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Experimental Investigation of Control Strategies for Ballast Tank Flow Management in Ocean Vehicles and Floating Structures

Faith Arowosafe[1†], Yogang Singh[1*†], Hajar Razhagi[1]

[1*]School of Engineering and Built Environment, Sheffield Hallam University, Howard Street, Sheffield, S1 1WB, United Kingdom.

*Corresponding author(s). E-mail(s): y.singh@shu.ac.uk;
Contributing authors: arowolayo@gmail.com; h.razhagi@shu.ac.uk;
†These authors contributed equally to this work.

Abstract

Effective ballast water management is critical for maintaining the stability, trim, and structural integrity of ocean vehicles and floating structures under dynamic operating conditions. This paper presents a comparative analysis of Proportional-Integral (PI), Proportional-Integral-Derivative (PID), and Model Predictive Control (MPC) strategies for ballast tank flow management. A dynamic system model capturing the behavior of a ballast tank was developed using an experimental system identification technique. This involved an experimental setup consisting of two interconnected tanks, simulating ship ballast tanks, equipped with a Telemecanique ultrasonic sensor for water level measurement and controlled via a Siemens SIMATIC S7-1200 Programmable Logic Controller (PLC), configured through the Totally Integrated Automation (TIA) Portal. The derived model was then implemented in MATLAB/Simulink for further analysis and validation. The controllers were designed, tuned, and evaluated based on performance metrics, including rise time, settling time, overshoot, and constraint handling. Results demonstrate that while PI and PID controllers provide satisfactory performance in steady-state conditions, their effectiveness diminishes under dynamic and constraint-laden scenarios. Conversely, MPC exhibits superior performance, particularly in managing operational constraints and disturbances, making it a robust candidate for real-time ballast flow control in advanced marine systems. The study underscores the potential of MPC to enhance the stability and operational efficiency of ocean vehicles and floating structures, paving the way for further research into hybrid and adaptive control strategies for ballast management systems.

Keywords: Ballast Tank Control, Model Predictive Control (MPC), PID Control, Ocean Vehicles, Floating Structures, MATLAB/Simulink.

1 Introduction and Literature Survey

Ballast tanks flow control is critical for maintaining a ship's stability and balance during various operations and under challenging conditions like wave-induced loads. Ballast tanks are used to maintain a ship's stability and balance during various operations such as loading, unloading, and navigation. By regulating the water volume in the tanks, vessels can control their buoyancy and trim, thereby ensuring safe and efficient operations [1].Ballast flow control is applied in various marine applications, such as submersible and semi-submersible offshore platforms, unmanned vessels, and Floating Production Storage and Offloading (FPSO) units. The ability of ballast control systems to maintain stability and operational efficiency is essential, playing a critical role in preventing the tilting or capsizing of Revolving Floating Cranes (RFC) [2]. Additionally, the importance of ballast systems in ensuring stability and enhancing safety during operations on offshore platforms are emphasized in [3].

Traditional control strategies, such as Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers, have demonstrated effective accuracy and response in managing ballast systems in marine applications [4, 5]. However, they face challenges in adapting to nonlinearities and external disturbances, limiting their performance under dynamic and complex operating conditions [6]. Model Predictive Control (MPC) has gained prominence as an advanced control technique in marine systems, leveraging its ability to predict future system behavior and optimize control actions. This approach enhances the system's capability to manage multivariable constraints and adapt to external disturbances effectively [7].

1.1 Motivation

A significant challenge in ballast control for marine systems lies in understanding the complex multivariable interactions, as ballast control is often integrated with other subsystems such as propulsion and power management. Ensuring real-time responsiveness while maintaining computational efficiency highlights the need for experimental exploration of advanced control strategies in terms of rise time, settling time, overshoot, and constraint handling. This has motivated the current study, which presents a comparative analysis of PI, PID, and MPC strategies for ballast tank flow management.

2 Experimental Setup and System Identification

2.1 Tank setup

The experimental setup comprises a two-tank system, where water is circulated between a lower reservoir tank and an upper ballast tank, as illustrated in Fig.2.1.

