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Decentralized proportional-integral controller based on dynamic decoupling technique using Beckhoff TwinCAT-3.1

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ABSTRACT

An improved technique for the design of decentralized dynamic decoupled proportional-integral (PI) controllers to control many variables of column flotation was developed and implemented in this paper. This work was motivated by challenges when working with multiple inputs and multiple outputs (MIMO) systems that are not controllable by conventional linear feedback controllers. Conventional feedback control design consists of various drawbacks when it comes to complex industrial processes. The introduction of decentralization, decoupling, and many advanced controls design methods overcomes these drawbacks. Hence, the design and implementation of control systems that mitigate stability for MIMO systems are important. The developed closed-loop model of the flotation process is implemented in a real-time platform using TwinCAT 3.1 automation software and CX5020 Beckhoff programmable logic controllers (PLC) through the model transformation technique. The reasons for using the CX5020 as an implementation environment were motivated by the reliability, and is built according to new industry standards, allowing transformation, which makes it more advantageous to be used more than any other PLCs. This is done to validate the effectiveness of the recommended technique and prove its usability for any multivariable system. Comparable numerical results are presented, and they imply that industrial usage of this method is highly recommended.

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1. INTRODUCTION

The results presented by Tshemese-Mvandaba *et al.* [1] indicated possibilities of enhancing the performance of multivariable systems using well-recognized controllers such as proportional-integral (PI) or proportional-integral-derivative (PID) with relevant design methods and decouplers. The performances of the closed-loop multivariable processes are affected by the interactions among the controlled and manipulated variables [2]. If a multivariable closed-loop process presents minor interactions, the decentralized control system is preferred and if interaction effects are more, then the decentralized control system with decouplers is required to reduce these interactions. It is still challenging to implement the control applications of multivariable industrial processes such as flotation columns, petrochemical, water purification, paper mill, and many more, because of their complexity [2]–[4], and the special need for an intelligent optimized PID controller to handle multi-purposes [4]–[6].

Flotation is commonly used in many industrial processes such as wastewater treatment to remove contaminants that are otherwise difficult to separate like floating solids, residual chemicals, droplets of oil, and fat, and in mineral processing to recover valuable minerals [7], [8]. Control of flotation processes is an important area of research for the metallurgical industry, and according to [9]–[11]. The introduction of flotation columns in mineral processing plants caught the attention of many researchers in the last two decades [12], [13] indicating that froth flotation is an important method for the separation of minerals. These minerals contained multiple metals such as copper or zinc and can be selectively extracted by using froth flotation. The main control objective of the column flotation process is to improve the metallurgical performance to ensure that the column operation comes to the reference values necessary for the specified recovery and position of the concentrate stream [1], [11].

Control strategies aimed at controlling multiple variables at the same time need to consider the interactions between controlled and manipulated variables. However, these strategies are not easy when real plant implementation is required. Hence, most industrial implementations still make use of PID tuning strategies, although they are time-consuming [12]. Many control strategies have been reviewed [5], [14]; however, this paper presents the implementation of a decentralized PI controller design based on a dynamic decoupling flotation process using the CX5020 programmable logic controllers (PLC) with TwinCAT 3.1 software environment. The reason for using this PLC as an implementation environment is motivated by the reliability of this platform and the fact that CX5020 is built according to new industry standards, allowing transformation which makes it more advantageous to be used more than any other PLC. The application of personal computers (PC) and PLC technologies produces better runtime results that can be easily implemented in the industrial environment as presented in this paper. This paper aims to simplify the implementation of a multivariable process by using a transformation approach that allows MATLAB/Simulink model to be transformed into a PLC via function block programming. Control strategies applied to the column flotation process are presented in different journals [15]–[17] presented two simple control strategies for stabilizing the process. In one of those schemes, the froth layer height is controlled by manipulating the non-floated flow rate, and the wash water is manually controlled, however, manual control of industrial processes needs to be avoided.

The introduction of various control design strategies is triggered by various drawbacks of the conventional feedback control design, especially with the introduction of complex industrial processes. Hence, the introduction of the improved controller design, decentralization, and decoupling of a system to overcome these drawbacks. Taking from the analysis presented by other researchers in the field of control, the paper presented by [1] is based on advancing the most implemented conventional controller called proportional-integral-derivative (PID), which has been widely used in a variety of processes. This paper is used to execute the runtime implementation of a decentralized PI controller design based on a dynamic decoupling flotation process using a PLC environment. PI and PIDs have been regarded as powerful strategies for regulatory control, but if the process is interrupted and optimal operating conditions change continuously, the performance of these techniques decreases. This issue arises from the fact that the PID does not use constraints, making it difficult to adapt to changes. Their high sensitivity to interactions between process variables adds a further drawback to these types of controllers. To compensate for these drawbacks, Shenoya and Kini [18] has presented a robust control configuration for multi-inputs multi-outputs (MIMO) systems using decentralized controllers. In processes with very complex dynamics, such as column flotation, traditional PI or PID control parameter design are not sufficient to keep the plant in optimal conditions without improvement. Hence, many researchers addressed these problems by complementing the PIDs with advanced control techniques such as optimal control, decentralization, and decoupling design methods, PID [18]. The adopted control parameter design allowed decent closed-loop response, and it requires some experience to decide which pole locations are the best for any problem, without tuning requirements. This technique based on the pole-placement scheme is used for the decentralized PI controller design to achieve the desired set-point tracking performance and disturbance rejection.

The real-time implementation of the designed technique is useful for industrial applications [19]. The most convenient PLC implementation of the closed-loop controlled plant in a real-time environment requires function block programming. Although this can be complex when dealing with multivariable systems, however, this can be solved through direct usage of the models developed in Simulink. MATLAB/Simulink is a well-established powerful tool for modeling and industrial used software [20], [21], hence the solution towards runtime control implementation of this flotation column system is modeled in this environment. Section 2 of this paper presents mathematical modeling and an overview of the transformation approach. The results are presented in section 3, followed by the discussion in section 4 and the conclusion in section 5.

