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A STUDY ON MODEL-FREE APPROACH FOR LIQUID SLOSH SUPPRESSION BASED ON STOCHASTIC APPROXIMATION

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Abstract

Recently, with the rapid growth in science and engineering, most of the real world process plants have been built on a large scale and complex systems. As a consequence, modeling of such systems may become very difficult and require a lot of effort. Therefore, it is necessary to develop a control method that does not depend on plant models, which is known as the model-free control approach. At the same time, it is also worthy to consider an optimization tool for the model-free approach that is simple to understand for engineers and can optimize a large number of control parameters in a fast manner. So far, there have not been enough literatures to discuss the application of model-free control schemes for the above demands.

Motivated by the above background, a model-free control scheme is considered in our study. Here, a Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm is suggested as a promising tool for the model-free control approach. Then, this research report focuses on assessing the effectiveness of the SPSA-based algorithm for model-free proportional-integral-derivative (PID) control tuning in liquid slosh problems. Slosh or oscillation of liquid inside a container often occurs in many cases, such as, vehicles or ships with liquid cargo carriers, molten metal industries, which is dangerous to handle by the operator. Moreover, sloshing of fuel and other liquids in moving vehicles may cause instability and rollover of the vehicle. For the past decades, various control strategies of liquid slosh motion are based on model-based control schemes. Nevertheless, these methods are difficult to apply in practice. The main reason is that their control schemes do not accurately consider the chaotic behaviour of slosh and the complex fluid dynamic motion in the container. Therefore, a model-free approach will be more attractive.

In this research project, we propose a model-free PID controller design based on Simultaneous Perturbation Stochastic Approximation for controlling liquid slosh. The effectiveness of the proposed model-free PID based SPSA is evaluated in terms of liquid slosh reduction, tracking performance, and computation time. In addition, the performance of the SPSA based methods is compared to the other stochastic optimization based approaches, which also includes the variants of SPSA based method, such as Global SPSA. In this study, a real experimental rig of liquid slosh plant is considered to validate the effectiveness of our proposed scheme. In particular, we develop our own liquid slosh model from the input-output data of real plant through the system identification method. Then, the proposed model-free PID based SPSA is applied to the developed model. The outcome of this study has shown that the SPSA based methods, especially the GSPSA based method, are successfully produced better control performances as compared with other stochastic methods. In particular, the proposed model-free PID scheme can produce slightly minimum liquid slosh motion while maintain the input tracking of the trolley position.

Abstrak

Sejak akhir-akhir ini, dengan perkembangan pesat sains dan kejuruteraan, kebanyakan sistem proses dunia sebenar dibina dalam skala yang besar dan kompleks. Akibatnya, pembinaan model system tersebut mungkin akan lebih sukar dan akan mengambil usaha yang lebih untuk disiapkan. Oleh itu, adalah menjadi keperluan untuk membangunkan kaedah kawalan yang tidak bergantung pada model system yang terkenal sebagai kaedah kawalan bebas model. Pada masa yang sama, adalah berbaloi untuk mengenalpasti kaedah pengoptimuman untuk kaedah kawalan bebas model yang mudah difahami oleh juutera-jurutera dan boleh menoptimumkan bilangan parameter kawalan yang banyak dalam masa yang pantas. Setakat ini, masih kurang lagi literatur yang membincangkan aplikasi kaedah kawalan bebas model untuk keperluan di atas.

Bermotivasi dari latar belakang di atas, satu skim kawalan bebas model telah dikenalpasti dalam kajian kami. Di sini, algoritma pengganggaran rawak gangguan serentak telah dicadangkan sebagai alat pengoptimuman yang terbaik untuk skm kawalan bebas model. Seterusnya, kajian ini lebih berfokus kepada penilaian keberkesanan algoritma pengganggaran rawak gangguan serentak untuk penalaan kawalan perkadaran-pengkamiran-pembezaan (PID) bebas model dalam masalah kocakan cecair. Kocakan ataupun getaran cecair dalam kontena selalunya berlaku dalam banyak situasi, iaitu, kenderaan atau kapal yang membawa muatan cecair, industri cairan besi, yang mana berbahaya kepada pengendali ataupun pekerja. Tambahan pula, kocakan cecair minyak dan cecair lain dalam kenderaan bergerak boleh menyebabkan ketidakstabilan dan menterbalikkan kenderaan tersebut. Sepanjang beberapa dekan yang lepas, pelbagai strategi kawalan kocakan cecair adalah berdasarkan skim kawalan berasaskan model. Walaubagaimanapun, kaedah-kaedah ini adalah sebenarnya sukar diaplikasi untuk sistem sebenar. Justifikasi utama adalah kerana skim kawalan mereka tidak secara tepat mengenalpasti ciri-ciri sebenar kocakan air dan kerumitan pergerakan dinamik cecair tersebut didalam kontena. Oleh itu, kaedah kawalan bebas model adalah sangat menarik untuk dicuba.

Dalam kajian ini, kami mencadangkan satu kawalan PID bebas model berasaskan

pengganggaran rawak gangguan serentak untuk mengawal kocakan cecair. Keberkesanan cadangan kaedah kawalan PID bebas model berasaskan SPSA dinilai dari segi pengurangan kocakan cecair, prestasi penjejakan dan masa komputasi. Sebagai tambahan, prestasi kaedah berasaskan SPSA dibandingkan dengan kaedah berasaskan pengoptimuman yang lain, yang mana termasuk juga variasi SPSA seperti Global SPSA. Dalam kajian ini, peralatan eksperimen sebenar kocakan cecair telah digunakan untuk menentusahkan keberkesanan kaedah yang dicadangkan. Secara terperinci lagi, kami telah membangunkan model kocakan cecair bderdasarkan data input dan output daripada system sebenar melalui kaedah sistem pengecaman. Seterusnya, kaedah kawalan PID berasaskan SPSA diaplikasi terhadapa model yangtelah dibangunkan. Hasil daripada kajian telah menunjukkan bahawa kaedah-kaedah berasaskan SPSA, terutamanya kaedah berasaskan GSPSA, telah Berjaya menghasilkan kawalan prestasi yang lebih baik berbanding kaedah yang lain. Secara lebih jelas, cadangan skim kawalan PID bebas model boleh menghasilkan kocakan cecair yang minimum dan dalam masa yang sama mengekalkan penjejakan posisi troli yang membawa cecair tersebut.

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Symbols and Definitions

In this report, we use the following symbols and definitions. The symbols $\mathbb{R}$ and $\mathbb{R}_+$ represent the set of real numbers and the set of positive real numbers, respectively. The symbol $\mathbb{S}^{n\times n}$ denotes the set $n\times n$ positive definite matrices. The cardinality of set $\boldsymbol{S}$ is denoted by $|\boldsymbol{S}|$. The vector whose elements are one is denoted by $\mathbf{1}$. For the vector $\boldsymbol{\theta}$, we use $\|\boldsymbol{\theta}\|$ to express the standard Euclidean norm. For the random variable V, the probability of event $V = a$ is represented by $\mathbb{P}(V = a)$. The expectation of the random variable b is denoted by $\mathbb{E}(b)$. For $\delta \in \mathbb{R}_+, \mathrm{sat}_\delta : \mathbb{R}^n \to \mathbb{R}^n$ denotes the saturation function whose i-th element given as follows:

$$\text{The } i\text{-th element of } \mathrm{sat}_\delta(\boldsymbol{\theta}) = \begin{cases} \delta & \text{if } \quad \delta < \theta_i \\ \theta_i & \text{if } \quad -\delta \le \theta_i \le \delta \\ -\delta & \text{if } \quad \theta_i < -\delta \end{cases}$$

where $\boldsymbol{\theta} \in \mathbb{R}^n$ and $\theta_i \in \mathbb{R}$ is the i-the element of $\boldsymbol{\theta}$.

Chapter 1

Introduction

1.1 Background and Research Motivation

1.1.1 What is model-free controller design?

Model-free controller design is to find a controller using the input-output (I/O) data of the systems, which are controlled tentatively, but without using explicit or implicit information of the plants such that the performance of the control objective is achieved. The conceptual structure of the model-free controller is described in Figure1.1. For example, the control objective is evaluated in terms of the minimization of the measured error and input of the controlled system, and minimization or maximization of the measured output (e.g., minimization of the fuel consumption, maximization of the power production). The control performance value of the given evaluation period is then used by the optimization tool to obtain an updated tuning value for the controller at the next iteration. This tuning process is iteratively performed until the final iteration.

The significant feature of this method is that both controller design and control system analysis are simultaneously performed based on the measured I/O data. In addition, since the controller is designed without using the plant model, this method can directly handle a large class of plants (possibly nonlinear) as long as the required measurement data is available.

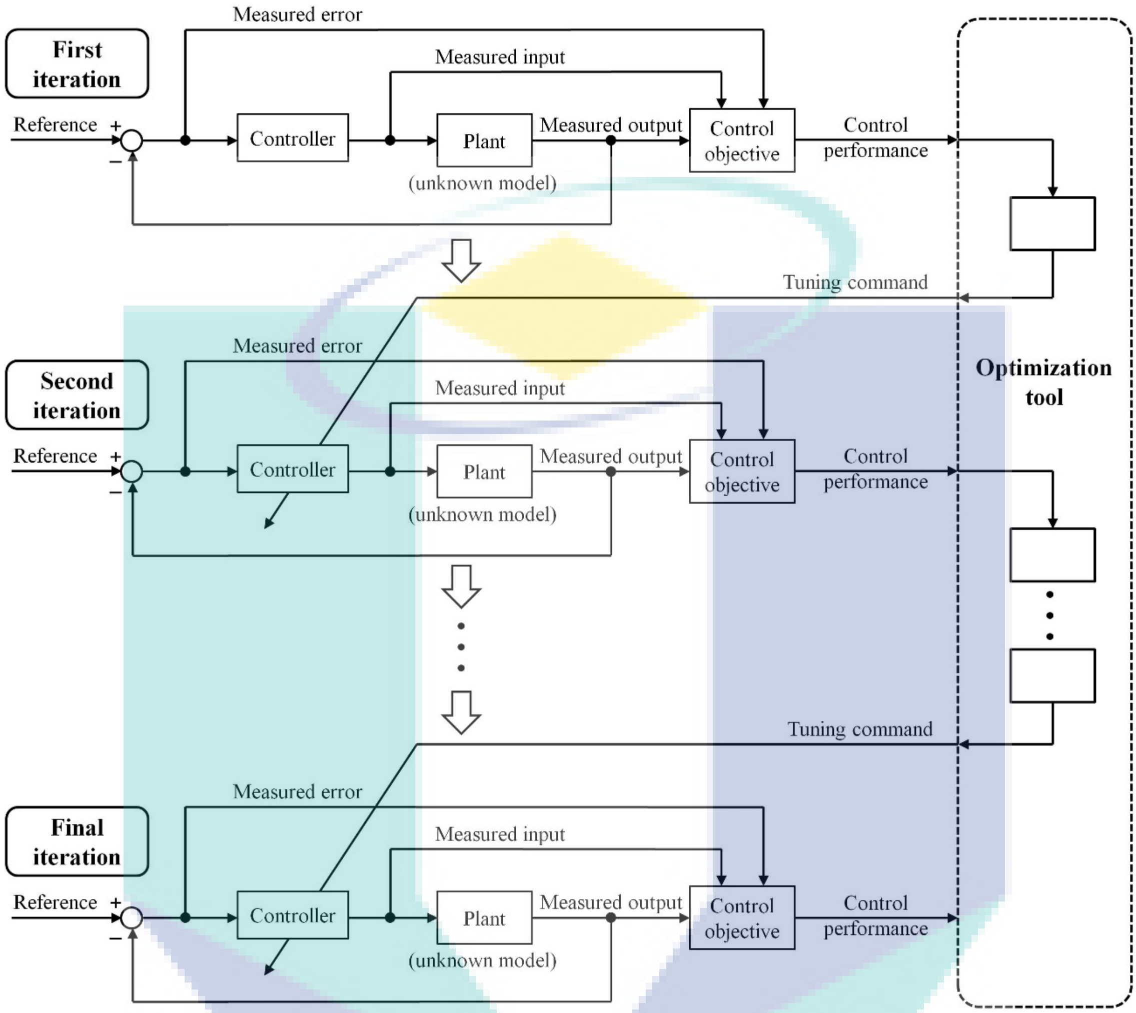

Figure 1.1: Model-free controller structure

1.1.2 Why model-free controller design?

The motivation and necessity of model-free controller design have been discussed in many literatures from the aspects of theory and applications. The main reasons for implementing this approach are summarized as follows:

(i) Independence of the plant models:

Today, with the rapid development of science and technology, practical plants in various fields, such as in the chemical industry, machinery, electronics, electricity, transportation and logistics, have grown up to a large-scale production and the processes have become more complex. As a result, modeling of the plants using first principles or system identification may become more difficult. Even if it is possible to develop such models, it may consume a lot of time and require a significant amount of effort. Therefore, the model-free control scheme is useful to overcome this situation, since this scheme does not explicitly include any parts or the whole of plant models.

(ii) No gap between control theory and real application:
The model-free controller design has overcome the unmodeled dynamics problem in the traditional model-based controller design, which may require a robust control framework. In other words, its control performance does not depend on the accuracy of the model. Finally, a huge gap between the control theory and real application vanishes, since the model-free controller design directly measures I/O data in real time from actual process plants.

(iii) Practical controller design:
From the perspective of practical applications, most of the industrial processes require low-cost and easy-to-install control algorithms. In other words, most of the engineers try to avoid complex mathematics and identification theory (which is the heart of the traditional model-based controller design),since it is hard to understand and requires additional effort and time. Therefore, a model-free control scheme, which requires less complexity, contributes great practical demands.

From the above reasons, model-free controller design is useful and it has become one of the important topics to be explored in both theory and applications.

1.1.3 Liquid Slosh Control Problem

Nowadays, slosh or oscillation of liquid inside a container often occurs in many cases. For example, ships with liquid cargo carriers are at high risk of generating sloshing load during operation [1]. In the metal industries, high oscillation can spill molten metal, which is dangerous to handle by the operator [2]. Meanwhile, sloshing of fuel and other liquids in moving vehicles may cause instability and undesired dynamics [3]. Hence, it is necessary to suppress this residual slosh induced by the container motion.

So far, various attempts in suppressing slosh are based on open-loop and closed-loop approaches. For example, input shaping scheme [4], [5] and some filtering techniques [6], [7] are used to generate a prescribed motion, which minimized the residual oscillation. These methods are able to reduce the slosh without needs for feedback sensors. However, these strategies are very poor in handling with any disturbances. On the other hand, closed-loop control or feedback control, which is well known to be less sensitive to disturbances and parameter variations, has also been adopted for reducing slosh. These include PID control [8], H_∞ control [9], sliding mode control [10] and iterative learning control (ILC) [11].

