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Development of Basic Process Control Structures ⋆

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Abstract: This paper treats development and research at the regulatory control layer in process control. It is noticed that very little attention is payed to this subject, with the exception PID controller tuning. The reason for this is discussed. Two examples of recent advances in the field treating feedforward control and ratio control, respectively, are presented. A goal of the paper is to point out the need for further research in the area. One reason for this is the great industrial impact such research may have, since the functions appearing in this layer are used at so many places in so many industries. A second reason is the need for well functioning regulatory control layers to form solid foundations for the advanced process control layers.

Keywords: Process control, PID control, regulatory control, feedforward control, ratio control, control structures.

1. INTRODUCTION

Process control is built up by a hierarchical structure that is often illustrated as in Figure 1. The basic layer consists of field devises such as sensors, actuators, pumps, and valves. On the next level, the regulatory control layer, we find PID controllers coupled together using basic control structures such as cascade control, feedforward control, ratio control, selector control, etc. On top of the regulatory control layer we have the advanced process control layer with e.g. Model Predictive Controllers (MPC). On the top of the hierarchy we find the production planning and optimization layer (Darby et al., 2011). This paper treats research and development in the regulatory control layer.

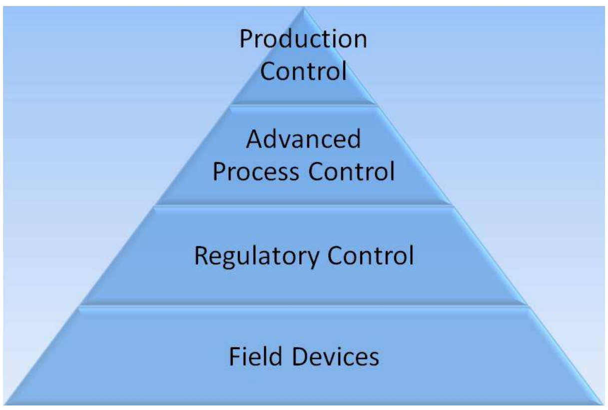

Fig. 1. The process control hierarchy.

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1.1 The digitalization

Process control instrumentations have gone through several major technology shifts, from pneumatics via electronic to computer-based. The most dramatic shift was the digitalization that occurred in the late seventies and early eighties, when instruments and controllers started to be implemented using micro computers. This was also the period when programmable logic controllers (PLC) and distributed control systems (DCS) started to appear.

The technology shifts are often abrupt and unplanned (Åström and Hägglund, 2005). The reason why a company decides to change technology is often pressure from costumers and competitors. A switch in technology often means that R&D staff has to be replaced by people that are familiar with the new technology, but often not with the old one. This means that there is a risk that information is lost during the transitions. Since the technology transfer has to be done fast, there is also a risk that the potential of the new technology is not utilized.

Before the digitalization, the two upper layers in the control pyramid in Figure 1 where performed by humans. Nowadays, most of the work in the three control layers are performed by computers. When it comes to research and development, the focus has been on the two upper layers, where we have seen many advances in the last decades. Model predictive control is one example. The computers have made it possible to run optimization procedures on line, and this technique has replaced much of the work that was done by humans before the digitalization.

1.2 The regulatory control layer

The regulatory control layers consist of PID controllers connected by advanced networks that have been developed by humans, often during several decades. There is impressing process and control knowledge utilized in these networks.

When the digitalization appeared in the seventies and eighties, the functions of the controllers and the control structures were mainly copied and retained. It was, of course, wise to have a bumpless transfer to the new technology and try to keep the knowledge behind these structures. It is also important that the operating staff is familiar with the control strategies and understands how to run the plants.

However, with few exceptions, the opportunities of having computers in the regulatory control layer was not utilized after this transition. When it comes to the basic control structures that are the building blocks for the instrumentation in the regulatory control layer, very little research and development has been presented. This is sad, because improvements in this layer may have great impacts. The regulatory control layer is also the foundation for the advanced process control layer that relies on well functioning lower layers.

