Adaptive PID Tuning

Using ORTO Agents

Dr Paul Oram
CEO, Ortomation Ltd

www.ortomation.io

paul@ortomation.io
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Abstract

The PID algorithm is the mainstay of continuous process control. Millions are installed globally, principally delivering the closed loop control of all key process variables e.g., flow, level, temperature, pressure etc. However, a large proportion of this installed base perform poorly. Reasons are numerous, for example, poor instrument ranging, incorrect valve sizing or mechanical problems e.g., 'stiction', can lead to inadequate SP tracking and disturbance rejection. More commonly, many underperform because they are simply not tuned correctly or not retuned periodically when process dynamics change. To help address this, adaptive control techniques can be employed to help maintain closed loop performance over time. This paper describes how, by reframing the adaptation problem as an optimization task, autonomous ORTO agents can provide adaptive PID tuning.

***Keywords**: PID; Adaptive Control; Real-time Optimization; ORTO Agents*

1. Introduction

1.1. Adaptive Control Overview

Adaptive control is the adjustment of a controller's structure and / or tuning parameters to meet a desired closed loop performance objective. Tuning parameters may initially be uncertain and / or vary over time. For example, as a heat exchanger fouls, control of the exit process temperature, by manipulating the counter cooling flow, may need to adapt to maintain the desired closed loop performance. One approach is model reference adaptive control (MRAC). Fig 1 shows a typical MRAC structure. A reference model, $G_R(s)$, describing the desired closed loop response, is firstly defined. The adjustment mechanism alters the controller parameters to minimize the difference between the reference model output and the closed loop output when both are subjected to the same $u(s)$ input changes.

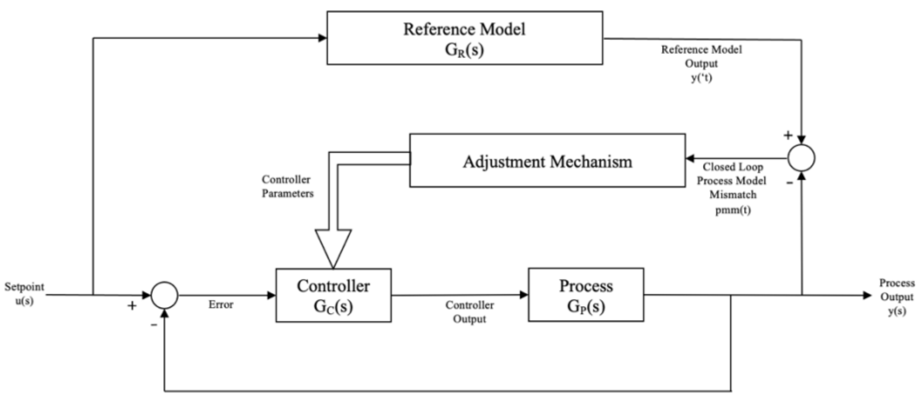

Fig. 1. MRAC Block Diagram

Adaptive control can be performed as a discrete 'tune-on-demand' task or continuously. Most modern control systems come with proprietary tune-on-demand facilities. However, few practical continuous adaptive process control solutions have been successfully deployed in practice. A thorough review of adaptive control techniques is given by *Astrom & Wittenmark 2013*.

1.2. ORTO Overview

ORTO (Oram Real-time Optimization) is a proprietary novel model-free real-time optimization approach, marketed by Ortomation Ltd. ORTO offers distinct advantages over traditional RTO technologies. These advantages include greater flexibility, a more intuitive design procedure and straightforward implementation. ORTO also automatically tracks non-stationary (time dependent) optima, e.g., caused by a change in operating philosophy, discrete system modifications, or changes in process dynamics over time. An ORTO scheme is built using independent ORTO agents, each manipulating one system variable. Being model free, ORTO agents have no prior knowledge of the optimization n-dimensional plane. The 'ORTO agent principle' ensures agents learn from each other and work together, to move to and then track the desired optimum value.

ORTO's primary purpose is to optimize a specific economic, environmental or safety variable within a physical system or process e.g., maximize chemical plant production against quality constraints, minimize fuel used in a power generation plant to meet an energy demand etc. However, being a universal optimization technology, ORTO can be applied to any dynamic optimization problem, as is demonstrated in this paper.

2. Optimization Objective Formulation

To use ORTO agents to deliver continuous adaptive control, i.e., be the adjustment mechanism depicted in Fig. 1, the adaptation task needs to be framed as an optimization problem. Let us assume that the P, I and D parameters of an ideal form PID controller are to be adjusted:

$$G_C(s) = P\left[1 + I\frac{1}{s} + D\frac{N}{1+N\frac{1}{s}}\right] \tag{1}$$

Let us also specify that the desired closed loop response is a first order lag:

$$G_R(s) = \frac{1}{1+\tau s} \tag{2}$$

Where:

P	Proportional gain
I	Integral gain
D	Derivative gain
N	Derivative filter coefficient (nominally set to 100)
τ	Reference model time constant

A suitable objective function is therefore:

Minimize:

$$pmm(s) = \frac{P\left[1+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}\right]G_P(s)}{1+P\left[1+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}\right]G_P(s)}u(s) - \left[\frac{1}{1+\tau s}\right]u(s) \tag{3}$$

By adjusting the tuning parameters P, I & D.

Subject to:

$$0 \le P \le P_h \tag{4}$$

$$0 \leq I \leq I_h \tag{5}$$

$$0 \leq D \leq D_h \tag{6}$$

To summarize, $G_P(s)$ is unknown, $u(s)$ is the input signal, $pmm(s)$ is a measured signal and the constants P_h, I_h, D_h, τ, and N are user defined.

3. ORTO Scheme Implementation

Appendix A describes the methodology for designing a typical process or system ORTO optimization scheme, however, the outlined steps are still valid for this unorthodox application. As described by the objective function, the manipulated variables (MVs) are the three tuning parameters and the optimization variable (OV), which we want to minimize, is the $pmm(t)$ signal. For this application there are no external constraint variables (CVs) or wild variables (WVs) to consider. A MRAC scheme is easily built in Matlab / Simulink. Fig 2 shows the scheme layout to be used for testing purposes.

