLC CONTROLLER FOR TEMPERATURE REGULATION

To identify the heating process of the extruder zone, which was modeled using the model shown in Fig. 1, model (1) was used, and based on approximation (3) the following parameter values were obtained: $k_p = 3.95$, $\tau = 82.63s$ and $T_1 = 124.67s$.



Fig. 1. Model of extruder zone

The model in Fig. 1 consists of a solid steel plate on which a 150W plate heater and a cooling fan are mounted on the bottom. The measurement of the current temperature value is performed using a type J thermocouple, which is connected to the ML1400 1766 L32-BWA PLC controller via an analog module 1762 IT4. The heater is switched on and off using a relay that switches the contactor on and off or using a voltage-controlled SSR relay (0-10V DC) obtained using the analog module 1762 IF2OF2 and a suitably written program. When using the S7-1200, the S7-1212 AC/DC/Rly with the appropriate analog modules is

used.

By applying equations (5-8), an approximation of the real process is obtained in the form of a differential equation (16), which is implemented by software written using the instructions of the selected PLC controller and placed in a suitably selected interrupt routine by taking the process value (pv) and control value (cv) as the input and output.

$$pv_k = A_1 pv_{k-1} + A_2 pv_{k-2} + B_1 cv_{k-1} + B_2 cv_{k-2}. \quad (16)$$

Model (16) can also be obtained using a PLC controller by recording the values for pv and cv taking a second-order model in the discrete domain (z -domain) as the system model. In the case of software implemented for the ML1400 PLC, the values for pv_k , pv_{k-1} , pv_{k-2} , cv_{k-1} and cv_{k-2} placed in the registers for placing the Float Point values of the PLC controller in the locations F8:0, F8:1, F8:2, F8:3, F8:4 respectively.

For the design of the DTSMC controller for temperature control of the extruder zone model, it is necessary to reflect the set temperature. For this purpose, model (9) is translated into error space using the relation:

$$x = x_d - e \quad (17)$$

where x is the current, x_d the given temperature value and e is the error, whereby the model is obtained in the form:

$$\begin{aligned} x_{1k+1} &= x_{1k} + T_s x_{2k} \\ x_{2k+1} &= -a_0 T_s x_{1k} + (1 - a_1 T_s) x_2 - b T u_k + T a_0 x_{dk} \end{aligned} \quad (18)$$

and the sliding surface is given in the form:

$$s(t) = \lambda e + \dot{e} \quad (19)$$

where the error e (17) is expressed in the discrete domain as:

$$e_k = x_{dk} - x_k \quad (20)$$

and the derivative of the error e is approximated using backward Euler approximation and the sliding surface is obtained in the form:

$$s_k = c_1 e_k + \lambda \frac{e_k - e_{k-1}}{T_s} \quad (21)$$

where is $c_2 = \lambda/T_s$.

For the system thus obtained, the control law (10) was implemented using a PLC controller for which interrupt routines were used, which represent a mechanism that enables the execution of parts of the program that are time-sensitive, the use of which enables the execution of the program code in exact time intervals that correspond to the

selection period. The interrupt routine contains a part of the program code that deals with the calculations of the values of the state coordinates, the sliding surface and the control.

The ML1400 supports interrupt routines within the Selectable Timed Interrupt (STI) function file [1], while the S7-1200 supports interrupt routines within the Cyclic Interrupt Organization Block (OB30-OB38) [5]. The interrupt routine call time is set so that it must be equal to the selection period. For both series of PLC controllers, the minimum time defined by the manufacturer is $t_{\min} = 1\text{ms}$, but it should always be taken into account that the actual execution time depends on the complexity of the entire code, the time required to read the input value and set the output value and the time required for communication, so the manufacturer's general recommendation is that the interrupt routine call period should not be less than 100ms , so that the selection period when implementing the DTSMC control law should not be less than the specified recommendation.

The program code for the ML1400 and S7-1200 PLC consists of the main routine within which other routines are called and the interrupt routine that is automatically executed with a preset period. The part of the RSLogix500 and TIAPortal V15 user software used to set the interrupt routine parameters is shown in Figs. 2 and 3 for the ML1400 and S7-1200 PLCs respectively.

