A RATIO CONTROL ARCHITECTURE FOR SET-POINT FOLLOWING AND LOAD DISTURBANCE REJECTION

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Abstract: In this paper a new ratio control architecture is proposed. Differently from the ratio controllers proposed in the literature, this one aims at achieving satisfactory performances with respect to both set-point following and load disturbances rejection specifications. Tuning rules are provided, so that no significant design effort is required to the user. Overall, the simplicity of the proposed control scheme makes it suitable to implement in the industrial context. Simulation results show the effectiveness of the methodology.

Keywords: Ratio control, PID controllers, tuning, set-point following, load disturbance rejection.

1. INTRODUCTION

PID controllers are undoubtedly the most adopted controllers in industrial settings, because of the good cost/benefit ratio they are able to provide. This is due to the fact that they are able to achieve satisfactory performances for a wide variety of processes and, at the same time, they are simple to use. In order to help the operators to satisfy control specifications with a limited design effort, a large number of tuning rules have been devised (O'Dwyer, 2003), together with methodologies for the design of those additional functionalities (such as anti-windup, feedforward action, gain scheduling, adaptive control and so on) that make the adoption of the basic PID algorithm successful in practical cases (Aström and Hägglund, 1995).
Often, PID controllers are employed as a fundamental component in more complex control schemes, where couplings between simple control systems are exploited. A significant example in this context is ratio control, where the control specification is to keep a constant ratio between two process variables, despite set-point changes and load disturbances. A ratio control problem can be found in many industrial processes such as chemical dosing, water treatment, chlorination, mixing vessels, waste incinerators. For example, in combustion systems it is necessary to control accurately the air-to-fuel ratio in order to obtain a high efficiency, and in blending processes a selected ratio of different flows has to be maintained in order to achieve a constant product composition.
Design methodologies for ratio controllers have not been much investigated in the literature. A significant contribution is the work of Hagglund (Hägglund, 2001), where a ratio control architecture named Blend station is proposed to improve set-point responses with respect to classic schemes. A different method has been presented in (Visioli, 2003). Therein, in addition to provide a perfect set-point response in the absence of model uncertainties, load disturbances rejection performances are also taken into account.
Aiming at improving the load disturbances rejection performances without impairing the set-point response, a new design methodology is proposed in this paper. It has to be stressed that, in general, the

adoption of more complex control schemes should not imply an increase of the design effort for the operator. Thus, tuning rules have been devised to guarantee a simple implementation of the method and therefore its suitability for industrial applications.
The paper is organized as follows. In Section 2 ratio control is reviewed and techniques proposed in the past are briefly discussed. In Section 3 the new method is presented. Simulation results are shown in Section 4 and conclusions are drawn in Section 5.

2. RATIO CONTROL

A ratio controller aims at keeping a predetermined constant ratio a between two process variables y_2 and y_1, despite set-point changes and load disturbances that might occur on the plant. The most employed control scheme in this context is the one shown in Figure 1 where each variable is controlled by two separate controllers C_1 and C_2 (typically of PI type) and the output y_1 of the first process P_1 is multiplied by a and adopted as the set-point signal of the closed-loop control system of the second process P_2, i.e. it is $r_2(t) = ay_1(t)$ (Shinskey, 1996). It has to be noted that in this case the set-point response of the second closed-loop system is necessarily delayed with respect to the response of the first one. This drawback is somewhat limited by imposing that the dynamics of the second loop be much faster than that of the first loop.
Thus, this choice is usually preferred to that of imposing $r_2(t) = ar_1(t)$ because in this case the required ratio is no more followed when a load disturbance occurs in the first loop, although a perfect set-point response (i.e. the desired ratio a is achieved during the whole transient) can be potentially achieved by selecting the same dynamics for the two loops.
In order to improve the set-point response performances with respect to the classic architecture of Figure 1 a different control architecture named Blend station has been proposed in (Hägglund, 2001). It combines the previous approaches by selecting

$$r_2(t) = a(\gamma r_1(t) + (1-\gamma)y_1(t)) \quad (1)$$

where γ is a constant parameter that actually weights the relative influence of the set-point r_1 on r_2 with respect to y_1 (note that for $\gamma = 0$ the classic scheme of Figure 1 is obtained). This solution however yields to a decrement in the load disturbance rejection performances and therefore should not be used when these are likely to occur.
An alternative scheme (shown in Figure 2) has been proposed in (Visioli, 2003). By choosing

$$F(s) = \frac{C_1(s)P_1(s)}{C_2(s)P_2(s)} \quad (2)$$

a perfect set-point response is obtained and by suitably selecting the design parameters (note that tuning rules