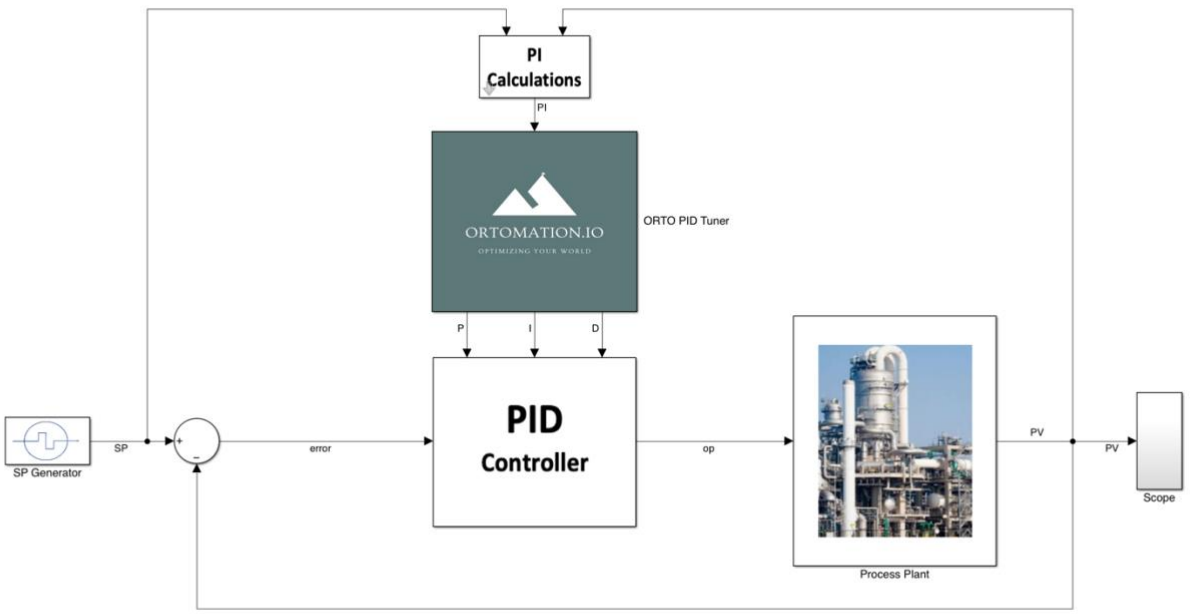

Fig. 2. ORTO Scheme - Simulink Block Diagram

Three ORTO agents are required, one for each MV (the P, I and D parameters). These are contained in the 'ORTO PID Tuner' block, as shown in Fig 3.

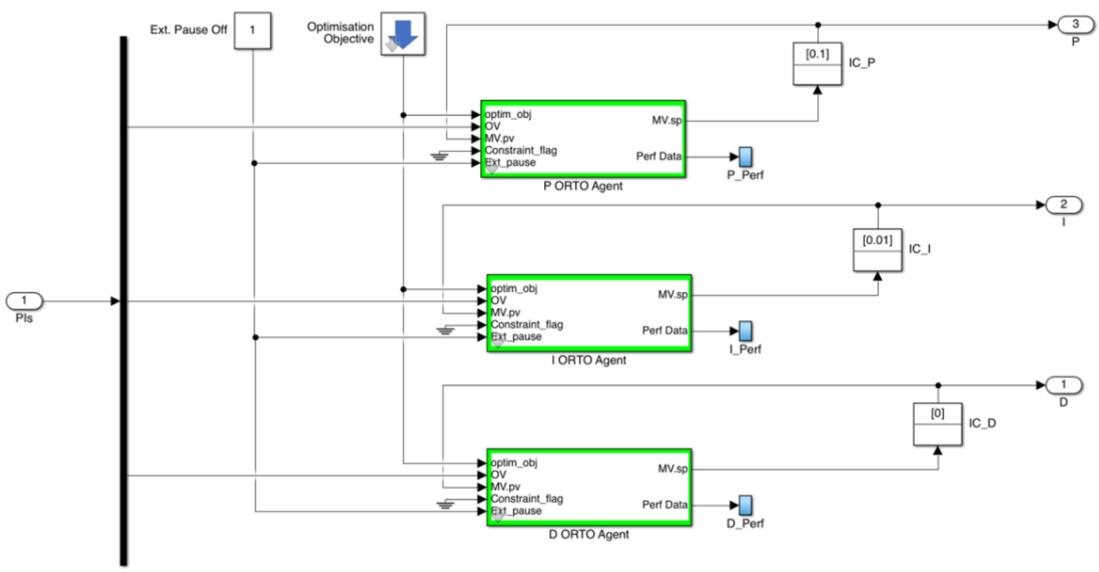

Fig. 3. Simulink ORTO PID Tuner Block

As can be seen in Fig 2., both the closed loop system and reference model are perturbed by the same input signal. This signal needs to be periodic, thereby allowing the ORTO agents to adjust the PID parameters within each half cycle. If amplitude of the perturbation signal varies, this needs to be compensated for in the OV calculations.

Unlike a traditional process optimization problem, for this adaptation task each agent is to be given a unique 'Performance Index' (PI) as its OV, calculated using $pmm(t)$ real-time data. Adjusting the P term, within the ideal form of the PID algorithm [1], also implicitly alters the I and D terms. It therefore has a larger impact on the whole transient response. To reflect this, the Integrated Time Absolute Error (ITAE) is calculated, as shown by [7] and used as the OV signal for the agent adjusting the P term. ITAE penalizes any persistent error.

$$OV|_P = \frac{1}{M_P}\int_0^{T_{sP}} |y(t) - y'(t)| t dt \tag{7}$$

Integral action is used to remove steady state offset, thus, the ORTO agent adjusting the I term, needs to act on overall error throughout the response. Average error, as calculated by [8], is therefore selected as its OV signal.

$$OV|_I = \frac{1}{M_I T_{sI}}\int_0^{T_{sI}} |y(t) - y'(t)| dt \tag{8}$$

Derivative, acting on the rate of change of error, is used to help stabilize the closed loop e.g., counteracting the destabilizing effect of integral action. The D action needs to address any instability early in the response. Thus, for the ORTO agent adjusting the D term, Integrated Absolute Error (IAE), divided by the integral of time, is used as its OV signal:

$$OV|_D = \frac{1}{M_D}\frac{\int_0^{T_{sD}} |y(t)-y'(t)| dt}{\int_0^{T_{sD}} t dt} \tag{9}$$

M_P, M_I and M_D used the in the PI calculations [7], [8] and [9] respectively are constants used to normalize the value, accounting for the amplitude of the input signal. For the purposes of testing, the sample times T_{s_P}, T_{s_I} and $T_{s_D}$are all set to half the input cycle time.

Having a different PI for each agent helps the agents work autonomously. Minimizing each inherently helps achieve the overall optimization objective, i.e., minimize the $pmm(t)$ signal.

4. Test setup: Process Dynamics, Reference Model and Perturbation Signal

For the purposes of testing the ORTO adaptive tuning scheme, the following initial process dynamics and fixed reference model have been chosen:

$$G_P(s)|_{t=0} = \frac{1.2e^{-20s}}{200s^2+20s+1} \tag{10}$$

$$G_R(s) = \frac{1}{1+50s} \tag{11}$$

The open loop response of the process described by [10] has overshoot i.e., is underdamped, with a settling time of ~150secs. A process with such dynamics is relatively uncommon; however, it has been selected to provide a suitably challenging test for the ORTO agents. A first order reference model, with a time constant of 50 seconds, is chosen, as this describes an acceptable closed loop response.