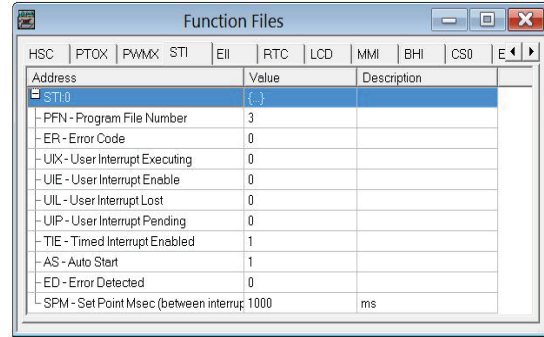


Fig. 2. ML1400 Interrupt Routine (STI) parameter setting

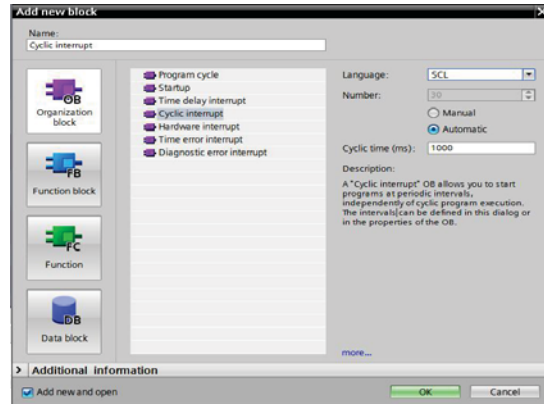


Fig. 3. S7-1200 Interrupt Routine parameter

For the sampling time period for the implemented temperature control, $T_s=1000ms$. The sliding surface equation (21) was also implemented in the interrupt routine according to the equations below and the program written using the instructions of the selected PLC controller according to equation (22). where the set temperature value sp is placed in the register F11 at location F11:4, and the values of the vector parameters $c^T=[c_1 \ c_2]$ are placed respectively at locations F13:0 and F11:1 when using ML1400, and when using S7-1200 a separate Data Block is created.

$$s_k = c_2(pv_{k-1} - pv_k) + c_1(sp_k - pv_k) \quad (22)$$

The software for the ML1400 was written using Ladder Diagram (LAD) instructions, the software for the S7-1200 using Structured Control Language (SCL) instructions. Part of the software for the realization of the sliding surface when using the ML1400 PLC is shown in Fig. 4.

For the vector c , the values according to (14) $c^T=[0.021 \ -1.14]$ and the parameter $k=37.56$ where taken. Part of the software for the realization of the sliding surface when using the S7-1200 PLC is shown in Fig. 5.

When using the control (10) and the ML1400 PLC controller, the response Fig. 6 to the set temperature value of $80^\circ C$ was obtained, starting from an ambient temperature of $23^\circ C$ (see Fig. 6), where the control signal was implemented by a program written in the LAD language shown in Fig. 7. The control signal is shown in the range of engineering units corresponding to the value of the PLC controller location in which the control signal value is located in the range from -16384 to $+16383$, which corresponds to a DC voltage in the range from -10 to $+10$ V. The response to a step change in the set temperature value starting from $80^\circ C$ to $100^\circ C$, $120^\circ C$ and $150^\circ C$ is given in Fig. 8, where the corresponding control signal is expressed in the range of engineering units shown in Fig. 9.

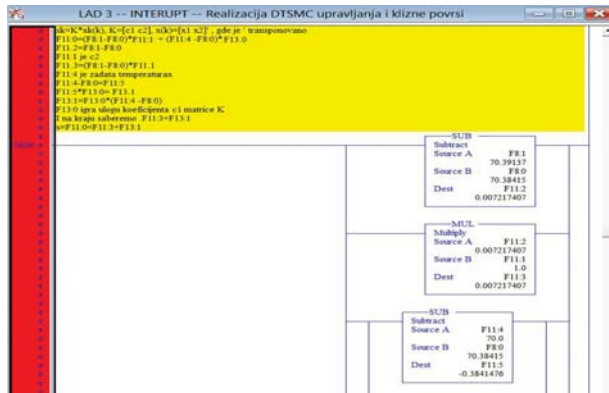


Fig. 4. Part of the software code for the realization of the sliding surface (ML1400 PLC)

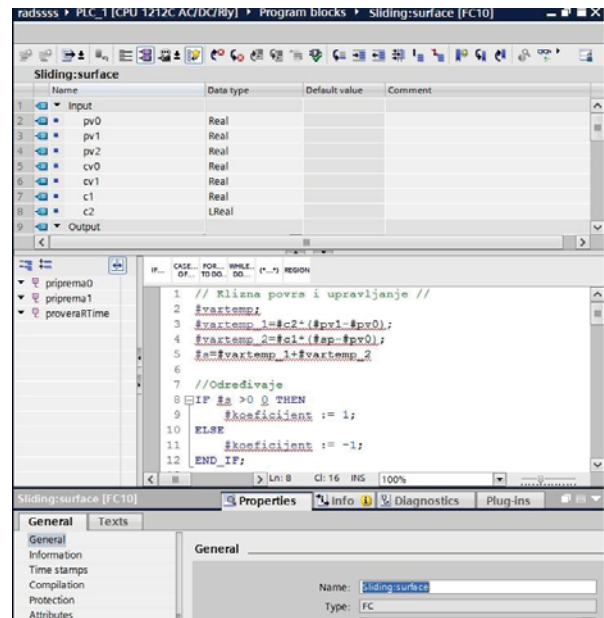


Fig. 5. Part of the software code for the realization of the sliding surface (S71200 PLC)

