

Implementing Discrete Control for the Horizontal Positioning of an Industrial Manipulator Using MATLAB

Iulia Clitan, Vlad Muresan, Mihail Abrudean, and Andrei Florin Clitan

Abstract—The presented paper describes the implementation of a discrete control law, for an industrial manipulator, using MATLAB as computer software. The software implementation is done in order to test the overall performances of the discrete control law, since the on-site testing is not possible due to the continuous functioning of the industrial manipulator as an unloading billets machine from a rotary hearth furnace, part of the hot rolling process. First, the magnitude optimum criterion, the Kessler variant, is applied as tuning method for the industrial manipulator's positioning system since the continuous model is already known, due to prior research. Further, the discrete control is derived from the pulse transfer function yielded from digitizing the continuous control. The discrete control law is implemented as a discrete control structure using unit delay blocks and as a dependency law using the MATLAB function block. The overall performances are tested, and they meet the performance expected by Kessler's tuning method.

Index Terms—Positioning system, industrial manipulator, magnitude optimum criterion (the Kessler variant), discrete control, dependency law.

I. INTRODUCTION

Manipulators are used in different branches of industry with high frequency, due to their robustness and ability to handle heavy loads, among others [1]–[4]. The present work describes the movement control of an industrial manipulator that is part of a hot rolling process [5]. This manipulator is designed to extract billets, from a rotary hearth furnace, that were heated at temperatures of up to 1300°C [6], [7]. Throughout the production chain several types of manipulators are in use, due to high temperatures and billets' loads. Moreover, due to the unfavorable working environment [8], the control of such industrial manipulators must be an automated one.

The industrial manipulator of interest is an electro-hydraulically one, and Fig. 1 shows its main components: the manipulator's pliers and a mobile arm capable of rotating around a static point, thus achieving a horizontal movement. The manipulator can also perform an advance movement or lowering/lifting the manipulator's arm, movements that require simple control, since the predetermined lengths of such movements are already known. A more complex and precise control strategy is required

however for the horizontal movement of positioning the pliers over the billet. Thus, this mandatory positioning control system represents the focus of the current research, since there is no admittance of heating any adjacent billets since this would result in waste of material.

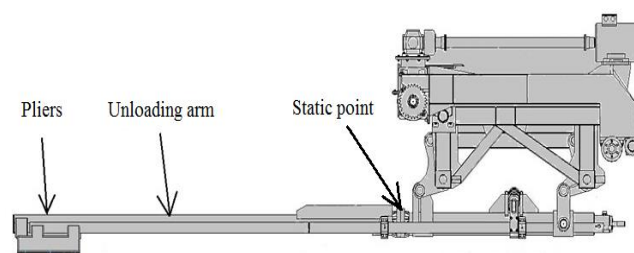


Fig. 1. Side view of the industrial manipulator and its main components [10].

The authors' prior research generated a continuous model for the movement of this manipulator in a horizontal plane [6]–[10], thus this would be the starting point of the present research. Based on a set of experimental data a continuous model, as the described $G_{sys}(s)$ transfer function, was previously obtained for the horizontal positioning process of this industrial manipulator, [6], [9]–[12]:

$$G_{sys}(s) = \frac{18}{(3s+1)(0.25s+1)} \quad (1)$$

The reference signal is a step type reference since it is represented by the displacement of the billet, to the right or to the left, from the industrial manipulator's axis (corresponding to the billet's extraction position) and the output of the process is considered to be the current position of the industrial manipulator, during the horizontal positioning.

The desire to implement an automatic control law on a cost-effective numerical device arises the need of obtaining a simple discrete control law for this system [13], [14], this being the aim of this paper. The authors choose to design a continuous control law, using the magnitude criterion, the Kessler variant. Further, the pulse transfer function and discrete control laws are obtained by digitizing the continuous control law using Zero Order Hold method [15]. The discrete control laws are implemented in MATLAB Simulink to test and validate the overall performances, since on site validation prior to the real implementation is not possible, due to the continuous technological flow of hot rolling process [16].

II. THE MAGNITUDE CRITERION, THE KESSLER VARIANT

The chosen tuning method is a criterion that allows

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optimal tuning of controllers for fast processes, without time delay. Such criterion ensures good behavior for the control structure at different references and disturbances. The criterion ensures the accuracy of the system at a step reference signal, a 4.5% overshoot and a settling time of about $6.73 \cdot T_{\Sigma}$.