The PID controller needs to be configured with an initial set of tuning parameters. These act as the initial conditions for the respective ORTO agents. The selected values are P=0.1, I=0.01 and D=0.01, which give a very poor closed loop response, as shown in Fig. 4. The ORTO agents must adjust the tuning parameters accordingly to achieve, as closely as possible, the desired model reference response, also shown in Fig. 4. The difference between the two responses in the PMM which the ORTO agents must minimize.

Again, for the purposes of testing, a simple square wave of magnitude 1.0 and period 5000s is to be used as the perturbation signal. To reiterate, the ORTO agents are autonomous and have no prior knowledge of the process dynamics [10]. They must work together to navigate and find the set of controller tuning parameters which minimize the PMM over time.

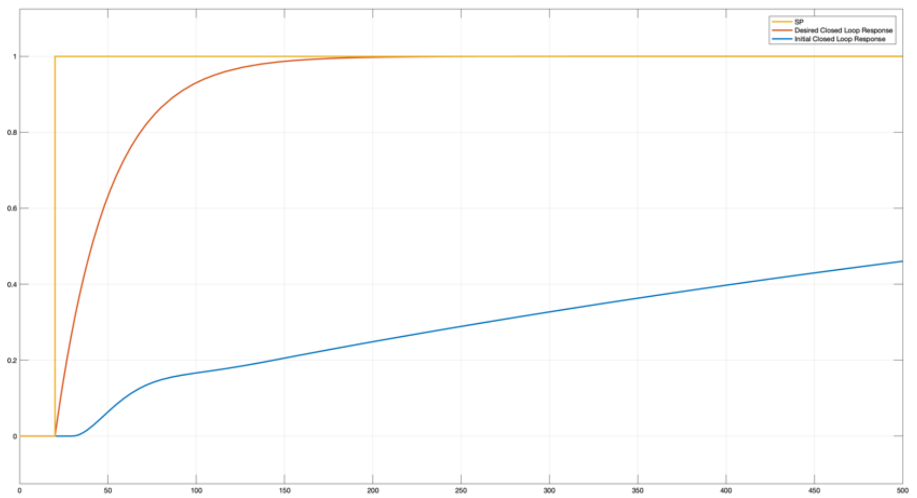

Fig. 4. Desired Closed Loop (Model Reference) Response and Initial Closed Loop Response with Initial Controller Tuning Parameters

5. ORTO Scheme Configuration

The chosen set-up parameters of each ORTO agent are detailed in Table 1.

ORTO Agent 1 (P) Initial Condition P=0.1	Optimization Objective	Minimize
	OV Engineering Range	[1 0]
	MV Engineering Range	[1 0]
	Sample Time (Secs)	2500
	Max. Move Size	0.05
	MV Upper and Lower Constraint Bounds	[1 0.01]
	Initial Push Direction?	+ve
ORTO Agent 2 (I) Initial Condition I=0.01	Optimization Objective	Minimize
	OV Engineering Range	[1 0]
	MV Engineering Range	[1 0]
	Sample Time (Secs)	2500
	Max. Move Size	0.02
	MV Upper and Lower Constraint Bounds	[1 0.01]
	Initial Push Direction?	+ve
ORTO Agent 3 (D) Initial Condition D=0.01	Optimization Objective	Minimize
	OV Engineering Range	[1 0]
	MV Engineering Range	[1 0]
	Sample Time (Secs)	2500
	Max. Move Size	0.02
	MV Upper and Lower Constraint Bounds	[1 0]
	Initial Push Direction?	+ve

Table 1. ORTO Agent Configuration

The rationale for the settings is as follows:

- **Optimization Objective:** PMM is to be minimized so is set to ‘minimize’ for all agents.
- **OV Engineering Range:** The $M_P, M_I$and $M_D$values in the PI equations [7], [8] and [9] respectively are selected to give an optimization Variable (OV) range of [0 1] for each agent.
- **MV Engineering Range:** The manipulated variables (MVs) are the PID parameters. Sensible ranges have been given. These can be extended if required.
- **Sample Times:** Each ORTO agent is set with the same sample time, equal to half the period of the input signal.
- **Max Move Size:** The maximum move is set to 1/20 of the MV range for the P agent. It is set more conservatively at 1/50 of the MV range for the I and D agents, as changes in P also change I and D due to the nature of the PID algorithm used [1].

- **MV Upper and Lower Constraint Bounds:** Set equal to the MV range values i.e., ORTO agents are free to move their respective model parameter across the specified parameter range.
- **Initial Push Direction:** Set to the 'best guess' of where optimum value may reside.

Appendix B provides a deeper overview of how ORTO agent configuration parameters should be set.

6. Simulation Analysis

To analyze ORTO's performance when used to deliver adaptive control, three case studies are now presented.

6.1. Case 1: PID Adaptation – Stationary Process Dynamics, No process Noise.

For the first test case, the process dynamics are kept fixed, and as described by [10]. The simulation run time is set to 3 days.

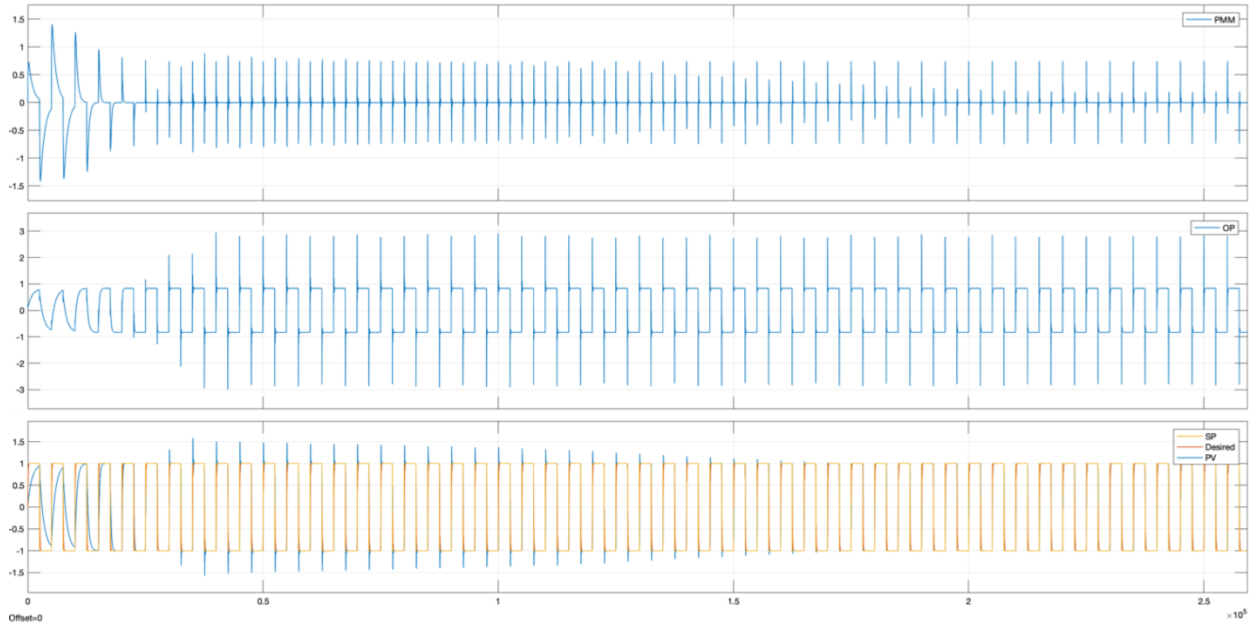

Fig. 5a. Case 1: Stationary process dynamics, perturbation signal period set to 5000 seconds. Simulation time 3 days. Closed loop response trends.