2. METHOD

To succeed in model transformation, it is important to understand the software platforms involved in the process of executing the task at hand [22]. In this case, MATLAB/Simulink for model development and TwinCAT 3.1 for integration and runtime implementation were used. MATLAB/Simulink software can generate codes from Simulink models to multiple targets using the Simulink Embedded Coder, formerly known as Real-Time Workshop. The Simulink Embedded Coder, in combination with Beckhoff automation's TwinCAT 3.1 target for MATLAB/Simulink (TE1400), enables the development of C++ code, which is subsequently compressed into a standard TwinCAT 3.1 module format. TwinCAT Standard simply uses the basic part of Visual Studio, with all its benefits in terms of processing and connecting to source code management tools. As the name suggests TwinCAT Integrated itself into Visual Studio. With support for the 3rd edition of IEC 61131-3, the C/C++, VB.NET programming languages, and links to MATLAB/Simulink in Microsoft Visual Studio, it is possible to program automation objects in parallel. The MATLAB/Simulink TwinCAT 3.1 Interface facilitates communication between MATLAB/Simulink and the TwinCAT 3.1 runtime [20], [23]. TwinCAT 3.1 delivers real-time parameter acquisition and visualization. The selected interfacing type displays the parameters and variables in TwinCAT 3's graphic interface, allowing real-time viewing and modification in runtime mode. The TwinCAT System Manager has been integrated into the development environment. Possible configuration, parameterization, program, and troubleshooting within the software environment are shown in Figure 1 for TwinCAT runtime program modules in different languages.

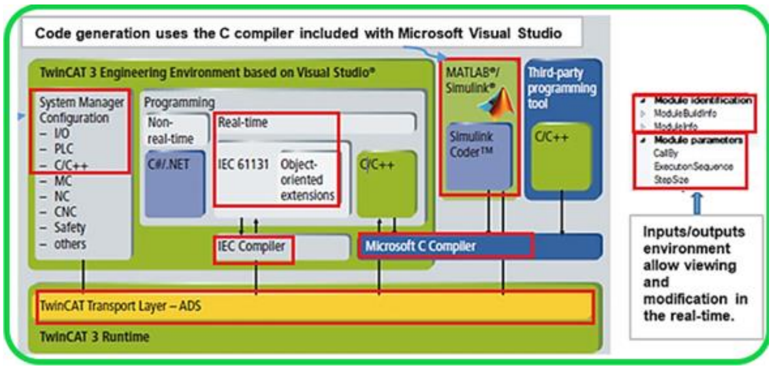


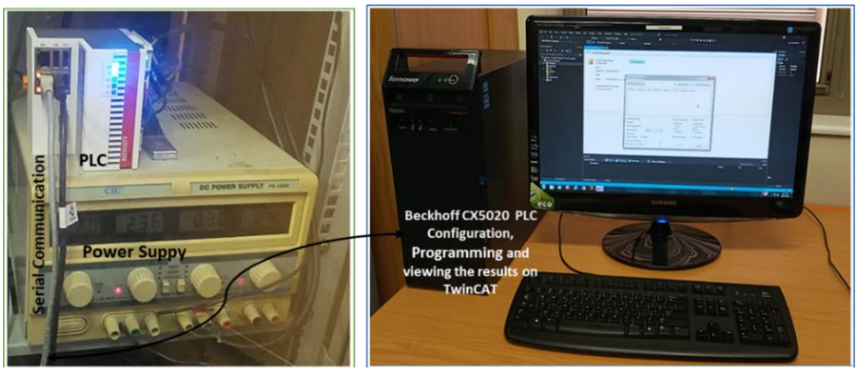
Figure 1. eXtended Automation Engineering (XAE): language support

The following steps need to be appropriately executed for the transformation of the model from Simulink to TwinCAT for real-time PLC implementation. Configuration: at this stage model Parameter Configurations such as simulation time, fixed-step time, and sample time are configured. To some extent, each computer-based model will have to use some discretization technique to reflect data flow in a physical system. Hence, it is important not to have variable step time, as this can create instability or error in the real-time mode of this operation. Code generation: the code generation and the building of the model process are started via the Simulink menu, tools, code generation and build model. Then the building process will start and can be monitored on the MATLAB workspace. Building process: the building process is initiated and executed via code generation, as a result, a TwinCAT module is generated. The generated file (TwinCAT module) is then used to build the TwinCAT component object model (TcCOM) module manually with Microsoft Visual Studio in a TwinCAT environment.

The developed experimental setup is presented in Figure 2. Figure 2(a) illustrates the power supply used to supply 24 V power to the PLC. On top of the power supply is the PLC used to achieve hardware implementation. The PLC is used as a physical control device to control the flotation system. All parameter setup and modifications are made on the device via the TwinCAT software as presented in Figure 2(b) and then sent or downloaded into the PLC using serial communication. The investigations of real-time setpoint tracking control for both the froth layer height and air holdup are made and various responses are presented under the results section.

2.1. Model overview and decouple design

A graphical representation of column flotation, with a gas bubble generator system utilized for the generation of the bubbles, is presented in Figure 3. Added at the top of the operational tank is a froth washing system, whose purpose is to wash away the infected minerals from the valuable minerals within the froth [16], [24]. The flotation column system as presented by [25], [26] is adopted, as it shows significant interactions between the controlled and manipulated variables. From the matrix transfer function, the bias system is affected by the transfer functions of both the froth layer height (h) and the air holdup (ε_g) systems. With the focus on simplifying the complex flotation system to the matrix transfer function presented by (1). This equation specifies the dominant features of this flotation process.