Research and development of the regulatory control layer is the topic of this paper. We start by giving two examples that illustrate the need and possibility to pay attention to the basic control structures in this layer, namely feedforward control and ratio control.

2. FEEDFORWARD CONTROL

If a disturbance is measurable, feedforward from this disturbance to the controller may improve the disturbance rejection significantly. The feedforward control structure is illustrated in Figure 2. The block diagram contains process P_1P_2 which determines the influence of control signal u on system output y, and another process P_3P_2 that relates measurable load disturbance d to system output y. Control signal u is composed of the output from feedback controller C plus the output from feedforward controller C_{ff}. The goal is to design the feedforward compensator C_{ff} so that the effect of the disturbance d on the process output y is minimized.

Perfect feedforward, which means that the effect of d is eliminated in y, is obtained when

$$C_{ff} = \frac{P_3}{P_1} \tag{1}$$

However, this compensator is seldom realizable. The compensator may be non-causal, it may be unstable, it may have infinite high-frequency gain because of derivative action, and it may require a more complicated structure than what is available.

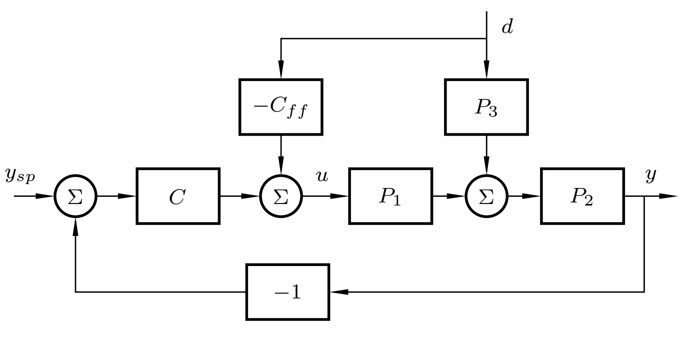

Fig. 2. Block diagram illustrating the feedforward control structure.

In this paper, the three process transfer functions are modeled as first-order systems with time delay, i.e.

$$P_1 = \frac{K_1 e^{-sL_1}}{1+sT_1},\ P_2 = \frac{K_2 e^{-sL_2}}{1+sT_2},\ P_3 = \frac{K_3 e^{-sL_3}}{1+sT_3} \tag{2}$$

More complex models can be used, but the first-order plus dead time model structure has become the standard model in process control applications.

It is assumed that the feedback controller is a PI or PID controller with transfer function

$$C = K\left(1 + \frac{1}{sT_i} + sT_d\right), \tag{3}$$

The feedforward controller C_{ff} is assumed to be either static or a lead-lag filter, i.e.

$$\begin{aligned} &\text{Static:} && C_{ff} = K_{ff} e^{-sL_{ff}} \\ &\text{Lead-lag:} && C_{ff} = K_{ff} \frac{1+sT_z}{1+sT_p} e^{-sL_{ff}} \end{aligned}$$

More complex structures are seldom used in process control. Using the models (2) the feedforward controller (1) becomes

$$C_{ff} = \frac{P_3}{P_1} = \frac{K_3}{K_1} \cdot \frac{1+sT_1}{1+sT_3} e^{-s(L_3-L_1)} \tag{4}$$

which means that

$$K_{ff} = \frac{K_3}{K_1} \quad T_z = T_1 \quad T_p = T_3 \quad L_{ff} = L_3 - L_1 \tag{5}$$

When $L_3 < L_1$, the optimal parameters given by (5) give a non-causal feedforward compensator, since L_{ff} becomes negative. This means that perfect feedforward is not possible in this case, and $L_{ff} = 0$ has to be used.

It is common to just have a static feedforward compensator. In this case

$$C_{ff} = K_{ff} = \frac{K_3}{K_1} \tag{6}$$

eliminates the effect of the disturbance in steady state.

