Faculty of Engineering

ADAPTIVE ITERATIVE LEARNING CONTROL WITH PROPORTIONAL INTEGRAL AMMONIUM BASED AERATION CONTROL (ILC-PI-ABAC)

Willyson Anak Steward

Bachelor of Engineering

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ADAPTIVE ITERATIVE LEARNING CONTROL WITH PROPORTIONAL INTEGRAL AMMONIUM BASED AERATION CONTROL (ILC-PI-ABAC)

WILLYSON ANAK STEWARD

A dissertation submitted in partial fulfilment
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ABSTRACT

Wastewater treatment is a complex dynamic system with wide number of states and parameters that process focus on the attainment of environmental objectives. WWTPs are prone to large perturbations in the entering stream and uncertainty in influent composition. Besides, complex interactions in biological processes within the ASP and nonlinearity of the control parameters, let to big challenges in optimisation of WWTP operation. Therefore, controlling the concentration of dissolve oxygen is the main objective and to provide sufficient and optimum amount of DO according to the microorganism's oxygen demand is important to running the plant with the least amount of energy. Thus, in this study, the idea of ILC with PI-ABAC feedback regulator is proposed to provide improvement in controlling DO level through incorporation and data learning of iteration data. The performance assessment of the proposed controller is carried out using Benchmark Simulation Model No 1 for three different influent condition which are dry, rain and storm influent. Assessment takes into account three main aspects which are evaluation in term of effluent violations, effluent average concentrations and evaluation based on the total operational cost index (OCI), average aeration energy per day (AE) and effluent quality (EQ) index. Comparison results with performance of default PI controller show improvement in majority of the measured parameter in term of effluent quality and reduction in effluent violation. In addition, ILC-PI- ABAC also contribute to reduction in energy consumption of the wastewater treatment plant with reduction of 23% to 24 % of average aeration energy per day. For the improvement of the control system, some of the approaches suggested is performance evaluation that involve first and second stage evaluation in order to obtain the data of plant performance and the control system. Therefore, providing sufficient data needed in measurement of the effectiveness of the proposed control system. In addition, the addition of the Simulink model for the ILC control monitoring system has been proposed to enable researchers to further monitor and analyse the ILC control system.

ABSTRAK

Rawatan air kumbahan merangkumi sistem dinamik yang kompleks dengan beberapa peringkat rawatan dan parameter yang pelbagai yang mana tujuannya memfokuskan kepada pencapaian objektif alam sekitar yang baik. Loji rawatan kumbahan terdedah kepada pelbagai gangguan dan ketidaktentuan dalam komposisi air kumbahan yang dirawat. Selain itu, tindak balas biologi yang komplek dalam proses enap cemar teraktif dan ketidaktentuan kandungan air kumbahan, memberikan cabaran besar dalam pengoptimuman operasi loji rawatan kumbahan. Oleh itu , pengawalan kepekatan oksigen terlarut adalah menjadi objektif utama dalam memperuntukan jumlah oksigen terlarut yang mencukupi dan pada kadar yang optimum agar dapat meminimumkan kos pengoperasian loji rawatan kumbahan. Oleh itu, dalam kajian ini, idea pengaplikasian *Iterative Learning Control (ILC)* berserta *Proportional Integral Ammonia Based Aeration Control System (PI-ABAC)* telah diketengahkan untuk penambahbaikan kawalan kadar oksigen terlarut (DO) melalui pembelajaran data lelaran. Penilaian prestasi terhadap sistem kawalan yang dicadangkan telah dilakukan menggunakan *Benchmark Simulation Model No 1(BSM1)* dengan mengambil kira tiga keadaan iaitu aliran masuk kumbahan dengan keadaan cuaca cerah, hujan dan hujan ribut. Penilaian mengambil kira tiga aspek utama iaitu penilaian dari segi pelanggaran efluen, kepekatan purata efluen serta penilaian berdasarkan jumlah *Operational Cost Index (OCI), Average Aeration Energy (AE)* dan *Effluent Quality Index (EQ)*. Hasil perbandingan dengan prestasi pengawal PI menunjukkan peningkatan dalam kebanyakan parameter yang diukur iaitu peningkatan dari segi kualiti efluen dan pengurangan pelanggaran efluen. Di samping itu, ILC-PI-ABAC juga menyumbang kepada pengurangan penggunaan tenaga loji rawatan air sisa dengan pengurangan 23% hingga 24% daripada purata tenaga pengudaraan sehari. Berapa pendekatan atau cadangan yang dikemukakan bagi penambahbaikan sistem kawalan adalah, penilaian berdasarkan kaedah penilaian peringkat pertama dan kedua bagi memperoleh data prestasi loji dan sistem kawalan. Hal ini demikian, memberi data yang secukupnya untuk mengukur keberkesanan sistem kawalan. Selain itu, cadangan penambahan Simulink model untuk sistem pemantauan kawalan ILC telah dekemukakan bagi membolehkan pengkaji memantau dan menganalisis sistem kawalan ILC dengan lebih lanjut.