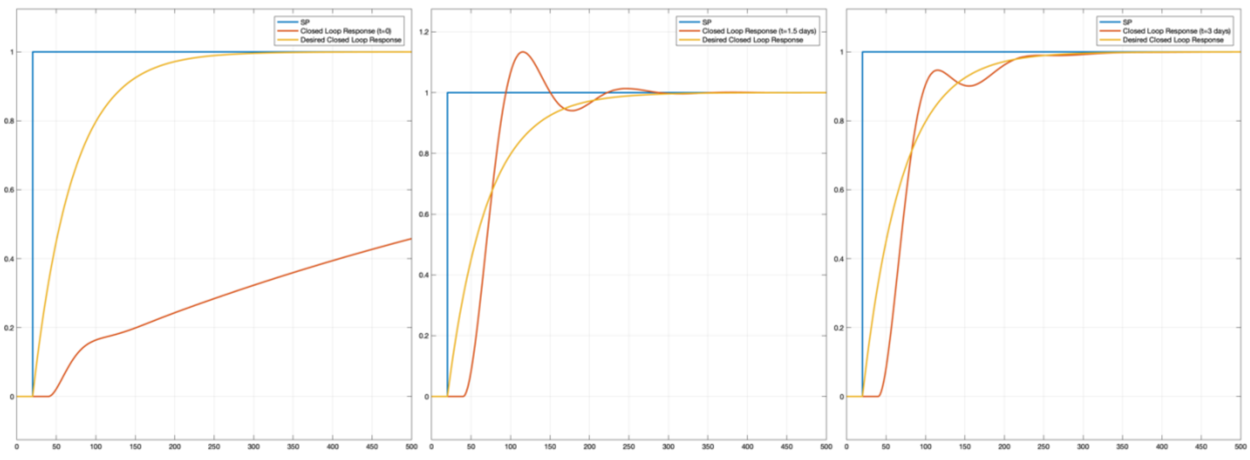

Fig. 5b. Case 1: Closed loop response versus desired at t=0, 1.5 and 3 days.

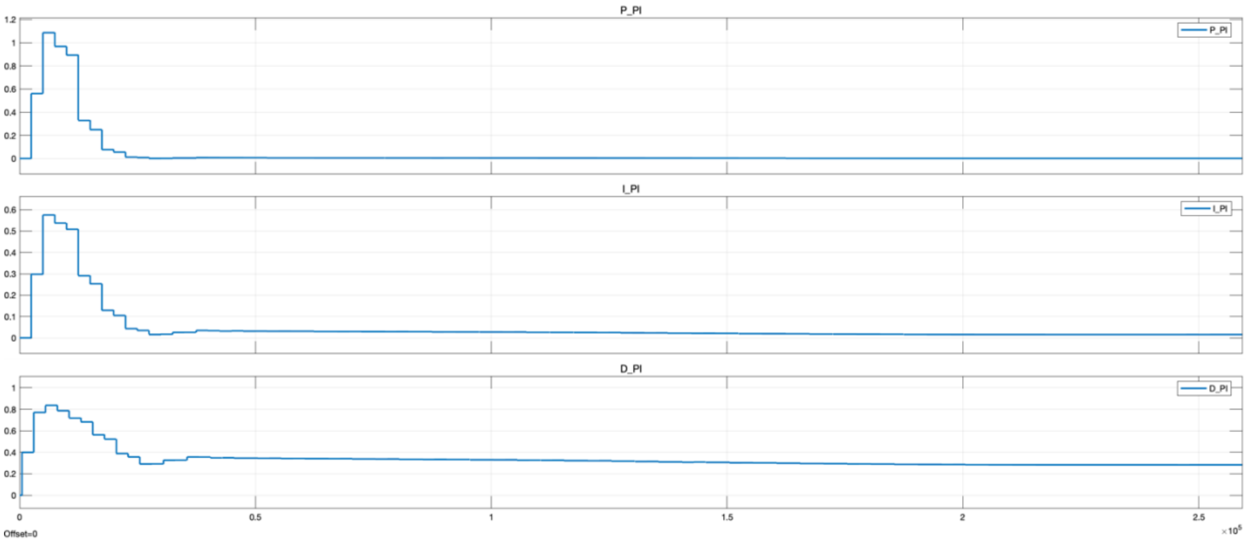

Fig. 5c. Case 1: Agent OV trends: PIs.

