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LabMIMO: An Open-source Virtual Laboratory for Process Control

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Abstract: The “LabMIMO” is an open-source, interactive, and user-friendly virtual learning workbench. This workbench is designed for nonlinear process control edification. This virtual laboratory offers the platform to comprehend and validate the essentials of a control system for the nonlinear coupled MIMO process. This paper presents the development details and impact of virtual labs on an engineering study. The process considered in the tool is unique and innovative Quadruple Conical Tank System (QCTS). The said system is developed and the mathematical model used in the tool is validated with actual physical laboratory setup. The LabMIMO consists the eight different experiments on open-loop and closed-loop system analysis for single-input single-output system and multi-input multi-output configurations of QCTS. It also covers the study on interaction and coupling effects for the nonlinear process. Diverse experimentations were intended to improve the knowledge on design and performance analyses of different classical and model-based control algorithms like MPC (Model Predictive Controller), Fuzzy Logic Controller (FLC), PID Controller. To ease E-learning, LabVIEW based a very accessible Graphical User Interface (GUI) developed. To address the very important requirement of virtual laboratory setup, the tool is made freely downloadable in a license-free executable file version.

Keywords : Virtual laboratory, MIMO Process Control, Nonlinear control, PID controller

1. Introduction

Looking at the classroom teaching methodology of the past and current age, there is lots of development from teaching methods to experimentation platforms, and it is rapidly changing due to upgrades in technology. The utilization of computer-based platforms in the teaching-learning process has become very popular in recent times. Across the world, lots of advances are going on for interactive virtual laboratories in an engineering discipline (S. Dormido, January 2003). Virtual laboratories also provide a comprehensive platform for learner in higher education, especially in engineering, to understand and enhance domain-specific knowledge using the online resources and keep scholar learning engaging up-to-date (Katsikis, September 2012). LabVIEW and MATLAB are widely used platforms for simulation and experimental research in engineering. The binary distillation column is a very complex and multivariable process. LabVIEW-based virtual laboratory for complex binary distillation columns is designed to understand dynamic aspects of distillation processes. The distillation column process is monitored through a LabVIEW-based SCADA package. The distillation plant and the computer connected through ILUDEST®. (Katsikas,

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September 2012). Many researchers have designed a different virtual platform for the engineering discipline like process control, electronics. A laboratory course in electronics at the undergraduate level developed on integrated electronics. This platform provides a remotely-triggered electronic circuit laboratory involving simultaneous simulation and real experiments. SPICE-based NI Mutism; WEBEMA and NI LabVIEW tools are used for the implementation of the laboratory (Chinmay K Maiti, 2012). LabVIEW-based online exercise for DC motors is designed and available openly for the users. The system largely focused on speed control, position control and modeling of direct current operated motors using a classical PID controller. It is a straightforward tool for a basic understanding of the control system fundamentals (Hiral Patel, August 2015). The Internet of Things (IoT) platform-based remote access-based laboratory provides realistic hands-on experiments over video flowing and telecontrol. The Internet of Things (IoT) platform-based experiments are now running using interface hardware like Arduino and R-Pia. Many open-source remote access-based laboratories provide more than 200 experiments in the engineering domain. (Hongwei Zhang, July 2017). Another familiar platform for research is MATLAB. It is a scientific tool for technical calculation and engineering applications, and many researchers have designed virtual laboratories for control systems on these platforms, especially in the Modeling of mechanical, electrical, and electromechanical systems. A very rich simulation-based practical is designed using MATLAB. There were many facilities available to find the transfer function of the system, open loop and close loop behavior of the system, root locus, bode plots, Nyquist plots, transient response, and steady-state response. (M.L.Roz, 2010). A JavaScript-based virtual laboratory for the benchmark Quadruple tank system is designed to perform experiments on multivariable system dynamics (S. Dormido, January 2003). The interaction and coupling effect add complexity in Control of Multiple –input Multiple-Output (MIMO). Undergraduate and postgraduate students facing lots of problems in understanding and designing a controller for a nonlinear MIMO system. Nonlinearity and constraints on inputs and output, other parameters like time delay, stability, and tuning problems of the controller, selection of manipulating, controlling variables add more complexity in the MIMO system (Karl Henrik Johansson, 2002). "LabMIMO" provides the platforms to perform the simulation for experiments on Quadruple Conical Tank System (QCTS). QCTS is a benchmark system to understand the working of the MIMO process. Level control of the conical tank is a challenging task due to its nonlinearity and constant change in the cross-sectional area, which depends on the cone inclination angle, the height of the cone, and the radius of the cone. Various control system-related experiments were designed in LabMIMO. This paper is mainly focused on designing and developing LabMIMO, the virtual laboratory platform for the control system, and its impact on the students. This article is divided into four sections. Section II illustrates the Quadruple conical tank system along with system model equations. LabMIMO tool and various experiments, and its usage are described in section III. The impact analysis of virtual labs for undergraduate students is concluded in section IV.