2.1 The problem

Figure 3 illustrates feedforward control applied to an example with process models

$$P_1 = \frac{e^{-2s}}{1+2s}, \quad P_2 = \frac{1}{1+s}, \quad P_3 = \frac{e^{-s}}{1+s} \tag{7}$$

in the case where feedback controller C is in manual mode (left), and when the controller is in automatic mode (right), respectively. A PI controller is tuned using the AMIGO rule (Åström and Hägglund, 2005), which gives the parameters $K = 0.32$ and $T_i = 2.85$. The design (4) gives the feedforward compensators

$$\begin{aligned} &\text{Static:} && C_{ff} = 1 \\ &\text{Lead-lag:} && C_{ff} = \frac{1+2s}{1+s} \end{aligned} \tag{8}$$

Figure 3 shows that the feedforward control works well when the feedback controller is switched off, but that the

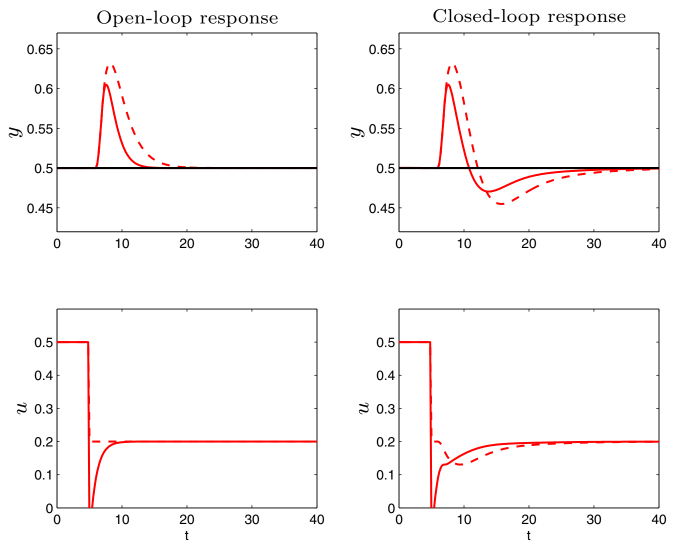

Fig. 3. Feedforward control applied to the process models (7) using static (dashed lines) and lead-lag (solid lines) feedforward compensators (8). The figure shows control with feedback controller in manual mode (left) and automatic mode (right), respectively.

control deteriorates with overshoots and longer settling times when both feedback and feedforward controllers are active. There are, in principle, two ways to treat the problem. One is to modify the feedback controller action and let the feedforward controller take care of the disturbance rejection, and the other way is to take the feedback action into account when designing the feedforward controller. These approaches are treated below.

2.2 Solution 1: Modify feedback controller action

A nice way to separate the feedforward action from the feedback controller was presented in (Brosilow and Joseph, 2002). The separation is obtained by adding another feedforward path, from the disturbance to the controller input, see Figure 4. If the compensator H is determined as

$$H = P_2\left(P_3 - P_1 C_{ff}\right) \tag{9}$$

feedback controller C will not influence the responses. It means that if the structure in Figure 4 where used in the example presented in Figure 3, the right-hand plots would have been equal to the left-hand ones.

In (Rodríguez et al., 2014, 2013), tuning rules for this control structure were obtained to account for inversion problems on the time delay and non-minimum phase behaviours.

2.3 Solution 2: Modify feedforward controller action

Another way to treat the problem with the interactions between the feedback and the feedforward controllers is to retain the structure in Figure 2, and modify the feedforward control action by taking the feedback controller into account in the feedforward design. It is interesting to note that while there are thousands of tuning procedures for the feedback PID controller, there are almost no methods for the feedforward controller.

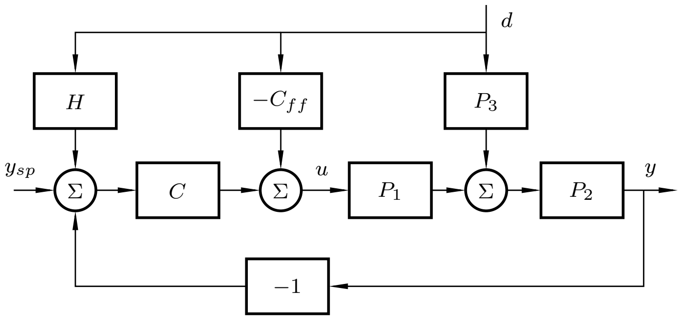

Fig. 4. Block diagram illustrating the feedforward control scheme according to (Brosilow and Joseph, 2002).