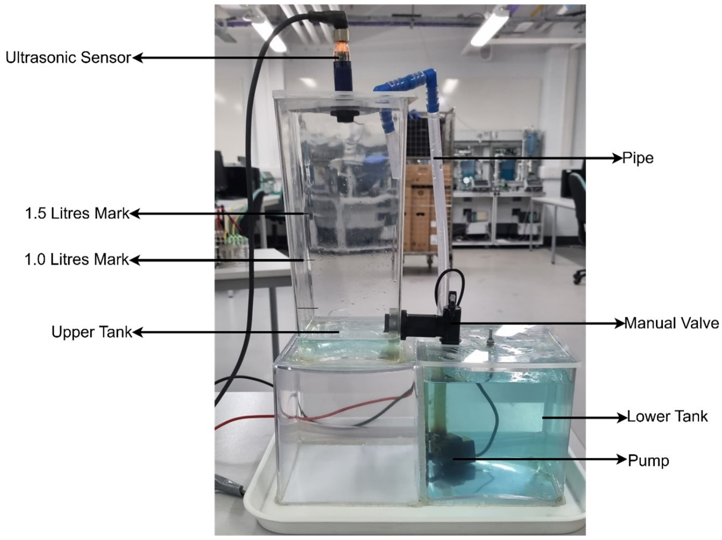

Fig. 1 Experimental tank setup featuring tanks, an ultrasonic sensor, a manual valve, and a pump. The system is used for collecting experimental data for system identification and PLC implementation.

Water is pumped from the reservoir to the ballast tank using a DC pump located in the lower tank. The upper tank is equipped with an ultrasonic sensor mounted on the lid, which continuously monitors the water level. Additionally, a manual tap is installed in the upper tank, allowing controlled outflow back to the reservoir, with a maximum capacity of 1.5 liters. The ultrasonic sensor transmits real-time data to the PLC, which processes the signal and dynamically adjusts the pump's flow rate based on the selected control strategy (PI, PID, or MPC).

2.2 Hardware

The tank model comprises various hardware components, with the experimental setup shown in Fig.2.1 as follows:

2.2.1 Pump

The system uses a 12V DC brushless submersible pump as shown in Fig.2 (a) with 240 litres per hour of maximum flow rate. It is made of ABS material and supports various liquids, including water, oil, and acids. With an IP68 waterproof rating, the brushless motor ensures quiet operation (¡35 dB) and functions within a temperature range of 0°C to 60°C [7].

2.2.2 Ultrasonic Sensor

The system employs a Telemecanique XX918A3F1M12 ultrasonic sensor, as shown in Fig.2 (b) operating at 12-24 VDC with a 0.051–0.508 m sensing range and a 0–10V analogue output. It features a plastic body, an epoxy front, and a Valox enclosure [8].

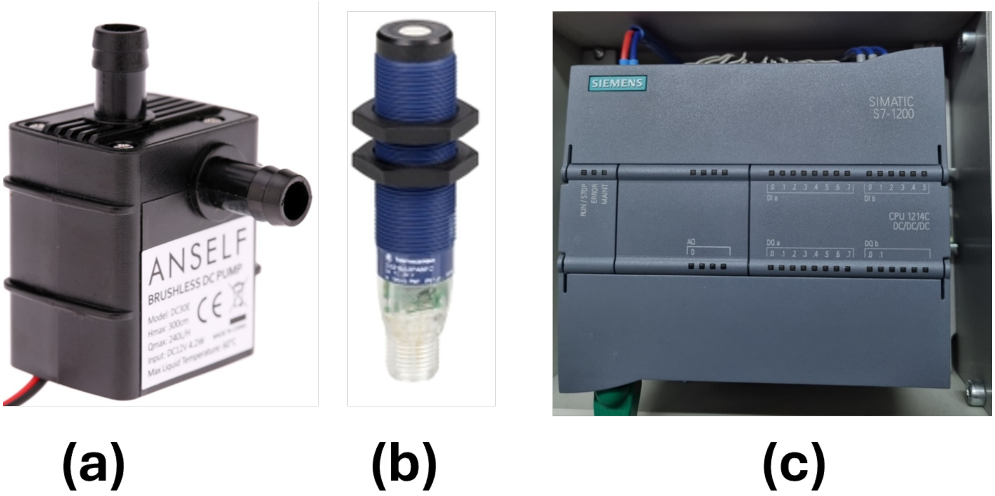

Fig. 2 Hardware components: (a) ANSELF Brushless DC pump (b) Ultrasonic sensor (c) Siemens S7-1200 PLC

2.2.3 PLC

A Siemens SIMATIC S7-1200 PLC (CPU 1214C, 6ES7214-1AG40-0XB0) as shown in Fig.2 (c) controls the experimental tank setup, offering a 24V DC supply, 14 digital inputs, 10 digital outputs (24V DC), and 2 analog inputs (0-10V). It was selected for its modularity and efficient monitoring through integrated software.