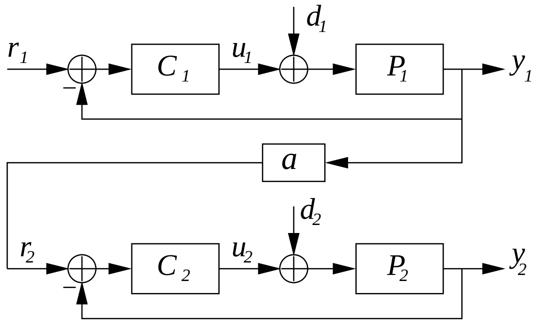

Fig. 1. The typical ratio control architecture.

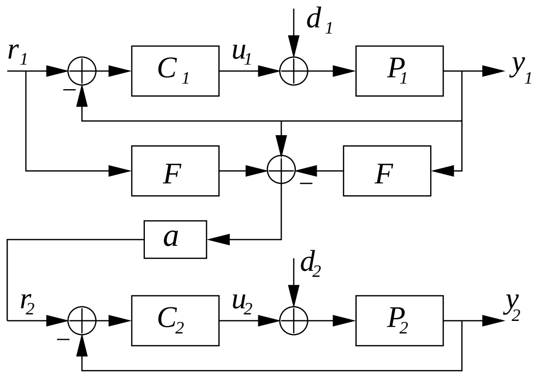

Fig. 2. An alternative ratio control architecture.

are explicitly provided) this is not paid by a decrement in the load disturbances rejection performances.
However, it appears that in all the considered methodologies the desired ratio is not followed when a load disturbance occurs in the second control loop (signal d_2 in Figures 1 and 2). In order to provide an effective solution for this problem a new architecture is proposed in the next section.

3. THE NEW ARCHITECTURE

The new control scheme is shown in Figure 3 and an explanation of it, together with tuning rules, is given in the following. First, a first order plus dead time (FOPDT) model for the two processes under control has to be obtained. This is what it is usually done in the industrial practice, and it can be performed with a variety of methods (e.g. the well-known area method (Aström and Hägglund, 1995)). Then, process P_1 has to be selected as the one with the largest estimated dead time, i.e. we have:

$$P_1(s) = \frac{K_1}{T_1 s+1}e^{-L_1 s} \qquad P_2(s) = \frac{K_2}{T_2 s+1}e^{-L_2 s} \qquad L_1 > L_2. \quad (3)$$

In case the two estimated dead times have the same value, the choice can be done arbitrarily.
By choosing

$$Q(s) := \frac{P_1(s)}{P_2(s)} = \frac{K_1(T_2 s+1)}{K_2(T_1 s+1)}e^{(L_1-L_2)s} \quad L_1 > L_2. \quad (4)$$

we have that the two loops have the same complementary sensitivity transfer function (whatever the controller C transfer function is) and therefore the desired ratio is maintained during the whole set-point response (assuming that no model uncertainties are present). In any case, in this context it is sensible to take C as a PI controller and the following tuning rule based on the pole-zero cancellation can be employed:

$$C(s) = K_c \frac{T_1 s + 1}{s}. \tag{5}$$

The choice of the design parameters K_c will be discussed in the next.