A fast process has some dominant time constants, noted T_k , and some parasites ones, noted T_{Σ} , with a dependency between the two as follows:

$$(5 \div 10) \cdot T_{\Sigma} \leq T_k \quad (2)$$

The horizontal positioning system is a fast process, since the process transfer function given in (1) complies with the dependency given in (2). The dominant time constant T_k equals 3 seconds and the parasite time constant equals 0.25 seconds. Moreover, it is a process without poles in origin, thus the controller's transfer function, according to the magnitude criterion, is:

$$H_C(s) = \frac{sT_k + 1}{2 \cdot k_f \cdot T_{\Sigma} \cdot s} \quad (3)$$

The continuous controller's transfer function is obtained as:

$$H_C(s) = \frac{3s + 1}{2 \cdot 18 \cdot 0.25 \cdot s} = \frac{3s + 1}{9s} \quad (4)$$

As can be noted, the resulted control law is a PI one, being a simple control law that guarantees zero steady state error at a step reference signal, thus a precise positioning control.

III. DIGITIZING THE CONTROLLER'S TRANSFER FUNCTION

This section deals with the conversion of the continuous PI transfer function into a discrete one and representing the resulting pulse transfer function in a discrete form, as a discrete dependency law between the control signal and the error signal.

The conversion of a continuous transfer function to a pulse transfer function one is done by means of the z -transform approximations. The method used for this conversion is the zero-order hold (ZOH), since it substitutes the digital to analog converters. The parameter necessary for de digitizing of the control law is the sample time, chosen as to comply with the Shannon theorem. Thus, the authors choose a sample time of 0.03 seconds [17]. The resulted discrete transfer function for the PI controller yielded from the magnitude criterion is given in (5):

$$H_C(z) = \frac{C(z)}{E(z)} = \frac{0.3333 - 0.33z^{-1}}{1 - z^{-1}} \quad (5)$$

where $C(z)$ represents the discrete control signal, and $E(z)$ represents the discrete error signal.

By cross multiplication we obtain the discrete dependency law, between the discrete control and the discrete error signal, as:

$$C(z) = 0.3333E(z) - 0.33z^{-1}E(z) + z^{-1}C(z) \quad (6)$$

From the above dependency law, the difference equation is deduced as (7), denoting that the control signal at each instant can be computed as an iterative procedure, depending on current and past values of the error signal and on past value of the control signal.

$$c_k = 0.3333 e_k - 0.33e_{k-1} + c_{k-1} \quad (7)$$

where c_k represents the current value of the control signal, e_k represents the current value of the error signal, e_{k-1} represents the error signal delayed with one sample time, c_{k-1} represents the control signal delayed once.

IV. DISCRETE CONTROL LAW IMPLEMENTATION USING COMPUTER SOFTWARE

The validation of the above discrete transfer function is done via computer simulation, using MATLAB, and by implementing the difference equation as an input-output structure with unit time delay blocks and implementing the discrete control law using MATLAB function block. The two implementations are compared based on the overall performances at unitary step type reference signals, and the performances imposed by the design method are verified.

A. Input-Output Control Structure with Unit Time Delays

Starting from the difference equation (7), a block structure is derived. This structure is implemented in MATLAB Simulink by converting the discrete dependency law as an input – output structure with unit delay blocks. The input is represented by the error signal while the output is represented by the control signal. The sample time of each delay block is set at 0.03 seconds (the sample time chosen for the digitizing of the controller's transfer function), and each delay block is used to generate the past value of the corresponding signal.

The resulted structure is depicted in Fig. 2, and it represents the exact implementation of the difference equation.

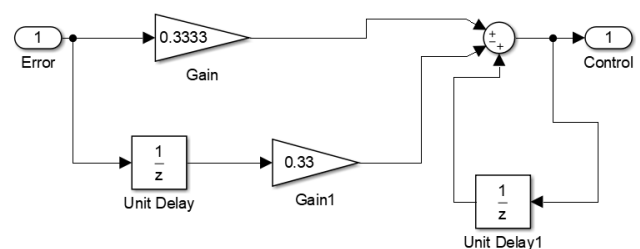


Fig. 2. The input-output discrete control structure with unit delay blocks.

B. Discrete Control Law Using MATLAB Function Block

As stated before, the past values of either the reference or the control signal represent the concerned values delayed with one sample time.

The input of the continuous controller, or of the discrete control structure with unit delay blocks, is given by the error signal, while for a discrete controller implemented on a numerical device the error signal must be computed within the control law (as the difference between the reference

signal's value and the output signal's value at each instance). Thus, the inputs necessary in order to implement the discrete control law are the reference and the controlled output signals. The discrete control law that results, after substituting the error signal is given in (8) as:

$$c_k = 0.3333(r_k - y_k) - 0.33(r_{k-1} - y_{k-1}) + c_{k-1} \quad (8)$$

where c_k represents the current value of the control signal, r_k represents the current value of the reference signal, y_k represents the current value of the output signal, r_{k-1} represents the past value of the reference signal, y_{k-1} represents the past value of the output signal, c_{k-1} represents the past value of the control signal.

The implementation of the horizontal positioning control is made using MATLAB Simulink and the function block. The function block allows for programming code to be inserted into a Simulink block structure. It allows the authors to implement and test the discrete law from (8), as it would be on a numerical device.