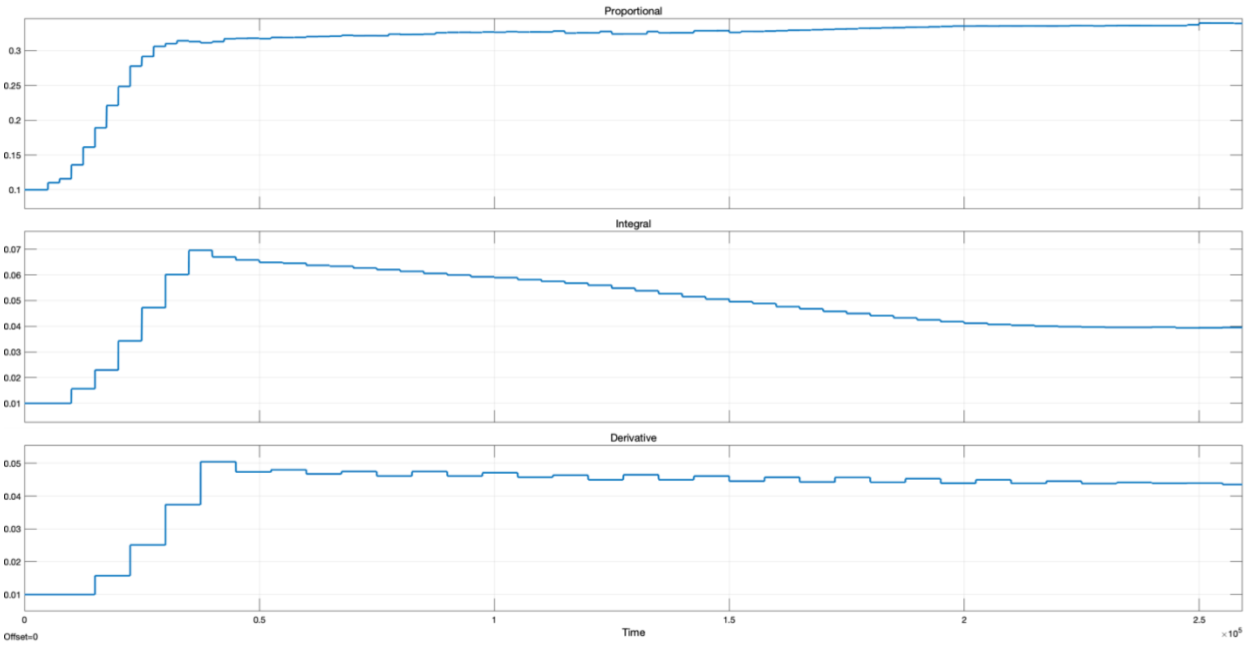

Fig. 5d. Case 1: Agent MV Trends: P, I and D Parameters.

As can be seen from Fig. 5a, the three ORTO agents drive their respective PID parameters to deliver a closed loop response close to the desired response, as described by the reference model, within approximately six cycles of the input signal. Fig. 5c and 5d show how the ORTO agents stabilize the P, I and D values after ~12 hours. Beyond this time, PMM is further reduced by slowly decreasing integral action, thereby reducing the closed loop overshoot, as illustrated in Fig 5b. There is an initial PMM spike after every SP move. This is a consequence of the process time delay, which cannot be removed by the closed loop action i.e., the desired closed loop can never to exactly attained because of the time delay.

Initial tuning takes a relatively large amount of time because of the ‘distance’ the ORTO agents must move their respective tuning parameters and because of the slow frequency of the perturbation signal. Convergence speed could be increased by having the initial PID values closer to the optimum and increasing the perturbation signal frequency. In addition, convergence speed could be further improved by increasing the maximum move sizes of each agent.

6.2. Case 2: PID Adaptation – Non-stationary Process Dynamics

Case 1 is now repeated with the process dynamics changing over a simulation run time of 10 days, as follows:

$$\left.\frac{1.2e^{-20s}}{200s^2+20s+1}\right|_{t=0} \Longrightarrow \left.\frac{2.4}{10s+1}\right|_{t=10days} \qquad (12)$$

Process parameters are varied linearly from their initial values through to their final values over the 10-day period. For example, the s^2coefficient is changed from 200 at rate of -200/10 units/day, reaching a value of 0 by the end of the 10-day simulation run. To reemphasize, the process transitions linearly from a second order underdamped process with time delay, to a first order process, having a faster settling time and double the steady state gain. Throughout the transition, the objective of the ORTO agents is to maintain, as closely as possible, the desired closed loop response [11]. Such changes in process dynamics would rarely happen but are chosen to test again the adaptive ability of the ORTO agents.

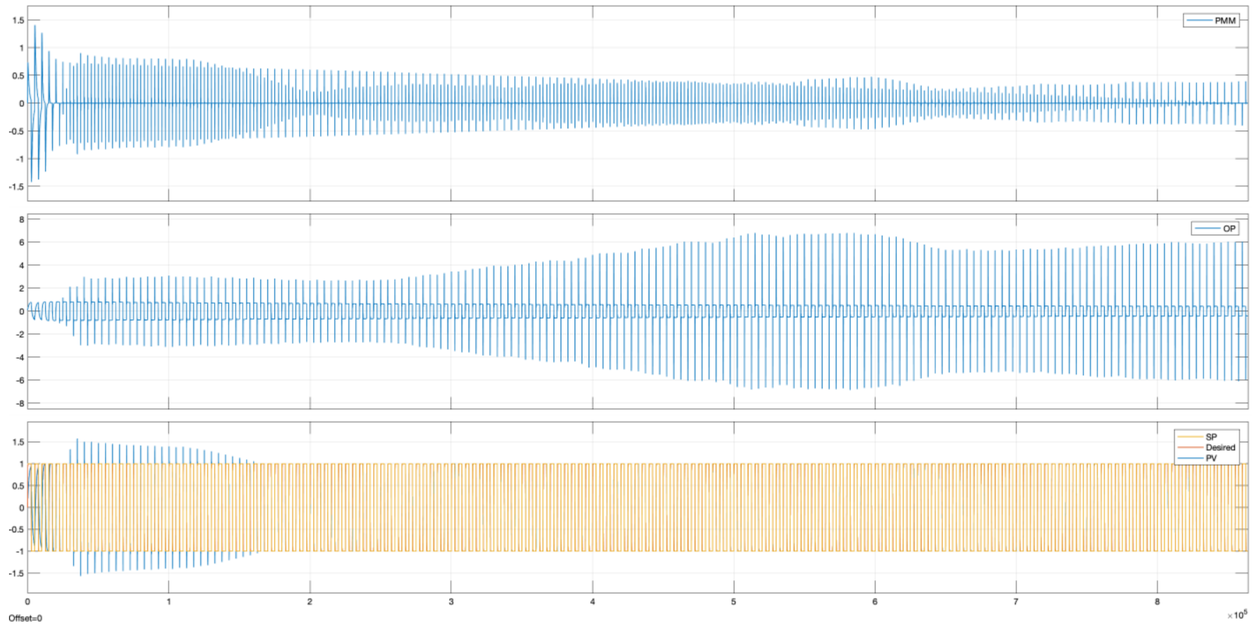

Fig. 6a. Case 2: Non-stationary process dynamics, perturbation signal period 5000 seconds. Simulation time 10 days. Closed loop response. trends.