For data collection, the system was powered on with all inputs and outputs connected. The ultrasonic sensor's signal wire was linked to the PLC's analog input, while the pump's signal wire was connected to the analog output. A simple PLC program was created to activate the analog output when a high signal was sent and was then downloaded using the Ethernet/IP protocol. Upon sending a high signal, the pump activated, allowing water inflow into the main tank. The analog input (tank water level) and analog output (pump flow rate) were monitored over time using the TIA Portal's "Trace" feature. The trace graph was exported as a .csv file and imported into MATLAB, yielding 282 data samples.

2.3 System Identification

The system identification process aims to analyse the dynamic behaviour of the experimental tank setup by evaluating the pump input voltage and water tank level data using *MATLAB/Simulink System Identification Toolbox*. To mitigate uncertainties arising from sensor noise, the input data were pre-processed to filter out noise. Fig.3 presents the system identification process in block diagram form.

The experimental data was imported as a time domain into the system identification application on MATLAB with a start time of 0s and a sample time of 0.1s. The

Fig. 3 System Identification Block Diagram

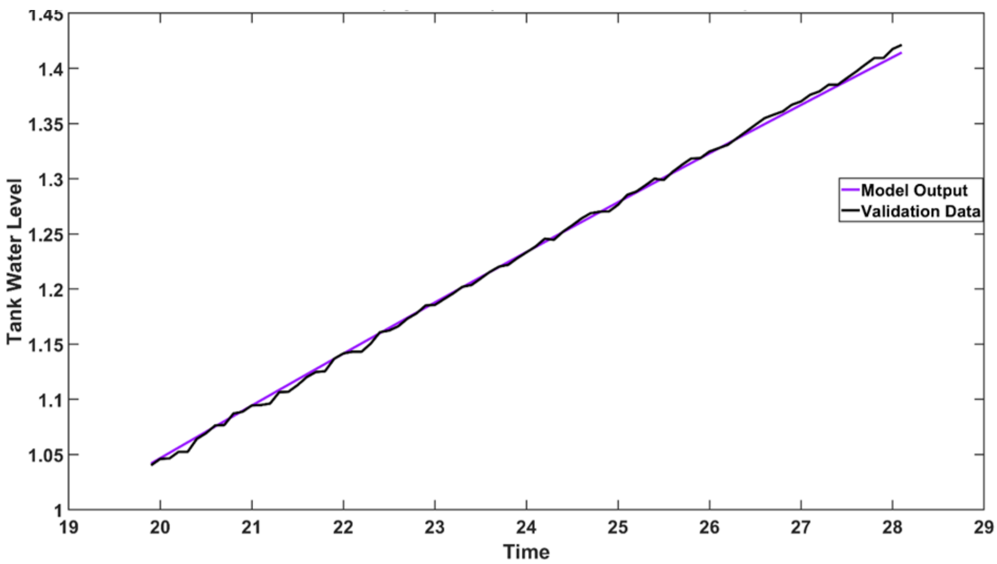

Fig. 4 Validation data against the model output derived from System Identification

data used for the system estimate was divided into evaluation and validation data sets by preprocessing the data. The data had a total of 282 samples, with 200 used for evaluation and 82 used for validation. A non-linear least square estimation with an automatically chosen line algorithm method was applied to compute the resultant transfer function as $G(s)$:

$$G(s) = \frac{0.006288}{s + 0.01417} \tag{1}$$

with a 97.28% fit between model output and validation data set as shown in Fig.4 with the complete process shown in Fig.5

2.4 Methodology

The methodology used for designing, implementing and analysing the flow control system using different control strategies has been shown in Fig.6

