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TUNING OF PID CONTROLLERS FOR LINEAR DYNAMIC SYSTEMS USING "BRUTE FORCE AND VISUAL" METHOD

SEŘIZOVÁNÍ REGULÁTORŮ PID PRO LINEÁRNÍ DYNAMICKÉ SYSTÉMY METODOU "HRUBÉ SÍLY A OD OKA"

Abstract

For PID controllers in control loops, which in practice still prevails, it is necessary to determine controller parameter values which assure sufficient quality and robustness of control. A lot of PID tuning methods is described and well established in daily use. They are often based either on behavior of closed control loop or on a mathematic model of the controlled plant (and its L-transfer function), which allow to determine controller parameters by direct calculation. With increasing computing power of HW and SW aids it could be beneficial to use a method for determining the optimal setting of PID controller by simulation of control loop behavior for various meaningful combinations of controller parameter values (state space search).

Proposed method "brute force and visual" of PID controller tuning is based on repeated simulation of control process as a reaction to Heaviside step of desired value and disturbing value for varying parameters of controller's P, I, D components. For discrete controller also impact of sampling period T was considered. For each of the individual simulation runs there is kept a diagram as an image file as well as the control optimality criterion value. After execution of all the simulation runs for parameter values from the considered searched state space the simulation outputs are sorted by value of the selected control optimality criterion. The parameters of the individual simulation which has scored best are used for setting of the real controller and evaluated in the real control loop.

From the simulations available for wide combination of parameter values it is possible to estimate position of isles of stability and choose the PID controller values by an expert choice.

Abstrakt

Při návrhu parametrů PID regulátoru (které jsou v praxi dosud nejobvyklejší) pro regulační obvody je zapotřebí stanovit parametry regulátoru tak, aby zajišťovaly dostatečnou kvalitu a robustnost regulace. Je definováno a v praxi zavedeno mnoho seřizovacích metod pro nastavení PID regulátorů vycházejících z chování uzavřeného regulačního obvodu či naopak z matematického modelu regulované soustavy (a jejího L-přenosu), které umožňují stanovit parametry regulátoru přímým výpočtem. S rostoucím výkonem HW a SW nástrojů může ale být výhodné použít přístup, který nalezne optimální hodnoty nastavení regulačního procesu na základě simulací a analýzy chování regulačního obvodu pro různé kombinace možných parametrů regulátoru.

Navržená metoda seřízení PID regulátoru lineárního dynamického systému „hrubou silou a od oka" je založena na opakované simulaci regulačního pochodu při skoku řídící veličiny a poruchové veličiny pro měnící se konstanty regulátoru P, I, D, (a v případě číslicového regulátoru i vzorkovací

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periodu T) pro smysluplné rozpětí hodnot – odtud „hrubou silou“ v názvu metody. Z každého běhu simulace je uložen diagram průběhů zajímavých veličin (žádaná veličina, regulovaná veličina, porucha) jako obrazový soubor a jsou pro tuto simulaci vypočteny hodnoty ukazatelů kvality regulace. Po provedení simulací pro všechny hodnoty parametrů z uvažovaného stavového prostoru jsou výstupy simulací setříděny podle ukazatelů kvality regulace; simulace s parametry regulace, která skórovala podle ukazatelů kvality regulace nejlépe, je pak podkladem pro nastavení parametrů regulátoru a ověření v reálném regulačním obvodu.

Protože máme k dispozici vizualizované podoby průběhů regulačního procesu pro mnoho kombinací vstupů, můžeme odhadnout i polohu a podobu „ostrovů stability“ a pro dosažení robustnější regulace volit parametry regulátoru i expertní volbou, tedy „od oka“.

Keywords

PID controller, PID tuning, control system, closed loop control, optimization, system identification, simulation, robust stability, state space search

1 INTRODUCTION

For case of a dynamical system behavior analysis we can take an assumption of linearization around the operation point and apply an approximate using a model of linear dynamical system. For linear dynamical systems control there is most common using of PID controllers. Although there has been invented, developed and commonly accepted a lot of methods of PID parameters tuning in order to achieve the desired control response, there is still possible to find new ways and methods how to perform the control loop tuning.