While filter Q is devoted to ensure good set-point following performances, filters H and G are devoted to improve the load disturbances response. The design of these transfer functions can be performed by taking into account the transfer functions from the load disturbance inputs d_1 and d_2 and the ratio error $e := ay_1 - y_2$, i.e. the input of the two filters. After somewhat trivial calculations, it results:

$$\begin{aligned} F_1(s) &:= \frac{e(s)}{d_1(s)} \\ &= -\frac{aP_1(s)}{1+P_1(s)(aH(s)+C(s))+P_2(s)G(s))} \end{aligned} \tag{6}$$

and

$$\begin{aligned} F_2(s) &:= \frac{e(s)}{d_2(s)} \\ &= \frac{P_2(s)}{1+P_1(s)(aH(s)+C(s))+P_2(s)G(s))}. \end{aligned} \tag{7}$$

Then, by choosing

$$H(s) = C(s) \tag{8}$$

and

$$G(s) = C(s)\frac{T_2 s+1}{T_1 s+1} = K_c \frac{T_2 s+1}{s} \tag{9}$$

and by approximating the time delay term in the denominator by a first order power-series expansion $e^{-Ls} \approx 1 - Ls$ (Chen and Seborg, 2002), we obtain:

$$F_1(s) = -\frac{aK_1 s}{(T_1 s+1)p(s)} e^{-L_1 s} \tag{10}$$

and

$$F_2(s) = \frac{K_2 s}{(T_2 s+1)p(s)} e^{-L_2 s} \tag{11}$$

where

$$\begin{aligned} p(s) = \; & (1 - aK_1K_cL_1 - K_1K_cL_1 - K_2K_cL_2)s + \\ & aK_1K_c + K_1K_c + K_2K_c. \end{aligned} \tag{12}$$

Hence, it results that $F_1(s)$ and $F_2(s)$ are second order transfer functions where the location of a pole can be arbitrarily selected by suitably choosing the design parameter K_c. Indeed, by fixing

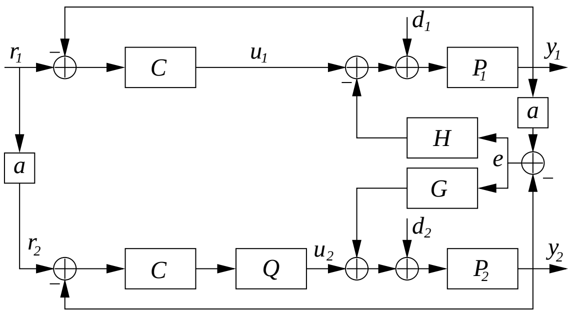

Fig. 3. The new ratio control architecture.

$$K_c = \frac{1}{aK_1L_1 + K_1L_1 + K_2L_2 + aT_fK_1 + T_fK_1 + T_fK_2} \tag{13}$$

we eventually have

$$F_1(s) = -\frac{aK_1/Ks}{(T_1 s+1)(T_f s+1)} e^{-L_1 s} \tag{14}$$

and

$$F_2(s) = \frac{K_2/Ks}{(T_2 s+1)(T_f s+1)} e^{-L_2 s} \tag{15}$$

where

$$K := aK_1K_c + K_1K_c + K_2K_c. \tag{16}$$

Summarizing, the devised control architecture has only one design parameter, namely the secondary time constant T_f of the load disturbances response, thus determining automatically the value of the proportional gain K_c of the PI controller.

In order to avoid even this design effort, a simple default choice can be imposed, for example by selecting

$$T_f = \frac{\min\{T_1, T_2\}}{10} \tag{17}$$

so that the load disturbances rejection performances are mainly limited by the processes time constants (note again that set-point following performances are addressed by equation (4)).

Finally, it is worth noting that the value of K is inversely proportional to the value of T_f, so that decreasing the value of T_f implies also that the peak value of the ratio error in the load disturbance response is decreased (see (14)-(15)).

Remark 1. It is worth stressing that Q results to be a simple lead/lag filter plus a dead time term and G and H are actually to PI controllers. Thus, no particular difficulty emerges in the implementation of the devised scheme.

4. SIMULATION RESULTS

Simulation results related to different kind of processes are presented in order to show the effectiveness of the devised approach. In each case, a unit set-point step is applied at time $t = 0$ s and then, a unit load disturbance step is applied to the first process P_1 at time $t = 40$ s and to the second process P_2 at time $t = 90$ s. For the sake of clarity the desired ratio a is fixed to one.

