Developing, Implementing, and Assessing Decoupling Control for UTP Air Pilot Plant

by

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18546

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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(Electrical and Electronics)

Approved by,

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January 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Asyilah Ahmad Astor

ABSTRACT

This paper aims to develop, implement and assessing MIMO system for Universiti Teknologi PETRONAS (UTP) Air Pilot Plant. MIMO system is far more complex than SISO system as MIMO system has multiple interactions. Condition number which often related to MIMO system is the measurement parameter for degree of interaction between variables of the system and variable interaction is the dynamics between manipulated-process variable and controlled-process variable pair. The higher the condition number, the higher the degree of process interaction. Those systems can be very challenging to adjust or control one input from affecting another output because the outputs are reliant to more than one input. Small changes or disturbance in inputs can resulted into a major chaos in the output. Usually, a multi-loop control configuration is applied to MIMO system. However, if the process interaction is significant, it is wise to consider multivariable control strategies such as decoupling control.

The proposed decoupling PI controller for MIMO system design is intended to remove the unwanted interaction and to achieve the set point desired. This designed decoupling PI controller is only implemented to Air Pilot plant that is located in Building 23 of UTP. However, the method could be applied to other 2-by-2 MIMO plant. Firstly, an open loop test is conducted to the plant. A step input change of 30% to 50% valve opening is applied to both input one at a time. The output response is the process reaction curve and transfer function of the system is determined by using first-order dead time assumption. Typical MIMO system tools such as steady state gain matrix, condition number, stability, controllability and relative gain array of the system are used to design the decoupling matrix. Lastly, the output results of simulation and real plant are compared to be evaluated and assessed.

The performance of the designed decoupling PI controller is based on output response of the real plant against virtual plant. The controller implemented in UTP Air Pilot plant demonstrated 54.50% fit to virtual plant. Even though it is not a 100% fit, decoupling PI controller still able to remove the unwanted interaction in the system and reach the desired set point.

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Chapter 1

INTRODUCTION

1.1 Background Study

Industrial processes are mostly multivariable systems such as distillation column and furnace system. The challenge in controlling the multivariable processes is a subject of effectiveness of the control. Single-input single-output (SISO) control system is not applicable to multiple-inputs multiple-outputs (MIMO) control system because of loop interaction [1, 2]. A multivariable process is said to have interaction when process input variables affect more than one process output variable. In some cases, the system has a really strong interaction that it become complicated to handle and this system is called ill-conditioned with strong directionality.

Customarily, control engineers implemented the single-loop Proportional, Integral and Derivative (PID) controllers to the multivariable system regardless the interaction effects. However, multi-loop control methods have grew along with years of understanding and now it is easier to understand and implement [3, 4]. The approaches can be consider sufficient if the process interactions of diverse channels are unassertive [5]. Nonetheless, if there is a substantial interaction, the effect of coupling has to take into consideration. Therefore, decoupling control is needed to reduce the effect of unfavorable interactions.

In this paper, a modeling of MIMO system is carried out and decoupling controller is developed, implemented and assessed. The chosen MIMO plant is Air Pilot plant in Universiti Teknologi PETRONAS located in Building 23.

1.2 Problem Statement

Essentially, all methods and results learned for single-variable system are applicable to multivariable systems [6]; however, controlling MIMO system is different than controlling SISO system due to multiple variables and interaction. Typically, the use of SISO technique in MIMO system neglect the effect of interaction. Interaction is defined as when process input variables affect more than one process output variable, for an example, in distillation system if SISO being use for reflux, the interaction could cause significant effect to the reboiler or vice versa.

The effect of undesired interaction can be reduced using decoupling method. Decoupling will retains the single-loop control algorithms and eliminated the effects of interaction[6]. Therefore, there is a need to develop and implement decoupling controller in order to control the MIMO system. The decoupling controller will be tested in both simulation as well as real experimental data and the result should be comparable to each other.

1.3 Objectives

The main objectives of this paper are:

i. To develop a MIMO model of Universiti Teknologi PETRONAS Air Pilot plant based on first-order dead time (FODT) assumption.
ii. To designed a decoupling with proportional gain and integral time (PI) controller for Universiti Teknologi PETRONAS Air Pilot plant.
iii. To implement the designed decoupling PI controller to Universiti Teknologi PETRONAS Air Pilot virtual plant and real plant.
iv. To evaluate and assess the performance of the designed decoupling PI controller on Universiti Teknologi PETRONAS Air Pilot plant against virtual plant.

1.4 Scope of Study

This paper is focusing on developing modeling procedures for a MIMO system using pilot plant. The assumption is based on first-order dead time system by employing empirical modeling. Then it will lead to the design of decoupler. The proposed decoupler is a subset of feedforward concept applied in SISO.

The designed decoupling PI control is simulated and implemented on a real plant which is the Air Pilot plant. The results in simulation and real application are analyzed, discussed and evaluated. The overall methodology is applied to the selected MIMO plant with the intention for future application in industrial plant.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Controlling of any process; either linear or nonlinear, is crucial especially for multivariable system. Some of budget spend by industries is to control the process plant. Hence, there is a need to find the most effective control system based on the desired outcome of the corporation on a process plant. This chapter will be discussing the analysis of past research and experiments conducted in order to relate with this paper. First, an introduction to control of multivariable processes, then, followed by multivariable interaction, and ends with the analysis and comparison of past papers and researches.

2.2 Multivariable Processes Control

Typically, in real-world control problems, there are two important components in process variable; variable to be controlled and variable to be manipulated. Usually, in MIMO system, it started with determining the interaction in the process, then to select a suitable multi-loop control method in which one manipulated variable for one control variable. However, if the process interaction is significant, it is wiser to consider other multivariable control methods simply because even the best multi-loop control system cannot provide the desired control. Multivariable control such as decoupling control or model predictive control are when the manipulated variable can relate to two or more of the controlled variables.

Multi-loop control method in industry, usually uses standard feedback controller for each loop which is one for every controlled variable. Commonly, it is done by selecting controlled and manipulated variables, then selecting the best pairing of controlled and manipulated variables and specifying the types of feedback controllers used. In 2×2 system in Figure 1, there are two outputs which are the controlled variables and two inputs which are the manipulated variables which yield four transfer functions as in equation 1.

Figure 1: 2×2 system block diagram.

$$\frac{Y_1(s)}{U_1(s)} = G_{11}(s) \quad \frac{Y_1(s)}{U_2(s)} = G_{12}(s)$$
$$\frac{Y_2(s)}{U_1(s)} = G_{21}(s) \quad \frac{Y_2(s)}{U_2(s)} = G_{22}(s) \tag{1}$$

Hence, the relation of input-output of the process can be written as:

$$Y_1(s) = G_{11}(s)U_1(s) + G_{12}(s)U_2(s)$$
$$Y_2(s) = G_{21}(s)U_1(s) + G_{22}(s)U_2(s) \tag{2}$$

Or in vector-matrix form as,

$$Y(s) = G(s)U(s) \tag{3}$$

Where $Y(s)$ and $U(s)$ are refers to the vectors and $G(s)$ is the transfer functions matrix of the process.

$$Y(s) = \begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix},\ U(s) = \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix}\ and\ G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{12}(s) \end{bmatrix} \tag{4}$$

Due to multiple variables, there are interaction present between inputs and outputs and that interactions may result in unwanted response between other control loops. The interactions in control loop are because of the existent of a third feedback loop, note the bold lines in Figure 2, and the complications of those interactions are closed-loop system could be unstable and it is difficult to tune the controller. More information about multivariable interactions will be discussed in Chapter 2.3.

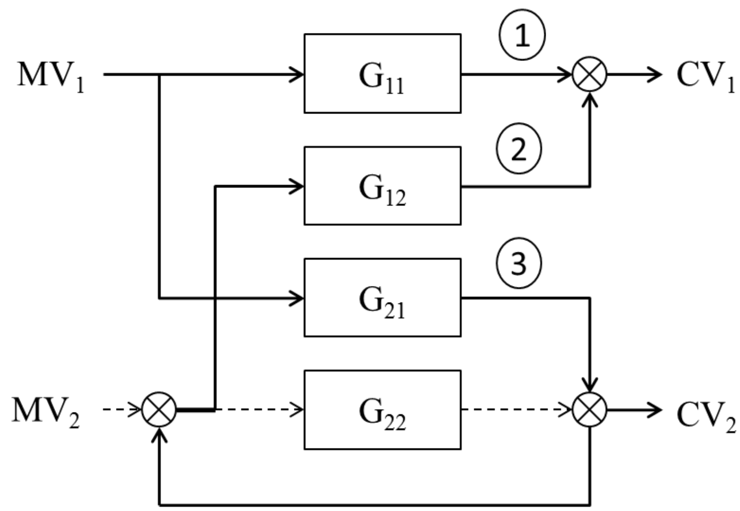

Figure 2: Example of third feedback loop effect to CV_1.

Alternatives methods to deal with unwanted control loop interactions are; one, to retune the feedback controllers; or two, to choice different controlled or manipulated variables; or three, to use another type of multivariable control methods such as decoupling control. The rationale behind of decoupling control systems is to use traditional controllers to recompense for process interaction and thus the control loop interactions reduce. Preferably, decoupling control is about allowing the only desired control variable to be affected by set point changes. Normally, a simple process model such as transfer function model is used to design decoupling controller.