Traditional methods of PID controller tuning (either based on closed loop behavior, or based on mathematic model of the controlled dynamical system) offer a way how to calculate "optimal" values of P, I, D parameters of PID controller. Alternatively, there is possible to consider methods based on analysis of simulated control loop behavior for reasonable PID configuration parameter value combinations (using a state space search).

This paper proposes a co called "Brute force and visual" method for PID controller tuning, which illustrates the abovementioned alternative approach.

2 METHOD DESCRIPTION

2.1 Context

During simulations we will monitor progression of plant output $y(t)$ as a reaction to changing the desired value $w(t)$ and disturbing value $v(t)$. To distinguish progressions in charts related to analogue and discrete controller, I have used indexes in variable names, e.g. values $y_1(t)$, $e_1(t)$ relate to control loop with PID controller, while values $y_2(t)$, $e_2(kT)$ relate to control loop with PSD controller. Disturbing value $v(t)$ is simulated as acting before the plant G_S for both control loops.

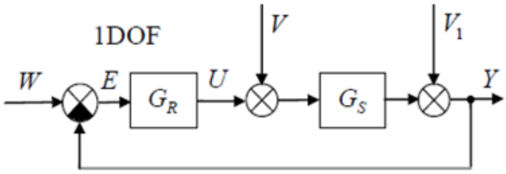


Figure 1 - Control loop with analogue controller (with one degree of freedom) [1]

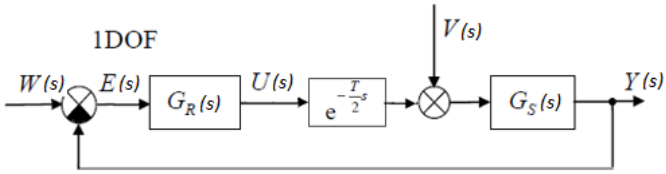
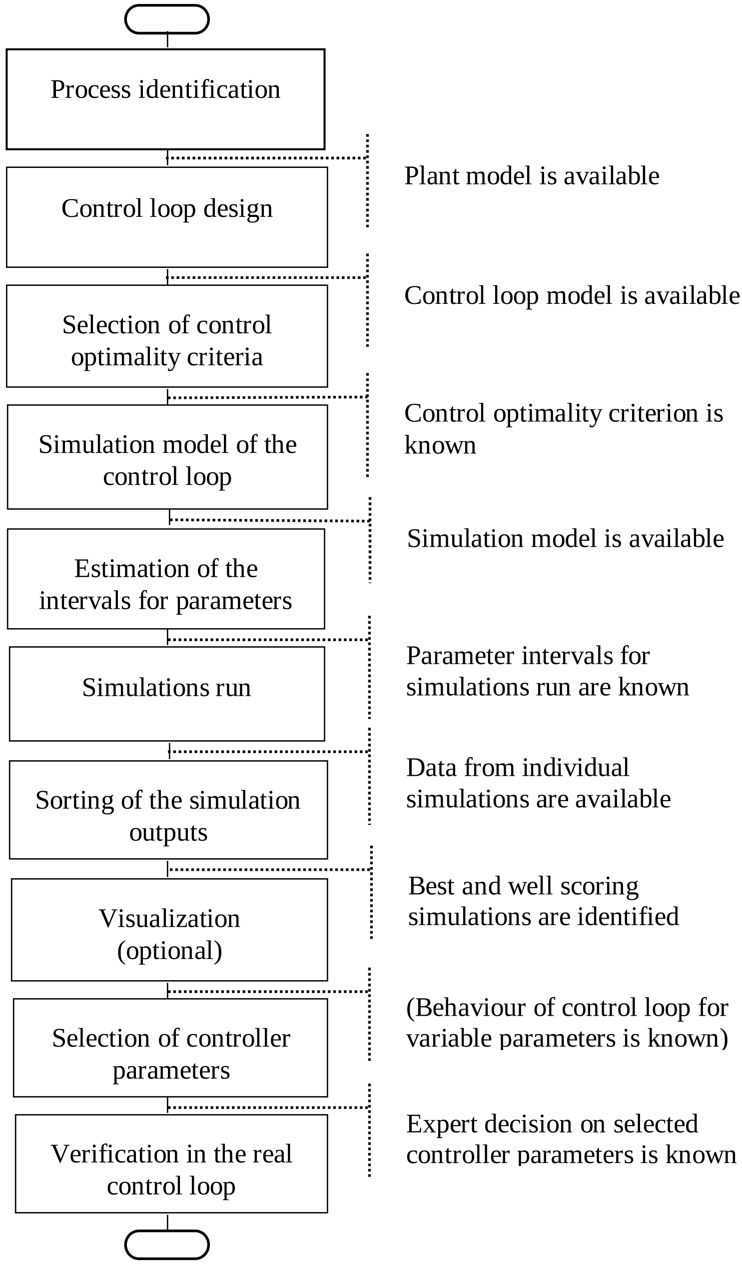