4.1 Example 1 - FOPDT processes

As a first example, two FOPDT processes have been considered:

$$P_1(s) = \frac{1}{4s+1} e^{-3s} \tag{18}$$

$$P_2(s) = \frac{1}{6s+1} e^{-2s}. \tag{19}$$

By applying the proposed method and the proposed tuning procedure, i.e. by applying formulas (4), (5), (8), (9), (13) and (17) with $K_1 = 1$, $T_1 = 4$, $L_1 = 3$, $K_2 = 1$, $T_2 = 6$, $L_2 = 2$, it results $T_f = 0.4$, $K_c = 0.11$, and

$$Q(s) = \frac{6s+1}{4s+1} e^{-s}, \tag{20}$$

$$C(s) = H(s) = 0.11 \frac{4s+1}{s}, \tag{21}$$

$$G(s) = 0.11 \frac{6s+1}{s}. \tag{22}$$

The two process outputs, together with the corresponding control variable signals are plotted in Figure 4. It appears that the desired ratio is maintained, as expected, during the whole set-point change transient response and that satisfactory performances are obtained also when a load disturbance occurs both on the first and on the second process. In order to provide a better understanding of the results, the ratio error $e(t)$ is plotted in Figure 5 and the outputs of the two filters H and G are plotted in Figure 6.

A comparison has been made with the method proposed in (Visioli, 2003) (see Figure 2). For this last technique, which outperforms the typical control scheme of Figure 1, results related to the process outputs and to the control variables are reported in Figure 7.

It turns out that the methodology proposed in this paper allows to address the occurrence of a load disturbance on the second process P_2 without decreasing significantly the performances obtained in the rejection of a load disturbance on the first process P_1.

4.2 Example 2 - High order processes

As a second example, a fourth order process and a second order plus dead time process have been considered, mainly in order to verify the effectiveness of the method in the presence of unstructured uncertainties:

$$P_1(s) = \frac{1}{(s+1)^4} \tag{23}$$

$$P_2(s) = \frac{1}{(s+1)^2} e^{-s}. \tag{24}$$

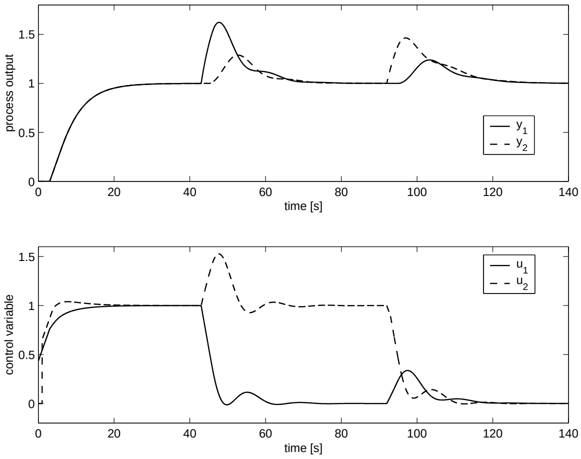

Fig. 4. Process outputs and control variables for example 1 with the new scheme.

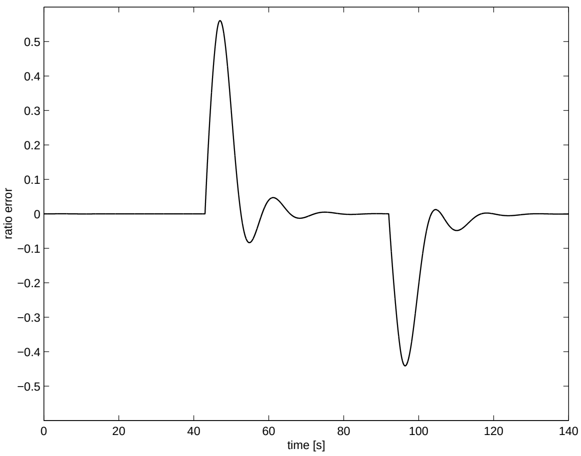

Fig. 5. Ratio error for example 1 with the new scheme.