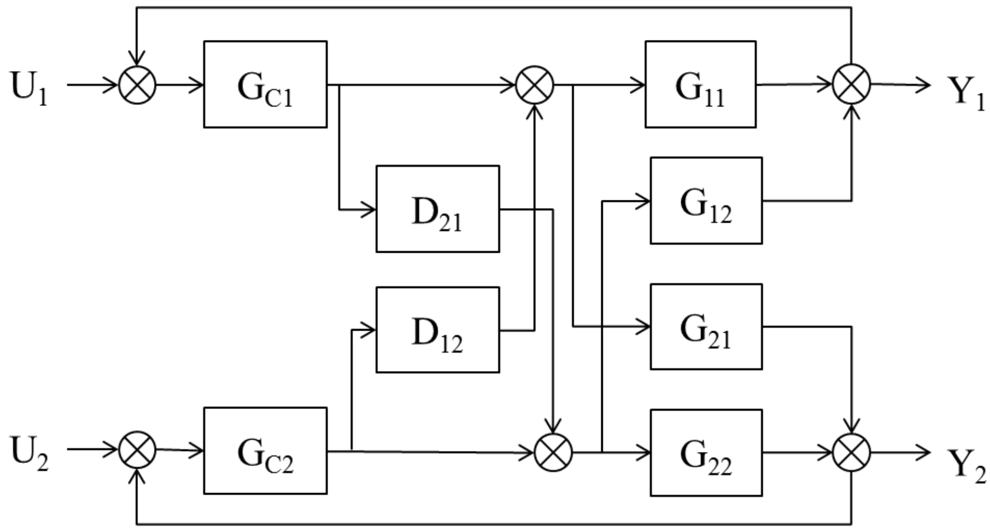

Figure 3: A potential decoupling control scheme for MIMO system

Based on Figure 3 above, the cross-controller, D_{12} , is used to remove the undesired effect of U_2 on Y_1. Therefore,

$$D_{12}G_{11}U_2 + G_{12}U_2 = 0 \tag{5}$$

As $U_2 \neq 0$, then

$$D_{12} = -\frac{G_{12}}{G_{11}} \tag{6}$$

Likewise, cross-controller, D_{21} , is used to cancel out the effect of U_1 on Y_2. Therefore, the general equation will be

$$D_{ij}(s) = -\frac{G_{ij}(s)}{G_{ii}(s)} \tag{7}$$

Commonly, there are three types of decoupling control which are, implicit decoupling through modified controlled variable and or manipulated variable and explicit decoupling or also called static decoupling in which the method presented above. However, most static decoupling control uses decoupling matrix instead and the equation is as below.

$$D_M = \frac{1}{\det G(0)} \begin{bmatrix} G_{22}(0) & -G_{12}(0) \\ -G_{21}(0) & G_{11}(0) \end{bmatrix} \tag{8}$$

2.3 Multivariable Interaction

MIMO system is far more complex than SISO system as MIMO system has multiple interactions [7]. Condition number is often related to MIMO systems; it is the measurement parameter for degree of interaction between variables of the system. Meanwhile, the variable interaction is the dynamics between manipulated-process variable (MV) and controlled-process variable (CV) pair. The higher the condition number, the higher the degree of process interaction. System with condition number more than one can be categorized as ill-conditioned system [8-12].

Ill-conditioned system is a system that is very challenging to adjust or control one input from affecting another output because the outputs are reliant to more than one input [8]. It also describes the properties of strong directionality of the system. Small changes or disturbance in inputs resulted into a major chaos in the output. It is stated that system with ill-conditioned can be detected from the gain matrix's singular value decomposition (SVD) [11]. Given that MIMO system with $n \times n$ as follow:

$$Y(s) = G(s)U(s) \tag{9}$$

Where *Y(s)*, *U(s)* and *G(s)* are the output, input and transfer function of the system respectively. From the transfer function, SVD of gain matrix yields:

$$G(s) = W\Sigma V^T \tag{10}$$

Where W and V is the orthogonal matrices of the transfer function, V^T is the transpose matrix of V and Σ is a diagonal matrix of singular values, $\sigma_i, i = 1,2, \dots, m$ and $\sigma_1 \geq \sigma_2 \dots \geq \sigma_m \geq 0$. The orthogonal matrices $V^T V = 1$ and $W^T W = 1$ [13]. The ratio of singular values defined the condition number of the system [11, 12].

Besides that, another alternative parameter that measure the process interaction in multivariable, according to Marlin T.E (1995) is Relative Gain Array (RGA) [14]. RGA is also used in recommending the best pairing of controlled and manipulated variables. It only requires the knowledge of steady state gains but not process dynamics. It was first suggested by Bristol (1966), the element in a matrix that formed by the ratio of open-loop gain to close-loop gain as shown below for 2×2 MIMO system [15] :

$$\text{Relative Gain Array, } \Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \quad (11)$$

In which λ_{ij} is defined as,

$$\lambda_{ij} = \frac{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{MV_k = constant, k \neq j}}{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{CV_k = constant, k \neq i}} = \frac{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{Other\ loops\ are\ open}}{\left(\frac{\partial CV_i}{\partial MV_j}\right)_{Other\ loops\ are\ close}} \quad (12)$$

Besides that, λ_{11} also can be calculated using,

$$\lambda_{11} = \frac{1}{1 - \frac{K_{12} K_{21}}{K_{11} K_{22}}} \quad (13)$$

Where K_{ij} is the steady state gain in the matrix.

Hence, RGA can also be written as,

$$\Lambda = \begin{bmatrix} \lambda_{11} & 1-\lambda_{11} \\ 1-\lambda_{11} & \lambda_{11} \end{bmatrix} \quad (14)$$

Level of multivariable interaction varies with the different ranges of relative gain, λ, as such $\lambda \leq 0$ is low interaction, $0 < \lambda < 1$ is moderate interaction, and $\lambda > 1$ is high interaction. Bigger relative gain, λ, meaning very high interaction and gain in closed-loop will be very small. The suitable pairing of input-output is also depending on the interaction level.

2.4 Past Research and Experiments

Table 1 shows the summary of recent experiments done in year 2014. All three paper are using different decoupling controller methods, however, it is only tested in simulation. Zhang, W. et. Al. (2014) proposed a two-degree-of-freedom control structure for MIMO systems with multiple time delays is proposed. The experiment is done by assigning a decoupler with a novel inversing design technique into several same independent SISO systems. Then, a PID controller is obtained for those SISO systems. Lastly, a secondary controller is designed to a close-loop function with the decoupler. The two controllers used give chances for better performance and robustness. Both disturbance and set-point can be adjusted accordingly to the controllers.

Ulemj et. Al. (2014) used a decoupling controller with feed-forward compensation for a Benchmark Boiler. Feed-forward compensator is designed to compensate the disturbance generated by change of set-point. First, an ideal decoupler with integral action is determined, then, the decoupler is approximated with PID controllers. Finally, an anti-windup compensator is design.

Table 1: Recent Experiments using Decoupler

Papers	Unit	Description
1 [16]	Title	'Same Controller in All Loops Controller Design for Multivariable Systems with Multiple Time Delays Based On Ideal Decoupler'
	Author (Year)	W. Zhang, B. Sun, B. Yang (2014)
	Method Used	Assigned same individual controller and individual decoupler for each system as in SISO system and one controller for the whole system which is MIMO.
	Conclusion	The design task can be simplified and tuning of disturbance rejection can be done by main controller meanwhile set point can be adjusted using second controller.
2 [17]	Title	'Multivariable Decoupling Control for A Benchmark Boiler'
	Author (Year)	D. Ulemj, C. Fu, W. Tan (2014)
	Method Used	A multivariable decoupling control method with feed-forward compensation
	Conclusion	Proposed method reduces interactions, achieved zero tracking error and with wide operating range.
3 [18]	Title	'Decoupled PID Controller for Wind Tunnel System'
	Author (Year)	T. Zhang, Z. Mao, P. Yuan (2014)
	Method Used	PID controller with reduced order model for decoupled wind process
	Conclusion	Proposed method performs better than normal PID controller.

Lastly, Zhang, T. et al. (2014), used decoupling PID control strategy to a wind tunnel control reduced order model is determined for the decoupled wind tunnel process and finally, a non-dimensional system. First, ideal decoupler is introduced in the control scheme, then, a tuning algorithm for PID is obtained. Result shown in this paper verified that decoupler PID controller performs better than simply PID controller.

Nevertheless, based on paper done by Tham et. Al. (2010), it is stated that when dynamic and static decoupler based on linear system is applied to nonlinear model, it will lead to poor performance [19]. It suggested Disturbance Observer (DO) methods to nonlinear process as DO lessen the effects of loop interaction even with presence of modeling errors. Therefore, DO is more suitable when a multivariable process is affected by an unmeasured disturbance.

Besides that, there are a number of ways in decoupling control method. Liu et. Al. (2012) reviewed nine method of adaptive decoupling control incorporated with other approaches and one conventional coupling control [20]. The adaptive decoupling control methods are:

i. With pole placement
ii. Based on generalized minimum variance
iii. Based on feedback control
iv. Based on generalized predictive control
v. Multivariable PID
vi. Based on neural network
vii. Based on fuzzy control
viii. Using reference model
ix. Based on feedback

Presently, the adaptive decoupling controllers are realized by attempting, training or adjusting, meaning that the theory is not perfect. Further investigation and researches into the technology of multivariable decoupling and real industrial process application is a must for future work.

Chapter 3

METHODOLOGY

3.1 Introduction

Figure 4 shows the steps in research methodology of this paper. Pre-phase is to do critical analysis of past research and planning for the entire project. First phase is to carry out plant modeling of UTP Air Pilot plant. Besides that, some of MIMO analysis such as condition number, stability, controllability and relative gain array are discussed. Second phase is to design the decoupling controller for the MIMO system. Decoupling matrix with proportional gain and integral time (PI) controllers are developed for the plant. Third phase is to implement the decoupling PI controller to virtual plant and actual plant. Lastly, phase four is to assess the performance of the decoupling PI controllers.