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LIST OF ABBREVIATIONS

ABAC	-	Ammonia Based Aeration System
AE	-	Aeration Energy
ASP	-	Activated Sludge System
BOD5	-	Biochemical Oxygen Demand
BSM1	-	Benchmark Simulation Model No 1
COD	-	Chemical Oxygen Demand
DO	-	Dissolved Oxygen
EQ	-	Effluent Quality
ILC	-	Iterative Learning Control
Ntot	-	Total Nitrogen
OCI	-	Operational Cost Index
SNH	-	Ammonia
TSS	-	Total Suspended Solid
WWTPs	-	Wastewater Treatment Plant System

CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the past few years, rapid development of urbanization and continuous advancement of industrialization has shown escalation in production and as well as its residue which contribute in water pollution problem mainly in urban area. Wastewater treatment is a complex dynamic system with wide number of states and parameters that process focus on the attainment of environmental objectives. Wastewater treatment plants (WWTPs) or municipal wastewater treatment is a combination of mechanical, biological, and chemical treatment with main treatment method known as activated sludge process and oxidation ditch process. Basically, the wastewater treatment process include removal of floating and portion of the suspended solids during primary treatment, which then followed by a biological treatment for nutrients and organic chemical treatment where nitrogen is removed through biological process known as activated sludge process (ASP) [1]. In ASP, the organic matters from influent or raw water are oxidised by microorganism to produce treated water or effluent. The treatment with ASP will result in formation carbon dioxide and new cell mass from organic matters. The new cell mass or known as a sludge contains both living and dead microorganism that producing phosphorus and nitrogen [2].

The benchmark is a simulation platform that provide layout of plant as simulation model, influent loads, test processes, and assessment criteria. The initial design of BSM1 consists of five-compartment of activated sludge reactor with two compartments are for anoxic tanks and the other three compartment are for aerobic tanks which then followed by secondary settler to makes up the benchmark plant. In this way, the plant provides basic configuration which combines nitrification with pre-denitrification as in commonly used in full-scale plant for biological removal of nitrogen. To evaluate the benchmark, a simple control approach is proposed, with the goal of manipulating the oxygen transfer coefficient for regulation of dissolved oxygen (DO) level in the last reactor compartment.

Based on BSM1, nitrification and denitrification are two essential processes that are involved in removal of nitrogen in activated sludge process. In fact, removal of nitrogen in ASP is a two-step process that involves simultaneous operation of both nitrification and denitrification processes. Nitrification is chemical process which involve oxidation of ammonium to nitrate. The nitrification process is carried out in the presence of oxygen in aerobic circumstances. The nitrate generated during the nitrification process, is subsequently transformed into gaseous nitrogen during the denitrification phase [3]. Denitrification phase is taken place in an anoxic (oxygen-free) environment. In nitrification process, DO is required by microorganisms for chemical reaction to occur and controlling of this variable is important for reaction to operate effectively. Improvement of DO control has been practiced for many years as to improve the effectiveness of chemical process in wastewater treatment system

WWTPs is well-known as a complicated multivariable and large-scale plant that necessitates a sophisticated control method. The primary purpose of wastewater treatment is to meet stringent effluent criteria and minimize operation expenses while maintaining quality of water treated [3]. One of major problem faced in wastewater treatment is continuously changing condition and nonlinearity of the parameters. Therefore, a control system which could improve the efficiency of treatment process through good control of DO concentration and nitrogen removal process during set-point adjustments is highly demanded.