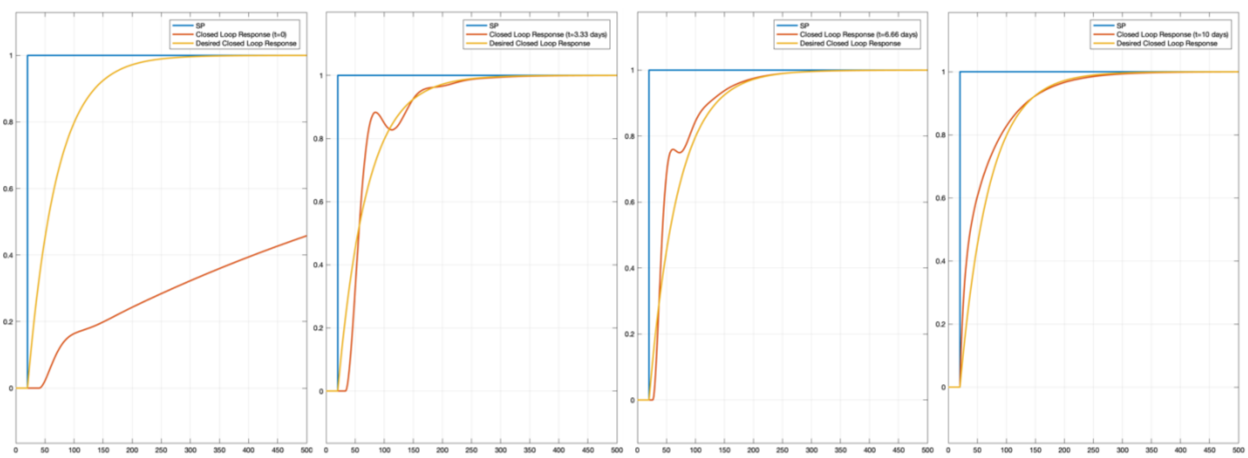

Fig. 6b. Case 2: Closed Loop Response versus Desired at t=0, 3.33, 6.66 and 10 days.

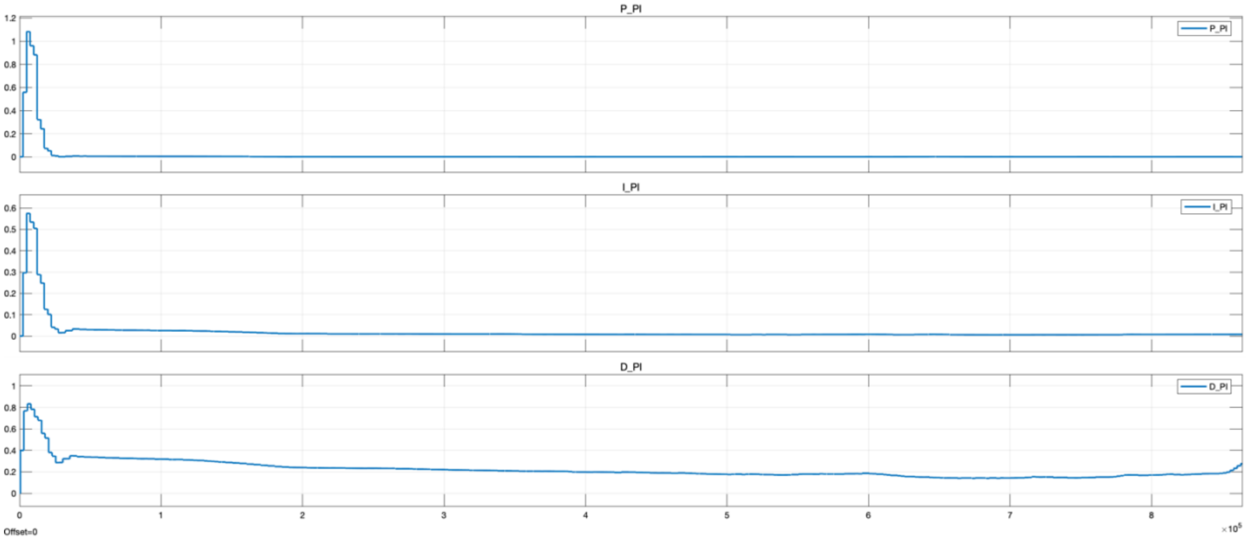

Fig. 6c. Case 2: Agent OV Trends: PIs.

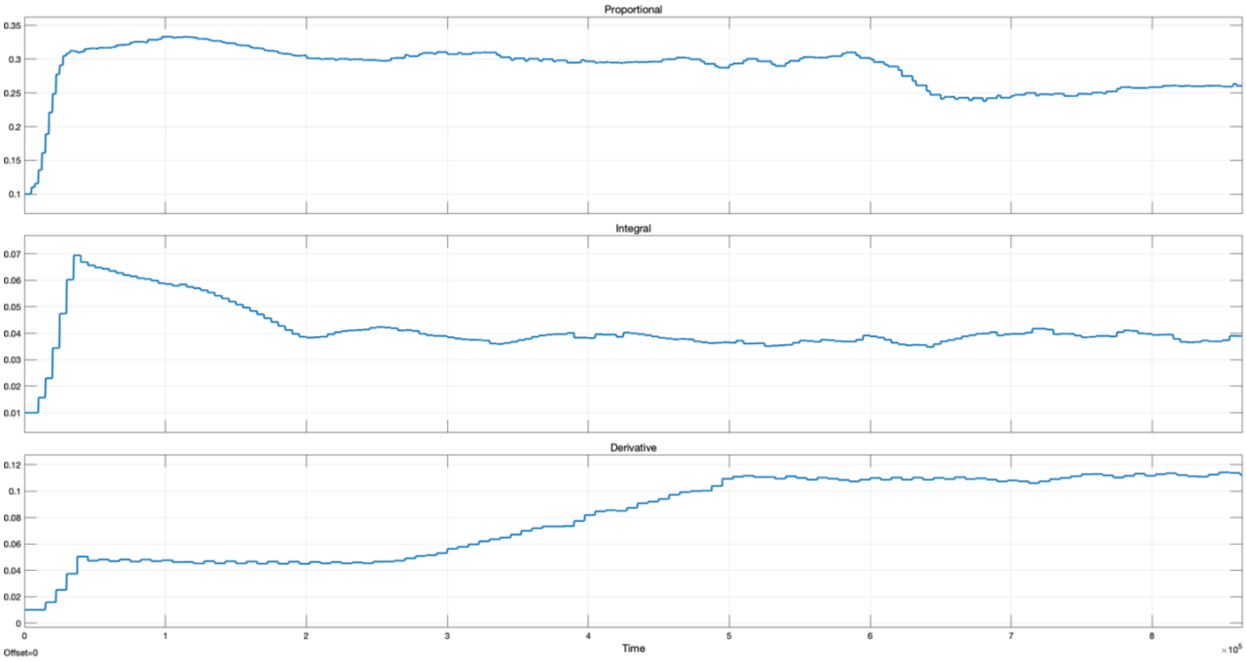

Fig. 6d. Case 2: Agent MV Trends: P, I and D Parameters

As with the previous case and as illustrated in Figs. 6a and 6c, tuning convergence occurs within the first six cycles of the input signal. Thereafter and as shown in Fig. 6b, the closed loop response adheres to, as closely as possible, the desired closed loop response as the process dynamics change [12]. Fig. 6d shows how the ORTO agents adjust the PID settings to achieve this, for example, initially decreasing integral action, then increasing derivative action.

The ability for ORTO to converge and then maintain optimum PID settings, as process dynamics change over time is thus demonstrated.

6.3. Case 3: PID Adaptation – Non-stationary Process Dynamics with Process Noise

Case 2 is now repeated but with an appreciable level of random noise applied (20% of input signal amplitude).