All four phases and information related to this project activity will be discussed in each subtopic which are;

i. UTP Air Pilot Plant
ii. Plant Modeling
iii. Decoupling Control design
iv. Implementation on Virtual Plant and UTP Air Pilot Plant
v. Evaluation and Assessment

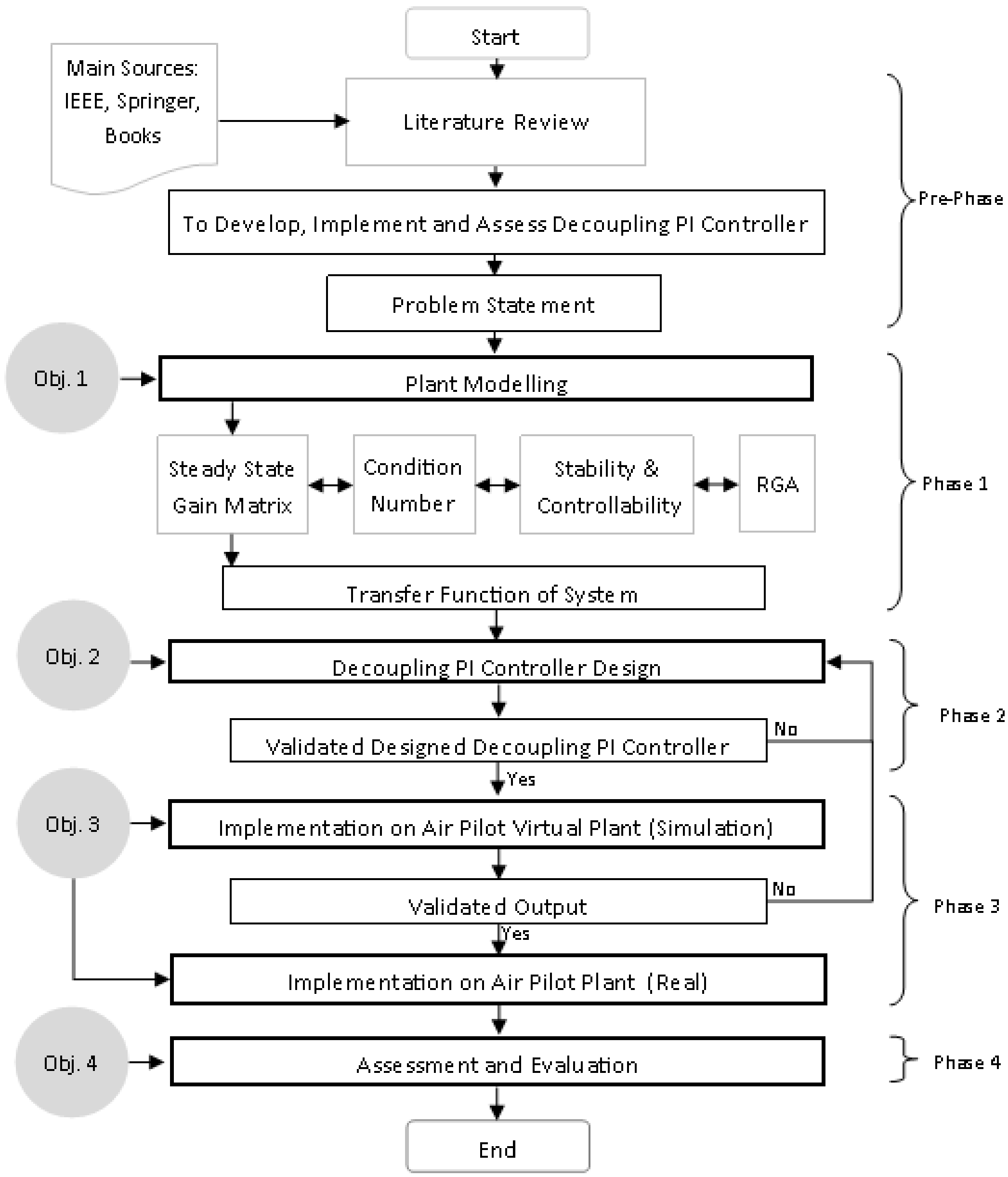

Figure 4: Steps in research methodology

3.2 UTP Air Pilot Plant

This project is executed using air pilot plant as shown in Figure 6 that is located in Block 23 of Universiti Teknologi PETRONAS. This plant model is interfaced with MATLAB in which test the input test signals implementation and input-output data extractions are programmed via MATLAB Simulink software as in Figure 7.

PCV-202 and PCV-212 is the two process control valves (PCV). Meanwhile, PT-202 and PT-212 is the pressure transmitters (PT). Those control valves are the input and the pressure transmitters are the output of the process. Since there are two control valves and two process transmitters, the plant is considered 2×2 MIMO system. Figure 5 illustrates the block diagram of the system, where inlet gas flow of PCV-202 and PCV-212 are the inputs, pressure of outlet PT-202 and PT-212 are the outputs and G_{11}, G_{12}, G_{21} and G_{22} is the transfer function of each process pair.

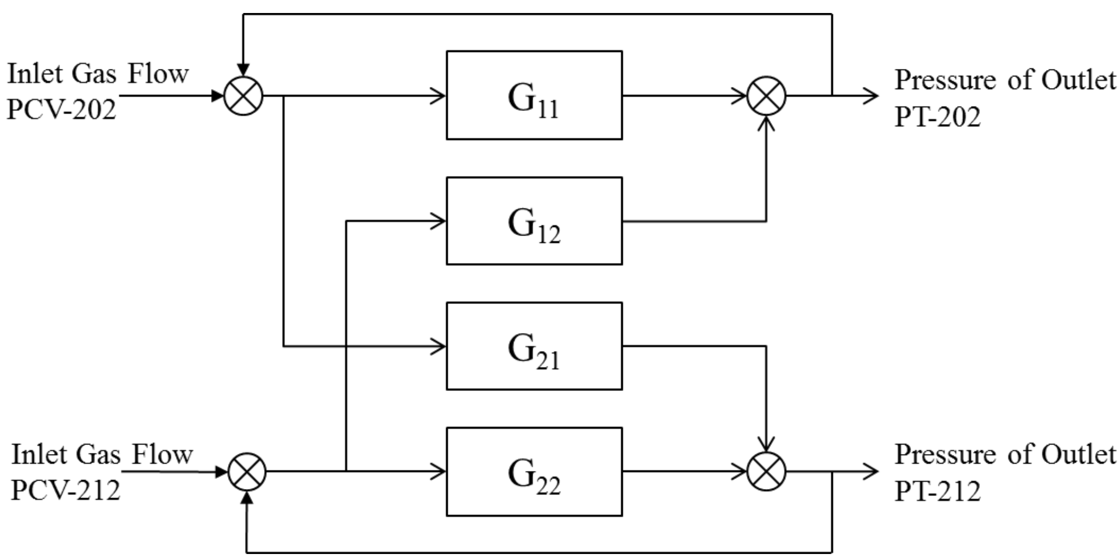

Figure 5: UTP air pilot plant block diagram

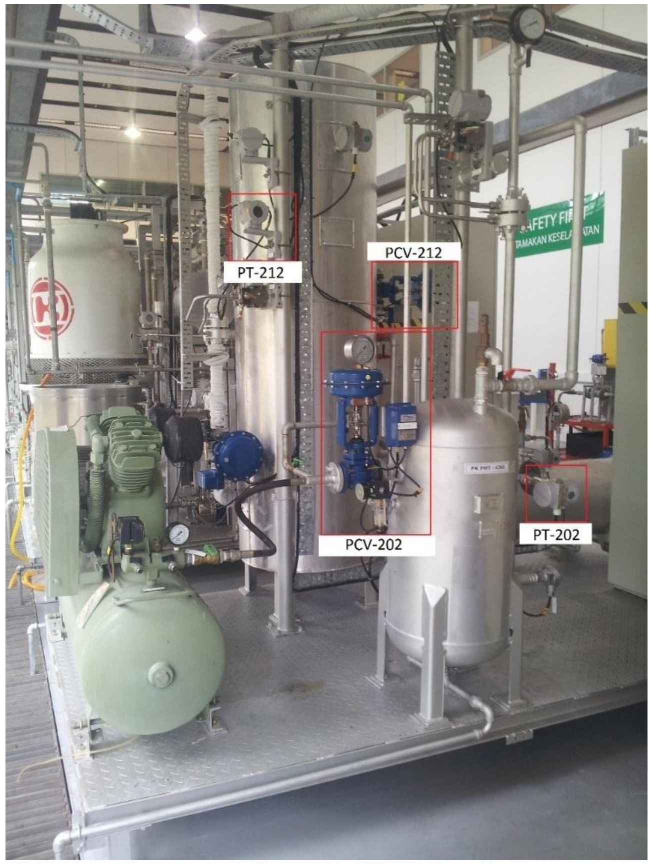

Figure 6: UTP air pilot plant

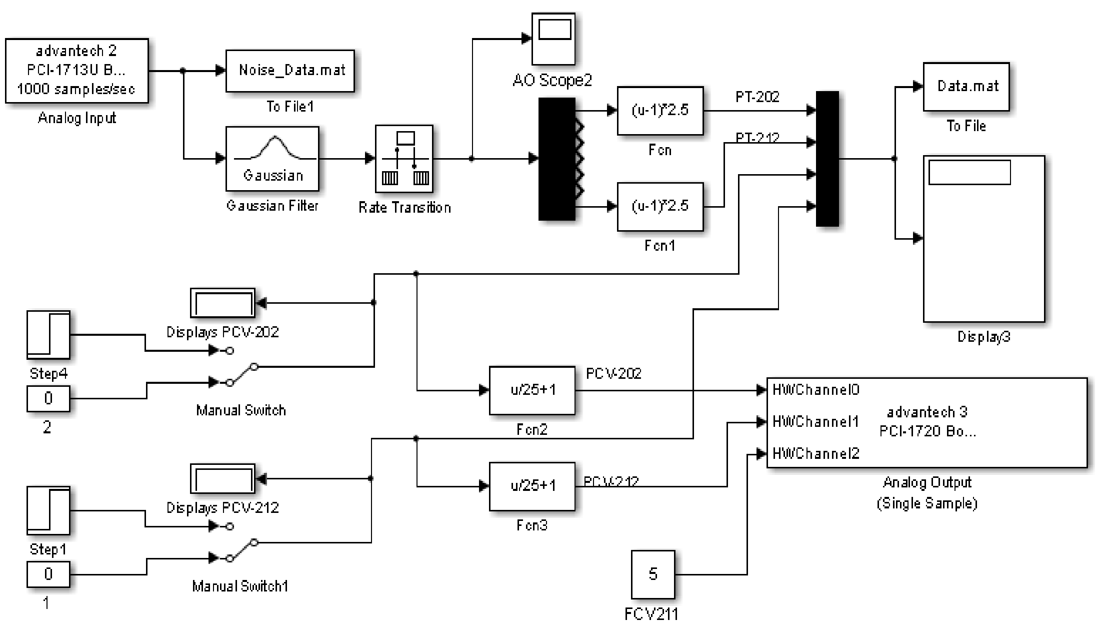

Figure 7: Air pilot plant with MATLAB Simulink Interfacing.