In (Shinskey, 1996), a design procedure for a lead-lag feedforward compensator was proposed, but it does not take the feedback controller into account. A similar approach was presented in (Seborg et al., 1989). (Isaksson et al., 2008) pointed out, probably for the first time, that the feedback controller should be taken into account when designing the feedforward compensator. A rather complicated solution, based on repeated least-squares optimization, was presented in the paper.

In (Guzmán and Hägglund, 2011), a simple feedforward control design method that takes the feedback controller into account was presented. The parameters of the feedforward compensator are calculated directly from the process models and the controller parameters. The goal of the design is to obtain a load disturbance response without overshoot that has a minimum IAE value. The design procedure given in (Guzmán and Hägglund, 2011) is:

(1) Set $L_{ff} = \max(0, L_3 - L_1)$. For a static feedforward, set $T_z = T_p = 0$ and go to step 3. For a lead-lag filter, set $T_z = T_1$ and go to step 2.
(2) Calculate T_p as:
$$T_p = \begin{cases} T_3 & L_1 - L_3 \le 0 \\ T_3 - \dfrac{L_1 - L_3}{1.7} & 0 < L_1 - L_3 < 1.7T_3 \\ 0 & L_1 - L_3 > 1.7T_3 \end{cases}$$
Go to step 3.
(3) Calculate the compensator gain, K_{ff}, as
$$K_{\ ff} = \frac{K_3}{K_1} - \frac{K}{T_i} IE$$
$$IE = \begin{cases} K_2K_3(T_1 - T_3 + T_p - T_z) & L_3 \ge L_1 \\ K_2K_3(L_1 - L_3 + T_1 - T_3 + T_p - T_z) & L_3 < L_1 \end{cases}$$
For a static feedforward go to step 5. For a lead-lag filter, go to step 4.
(4) Analyze the high-frequency gain, $K_{ff}\kappa$, based on the design performed in the previous steps ($\kappa = T_z/T_p$). If the resulting high-frequency gain is acceptable, go to step 5. Otherwise, modify κ to reach the desirable high-frequency gain and change T_p as:
$$T_p \ge \frac{T_z}{\kappa}.$$
Go to step 3.
(5) End of the design process.

For the example presented in Figure 3, the following feedforward compensators are obtained:

$$\begin{aligned} \text{Static:} \quad & C_{ff} = 0.775 \\ \text{Lead-lag:} \quad & C_{ff} = 0.956 \frac{1+2s}{1+0.404s} \end{aligned} \tag{10}$$

The results are presented in Figure 5. The figure shows that the overshoots in the responses are removed, and that the settling time has been reduced compared to both the open and closed loop responses obtained in Figure 3.

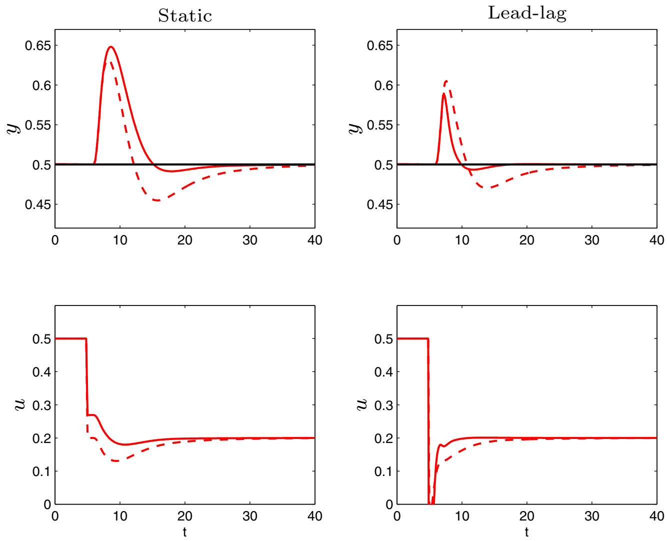

Fig. 5. Feedforward control applied to the process models (7) using the feedforward design (8) (dashed lines), and the new design given in (Guzmán and Hägglund, 2011) (solid lines).