As shown in the above, many approaches use model-based control strategies, which are difficult to apply in practice. This is because their control schemes do not accurately consider the chaotic nature of slosh and the complex fluid dynamic motion in the container. Therefore, a model-free approach will be more attractive. On the other hand, a simultaneous perturbation stochastic approximation (SPSA) would provide us a promising tool for model-free approach. This is because the SPSA method is known to be effective for a variety of model-free optimization problems even for high-dimensional parameter tuning [12], [13]. However, it is not clear whether it works for liquid slosh problems, since there are few literatures to discuss the application of the SPSA to the problems.

1.2 Research Objectives

The objective of this project is given as follows:

(i) To develop a model-free controller framework based on simultaneous perturbation stochastic approximation (SPSA) for liquid slosh problem

(ii) To study and analyze the performance of model-free PID controller tuning based SPSA in terms of level of slosh suppression, point-to-point tracking capability and speed of the cart response.

1.3 Scope of Project

In order to evaluate the performance of the model-free approach, an experimental rig is considered, which consists of a small motor-driven liquid tank performing rectilinear motion as shown in Figure 1.2. Moreover, several multi-fluidic sensors are considered to precisely measure the displacement of the liquid surface. Here, the model-free design is used to tune a given controller (PI, PD or PID) such that the liquid slosh is minimized, while achieving desired cart position. Then, the performance of the proposed method is assessed in terms of level of slosh reduction in time and frequency domains, point-to-point tracking capability, speed of the cart response, and computational complexity. Here, the Matlab and Lab view software were used in the simulation and experimental works.

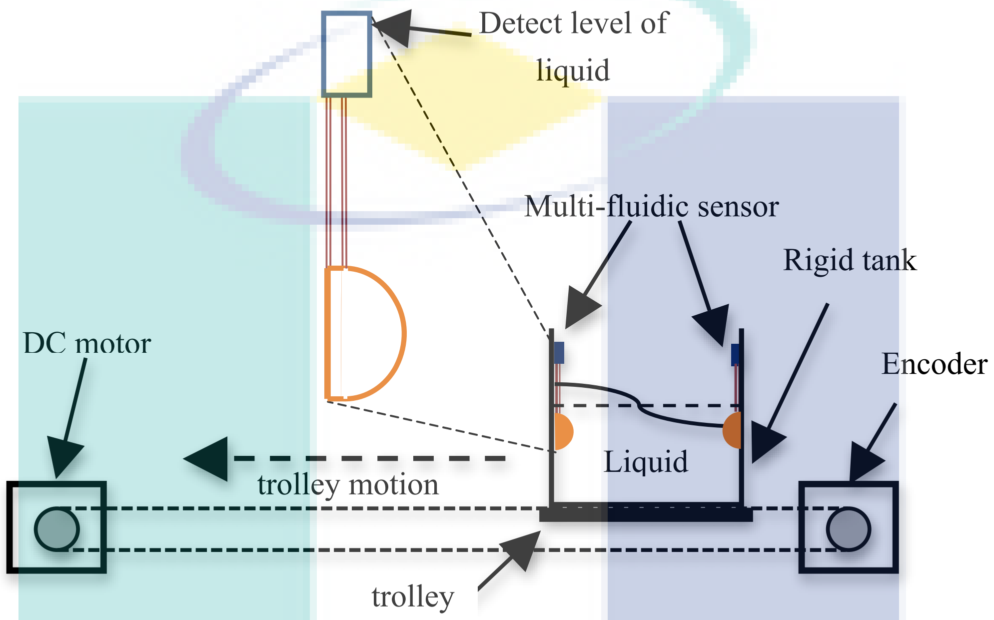

Figure 1.2: Diagram of motor-driven liquid tank system

1.4 Organization of Report

This report is organized as follows.

Chapter 2 describes a literature survey on recent tools in model-free controller framework. These include the population and trajectory based optimization. Then, we also discussed the existing control schemes for liquid slosh problem, which are monopoly by the model-based control schemes. In addition, we also highlight the motivation of using model-free control framework based on SPSA algorithm.

In Chapter 3, a general framework of the model-free controller design by standard simultaneous perturbation stochastic approximation is presented. A step-by-step procedure of the SPSA algorithm is shown. This is followed by illustrative examples to indicate the effectiveness of the SPSA algorithm. Then, we show how to implement the standard SPSA algorithm for a model-free design controller based on a general control objective function. In the next sub section, the problem formulation of PID control for liquid slosh plant is presented. This is followed by the procedure of model-free PID controller design based on SPSA for liquid slosh problem.

Chapter 4 presents a performance analysis of SPSA-based algorithm for model-free PID tuning of liquid slosh systems. Their performances are evaluated in terms of the liquid slosh reduction, tracking performance, and computation time. Furthermore, the performance comparison with other stochastic optimization-based approaches is also considered.

Chapter 5 concludes this report.

Chapter 2

Literature Review

2.1 Review on tools for model-free controller design

The fundamental essence of the model-free controller design concerns data-based optimization tools to determine the optimal controller. So far, there exist a large number of data-based optimization methods. In general, they can be divided into two classes of optimization methods:- multi-agent-based optimization and single-agent-based optimization.

The multi-agent-based optimization methods include particle swarm optimization [14], artificial bee colony [15], ant colony optimization [16], bacterial foraging [17], genetic algorithm [18], differential evolution [19], artificial immune system [20], and spiral optimization [21]. These optimization methods, which are also called population-based searches, normally employ a huge number of agents over a large set of feasible solutions. Then, these agents will interact with one another through some specific mechanism and try to improve multiple candidate solutions. However, these methods perform well only for a small number of design parameters, which is no more than 10. In order to handle a large number of design parameters, a cooperative version of them has been introduced, e.g., cooperative co-evolutionary [22], cooperative particle swarm optimization [23], cooperative genetic algorithm [24], and cooperative artificial bee colony [25]. Most of these optimization methods are commonly invented by the computer science community and they have tested their algorithms on artificial benchmark problems, e.g., Rosenbrock, Rastrigin, Griewank, Schaffer and Sphere functions. Therefore, the effectiveness of their optimization methods in the actual control problems is not clear.

Recently, there have also been literatures that use these population-based searches for model-free controller design such as in tuning the controller for robotic systems [26-29], industrial and automation plant [30-33], renewable energy plant [34-36], and transportation systems [37-39]. However, these optimization tools require heavy computation time to achieve convergence due to the number of evaluated objective functions per iteration being proportional to the number of agents. Thus, a tool that requires less computation time is needed.

Meanwhile, the single-agent-based algorithms, which are also called single solution searches, include random search [40], variable neighborhood search [41], simulated annealing [42], stochastic gradient [43], Tabu search [44,45], simultaneous perturbation stochastic approximation (SPSA) [46], smoothed functional algorithm [47], iterated local search [48], and greedy randomized adaptive search procedure [49]. These approaches concentrate on modifying and improving a single candidate solution based on the random perturbation of its design parameter elements. Therefore, they require less computation time in their design process than the multi-agent-based searches. As a result, these optimization methods would be an attractive tool for the model-free controller design.

Recent applications of these methods in the model-free control scheme mostly include the tuning of the parameters in the classical PID controller and intelligent controllers such as fuzzy logics and neural networks. For example, a simulated annealing has been used for the PID tuning in a multi-objective optimization problem. Their method has been evaluated in a super-maneuverable fighter aircraft system [50]. A Tabu search for tuning the PID controller in a simple process plant has been introduced by [51]. Similar work has also been reported in [52] by performing a comparison with Ziegler-Nichols, genetic algorithm and differential evolution methods. In [53,54], a model-free PID tuning based on the SPSA method has been presented. For example, in [54], the SPSA method has been embedded in a field-programmable gate array (FPGA) for online PID tuning. Meanwhile, for the fuzzy logic controller case, a Tabu search has been used in tuning the fuzzy rules [55] and membership functions [56]. In [57], a simulated annealing is used fortuning the input scaling factor of fuzzy membership functions, and has been tested on a drilling force plant. The similar tuning strategy has been reported in [58] by using the SPSA method for a three-dimensional fuzzy logic controller. On the other hand, in the neural network controller case, the SPSA algorithm is used to tune a large number of neurons of the neural network controller with applications in a water treatment plant [59, 60] and trajectory tracking of a two-link robot [61]. However, most of the presented work only considers a small number of the control design parameters, except for a few results in [59-61]. Therefore, it is necessary to investigate the effectiveness of these methods in optimizing high-dimensional control design parameters.

2.2 Motivation of using SPSA as a tool for model-free controller design

The simultaneous perturbation stochastic approximation is a highly efficient algorithm that approximates the gradient based on only a small number of measurements of the objective function. In particular, the flow diagram of the SPSA algorithm is illustrated in Figure 2.1. Based on the selected SPSA coefficients, each element of the current design parameter is perturbed in random directions to obtain two design parameter vectors. Then, the objective function of each perturbed vector is measured. Furthermore, the gradient approximation is obtained from these measured objective functions. Finally, the design parameter is updated based on this gradient approximation until the termination criterion is satisfied. As a result, the updated design parameter always has an opportunity to find a good trajectory direction towards a local optimal solution.

In this study, we use the SPSA method as a tool for model-free controller design. The motivation of utilizing the SPSA method is stated as follows. Firstly, the searching mechanism of this algorithm is easy to implement, especially in real time control applications. This is because its pseudo-code only involves several instructions, which is comfortable to execute by engineers or programmers. Also, the algorithm requires a smaller number of coefficients that need to be specified, and there are some guidelines providing insight into how to select these coefficients in practical applications. Secondly, it exhibits less computation time, since only two measurements of the objective function are required per iteration to update the design parameter. Thirdly, the SPSA algorithm is suitable to solve a high-dimensional optimization problem. This is because the gradient approximation is only based on the measured objective functions, which are independent of the dimension of the design parameter. Note that this gradient approximation is very efficient, since we do not need to perform a brute-force search that enumerates all possible candidates from various combinations of elements to obtain the solution. Moreover, based on the same reason, this algorithm is useful when it is very costly or impossible to directly measure the gradient of the objective function. In other words, it does not require any explicit form of the objective function. From the above motivations, the SPSA algorithm can be a promising tool for model-free controller design.

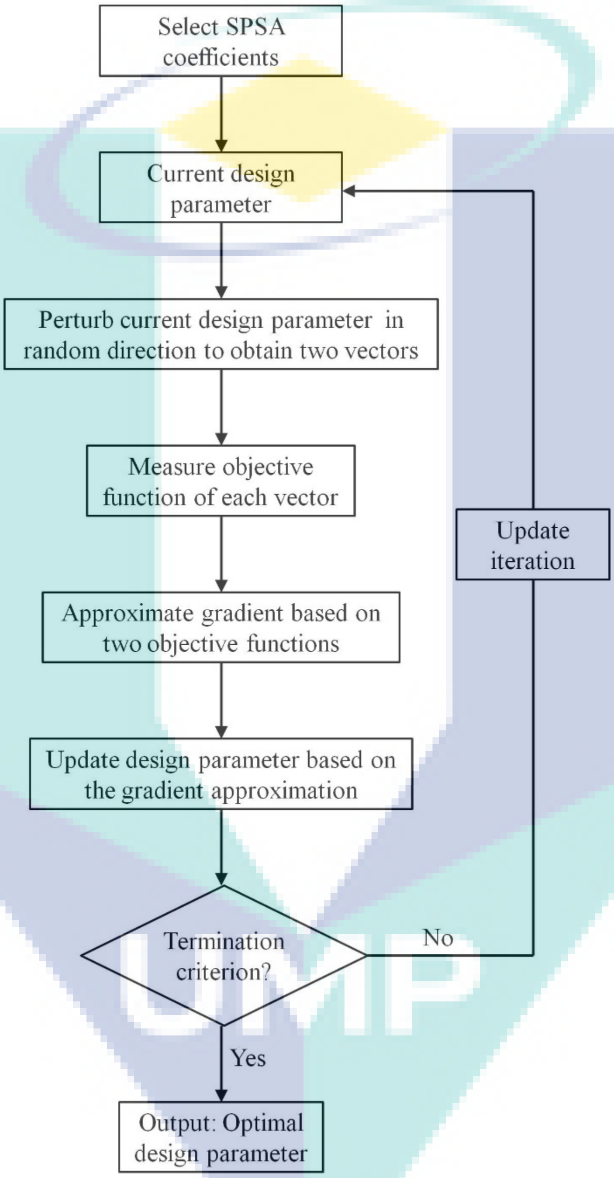

Figure 2.1: General flow of SPSA algorithm

Simultaneous perturbation stochastic approximation (SPSA) is a method to optimize the design parameters such that a pre-specified objective function is minimized or maximized. The fundamental theory of SPSA was introduced by James C. Spall from John Hopkins University in 1992 [46]. This algorithm is efficient in high-dimensional problems, providing a good solution for a relatively small number of measurements of the objective function. In the last two decades, the SPSA has been applied to numerous applications such as queuing systems, industrial quality improvement, aircraft design, pattern recognition, air traffic management, sensor placement, parameter estimation, and fault detection.

2.3 Reviews on Control Schemes for Liquid Slosh Plant

Recently, liquid slosh problems have received a great deal of attention due to their safety issue in vehicle transportations and numerous number of applications in various industries. However, controlling such systems still faces numerous challenges that need to be addressed. The control strategies for liquid slosh reduction can be cluster into two main parts, which are mechanical design part and control design part. In mechanical design part, the researchers are interested to improve the whole mechanical structure of tank or vehicle to reduce liquid slosh motion. For example, they may propose different shape of tank or introduce some kinds of damper inside the tank. Meanwhile, in the control design part, they are interested in developing an efficient control algorithm to suppress the slosh. For such a case, they must clearly observe the slosh behaviour through available sensors to detect the slosh. Perhaps, the sensor design for detecting slosh also become very interesting topics to be discovered.