3.3 Plant Modeling

In order to define the plant transfer function, it needs the steady state gain matrix. The steady state gain matrix is calculated using the plant input-output data and the calculation is as below where PCV-202 is U_1, PCV-212 is U_2, PT-202 is Y_1 and PT-212 is Y_2.

$$K = \begin{bmatrix} \frac{\Delta Y_1}{\Delta U_1} & \frac{\Delta Y_1}{\Delta U_2} \\ \frac{\Delta Y_2}{\Delta U_1} & \frac{\Delta Y_2}{\Delta U_2} \end{bmatrix} \tag{15}$$

Two experiments are conducted to obtain the steady state gain matrix. First experiment is to manipulate PCV-202, U_1 and maintain PCV-212, U_2. PCV-202 is fixed to 30% open and PCV-212 is 40% open. Then the process is run until it reached steady state for about 10 minutes. Next, PCV-202 is increased to 50% open; however, PCV-212 is maintained at 40% open. Later, when both outputs reached its steady state after the step change in U_1, the results are recorded. The second experiment is similar to previous experiment except that PCV-202, U_1 is maintained and PCV-212, U_2 is manipulated instead. The steady state gain matrix is obtained through Equation 15.

After steady-state gain matrix is attained, the transfer function can be calculated using general equation for transfer function as Equation 16 below with time constant, τ, as in Equation 17 in which can be acquired from graphs in steady state gain matrix experiments. The summary of these experiments is as shown in Figure 8.

$$G(s) = \begin{bmatrix} \frac{K_{11}}{\tau_{Y_{11}}s + 1} & \frac{K_{12}}{\tau_{Y_{12}}s + 1} \\ \frac{K_{21}}{\tau_{Y_{21}}s + 1} & \frac{K_{22}}{\tau_{Y_{22}}s + 1} \end{bmatrix} \tag{16}$$

$$\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%}) \tag{17}$$

Step Input Test- Experiment 1

Step 1: Run the plant.
Step 2: Set PCV-202 to step input of initial value of 30% open and final value of 50% with time step of 10 X 60 seconds.
Step 3: Set PCV-212 to 40% open.
Step 4: Wait for about 1500 seconds (25 minutes).
Step 5: Stop the plant.
Step 6: Plot the graph.
Step 7: Calculate the steady state gain using $K = \frac{\Delta_{Output}}{\Delta_{Input}}$ *eqn. (15).*
Step 8: Calculate the time constant, τ using $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$*eqn. (17).*
Step 9: Produce the transfer function as in *eqn. (16)*, $G(s) = \frac{K_{ij}}{\tau_{ij}S + 1}$.

Step Input Test- Experiment 2

Step 1: Run the plant.
Step 2: Set PCV-212 to step input of initial value of 30% open and final value of 50% with time step of 10 X 60 seconds.
Step 3: Set PCV-202 to 40% open.
Step 4: Wait for about 1500 seconds (25 minutes).
Step 5: Stop the plant.
Step 6: Plot the graph.
Step 7: Calculate the steady state gain using $K = \frac{\Delta_{Output}}{\Delta_{Input}}$ *eqn. (15).*
Step 8: Calculate the time constant, τ using $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$*eqn. (17).*
Step 9: Produce the transfer function as in *eqn. (161)*, $G(s) = \frac{K_{ij}}{\tau_{ij}S + 1}$.

Figure 8: Summary of transfer function experiments.

Based on Singular Value Decomposition, the value of Σ which is a diagonal matrix of singular values, σ_i, condition number of the system is obtained through ratio of bigger value of $\sigma_i$with smaller value of σ_i. Controllability of the system is depending on the determinant of steady state gain matrix. The system is said to be controllable if the determinant |K| ≠ 0. Stability of the system can be determine based on the steady state gain matrix and if the pole is located on left hand plane, then the system is considered stable. Lastly, Relative Gain Array (RGA) is calculated using Equation 13 and Equation 14 in Chapter 2.3. All results and graphs are obtained and recorded.

3.4 Decoupling Control Design

Decoupling control design started with calculating the decoupling matrix using Equation 7 in Chapter 2.2. Then, using linear (LTI) objects and control design block as shown in Figure 9 for automatic tuning of decoupling matrix values with proportional gain and integral time parameters for both controllers. Summary of decoupling control design steps are in Figure 10.

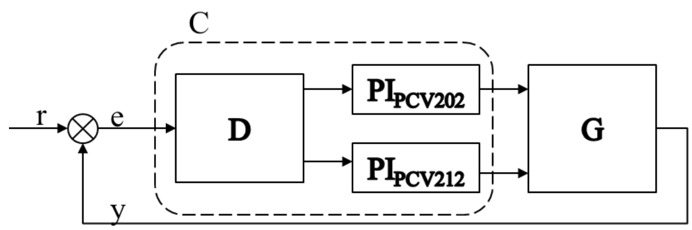

Figure 9: Block diagram of decoupling PI controller.

Decoupling Control Design

Step 1: Calculate decoupling matrix

$$D_M = \frac{1}{\det G(0)} \begin{bmatrix} g_{22}(0) & -g_{12}(0) \\ -g_{21}(0) & g_{11}(0) \end{bmatrix} \quad \textit{eqn. (7)}$$

Step 2: Coding the function

i. Key in the model of the plant.
ii. Key in the decoupling matrix in '*ltiblock.gain'* function.
iii. Key in the two controllers in '*ltiblock.pid*' function.
iv. Set the crossover bandwidth.
v. Connect all blocks.

Step 3: Execute the coding.

Step 4: Validate the design. If not satisfied, repeat *Step 2* by changing the crossover bandwidth.

Step 5: The tunable details is shown in MATLAB command window.

Figure 10: Summary of decoupling control design steps.

3.5 Implementation on Virtual Plant and UTP Air Pilot Plant

The designed decoupling PI controllers are implemented on a virtual plant as in Figure 11. DM is the decoupling matrix, PID_Y1 and PID_Y2 are the two PI controllers. One set point is set to a step change of 2 bar to 3.5 bar and another set point is set constant at 2 bar only. The experiment is executed and repeated again with the set point vice versa. The data obtained is plotted and validated before applying to UTP Air Pilot plant. If the virtual plant result is not satisfied, the decoupling controller design steps are repeated with another value of crossover bandwidth then it will be tested out again on virtual plant until satisfied.

To implement the decoupling controllers on UTP Air Pilot plant, the tested parameters of decoupling matrix and PI controllers are set in the plant as in Figure 12. First, the experiment is executed with both set point of PT-202 and PT-212 are 2 bar. Then, after 1000 seconds or roughly 16 minutes, set point of PT-202 is change to 3.5 bar and the other just constant. The same experiment is repeated with PT-202 constant throughout the experiment and PT-212 changed from 2 bar to 3.5 bar. The data obtained is plotted and validated. The summary for whole process as in Figure 13.

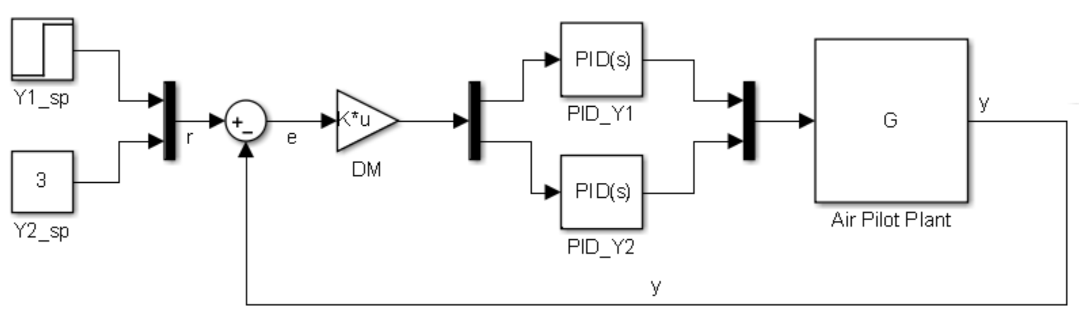

Figure 11: Decoupling implementation using Simulink (only)

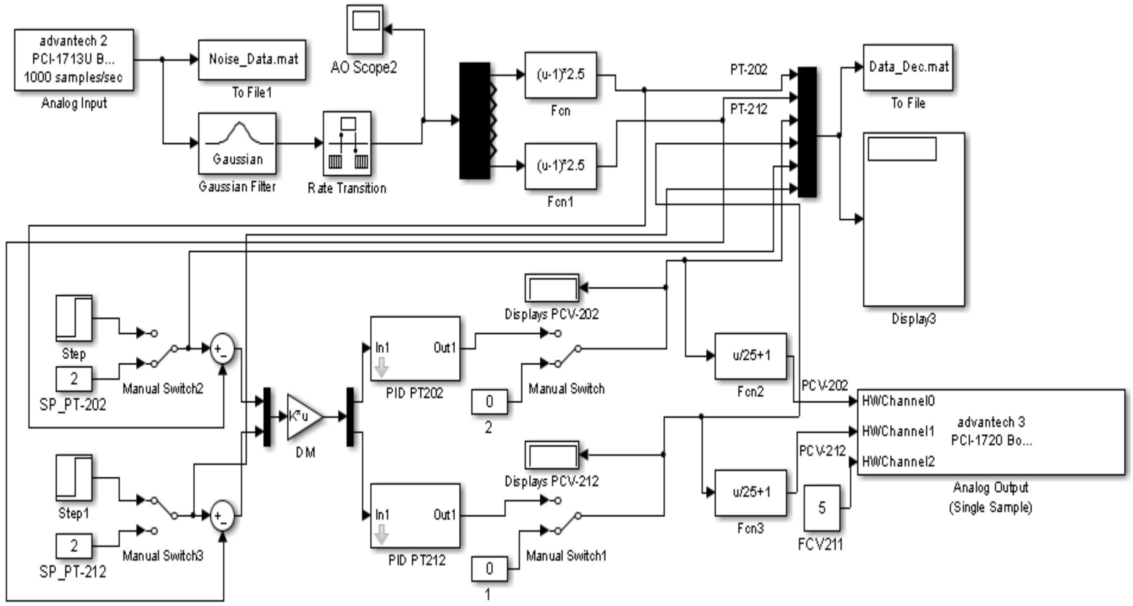

Figure 12: Decoupling implementation using UTP air pilot plant.