(a) (b)

Figure 2. Experimental setup: (a) PLC and power supply and (b) industrial PC for engineering

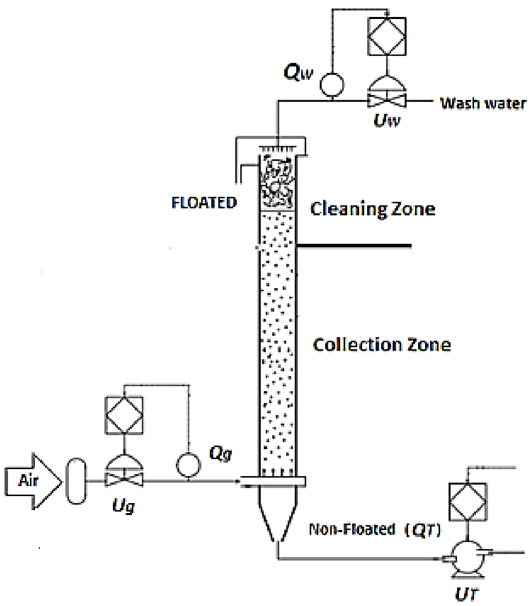


Figure 3. Schematic diagrams of the pilot flotation column and associated instrumentation [1]

$$G_P(s) = \begin{bmatrix} h(s) \\ \varepsilon_g(s) \end{bmatrix} = \begin{bmatrix} \frac{-(1.029\times10^{-3}s+2.3\times10^{-5})}{(s+4.02\times10^{-4})(s+1.92\times10^{-2})} & \frac{-1.59\times10^{-4}s+4.33\times10^{-7}}{(s+4.02\times10^{-4})(s+7.981\times10^{-3})} \\ \frac{7.6\times10^{-5}}{(s+1.92\times10^{-2})} & \frac{7.78\times10^{-5}}{(s+7.81\times10^{-3})} \end{bmatrix} \begin{bmatrix} Q_W(s) \\ Q_g(s) \end{bmatrix} \quad (1)$$

G_{11} and G_{12} are the transfer functions related to the froth layer height, and the transfer functions related to the air holdup process in the recovery zone are G_{21} and G_{22}. Since the flotation system is an interconnected plant, a need to design a decoupling method to minimize the interconnections was identified. Figure 4 represents a 2×2 column flotation system with a decoupler model connected at the input of the plant model. The desirable decoupling strategy to implement for the column flotation process would be dynamic decoupling, thus, ensuring the process interactions are completely compensated for within the system [27]. The process's transfer function matrix ($G_p(s)$) requires the creation of a transfer function matrix $D(s)$, such that $G_p(s) \bullet D(s)$ is a diagonal transfer function matrix $M(s)$ as shown in (2), and the resulting (7).

$$M(s) = G_P(s) \bullet D(s) \tag{2}$$

$$\begin{bmatrix} M_{11}(s) & M_{12}(s) \\ M_{21}(s) & M_{22}(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \cdot \begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix} \tag{3}$$

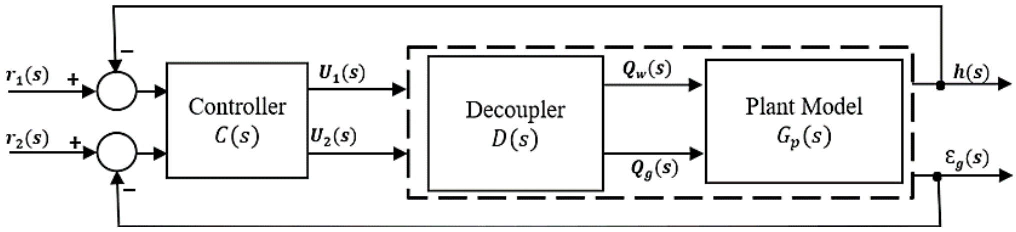


Figure 4. Block representation of the decoupled controlled system

The matrix in (2) can be represented by its components, as shown in (3). The idea is to design the elements of the decoupler in such a way that the interconnections between the process model outputs are eliminated which will allow the design of the process controllers to be implemented in a decentralized dynamic decoupled system. M_{12}=M_{21}=0 and D_{11}=D_{22}=1, so, setting the diagonal matrix for the representation of the decoupled process is applied and summarized in (4).

$$\begin{bmatrix} M_{11}(s) & 0 \\ 0 & M_{22}(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12} \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \cdot \begin{bmatrix} 1 & D_{12}(s) \\ D_{21}(s) & 1 \end{bmatrix} \tag{4}$$

Multiplication of the matrixes in (4) produces (5) and, using (5), solves the matrix *M(s)* for *M(s)* to be diagonal. The obtained dynamic decouplers are presented in (6), with the model of the process. The obtained decoupled model of the process is represented by (7).

$$\begin{bmatrix} M_{11}(s) & 0 \\ 0 & M_{22}(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) + G_{12}(s) * D_{21}(s) & G_{11}(s) * D_{12}(s) + G_{12}(s) \\ G_{21}(s) + G_{22}(s) * D_{21}(s) & G_{21}(s) * D_{12}(s) + G_{22}(s) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} M_{11}(s) & 0 \\ 0 & M_{22}(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \cdot \begin{bmatrix} 1 & -\frac{G_{12}}{G_{11}} \\ -\frac{G_{21}}{G_{22}} & 1 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} \mathrm{h(s)} \\ \varepsilon_g(s \end{bmatrix} = \begin{bmatrix} G_{11}(s) - \frac{G_{21}(s)}{G_{22}(s)} G_{12}(s) & 0 \\ 0 & G_{22}(s) - \frac{G_{21}(s) G_{12}(s)}{G_{11}(s)} \end{bmatrix} = \begin{bmatrix} \frac{-873.68\times10^{-6}}{s+0.000402} & 0 \\ 0 & \frac{6.6057\times10^{-5}}{s+0.00781} \end{bmatrix} \tag{7}$$

The general model representation of the decoupled process with diagonal transfer function matrix as shown in (2) and the completed decoupled model of the process presented in (7) might be undesirable processes. However, the process to design the dynamic decoupled model for this system is explained in [1]. The transfer functions of the designed decoupled process are integrated with the controller design technique presented in the following section. The description of the process followed when designing the decentralized PI controller for the decoupled model of the flotation process is also explained in [1].

