COMETa2026
8th INTERNATIONAL SCIENTIFIC CONFERENCE
12th - 14th November 2026
Jahorina, B&H, Republic of Srpska
University of East Sarajevo
Faculty of Mechanical Engineering
Conference on Mechanical Engineering Technologies and Applications

TUNING OF FOPI CONTROLLER FOR HIGH-ORDER MULTIVARIABLE SYSTEMS

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Abstract: High-order multivariable systems are challenging to control because of loop interactions and complex dynamics. This paper investigates fractional-order proportional–integral (FOPI) control of high-order two-input two-output (TITO) systems using a simplified decoupler. The decoupling strategy reduces loop interactions, enabling the design of individual fractional-order controllers. Controller parameters are tuned using the Approximate M-constrained Integral Gain Optimization (AMIGO) method with the Integral of Absolute Error (IAE) as the performance criterion. The proposed approach is evaluated through simulations of three high-order TITO process models and compared with conventional autotuned PI controllers. The results show that the proposed FOPI control strategy achieves improved closed-loop responses across the investigated models, demonstrating the effectiveness of fractional-order control combined with simplified decoupling for complex multivariable processes.

Key words: Decoupling, Fractional Order Proportional Integral Controller, High-order multivariable systems, Multivariable control, Two Input Two Output process

1 INTRODUCTION

The control of multivariable systems has, for many years, represented a challenging research problem and has attracted considerable attention from researchers. When such systems are described by high-order mathematical models, the level of complexity is further increased. Therefore, the application of fractional-order PI (FOPI) controllers emerges as a logical approach to achieving the desired dynamic behavior of such systems. Following the introduction of the FOPI controller [1], its application has expanded significantly in the field of automatic control, including

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the systems investigated in this paper. Some considerations regarding FOPI controllers are presented in [2-6]. The application of fractional-order control to multivariable control systems is discussed in [7]. However, FOPI controllers for high-order multivariable systems were designed in [8,9]. The aim of this paper is to contribute to the investigation of the characteristics of high-order multivariable systems controlled by FOPI controllers.

The paper is organized into five sections, as follows. Following the introduction in the first section, the second section presents the specific characteristics of controlling high-order multivariable systems. The third section presents the design methodology for fractional-order proportional–integral controllers for the previously decoupled system. The effectiveness of the proposed approach is demonstrated through three illustrative mathematical models in Section 4. Finally, section 5 presents the main conclusions, followed by the list of references

2 CONTROL OF HIGH ORDER MULTIVARIABLE SYSTEMS

High-order multivariable systems are characterized by multiple interacting inputs and outputs, coupled dynamic behavior, higher-order transfer functions, and several dominant and non-dominant time constants. In such systems, a change in one manipulated variable may simultaneously affect several controlled variables, resulting in significant loop interactions and complex transient responses. The presence of multiple poles, delays, nonlinearities, and parameter variations can further increase the difficulty of achieving satisfactory control performance. Conventional PI controllers, although effective for many low-order processes, may provide limited flexibility when applied independently to highly coupled high-order systems because they are based on integer-order differentiation and integration and generally offer fewer degrees of freedom for shaping the closed-loop response.

Fractional-order proportional–integral (FOPI) controllers provide an extended control structure that can be particularly suitable for high-order multivariable processes. A FOPI controller introduces an additional fractional-order parameters, namely the integral order λ, in addition to the conventional controller gains K_p, and K_i. Its transfer function can be expressed as

$$G_c(s) = K_P + \frac{K_i}{\lambda} \tag{1}$$

where $0.5 < \lambda < 1.5$ need not be restricted to integer values. These additional tuning parameters provide greater flexibility in adjusting the magnitude and phase characteristics of the controller over a wide frequency range. Consequently, FOPI controllers can be designed to improve transient response, reduce overshoot and settling time, and provide enhanced robustness against variations in process dynamics. For a multivariable system, FOPI controllers can be incorporated within a decentralized or centralized control architecture, depending on the degree of interaction among the process variables.

For a high-order multivariable system represented by a transfer matrix $G(s)$, the control objective is to determine a suitable controller matrix $C(s)$ such that the interactions among the input–output loops are minimized while maintaining stability and desired tracking performance. In a decentralized configuration, individual FOPI controllers can be assigned to the paired input–output loops, while a decoupling scheme may be employed before controller implementation to reduce cross-coupling effects. The increased number of tuning parameters in FOPI control also makes

optimization-based tuning approaches attractive, where performance indices such as IAE, ISE, ITAE, or a weighted combination of these criteria can be minimized. Thus, although the control of high-order multivariable systems remains challenging because of system complexity and loop interactions, the additional fractional-order degrees of freedom offered by FOPI controllers provide a promising framework for achieving improved tracking, disturbance rejection, and robustness compared with conventional integer-order controllers. In practice, a fractional order controller can be implemented by approximating its fractional order operators using standard methods such as the Oustaloup recursive approximation. This technique converts the fractional order transfer function into an equivalent integer-order rational transfer function over a specified frequency range, enabling implementation using digital controller. The resulting controller can be discretized for real time execution, considering sampling time, computational complexity, and the desired control performance.