Research on improving the mechanical design of tank or carrier has started earlier than the control design part. It is started from 1960 by Budiansky [62], which is the first researcher studies on the liquid slosh impact on the circular canal and spherical tanks. Other earlier works are reported in [63] from Fischer, which is then focused on the cylindrical tank. In parallel with software advancement in the past few decades that can simulate the fluid dynamics of slosh with different type of tank shape, many researchers can further improve and optimize the shape of the tank or carrier. Recent works on improving the tank shape are reported in [64-70]. On the other hand, instead of proposing an improved shape of tank, there are also studies on introducing a kind of damper or baffles inside the tank to reduce the liquid slosh. This kind of baffles is promising strategy since it is widely applied for a long type cylindrical tank such as in fuel tank lorry or vessel. Their works reported in [71-79]

The controller design part of liquid slosh motion mostly focused on regulate the cart or trolley (that carrying the liquid) such that it can track a prescribed trajectory precisely with minimum liquid slosh inside the tank. In order to achieve these objectives, various control methods using different techniques have been introduced. Bridgen et al. [4], Aboel-Hassan et al. [5] proposed an input shaping controller, which is in the class of feed-forward control design. This method can be also considered a data-based or model-free control scheme since it is designed based on the frequency of slosh oscillation data. The relevant work also being done by Baozeng and Lemei [80]. However, the feed-forward control scheme has a drawback of handling any unexpected disturbance since there is no feedback signal to be controlled. Therefore, many researchers are focused on developing numerous feedback control strategies for liquid slosh suppression, such as Sliding Mode Controller [81-86], Linear Quadratic Regulator [87-89], H-infinity [90-91], and Variable Structure Control [92]. Those mentioned methods heavily depend on the state space model of the system, which may not represent the chaotic nature of slosh motion and also may not considering the unmodeled dynamics. A similar class of model-based feedback controller has been reported by Nair et al. [93] and Sira-Ramirez [94]. Here, a nonlinear higher order Sliding Mode Controller and flatness generalized PI control are introduced in [93] and [94], respectively. Meanwhile, in [95], an active force control (AFC) has been proposed by combining it with conventional PID control scheme. It is shown that the composite PID-AFC provides better slosh reduction than the standalone PID. On the other hand, tools of computational intelligence - such as artificial neural networks and fuzzy logic controllers - have been credited in various applications as powerful tools capable of providing robust controllers for mathematically ill-defined systems. This has led to recent advances in the area of intelligent design in tank shape [96, 97]. Various fuzzy based controllers have been applied in the control of liquid slosh which have led to satisfactory performances [98-101]. Grundelius [11] used an iterative learning control technique for controlling liquid slosh in industrial packaging machine.

Based on the above survey, most of the control design are highly depend on the developed model. In other words, they need to use the information of the model to design the control parameters. However, the obtained control parameters may not accurately control the real slosh system due to unmodeled dynamics feature in the model and also some simplification to the model. Therefore, it is necessary to develop the control strategy based on the real data from the system instead of using model, which is called model-free control.

Chapter 3

Model-Free PID based SPSA for Liquid Slosh Plant

3.1 Simultaneous Perturbation Stochastic Approximation

A general framework of the SPSA algorithm is presented in this section. Consider the optimization problem given by

$$\min_{\boldsymbol{\theta}\in\mathbb{R}^n} f(\boldsymbol{\theta}) \tag{3.1}$$

where $f:\mathbb{R}^n \to \mathbb{R}$ is an unknown objective function and $\boldsymbol{\theta}\in\mathbb{R}^n$ is the design variable.

The SPSA algorithm [46] iteratively updates the design parameter to search an optimal solution $\boldsymbol{\theta}^* \in\mathbb{R}^n$ of (3.1). The update law is

$$\boldsymbol{\theta}(k+1) = \boldsymbol{\theta}(k) - a(k)g(\boldsymbol{\theta}(k)) \tag{3.2}$$

for$k$ = 0,1,… where $a(k)$ is the gain and $g(\boldsymbol{\theta}(k))$ is the update vector given by

$$g(\boldsymbol{\theta}(k)) = \frac{f(\boldsymbol{\theta}(k)+c(k)\Delta(k)) - f(\boldsymbol{\theta}(k)-c(k)\Delta(k))}{2c(k)} \begin{bmatrix} \Delta_1(k) \\ \Delta_2(k) \\ \vdots \\ \Delta_n(k) \end{bmatrix} \tag{3.3}$$

In (3.3), $c(k)$ is another gain, $\Delta(k)$ is the n-dimensional random perturbation vector and $\Delta_i(k)$ is the i-th component of the vector $\Delta(k)$. For example, the gains $a(k)$ and $c(k)$ are given by $a(k) = a/(k+1+A)^{\alpha}$ and $c(k) = c/(k+1)^{\gamma}$, respectively, for nonnegative numbers a, c, A, α, and γ. Meanwhile, $\Delta(k)$ is, for example, drawn from the element-wise Bernoulli distribution

$$\begin{cases} \mathbb{P}(\Delta_i(k) = 1) = 0.5, \\ \mathbb{P}(\Delta_i(k) = -1) = 0.5. \end{cases} \tag{3.4}$$

Note that, the selection of non-negative coefficients a, c, A, α, and γ will be performed by some guidance reported in [46].

Then, the SPSA algorithm is executed by the following steps:

Step I: Select the non-negative coefficients a, c, A, α, and γ for the SPSA gain sequences $a(k) = a/(k+1+A)^{\alpha}$ and $c(k) = c/(k+1)^{\gamma}$. Set the initial conditions of the design parameters $\boldsymbol{\theta}(0)$ and set $k = 0$.

Step II: Generate n-dimensional random perturbation vector $\Delta(k)$.

Step III: Obtain two values of the objective functions $f(\boldsymbol{\theta}(k) + c(k)\Delta(k))$ and $f(\boldsymbol{\theta}(k) - c(k)\Delta(k))$.

Step IV: Calculate the vector $g(\boldsymbol{\theta}(k))$ in (3.3).

Step V: Execute the update law in (3.2) and obtain $\boldsymbol{\theta}(k+1)$.

Step VI: If a pre-specified termination criterion is satisfied, the algorithm terminates with the solution $\boldsymbol{\theta}^* := \arg \min_{\boldsymbol{\theta} \in \{\boldsymbol{\theta}(0), \boldsymbol{\theta}(1), \ldots, \boldsymbol{\theta}(k+1)\}} f(\boldsymbol{\theta})$. Otherwise, set $k = k+1$ and go to Step II.

On the other hand, the standard SPSA algorithm also can be applied to the maximization problem

$$\max_{\boldsymbol{\theta} \in \mathbb{R}^n} f(\boldsymbol{\theta}) \tag{3.5}$$

where f and $\boldsymbol{\theta}$ are similarly defined in (3.1). A solution to the problem in (3.5) is obtained by the following iterative procedure

$$\boldsymbol{\theta}(k+1) = \boldsymbol{\theta}(k) + a(k)g(\boldsymbol{\theta}(k)) \tag{3.6}$$

where $a(k)$ and $g(\boldsymbol{\theta}(k))$ are similarly defined in (3.2) and (3.3), respectively.

3.2 Convergence conditions of the SPSA algorithm

This section presents the convergence conditions of the standard SPSA algorithm, which can be described in the following theorem.

Theorem 3.1. [46] For the algorithm in (3.2), suppose that $\boldsymbol{\theta}(0) \in \mathbb{R}^n$ is given. Then,

$$\lim_{k\to\infty} \boldsymbol{\theta}(k) = \boldsymbol{\theta}^* \text{ w.p.1} \tag{3.7}$$

Subject to the following assumptions:

(A1) $a(k), c(k) > 0\ \forall k$, $\lim_{k\to\infty} a(k) = 0$, $\lim_{k\to\infty} c(k) = 0$, $\sum_{k=0}^{\infty} a(k) = \infty$, and $\sum_{k=0}^{\infty} (a(k))^2/(c(k))^2 < \infty$.

(A2) For some $\alpha_1, \alpha_2 > 0$, $\mathrm{E}(f(\boldsymbol{\theta}(k) + c(k)\Delta(k))^2) \le \alpha_1$, and $\mathrm{E}(\Delta_i(k)^{-2}) \le \alpha_2$ $(i = 1,2,\ldots,n)\ \forall k$. Moreover, for almost all $\boldsymbol{\theta}(k)$ (at each $k \ge \pi$ for some $\pi < \infty$) and some $\alpha_3 > 0$, $f^{(3)}(\boldsymbol{\theta}) := \partial^3 f / \partial\boldsymbol{\theta}^{\mathrm{T}}\partial\boldsymbol{\theta}^{\mathrm{T}}\partial\boldsymbol{\theta}^{\mathrm{T}}$ exists continuously with individual elements bounded by α_3 for all $\boldsymbol{\theta}$ in an open neighborhood of $\boldsymbol{\theta}(k)$.

(A3) $\|\boldsymbol{\theta}(k)\| < \infty\ \forall k$ w.p.1

(A4) $\boldsymbol{\theta}^*$ is an asymptotically stable solution of the differential equation

$d(\chi(t))/dt = -g(\psi)$.

(A5) Let $\boldsymbol{D}(\boldsymbol{\theta}^*)$ be the domain attraction for the point $\boldsymbol{\theta}^*$, i.e., $\boldsymbol{D}(\boldsymbol{\theta}^*) := \{\chi_0 : \lim_{t\to\infty} \chi(t \mid \chi_0) = \boldsymbol{\theta}^*\}$ where $\chi(t \mid \chi_0)$ denotes the solution to the differential equation in **(A4)** for $\chi(0) = \chi_0$. Then, there exists a compact set $\boldsymbol{S} \subseteq \boldsymbol{D}(\boldsymbol{\theta}^*)$ such that $\boldsymbol{\theta}(k) \in \boldsymbol{S}$ infinitely often for almost all sample points.

The detail of the proof of Theorem 2.1 is described in [46].

Remark 3.1. Suppose the measurement noise term is denoted by $\varphi(k)$, such that $f(\boldsymbol{\theta}(k) + c(k)\Delta(k)) + \varphi(k)$. In this study, we assume that $\varphi(k) = 0$. Nevertheless, the standard SPSA algorithm also works well if the measurement noise term exists $(\varphi(k) \neq 0)$. This fact is proven by [46].

3.3 Illustrative Examples

In this section, we present two examples to illustrate the effectiveness of the standard SPSA algorithm in the previous section.

Example 1: Consider a smooth Rastrigin test function with n = 100 given by

$$f(\boldsymbol{\theta}) = \sum_{i=1}^{n} \theta_i^2 - 10\cos(2\pi\theta_i) + 10 \tag{3.8}$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots, \theta_{100}]^{\mathrm{T}}$. Note that $f(\boldsymbol{\theta}^*) = 0$ at $\boldsymbol{\theta}^* = [0,0,\ldots,0]^{\mathrm{T}}$. The initial condition is selected to closed to $\boldsymbol{\theta}^*$ after performing several preliminary simulations. Let $\boldsymbol{\theta}(0) = [0.05, 0.05, \ldots, 0.05]^{\mathrm{T}}$ that yields $f(\boldsymbol{\theta}(0)) = 49.1935$. Here, we choose $a = 0.002$, $A = 150$, and $c = 0.5$ in the gains $a(k) = a/(k+1+A)^{0.9}$ and $c(k) = c/(k+1)^{1/6}$. Next, $\Delta(k)$ is drawn from the element-wise Bernoulli distribution in (3.4).

Figure 3.1 shows the responses of the objective function in 4000 iterations for 50 independent trials. In terms of the statistical analysis, the mean, best, worst and standard deviation values of resultant objective functions are depicted as 0.0264, 0.0188, 0.0349 and 0.0043, respectively. It shows that the SPSA algorithm converges to the optimal solution.

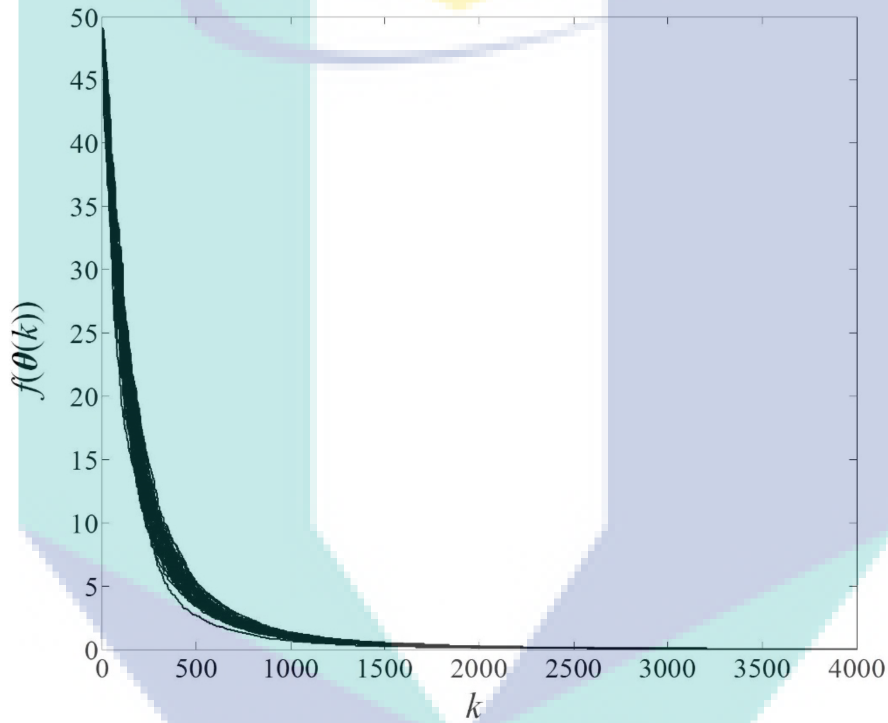

Figure 3.1: Response of the objective function $f(\boldsymbol{\theta}(k))$ in Example 1

Example 2: Consider a non-smooth Ackley test function given by

$$f(\boldsymbol{\theta}) = 19 - 20e^{-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n}\theta_i^2}} + e^{\frac{1}{n}\sum_{i=1}^{n}\sin(2\pi|\theta_i|)} \tag{3.9}$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots, \theta_n]^{\mathrm{T}}$, $n = 20$and $f(\boldsymbol{\theta}^*) = 0$ at $\boldsymbol{\theta}^* = [0,0,\ldots,0]^{\mathrm{T}}$. Let $\boldsymbol{\theta}(0) = [9,9,\ldots,9]^{\mathrm{T}}$, so $f(\boldsymbol{\theta}(0)) = 16.5848$. In this example, we set the gain sequences $a(k) = 50/(k+11)$ and $c(k) = 2/(k+1)^{1/6}$ with $\Delta(k)$ is set to be the same as in the previous example.

The responses of the objective function in 2000 iterations for 50 independent trials are shown in Figure 3.2. Meanwhile, the mean, best, worst and standard deviation values of resultant objective functions are recorded as 2.7049×10^{-4}, 5.4985×10^{-5}, 0.0070 and 0.0011, respectively. It indicates that the SPSA algorithm still maintains a good convergence in most of the trials, even for the non-smooth function.