3. RATIO CONTROL

In ratio control, the control objective is to keep the ratio between two signals, normally flow measurements, at a desired value in spite of variations in setpoints and load disturbances, and possible control signal saturations. Ratio control is very common in process control. It is estimated that around 15% of all controllers in a process control plant are used for ratio control.

The control problem is to synchronize two flow control loops, with process models P_1 and P_2, controllers C_1 and C_2, flow measurement signals y_1 and y_2, control signals u_1 and u_2, and flow setpoints r_1 and r_2.

The two flows should be controlled so that a desired ratio a between them is retained, i.e.

$$\frac{y_2}{y_1} = a$$

It is assumed that the flow demand r is provided as the setpoint to the first flow, i.e. $r_1 = r$. In this application, it is assumed that keeping the ratio a is most important, and keeping the flow is less important.

There are two solutions that form the industrial standard today, the parallel ratio station and the series ration station.

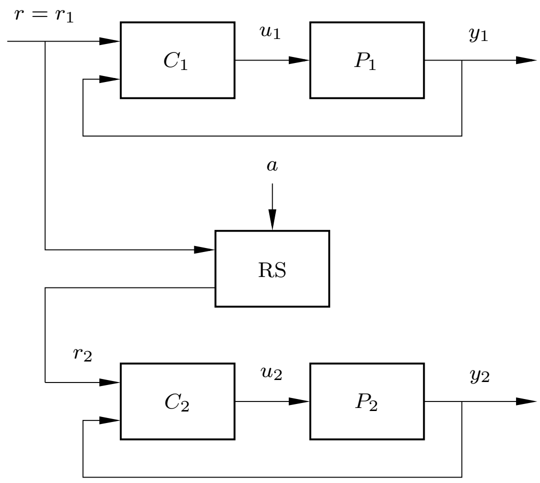

Fig. 6. Ratio control using a parallel ratio station (RS) applied to setpoint r_1.

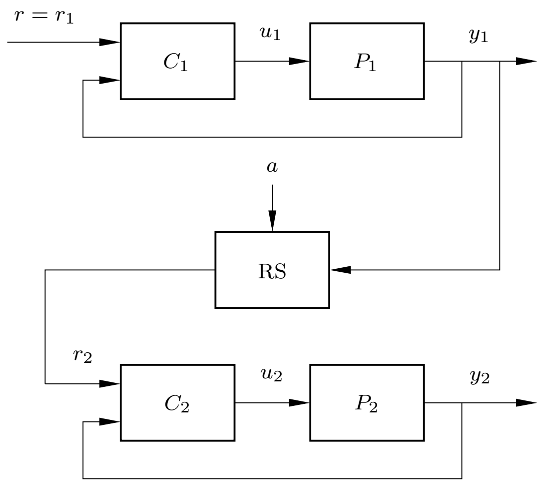

Fig. 7. Ratio control using a series ratio station (RS) applied to flow y_1.

3.1 *The parallel ratio station*

The parallel ration station is presented in Figure 6. Here, setpoint r_2 is determined as

$$r_2 = ar_1 \tag{11}$$

If controllers C_1 and C_2 have integral action, and provided that the control signals are not saturated, the control objective is obtained in steady state, i.e. $y_1 = r$ and $y_2/y_1 = a$.

However, the parallel ratio station is an open-loop approach in the sense that there is no attempt to keep the ratio during load disturbance responses, at control signal saturations, or when one of the controllers is switched to local setpoint or manual control.