Figure 2 - Control loop with discrete controller transformed to continuous (for small T values)

2.1 "Brute force and visual" method - sequence of steps



2.1.1 Process identification

Estimation of controlled process parameters. Outcome of the step is as good as possible model of the process, expressed in Laplace domain. Some process identification methods are mentioned in [2], [3], [5].

2.1.2 Control loop design

Selection of controller of suitable type. Optionally, selection of control loop elements for improving the quality of control (like filters, etc.).

2.1.3 Selection of control optimality criteria

Based on nature of controlled plant, control optimality criteria have to be decided. Optionally, when more criteria to be balanced, this could lead to multi-objective optimization problem with linear scalarization.

2.1.4 Simulation model of the control loop

Creation of the simulation model of the control loop using a suitable simulation software package (e.g. Matlab, Scilab, etc.). For the simulation model the physical parameters and limits of the real elements of the control loop have to be considered (for example by including anti-windup in the model design).

2.1.5 Estimation of the intervals for parameters

Adjustable parameters for analogue PID controller are weights of K_P-proportional, K_I-integral and K_D-derivative component, for discrete PSD regulator also T-sampling frequency to be considered. Eventually, parameters of filter(s) N to be also taken into account.

Definition of intervals is trade-off between too complex simulation and potential exclusion of the optimal set point from the searched state space. If needed, exploratory run of the simulation with the wider interval and less fine step on the model could help in defining thresholds of the intervals for adjustable parameters. For the final run of the simulation the step could be set finer, resulting in more detailed coverage of the state space subset with the simulation outputs.

2.1.6 Simulations run

Simulation runs on control loop model for adjustable parameter values moving between thresholds with the reasonably selected step value.

Each individual simulation run (e.g. simulation for unique composition of adjustable control loop parameters) comprise reaction to Heaviside step of desired value w and/or disturbing value v, captured as a chart and saved on persistent media for further evaluation, and the simulations control optimality criteria values are calculated and kept.

2.1.7 Sorting of the simulation outputs

Outputs from the individual simulation runs are sorted by the value of the selected control optimality criteria. Optionally, if a multi-objective optimization to be performed, sorting could be done by the value of linear scalarization of control optimality criteria.

2.1.8 Visualization (optional)

Charts collected from individual simulation runs, sorted into sequences by ascending/descending values of interesting parameters (typically by control optimality criteria value), could easily form a base of visualization. Video stream could be created as an animation of individual frames and will illustrate behavior of the control loop for changing values of adjustable parameters.

2.1.9 Selection of the optimal controller parameters

Simulation indicated in the sorting of individual simulations as extreme (for example having minimal value of the selected control optimality criteria) can be declared as optimal in given resolution of the adjustable parameters – e.g. for given step size. More precise value of optimal adjustable parameter values could be obtained by specifiable simulation run just in narrow intervals and a mild step size.

In some cases, there might be a reason why a simulation minimizing value of the selected control optimality criteria is not chosen as the most suitable one and an expert decision (for example based on visualisation of control loop behaviour) could prefer a better one (more robust, with some other advantages).