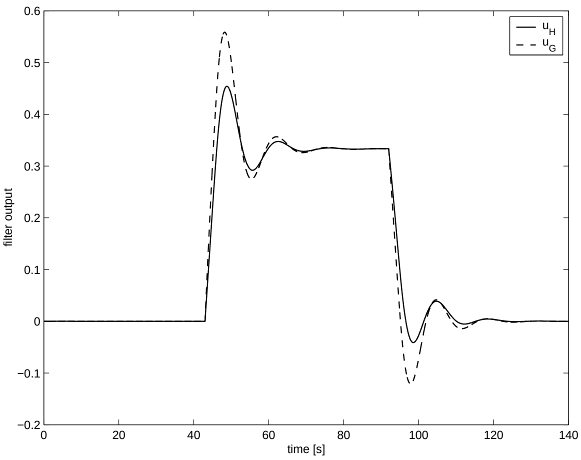

Fig. 6. Filters H and G outputs for example 1 with the new scheme.

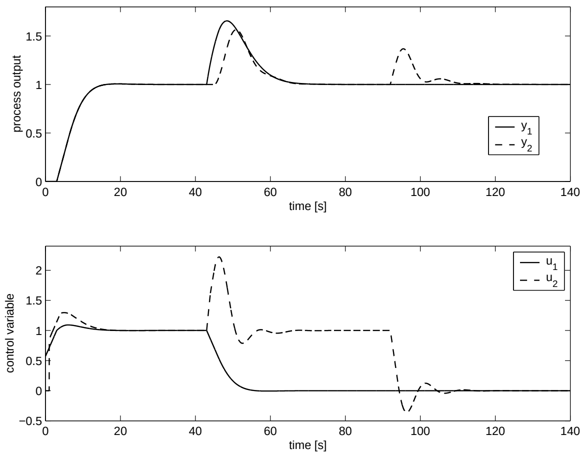

Fig. 7. Process outputs and control variables for example 1 with the scheme of Figure 2.

Two FOPDT transfer functions have been estimated by applying the area method (which is based on the open-loop step response). It results $K_1 = 1$, $T_1 = 1.84$, $L_1 = 1.92$, $K_2 = 1$, $T_2 = 1.39$, $L_2 = 1.57$. Based on these values, it has been fixed $T_f = 0.14$, $K_c = 0.17$, and

$$Q(s) = \frac{1.39s+1}{1.84s+1}e^{-0.35s}, \tag{25}$$

$$C(s) = H(s) = 0.17\frac{1.84s+1}{s}, \tag{26}$$

$$G(s) = 0.17\frac{1.39s+1}{s}. \tag{27}$$

Results obtained with the new method are reported in Figures 8-10, while those obtained with the architecture of Figure 2 are shown in Figure 11. Obviously, a perfect set-point response (in the sense that has been explained in Section 2) is no more achieved, but results are still satisfactory despite approximated models have been adopted. Comparing the two approaches, the same considerations done for example 1 can actually be done also for this example.
Remark 2. Note that results obtained with the typical ratio control architecture of Figure 1 have not been reported as they can be found in (Visioli, 2003). Further, results related to the Blend station (Hägglund, 2001) have also not been considered because in that approach the load disturbance rejection performances are not addressed.
Remark 3. It is worth stressing that better results can be possibly obtained with the new scheme if a different choice of the transfer functions of the two filters H and G is done. However, it has to be take into account that load disturbances rejection performances are in any case limited by the different (apparent) dead times of the two processes and most of all, the simplicity of the implementation (and therefore the avoidance of a significant design effort for the user) is a major requirement to obtain a satisfactory cost/benefit ratio in the industrial context.