2.2. Transformed models and controller design technique

The process to design the dynamic decoupled model for this system is completed. Therefore, the transfer functions of the designed decoupled process are integrated with the designed controller. The aim is to design controllers to keep the system outputs as close to the target values as possible by reducing the errors between input and output or feedback to zero at a steady state using shorter response times. The control integral action is very helpful in eliminating the system's steady-state error. As a result, it is only reasonable to utilize a PI controller that ultimately has the transfer function (8).

$$C(s) = K_p(1 + K_I \frac{1}{s}) \tag{8}$$

where K_P and K_I are the controller regulation parameters demonstrating the controller gain constant and the integral gain constant, respectively. The pole placement design technique purely attempts to find controller settings that give the desired closed-loop poles. The arrangement is built in such a way that the control strategy originates from the desired system response, making it simple to find the controller gains mathematically [1]. The closed-loop poles can be freely selected by adjusting the controller's gains K_P and K_I. As a result, the system's controller transfer matrix *C(s)* is presented by (9).

$$C(s) = \begin{bmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{bmatrix} = \begin{bmatrix} K_{p1}(1 + K_{I1}\frac{1}{s}) & 0 \\ 0 & K_{p2}(1 + K_{I2}\frac{1}{s}) \end{bmatrix} \tag{9}$$

The PI controllers' parameters for the process's loops are designed, using (7) and (9) for *M(s)* and *C(s)* respectively. Thus, the decoupled system is built by including the two diagonal PI controllers. As shown in (10) is the indication of *M(s)*C(s)*, which is the decoupled model to be used further for the controllers' parameter design.

$$M(s) * C(s) = \begin{bmatrix} \frac{-873.68e^{-6}K_{P1}\left(1+K_{I1}\frac{1}{s}\right)}{s+0.000402} & 0 \\ 0 & \frac{6.6057e^{-5}K_{P2}\left(1+K_{I2}\frac{1}{s}\right)}{s+0.00781} \end{bmatrix} = \begin{bmatrix} h(s) \\ \varepsilon_g(s) \end{bmatrix} \tag{10}$$

The technique followed when designing the decentralized PI control parameters for the decoupled model of the flotation process is developed following the flowchart in Figure 5 [1], [28]. Generally, it is necessary to specify where closed-loop poles must lie, and to calculate the controller parameters. Investigations of the performance of the closed-loop system are performed to verify the system's capability for set-point tracking. The control area is shown by two PIs in Figures 6(a) and 6(b) receive the error signal, which is produced by the difference between the set point and the system's output feedback signal. The control action aims at correcting the offset to make sure each system loop follows any reference point.

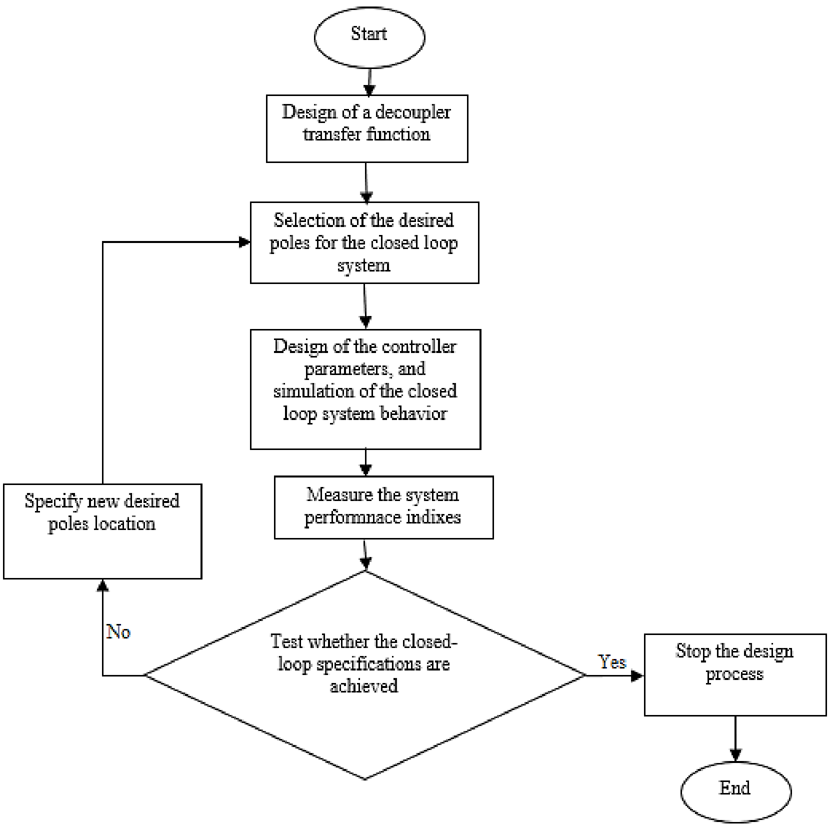
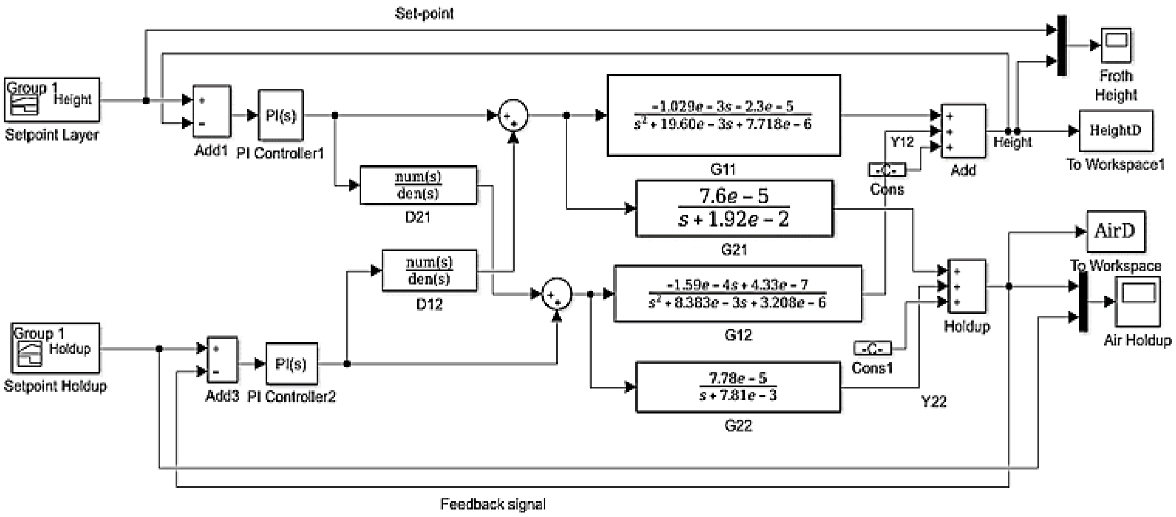
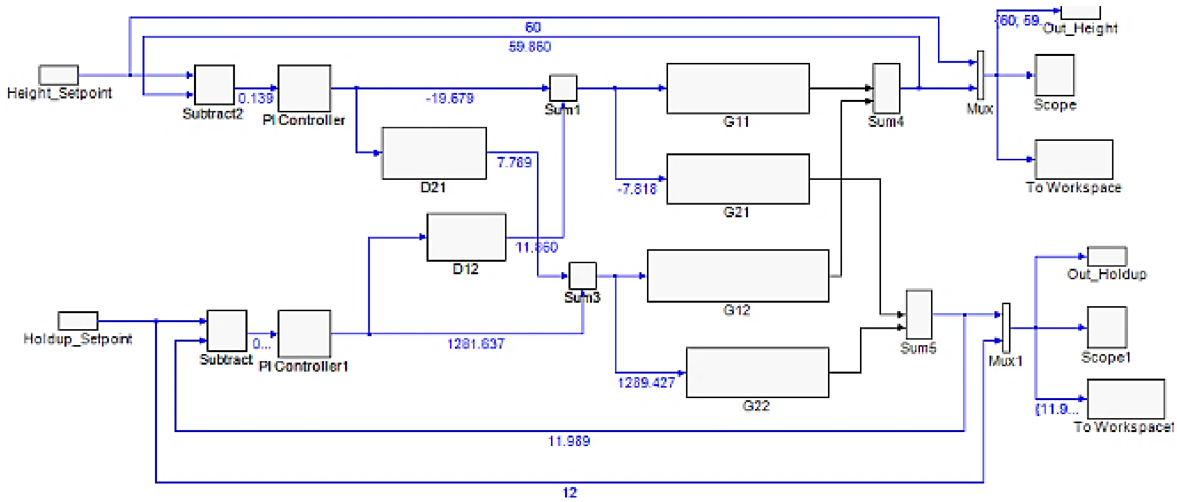