2.1.10 Verification of realized parameter values in a real control loop

Parameter values realized during simulations on model of real control loop to be verified in a real control loop – e.g. set for real controller and evaluated.

3 DEMONSTRATIONS

3.1.1 Example of process identification

Instead of an application of system identification method, for simplification a plant (with transfer function G_S) will be used:

$$G_s = G_{LPF} G_{DC} = \frac{1}{0,003s+1} \cdot \frac{1}{10s^2+0,1s} \tag{1}$$

where: G_{LPF} - transfer function of low-pass filter, G_{DC} - transfer function of an integral plant (DC servomechanism).

3.1.2 Example of control loop design

Two identical control loops were simulated in a run, with the same plant (1), differing only by a controller used:

- Control loop with analogue PID controller
- Control loop with discrete PSD controller

Transfer function of analogue PID controller (standard PID controller without interaction, in parallel structure, with low-pass filter on derivative element) $G_R(s)$ will be:

$$G_R(s) = K_P + \frac{K_I}{s} + \frac{NK_D}{1+\frac{N}{s}} \tag{2}$$

where: K_P - weight of proportional component, K_I - weight of integral component, K_D - weight of derivative component, N - filter parameter on derivative component

From transfer function (2) of analogue PID controller using backward Euler summation is constructed transfer function of discrete PSD controller $G_R(z)$:

$$G_R(z) = K_P + \frac{K_I T}{z-1} + \frac{NK_D(z-1)}{(1+NT)z-1} \tag{3}$$

where: T - is sampling period.

For simulation of the discrete PSD controller there has been inferred its difference equation:

$$u[k] = -\frac{a_1}{a_0}u[k-1] - \frac{a_2}{a_0}u[k-2] + \frac{b_0}{a_0}e[k] + \frac{b_1}{a_0}e[k-1] + \frac{b_2}{a_0}e[k-2] \tag{4}$$

where:

$$\begin{aligned} a_0 &= 1 + NT \\ a_1 &= -(2 + NT) \\ a_2 &= 1 \\ b_0 &= K_P(1+NT) + K_I T(1+NT) + K_D N \\ b_1 &= -\left[K_P(2+NT) + K_I T + 2K_D N\right] \\ b_2 &= K_P + K_D N \end{aligned} \tag{5}$$

3.1.3 Example of control optimality criteria selection

Fitness function to be minimised is the integral of the absolute error I_{IAE} and is defined as:

$$I_{IAE} = \int_0^\infty |e(t)|\,dt \tag{6}$$

The sample simulation has determined the values of I_{IAE} criteria a) for the whole simulation run b) for the Heaviside step of desired value w only c) for the Heaviside step of disturbing value v only

3.1.4 Example of simulation model

Sample simulation model of the control loop has been created using open source software package Scilab – module XCos [4], [6]. Simulation diagram is shown on **Figure 3.**

For simulation were used two control loops with the identical plant, differing only by the controller used (PID vs. PSD controller, both controllers are of one degree of freedom and have got filtration on derivative element).

