REAL TIME SIMULATION EXPERIMENTS WITH SELF TUNING CONTROL ALGORITHM

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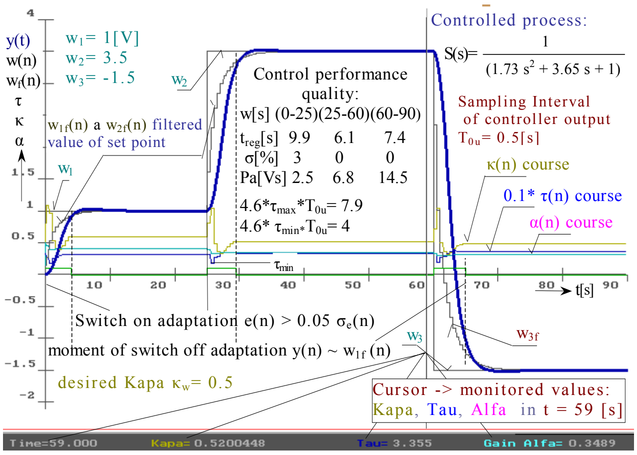
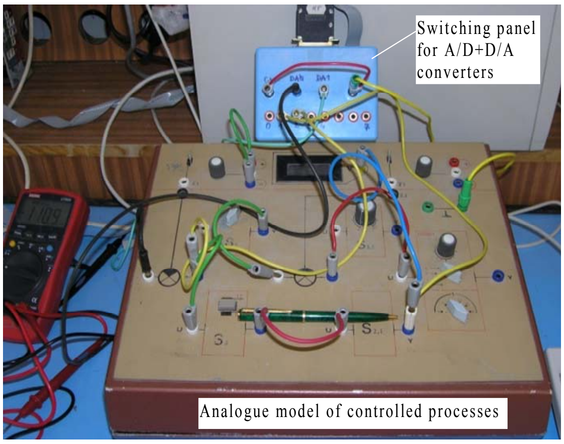
Abstract

This paper introduces self-tuning identification free PSD control algorithms. On the basis of detailed analysis of algorithm function made by simulation experiments, several modification of original algorithm have been proposed, realized and checked. These were executed in simulation environments created by real time operating analogue models of controlled processes, connected with PC through A/D and D/A converters. Verification of control loop performance quality was executed with proportional second to five order controlled processes for step responses on set point and disturbances. Simulation experiments documented robustness of algorithm. These were executed in real time, while parameters and order of transform function were changing. Loop responses were characterized with numeric data quality of control loop step response behaviour.





Keywords: simulation experiments, real-time, self-tuning control, control performance.

Presenting Author's biography

Prof. Ing. M. Alexík, PhD. has been working at the University of Žilina, Slovak Republic at the department of Technical Cybernetics for more than 30 years. He is one of leading scientist in the area of modeling and simulation in Slovak republic as well as member of several national and international societies and editorial boards of scientific journals. He is a board member of Czech and Slovak Simulation society and EUROSIM board member. Areas of his scientific interest are: modeling and simulation of dynamic systems, especially in *biomedicine* – eye-hand and eye-leg dynamics when driving a vehicle; *dynamics of transport means and processes;* optimal trajectory of train, underground, trolleybus, etc, *self-tuning control* - real time simulation of self tuning identification free algorithm and self tuning algorithm with continuous identification.

1 Introduction

Self-tuning identification free PSD algorithm has been realised for more commercial controllers. The best known are Foxboro EXACT, Alfa Laval Automation ECA 400 controller, Honeywell UDC 600 controller, and the Yokogawa SLPC 181/281 controllers [6]. The tuning procedures for all commercial products are described only in general, detailed algorithms are not released to public. It is therefore not possible to use them for research or educational purposes. One of well described self tuning identification free algorithms is PSD algorithm, described in [7], [8], [9]. Therefore the author realised several simulation experiments with mentioned algorithm, partially described in [3], [4]. This paper shortly describes real time simulation experiments with modifications of mentioned self-tuning control algorithm. These modifications were derived and verified by authors in [5].

Real time simulation experiments have show that the proposed modified algorithm is more robust that the original one and provides better quality of control loop performance.

Verification of control loop performance quality was executed with proportional second to five orders of controlled processes realised on continuous model of controlled plants [2]. Control responses for processes with parameters and sampling intervals changes are described in paper.

2 Self Tuning Identification Free Algorithm

In original formulation the algorithm computes "oscillation" of control loop performance "κ" (on the basis of filtered control error and their differences calculation) in every sampling interval. Global time constant of control loop performance, which is also "filtering constant" for set point jump and filtered control error with differences is calculated from differences of control error. From mentioned variables, with comparison of oscillating set point, the proportional, derivative and global gain of control loop are calculated. Figure 1 shows scheme for basic parameters of controller calculation.