<u>Virtual Plant Implementation</u>

Step 1: Set set-point of PT-202 to step input of initial value of 2 bar and final value of 3.5 bar with time step of 1000 seconds.
Step 2: Set set-point of PT-212 to 2 bar.
Step 3: Set experiment time to 2000 seconds.
Step 4: Executed the virtual plant.
Step 5: Plot the graph.
Step 6: Repeat step 1 until step 5 with PT-202 constant of 2 bar and PT-212 step change of 2 bar to 3.5 bar.

<u>UTP Air Pilot Plant Implementation</u>

Step 1: Run the plant.
Step 2: Set set-point of PT-202 to step input of initial value of 2 bar and final value of 3.5 bar with time step of 1000 seconds.
Step 3: Set set-point of PT-212 to 2 bar.
Step 4: Wait for about 2000 seconds
Step 5: Stop the plant.
Step 6: Plot the graph.
Step 7: Repeat step 1 until step 6 with PT-202 constant of 2 bar and PT-212 step change of 2 bar to 3.5 bar.

Figure 13: Summary of Decoupling Controller Implementation

3.6 Evaluation and Assessment

The result of implementation of decoupling controller in UTP Air Pilot plant is assessed by the steady state gain offset, settling time, and overshoot. Then, the performance is analyzed and discussed.

Chapter 4

RESULT AND DISCUSSION

4.1 Plant Modeling

Table 2 below shows the two experiment done for open loop test. In experiment 1, valve PCV-202 is increased from 30% opening to 50% opening while PCV-212 is constant. Vice versa for experiment 2.

Table 2: Open Loop Test

Valve (Input)	Experiment 1	Experiment 2
PCV-202	30% → 50%	40%
PCV-212	40%	30% → 50%

4.1.1 Experiment 1

Figure 14 shows the graph of open loop test when input U_1 is applied with step input signal of 30% open to 50% open while input U_2 is constant for 40% open. The green line is PT-202 which is output Y_1 and red line representing PT-212 which is output $Y_{2.}$

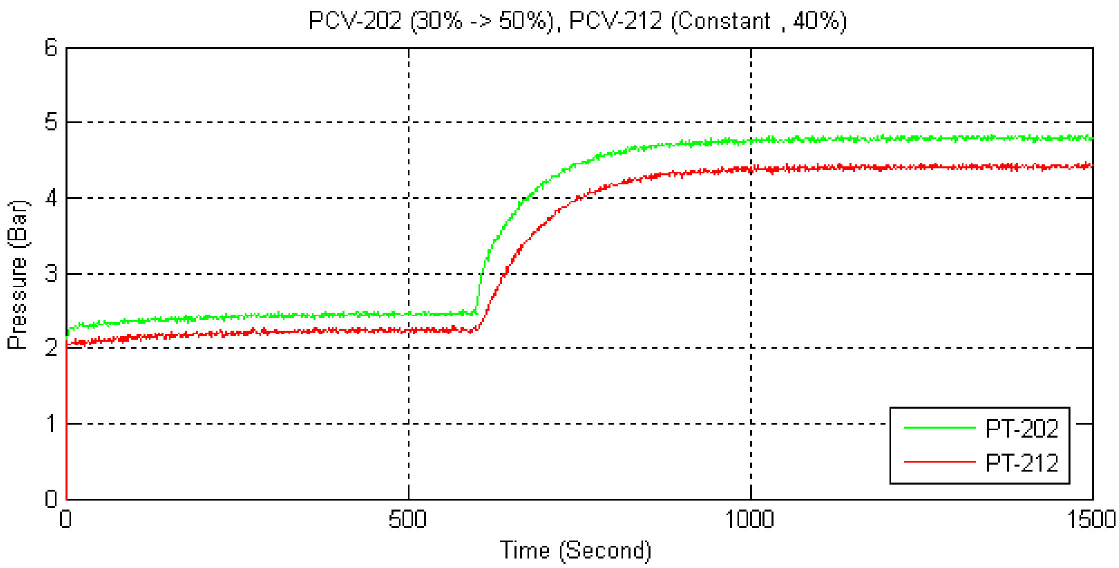

Figure 14: Graph of open loop test, experiment 1.

Table 3: Data of Step Input Test: Experiment 1

Output 1, Y_1, PT-202						
		Time (s)	Value (bar)		Time (s)	Value (bar)
Percentage of settling time, t_S	0%	600	2.454	100%	1099	4.757
Time of change in output, $t_{\Delta\%}$	$t_{\Delta 28\%}$	612	3.079	$t_{\Delta 63\%}$	665	3.910
Settling time, t_S (s)	1099 – 600 = 499					
Change in Output, Δ	4.757 – 2.454 = 2.303					
Output Gain, $K_P = \frac{\Delta}{\delta}$	2.303/20 = 0.115					
Time Constant, $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$	1.5(665-612) = 79.5					
Output 2, Y_2, PT-212						
		Time (s)	Value (bar)		Time (s)	Value (bar)
Percentage of settling time, t_S	0%	600	2.262	100%	1053	4.383
Time of change in output, $t_{\Delta\%}$	$t_{\Delta 28\%}$	636	2.861	$t_{\Delta 63\%}$	692	3.602
Settling time, t_S (s)	1053 – 600 = 453					
Change in Output, Δ	4.383 – 2.262 = 2.121					
Output Gain, $K_P = \frac{\Delta}{\delta}$	2.121/20 = 0.106					
Time Constant, $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$	1.5(692-636) = 84					

Based on Table 3, both outputs reach the steady state approximately after 1000 second with no delay. It is proven that output gain of Y_1 is greater than Y_2 with K_{P11}= 0.11515 and K_{P21}= 0.10605. However, output Y_2 has faster settling time, t_S, higher change in output, Δ and bigger time constant, τ compared to output Y_2. - Output Y_1 has 499 second of settling time, 2.303 bar of change in output and time constant of 79.5. Meanwhile, output Y_2 has 453 second of settling time, 2.121 bar of change in output and time constant of 84.

4.1.2 Experiment 2

Figure 15 shows the graph of open loop test when input U_2 is applied with step input signal of 30% open to 50% open while input U_1 is constant for 40% open. The green line is PT-202 which is output Y_1 and red line representing PT-212 which is output Y_2. Based on Table 4, both outputs reach the steady state approximately after 1200 second with no delay but with opposite directionality compared to experiment 1. Y_2 output gain is greater than Y_1 with K_{P22}= -0.08615 and K_{P12}= -0.07350. The negative sign indicates the directionality of the system. However, output Y_2 has faster settling time, t_S, higher change in output, Δ and bigger time constant, τ compared to output Y_2. Output Y_1 has 539 second of settling time, 1.470 bar of change in output and time constant of 99. Meanwhile, output Y_2 has 424 second of settling time, 1.723 bar of change in output and time constant of 102.

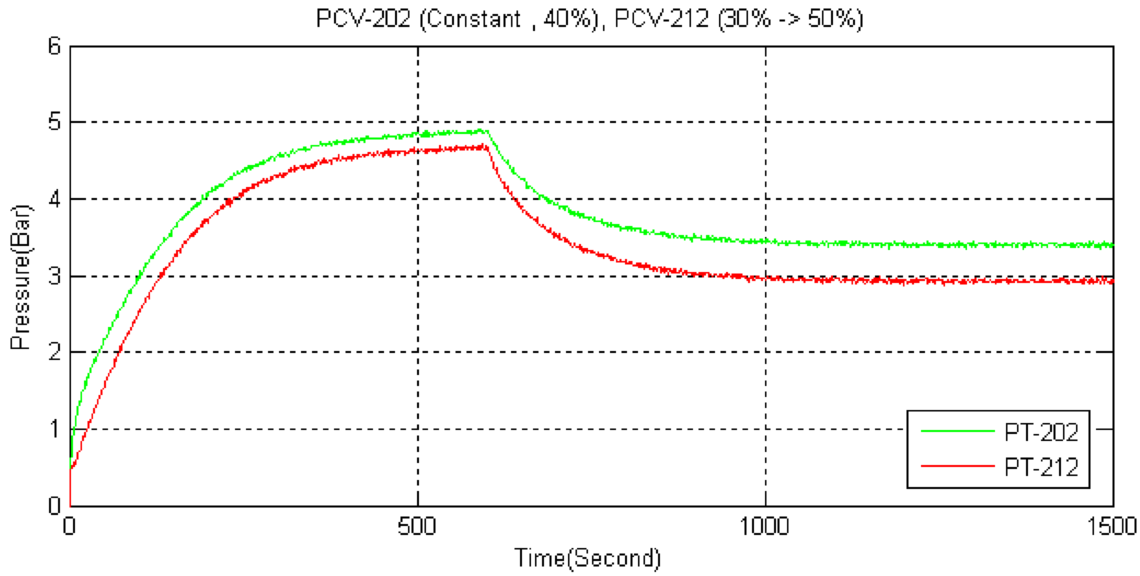

Figure 15: Graph of open loop test, experiment 2

Table 4: Data of Step Input Test: Experiment 2

Output 1, Y_1, PT-202						
		Time (s)	Value (bar)		Time (s)	Value (bar)
Percentage of settling time, t_S	0%	600	4.879	100%	1138	3.409
Time of change in output, $t_{\Delta\%}$	$t_{\Delta 28\%}$	630	4.462	$t_{\Delta 63\%}$	696	3.957
Settling time, t_S (s)	1138 – 600 = 538					
Change in Output, Δ	3.409 – 4.879 = – 1.470					
Output Gain, $K_P = \frac{\Delta}{\delta}$	–1.470/20 = –.0.07350					
Time Constant, $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$	1.5(696 – 630) = 99					