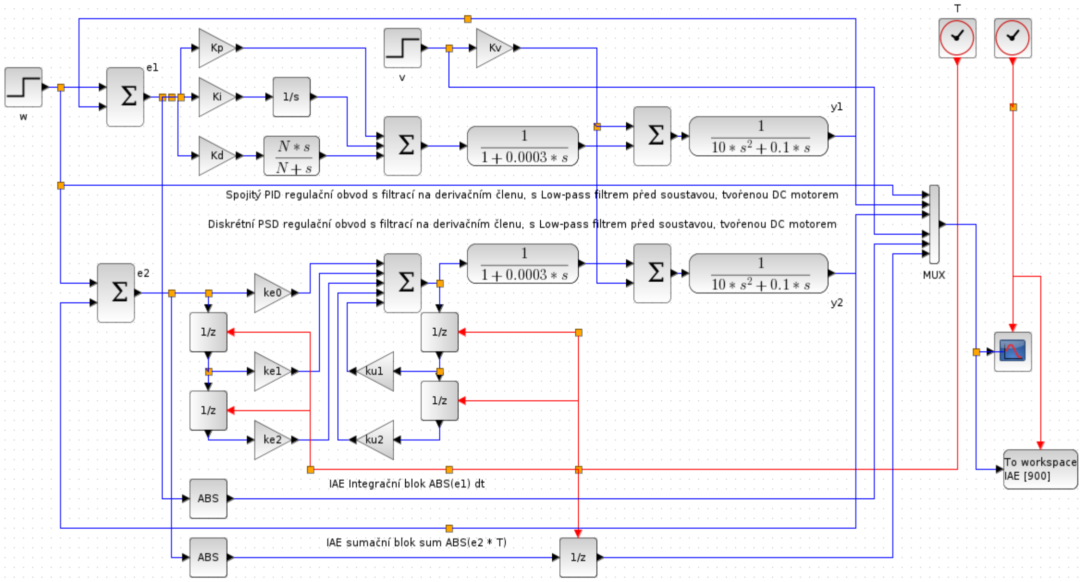


Figure 3 - Simulation diagram of control loops with PID and PSD controller, [4], [5], [6]

3.1.5 Example of intervals for parameters

Simulation parameters (891 runs):

$$
\begin{aligned}
K_p &= \langle 0, step : 50, 400 \rangle \\
K_I &= \langle 0, step : 50, 400 \rangle \\
K_D &= \langle 0, step : 20, 200 \rangle \\
T &= 0{,}01[s] \\
N &= 20
\end{aligned}
\tag{7}
$$

3.1.6 Example of simulations run

Output of each of the individual simulation runs has been stored as a file in a folder, see **Figure 4**.

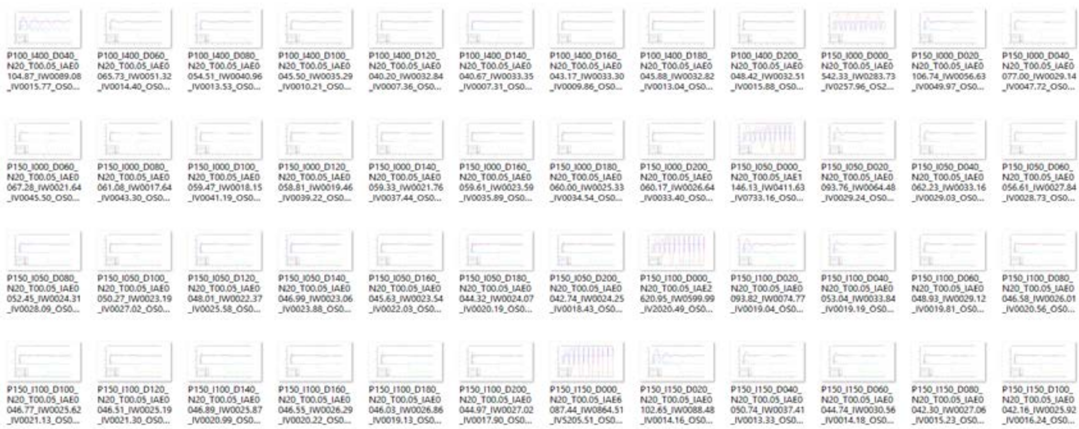


Figure 4 - Example of Simulation output folder

3.1.7 Example of simulation outputs sorting

For control of simulation run has been used a Python script. Calculated values of the control optimality criteria are a part of the simulation output file name. Based on them, it is an easy task to sort the files and create a sequence in ascending/descending order.