3 DESIGN OF FOPI CONTROLLERS FOR HIGH ORDER SYSTEMS

The fractional-order proportional–integral (FOPI) controller operates on the same fundamental principle as the conventional PI controller; however, it provides greater flexibility in achieving the desired system response due to the introduction of two additional fractional-order tuning parameters. Unlike the conventional PI controller, which has three tuning parameters, the FOPI controller has five parameters: the proportional gain K_p, integral gain K_i, derivative gain K_d, fractional integral order λ. Here, λ represents the fractional order of integration. By appropriately tuning these five parameters, the FOPI controller can provide improved control performance and greater flexibility in shaping the dynamic response of the system. The equation of the FOPI in Laplace domain is given by (1). A usually specified control requirement is also to minimise the Integral of Absolute Error (IAE). The Approximate M-constrained Integral Gain Optimisation (AMIGO) method is used to determine the controller parameters because it is suitable for first order plus dead time (FOPDT) models, which very well describe most of processes in industry. Proportional and integral parametres are given by (2) and (3), where K is process gain, T is process time constant, L is process dead time and T_i is integral time constant

$$K_p = \frac{1}{K}\left(0.2 + 0.45\frac{T}{L}\right) \tag{2}$$

$$T_i = \left(\frac{0.4L + 0.8T}{L + 0.1T}\right)L \tag{3}$$

3.1 Decoupler design

Multi-loop proportional–integral (PI) controllers are widely employed for processes with relatively small loop interactions due to their practical advantages, including a simple control structure and a limited number of tuning parameters. In general, the design and implementation of multi-input multi-output (MIMO) controllers are more complex than those of single-input single-output (SISO) controllers because of the interactions among the control loops. To simplify the controller design and reduce the effects of loop interactions, the MIMO process can be transformed into a set of approximately independent single-loop systems using an appropriate decoupling

strategy, followed by the implementation of individual controllers for the decoupled loops.

Decoupling techniques are employed in multivariable control systems to reduce the interactions among individual control loops and thereby improve the overall control performance. The three commonly used decoupling strategies are ideal decoupling, simplified decoupling, and inverted decoupling. Ideal decoupling generally results in relatively complex decoupler elements. Although it can facilitate the independent tuning of the controller transfer matrix, its practical implementation is often limited because of the complexity of the resulting decoupler. Simplified decoupling is one of the most widely adopted approaches because of the relatively simple structure of its decoupling elements, which makes it attractive for practical applications. Inverted decoupling is another alternative; however, its implementation is less common in practical multivariable control systems.

The performance of decoupling techniques is strongly influenced by modelling uncertainties and parameter variations. In particular, ideal and inverted decouplers can be sensitive to modelling errors, which may adversely affect the decoupling performance. A decentralized controller can provide satisfactory control performance when the interactions among the process loops are relatively weak. However, when significant loop interactions are present, independent loop controllers may result in degraded transient and steady-state performance. Furthermore, decentralized PI controllers may encounter difficulties in stabilizing a multivariable system when unstable poles are present in the individual process transfer functions. In such cases, centralized control strategies provide improved coordination among the control loops and reduce the effects of loop interactions than decentralized control.

Let $G_p(s)$is the process transfer function matrix,

$$G_p(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{4}$$

The simplified decoupler is given as [13]

$$D(s)=\begin{bmatrix} 1 & \dfrac{-g_{12}(s)}{g_{11}(s)} \\ \dfrac{-g_{21}(s)}{g_{22}(s)} & 1 \end{bmatrix} \tag{5}$$

The output of the TITO system with decoupler is

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix}=\begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix}\times\begin{bmatrix} 1 & d_{12}(s) \\ d_{21}(s) & 1 \end{bmatrix} \tag{6}$$

$$G_p(s)D(s)=\begin{bmatrix} q_{11}(s) & 0 \\ 0 & q_{22}(s) \end{bmatrix} \tag{7}$$

where the loop transfer function is

$$q_{11}(s)=g_{11}(s)-\frac{g_{12}(s)g_{21}(s)}{g_{22}(s)} \tag{8}$$

$$q_{22}(s) = g_{22}(s) - \frac{g_{21}(s)g_{12}(s)}{g_{11}(s)} \tag{9}$$

4 SIMULATIONS AND RESULTS

Model 1: The TITO process considered in this study is described based on the formulation reported [10] . The corresponding transfer function matrix $G_p(s)$ of the TITO process is given by:

$$G_p(s) = \begin{bmatrix} \dfrac{0.5}{(0.1s+1)^2(0.2s+1)^2} & \dfrac{-1}{(0.1s+1)(0.2s+1)^2} \\ \dfrac{1}{(0.1s+1)(0.2s+1)^2} & \dfrac{2.4}{(0.1s+1)(0.2s+1)^2(0.5s+1)} \end{bmatrix} \tag{10}$$