1.2 Problem Statement

The increase in population, rapid development of urbanization and continuous advancement of industrialization contribute to more sewage sludge production. As a result, the disposal of domestic sewage sludge is becoming more significant, putting a financial strain on wastewater treatment firms. The disposal of home sewage sludge would result in a slew of environmental and health risks. Therefore, sewage sludge disposal must be treated properly to avoid producing significant problems in the country. It is estimated that by 2020, 7 million metric tonnes of sewage sludge will be produced annually, up from the current 3 million metric tonnes[5]. According to Siti Noorain, [5]the cost of controlling sewage sludge is around US$ 0.33 billion per year. Malaysia has been producing more than 4.5 million cubic metres of residential sludge annually since 2005, according to data from the Indah Water Consortium, and the volume of sludge generated has been increasing year after year.

WWTPs are prone to large perturbations in the entering stream and uncertainty in influent composition, which make it difficult to manage. Besides, complex interactions in biological processes within the ASP and nonlinearity of the control parameters, let to big challenges in WWTP operation and process control in WWTP, aeration section contribute about 50-90 percent of the total energy demand. Most of research on ASP optimisation related to aeration control are focusing on the concentration of dissolved oxygen, with the goal to lowering the operations costs by reducing energy consumption during the process. Therefore, the controlling the concentration of dissolve oxygen is become the main objective and to provide sufficient and optimum amount of DO according to the microorganism's oxygen demand is important to running the plant with the least amount of energy. However, the uncertainty of the influent parameter led to difficulty in determining the exact amount oxygen needed during activated sludge process. Therefore, many control systems are designed to maintain DO at a pre-determined setpoint.

1.3 Research Objectives

a. To design an adaptive PI ABAC controller, combine with iterative learning controller (ILC).
b. To evaluate the performances of the ILC-PI-ABAC in terms of Total effluent violation of Nitrogen level (Ntot) and Ammonia Nitrogen level (SN) and Effluents concentration of Ammonia (SNH), Total Suspended Solid (TSS) , Total Nitrogen (N), Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD).
c. To evaluate the performance of the ILC-PI-ABAC controller based on the aeration energy.

1.4 Research Scope

a. The simulation is emphasizing on the Benchmark Simulation Model No. 1 (BSM1) using MATLAB Simulink simulation Platform
b. The work is concerns on the improvement of PI controller for ammonium-based aeration control of activated sludge system. The main studies will focus on manipulation of DO during activated sludge process.
c. In the simulation, the improvement of effluent water quality is considered. That quality is total nitrogen (Ntot), biochemical oxygen demand (BOD5), chemical oxygen demand (COD), ammonia (SNH), and total suspended solids (TSS)
d. The effectiveness of developed adapted ILC-PI-ABAC controller for ammonium-based aeration control is compared to the default benchmark PI controller's performance.

1.5 Organization of the report

The report's structure is organized as follows. Chapter 1 is introduction of the study that include research background, statement of problem, objective, and research scope. Meanwhile chapter 2 discuss on literature review of study related to the research topic as well as research gap of the studies. In this section, total of ten studies is discuss and most of its are focus on control system for improvement of WWTPs mainly in regulation of dissolved oxygen for activated sludge process. Chapter 3 is about methodology that briefly explain on BSM1 model use for simulation of WWTPs and performance evaluation of new proposed control system. Development of proposed control system which is combine Iterative learning control (ILC) with PI controller for ammonium-based aeration (ABAC) are also discuss in this section. The analysis and discussion of the results will be covered in more detail in Chapter 4. This chapter also covers the issue that arose during the project's conclusion. The information is gathered, and the simulation's outcomes will be evaluated. The outcome is compared to the performance of Benchmark Model Simulation No 1. Lastly, Chapter 5 is about the conclusion of this project and future recommendations.