Output 2, Y_2, PT-212						
		Time (s)	Value (bar)		Time (s)	Value (bar)
Percentage of settling time, t_S	0%	600	4.653	100%	1024	2.930
Time of change in output, $t_{\Delta\%}$	$t_{\Delta 28\%}$	626	4.146	$t_{\Delta 63\%}$	694	3.558
Settling time, t_S (s)	1024 – 600 = 424					
Change in Output, Δ	2.930 – 4.653 = –1.723					
Output Gain, $K_P = \frac{\Delta}{\delta}$	–1.723/20 = –0.08625					
Time Constant, $\tau = 1.5(t_{\Delta 63\%} - t_{\Delta 28\%})$	1.5(694 – 626) = 102					

4.1.3 MIMO Analysis

I. Transfer Function

$$G(s) = \begin{bmatrix} \frac{K_{11}}{\tau_{Y_{11}} s + 1} & \frac{K_{12}}{\tau_{Y_{12}} s + 1} \\ \frac{K_{21}}{\tau_{Y_{21}} s + 1} & \frac{K_{22}}{\tau_{Y_{22}} s + 1} \end{bmatrix} = \begin{bmatrix} \frac{0.115}{79.5s + 1} & \frac{-0.073}{99s + 1} \\ \frac{0.106}{84s + 1} & \frac{-0.086}{102s + 1} \end{bmatrix}$$

The transfer function of the system is obtained from steady-state gain, K_{ij} and time constant, τ, from the experiment. This transfer function is model of this plant. This model is based on first-order dead time (FODT) system with the assumption dead time of 0.

II. Steady State Matrix Gain

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} \frac{\Delta CV_1}{\Delta MV_1} & \frac{\Delta CV_1}{\Delta MV_2} \\ \frac{\Delta CV_2}{\Delta MV_1} & \frac{\Delta CV_2}{\Delta MV_2} \end{bmatrix} = \begin{bmatrix} 0.115 & -0.073 \\ 0.106 & -0.086 \end{bmatrix}$$

Steady state gain matrix is calculated as shown above. All the gain is relatively small and two of the gains show negative sign which indicate the directionality of the system.

III. Stability

The stability of the system is defined by the poles. The poles are calculated from denominator when G(s) = 0. When,

$$\begin{bmatrix} 79.5s + 1 & 99s + 1 \\ 84s + 1 & 102s + 1 \end{bmatrix} = 0$$

Then $s = \begin{bmatrix} -0.013 & -0.010 \\ -0.012 & -0.010 \end{bmatrix}$

All the poles are located in left hand plane as in Figure 16. Therefore, the system is stable.

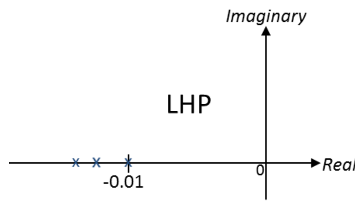

Figure 16: Poles of the system

IV. Controllability

$$\det|K| = det \begin{vmatrix} 0.11515 & -0.07350 \\ 0.10605 & -0.08615 \end{vmatrix}$$

$$= (0.11515)(-0.08615) - (-0.07350)(0.10605) = -0.00213$$

Since, $\det|K| \neq 0$, the system is controllable. In contrary of condition number of the system, even though the system is an ill-conditioned system, but it is controllable.

V. SVD, Condition Number

$G(s) = W\Sigma V^T$, thus, the singular value decomposition matrices are,

$$G(s) = \begin{bmatrix} -0.7070 & -0.7072 \\ -0.7072 & -0.7070 \end{bmatrix} \begin{bmatrix} 0.1929 & 0 \\ 0 & 0.0110 \end{bmatrix} \begin{bmatrix} -0.8109 & -0.5852 \\ 0.5852 & -0.8109 \end{bmatrix}$$

With $\Sigma = \begin{bmatrix} 0.1929 & 0 \\ 0 & 0.0110 \end{bmatrix}$, Therefore, condition number, C.N is $\frac{0.1929}{0.0110} = 17.536$

Condition number that is greater than 10 is categorized as ill-conditioned system and this MIMO plant has condition number of 17.536, which mean it is an ill-conditioned system.

VI. Relative Gain Array

RGA, $\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} = \begin{bmatrix} \lambda_{11} & 1-\lambda_{11} \\ 1-\lambda_{11} & \lambda_{11} \end{bmatrix}$,

$$\lambda_{11} = \frac{1}{1 - \frac{K_{12}K_{21}}{K_{11}K_{22}}} = \frac{1}{1 - \frac{(-0.07350)(0.10605)}{(0.11515)(-0.08615)}} = 4.6672,$$

Therefore, $\Lambda = \begin{bmatrix} 4.6672 & -3.6672 \\ -3.6672 & 4.6672 \end{bmatrix}$

The relative gain array of the system is calculated as shown. The best suitable pairing of the system would be input U_1 – output Y_1 and input U_2 – output Y_2.

4.2 Decoupling Control Design

Decoupling Matrix,

$$D_M = \frac{1}{\det G(0)} \begin{bmatrix} g_{22}(0) & -g_{12}(0) \\ -g_{21}(0) & g_{11}(0) \end{bmatrix}$$

$$= \frac{1}{-0.002152} \begin{bmatrix} -0.086 & 0.073 \\ -0.106 & 0.115 \end{bmatrix}$$

$$= \begin{bmatrix} 39.96 & -33.92 \\ 49.26 & -53.44 \end{bmatrix}$$

Using linear (LTI) object and control design block in MATLAB, with final peak gain of 0.986, and number of iterations of 34, the decoupling matrix is

$$D = \begin{bmatrix} 21.47 & -18 \\ 33.74 & -38 \end{bmatrix}$$

And the proportional gain and integral time for both controllers are as in Table 5 below:

Table 5: PI Controller Parameter

Controllers	Proportional Gain	Integral Time
PT-202	1.34	0.023
PT-212	1.64	0.021

4.3 Decoupling Implementation and Assessment

Figure 17 shows the output of decoupling PI controller in virtual plant. The set point of controlled variables is denoted as r (1) representing set point of PT-202 and r (2) representing set point of PT-212, meanwhile the output is denoted as y (1) representing output of PT-202 and y (2) representing output of PT-212. When r (1) is increased from 2 to 3.5, y (1) increases accordingly and y (2) maintains with slight dip in output. Similarly, when r (2) is increased from 2 to 3.5, y (2) increases and y (1) maintains with slight overshoot. This shows that the decoupling PI controller is able to eliminate the unwanted interaction in the system.

The decoupling PI controller designed is continued to UTP Air Pilot plant and the result is shown in Figure 18. Once more, the decoupling PI controller proved that it able to remove the undesired interaction in the system. When set point of PT-202 is changed from 2 bar to 3.5 bar, PT-202 able to reach the targeted set point while PT-212 managed to maintain its set point with slight dip around 30.00%. Also when set point of PT-212 is changed to 3.5 bar while PT-202 is constant, PT-212 is almost able to reach the desired set point with gain offset of -0.15 bar and PT-202 with gain offset of -0.10 bar and overshoot of 31.58%. The data collected below in Table 6 only accounted the result pass the set point changes (after 1000 second).

Table 6: Decoupling PI controller output on UTP Air Pilot plant.

Set Point	**Experiment 1**			**Experiment 2**		
PT-202	2 bar → 3.5 bar			2 bar constant		
PT-212	2 bar constant			2 bar → 3.5 bar		
Output	**Gain Offset**	**Settling Time**	**Overshoot**	**Gain Offset**	**Settling Time**	**Overshoot**
PT-202	0.00 bar	491 s	0.00 %	0.10 bar	483 s	31.58 %
PT-212	0.00 bar	501 s	-30.0 %	0.15 bar	489 s	0.00 %

The settling time for all outputs are considered longer, however, this is an acceptable settling time for the system as when designing decoupling PI controller with faster response resulted in oscillating output. Oscillating output may be damaging to control valve as it opens and closes frequently in short interval of time and it is not a robust system.

Virtual plant is definitely a simulation in which it is in ideal state, meanwhile real plant is operated in reality. There are a lot of other factors that can affect the system such as mechanical factor and instrumentation factor. In control system industries, virtual plant is used as a general representation of the real plant and the output is reflected as a guide to how those specific controllers behave in a real plant. Testing out a controller in a real plant usually does not happen as it requires a shutdown on entire operation and cost a significant amount of money.