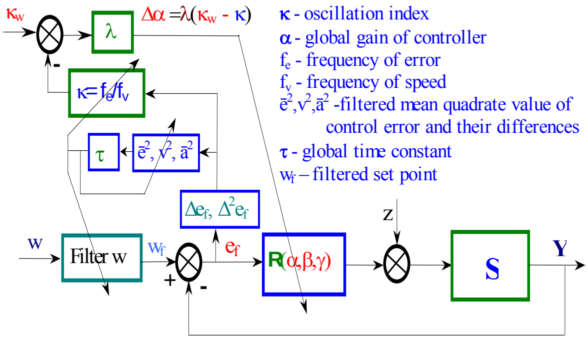


Fig. 1 Scheme of self tuning algorithm calculation

The main premise about control loop performance as considered in Maršík [2] is, that step responses behaviour of control loop may be characterised by two constant: global time constant "τ" (1) and index of loop oscillation "κ" (2). Next one states that the best oscillation (required value of oscillation) are "κ_w = 0,5" and that global gain of controller "α" depends from instantaneous "κ_w" (3). Next equations are computed in every sampling interval inside adaptation loop. Adaptation loop is turned on/of on the basis of comparison filtered control error with filtered dispersion of error (4). Controller output is computed by equation (5).

$$\tau(n) = \frac{2}{f_v} = 2\pi\sqrt{\frac{\overline{v^2}(n-1)}{\overline{a^2}(n-1)}}$$
$$\overline{e^2}(n) = \frac{e^2(n) + \tau(n)\overline{e^2}(n-1)}{1+\tau(n)} \qquad (1)$$
$$\overline{(\Delta e(n))^2} = \overline{v^2}(n) = \frac{v^2(n) + \tau(n)\overline{v^2}(n-1)}{1+\tau(n)}$$

$$f_e(n) = \frac{1}{\pi}\sqrt{\frac{\sigma_v^2}{\sigma_e^2}} = \frac{1}{\pi}\sqrt{\frac{\sum_{i=0}^{n}(\Delta e(i))^2}{\sum_{i=0}^{n} e^2(i)}} = \frac{1}{\pi}\sqrt{\frac{\overline{v^2}}{\overline{e^2}}}$$

$$f_v(n) = \frac{1}{\pi}\sqrt{\frac{\sigma_a^2}{\sigma_v^2}} = \frac{1}{\pi}\sqrt{\frac{\sum_{i=0}^{n}(\Delta^2 e(i))^2}{\sum_{i=0}^{n}(\Delta e(i))^2}} = \frac{1}{\pi}\sqrt{\frac{\overline{a^2}}{\overline{v^2}}} \qquad (2)$$

$$\kappa(n) = \frac{f_e(n)}{f_v(n)} = \frac{\sum_{i=0}^{n}(\Delta e(i))^2}{\sqrt{\sum_{i=0}^{n} e^2(i)\sum_{i=0}^{n}(\Delta^2 e(i))^2}} = \frac{\overline{v^2}}{\sqrt{\overline{a^2}\,\overline{e^2}}}$$

$$\Delta\alpha = \lambda(\kappa_w\alpha_{krit} - \alpha) = \alpha\frac{0.5}{\pi}\sqrt{\frac{\overline{a^2}}{\overline{v^2}}}\left[\frac{\kappa_w}{\kappa} - 1\right] \qquad (3)$$

$$\sigma_e^2(n) = \frac{e^2(n) + 3\tau(n)\sigma_e^2(n-1)}{1+3\tau(n)}$$
$$w_{filt}(n) = \frac{w(n) + \tau(n)w_{filt}(n-1)}{1+\tau(n)}, \qquad (4)$$

$$u(n) = \alpha(n)\beta(n)e(n) + \sum_{i=0}^{n}\alpha(i)e(i) + \alpha(n)\gamma(n)\Delta e(n)$$
$$= u_p(n) + u_i(n) + u_d(n)$$
$$r_p = \alpha(n)\beta(n), \quad r_i = \alpha(n), \quad r_d = \alpha(n)\gamma(n) \qquad (5)$$
$$r_p \text{ - P gain}, \quad r_i \text{ - I gain}, \quad r_d \text{ - derivate gain}$$
$$\sqrt{\overline{e^2}} = \beta\sqrt{\overline{(\Delta e)^2}} = \gamma\sqrt{\overline{(\Delta^2 e)^2}} \text{ – then } \beta(n),\ \gamma(n)$$

On the basis of detailed analysis of algorithm function, several modifications of control algorithm have been proposed, realised and checked by real time simulation experiments. Fig. 2 shows simulation experiment (control loop set point step responses) with modified algorithm for second order controlled process in the control loop. This figure also depicts adjusting of basic parameters of control algorithm, which were analysed in the course of algorithm modifications research, which can be realised only by simulation experiments. Step responses of control loop shown in Fig. 2 document, that premises mentioned above are approximately valid. Index of oscillation is approximately κ = 0.5 in steady state and global time constant corresponds with settling time of control loop behaviour.

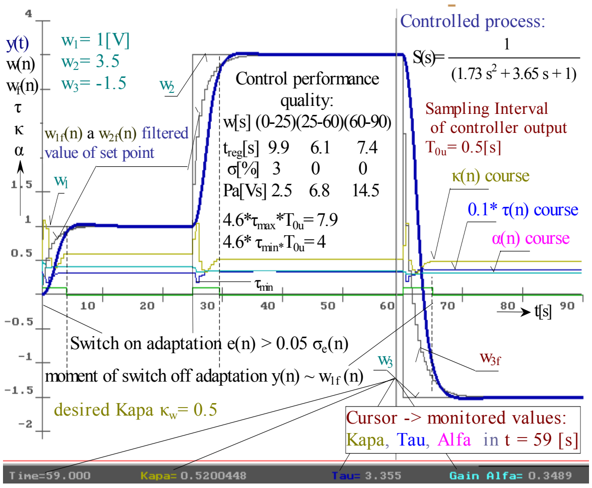


Fig 2. Adjusting of A_PSD_M algorithm parameters during set point step response

Global time constant "τ", integrating gain "α" and derivation gain "γ" are computed as ratio value towards "T_{0u}" - controller output sampling interval. Therefore algorithm is robust for large scale of sampling interval change and is also prepared for adaptive changing of sampling interval.