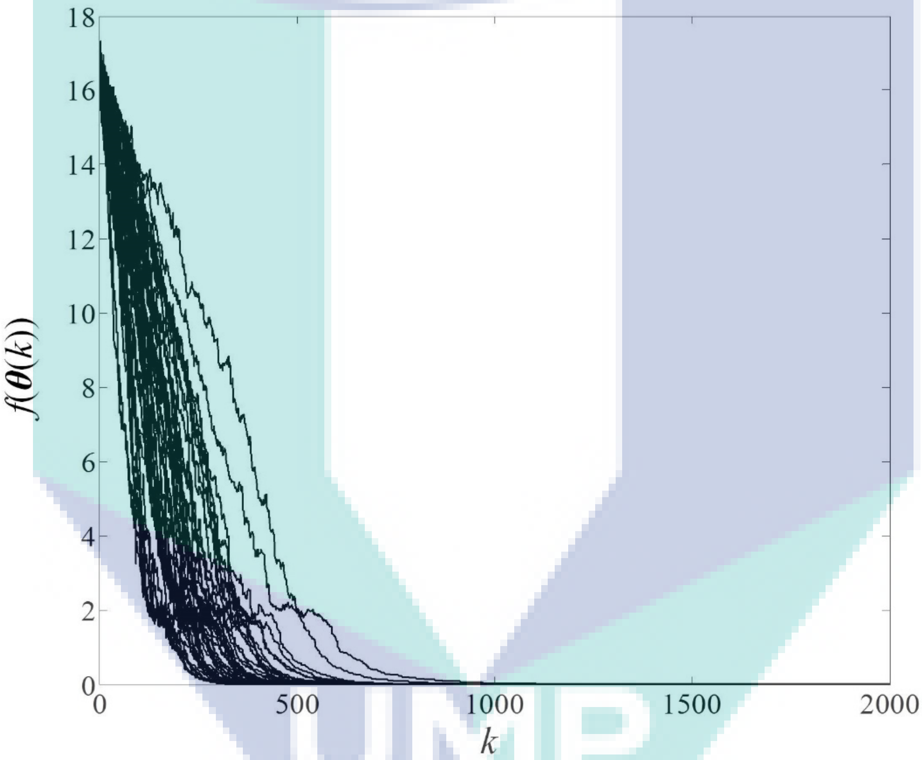

Figure 3.2: Response of the objective function $f(\boldsymbol{\theta}(k))$ in Example 2

Both examples clarify that the SPSA algorithm can solve high-dimensional problems by using only two measured objective functions per iteration. Also, the SPSA algorithm is applicable to both smooth and non-smooth objective functions as long as the measured objective functions are available. Therefore, these facts indicate that this algorithm is a promising tool for a model-free control scheme.

3.4 Framework of Model-Free Controller Design based on SPSA

Firstly, it is presented on how to apply the SPSA algorithm to the model-free controller design. In general, let $J(\boldsymbol{\kappa}):\mathbb{R}^n \to \mathbb{R}$ be the function specifying the controller performance and $\boldsymbol{\kappa}\in\mathbb{R}^n$ be the control parameter. Assume that the relation between $\boldsymbol{\kappa}$ and J is unknown. Then, a general model-free controller design is summarized as follows:

Step 1: Determine the initial value $\boldsymbol{\kappa}(0)$ and a pre-specified termination criterion.

Step 2: Perform the SPSA algorithm in Chapter 2.1 to the objective function J and the design parameter $\boldsymbol{\kappa}:=(\kappa_1,\kappa_2,\ldots,\kappa_n)$, i.e., by regarding J and $\boldsymbol{\kappa}$ as f and $\boldsymbol{\theta}$, respectively.

Step 3: After the pre-specified termination criterion is satisfied, the algorithm terminates with the solution $\boldsymbol{\kappa}^* = \boldsymbol{\theta}^*$.

Next, it is worth to clarify the applicable condition of this framework. Basically, the above framework can be applied to a given closed-loop feedback system, which already consists of a stabilizing controller for an unknown plant model. Here, the model-free controller design scheme is used to improve the control performance of the given system by tuning its stabilizing controller based only on the I/O data of the plant.

3.5 Problem Formulation of PID Control for Liquid Slosh Plant

Consider the PID control system for liquid slosh problem depicted in Figure 3.3, where the reference, control input, the lateral axis of the tank measurement and the slosh angle measurement is respectively represented by $r(t)$, $u(t)$, $y(t)$ and $\theta(t)$. While plant G, represented the liquid slosh system.

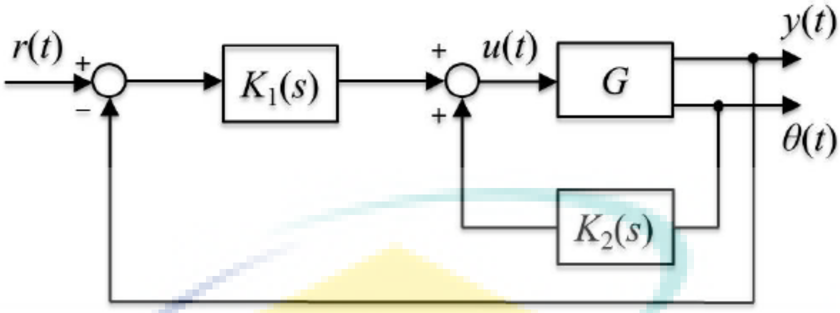

Figure 3.3: Liquid Slosh PID Control System

The symbol $K_i(s)$ $i = 1,2$ is the controller that given for the PID controller

$$K_i(s) = P_i\left(1 + \frac{1}{I_i s} + \frac{D_i s}{1 + (D_i / N_i)s}\right) \tag{3.10}$$

where $P_i \in \mathbb{R}$, $I_i \in \mathbb{R}$, $D_i \in \mathbb{R}$ and $N_i \in \mathbb{R}$ is the proportional gain, integral time, derivative time and filter coefficient respectively. Next, in Fig. 1, the performance index of the control system is introduced. Let

$$\hat{e} = \int_{t_0}^{t_f} |r(t) - y(t)|^2 \, dt, \tag{3.11}$$

$$\hat{\theta} = \int_{t_0}^{t_f} |\theta(t)|^2 \, dt, \tag{3.12}$$

$$\hat{u} = \int_{t_0}^{t_f} |u(t)|^2 \, dt, \tag{3.13}$$

where the time interval $[t_0, t_f]$ correspond to the period of the performance evaluation, $t_0 \in \{0\} \cup \mathbb{R}_+$ and $t_f \in \mathbb{R}_+$. The objective function is interpreted as follows

$$J(\mathbf{P}, \mathbf{I}, \mathbf{D}, \mathbf{N}) = w_1\hat{e} + w_2\hat{\theta} + w_3\hat{u}, \tag{3.14}$$

where $\mathbf{P} = [P_1 \quad P_2]^{\mathrm{T}}$, $\mathbf{I} = [I_1 \quad I_2]^{\mathrm{T}}$, $\mathbf{D} = [D_1 \quad D_2]^{\mathrm{T}}$ and $\mathbf{N} = [N_1 \quad N_2]^{\mathrm{T}}$. $w_1 \in \mathbb{R}$, $w_2 \in \mathbb{R}$ and $w_3 \in \mathbb{R}$ are the designated weighting coefficients by the designer and the values are chosen with the same method of the standard Linear Quadratic Regulator

(LQR) problem. The expressions $w_1\hat{e}$ and $w_2\hat{\theta}$ in (3.14) corresponded to the tracking error, while $w_3\hat{u}$ expression corresponded to the control input energy. Thus, the optimization problem for data-driven PID controller can be expressed as follows:

Problem 3.1. Find the $K(s)$, a PID controller where the control objective $J(\mathbf{P},\mathbf{I},\mathbf{D},\mathbf{N})$ with respect to **P, I, D**, and **N** is minimizes in corresponded with the measurement data $(u(t), y(t), \theta(t))$, for the PID control system in Figure 3.3.

3.6 Model-Free PID Controller Design Based on SPSA

In this section, the SPSA algorithm in Section 3.1 is applied for model-free PID tuning. Firstly, let the design parameter is defined as follows:

$$\psi = [\mathrm{P}_1\ \mathrm{P}_2\ \mathrm{I}_1\ \mathrm{I}_2\ \mathrm{D}_1\ \mathrm{D}_2\ \mathrm{N}_1\ \mathrm{N}_2]^{\mathrm{T}} \in \mathbb{R}^8 \tag{3.15}$$

The logarithmic scale is employed to the design parameter ψ to accelerate the exploration of the design parameter with the setting of $\psi_i = 10^{\theta_i}\,(i = 1,2,\ldots,8)$, and the objective function can be expressed as $J = [10^{\theta_1}\quad 10^{\theta_2}\quad \cdots\quad 10^{\theta_8}]^{\mathrm{T}}$. Finally, our design procedure is described as follows:

Step 1: Let $\theta_i = \log\psi_i$ and determine the maximum iteration number, $k_{\max}$.

Step 2: Perform SPSA algorithm in Section 3.1 for the objective function in (3.14).

Step 3: After reaching $k_{\max}$, record the optimal output $\boldsymbol{\theta}^* = \boldsymbol{\theta}(k_{max})$. Then, apply the $\psi^* = [10^{\theta_1^*}\quad 10^{\theta_2^*}\quad \cdots\quad 10^{\theta_8^*}]^{\mathrm{T}}$ to $K_i(s)$ in the PID control system in Figure 3.3.

Remark 3.3. Note that, during the optimization process, there is a possibility that the design parameters grow rapidly and suddenly are trapped in an unfeasible region. As a result, we obtain an undesirable solution. In order to avoid this problem, [94] has proposed a modified version of the SPSA algorithm. There, a saturation function $\mathrm{sat}_\delta(\cdot)$ has been introduced in (3.2). That is,

$$\boldsymbol{\theta}(k+1) = \boldsymbol{\theta}(k) - \mathrm{sat}_{\delta}(a(k)g(\boldsymbol{\theta}(k))) \tag{3.12}$$

In the next part of this report, the improved update law in (3.12) is adopted instead of (3.2).

Chapter 4

Results and Discussions

In this chapter, the effectiveness of the proposed model-free PID tuning based on SPSA is demonstrated. Firstly, a liquid slosh model is briefly described. Then, the SPSA based method is tested to the developed model.

4.1 Liquid Slosh Plant and Model

In order to develop the liquid slosh model, we consider a real plant of liquid slosh plant as shown in Figure 4.1. This plant or experimental setup is important to evaluate the effectiveness of the proposed model-free controller approach. The detail description of the plant is given as follows:

(i) **Mechanical structure**
It involves the development of platform for rectilinear motion of the trolley. The travelling range of the trolley which carries the liquid tank is around 100 mm. A cube water tank with dimension 150 x 150 x150 mm is considered.

(ii) **System actuator and position measurement**
The liquid slosh plant has only one actuator to drive the rectilinear motion of the trolley. Here, we will use a single DC motor with embedded high resolution encoder to precisely observe the position of the trolley. Note that the rotation of the DC motor will move the trolley in a rectilinear motion either forward or backward movement.

(iii) **Data acquisition mechanism**
In this study, the proposed control scheme is developed in Matlab/Lab view software and it will control the liquid slosh plant in real time. On the other hand, we also can develop our own liquid slosh model from input and output data of

liquid slosh plant. Therefore, we need a data acquisition card to communicate the liquid slosh plant with the control environment in PC. In particular, we can send the signal from the PC (through Matlab/Lab view software) to rotate the DC motor while recording the position of the trolley from the plant to the PC, simultaneously.

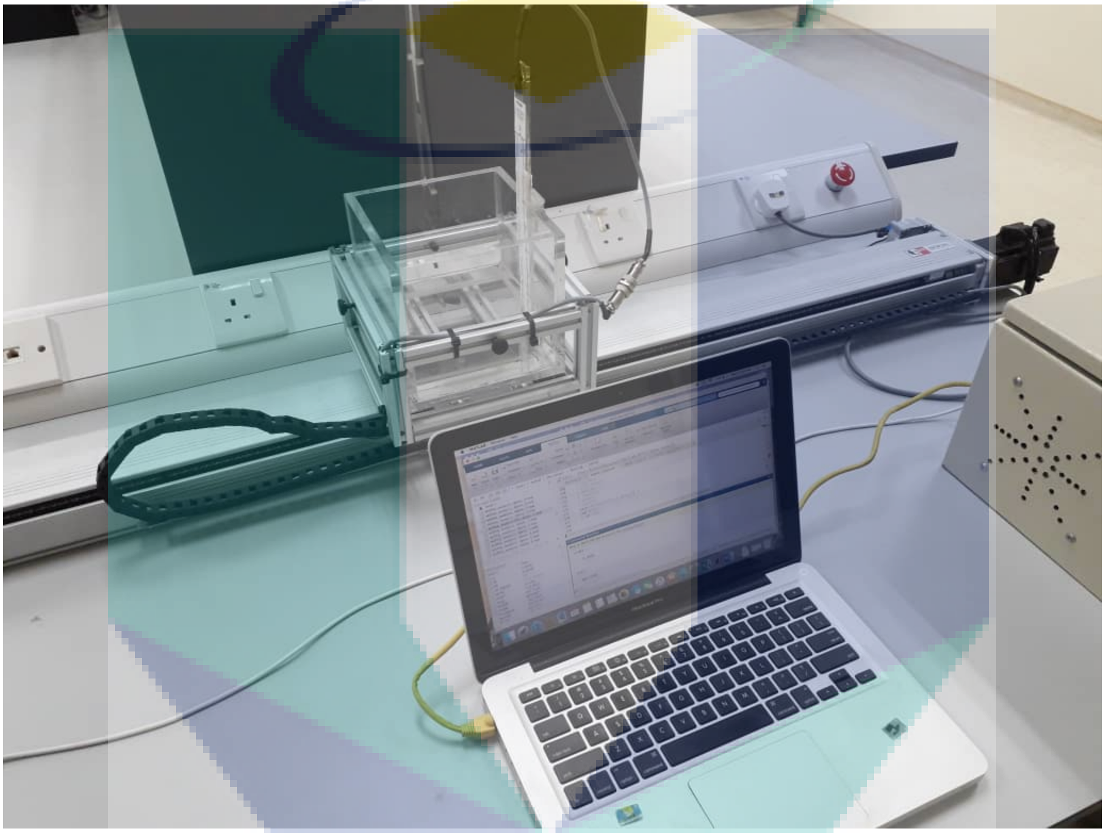

Figure 4.1: Experimental rig of liquid slosh plant

Our liquid slosh model is developed using the combination of system identification and first principle methods. In particular, we adopt the standard model of liquid slosh plant from [10], as shown below:

$$M\ddot{y} + ml\cos\theta\ddot{\theta} - ml\dot{\theta}^2\sin\theta = u, \tag{4.1}$$

$$ml\cos\theta\ddot{y} + ml^2\ddot{\theta} + d\dot{\theta} - mgl\sin\theta = 0, \tag{4.2}$$

where M, m, l, d and g are respectively the mass of the tank with liquid, mass of the liquid, liquid slosh hypotenuse length, damping coefficient and gravity. Note that the above model or system's dynamic equation is developed using the Euler-Lagrange formulation. Then, the parameters of M, m, l, d and g in (4.1) and (4.2) are determined using the system identification method, where the input and output data are taken from our real liquid slosh plant by applying a quick-stop experiment. The real parameters of the plant are depicted in Table 4.1, after using the system identification tool box in Matlab.