Figure 5. Flow-chart of the summary pole selection procedure [1]



(a)



(b)

Figure 6. Function blocks representation of the decentralized dynamic decoupled system model, (a) Simulink block diagram and (b) TwinCAT engineering

Table 1 introduces various set-point changes used to evaluate the performance of the proposed multivariable system. The set-points of $h = 60$ cm and $\varepsilon_{gcz} = 18\%$ as tabled below are used as the first case study of the investigations. The input/output environment within TwinCAT will allow real-time viewing and modification in runtime mode.

Table 1. Outline Set-points for closed-loop systems' performance evaluation

Simulated and Implemented Study Case	Setpoint		Transformed processes with PI controllers	
	h	ε_{gcz}	Froth layer height (cm)	Air holdup (%)
1	40-60 (cm)	12-20-15 (%)	Step set-point of 40 to 60 (cm)	Pulse set point of 12-20-15(%)
2	50-70-60 (cm)	10-18 (%)	Pulse changes of the setpoint from 50 to 70 to 60 (cm)	Step changes of the setpoint from 10 to 18 (%)
3	80-60-80 (cm)	4-5-4 (%)	Rectangular pulse change of the setpoint signal	Rectangular pulse change of the setpoint signal

2.3. Model evaluations

The closed-loop flotation process as developed in Simulink is transformed into TwinCAT 3.1 software environment for hardware implementation. Because the data and parameter connections are the same in both platforms, there is a one-to-one correspondence of function blocks between Simulink and TwinCAT 3.1, according to the transformation methodology. The real-time implemented cases are presented below, followed by the results illustrated in section 3.

In case study 1, the set-point of the froth layer height is established from 40 cm and increased to 60 cm, while the holdup is set to start at 12%, increased to 20% at 10 seconds, and decreased to 15% at 60 seconds. The simulated and implemented results for this case are presented in Figures 7 and 8 under the results section.