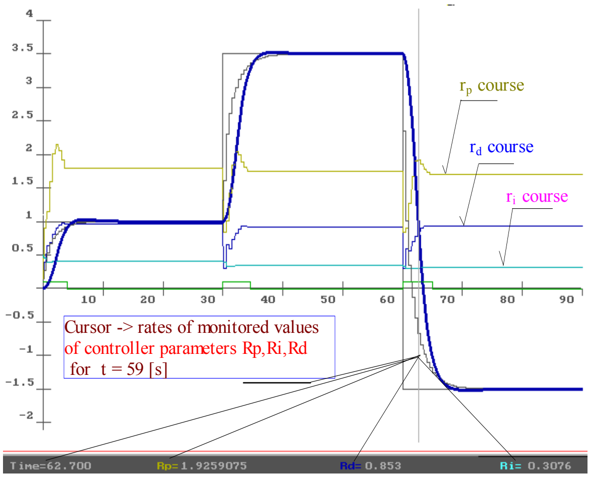


Fig 3 Controller parameters adjustment

Fig. 3 shows control loop set point step responses for the same process as on fig. 2 with controller parameters adjustment.

Robustness of algorithm toward sampling interval of controller output changing was qualified by characteristic of set point response quality present in figure. This numeric data shall be applied for examination of applicability of algorithm modifications.

3 Environment for Real Time Simulation Experiments

Real time experiments with initial and modified control algorithm were realized in simulation environment shown in Fig. 4 and Fig. 5.

Transient responses of plants, which were used by simulation experiments, are shown on Fig. 6. Simulation environment applied for experiment enables real time changes of controlled process parameters, f. e. relative damping ($S_{2,a}$, $S_{2,T}$) and gain or capacity lag order (S_i, K). Simulation environment based on micro controller, which enables modelling of processes with non-minimal phase and delay was described in [2].

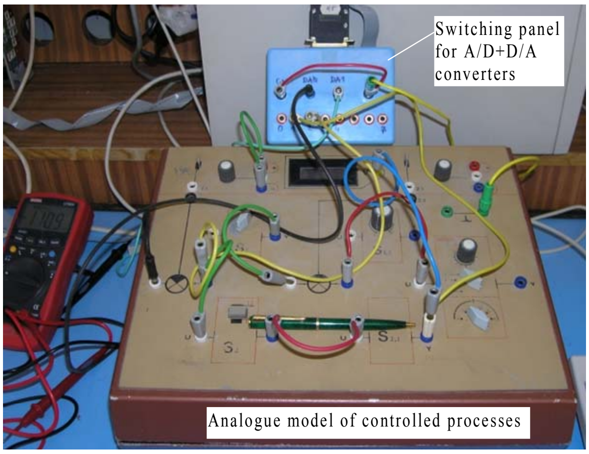


Fig 4 Analogue model of controlled processes

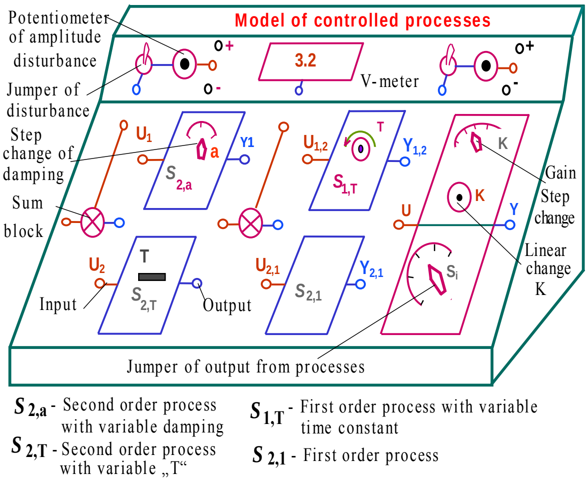
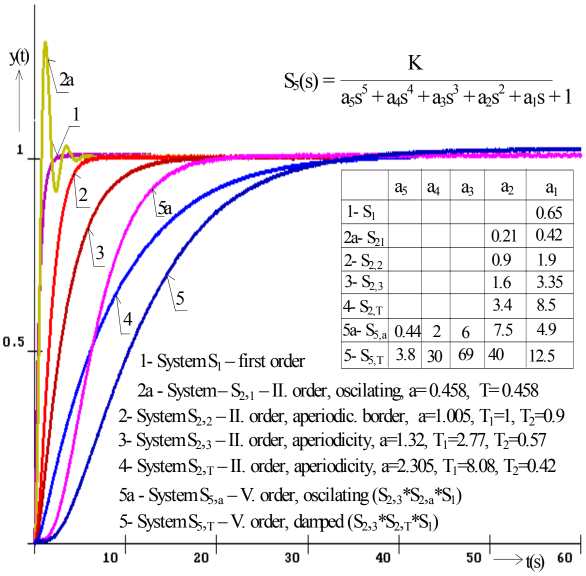


Fig 5 Analogue model of controlled processes



	a_5	a_4	a_3	a_2	a_1
1- S_1					0.65
2a- S_{21}				0.21	0.42
2- $S_{2,2}$				0.9	1.9
3- $S_{2,3}$				1.6	3.35
4- $S_{2,T}$				3.4	8.5
5a- $S_{5,a}$	0.44	2	6	7.5	4.9
5- $S_{5,T}$	3.8	30	69	40	12.5

Fig 6 Transient responses of controlled processes model

4 Initial algorithm modifications and their effect on control loop responses.

On the basis of detailed analysis of algorithm function the following modifications have been proposed, realised and checked by real time simulation experiments:

-Anti Reset Windup modification of controller output calculation,

-modification of global time constant of control loop performance calculation,

-modification of global gain of control loop performance calculation,

-modification of controller output computation at algorithm set up by plant dead time ,

calculation of two global times constant: filtered set point, control loop performance,

-continuous calculation of recommended sampling interval of controller output.