Table 4.1: Parameters of Liquid Slosh Model

Parameter	**Value**	**Unit**
M	6.0	kg
m	1.32	kg
l	0.052126	m
d	3.0490×10-4	kg m^2/s
g	9.81	m/s^2

4.2 Performance Comparison and Analysis

Based on the obtained liquid model in Section 4.1, we apply the proposed model-free PID based SPSA using the Matlab environment. In order to evaluate the performance of the SPSA-based methods, we perform 30 independent trials to the liquid slosh model. Then, after the termination criterion is satisfied, the proposed method is evaluated based on the following performance criteria

(i) The statistical analysis of the objective function $J(\boldsymbol{P},\boldsymbol{I},\boldsymbol{D},\boldsymbol{N})$, total norm of the error $\hat{e}$, slosh angle $\hat{\theta}$ and total norm of the input $\hat{u}$. Specifically, the mean, best, worst, and standard deviation values of them are observed from 30 independent trials.

(ii) The average computation time from 30 independent trials.

Remark 4.1. In this comparative study, the parameters of each SPSA-based method, e.g., the gain sequences $a(k)$ and $c(k)$ are selected heuristically such that it yields the best control performance. Therefore, these parameters may be varied between each method.

The controller $K_i(s)$ $i=1,2$ is the PID controller in a feedback control structure as shown in Figure 3.3. The corresponding design parameters are presented in Table 4.2.

Next, the reference cart/trolley position as follow:

$$r(t) = \begin{cases} 0, & 0 \le t \le 0.5 \\ 0.5, & 0.5 < t \le 20 \end{cases} \tag{4.3}$$

Our aim is to find an $\boldsymbol{\theta} \in \mathbb{R}^8$, which minimizes the performance index J in (3.14) for $w_1 = 100$, $w_2 = 100$, $w_3 = 5$, $t_0 = 0$, and $t_f = 20$. We set the parameters of the SPSA based algorithm as $a(k) = 0.005/(k + 24)^{0.6}$, $c(k) = 0.2/(k + 1)^{0.1}$, $\delta = 0.1$, and $k_{\max} = 200$. The initial condition $\boldsymbol{\theta}(0)$ is given in Table 4.2, which is assumed to produce a stable closed-loop system during the evaluation period.

Figure 4.2 shows the response of the objective function after 200 iterations and the resulting design parameter $\boldsymbol{\theta}^*$ is tabulated in Table 4.2. It clarifies that, the SPSA based method successfully minimizes the objective function and yields optimal PID parameters. Meanwhile, the responses of $y(t)$, $\theta(t)$ and $u(t)$ are shown in Figures 4.3, 4.4 and 4.5. In these figures, the thin grey line represents the responses at $k = 0$ and the thick black line represents the responses at $k = 200$, which is the optimal design parameters. It shows that the cart settles to the desired position in about 3 seconds (see Figure 4.3) with slightly minimum overshoot. Meanwhile, the proposed controller is also able to suppress the slosh angle after 200 iterations. The obtained slosh angle amplitude range has been reduced from -0.065 – 0.028 radian (at $k = 0$) to only -0.025 – 0.008 radian (at k =200), which is almost 88.71 % of slosh amplitude reduction. Moreover, the liquid slosh oscillation is able to settle down at nearly 6 seconds, which is better than the initial PID parameters. Furthermore, acceptable control input energy (see Figure 4.5) is used to achieve the control objective. It shows that the range of control output amplitude has been reduced from -12 – 12 Newton to -1 – 6.2 Newton, which is almost 70% reduction. Hence, we can confirm that the model-free PID tuning based on SPSA method has a good potential in reducing the liquid slosh while maintaining the desired cart position and used minimum input energy.

Remark 4.2. Note that, in this underactuated system control framework, one might produce faster settling time in the cart position response. However, they need to sacrifice a higher amplitude response in the slosh angle with may also produce higher oscillation and longer settling time. Therefore, in this model-free control scheme, the chosen weights for both slosh angle reduction and cart trajectory tracking are also play an important role to obtain an optimum results. This is also similar for the chosen weight of control output since one might consider an effective input energy to the system.

On the other hand, our study is not limited to the standard SPSA algorithm. Here, we also adopt the model-free PID control scheme with other variant of SPSA, which is Global SPSA. In [12], it has been shown that the GSPSA based method is able to produce better control performance than other variants of SPSA algorithm. In order to implement the model-free PID based GSPSA in our slosh control problem, the updated equation in (3.12) is modified by adding $b(k)d(k)$. Here, $b(k)$ is a gain sequence and $d(k)$ is random perturbation vector that is produced independently from $\Delta(k)$ in (3.4). Please refer [12] for the detail of the algorithm. This additional term is introduced such that it can avoid any possibility of trapping in local minima in standard SPSA algorithm. The effectiveness of our SPSA based algorithms (SPSA and GSPSA) are also compare with standard Random Search (RS) algorithm, which is well known memory based algorithm. Note that the performance of the GSPSA and RS-based algorithms are also evaluated based on the same criteria as stated in Section 4.2.

Table 4.3 tabulated the statistical comparative assessment between SPSA, GSPSA and RS based algorithms. The performance of the algorithms is compared through the objective function, total norm of error, total norm of slosh angle and total norm of input, in terms of mean, best, worst and standard deviation. Moreover, the computation time of each algorithm is also observed. In terms of the objective function, the GSPSA based algorithm slightly produce better mean and best values than the SPSA and RS based methods. The similar pattern is also observed in total norm of input, where the GSPSA slightly produce lower mean and best values. However, in terms of total norm of error and slosh angle, the SPSA based algorithm produce the lowest mean values, while, the GSPSA based algorithm produce the lowest best values. In terms of the computation time, the RS based method slight produce lowest value as compared to the SPSA based methods. In overall, it is proven that the SPSA based methods are able to produce better control performance than other stochastic based approach even the RS based method has the capability to memorize the best optimal parameter during its tuning process.

Table 4.2: Design parameters

ψ	PID gain	$\theta(0)$	ψ corresponding to $\theta(0)$ (x10^3)	θ*	ψ* corresponding to θ* (x10^3)
ψ_1	P_1	1.0	0.0100	0.5300	0.0034
Ψ_2	I_1	3.5	3.1623	3.2996	1.9936
Ψ_3	D_1	0.0	0.0010	0.2524	0.0018
Ψ_4	N_1	1.0	0.0100	0.4233	0.0027
Ψ_5	P_2	2.0	0.1000	2.0323	0.1077
Ψ_6	I_2	1.0	0.0100	0.2810	0.0019
Ψ_7	D_2	0.0	0.0010	-0.7207	0.0002
Ψ_8	N_2	1.0	0.0100	1.3460	0.0222

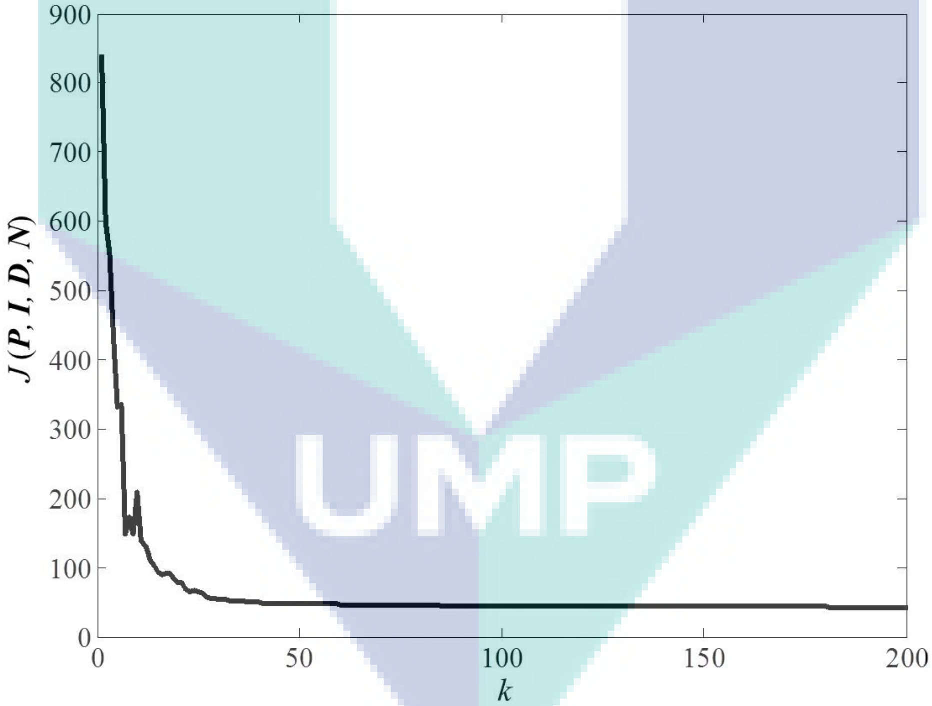

Figure 4.2: Response of the objective function

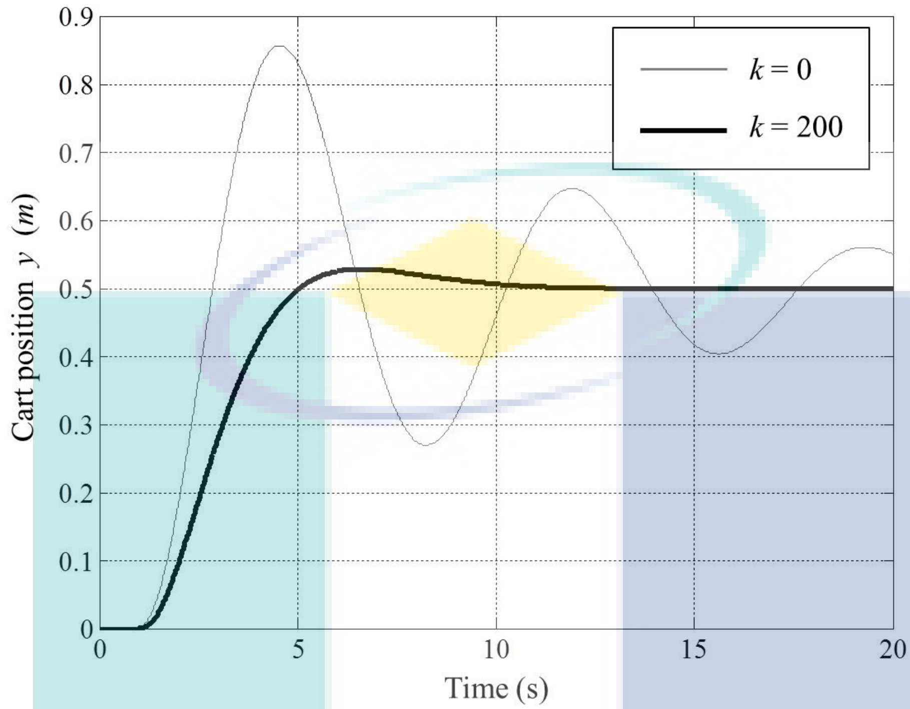

Figure 4.3: Cart/trolley position response

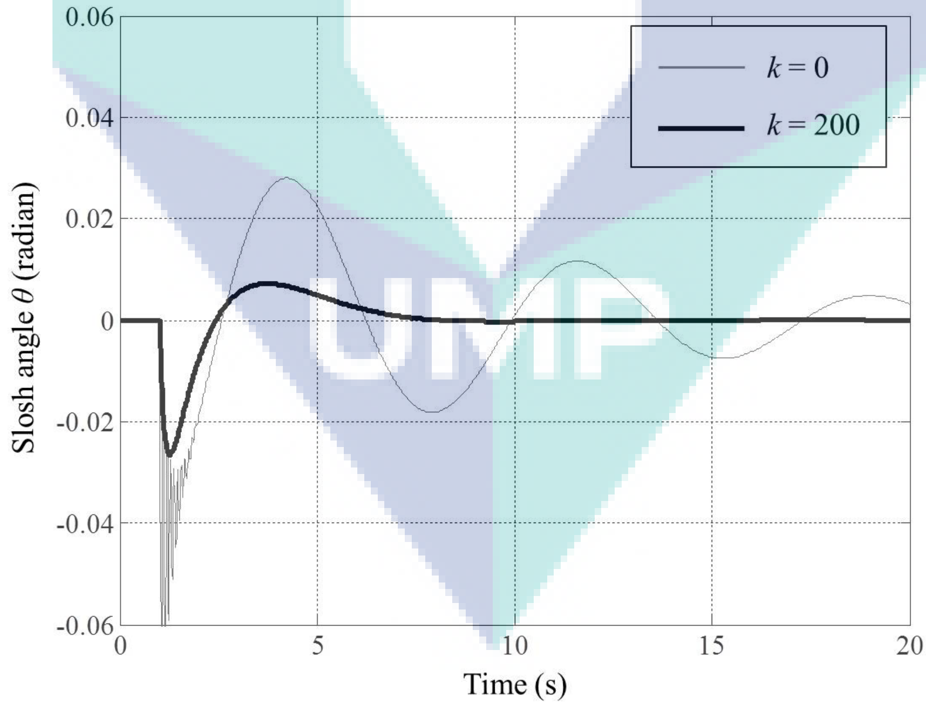

Figure 4.4: Slosh angle response

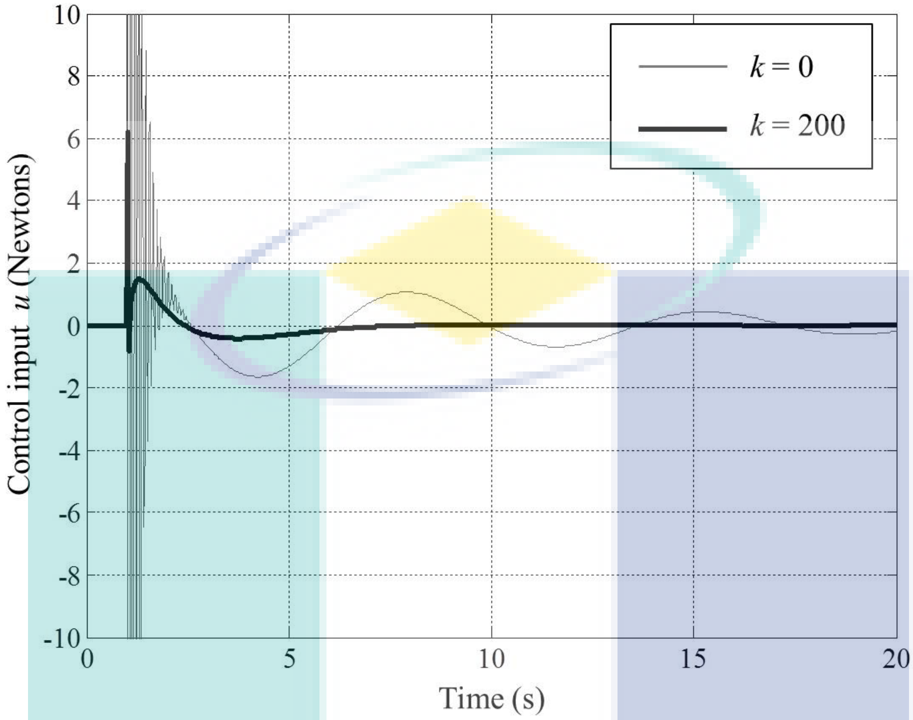

Figure 4.5: Control output response

Table 4.3: Statistical performance comparison between SPSA based method and other based methods