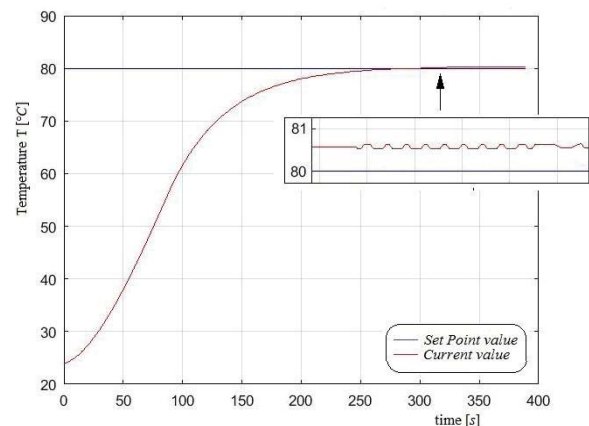


Fig. 6. Temperature response for set temperature of $80^\circ C$

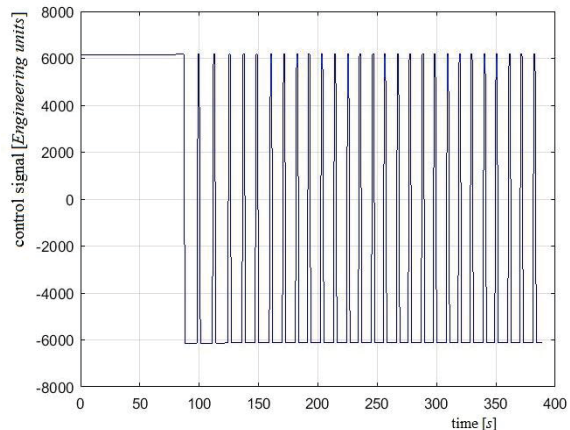


Fig. 7. Control signal for a set temperature of $80^\circ C$

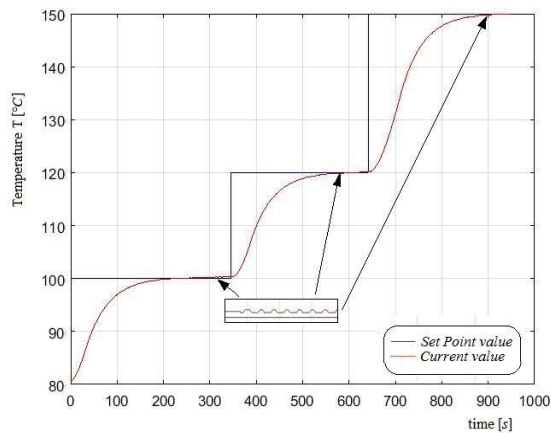


Fig. 8. Temperature response for a step-by-step temperature setpoint

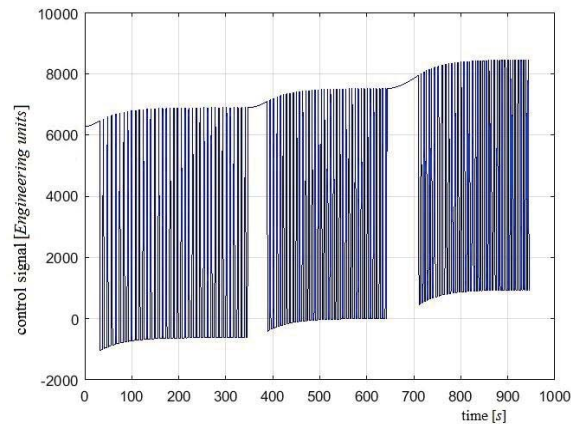


Fig. 9. Control signal for a step-by-step temperature setpoint

IV. CONCLUSION

The purpose of small PLCs is to control simpler processes using sequential algorithms and PID control laws. The paper shows the possibility of expanding their use in controlling nonlinear processes using DTSMC control laws on the example of temperature control. The main limitation is reflected in the choice of the value of the sampling period, which must not be less than 0.1s. The application is fully justified and possible in the case of slower industrial processes such as temperature, level, and pressure control.

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