2. Quadruple Conical Tank System

In industry, the majority of the processes are nonlinear and multivariable by nature. Major challenges in the nonlinear process are varying dynamics and changes in operating points. Interaction between the input and output variable, pairing of controlled and manipulated variables, constrained on input and outputs of the system, and stability and controller tuning are the key issues of the MIMO process. To understand all the major dynamics of the nonlinear MIMO process, the Quadruple Conical Tank System (QCTS) is the most suitable laboratory-scale system. The quadruple conical tank system consists of four interconnected conical-shaped tanks as shown in figure 1. The motive is to control the levels of the bottom two tanks by controlling the input pump voltage. Pump1 passes the liquid to tank 1 and tank 4 and pump2 passes the liquid to tank 2 and tank 3 through a three-way valve. The flow rate of the liquid in the tanks is controlled by the position of the three-way valve which is represented by γ. Thus, by controlling the value of γ, each pump pumps the liquid to two tanks i.e., one of the bottom tanks and its diagonally placed tank.

The interacting valves R1 create interaction between the bottom two tanks and R2 create interaction between the upper two tanks. The degree of interaction can be varied by changing the values of R1 and R2. If the R1 and R2 values are kept 0 then the QCTS is without interaction and when the values of R1 and R2 are 1 then the QCTS is with interaction. This interaction adds non-linearity to the system.

Mathematical Modelling is key to learn the behaviour of any system with time under the impacts of any changes and designing of the controller needs to develop the model. The validation of the model can be proved through a comparison of two different ways, one is experimentally and theoretically.

The first principles-based process model is obtained and validated with an experimental model of a physical system which together defines the system.

3. Labmimo Virtual Laboratory Platform

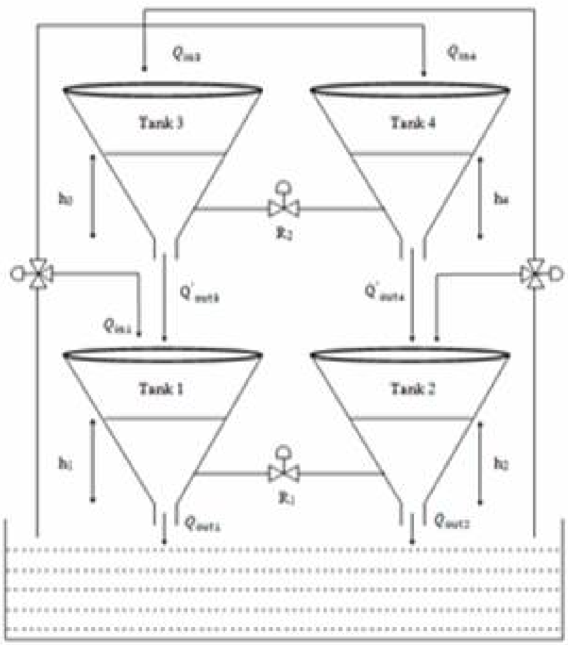

Fig. 1. Schematic of Quadruple Conical Tank system with interaction

A LabVIEW is the software platform provided by National Instrumentation (NI). The purpose of designing and developing a LabMIMO virtual laboratory is to address the need for free and open-

$$\frac{dh_1}{dt} = \frac{1}{\alpha h_1{}^2}\left[\gamma_1 K_1 V_1 + a_3 r_3\sqrt{2gh_3} + sign(h_3 - h_4)R_2 a_{34} r_3\sqrt{2g|h_3 - h_4|} - a_1 r_1\sqrt{2gh_1} - sign(h_1 - h_2)R_1 a_{12} r_1\sqrt{2g|h_1 - h_2|}\right]$$

$$\frac{dh_2}{dt} = \frac{1}{\alpha h_2{}^2}\left[\gamma_2 K_2 V_2 + a_4 r_4\sqrt{2gh_4} + sign(h_3 - h_4)R_2 a_{34} r_4\sqrt{2g|h_3 - h_4|} - a_2 r_2\sqrt{2gh_2} + sign(h_1 - h_2)R_1 a_{12} r_2\sqrt{2g|h_1 - h_2|}\right]$$

$$\frac{dh_3}{dt} = \frac{1}{\alpha h_3{}^2}\left[(1-\gamma_2)K_2 V_2 - a_3 r_3\sqrt{2gh_3} - sign(h_3 - h_4)R_2 a_{34} r_3\sqrt{2g|h_3 - h_4|}\right]$$

$$\frac{dh_4}{dt} = \frac{1}{\alpha h_4{}^2}\left[(1-\gamma_1)K_1 V_1 - a_4 r_4\sqrt{2gh_4} + sign(h_3 - h_4)R_2 a_{34} r_4\sqrt{2g|h_3 - h_4|}\right]$$