Algorithm		**RS**	**SPSA**	**GSPSA**
$J(\boldsymbol{P}, \boldsymbol{I}, \boldsymbol{D}, \boldsymbol{N})$	Mean	42.4064	42.2984	**41.9701**
	Best	41.6587	41.3127	**41.2987**
	Worst	43.7629	**43.2125**	44.3735
	Std	0.5079	**0.4633**	0.6045
Total Norm of Error and Slosh angle	Mean	0.3219	**0.3189**	0.3225
	Best	0.3102	0.3030	**0.2887**
	Worst	0.3515	**0.3402**	0.3533
	Std	**0.0086**	0.0096	0.0129
Total Norm of Input	Mean	2.0924	2.1965	**1.9709**
	Best	1.8211	1.8021	**1.5686**
	Worst	**2.4319**	3.1634	2.6442
	Std	**0.1473**	0.2950	0.2179
Average Computation Time, second		**60.2341**	84.2601	85.5512

Chapter 5

Conclusion

In this research report, a framework of model-free control scheme based on the simultaneous perturbation stochastic approximation has been established. Based on the general step-by-step procedure of this framework in Chapter 3, the effectiveness of the SPSA-based method has been investigated for liquid slosh control problem. The goal is to obtain the optimal PID control parameter based on only input and output data such that the liquid slosh is minimized while the cart position follows the desired trajectory. In general, it shows that the SPSA-based methods have a good potential in obtaining acceptable results within a few minutes through extensive simulation and experimental works. In particular, from the control performance and the statistical results indicate that the GSPSA-based algorithm outperforms the SPSA and stochastic optimization-based methods.

As shown in the above, the main philosophy of the proposed framework is that it can be applied to improve the given stabilizing controller of systems with unknown plant models such that the control performance is achieved. Our investigation shows that the model-free controller scheme based on SPSA has a good potential in improving the given stabilizing controller by using only the I/O data of the plant. In particular, based on the above control problems, this framework has successfully accomplished the desired control objective by tuning a large number of control parameters in a practical convergence time. Moreover, we have shown that some modifications to the standard SPSA algorithm are necessary to handle each control problem. Note that these modifications are unique for each problem and it would become an informative guideline for others in solving a similar problem framework.

Finally, this report is concluded by highlighting some open problems as follows: The first is to develop theoretical results for model-free controller design framework. In particular, a new stability analysis for model-free controller design, which is based on only I/O measurement data, would be an important topic to be explored. The second is the robustness issues in model-free controller design. Here, a new definition of robustness of model-free controller framework should be considered, unlike the model-based controller, where the robustness refers to the ability of controllers to deal with unmodeled dynamics. The third is to upgrade the optimization tool such that it converges to a global solution with fast controller tuning. This appealing feature implies that the algorithm may automatically combine the broad search required for global optimization with the localized search that is tied to the gradient approximation.

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RESEARCH REPORT UMP GRANT
Laporan Prestasi Skim Geran UMP

Final	v	Progress		*Progress Period : ____________________*	*v Please tick*

PROJECT DETAILS *(Keterangan Projek)*

A	**Grant No**	150344
	Faculty/CoE	FKEE
	Project Title	A STUDY ON MODEL-FREE APPROACH FOR LIQUID SLOSH SUPPRESSION BASED ON STOCHASTIC APPROXIMATION
	Project Leader	DR. MOHD ASHRAF AHMAD
	Project Member	1. DR. MOHD SYAKIRIN RAMLI 2. DR. RAJA MOHD TAUFIKA RAJA ISMAIL 3. MOHD FALFAZLI MAT JUSOF 4. MOHD HELMI SUID 5. DR. AHMAD NOR KASRUDDIN NASIR

PROJECT ACHIEVEMENT *(Pencapaian Projek)*

B

ACHIEVEMENT PERCENTAGE				
Project progress according to milestones achieved up to this period	**0 - 25%**	**26 - 50%**	**51 - 75%**	**76 - 100%**
Percentage (please state %)				100%

EXPENDITURE *(Perbelanjaan)*

C

Budget Approved *Peruntukan diluluskan*	**Amount Spent** *Jumlah Perbelanjaan*	**Balance** *Baki*	**% of Amount Spent** *Peratusan Belanja*
RM 30,000	**RM 29,624**	**RM 376**	**98.75 %**

RESEARCH OUTPUT *(Output Penyelidikan)*

D

NO OF PUBLICATION

KPI FOR NO OF PUBLICATION

	ISI	Scopus	Index Proceedings	Others
KPI		**1**	**2**	
Achievement		**2**	**2**	

The contribution of funder (UMP, MOHE, MOSTI, Industry etc.) as the fund provider must be acknowledged at all times in all forms of publications. Please state the grant number (RDU/UIC) and grant name.

Number of articles/ manuscripts/books *(Please attach the First Page of Publication)*	**ISI**	**Scopus**
	1. 2.	1. M.Z. Mohd Tumari, A.F. Zainal Abidin, A.S.R.A. Subki, A.W. Ab Aziz, M.S. Saealal, M.A. Ahmad, "PSO fine-tuned model-free PID controller with

		derivative filter for liquid slosh suppression", Journal of Advanced Manufacturing Technology, 2018, Accepted. 2. M.Z. Mohd Tumari, W.N. Abd Rashid, M.S. Saealal, M.A. Ahmad, M.H. Suid, M.R. Ghazali, "Liquid slosh suppression by using model-free fuzzy logic controller", Journal of Telecommunication, Electronic and Computer Engineering, 2018, Accepted.
Conference Proceeding *(Please attach the First Page of Publication)*	**International**	**National**
	1. M.A. Ahmad, M.A. Rohani, R.M.T. Raja Ismail, M.F. Mat Jusof, M.H. Suid, A.N.K. Nasir, "A model-free PID tuning to slosh control using simultaneous perturbation stochastic approximation", Proceedings of 5th IEEE International Conference on Control Systems, Computing and Engineering, pp. 343-347, 2015. 2. M.A. Ahmad, R.M.T. Raja Ismail, "A data-driven sigmoid-based PI controller for buck-converter powered dc motor", Proceedings of IEEE Symposium on Computer Applications and Industrial Electronics, pp. 81-86, 2017.	1. 2.

HUMAN CAPITAL DEVELOPMENT

KPI FOR HUMAN CAPITAL DEVELOPMENT

	PhD Student	Master Student
KPI		
Achievement		

Human Capital Development	**Number**				**Others** (please specify)
	On-going		**Graduated**		
Citizen	Malaysian	Non Malaysian	Malaysian	Non Malaysian	
PhD Student	1				
Masters Student	1				
Undergraduate Student					
Total	2				

Name of Student: **ID Matric No:** **Faculty:** **Thesis title:** **Graduation Year:**	NIK MOHD. ZAITUL AKMAL BIN MUSTAPHA PEE16001 FKEE - -

Name of Student:	NOR SAKINAH BINTI ABDUL SHUKOR
ID Matric No:	MEL16005
Faculty:	FKEE
Thesis title:	-
Graduation Year:	-
*** enter for more space*	

INTELECTUAL PROPERTIES

KPI FOR INTELECTUAL PROPERTIES

Patent, Copyright, Trademark,Industrial Design: ____________

Patent, Copyright, Trademark, Industrial Design ect	-

OTHERS

KPI FOR OTHERS

Prototype, Technology,Collaborations etc: ____________

Prototype, Technology, Collaborations etc	**-**

ASSET *(Aset)*

E

Bil	**Peralatan** *(Equipment)*	**Model**	**No Daftar Aset** *(Asset Tagging No)*	**Amount** (RM)	**Lokasi** *(Location)*

PRODUCT DESCRIPTION FOR UMP R&D DIRECTORY (SHORT & BRIEF) *Only for Final Report*

F

PRODUCT PICTURE FOR UMP R&D DIRECTORY *Only for Final Report*

G

SUMMARY OF RESEARCH FINDINGS (*Ringkasan Penemuan Projek Penyelidikan)*

H

Liquid slosh in a moving container constitutes a challenging problem with regard to the safety of transportation systems. Most research on the control of liquid slosh has focused on the model-based controller. However, it is difficult to apply the model-based controller in real liquid slosh due to several reasons, such as, the difficulty to obtain accurate model of slosh due to its chaotic nature, unmodeled dynamics problem, and huge gap between control theory and real applications. Therefore, a data-driven controller will be more convincing approach for liquid slosh suppression.

This study aims to derive, validate and analyze a novel data-driven control scheme based on improved stochastic approximation for liquid slosh suppression. In particular, an improved simultaneous perturbation stochastic approximation (SPSA) is used to tune a given controller (e.g., PID) such that the liquid slosh is reduced, while achieving desired cart position. Here, the conventional SPSA is modified by introducing a saturation function for each element at its update vector. This improvement is expected to avoid the updated vector produces an unstable solution. Meanwhile, the random gain at the upper and lower bounds will ensure the algorithm achieves global optimal solution.

	To evaluate the performance of the proposed data-driven controller, an experimental rig, which consists of a motor-driven liquid tank performing rectilinear motion, is considered. Moreover, several floating accelerometers are considered to measure the liquid slosh. Then, the performance of the proposed method is assessed in terms of level of slosh reduction, point-to-point tracking capability, and computational complexity. The significance output of this study is that the proposed data-driven control scheme is able to provide better liquid slosh suppression without even know the exact model of the plant. At the end, this data-driven framework will be useful to apply in molten metal industry and vehicles with liquid cargo.
PROBLEMS / CONSTRAINTS IF ANY *(Masalah/ Kekangan sekiranya ada)*	
I	The difficulty to make sure the design of experimental setup is alligned with the given schedule. In that case, we have applied for 6 months extension of this grant and it has been approved by PNI.
Date : 26 Jun 2018 *Tarikh*	**Project Leader's Signature:** *Tandatangan Ketua Projek*
COMMENTS, IF ANY/ ENDORSEMENT BY FACULTY (*Komen, sekiranya ada / Pengesahan oleh Fakulti)*	
J	**Recommend / Not Recommend / KIV / Need Ammendment** .... **Name:** **Signature:** *Nama:* *Tandatangan:* **Date:** *Tarikh:* **** Dean/TDR/Director/Deputy Director**
COMMENTS, IF ANY/ ENDORSEMENT BY RMC PNI (*Komen, sekiranya ada / Pengesahan oleh RMC PNI)*	

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PSO Fine-tuned Model-Free PID Controller with Derivative Filter for Liquid Slosh Suppression

Mohd Zaidi Bin Mohd Tumari, Amar Faiz Bin Zainal Abidin, A Shamsul Rahimi Bin A Subki, Ab Wafi Bin Ab Aziz, Muhammad Salihin Bin Saealal, Mohd Ashraf Bin Ahmad

Abstract— The disordered behavior of liquid slosh and the complex fluid dynamic motion in the container makes the conventional model-based control approaches complex and challenging to implement in practice. This paper presents investigations into the development of PSO fine-tuned model-free PID controller with derivative filter (PIDN) for liquid slosh control. Two parallel PIDN controllers are developed for both lateral tank position and liquid slosh angle control where 8 PIDN parameters consist of Kp, Ki, Kd and filter coefficient, N are fine-tuned using particle swarm optimization (PSO) algorithms and Sum Absolute Error (SAE) and Sum Square Error (SSE) are chosen as it fitness functions. With the purpose to confirm the design of control scheme, a liquid slosh model is considered to represent the lateral slosh movement. Supremacy of the proposed approach is shown by comparing the results with manual heuristic tuning method. The performances of the control schemes are accessed in terms of lateral tank tracking capability, level of liquid slosh reduction and time response specifications. Finally, it is seen from the simulation results that the proposed control technique has able to decrease the liquid slosh without explicitly model the liquid slosh behavior.

Index Terms—Liquid slosh control, SSE, PID, PSO

I. Introduction

Usually, the uncontrolled free surface of liquid has an inclination to undergo large excursions, even for a very small movement of the container. The movement of the free liquid surface inside the container is named slosh. Liquid sloshing can disturb the performance of the system because it produces an additional forces and moments. Consequently, liquid sloshing has been a serious problem in many cases. For example, in the ship industries, the dynamic behavior of a vessel at sea is alarmingly troubled by the dynamics of moving partly filled tanks carried onboard [1]. In the metal industries, the pouring work has been usually working by human operator that produces sloshing to the molten metal. Then, the molten metal frequently overflows out of the ladle due to the too much sloshing, and dust, air bubble and inclusion are also trapped in the molten metal [2]. Moreover, the fluid slosh forces and dynamic load transfers in the lateral and longitudinal directions and parametric uncertainties caused by moving liquid cargo affect the overall dynamics of the vehicle [3]. Consequently, it is crucial to reduce this residual liquid slosh causing from the container movement.