The values for the past reference, past output and past control signal, needed for computing the control law, are generated using discrete unit delay blocks, and are given to the MATLAB function as inputs (see Fig. 3). The sample time of the unit delay blocks is set at 0.03 seconds.

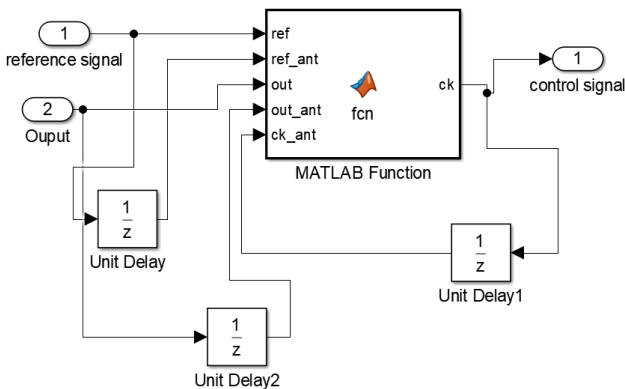


Fig. 3. The discrete controller implementation using MATLAB function.

The output of the function block is represented by the control signal. As stated before, the control block requires two external input ports, the step reference signal and the output of the positioning process, in order to compute the dependency law from (8) and generate the control signal iteratively.

C. Simulation Results for Both Control Implementations

The discrete controllers described in previous subsections, are inserted into a unitary feedback control structure along with the positioning process continuous transfer function to verify the functioning of the control structure. For the input-output discrete control structure the input signal is represented by the error signal between the reference and the controlled output signals, while for the discrete controller using MATLAB function, the reference and the controlled output are given directly as inputs to the control block.

The two control structures are simulated in MATLAB Simulink at unitary step reference signals. The two controlled structures are compared graphically by plotting the controlled output, that represents the current position of the

manipulator's pliers for both control structures in Fig. 4. It can be noted from the plot analysis that the controlled output behaves the same for both control structures. The overall performances, generated by the discrete control structure derived from the magnitude optimum criterion, Kessler variant, are an overshoot of 5% and a settling time of 2.14 seconds, slightly higher than expected, due to the digitization of the continuous transfer function and usage of the discrete form of the controller.

Since the overlapping of the two signals can be observed from Fig. 4 analysis, the discrete law from (8) and its implementation is being validated.

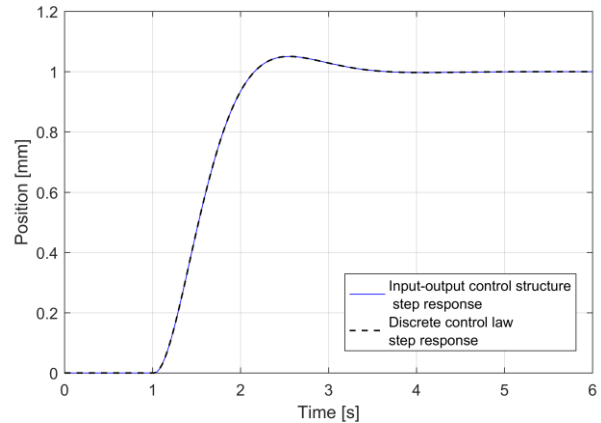


Fig. 4. Simulated step response for both discrete control implementations.

V. CONCLUSION

The research presented in this paper deals with the digitization of a continuous control for the horizontal positioning of an industrial manipulator. The magnitude optimum criterion, the Kessler variant, is applied in order to obtain a PI control, since the electro-hydraulically driven movement is a fast process. The discrete control law is necessary for the implementation on a cost-effective digital device.

In order to test and validate the discrete control law, MATLAB computer software was used for two types of discrete implementation of the control law. First an input-output discrete control structure is used, with discrete unit time delay blocks to represent the required past values of the signals. Second, MATLAB function is used to implement the exact code of the discrete dependency law. For the simulated discrete dependency law, the error signal is computed within the control law just like it would be on a real implementation on a microcontroller, using the MATLAB function block to generate at each instance a value on the output port based on the inserted control code, and the values received on the input ports for the reference and the controlled output.

Both control structures are tested and validated at unitary step reference signals, via computer simulation, since on site validation prior to the real implementation is not possible, due to the continuous technological flow of hot rolling process. The overlapping of the step responses generated by both control structures validate the discrete dependency law between the control signal and the reference, the output and the past values of the corresponding signals.

The overall transient response performances are slightly higher than those imposed by the Kessler tuning criterion, due to the digitization of the continuous transfer function and usage of the discrete form of the controller.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

IC conducted the research and all mathematical model, algorithm and wrote the paper; VM analyzed all paper and the English grammar; IA contributed in the experimental stand; FC work in the introduction and state of art. All authors had approved the final version.

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