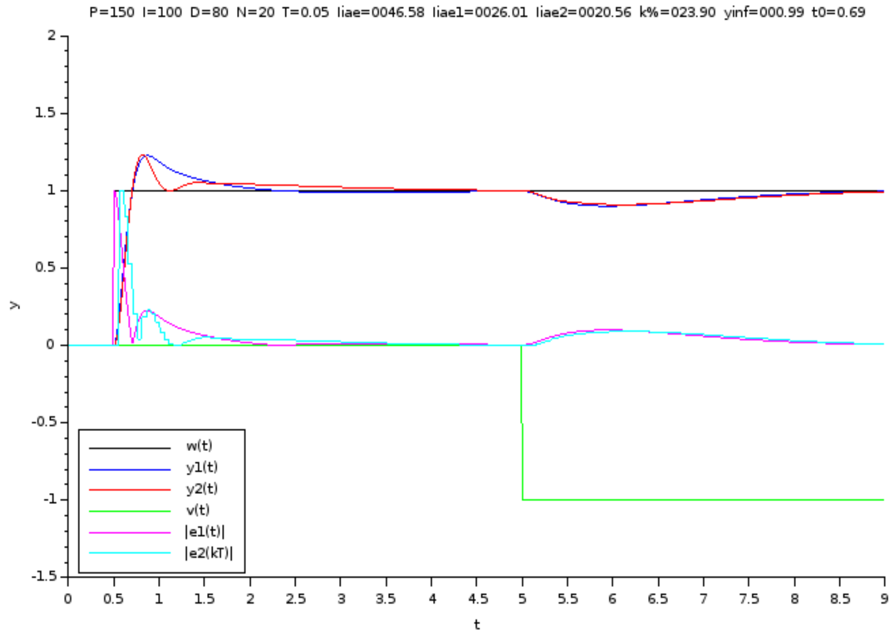


Figure 5 - Output of simulation scoring best in the selected control optimality criteria

3.1.8 Visualization example

Charts collected from individual simulation runs are converted to video stream using ffmpeg utility [7]. The command line to be run in Linux terminal for obtaining the video stream (with assumption the individual frames are made available in a folder) could look similarly to:

ffmpeg -framerate 2 -pattern_type glob -i "__.png" -vf scale=640:ih*480/iw -c:v libx264 -profile:v high -crf 20 -pix_fmt yuv420p PI.mp4*

Resulting video stream in mp4 format is on **Figure 6**.