However, controlling liquid slosh still faces plentiful degrees of difficulties that need to be considered before they can be used in much in everyday real-life applications. The control concern of the liquid slosh is to design the controller so that the liquid tank can reach a desired position or track a prescribed trajectory accurately with minimum sloshing of liquid. In order to achieve these objectives, several studies in the literature reporting on liquid slosh control. A considerable amount of literature has been published on passive methods to control liquid slosh due to the nonavailability of the measurement of the slosh. For instance, passive elements such as slosh absorbers and baffles are basically used to deplete the slosh energy [4] [5]. These methods increase weight, construction time and complexity. Another methods in suppressing the liquid slosh are based on open-loop and closed-loop control. For example, input shaping technique [6] [7], combined input shaping and command smoothing [8], filtering techniques [9] and minimum time feedforward control [10] are used to generate a prescribed motion, which minimized the residual liquid slosh. These methods are able to decrease the liquid slosh without using the feedback sensors. Unfortunately, these open-loop control schemes are very poor in handling with any disturbances occurred. As an alternative, feedback control or closed-loop control, which is well known to be less sensitive to disturbances and parameter

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Liquid Slosh Suppression by using Model-Free Fuzzy Logic Controller

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***Abstract*—This paper presents a control scheme for liquid slosh control by using model-free control scheme. Model-based control techniques are challenging to apply in practice. Therefore, model-free Fuzzy Logic Controller (FLC) will be used for liquid slosh control.Two inputs of fuzzy inference system which are system error and derivative error are scaled by two coefficients, K_{in1} and K_{in2} respectively. Five triangular membership functions are defined for both inputs while nine triangular membership functions are defined for the output which is scaled by a coefficient K_{out}. The rule matrix is based on the Macvicar Whelan matrix. In order to confirm the design of control scheme, a liquid slosh model is considered to represent the lateral slosh motion. The simulation results prove that the model-free fuzzy logic control scheme has able to reduce the liquid slosh without unambiguously model the liquid slosh behavior.**

***Index Terms*—Liquid slosh; fuzzy logic controller; membership functions; Macvicar Whelan matrix;**

I. INTRODUCTION

Recently, liquid slosh inside a container always happens in many circumstances. For example, in the ship industries, the dynamic behavior of a vessel at sea is critically affected by the dynamics of moving partly filled tanks carried onboard [1]. In the metal industries, the pouring work has been generally employed by human operator that generates sloshing to the molten metal. Then, the molten metal often overflows out of the ladle due to the excessive sloshing, and dust, air bubble and inclusion are also trapped in the molten metal [2]. Meanwhile, the fluid slosh forces and dynamic load transfers in the lateral and longitudinal directions and parametric uncertainties caused by moving liquid cargo affect the overall dynamics of the vehicle [3]. Therefore, it is essential to suppress this residual slosh induced by the container motion.

Several studies investigating in suppressing slosh have been carried out based on open-loop and closed-loop approaches. For example, input shaping technique [4] [5], combined input shaping and command smoothing [6], filtering techniques [7] and minimum time feedforward control [8] are used to generate a prescribed motion, which minimized the remaining oscillation of the liquid slosh. Those methods are able to suppress the slosh without usethe feedback sensors. Regrettably, these techniques are very insignificantto compensate with any disturbancesoccurred. Instead, closed-loop control, which is well acknowledged to be less sensitive to disturbances and parameter variations, has also been used for reducing the liquid slosh. These include active force control (AFC) [9], PID control [10], ?$_{?}$ control [11], sliding mode control [12] and Variable Gain Super-twisting Algorithm (VGSTA) for output feedback control [13].

It appears from the aforementioned investigations that most attention has been paid to use model-based control strategies. It has conclusively been shown that the model-based control techniques are challenging to apply in practice and do not precisely consider the chaotic nature of liquid slosh and the complicated fluid dynamic motion in the container. Hence, a model-free control technique will be more attractive to implement for the liquid slosh control. Instead, a model-free Fuzzy Logic Controller (FLC) would provide us a promising approach for the liquid slosh suppression. FLC has been widely used because this method is quite useful in terms of reliability and robustness. FLC is simple to control, low cost and the possibility to design without knowing the exact mathematical model of the system. Although FLC have been widely used on the various application such as in [14]-[19], there has been limited use on liquid slosh suppression. Nevertheless, it is not clear whether model-free FLC can really works for liquid slosh suppression since there are limited works in the literature have discussed the application of the FLC to the problems.

Therefore, this paperpurposes to investigate the effectiveness of the model-free FLC for liquid slosh suppression based on Macvicar Whelan matrix rules. To evaluate the performance of the proposed model-free FLC approach, a liquid slosh model in [20] which consists of a small motor-driven liquid tank performing a rectilinear motion is considered. Here, the FLC is used to minimize the liquid slosh while achieving the desired cart position. Then, the performance of the proposed method is assessed in term of level of slosh reduction and cart's position tracking capability.

The rest of the paper is organized as follows. Section II discusses about the liquid slosh model. In Section III, the model-free FLC method is explained. In Section IV,simulation results and discussion are presented. Finally, this paper is concluding in Section V.

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A Model-Free PID Tuning to Slosh Control using Simultaneous Perturbation Stochastic Approximation

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***Abstract*—This paper addresses an initial study of a model-free PID tuning based on simultaneous perturbation stochastic approximation (SPSA) for liquid slosh control. The SPSA method is used to optimize the PID parameters such that the liquid slosh is minimized. In order to validate our model-free design, a liquid slosh model is considered to represent the lateral slosh motion. The simulation results demonstrate that the proposed model-free method has a good potential in reducing the liquid slosh without explicitly modeling the liquid slosh behavior.**

I. Introduction

Nowadays, slosh or oscillation of liquid inside a container often occurs in many cases. For example, ships with liquid cargo carriers are at high risk of generating sloshing load during operation [1]. In the metal industries, high oscillation can spill molten metal, which is dangerous to handle by the operator [2]. Meanwhile, sloshing of fuel and other liquids in moving vehicles may cause instability and undesired dynamics [3]. Hence, it is necessary to suppress this residual slosh induced by the container motion.

So far, various attempts in suppressing slosh are based on open-loop and closed-loop approaches. For example, input shaping scheme [4], [5] and some filtering techniques [6], [7] are used to generate a prescribed motion, which minimized the residual oscillation. These methods are able to reduce the slosh without needs for feedback sensors. However, these strategies are very poor in handling with any disturbances. On the other hand, closed-loop control or feedback control, which is well known to be less sensitive to disturbances and parameter variations, has also been adopted for reducing slosh. These include PID control [8], H_∞ control [9], sliding mode control [10] and iterative learning control (ILC) [11].

As shown in the above, many approaches use model-based control strategies, which are difficult to apply in practice. This is because their control schemes do not accurately consider the chaotic nature of slosh and the complex fluid dynamic motion in the container. Therefore, a model-free approach will be more attractive. On the other hand, a simultaneous perturbation stochastic approximation (SPSA) [12] would provide us a promising tool for the model-free approach. This is because the SPSA method is known to be effective for a variety of model-free optimization problems without require any explicit form of the objective function [13], [14]. However, it is not clear whether it works for liquid slosh problems since there are a few works in the literature have discussed the application of the SPSA to the problems.

This study aims to investigate the effectiveness of the model-free PID tuning for liquid slosh suppression based on simultaneous perturbation stochastic approximation. To evaluate the performance of the proposed model-free approach, a liquid slosh model in [15] which consists of a small motor-driven liquid tank performing a rectilinear motion is considered. Here, the SPSA method is used to tune a given PID controller such that the liquid slosh is minimized while achieving desired cart position. Then, the performance of the proposed method is assessed in terms of level of slosh reduction and cart's position tracking capability.

The rest of the paper is organized as follows. Section II formulates the problem of model-free PID controller tuning to slosh control. In Section III, the simultaneous perturbation stochastic approximation based method is explained. Simulation results and discussion are presented in Section IV. Finally, some concluding remarks are given in Section V.

Notation: The symbols $\mathbb{R}$ and $\mathbb{R}_+$ represent the set of real numbers and the set of positive real numbers, respectively. For the random variable V, the probability of event $V = a$ is represented by $\mathbb{P}(V = a)$. For $\delta \in \mathbb{R}_+$, $\text{sat}_\delta : \mathbb{R}^n \to \mathbb{R}^n$ denotes the saturation function whose ith element given as follows:

$$\text{The } i\text{th element of } \text{sat}_\delta(\boldsymbol{x}) = \begin{cases} \delta & \text{if } \delta < x_i, \\ x_i & \text{if } -\delta \leq x_i \leq \delta, \\ -\delta & \text{if } x_i < -\delta, \end{cases}$$

where $x_i \in \mathbb{R}$ is the ith element of $\boldsymbol{x} \in \mathbb{R}^n$.

II. Problem Formulation

Consider the PID control system for liquid slosh problem depicted in Fig. 1, where $r(t)$, $u(t)$, $y(t)$, and $\theta(t)$ are the reference, the control input, the measurement of lateral

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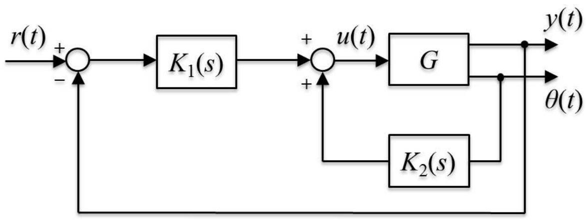

Fig. 1: PID control system for liquid slosh problem

position of the tank, and the measurement of slosh angle, respectively. The plant is the motor-driven liquid tank system G. The controller $K_i(s)$ $(i = 1, 2)$ is the PID controller

$$K_i(s) = P_i \left(1 + \frac{1}{I_i s} + \frac{D_i s}{1 + \dfrac{D_i}{N_i} s} \right), \tag{1}$$

where $P_i \in \mathbb{R}$ is the proportional gain, $I_i \in \mathbb{R}$ is the integral time, $D_i \in \mathbb{R}$ is the derivative time, and $N_i \in \mathbb{R}$ is the filter coefficient.

The performance index for the control system in Fig. 1 is given by

$$J(\boldsymbol{P}, \boldsymbol{I}, \boldsymbol{D}, \boldsymbol{N}) = w_1 \hat{e} + w_2 \hat{\theta} + w_3 \hat{u}, \tag{2}$$

where

$$\hat{e} = \int_{t_0}^{t_f} (r(t) - y(t))^2 dt, \tag{3}$$

$$\hat{u} = \int_{t_0}^{t_f} u(t)^2 dt, \tag{4}$$

$$\hat{\theta} = \int_{t_0}^{t_f} \theta(t)^2 dt. \tag{5}$$

In (2), $w_1 \in \mathbb{R}$, $w_2 \in \mathbb{R}$ and $w_3 \in \mathbb{R}$ are weighting coefficients which are defined by the designer. The matrices $\boldsymbol{P}$, $\boldsymbol{I}$, $\boldsymbol{D}$ and $\boldsymbol{N}$ are defined as $\boldsymbol{P} := [P_1 \ P_2]^\top$, $\boldsymbol{I} := [I_1 \ I_2]^\top$, $\boldsymbol{D} := [D_1 \ D_2]^\top$, $\boldsymbol{N} := [N_1 \ N_2]^\top$. Note that the first and second terms in (2) correspond to the tracking error, while the third means the control input energy. Here, the values of w_1, w_2 and w_3 are selected in a similar way to the standard Linear Quadratic Regulator (LQR) problem. The limits of integration of the integrals in (3)-(5), i.e., $t_0 \in 0 \cup \mathbb{R}_+$ and $t_f \in \mathbb{R}_+$ are respectively the upper and lower bounds of the time interval $[t_0, t_f]$, which corresponds to the period for evaluating the control performance. Then, the model-free PID problem can be described as follows:

Problem 2.1. For the feedback control system in Fig. 1, find a PID controller $K_i(s)$ $(i = 1, 2)$, which minimizes $J(\boldsymbol{P}, \boldsymbol{I}, \boldsymbol{D}, \boldsymbol{N})$ with respect to $\boldsymbol{P}$, $\boldsymbol{I}$, $\boldsymbol{D}$, and $\boldsymbol{N}$ based on the measurement data ($u(t)$, $y(t)$, $\theta(t)$).

III. PID Controller Design Based on Simultaneous Perturbation Stochastic Approximation

This section presents the main idea to solve Problem 2.1. Firstly, the SPSA algorithm [12] is briefly described. Then, a model-free PID tuning method based on the SPSA algorithm is explained.

A. Simultaneous Perturbation Stochastic Approximation

Consider the optimization problem given by

$$\min_{\boldsymbol{x} \in \mathbb{R}^n} f(\boldsymbol{x}) \tag{6}$$

where $f : \mathbb{R}^n \to \mathbb{R}$ is the objective function and $\boldsymbol{x} \in \mathbb{R}^n$ is the design parameter. The SPSA algorithm iteratively updates the design parameter to search an optimal solution $\boldsymbol{x}^* \in \mathbb{R}^n$ of (6). The updated law is given by

$$\boldsymbol{x}(k+1) = \boldsymbol{x}(k) - a(k)\boldsymbol{g}(\boldsymbol{x}(k), \boldsymbol{\Delta}(k)), \tag{7}$$

for $k = 0, 1, \cdots$, where $a(k)$ is the gain, $\boldsymbol{g}(\boldsymbol{x}(k), \boldsymbol{\Delta}(k))$ is the estimation of the gradient at the iterate $\boldsymbol{x}(k)$, which is given by

$$\boldsymbol{g}(\boldsymbol{x}(k), \boldsymbol{\Delta}(k)) = \begin{bmatrix} \dfrac{f(\boldsymbol{x}(k) + c(k)\boldsymbol{\Delta}(k)) - f(\boldsymbol{x}(k) - c(k)\boldsymbol{\Delta}(k))}{2c(k)\Delta_1(k)} \\ \vdots \\ \dfrac{f(\boldsymbol{x}(k) + c(k)\boldsymbol{\Delta}(k)) - f(\boldsymbol{x}(k) - c(k)\boldsymbol{\Delta}(k))}{2c(k)\Delta_n(k)} \end{bmatrix}. \tag{8}$$

In (8), $c(k)$ is another gain, and $\boldsymbol{\Delta}(k)$ is the n-dimensional random perturbation vector. For example, the gains $a(k)$ and $c(k)$ are given by $a(k) = a/(A + k + 1)^\alpha$ and $c(k) = c/(k+1)^\gamma$, respectively, for nonnegative numbers a, c, A, α, γ. Meanwhile, $\boldsymbol{\Delta}(k)$ is, for example drawn from the Bernoulli distribution

$$\begin{cases} \mathbb{P}(\Delta_i(k) = 1) = 0.5, \\ \mathbb{P}(\Delta_i(k) = -1) = 0.5, \end{cases} \tag{9}$$

and $\Delta_i(k)$ is its ith component. Note that the convergence conditions of the SPSA algorithm and the guidance to choose $a(k)$, $c(k)$, and $\boldsymbol{\Delta}(k)$ are explained in [12].