Chapter 2

LITERATURE REVIEW

2.1 Introduction to Wastewater Treatment Plant

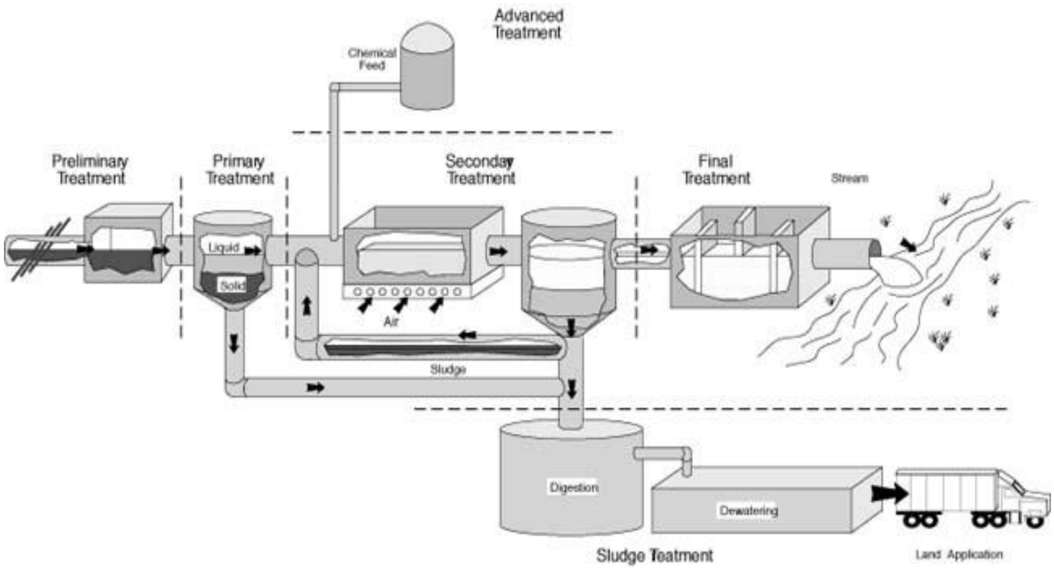

Figure 2.1: Wastewater Treatment Plant [7]

A wastewater treatment plant is a sophisticated facility that removes contaminants from both industrial and domestic wastewater. [6]. Some of the goals of wastewater treatment are reduction of nutrient concentration and biodegradable organic substances in wastewater influence, pathogens eradication and to recycle as well as reuse wastewater. In WWTPs there are four level of treatment which are preliminary, primary, secondary and tertiary treatment [7]. Preliminary treatment focus on removing grits and coarse suspended using grit chamber and screening method. Primary treatment involves removal of inorganic and settleable solids through process called sedimentation. In this process, up to 70% of suspended solid, 50% of BOD5 and 65% of gris and oil can be remove including heavy metals and some organic phosphorus and nitrogen. Effluent of primary treatment is referred as primary treatment. In the other hand, secondary treatment is a treatment used to remove residual pollutant from primary effluent such as nitrogen and phosphorus compounds. Some of treatment method are activated sludge methods, anaerobic treatment, stabilization ponds, oxidation ditches etc.

Finally is tertiary treatment. Tertiary treatment is the last treatment or advance treatment in WWTPs that which include removal of heavy metals, bacteria, viruses, nitrogen, phosphorus etc. In this stage, Chlorine is injected for disinfection process together with Ozone and irradiation with Ultraviolet (UV) as to meet current effluent standard. Method uses in tertiary treatment is known as disk filtration. Disk filtrations utilize large disk of membrane material or cloth media for filtration inside large rotating drums.

2.2 Activated Sludge Process

Activated sludge is a reduction of sludge particles in wastewater by growth of aeration organisms in aeration tanks [8]. A basic activated sludge system is made up of several interconnected components which are an aeration tank for biological treatment process, aeration source such as oxygen for mixing and a clarifier which is a tank for separation of solid settle from treated wastewater. Screened wastewaters contain high amount of organism from a secondary clarifying tank which then formed into mixed liquor. In aeration tank, mixed liquor is provided with oxygen for aerobic bacteria to thrive and multiply rapidly producing new cells with sufficient food and aeration source. The mixture then keeps stirred for a period to keep its solid suspension before flowed to clarifier tank and form sediment. The sediment is either returned to the aeration tank to mix with the incoming wastewater influent or discarded as excess in a process known as wasting. Meanwhile the treatment leftover above the sludge which is a clear liquid known as supernatant flowed for further treatment as needed.

The Biochemical Oxygen Demand (BOD) is another feature of wastewater that is strictly regulated [10]. Many components of wastewater, such as microorganisms that feed on contaminants in the wastewater influent, place an oxygen demand on a wastewater treatment system or a receiving stream. Since bacteria require oxygen to breakdown contaminants, DO is absorbed from the stream. The quantity of oxygen required for biodegradation of the contaminant increases as the pollution load in the wastewater influent increase. Other organic pollutants, such as ammonia, contribute to the oxygen demand since oxygen is necessary for the nitrification process, which converts ammonia to nitrate. As a result, total BOD equals the sum of carbonaceous and nitrogenous oxygen demand (CBOD and NOD, respectively) [11].