Real time simulation experiments have shown that the proposed modification provides more robustness than the original one and provides better quality of control loop performance. Adaptation scheme of controller global gain calculation for modified algorithm is shown on Fig. 7. Comparison with scheme on fig. 1 shows, that new constants *k_Tau*, *k_TauR*, *k_alf*, *k_reg*, *k_kapa* were added to the algorithm calculation. The initial condition for algorithm constant and possibility added in (5) second derivative gain is also important. Derivation of mentioned constant and simulation experiments for verification of effect from this constant to control loop step response quality, is described in [5]. Some of 85 simulation experiments (with 450 step responses) with initial and modified algorithms in the loop, documented and described in [5] are shown on the following figures.

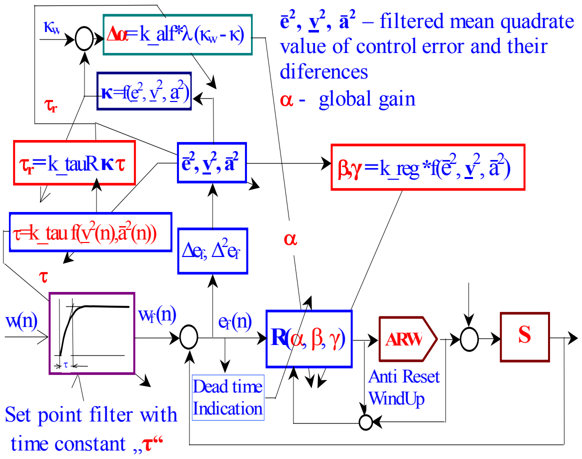


Fig. 7 Scheme of algorithm parameters adaptation, after modification.

Controller output constraint is a attribute of every real controller, represented in simulation by D/A converter output limitation. Because synthesis of control algorithms and also its computing in the control loop assumes linear behaviour of controlled processes, non – linearity of “output limitation” in integral part of controller brings on “wind up” effect (see response 1 in fig. 8) on step response of control loop. From technological point of view, oscillation of controller output (response 4 in fig. 8) is also not suitable. Extension of control algorithm by anti reset windup (ARW) part may eliminate wind up effect, provided responses without limitation have not overshoot. Although initial algorithm has no ARW part, control performance is stable, what demonstrates good robustness of initial algorithm, but control performance for algorithm with ARW modification (responses 2, 3) is much better.

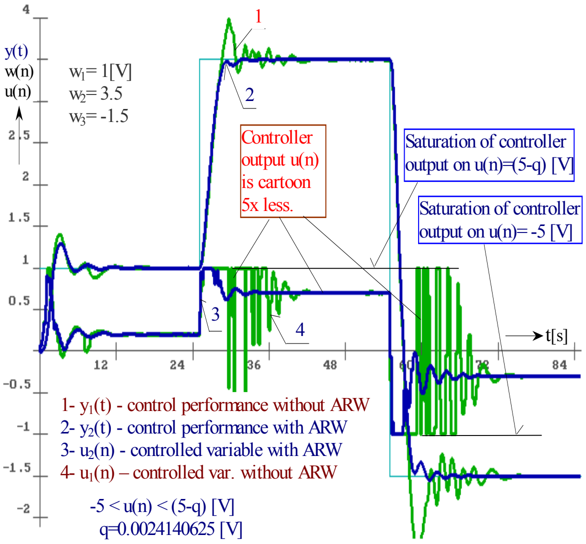


Fig 8 Effect of ARW modification on control performance, modified algorithm with $S_{2,3}$.

Influence of initial conditions on control performance can by seen by comparing Fig. 9 with initial algorithm response on Fig. 3 (initial condition for global time constant). Large contrast on control performance quality was reason to search for a better initial condition in modified algorithm and analysis for global time constant "τ" and global gain "α" computing. Responses on Fig. 10 with modified algorithm have better numerical data of loop response quality, which is documented in table on Fig. 10.

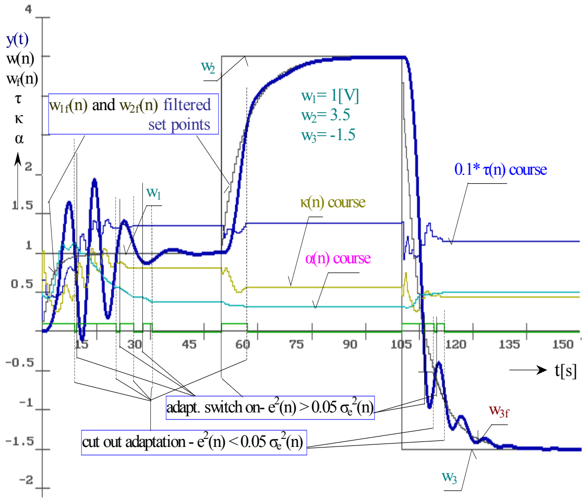
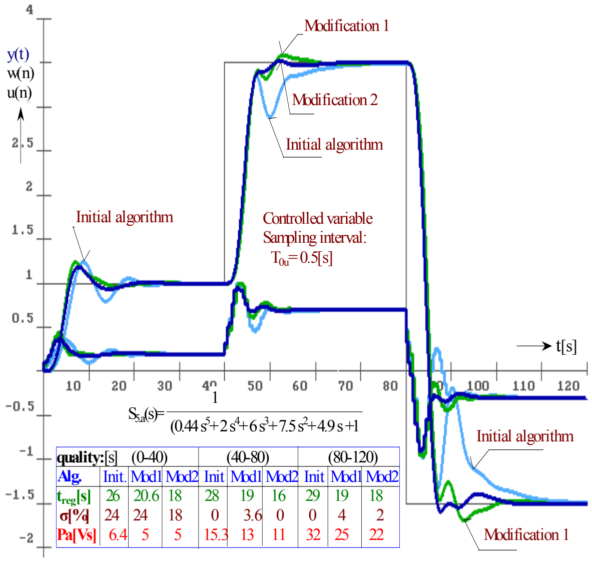