B. Model-Free PID Controller Design

In this section, the SPSA algorithm in Section III.A. is applied for model-free PID tuning. Firstly, let the design parameter is defined as follows:

$$\boldsymbol{\psi} = [P_1 \ P_2 \ I_1 \ I_2 \ D_1 \ D_2 \ N_1 \ N_2]^\top \in \mathbb{R}^8. \tag{10}$$

Then, in order to accelerate the design parameter $\boldsymbol{\psi}$ searching, we employ the logarithmic scale to the design parameter by setting $\psi_i = 10^{x_i}$ $(i = 1, 2, \ldots, 8)$ with the objective function $J([10^{x_1} \ 10^{x_2} \ \ldots \ 10^{x_8}]^\top)$. Finally, our design procedure is described as follows:

Step 1: Determine the maximum number of iterations $k_{\max}$ and let $x_i = \log \psi_i$ $(i = 1, 2, \ldots, 8)$, and select the initial value $\boldsymbol{x}(0)$.

Step 2: Execute the SPSA algorithm in (7) for the objective function in (2).

Step 3: After $k_{\max}$ iterations, the output $\boldsymbol{x}^* := \boldsymbol{x}(k_{\max}) \in \mathbb{R}^n$ is obtained. Then, $\boldsymbol{\psi}^* := [10^{x_1^*} \ 10^{x_2^*} \ \ldots \ 10^{x_8^*}]^\top$ is applied to the PID controller $K_i(s)$ $(i = 1, 2)$ in the feedback control system in Fig. 1.

Remark 3.1. Note that the standard SPSA algorithm in (7) does not always give a stable solution during the optimization process. This is due to a possibility that the design parameters become a very large value and suddenly trapped in an unfeasible region. In order to avoid this problem, we adopt a modified SPSA algorithm, which has been introduced in [16]. There, a saturation function $\mathrm{sat}_\delta(\cdot)$ has been used in (7). That is,

$$\boldsymbol{x}(k+1) = \boldsymbol{x}(k) - \mathrm{sat}_\delta\Big(a(k)\boldsymbol{g}(\boldsymbol{x}(k), \Delta(k))\Big). \tag{11}$$

In the following part of this paper, the improved update law in (11) is adopted instead of (7).

IV. Simulation Results

In this section, the effectiveness of the proposed model-free PID tuning based on SPSA is demonstrated. Firstly, a liquid slosh model in [15] is briefly described. Then, the SPSA based method is tested to the developed model.

A. Liquid Slosh Model

We consider a liquid slosh model in [15] that performing a rectilinear motion as shown in Fig. 2. Then, the Euler-Lagrange equations in y and θ, which produce dynamic equations of the system, is given by

$$M\ddot{y} + ml\cos\theta\ddot{\theta} - ml\dot{\theta}^2\sin\theta = u, \tag{12}$$

$$ml\cos\theta\ddot{y} + ml^2\ddot{\theta} + d\dot{\theta} + mgl\sin\theta = 0, \tag{13}$$

where M, m, l, g, and d are mass of the tank and liquid, mass of the liquid, hypotenuse length of the liquid slosh, gravity, and damping coefficient, respectively. For simplicity, let the measurement outputs of the system is defined by $[y(t)\ \ \theta(t)]^\top := G(u(t))$. Then, our control objective is to suppress the slosh angle θ in a moving tank while achieving a desired position y.

B. Numerical Example

Consider a liquid slosh plant G from the model in Section IV-A. with the system parameters depicted in Table I. Note that these parameters depend on the liquid fill ratio, tank geometry, and liquid characteristics. Here, these parameters have been identified using a quick-stop experiment as reported in [17]. Next, the reference of the cart position is given by

$$r(t) = \begin{cases} 0, & 0 \le t \le 0.5, \\ 0.5, & 0.5 < t \le 20. \end{cases} \tag{14}$$

The controller $K_i(s)$ $(i = 1, 2)$ is the PID controller in a feedback control structure as shown in Fig. 1. The corresponding design parameters are presented in Table II. Our aim is to find an $\boldsymbol{x} \in \mathbb{R}^8$, which minimizes the performance index J in (2) for $w_1 = 100$, $w_2 = 100$, $w_3 = 5$, $t_0 = 0$, and $t_f = 20$. We set the parameters of the SPSA based algorithm as $a(k) = 0.005/(k+24)^{0.6}$, $c(k) = 0.2/(k+1)^{0.1}$, $\delta = 0.1$, and $k_{\max} = 200$. The initial condition $\boldsymbol{x}(0)$ is given in Table II, which is assumed to produce a stable closed-loop system during the evaluation period.

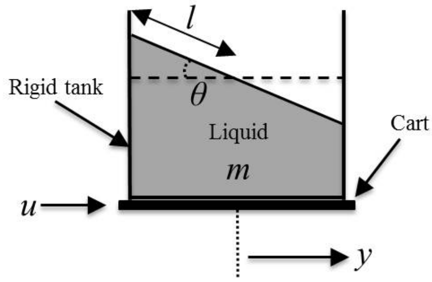

Fig. 2: Liquid slosh motion

TABLE I: Parameters of the Liquid Slosh Model

Parameter	Value	Unit
M	6.0	kg
m	1.32	kg
l	0.052126	m
g	9.81	m/s^2
d	3.0490×10^{-4}	kg m^2/s

Fig. 3 shows the response of the objective function after 200 iterations and Table II shows the resulting design parameter $\boldsymbol{x}^* \in \mathbb{R}^8$. It clarifies that, the SPSA based method successfully minimizes the objective function and yields optimal PID parameters. Meanwhile, the responses of $y(t)$, $\theta(t)$, and $u(t)$ are shown in Figs. 4, 5, and 6, respectively. In these figures, the thin grey line represents the responses at $k = 0$ and the thick black line represents the responses at $k = 200$, which is the optimal design parameters. It shows that the cart settles to the desired position in about 3 s (see Fig. 4) with better liquid slosh suppression. Furthermore, acceptable control input energy (see Fig. 6) is used to achieve the control objective. Hence, we can confirm that the model-free PID tuning based on SPSA method has a good potential in reducing the liquid slosh while maintaining the desired cart position.

V. Conclusion

In this paper, a preliminary study of a model-free PID tuning based on SPSA method for liquid slosh suppression has been addressed. The proposed method has been tested to liquid slosh model in [15]. The simulation results demonstrate that the model-free PID approach based on SPSA yields a minimal liquid slosh, while achieving the desired cart position.

In the future, the applicability of the proposed method for an online model-free approach will be investigated using a motor-driven liquid slosh experimental rig.

Acknowledgement

The work was partly supported by Research Grant RDU150344 from the Research and Innovation Department, University of Malaysia Pahang.

TABLE II: Design Parameters

$\boldsymbol{\psi}$	PID gain	$\boldsymbol{x}(0)$	$\boldsymbol{\psi}$ corresponding to $\boldsymbol{x}(0)$ ($\times 10^3$)	$\boldsymbol{x}^*$	$\boldsymbol{\psi}^*$ corresponding to $\boldsymbol{x}^*$ ($\times 10^3$)
ψ_1	P_1	1.0000	0.0100	0.5300	0.0034
ψ_2	I_1	3.5000	3.1623	3.2996	1.9936
ψ_3	D_1	0.0000	0.0010	0.2524	0.0018
ψ_4	N_1	1.0000	0.0100	0.4233	0.0027
ψ_5	P_2	2.0000	0.1000	2.0323	0.1077
ψ_6	I_2	1.0000	0.0100	0.2810	0.0019
ψ_7	D_2	0.0000	0.0010	-0.7207	0.0002
ψ_8	N_2	1.0000	0.0100	1.3460	0.0222

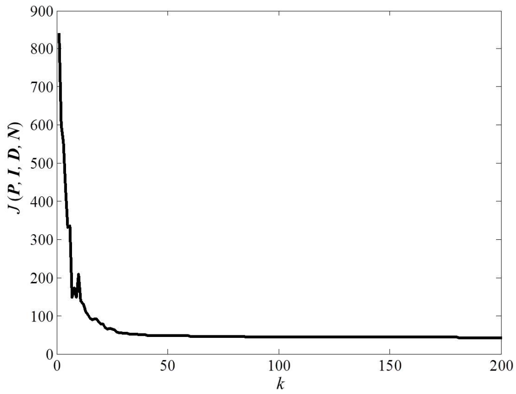

Fig. 3: Objective function

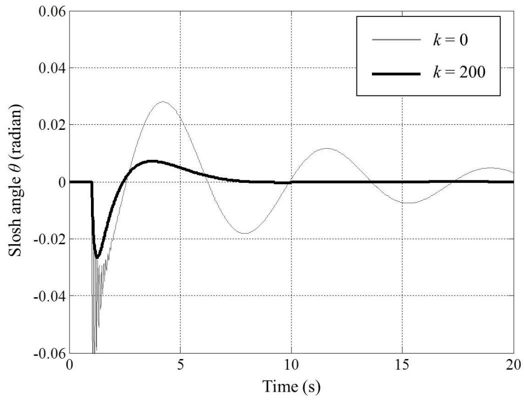

Fig. 5: Slosh angle response

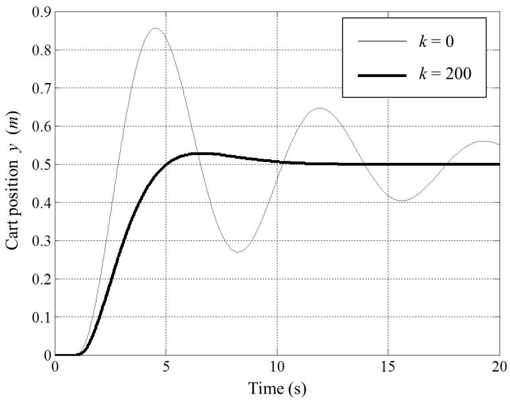

Fig. 4: Cart position response

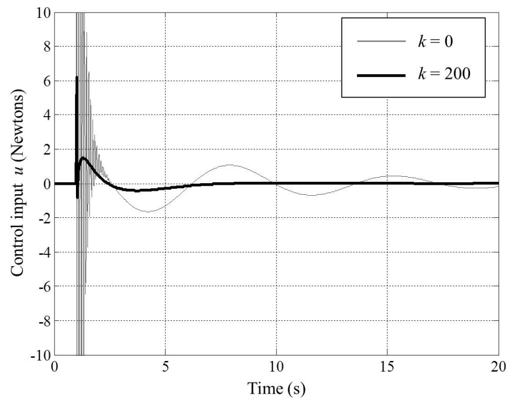

Fig. 6: Control input response

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A Data-Driven Sigmoid-based PI Controller for Buck-Converter Powered DC Motor

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***Abstract*—This paper presents a novel data-driven sigmoid-based PI for tracking of angular velocity of dc motor powered by a dc/dc buck converter. A global simultaneous perturbation stochastic approximation (GSPSA) is employed to find the optimum sigmoid-based PI parameters such that the angular velocity error is minimized. The merit of the proposed approach is that it can produce fast PI parameter tuning without using any plant model by measuring the I/O data of the system. Moreover, the proposed PI parameters that are varied based on sigmoid function of angular velocity error has great potential in improving the control performance compared to the conventional PI controller. A well-known buck converter powered DC motor model is considered to validate our data-driven design. In addition, the performances of the proposed method are examined in terms of angular velocity trajectory tracking and duty cycle in comparison with other existing approaches. Numerical example shows that the data-driven sigmoid-based PI approach provides better control performances as compared to existing methods.**

***Index Terms*—Data-driven, variable structure PI, buck converter powered dc motor, tracking control.**

I. Introduction

Nowadays, many applications of dc motors require a high precision motion, such as rolling mills, electric cranes, conveyor belts and liquid carriers. Generally, many researchers apply conventional pulse width modulation (PWM) signals to drive the dc motor. However, this approach provides an unsatisfactory dynamic behavior due to hard switching strategy, which causing sudden changes in the current and voltage of the dc motor [1]. In order to solve this issue, a dc/dc buck converter is utilized, which allows to control the stepless velocity and smoothness. In particular, it can track both desired angular velocity and position trajectory by adjusting the required motor input voltage.

So far, a large number of methods have been widely reported in controlling buck-converter powered dc motor. In [2], a classical proportional-integral (PI) controller is utilized to regulate the the dc motor angular velocity. Here, they apply the controller to a fourth-order mathematical model of buck converters with a dc motor. Likewise, for the same mathematical model, a feedback controller based on damping injection and energy shaping has been synthesized in [3]. In [1], [4] and [5], a flatness based approach is employed for a smooth tracking of angular velocity of dc motor driven by dc/dc buck converter. The controller in [1] and [4] was obtained through a fourth-order model deduced in [2], while the controller in [5] was designed based on simplified second-order model. Note that in the second-order model, it is assumed that the converter capacitor current and the motor armature inductance to be negligible. Furthermore, a GPI control based on sliding mode-delta modulation is proposed in [6]. Here, they used the simplified mathematical model in [5]. Moreover, in [7], a backstepping controller with both adaptive and non-adaptive versions were derived from fourth-order mathematical model. Their numerical simulation show that the adaptive version provides better performance with load torque variations. Other control approaches for dc/dc buck converter powered dc motors include PI and LQR controllers [8], PI-Fuzzy controller [9], neural network controller [10], H_∞ controller [11], robust control law based on active disturbance rejection [12], and two-stage control based on differential flatness [13].

As shown in the above, most of the designed approaches has focused on the model-based controllers, which are derived from second or fourth-order mathematical model. However, it is difficult to apply the traditional model-based controller in real buck-converter powered dc motor systems due to several reasons, such as, the inaccuracy of simplified model, unmodeled dynamic problems, and huge gap between control theory and real applications. As a results, a data-driven controller will be more convincing solution. In particular, the data-driven controller is designed based on input-output data of the systems without using explicit or implicit information of the plants. Here, the data-driven controller based on PID structure is highly preferable due to its simplicity in design and implementation [14]. Furthermore, the performance of conventional PID controller can be improved by modifying it to variable structure PID (VS-PID), which has been widely reported in many literatures [15]–[17]. Hence, it is worth evaluating the capability of data-driven VS-PID controller for tracking of angular velocity trajectory of buck-converter powered dc motor.

This paper aims to explore the capability of the data-driven sigmoid-based PI for tracking of angular velocity trajectory of buck-converter powered dc motor. Note that, the sigmoid-based PI, which is in the family of VS-PID, has been introduced in [17]. It offers great potential to improve the control performance by varying the PI parameters based

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