Equations Parameters:
H (cm) – Total Height of conical tank (75cm)
R – Radius of Top of Tank (19cm)
h – Height of liquid in Tank
r - Radius of water in Tank
h_1, h_2, h_3, h_4 (cm) – Height of liquid in tank 1,2,3,4 respectively
V_1, V_2 (V) – Voltage of pumps 1 &2

g_1, g_2 – Flow distribution to the lower and upper diagonal tank of valve 1 and 2
A_i (cm2) = $\left(\pi\frac{R^2}{H^2}\right)h_i{}^2 = (\alpha)h_i{}^2$ The cross-sectional area of i[t] Conical Tank
V(cm^3) – Volume of the conical tank
a (cm^2) – Cross-sectional area of Pipe
Q_{in} $\left(\frac{cm^3}{sec}\right)$ – Input Pump flow
$Q_{\text{out}}\left(\frac{cm^3}{sec}\right)$ – Output flow
g ($981\frac{cm}{sec}$)– Acceleration due to gravity
K_1, K_2 – Pump Flow Constant (70.67 $\frac{cm^3}{sec}$)
r_1, r_2, r_3, r_4 – Drain valves of tank 1,2,3,4 respectively
γ_1, γ_2 – Diverter Valve Constants
R_1, R_2 – Manual Valve for Interaction
a_{12} – Area of the pipe between Tank 1 and Tank 2
a_{34} – Area of the pipe between Tank 3 and Tank 4

source online/offline research laboratories for students working in the control and automation domain. In designing the LabMIMO platform, mainly the control design and simulation module of LabVIEW is used along with other modules. Industrial standards and the user-friendly graphical user interface are designed. A scholar can download all the required laboratory program files from the google website: https://sites.google.com/view/labmimo-virtual-laboratory/home, ttps://labmimo.in/. Eight experiments are designed in the area of the control system. All the experiment's detailed theory and explanation are also available in PDF format. All the experiments operating step along with graphics are available under the help menu of LabMIMO laboratory. Details of Experiments:

1. First principle based modeling of the nonlinear MIMO process.

- The main aim of this experiment is all about enhanced fundamental knowledge of mathematical modeling of Nonlinear Coupled

MIMO systems.

- In this experiment, students have to generate the first principle-based mathematical Model of the Quadruple Conical tank system.

- Students/Users have to verify the effect of interactions and coupling in mathematical modeling for different configurations of QCTS. There are six different configurations like, coupled conical tank interacting-noninteracting, Single input single output first, second and third order system and MIMO system.

2. Perform open-loop response analysis for the Nonlinear MIMO system.

- This experimentation teaches the effect of coupling and interaction using open-loop step response analysis.

- In these experiments, the QCTS process model is used as a reference model, and use/students can generate open-loop step response for different configurations of QCTS system along with different operating conditions of three-way diverting valves, drain valves and interaction valves.

- Detailed comparative analysis performed for various operating conditions and the result is generated in tabular and graph forms.

3. Design a PID controller for a nonlinear SISO Conical Tank system.

- PID is a very Classical Model Free controller. The idea behind this experiment is to test and validate the performance of the PID controller on the nonlinear system.

- Students have to find the ideal or most optimal suitable parameter by a hit and run method to cover the entire range of operating points of the tank system.

- Obtain an open-loop response and conclude what needs to be improved

- Set a proportional control gain optimal value to control the rise time

- Set an integral control gain optimal value to control the compensate steady state

- Set a derivative control to gain optimal value to control the compensate overshoot.

4. Performance analyses of Two loop decreolized PID controller for the MIMO system

- In this experiment, the two-loop decentralized PID controller is planned for a multi-input multi-output system.

- Users can do PID controller Performance analysis based on setpoint tracking and important error.

- Post-analysis facilities are available. All results available on an excel sheet by single click and error analysis can be done using different methods.

5. Design a Dynamic decoupler using Relative Gain Array (RGA) methods for MIMO systems.

- This experimentation teaches about the effect of coupling and how to eliminate the impact of the undesired cross-couplings using simple Steady-State Decoupling.