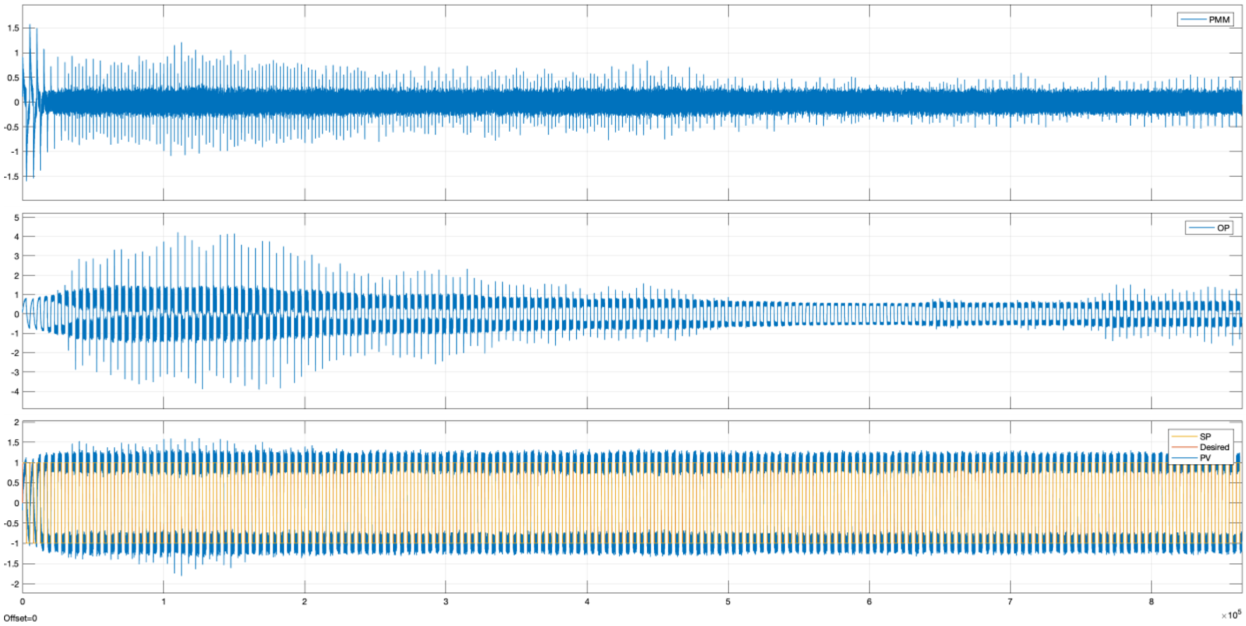

Fig. 7a. Case 3: Non-stationary process dynamics, perturbation signal period 5000 seconds. Simulation time 10 days. Closed loop response trends.

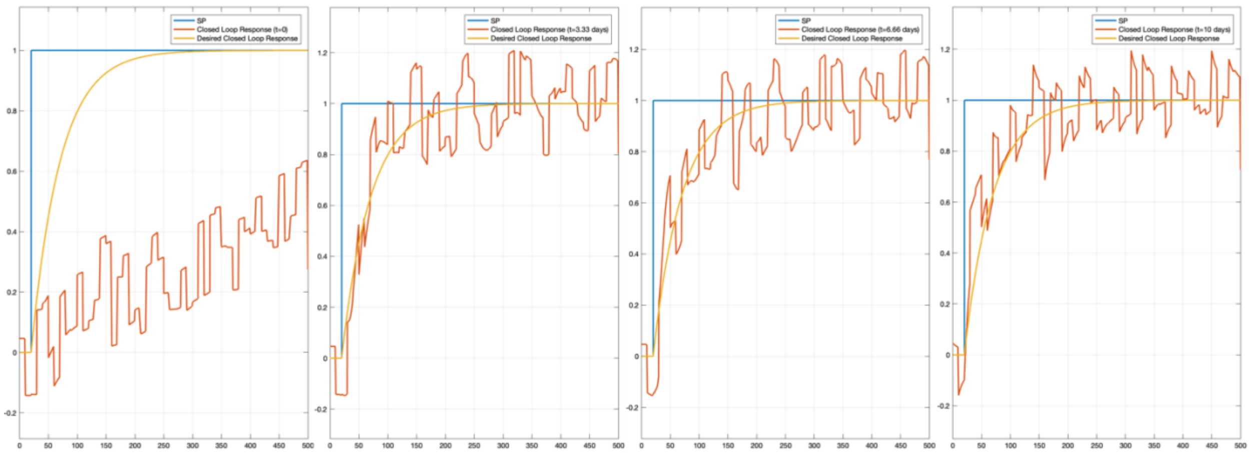

Fig. 7b. Case 3: Closed Loop Response versus Desired at t=0, 3.33, 6.66 and 10 days.

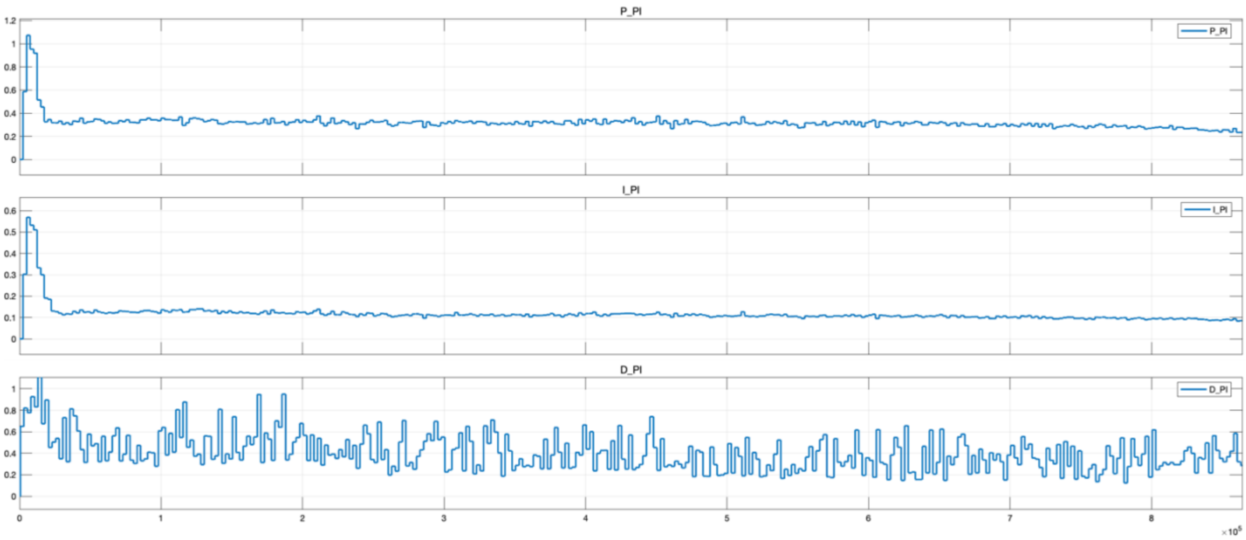

Fig. 7c. Case 3: Agent OV Trends: PIs.