3.2 *The series ratio station*

The structure of the series ration station is presented in Figure 7. In the series ratio station, the first loop is a master loop, and the second one is a slave loop, and the input to the ratio station is the process output of the

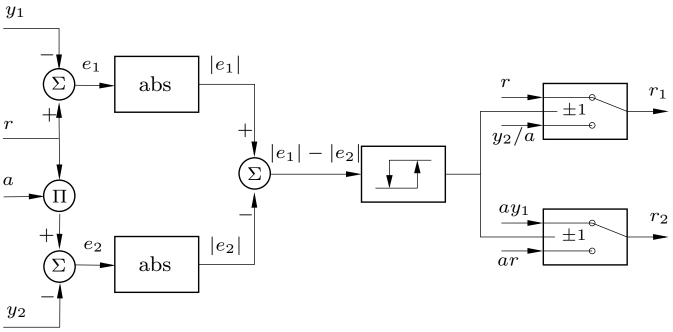

Fig. 8. Block diagram presentation of the tracking ratio station (TRS).

master loop instead of the setpoint. Here, setpoint r_2 is determined as

$$r_2 = ay_1 \tag{12}$$

i.e. by multiplying flow y_1 with the desired ratio a.

The advantage of the series implementation of the ratio station compared to the parallel one is that load disturbances and control signal saturations appearing in the master loop are compensated for in the slave loop, leading to a better tracking of the ratio in these cases. The ratio will also be retained when the master controller is switched to local setpoint or manual control. Load disturbances, saturations, and mode switches in the slave loop are still not treated.

A drawback of the series implementation is that the ratio will not be kept during setpoint variations, since the second flow y_2 will always be delayed compared to the desired flow ay_1. Another drawback is that measurement noise in the master loop is introduced in the slave loop via the setpoint r_2. This may cause wear on the actuators. The problem can be reduced by feeding the setpoint to the slave controller through a low-pass filter.

3.3 The tracking ratio station

A new ratio control structure was presented in (Hägglund, 2017). The idea is to switch the roles of master and slave between the two controllers depending on the magnitudes of their control errors, so that the loop with the largest control error becomes master and follows the flow setpoint, and the loop with the smallest control error becomes slave and follows the process output of the other loop. Figure 8 gives a block diagram representation of the tracking ratio station.

The tracking ratio station is symmetric in the sense that both loops are treated in the same way. A nice feature is that it takes care of all disturbances mentioned earlier, namely changes in flow setpoint, load disturbances, and control signal saturations. It will also track the ratio when one of the controllers is switched to manual mode or takes a local setpoint instead of the external one.

Figure 9 shows simulation results from a case where

$$P_1 = P_2 = \frac{1}{(1+s)^2} \tag{13}$$

and the controllers are PI controllers tuned using the AMIGO tuning rule, (Åström and Hägglund, 2005), giving parameters $K = 1.71$ and $T_i = 1.33$. The desired ratio is $a = 1$.

Figure 9A shows responses to a setpoint change. The two process outputs follow each other very well. The strategy is a switching strategy, which means that the tracking is obtained by a high control signal activity. Ways to reduced this activity are discussed in (Hägglund, 2017).

Figure 9B shows responses to step load disturbances at the process inputs. It is seen that the undisturbed process output leaves its former setpoint and goes towards the other process output to try to keep the ratio.

Figure 9C illustrates what happens when one of the controller outputs becomes saturated. The other loop follows the saturated one, and the flow setpoint is not kept anymore.

Figure 9D finally demonstrates what happens when one of the controller is switched to manual mode. Also in this case, it is attempted to keep the ratio and the flow setpoint is not tracked.

4. BASIC PROCESS CONTROL STRUCTURES

We have now seen examples of research and development of basic process control structures in the regulatory control layer. The Brosilow feedforward structure was presented in 2002, the feedforward tuning rule was presented in 2011, and finally the tracking ratio station was presented in 2017. So, all these results are presented several decades after the digitalization that made the process control instrumentation computer based. It illustrates the lack of development and research in this area. The problem was also treated in (Hägglund, 2013).