- Relative gain array methods for identifying the proper pairing of input and output variables for the MIMO system.

6. Comparative analysis of different Tuning rules of PID controller on SISO/MIMO system

- This experiment provides fundamental knowledge about the selection of a proper PID auto tuner for a nonlinear MIMO system.

- Experiment having the facilities for testing the PID auto tuner performance for internal model control, Zieglar-Nichols, Cohen-coon, and Chien Hornes Reswick rules.

- Users/Students can set the tuning specification for servo and regulatory.

7. Fuzzy logic-based Controller

- This experiment is designed to understand the behaviour of the Fuzzy Logic Controller (FLC). The decentralized fuzzy controller scheme is the learning outcome of this experiment. The designed scheme controls the dual separate loops and the height of Tank 1 and Tank 2.

- The rules-based FLC is designed for all the possible configurations of QCTS.
- There were two approaches implemented. Considering the entire operating range of the conical tank system, a single rule-based fuzzy system is designed. In the second approach, the operating range of the conical tank is divided into different regions and for each region different zone-wise rules are implemented to address the nonlinearity of the conical tank system.
- To design a multi-input fuzzy system interface model, 'error' and 'change in error' are considered as input. and one output 'voltage' for a bottom tank is considered as a manipulated variable. Students can select different membership functions for control and manipulated variables.

8. MPC controller for SISO and MIMO process

- This experiment is designed to enhance the fundamental knowledge of Model-based Control algorithms.
- In this experiment, the students/user selected the different configurations of the MIMO system and obtained the process model.
- Model-based control algorithms for SISO and MIMO can be performed using dual or barrier optimization methods.
- Effect of weight and constraint on input and output variables can be tested and validated using Constrained MPC.

Case Study 1: This example demonstrates how to use the PID Autotuning Design to obtain PID parameters based on setpoint and process variables collected in another loop.

Learning Outcome of Case study 1:

Effect of PID controller parameters on the nonlinear conical tank system.

Instructions to be followed by the students:

1. Run the VI (LabVIEW exe) and wait until the process variable (PV) reaches near the setpoint

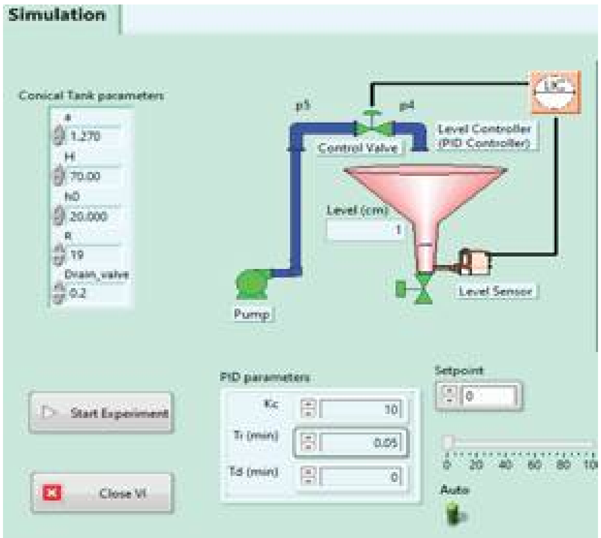

Fig. 2; GUI for PID controller Experiment for SISO Conical Tank

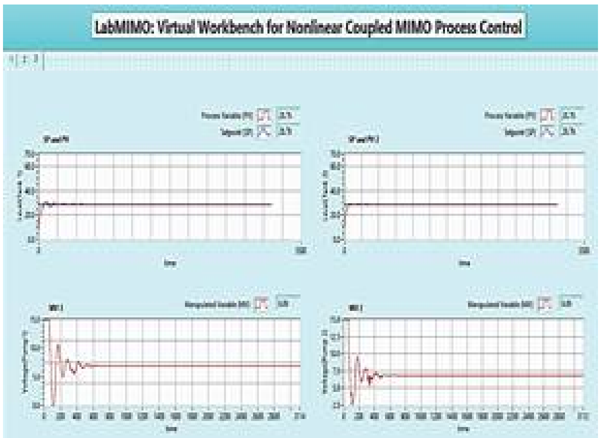

Fig. 3: Results for RGA based Decoupler for MIMO system

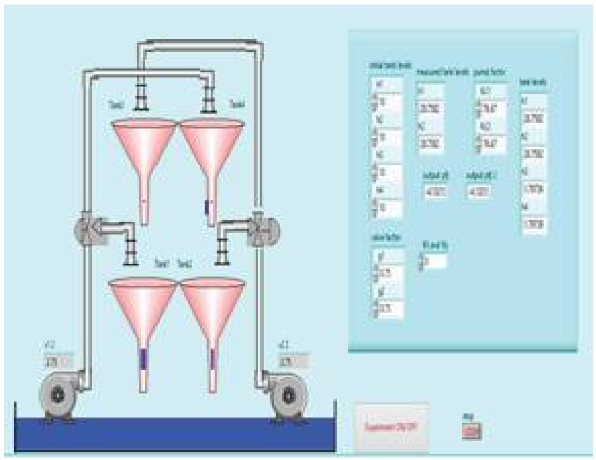

Fig. 4 : GUI for MIMO Two loop PID controller

(SP).