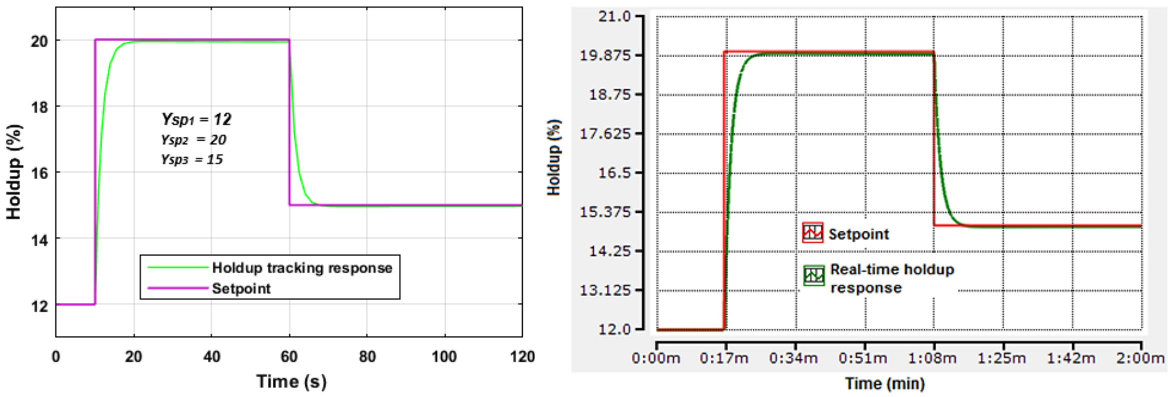
Case study 2 establishes the set-point of the froth layer height to start at 50 cm, the set-point change is applied at 0.17 minutes to move the signal from 50 cm to 70 cm and decreased to 60 cm at 1.08 cm, while the holdup is set to start at 10% and increased to 18% at 0.17 minutes, as presented in Figures 9 and 10, respectively. In real-time or let us say real-life situations, this is applied by collecting a huge number of mineral particles from the collection zone that would increase the froth layer. Then the drop of froth layer height at 1.08 minutes is made possible by adding wash water on the top of the column, and this is done to wash away an unwanted mineral that might be present.

In case study 3, both set points of the air holdup and froth layer height altered their states by changing the set point, to observe the system's operational behavior. Figure 11 presents a setpoint change in the holdup from 4% to 5% at 0.17 minutes and a decrease from 5% to 4%. The froth layer height in Figure 12 starts at 80 cm, while the applied holdup is at 4%. Irregular changes are applied at 0.17 minutes, where the set-point of the layer height is dropped to 60 cm. Adding the wash water on top of the column result in a drop of froth layer height. This is done to see how well the closed-loop system tracks any set-point or if the behavior of the set-point change can be successfully tracked under any circumstances.

As specified by Ng *et al*. [29] and Vieira *et al*. [30] flotation is the process of splitting valuable minerals from a mixture by creating a froth on which minerals separate. The following section presents the simulation results and real-time PLC implemented results of the flotation presented in TwinCAT environment. These figures are put next to each other for easy comparison of the results. The behavior and the values are the same for both environments. This indicates a successful transformation between the two environments. The transformation has made the PLC real-time implementation much easy if the configuration and the building process are done correctly. The desired variables were achieved and viewed using TwinCAT 3 runtime mode which integrates with Beckhoff PLC CX5020. The results are presented in the following section.

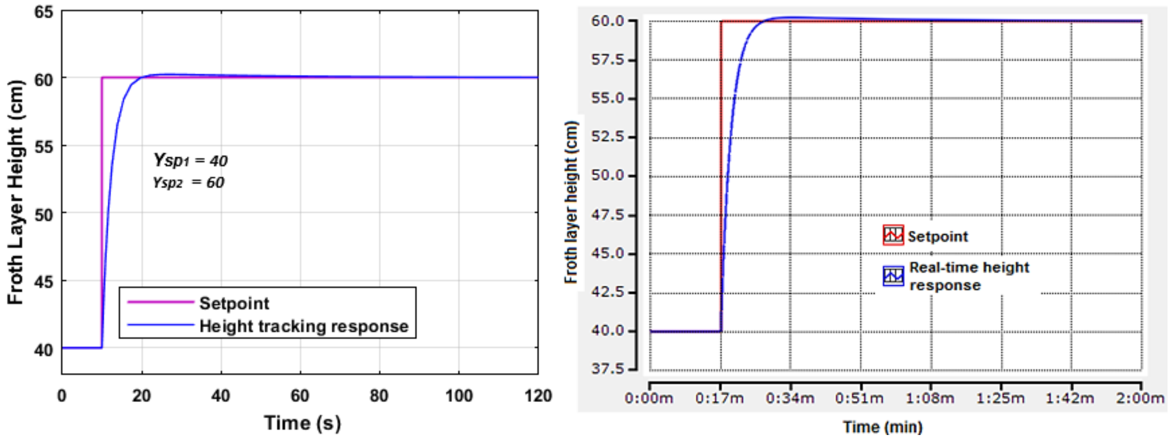
3. RESULTS AND DISCUSSION

A comparison of the obtained results demonstrated successful real-time PLC implementation results as displayed in the TwinCAT environment. The designed controller based on dynamic decoupling is an effective strategy to be used irrespective of the set-point variations and disturbance influence. Decoupling the model of the process has proven to be an effective strategy to reduce the influence of the interactions in the closed-loop control and consistently keep the system stable. The presented results have proven possibilities of model transformation using MATLAB/Simulink and TwinCAT software environments. Figures 7 to 12 present simulation results on (a) the left-hand side in comparison to Beckhoff PLC real-time implemented results on (b) the right-hand side.



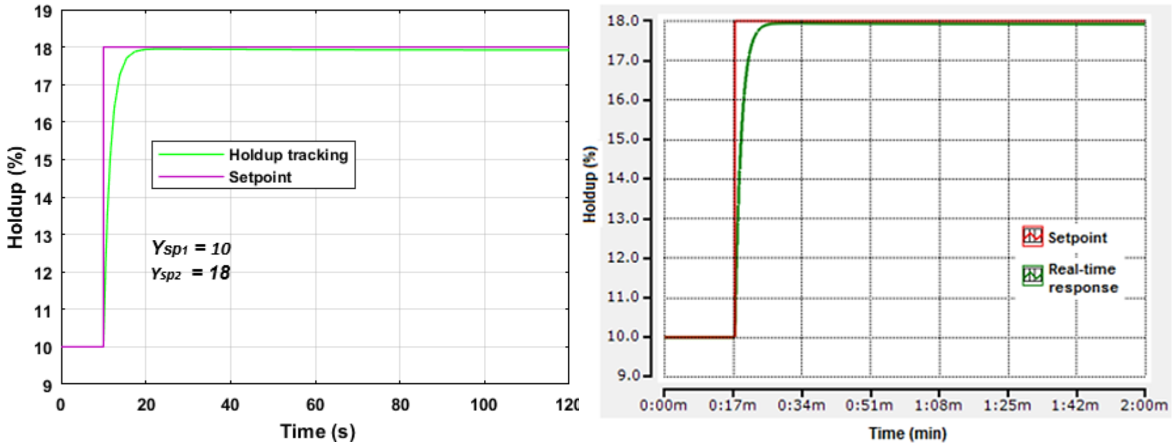
(a) (b)