The contents of an activated sludge reactor's aeration mixture must meet two crucial requirements: mixing of the influent must occur, and a large amount of oxygen must be supplied to the aeration mixture [8]. Adequate mixing of the influent is important to increase contact between the incoming pollutants and biomass in aeration tank. Aeration must supply adequate oxygen to the mixed liquor’s huge population of aerobic, as well as other organisms. In most wastewater treatment plant, operators commonly regulate the aeration rate to maintain a DO concentration of 2-3mg/L at the aeration tank’s discharge end. Higher DO concentrations contribute to high power consumption while a low DO value (less than 1 mg/L) may reduce the efficiency of the system [3].

The volume of air that must be provided to the aeration tank to achieve the necessary DO concentration is influenced by several factors. As the BOD loading increases, more oxygen and air will be required to metabolise the waste and keep the DO concentration within the acceptable range. Furthermore, when the amount of biomass in the system grows, the amount of oxygen available to each organism must be maintained, as each organism will use the amount of oxygen required to survive. Factors that affect the amount of air supplied includes the treatment objectives such as Nitration and Denitrification. Decomposition of 1 pound of BOD requires 1.0 to 1.5 pounds of oxygen, whereas nitrification requires up to 4.5 pounds of oxygen to convert 1 pound of ammonia to nitrate. [12].

The aeration equipment’s Oxygen Transfer Efficiency plays an important part in optimizing the amount of oxygen supply to the organisms. The oxygen supplied to the aeration tank may not be completely dissolved in the water, instead, some of it bubbles to the top and is lost to the atmosphere. Standard oxygen transfer efficiency (SOTE) for most aeration systems in clear water and at 15 feet of submergence ranges from roughly 10% to 40%. Standard Oxygen Transmission Rate (SOTR), which is measured in pounds of oxygen transmitted per horsepower hour, can be used to describe the oxygen transfer.

Adding on, the Actual Oxygen Transfer Rate (AOTR) in wastewater is considered much lower than SOTR. Some factors that affect the oxygen transfer which include the type of equipment used, air temperature, water chemical properties, and oxygen uptake rate. The AOTR, for example, could be around 2.5 pounds of oxygen per horsepower hour. While the SOTR for a specific aeration system could result in as much as 6.5 pounds of oxygen per horsepower hour [13].

2.3 Weather influent effect to wastewater treatment plant effluents

One of the major factors that greatly influence the ecosystem of wastewater treatment plant is the weather condition. weather conation such as dry, rain and storm results in different rainfall amount which then cause in nonlinearity of wastewater influent. As consequences, results in inconsistency of wastewater treatment operation, as it has to fulfil the treatment requirement which depend on the current condition of influent parameter. In fact, effluent parameter also changing. Over the year, several studies have been conducted as to investigate and analyse weather impact on WWTPs. Most of the research focusing on to main weather condition which are dry and rain weather.

In [31] Makuwa et al conducted studies on weather impact to performance of wastewater treatment plant in Northwest Province, South Africa. The study focusses two type of weather parameter which dry and wet season with objective to evaluate the impact of seasonal fluctuations in temperature and rainfall on chemical parameters of both influent and effluent of wastewater treatment plant. According to this study, the wet season has higher temperatures and more rainfall than the dry season, which in turn has lower temperatures and less rainfall on average. For WWTPs that are connected to stormwater systems, the heavy rainfall influences the inflow rate and consequently alter the performance of the treatment plant.

As for the ammonia parameter, ammonia by-products of anaerobic digestion are linked to high ammonia concentrations in influent, but nitrification and de-nitrification processes may be responsible for low ammonia concentrations at the effluent point [32]. The study found that the average ammonia concentration in the influent was higher in the dry season (43.18 mg/L) than the wet season (37.09 mg/L), while the final effluent discharged during the dry and wet seasons had concentrations of 0.27 and 3.68 mg/L, respectively. Regardless of the influent concentration, the effluent ammonia concentration produced or discharged depends on the reduction rate which scientifically affected by weather condition. The average reduction for the dry and wet seasons was 99.37% and 90.08 %, respectively.

COD is a metric for wastewater quality that is used to examine the performance of WWTPs [33]. Anaerobic conditions caused by high COD can be hazardous to aquatic life [34]. In anaerobic treatment of activated sludge process, anaerobic microorganisms metabolize COD into biogas in an anoxic condition [35]. Lower COD levels are mainly related to dilution due to increased water flow rate during the rainy season. In the dry season, the plant reduced COD by 95.45 to 96.13 percent. Meanwhile, COD reductions during the wet season were between 92.56 and 96.55 percent. Research by [36] at Boundary WWTP in Eldoret Municipality, Uasin-Gishu County, Kenya demonstrated COD reductions of 89.23 and 93.91 percent, respectively, in dry and wet weather phase.