Most of the research in the process control community has been focusing on the two upper control layers, i.e. more advanced control methods. A problem is that the layers in the pyramid are relying on the lower levels. If the field devices in the bottom layer are not working properly, the control functions in the upper layers will not do so either. Much attention has, e.g., been paid to the fact that so many valves in industry have too much stiction resulting in stic-slip motion in the control loops. In the same way, badly tuned controllers and basic control structures that are used in bad ways or not working properly in the regulatory control layer will limit the possible achievements in the advanced process control layer. This was pointed out by (Ender, 2001).

There are sometimes proposals to remove the regulatory control layer and put the advanced process control layer directly on top of the field devices, i.e. to let MPC controllers do all the work. First of all, the knowledge that is created during decades and utilized in the regulatory control layer is then lost. Secondly, it means a shift, not in hardware technology but in concepts, that may be hard for the personnel to grasp. The solution to this has in many cases been to hire consultants, which may turn out to be an expensive solution.

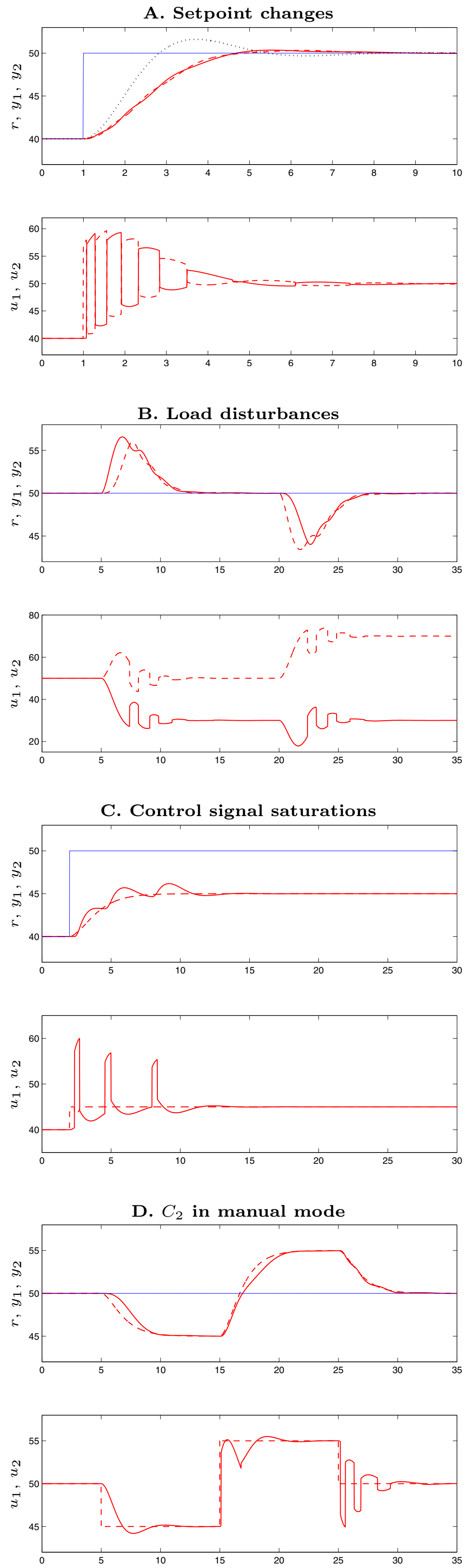

Fig. 9. Simulation results for the tracking ratio station at setpoint changes (A), load disturbances (B), control signal saturations (C), and when one of the controllers is operating in manual mode (D).

5. CONCLUSIONS

This paper has reviewed development of two basic process control structures appearing in the regulatory control layer, namely feedforward control and ratio control.

The regulatory control layer is an almost neglected area when it comes to research and development, with one exception. The research about PID controller tuning has been very active since the early eighties. However, very little work has been presented related to the basic control structures that connect the PID controllers.

40 years after the technology shift to computer-based control systems, it is high time to pay attention to these basic control structures, to improve the existing ones and to develop new. The impact of advances in this field has a great potential, since these structures appear at so many places in so many process industries.

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