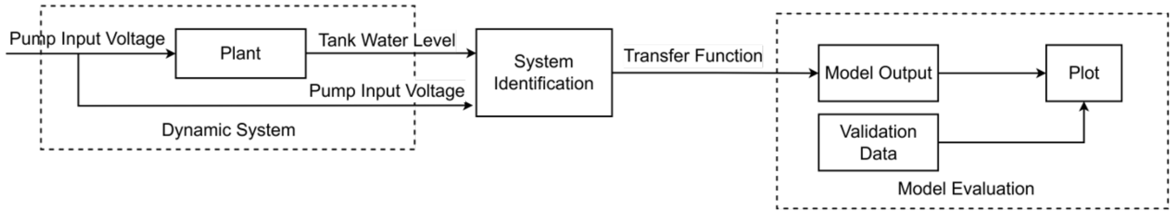

Fig. 5 System Identification process

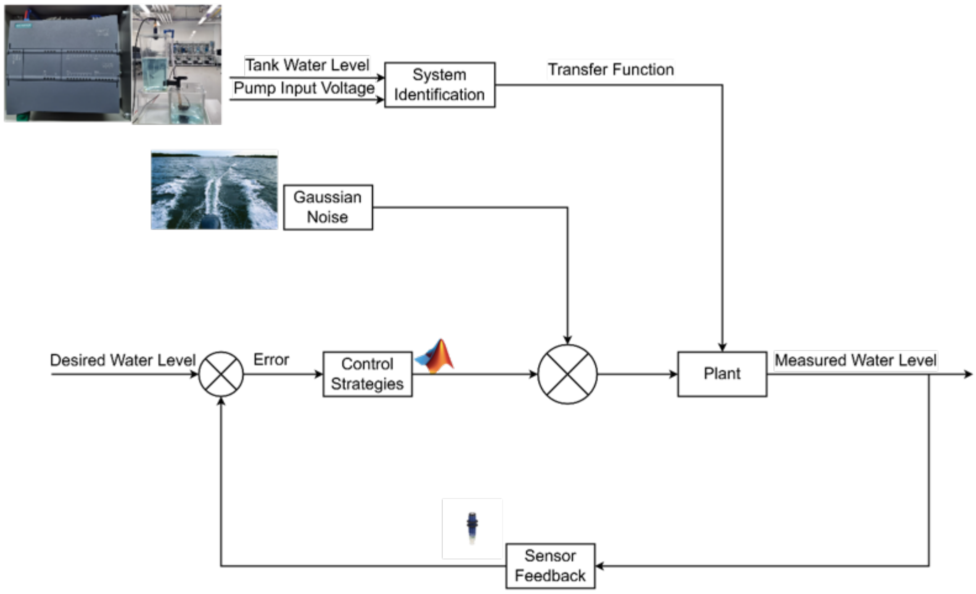

Fig. 6 Methodology for flow control system design

This study compares the design and analysis of PI, PID, and MPC controllers in Simulink to identify the most suitable option for the experimental setup as shown in Fig.7 in terms of rise time, settling time and overshoot %. In the Simulink design, the controllers were individually connected to the plant model as a continuous transfer function. For the PI and PID controllers, the input was the difference between the reference signal and the controller's output, providing feedback to the controller. For the MPC controller, the reference input was connected to the reference signal, the plant output was linked to the measured output signal, and the manipulated variable was connected to the plant's input.

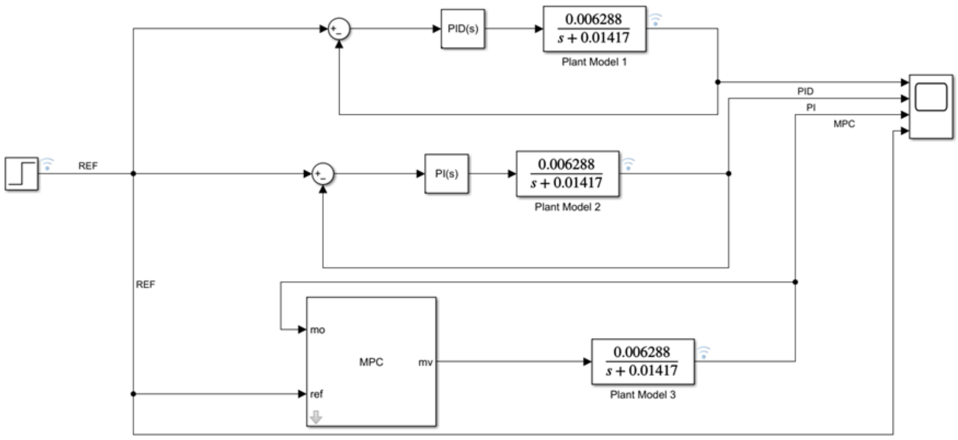

Fig. 7 Simulink controller design

Table 1 PI and PID parameters

Controller	PI	PID
K_P	235	101
K_I	3.5	1.5
K_D	-	2.03

2.4.1 Controllers Tuning

For the PI and PID controllers, the initial tuning was performed using MATLAB's automatic PID tuning tool, followed by manual tuning to achieve the desired performance. The final parameters for the controller have been tabulated in Table1. For MPC, tuning involved defining prediction and control horizons, with constraints applied to maintain water levels between 0 and 2. The final MPC parameters were: NP: 10, NC: 2, Ts: 0.1s.