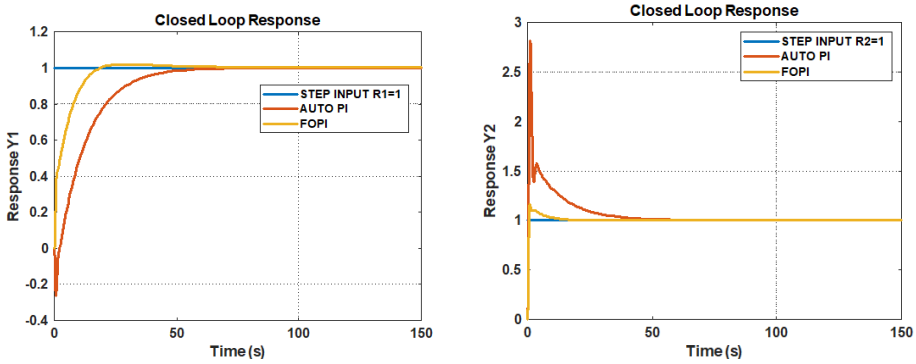

Figure 1. *Closed loop response (Model 1)*

Model 2: The higher order TITO process considered in this study is described based on the formulation the corresponding transfer function matrix $G_p(s)$ of the TITO process is given by [11]

$$G_p(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{11}$$

$$g_{11}(s) = \frac{134.0243s^3 + 295.3529s^2 + 53.5176s + 0.5855}{s^4 + 2.4617s^3 + 0.9859s^2 + 0.1107s + 0.0008} \tag{11a}$$

$$g_{12}(s) = \frac{-0.0312s^2 - 0.0062s - 0.0001}{s^4 + 2.4617s^3 + 0.9859s^2 + 0.1107s + 0.0008} \tag{11b}$$

$$g_{21}(s) = \frac{-9.2834s^3 - 15.0312s^2 - 2.6325s - 0.0123}{s^4 + 2.4617s^3 + 0.9859s^2 + 0.1107s + 0.0008} \tag{11c}$$

$$g_{22}(s) = \frac{0.0699s^3 + 0.0340s^2 + 0.0042s + 0.00002910}{s^4 + 2.4617s^3 + 0.9859s^2 + 0.1107s + 0.0008} \tag{11d}$$

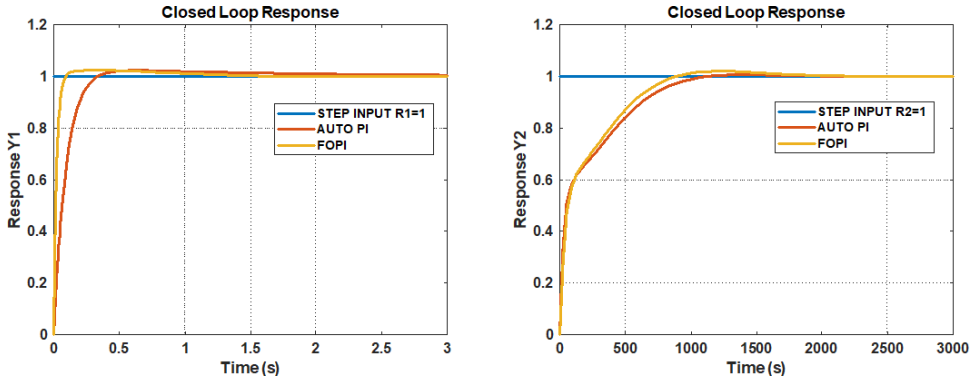

Figure 2. *Closed loop response (Model 2)*

Model 3: The higher order TITO process considered in this study is described based on the formulation the corresponding transfer function matrix $G_p(s)$ of the TITO process is given by [12].