Fig. 9 Responses on w(t) changes -initial algorithm., $S_{5,a}(s)$, course of kappa, alfa a Tau



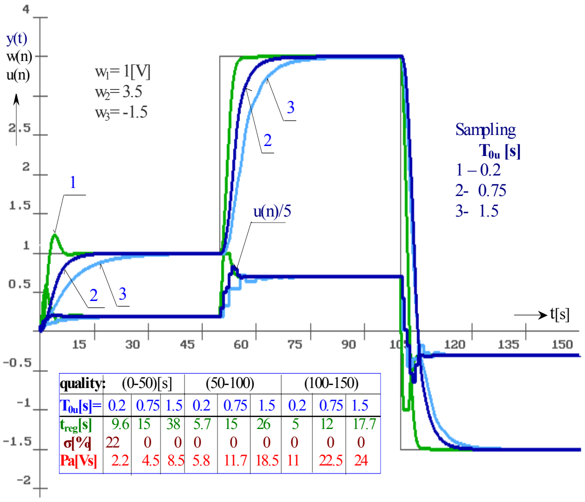
$$S_{5,a}(s)=\frac{1}{(0.44\,s^5+2\,s^4+6\,s^3+7.5\,s^2+4.9\,s+1}$$

quality:[s]	(0-40)			(40-80)			(80-120)		
Alg.	Init.	Mod1	Mod2	Init	Mod1	Mod2	Init	Mod1	Mod2
t_{reg}[s]	26	20.6	18	28	19	16	29	19	18
σ[%]	24	24	18	0	3.6	0	0	4	2
Pa[Vs]	6.4	5	5	15.3	13	11	32	25	22

Fig. 10 Responses of w(t) changes –initial and modified algorithm for $S_{5,a}(s)$ (real time)

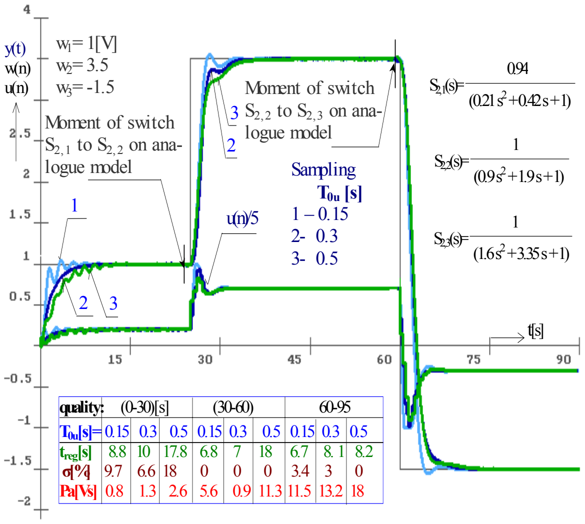
5 Simulation Experiments Results with Modified Algorithm

Most interesting simulation experiments from algorithm adaptation ability point of view are experiments with switching parameters of controlled process, shown on Fig. 12 till Fig, 15. 15. If control algorithm is able to cope with step change of controlled process parameters, then it is robust also towards slow change of parameters. Responses on Fig. 11 can be compared to responses from initial algorithm. Settling times on control performance with modified algorithm are around 50 % shorter than on initial algorithm, which confirms the applicability of the modification. The main weakness of algorithm is specification of sampling interval of the controller output. This problem will be solved in next step of research by continuous adaptive changing of sampling interval, which was commented in [5].



quality:	(0-50)[s]			(50-100)			(100-150)		
T_{0u}[s]=	0.2	0.75	1.5	0.2	0.75	1.5	0.2	0.75	1.5
t_{reg}[s]	9.6	15	38	5.7	15	26	5	12	17.7
σ[%]	22	0	0	0	0	0	0	0	0
Pa[Vs]	2.2	4.5	8.5	5.8	11.7	18.5	11	22.5	24

Fig 11 Responses of w(t)changes, modified algorithms, for $S_{2,3}$



$$S_{2,1}(s)=\frac{0.94}{(0.21\,s^2+0.42\,s+1)}$$

$$S_{2,2}(s)=\frac{1}{(0.9\,s^2+1.9\,s+1)}$$

$$S_{2,3}(s)=\frac{1}{(1.6\,s^2+3.35\,s+1)}$$

quality:	(0-30)[s]			(30-60)			60-95		
T_{0u}[s]=	0.15	0.3	0.5	0.15	0.3	0.5	0.15	0.3	0.5
t_{reg}[s]	8.8	10	17.8	6.8	7	18	6.7	8. 1	8.2
σ[%]	9.7	6.6	18	0	0	0	3.4	3	0
Pa[Vs]	0.8	1.3	2.6	5.6	0.9	11.3	11.5	13.2	18

Fig 12 Responses of w(t)changes, modified algorithms, change over S_{21} -> $S_{2,2}$ -> -> $S_{2,3}$

Next four pictures document robustness of modified self-tuning algorithm. Fig. 12 shows set point step responses for three sampling intervals with switching parameters of three second order-controlled processes

Fig. 13 shows set point step responses for three sampling intervals with switching parameters of two third order-controlled processes. In the first part of Fig. 12 and Fig. 13 (set point w = 1), where controlled processes with small relative damping (oscillating process) in the control loop are shown, control performance quality can be improved by further modifying of the algorithm.