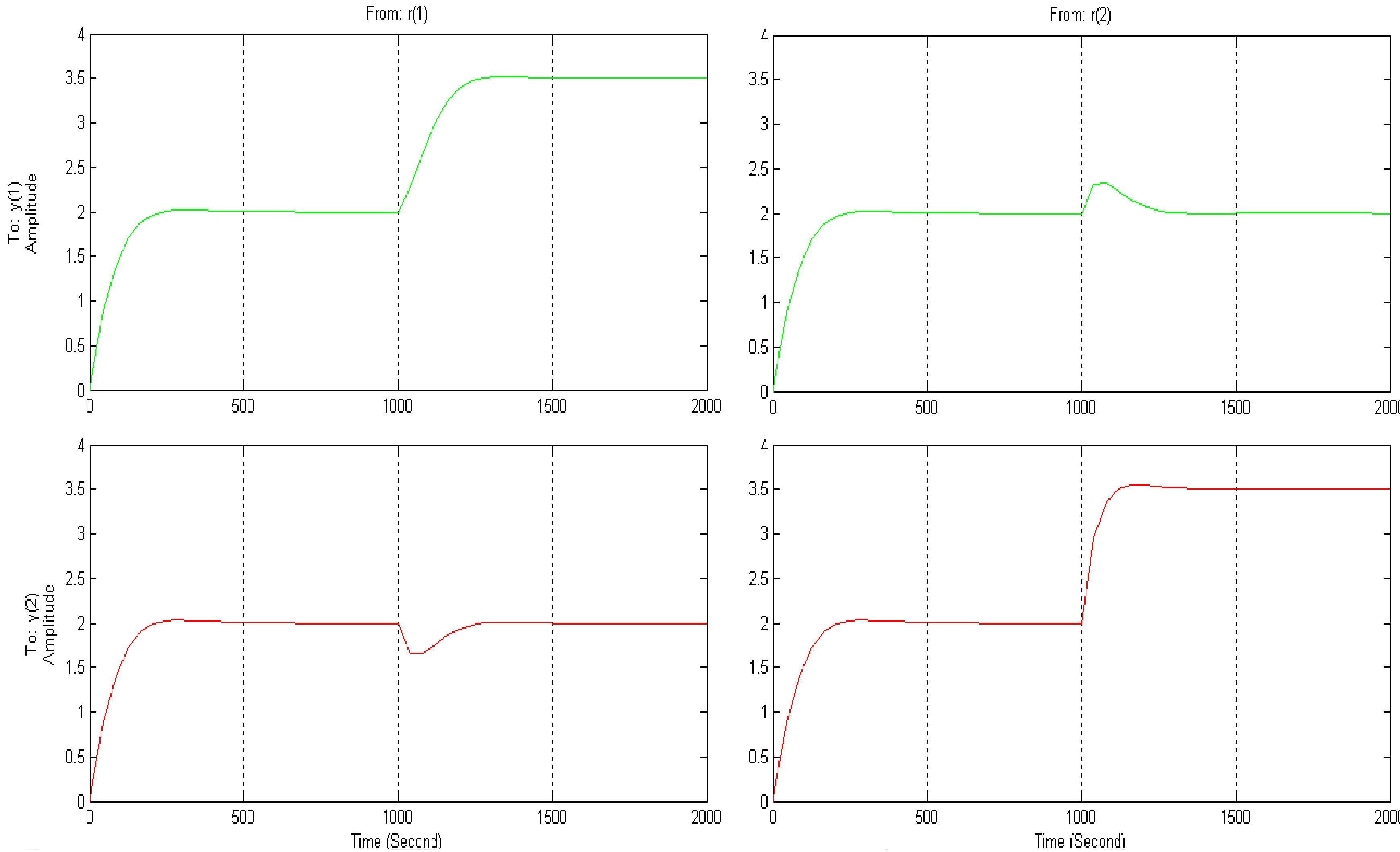

Figure 17: Decoupling PI controller in Virtual Plant.

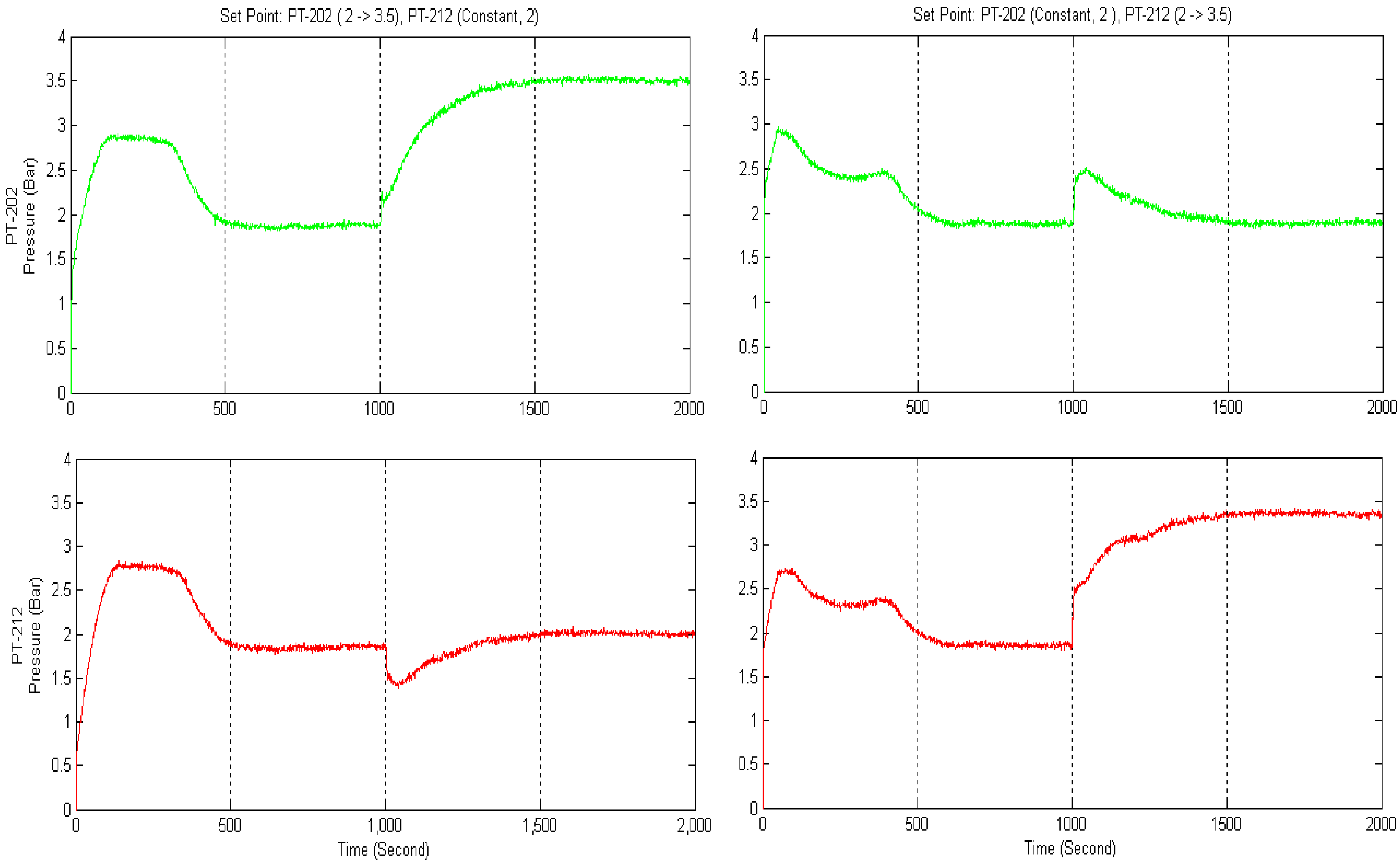

Figure 18: Decoupling PI controller in UTP Air Pilot Plant.

Chapter 5

CONCLUSION

5.1 Conclusion

The four objectives of this project are to develop a MIMO model for UTP Air Pilot plant, to designed a decoupling PI controllers for the plant, to implement the designed decoupled PI controllers in a virtual plant and real plant and lastly, to evaluate and assess the performance of the decoupled PI controller.

The first objective is achieved by conducting an open loop test and it produces the transfer function of the system that is the model of the plant. Then, using the values acquired from the experiment, the model of the plant is analyzed in term of system condition number, stability, controllability and relative gain array (RGA) of the system. From its SVD, the system is proven to displays an ill-conditioned system. However, the system is found stable and controllable. RGA of the system indicate that there is strong interaction between inputs and outputs. These further analyses are based on transfer function of the system and it informs some of the behavior and characteristics of the structure that is might be useful for later modification to the system.

Second and third objectives is achieved by first, calculating the decoupling matrix, then he decoupling matrix, proportional gain and integral time for both controllers are designed. Those values are implemented later on virtual plant and real plant.

Lastly, the final objective, to evaluate and assess the performance of the decoupling PI controllers. The designed decoupling controller demonstrated that it able to remove the unwanted interaction response from its MIMO system. There is slight offset error for set point PT-212 about 0.10 bar and 0.15 bar respectively. The gain offset error is very small however, it still managed to able to reach somewhat the wanted set point. Nevertheless, the large error of settling time only indicates that the outputs require longer settling time as faster response system resulted in oscillating response and may be damaging to control valves as it repeatedly opens and closes in small interval time. Similarly, overshoot error that is about 31% and still within healthy range of overshoot but smaller overshoot or dip would be better.

All the project works presented above are done to prove that decoupling controller can be used to remove the unwanted interaction in MIMO system. Even though with small offset error, longer settling time and slight overshoot or dip, the designed decoupling controller is feasible and can be applied to real plant. Both outputs in simulation and real plant proved that decoupling controller is capable in removing the undesired interaction in the system. The decoupling matrix cancel out the unwanted effect in each process and PI controllers help realizing the desired output for the system.

5.2 Recommendation

With the time constraint, only several decoupling PI controllers' parameters are tested. It is recommended that different set of decoupling PI controllers are implemented so that better desired output, maybe with a slight smaller overshoot is preferable, is obtained.

This project uses conventional decoupling control method. It is known that there are several other ways to implement decoupling control [20]. Those other methods should be tested as well and another technique should be introduced for better decoupling control or for any multivariable processes control system.