2.5 Results and Discussion

The simulation involved setting a reference tank level of 1.5L, and the controllers' response over 50 seconds was obtained as shown in Fig.8.

To test the constraint handling capacity of the MPC controller, a reference tank level of 2.5L was set, and the resultant plot can be seen in Fig.9.

The results indicate that the MPC controller outperforms the others, achieving the fastest rise time (0.8s) and settling time (2.5s) with no overshoot, while effectively maintaining water levels within constraints, making it ideal for real-time ballast adjustments in dynamic conditions. The PI controller demonstrated moderate performance with a rise time of 1.5s and no overshoot, making it suitable for steady-state operations but lacking effective constraint handling. In contrast, the PID controller exhibited the

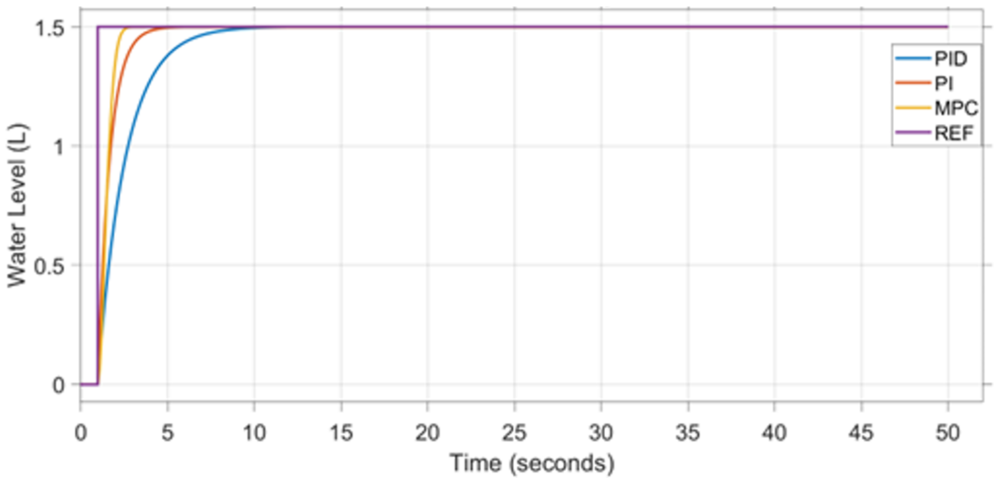

Fig. 8 Controller Responses

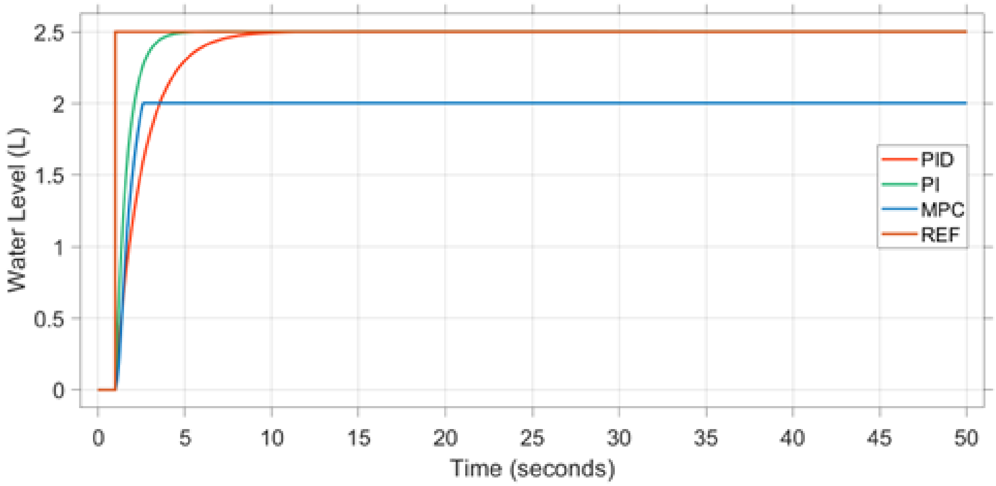

Fig. 9 Constraint handling

slowest response, with a rise time of 3.5s and minimal overshoot (0.03%), limiting its suitability for complex ballast systems due to its inability to manage constraints effectively. A summary of each controller's performance based on the performance metrics is presented in Table2.

2.6 Acknowledgement

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Table 2 Summary of performance

Control Strategy	Rise Time (s)	Settling Time (s)	Overshoot (%)
PI	1.5	3.9	0
PID	3.5	7.9	0.0326
MPC	0.8	2.5	0

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