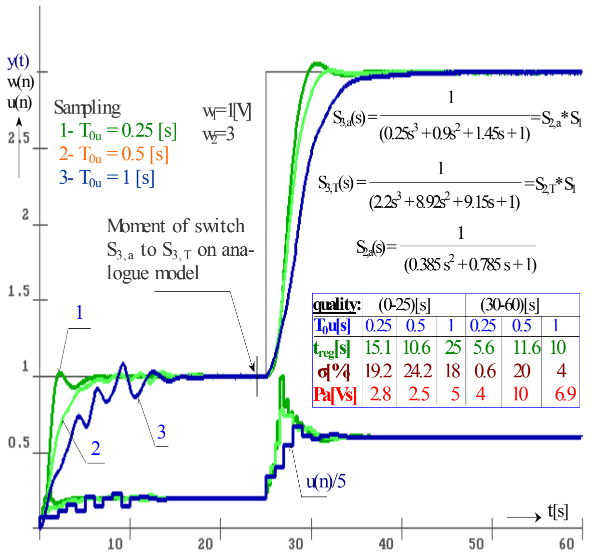


Fig 13 Responses of w(t) changes, modified algorithms, change over $S_{3,a}$ -> $S_{3,T}$

Fig. 14 and Fig 15 shows set point step responses for three sampling intervals with dynamics of controlled process changing by parameters change over for two fifth order-controlled processes.

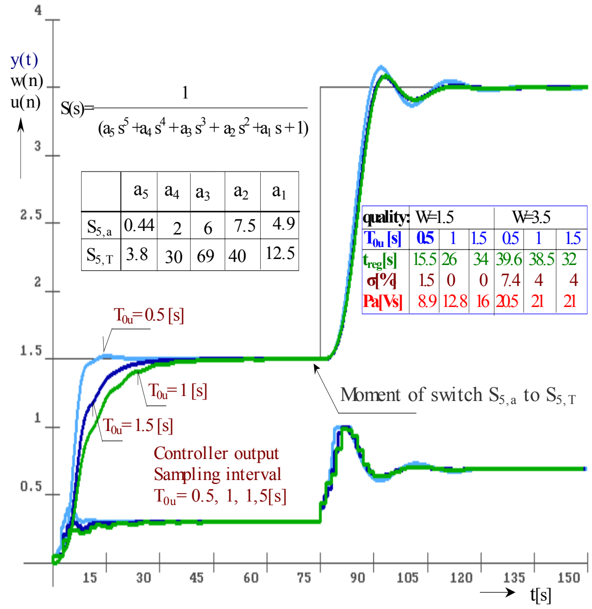


Fig. 14 Responses of w(t)changes, modified algorithms, change over $S_{5,a}$ -> $S_{5,T}$

Responses on Fig. 8, 9, 10, 14, were realised by digital simulation. Responses on Fig. 2, 6, 12, 13, were realised by hybrid real time simulation. First order digital filter with time constant T_f =25 [ms] was applied for regulated variable.

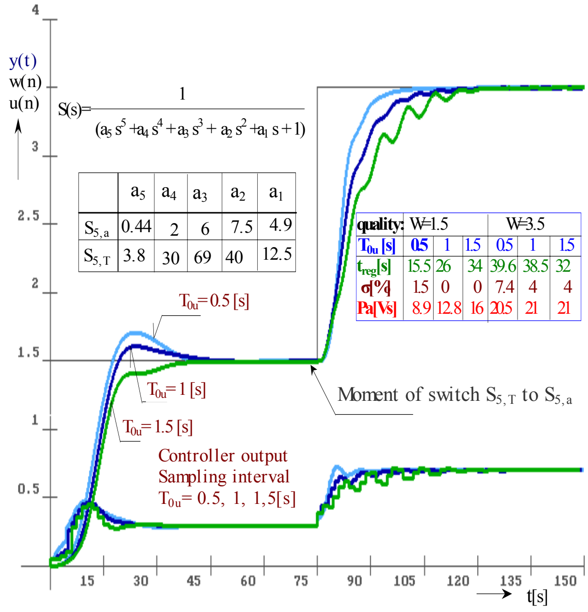


Fig. 15 Responses of w(t)changes, modified algorithms, change over $S_{5,T}$ -> $S_{5,a}$.

Robustness and adaptivity of control algorithm to set point changing is documented on Fig 16. As can be seen without numerical data, control performance quality (t_{reg} – settling time, σ - overshoot, Pa – integral of absolute value of the error) are improve after set point changing (settling time and overshoot are reduced)