Figure 7. Comparing the performance of the air holdup system: (a) Simulink results and (b) real-time PLC results



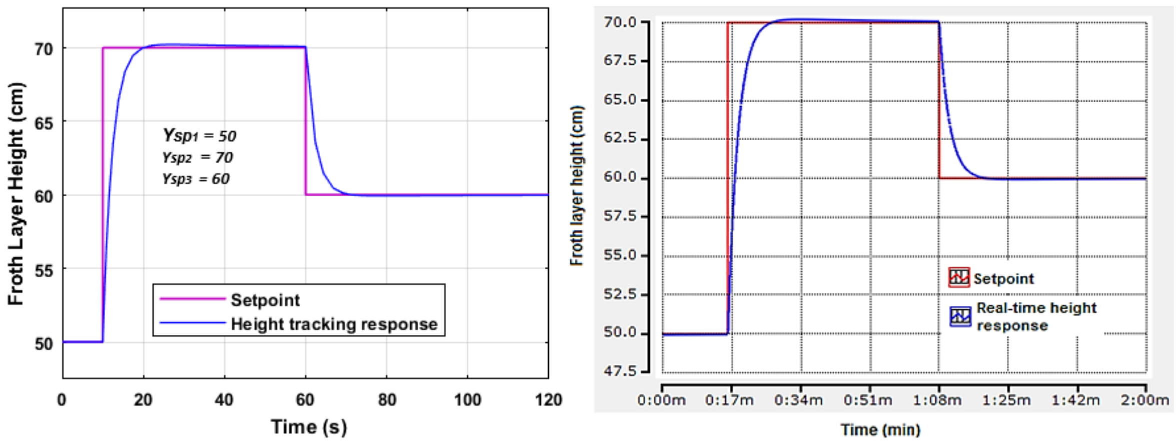
(a) (b)

Figure 8. Comparing the performance of the froth layer height: (a) Simulink results and (b) real-time PLC results



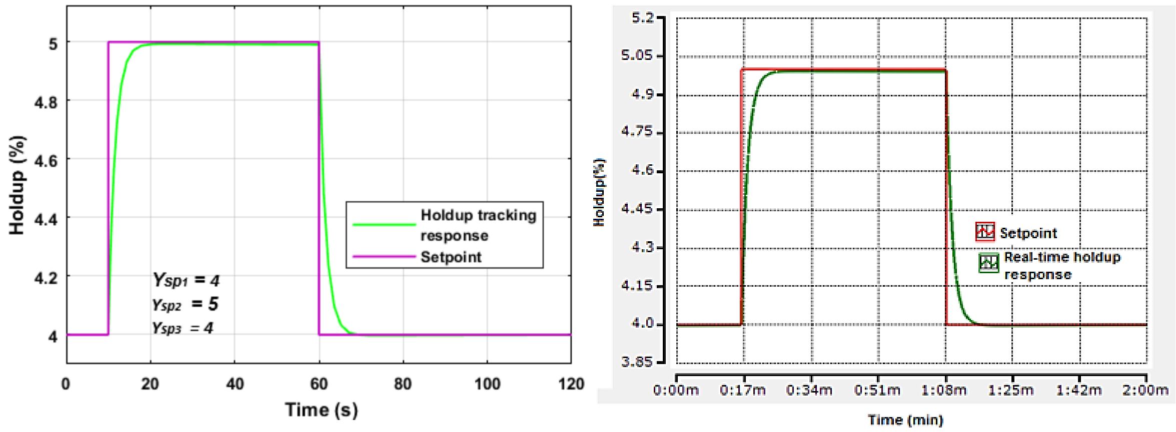
(a) (b)

Figure 9. Comparing the performance of the air holdup system: (a) Simulink results and (b) real-time PLC results



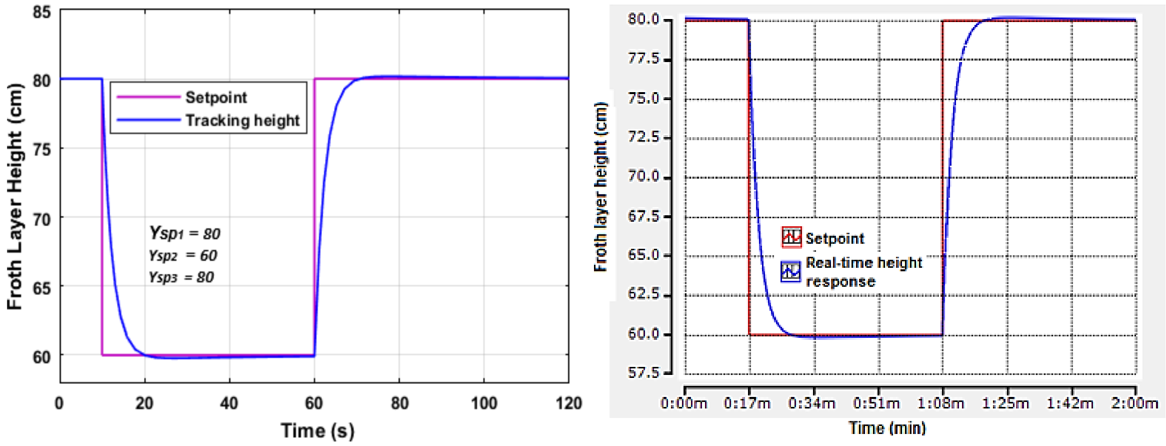
(a) (b)