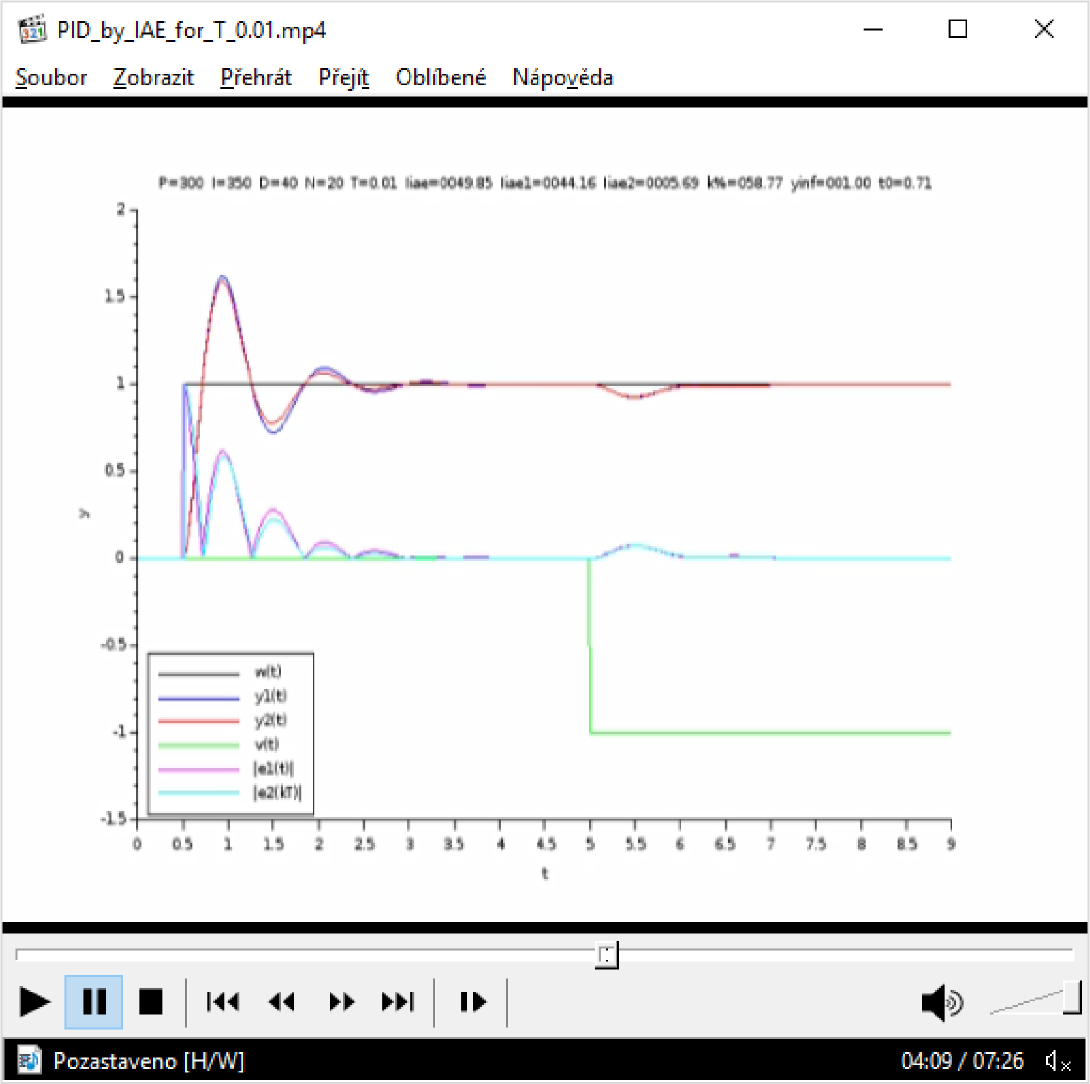


Figure 6 - Video stream created from individual simulations, sorted by IAE value

3.1.9 Example of the optimal controller parameters selection

Simulation with minimum I_{IAE} is declared as optimal for selected simulation parameters and is shown on **Figure 5.**

3.1.10 Verification of realized parameter values in a real control loop

Final evaluation of tuned PID controller in the real control loop must be done prior productive deployment.

4 CONCLUSIONS

Tuning of the analogue PID and discrete PSD controller using the proposed method is effective and provides robust control. As an additional gain we get a control loop behavior map also for parameter values in vicinity of the optimal set point. Method is universal in meaning it can be applied for any state space search simulations, provided the evaluation metrics can be determined and is computable. Data collected during the simulations run could be used for adaptive controller tuning in real time, which is the subject of the further research.

REFERENCES

[1] VÍTEČKOVÁ, M. & VÍTEČEK, A. *Vybrané metody seřizování regulátorů.* http://books.fs.vsb.cz. [Online] [Citace: 8. Leden 2018.] http://books.fs.vsb.cz/ZRMS/vybrane-metody-serizovani-regulatoru.pdf.

[2] —. *Offline Least-Square System Identification.* http://scilab.ninja. [Online] [Citace: 8. Leden 2018.] http://scilab.ninja/offline-least-square-system-identification/.

[3] *Identifikace systémů z přechodových charakteristik.* [Online] [Citace: 8. Leden 2018.] http://books.fs.vsb.cz/Identifikace/str/metody.htm.

[4] DEW. *Discrete-time PID Controller Implementation.* http://scilab.ninja. [Online] [Citace: 8. Leden 2018.] http://scilab.ninja/discrete-time-pid-controller-implementation/.

[5] —. *HIL Implementation of Harmonic Drive Motor (Part I) - Discretization and Simulation.* Scilab Ninja. [Online] [Citace: 8. Leden 2018.] http://scilab.ninja/hil-implementation-of-harmonic-drive-motor-part-i/.

[6] —. *About Scilab.* www.scilab.org/. [Online] [Citace: 8. Leden 2018.] https://www.scilab.org/en/scilab/about.

[7] —. *About FFmpeg. FFmpeg.* [Online] [Citace: 8. Leden 2018.] https://www.ffmpeg.org/about.html.