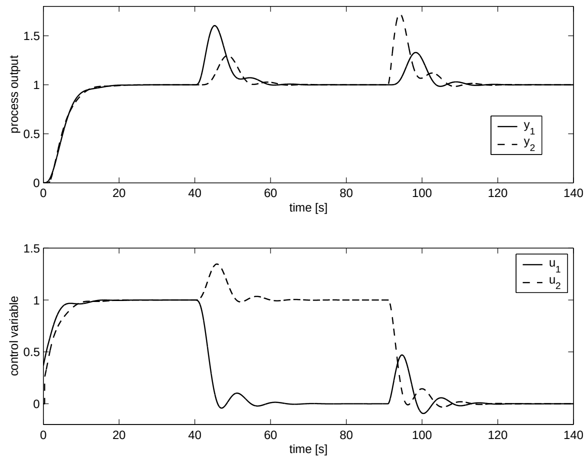

Fig. 8. Process outputs and control variables for example 2 with the new scheme.

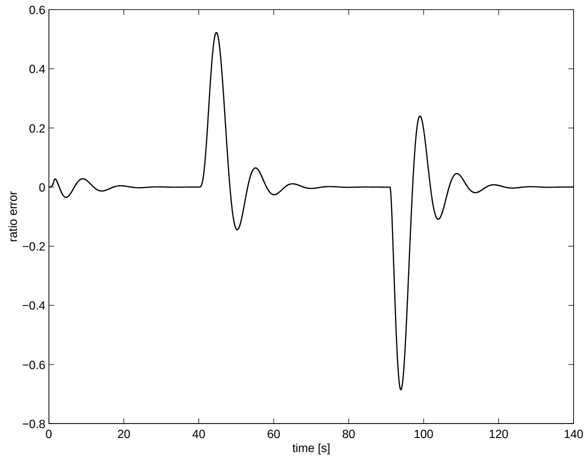

Fig. 9. Ratio error for example 2 with the new scheme.

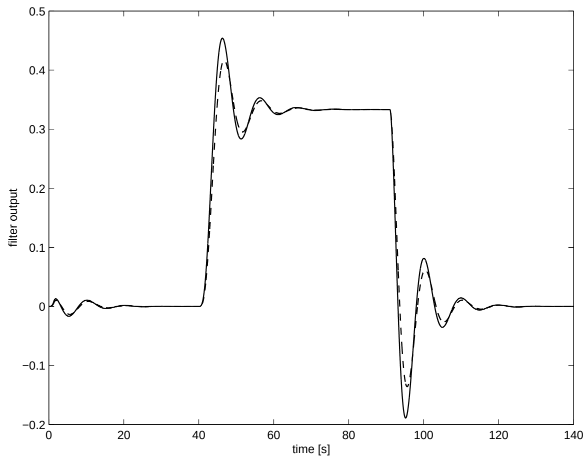

Fig. 10. Filters H and G outputs for example 2 with the new scheme.

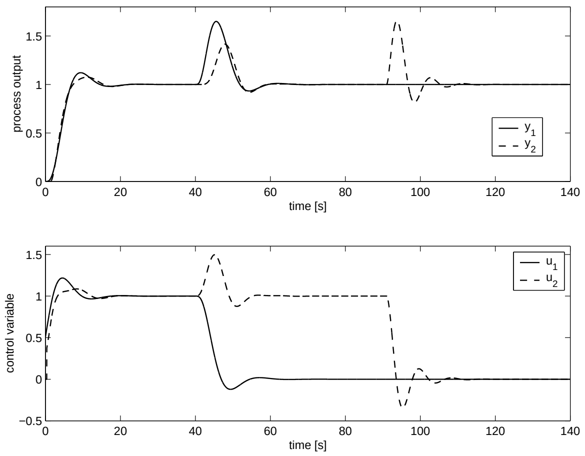

Fig. 11. Process outputs and control variables for example 2 with the scheme of Figure 2.

5. CONCLUSIONS

In this paper a new ratio control architecture has been proposed. The major feature of the devised architecture is that it addresses both set-point changes and load disturbances that might occur on the two processes. A tuning procedure has been proposed in order to avoid any significant tuning effort for the user and to make the proposed methodology suitable to be applied in the industrial context.

Results show that the technique represents a sound alternative choice with respect to the one presented in (Visioli, 2003) whereas disturbances occurring on the second process are of concern.

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