It is well known that an increase in nitrate concentration speeds up algae growth, resulting in eutrophication or algae bloom Some bad impact that produce are increase in oxygen demand, death of certain aquatic life forms, and unpleasant odours to environment. Same as COD, nitrate entering and discharge from the wastewater plants was higher in the dry season than the rainy season. For both influent and effluent, [37] found that nitrate concentrations were higher during the dry rather than the rainy season. The reduction efficiency for nitrate varied between 22.95 and 17.1 percent in the dry season and between 31.94 and 88.32 percent in the rainy season. According to [38], the performance of nitrate reduction in dry and wet seasons was 48.97 % and 42.86 %, respectively, meanwhile in [31] the plant was able to reduce nitrate in dry and wet seasons by 2.97% and 65.30%, respectively.

2.4 Iterative Learning Control

Iterative Learning Control (ILC) is a method of tracking control for systems that operate in a repetitive mode. Reliability testing rigs, chemical batch processes, and robot arm manipulators is some examples of the process industries that perform execution of the same task with a finite duration repeatedly. The main idea behind ILC control method is to repetitively learn and use the information of previous iteration data for improvement of control signal for the next iteration trial. An ILC algorithm is effective for used in dynamic system that provided with reference trajectory. A fundamental schematic representation of an ILC system is shown in Figure 2.2, where the memory component stores both control input and system output computed from the prior trial data. For ILC to work perfectly, its system must be construct with sequence system that supervise and responsible in controlling the sequence of both input and output of iteration signal. This makes it able for the system to keep the input in sequence that, when added to the system, generates sequential output. thus, as the trial number increases the trial control input, reference trajectory and control output are converging where the relevant signal space norms are used to measure convergence. These characteristics are known as convergent learning. Since the first introduction of the system, a significant amount of work has been done on ILC and RC, and in each case, there is convincing evidence of experimental verification in both the lab and real-world application scenarios.

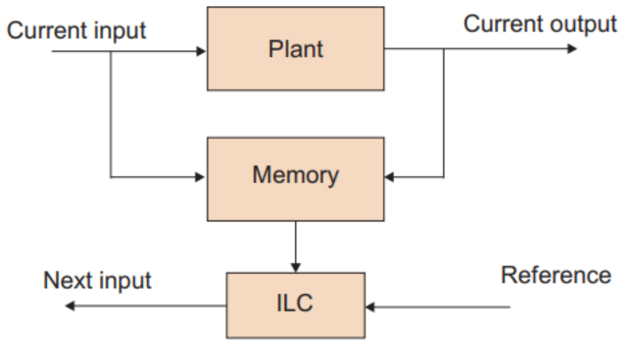

Figure 2.2: Fundamental Structure of Iterative Learning Control [39]

In [39] Bristow et al provide discussion on ILC control update structure. ILC sequentially enhances tracing of the reference signal using data from preceding tasks' execution. The control input must be updated in between trials to achieve this. The input is significantly impacted by trial error, the deviation between trial output and referenced signal. Figure 2.3 illustrate the theory on how sequential learning operation is perform in ILC system.

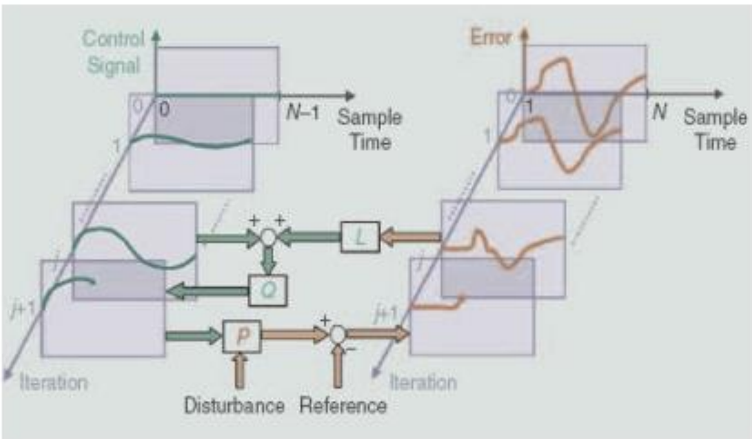

Figure 2.3: Iterative learning control update structure [39]