Figure 10. Comparing the performance of the froth layer height: (a) Simulink results and (b) real-time PLC results



(a) (b)

Figure 11. Comparing the performance of the air holdup system: (a) Simulink results and (b) real-time PLC results



(a) (b)

Figure 12. Comparing the performance of the froth layer height: (a) Simulink results and (b) real-time PLC results

Since the data and parameter connections are the same in both platforms, there is a one-to-one correspondence of function blocks between Simulink and TwinCAT 3.1, according to the transformation methodology. Table 2 presents the performance indices simulated using Simulink software, and this is in comparison with Table 3, which presents the real-time characteristics behavior. The Real-time results show the effectiveness of set-point tracking control and disturbance rejection as assessed in this section. The desired variables were achieved and viewed using TwinCAT 3 runtime mode. One of the reasons for using the Beckhoff PLC CX5020 as an implementation environment was motivated by the reliability of this platform and the fact that the hardware used for this implementation is built according to new industry standards and allows transformation which makes it more advantageous for industrial use more than any other PLC.

Table 2. Performance indices of simulated decentralized dynamic decoupled for the flotation process

Study Case	MATLAB/Simulink results analysis			
	Loops	Rise time (s)	Settling time (s)	Peak overshoot M_P (%)
1	Height	4.91	18.05	0.02
	Air	3.4	66.17	0.05
2	Height	4.908	69.5	0.02
	Air	3.4	15.0	0.05
3	Height	4.9	69	0.02
	Air	3.4	66.3	0.05

Table 3. Performance indices of the real-time decentralized dynamic decoupled for the flotation process

Case studies	TwinCAT PLC real-time results analysis			
	Loops	Rise time (s)	Settling time (s)	Peak overshoot M_P (%)
1	Height	5.1	20	0.01
	Air	2.55	69	0
2	Height	5.1	74	0.01
	Air	2.55	14	0
3	Height	5	73	0
	Air	2.55	68	0

The following are the real-time simulation results from the investigations and experiments conducted for the decentralized dynamic decouple system. It can be noted from the characteristic behavior both loops are not poorly influenced by the set-point changes applied in the holdup loop and froth layer height at the same time. Comparing the characteristics of behavior in Tables 2 and 3, it can be noted that the decentralized decoupled systems are a good option for the rejection of the random variations that might occur in the control signal when the column flotation system is implemented in runtime mode. These results also agree with results obtained from the Simulink environment. This implies that industrial usage of this method can be highly recommended.

The suitability of closed-loop control systems following function block programming concepts is demonstrated through simulations. The model transformation between the two environments MATLAB/Simulink and TwinCAT 3.1 is created in this paper based on modeling, data analysis, and runtime implementation. The ability to combine the MATLAB/Simulink control function blocks into the TwinCAT 3.1 function blocks for real-life industrial implementation has been demonstrated by the real-time implementation outcomes of the closed-loop process for the presented situations and more performed investigations. The paper's contributions are designed to give a foundation for understanding the principles of model transformation, the TwinCAT software engineering and runtime environments, PLC implementation, and its application to industrial distributed control systems.

The generated software model from MATLAB/Simulink environment to TwinCAT 3.1 environment is utilized to perform the real-time execution of the closed-loop flotation process with different control conditions to demonstrate the effectiveness of the transformation. Software integration of Simulink and TwinCAT 3 gives possibilities of implementing linear or nonlinear controllers with MIMO processes in runtime mode. The proposed controller design scheme and its application of PC and PLC technologies have produced better real-time results in comparison with the classical controller design. These results are used to motivate industrial use of the developed algorithm, other than classical control methods only. The good thing about model transformation applied in this paper it automatically translates each state flow block into customized basic function blocks with the inputs, outputs, and parameters as their Simulink counterparts. Although the result could not be included in this paper due to the limited number of pages, it was noted that the characteristic behavior of the system was not poorly influenced by the applied random disturbance and the set-point changes applied at the same time.

4. CONCLUSION

Column flotation is a process in which different minerals are separated selectively. Investigations and developments of the decoupled multivariable models of the column flotation process were conducted. A comparison between the characteristics behavior of the closed loop decentralized coupled flotation system and dynamic decoupled flotation system was conducted and presented before. Through these results it was noted that the algorithm based on a decentralized-coupled system has limitations in terms of variations that can be applied, random variation resulted in several overshoots. Hence, a decentralized dynamic decoupling approach was introduced and simulated.

This paper’s focus is based on the real-time implementation using PLC, and TwinCAT real-time environment in comparison to the simulation results. The modeling of the column flotation process and the design of the control parameters for the decoupled flotation system were described. The model transformation between MATLAB/Simulink and TwinCAT 3.1 is generated in this paper based on modeling, data analysis, and runtime implementation that will be useful for the implementation of industrial projects. The ability to combine the Simulink control function blocks into the PLC via TwinCAT function blocks for real-life industrial implementation has been demonstrated by the real-time implementation outcomes of the presented closed-loop flotation process. The generated software algorithms from MATLAB/Simulink to TwinCAT 3 engineering environment are utilized to perform the real-time execution of the closed-loop flotation process with different control conditions to demonstrate the effectiveness of the transformation. Different case studies based on the closed-loop dynamic decoupled system are outlined in this paper. It can be noted from the characteristic behavior both loops are not poorly influenced by the set-point changes applied in the holdup loop and froth layer height at the same time. This indicates that the decentralized decoupled systems are a good option for the rejection of the random variations that might occur in the control signal when the column flotation system is implemented in runtime mode. Additionally, these results agree or are the same for both environments. The combined usage of the Beckhoff PLC and TwinCAT 3.1 environments has opened more possibilities for the industry to implement beneficial academic findings, through the integration of Simulink and TwinCAT 3.1 software. This technique can also be advantageous to be used for the industrial implementation of different processes.

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