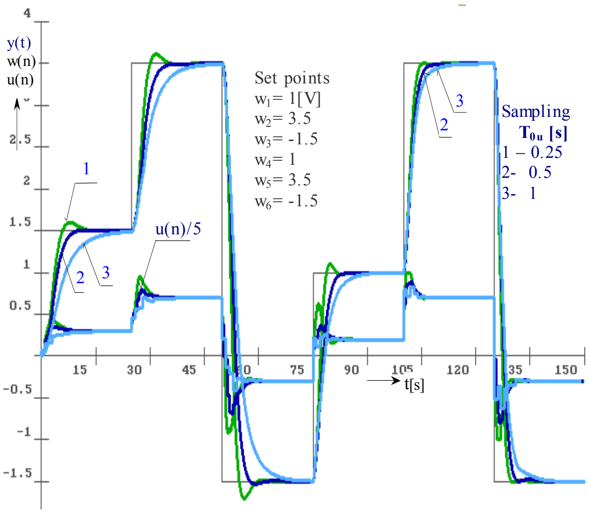
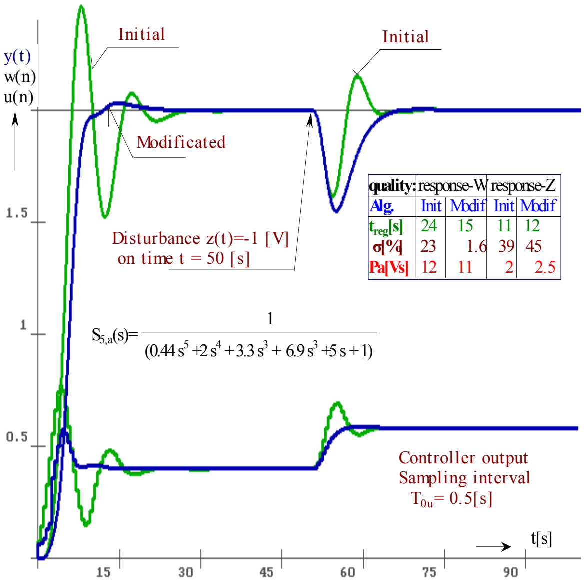


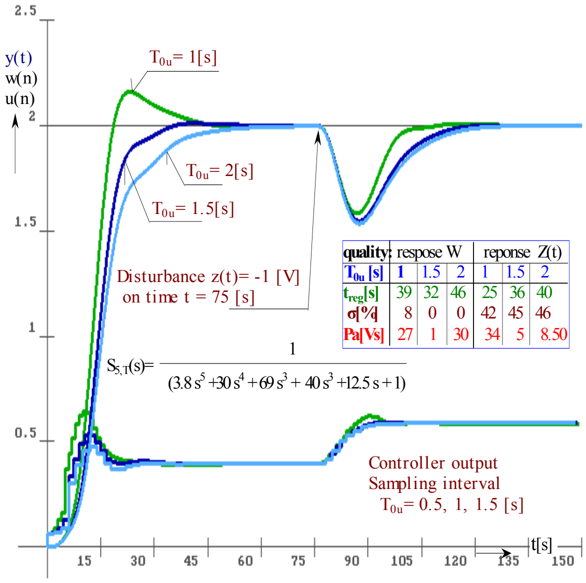
Fig. 16 Responses of w(t)changes, modified algorithms.

Figure 17 and Fig 18 shows set point and disturbance step responses for two initial and modified algorithms with fifth order weakly and heavy damped processes in the loop. Improvement of control performance quality was achieved for responses from both set point and disturbance.



quality:	response-W		response-Z	
Alg.	Init	Modif	Init	Modif
t_{reg}[s]	24	15	11	12
σ[%]	23	1.6	39	45
Pa[Vs]	12	11	2	2.5

Fig. 17 Responses of set point and disturbance changes



quality:	respose W			reponse Z(t)		
T_{0u} [s]	1	1.5	2	1	1.5	2
t_{reg}[s]	39	32	46	25	36	40
σ[%]	8	0	0	42	45	46
Pa[Vs]	27	1	30	34	5	8.50

Fig. 18 Responses of set point and disturbance changes

Responses on Fig. 8, 9, 10-18, were realised by digital simulation. Responses on Fig. 2, 6, 12, 13, were realised by hybrid real time simulation. First order digital filter with time constant T_f =25 [ms] was applied for regulated variable.

Continuous calculation of recommended sampling interval of controller output is documented on the next three figures. This calculation will be added in the further experiments for implementation of adaptive changing of controller output sampling interval. Recommended sampling interval is calculated from global time constant of control loop performance (1). This constant is calculated as ratio value towards "T_{0u}" - instantaneous value of controller output sampling interval. If the recommended sampling interval is known, the problem with dynamics changing of controller sampling (and controller structure) should be solved for its adaptive changing.

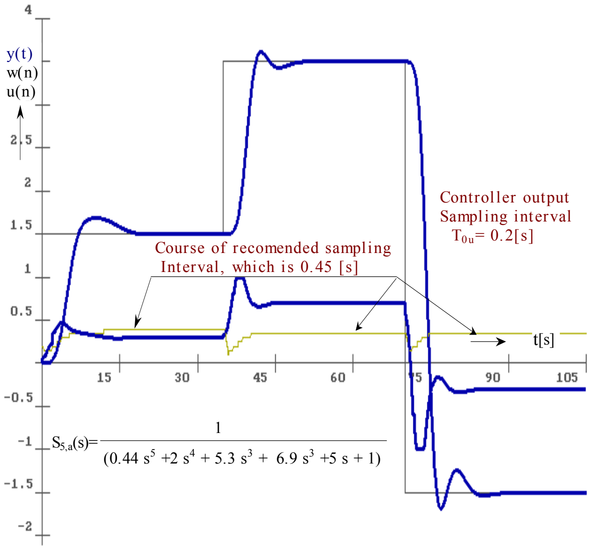


Fig. 19 Responses of w(t) changes –fifth order plant with recommended sampling interval