2. In the PID Autotuning Design section, select the type of algorithm, type of controller, and excitation amplitude for the 'open loop step response'. Then, click Autotune to start the process. Select the Identified Plant Parameter tab and see the results from the identification.

3. When the tuned PID gains do not change anymore, the identification is done and you have the option to accept by clicking Accept gain, which will transfer the new gain to PID Gains.

4. Click the Autotune button again to go back to the automatic control state. You can try different options and repeat this process.

5. Click Stop to stop the VI.

6. The results are shown in the figure 2-4.

In the Figure 2, users have the settable parameter for gain of PID controller. As the hit and run methods will provide the understanding of the effect of PID controller gains. In the figure 3 the system response is improved because of the relative gain array methods and it removes the coupling effect of the manipulated variables and provides a fast and desirable set point trajectory. Figure 4 shows the user interface for MIMO software.

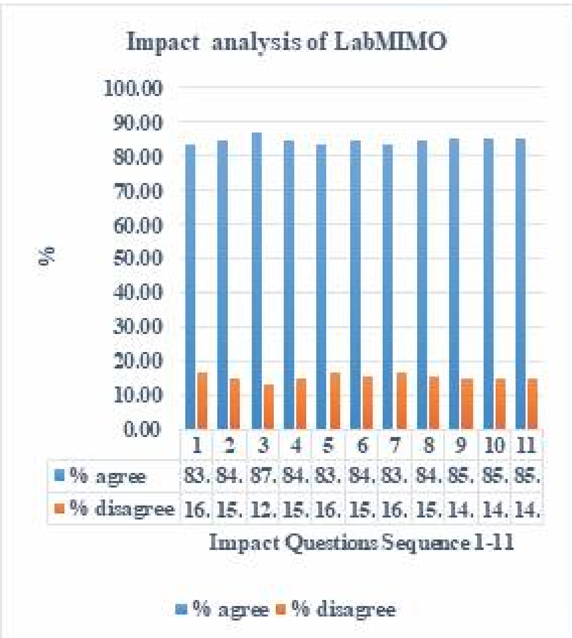

Fig. 5 : Impact analysis of LabMIMO

4. Benefits And Impact Of Virtual Labs

Scholars need theoretic and technical preparation to engage in an expressive hands-on laboratory. Virtual lab's like LabMIMO will serve the purpose and enhance the student's knowledge in the field of Process Control. This virtual laboratory is a part of the curriculum and used by the undergraduate students of Instrumentation and control engineering. The required software and manual are available to all the students on the Google website. Impact analysis for benefits of virtual lab covers the participants consisted of 62 students. Figure 5 shows the impact analysis of LabMIMO tool.

Questionnaire for impact analysis is listed below.

1. Learning and using the " LabMIMO tool" easy or not?

2. Is 'LabMIMO' provide a way to acquire more knowledge in the area of nonlinear control systems in an efficient manner?

3. Can 'LabMIMO' make the learning of topic nonlinear control systems more enjoyable?

4. Any prior knowledge of LabVIEW required to use the "LabMIMO" tool?

5. Do you like the design and layout of the GUI of 'LabMIMO'?

6. Conceptual learning of PID controllers covered?

7. Conceptual learning of MPC controllers covered?

8. Experiments Images and graphics help me to learn and understand problem recklessness.

9. LabMIMO Knowledge helps to solve industrial problems?

10. Do you feel relevant with the practical problem of linear and nonlinear behavior?

11. Conceptual learning of Fuzzy controllers covered?

5. Conclusion

Open-source virtual laboratory-based learning is a requirement for engineering education. It offers scholars the possibility to get industrial experience and a problem solving approach without hardware. This paper presented a collaborating proposed solution for the nonlinear process control area. A virtual laboratory "LabMIMO" enhances the student's knowledge and provides a better platform to do analysis, design, development, implementation, and evaluation of PID controller, Fuzzy logic controller, and MPC controller in a better way concerning practical nonlinear process applications.

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