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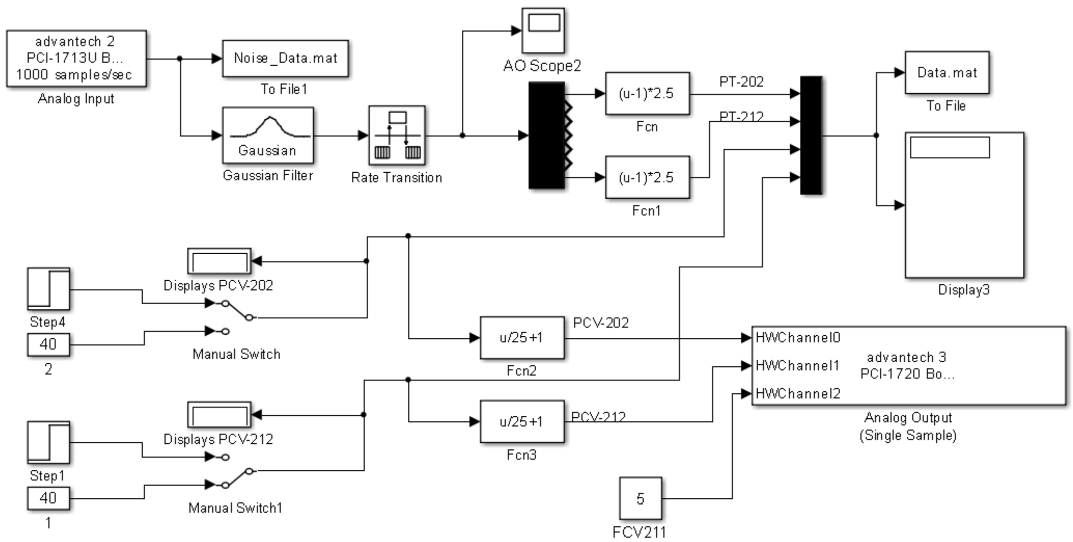
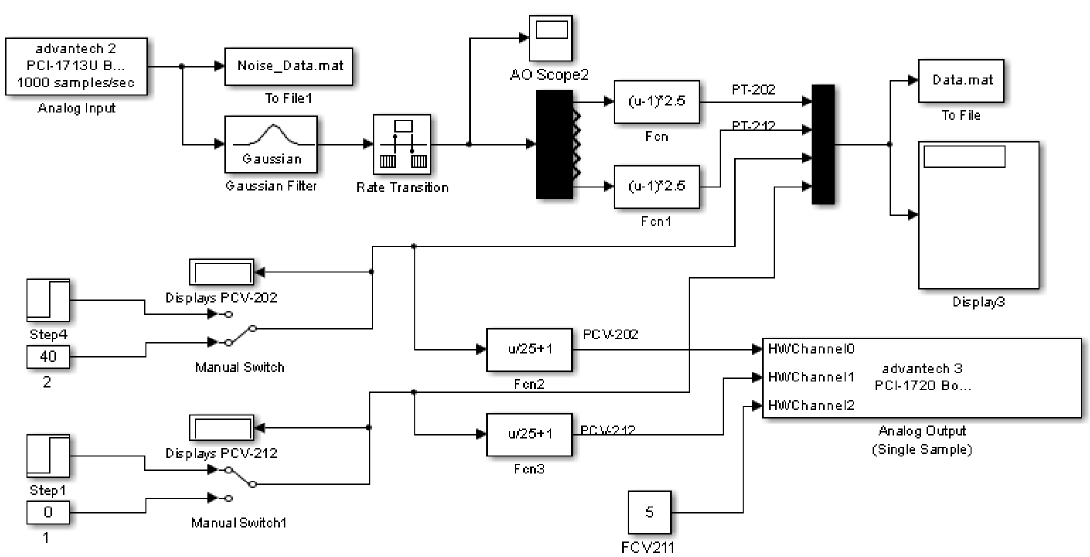
Appendix 1



Open loop test – Experiment 1



Open loop test – Experiment 2

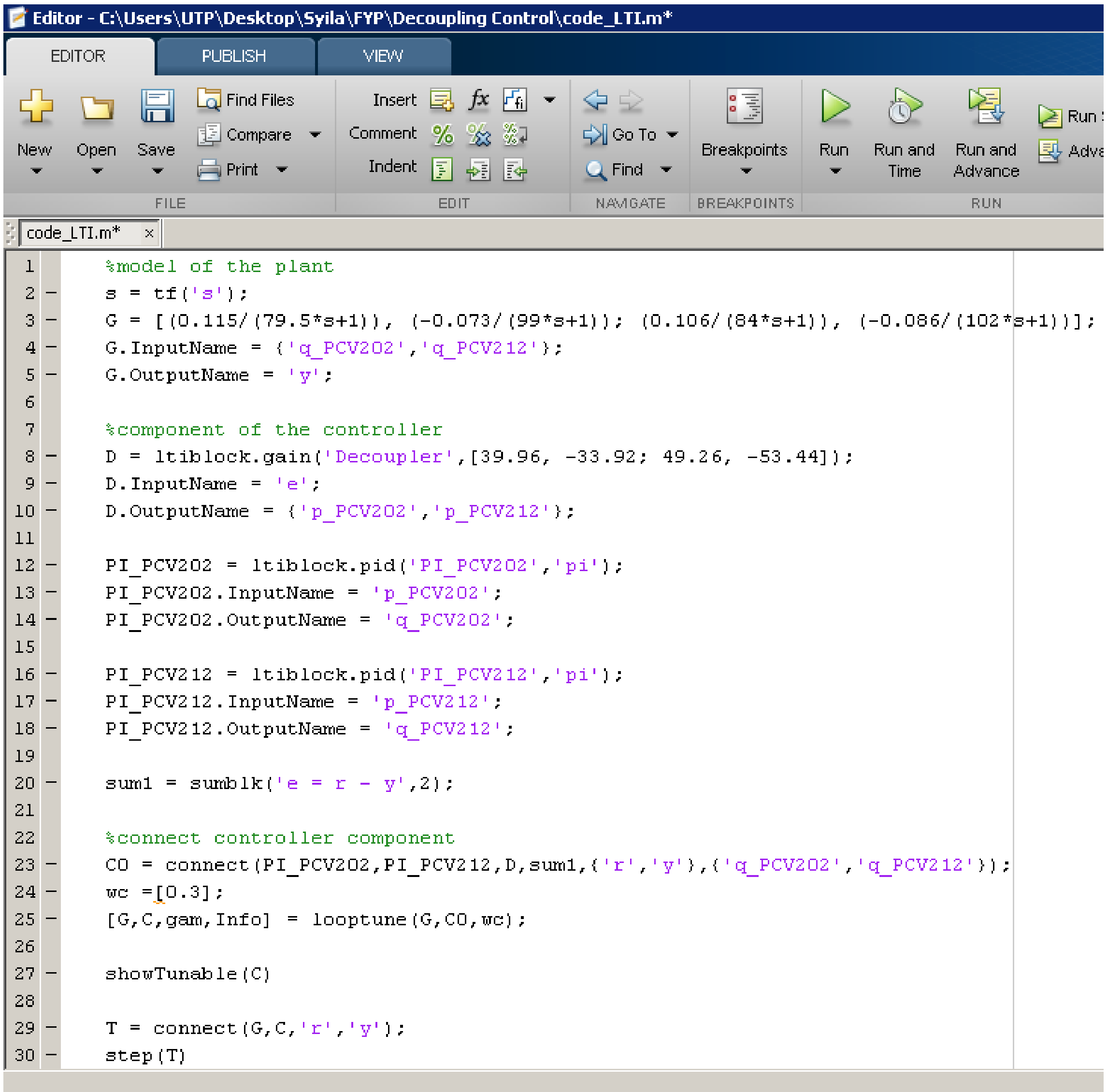
Appendix 2

Singular Value Decomposition and Condition Number

```
>> K=[0.11515, -0.07350; 0.10605, -0.08615];
>> [W,E,V]=svd(K)

W =

   -0.7070   -0.7072
   -0.7072    0.7070


E =

    0.1929         0
         0    0.0110


V =

   -0.8109   -0.5852
    0.5852   -0.8109

>> CN=0.1929/0.0110

CN =

   17.5364

>>
```

Appendix 3

Coding for decoupling matrix and PI controllers using LTI object and Control Design




```matlab
%model of the plant
s = tf('s');
G = [(0.115/(79.5*s+1)), (-0.073/(99*s+1)); (0.106/(84*s+1)), (-0.086/(102*s+1))];
G.InputName = {'q_PCV202','q_PCV212'};
G.OutputName = 'y';

%component of the controller
D = ltiblock.gain('Decoupler',[39.96, -33.92; 49.26, -53.44]);
D.InputName = 'e';
D.OutputName = {'p_PCV202','p_PCV212'};

PI_PCV202 = ltiblock.pid('PI_PCV202','pi');
PI_PCV202.InputName = 'p_PCV202';
PI_PCV202.OutputName = 'q_PCV202';

PI_PCV212 = ltiblock.pid('PI_PCV212','pi');
PI_PCV212.InputName = 'p_PCV212';
PI_PCV212.OutputName = 'q_PCV212';

sum1 = sumblk('e = r - y',2);

%connect controller component
C0 = connect(PI_PCV202,PI_PCV212,D,sum1,{'r','y'},{'q_PCV202','q_PCV212'});
wc =[0.3];
[G,C,gam,Info] = looptune(G,C0,wc);

showTunable(C)

T = connect(G,C,'r','y');
step(T)
```

Result for previous coding.

Command Window

```
>> code_LTI
Final: Peak gain = 0.986, Iterations = 34
Decoupler =

  d =
             u1       u2
   y1     21.47      -18
   y2     33.74      -38

Name: Decoupler
Static gain.
-----------------------------------
PI_PCV202 =

              1
  Kp + Ki * ---
              s

  with Kp = 1.34 , Ki = 0.02346

Name: PI_PCV202
Continuous-time PI controller in parallel form.
-----------------------------------
PI_PCV212 =

              1
  Kp + Ki * ---
              s

  with Kp = 1.64 , Ki = 0.0211

Name: PI_PCV212
Continuous-time PI controller in parallel form.
>>
```