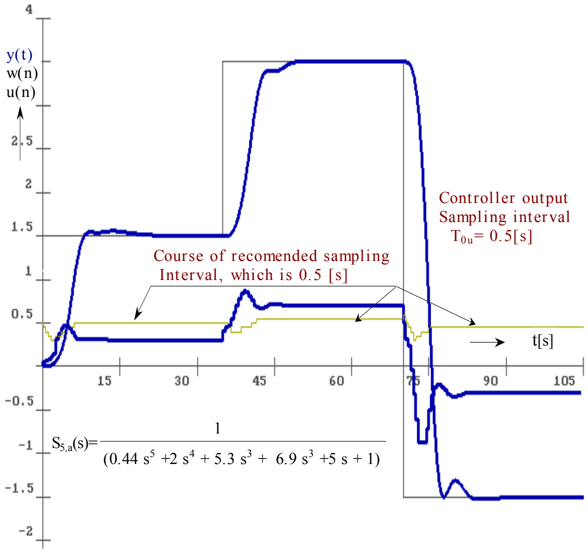


Fig. 20 Responses of w(t) changes –fifth order plant with recommended sampling interval

On the Fig. 19 the realised sampling is T_{0u}= 0.2 [s] and recommended sampling is T_{0u}= 0.4 [s]. For better control performance quality it is needed to scale up the sampling and for control performance in Fig. 21 it is needed to reduce it. Described concept of recommended sampling calculation appears correct.

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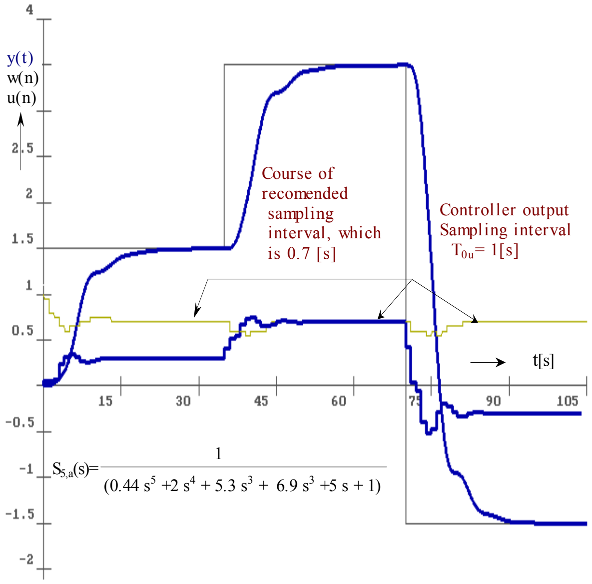

Fig. 21 Responses of w(t) changes –fifth order plant with recommended sampling interval

5 Conclusions and Outlook

On the basis of PSD self-tuning algorithm suggested by V. Maršík, we designed and verified more modification of this algorithm by real time simulation experiment. Modified self-tuning algorithm is more robust towards changing of controlled process parameter and controller output sampling interval than initial algorithm. Verified modification also enables adaptive changing of controller sampling interval, which was prepared, but no verified yet. Real time simulation experiments were realised under programming environment AdaptLab (including A/D and D/A converters), realised by the author. Further experiments will be focused on the implementation of adaptive changing of controller output sampling interval.

From the research point of view, the most significant fact is that it is not possible to propose any modification without prior simulation experiment technique. In this case, simulation experiments are not only drawing of the control loop responses. There are lots of various parameters in this algorithm, which are adjusting according to control loop dynamics. Therefore the influence of these parameters on control performance quality cannot be determined analytically but only as iterative process of finding the parameters interconexity by simulation experiments.

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References

[1] Alexík, M.: Adaptive Self-Tuning PID Algorithm Based on Continuous Synthesis. A Proceeding from the 2nd IFAC Workshop, *New Trends in Design of Control Systems.* Smolenice, Slovak Republic, 7-10 September 1997. pp.481-486. Published for IFAC by Pergamon an Imprint of Elsevier Science, 1998

[2] Alexík S., Alexík M.: Simulation Environment for Real Time Verification of Control Algorithm. In: Proceedings of 5th Vienna Symposium on *Mathematical Modelling*. February 8-10 2006, Vienna University of Technology, Austria. ARGESIM Report no.30. pp. 3-1 – 3-10. Published by ARGESIM and ASIM, Arbeitgemeischaft Simulation Fachausschuss GI im Bereicht ITTN –Informationstechnik und Technische Nutzung der Informatik. Volume 2: Full Papers CD. ISBN 3-901608-30-3

[3] Alexík S.: Analysis of MARSIK algorithm on Aström's benchmark systems for PID control In: Proceedings of 37th international conference MOSIS '03. Modelling and simulation of systems : - Ostrava: MARQ, 2003. - ISBN 80-85988-86-0. - pp. 36-40.

[4] Alexík S., 2003b: Novel adaptive method of setting parameters for Marsik control algorithm In: *Communications.* Scientific letters of the University of Žilina. - ISSN 1335-4205. - Roč. 5, n. 4 (2003), pp. 63-65

[5] Alexík S., 2007: *Modification of self tuning PSD control algorithm* (in Slovak). PhD thesis. January 2007. Faculty of management, control and informatics, University of Žilina.

[6] Äström, K.J., Hägglund, H.,1995.:*PID controllers: Theory, design, and tuning*, 2nd ed. Research Triangle Park, NC: Instrument Society of America, 1995.

[7] Görner, V., Maršík, J, Klán P., 1990: *Crossways automatic control II* (in Czech). Softwarové noviny č. 6 (1990). pp. 27 – 38

[8] Maršík, J.,1981.: Simple algorithm for discrete adaptive control (in Czech). Research review. ÚTIA ČSAV, č. 1106. UTIA ČSAV Praha, 1981.

[9] Peterka V. a kol., 1982: Algorithm for adaptive mikro controller control of technologic processes (in Czech). In: Proceeding. UTIA ČSAV Praha. part II., pp.168-196. Praha 1982.