$$G_p(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{12}$$

$$g_{11}(s)=\frac{2.926\cdot10^{2}s^{4}+1.9152\cdot10^{4}s^{3}+1.2667\cdot10^{7}s^{2}+5.5825\cdot10^{7}s+4.7959\cdot10^{9}}{s^{5}+1.2308\cdot10^{2}s^{4}+6.993\cdot10^{4}s^{3}+1.5098\cdot10^{6}s^{2}+3.5504\cdot10^{8}s+8.233\cdot10^{-6}} \tag{12a}$$

$$g_{12}(s)=\frac{-4.4533\cdot10^{3}s^{3}-3.246\cdot10^{6}s^{2}-1.4362\cdot10^{7}s-1.2403\cdot10^{9}}{s^{5}+1.2308\cdot10^{2}s^{4}+6.993\cdot10^{4}s+1.5098\cdot10^{6}s^{2}+3.5504\cdot10^{8}s+8.233\cdot10^{-6}} \tag{12b}$$

$$g_{21}(s)=\frac{-3.8382\cdot10^{4}s^{3}-1.7068\cdot10^{7}s^{2}-8.3584\cdot10^{7}s-6.4967\cdot10^{9}}{s^{5}+1.2308\cdot10^{2}s^{4}+6.993\cdot10^{4}s^{3}+1.5098\cdot10^{6}s^{2}+3.5504\cdot10^{8}s+8.233\cdot10^{-6}} \tag{12c}$$

$$g_{22}(s)=\frac{2.506\cdot10^{2}s^{4}+1.6229\cdot10^{4}s^{3}+6.6134\cdot10^{6}s^{2}+3.0476\cdot10^{6}s+2.4813\cdot10^{9}}{s^{5}+1.2308\cdot10^{2}s^{4}+6.993\cdot10^{4}s^{3}+1.5098\cdot10^{6}s^{2}+3.5504\cdot10^{8}s+8.233\cdot10^{-6}} \tag{12d}$$

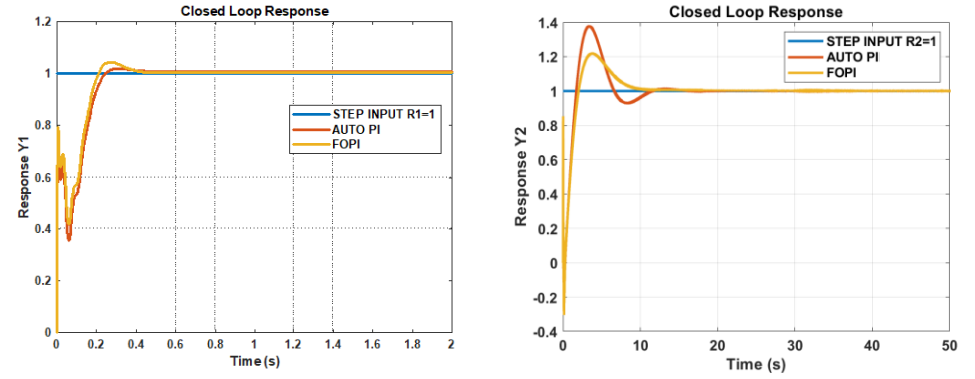

Figure 3. *Closed loop response (Model 3)*

Table 1 presents the tuning parameters obtained for the autotuned PI and proposed FOPI controllers for the three TITO process models.

Table 1. Tuning Parameters for various Systems

Model	*Autotuned PI Controller*				*FOPI Controller*			
Model 1	*Loop 1*		*Loop 2*		*Loop 1*		*Loop 2*	
	K_p	T_i	K_p	T_i	K_p	T_i	K_p	T_i
	0.9221	*0.2817*	*0.1851*	*0.6126*	*0.847*	*0.327*	*0.174*	*0.3021*
					λ *=1.1*		λ *=1.1*	
Model 2	*0.028*	*0.054*	*0.15*	*0.2965*	*0.007*	*1.372*	*0.12*	*0.297*
					λ *=1.3*		λ *=0.8*	
Model 3	*1.585*	*0.1715*	*0.305*	*1.3045*	*1.924*	*0.208*	*0.2*	*0.855*
					λ *=0.8*		λ *=0.8*	

5 CONCLUSION

The proposed control strategy for high-order multivariable systems, incorporating FOPI controllers, together with a simplified decoupler, has illustrated to be successful based on simulations conducted on three models. Namely, in all three tested cases, the responses obtained using the FOPI controllers exhibited predominantly better characteristics compared with those obtained using conventional integer-order PI controllers. Based on the conducted research, it can be concluded that the application of this type of controller is highly beneficial, as its inherent flexibility provides greater possibilities for achieving high-quality control of complex systems such as those considered in this study. Future research may be directed towards the design of FOPI controllers for multivariable systems with more than two inputs and outputs.

ACKNOWLEDGMENT

This study was supported by the Serbian Ministry of Science, Technological Development and Innovation from the grant 451-03-34/2026-03/200108.

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