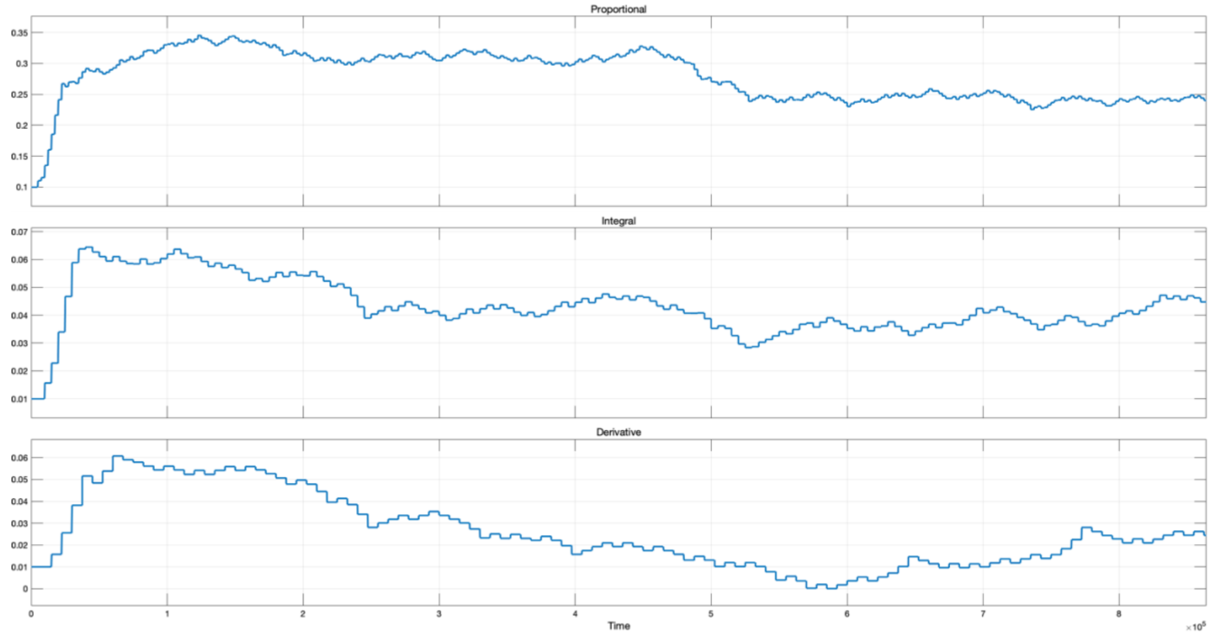

Fig. 7d. Case 3: Agent MV Trends: P, I and D Parameters

As with case #2, and as illustrated in Figs. 7a and 7c, tuning convergence occurs within the first six cycles of the input signal. Thereafter, the presence of process noise does change the adaptive tuning, however, as shown in Fig. 7b, the desired closed loop response is still adhered to. Fig. 7d shows that the proportional and integral parameters follow a similar, albeit noisier path as those with no process noise present. However, the derivative ORTO agent drives the value down, presumably because the adverse impact of noise on the closed loop response is amplified by derivative action.

The ability for ORTO to converge and then maintain optimum PID settings as process dynamics change over time, even in the presence of appreciable process noise, is thus demonstrated. Note, where noise is appreciable, a suitable low pass filter could be used in the measurement feedback path. ORTO agents would then have to incorporate the resulting changes in the closed loop response into the adaptation of the PID parameters.

7. Conclusions and Further Work

All process dynamics change over time i.e., they are 'non-stationary'. Discrete changes may occur due to an operator action or abrupt change in equipment operation. Continuous changes in process dynamics may occur due, for example, to fouling or degradation of process equipment. The test cases presented in this paper demonstrate that continuous on-line adaptation of controller parameters is successfully delivered by ORTO agents, even when faced with non-stationary dynamics and appreciable process noise.

It is acknowledged that the application of a low frequency cyclical perturbation signal of adequate strength, namely at least double the average value of the process noise, can be detrimental. The resulting process disturbance and mechanical wear of the final control element may outweigh any continuous tuning benefits. If this is the case, an alternative strategy could be to use the ORTO agents in a 'tune-on-demand' capacity, as and when closed loop performance deteriorates enough to warrant it. Again, testing has demonstrated that ORTO agents can be used in such a capacity.

There are many other scenarios which could be examined. For example, further test cases could explore the impact of loop interaction and external wild variables (process disturbances) on adaptation performance. Adaptive tuning when controlling a highly non-linear process e.g., at different points across the operating range, could also be examined.

References

Åström, K. J., Wittenmark, B., "Adaptive Control", Second Edition.

Appendix A. ORTO Scheme General Design Methodology

The procedure to design and build an ORTO scheme, for any given process or system, is as follows:

Step 1: Review business objectives. Identify the key commercial, environmental or safety variable to be optimized (OV).

Step 2: Identify all manipulated variables (MVs) which have an influence on the optimization objective and define the range within which an ORTO agent can safely move them within. The number of MVs identified equals the number of ORTO agents required.

Step 3: Identify any wild 'feed-through' variables (WVs) which directly impact the optimization variable, irrespective of MV action. Modify the OV to take account of the WVs accordingly.

Step 4: Identify any external constraint variables (CVs) that the optimization must respect e.g., product quality variables.

Step 5: Implement each ORTO agent, with outputs cascaded to each respective MV and with OV, MV readback and CV logic inputs configured.

Step 6: Configure each ORTO agent by setting the parameters, as listed and described in Appendix B.

Step 7: Switch each ORTO agent on, in turn, monitoring OV improvements. Adjust maximum move sizes and search space, as confidence grows in optimization performance. Remove any ORTO agents making a negligible contribution. Add further ORTO agents as additional MVs are identified.

Appendix B. ORTO Agent Configuration Parameters

Optimization Objective	Set to 'Maximize' or 'Minimize'. All ORTO agents must have the same optimization objective within an optimization scheme.
OV Engineering Range (EU) MV Engineering Range (EU)	Knowing the OV and MV ranges helps ORTO to calibrate its MV moves.
Sample Time (Secs)	Set as a function of system dynamics. Combined with maximum move size, sets the speed of optimization.
Max. Move Size (EU)	The maximum acceptable net move across the defined sample time. Setting maximum move size too low will slow down optimization. Setting it too high may cause excessive movement of MV at around the optimum value.
MV Hi-Lo Constraint Bounds (EU)	The bounds within which the MV can be moved.
Initial Push Direction	Set to 'Positive', 'Negative' or 'Not Sure'. Direction is a function of the initial condition i.e., starting point.