Development of an Automated System for the Monitoring and Control pH and Conductivity of a Dampening Solution

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Abstract *— The influence of dampening solution parameters on the final printing quality has been remarked on many researches during the last decades. There are many parameters that need to be controlled on a fountain solution as pH, conductivity, temperature, and water hardness to obtain a good printing quality. Two of the most important parameters are conductivity and pH level. Conductivity and pH variations can lead to problems due to a disturbed ink / water balance, increased wear of printing plates, and more. This project focuses in the design of an automated control to keep conductivity and pH of the fountain solution in a Heidelberg Press in control. The most challenging topics in modern control theory is non-linear control and pH and conductivity shown a non-linear characteristic. It was recommended after evaluate control theories a Model-Free Adaptive control was selected over PID control, pH fuzzy logic control, and PID error square control.*

Key Terms *— Conductivity Control, Fountain Solution (Dampening Solution), Model-Free Adaptive Control, pH Control,*

INTRODUCTION

ABC Pharma Printing (ABCPP) is a North American based printing and converting company specializing in manufacturing pressure sensitive pharmaceutical roll labels, pharmaceutical package inserts and outserts, and innovative folding cartons for the branded and generic pharmaceutical industry, as well as the medical device and health-care related package goods industries.

ABCPP is not Food and Drug Administration (FDA) regulated but as pharmaceutical printing producer follows PS 9000 standard used by pharmaceutical packaging industry which it is harmonized with ISO 9001 standard requirements. Usually, printed products are categorized into commercial printing and periodicals. This classification differentiates printed matter with regard to its frequency of publication. Since the production process also depends largely on these basic conditions, print shops usually specialize in one or the other market segment. [1][2]

A final printed piece has three components: paper, ink, and fountain solution emulsified in the ink. Accurate fountain (dampening) solution concentration control is essential for consistent, high-quality results in lithography and offset printing. Low concentration can cause drying on the non-image area of the plate resulting in tinting, scumming, blanket piling, etc. High concentrations, on the other hand, bring about over-emulsification of the ink. This results in weakening of color strength and changes in ink rheology (body and flow properties). Correct concentration will allow the non-image areas of the plate to be appropriately wetted. [3]

THEORETICAL BACKGROUND

This short overview shows that the offset printing technology must be viewed as a multi-parameter system. Changing just one of the parameters can have an immediate effect on the printing process.

Printing

Printing is described as the process of transferring ink onto paper (or another substrate) via a printing plate. The four classic (conventional) printing technologies: are Letterpress (Relief) Printing, Gravure Printing, Screen Printing, and Lithographic Printing. Offset printing is an indirect lithographic printing technology. [2]

Printing Plates

The plates used in offset printing are thin (up to about 0.3 mm), and easy to mount on the plate cylinder, and they mostly have a mono-metal (aluminum) or, less often, multi-metal, plastic or paper construction. [2]

Printing Ink

The ink used in offset printing is usually a highly viscous mixture having the basic components of ink pigment, vehicle (binder), additives, and carrier substance. [2]

Inking Units

During the printing process, a thin film of ink is transferred from the image areas of the plate to the substrate (ink film thickness on the substrate around 1μm). The inking unit's function is to provide a constant supply of fresh ink to the image areas on the plate to maintain a constant inking process. The amount of ink "used up" must be fed back to the system. There must be an equal balance between ink fed and ink dispensed in order to avoid variations in the ink density on the printed image. [2]

Another important factor for the print quality is the uniformity of the ink film thickness on the image areas of the plate or the image areas of the substrate. It is a postulate of offset printing that the film of ink should be of the same thickness across the entire printed sheet. Reproduction technology for the creation of color separations is based on this principle. Consequently, the criteria determining quality [2] are temporary fluctuations of the average ink film thickness (quantity balances), and uniformity of the ink film thickness on the image areas of the plate or the printed areas of the substrate.

Dampening Solution

Since successful ink transfer requires compatible chemistry, matching ink and fountain solutions is critical. The fountain solutions must keep the printing plate clean while allowing the ink to transfer efficiently. These properties can be provided by use of a fountain solution concentrate. [1]

Fountain solution concentrates

Fountain solution concentrates are aqueous mixtures of different components. The key measurements of a fountain solution are pH, conductivity, temperature, and others.

pH

pH is the unit of measurement for acidity or alkalinity. A neutral solution such as pure water has a pH value of 7. Solutions with a lower pH are called acidic, and solutions with a higher pH are called alkaline. The pH scale ranges from 0 to 14. [1]

In the conventional offset printing process the dampening solution is used to separate the image and non-image areas, that is, to prevent the transfer of ink onto non-image areas of the printing plate. The dampening solution consists mainly of water. Experience has shown that in conventional offset printing the dampening solution should have a pH value between 4.8 and 5.5. Dampening solution usually contains plate preservative agents, wetting agent, isopropyl alcohol (IPA), buffer substances, and anti-microbe additives. [2]

Possible printing problems when the pH value of fountain solution is low: prolonged ink drying time, poor solidification of the ink film (which influences rub resistance), increased wear of printing plates, and roller stripping (ink does not spread evenly across roller surface due to surface not accepting ink). [1] Possible printing problems when the pH value of fountain solution is high: emulsification of ink and build-up on ink rollers, saponification of the ink (the ink goes into the water), and plates will not clean up on starts. [1]

Conductivity

Conductivity is a liquid's capacity to conduct electrically charged particles. All dissolved electrolytes in the liquid result in certain numbers of positive and negative charges. This property is used to determine the dosage of fountain solution, or assess the quality of the tap water. The influence of paper on conductivity, depending on paper type, is often expressed as an increase of conductivity (5–10%) of the fountain solution caused by paper components extracted out of the top layer. However, in practice such values are always influenced by natural processes of production and consumption of the fountain solution, which means that the interaction cannot be easily expressed by way of a simple graphic. A high conductivity does not necessarily cause problems. Different types of additives can result in different conductivity values at the same dosage level, without any relation to quality. [1]

Buffers

To keep the pH on a stable level, the fountain solution must be buffered. The pH can be influenced by an interaction between fountain solution, paper and ink. For this reason, fountain solution systems are always buffered to avoid pH fluctuations. To design pH levels and to make a stable fountain solution, a salt combination is necessary. [1]

Correct combinations of acid in the buffer are needed for thorough plate wetting without any deposition. In order to achieve the necessary thorough plate wetting without, on the other hand, causing deposition, the buffer must contain the correct combinations of acid. [1]

Dampening Units

Conventional offset printing requires a dampening system to supply a very thin film of dampening solution (approx. 2 μm) to the non-printing elements of the printing plate. Since part of the dampening solution is printed via the ink, plate, and blanket and another part evaporates, it is necessary to have a constant supply of dampening solution. Continuous/film-type dampening units are shown in Figure 1. [2]

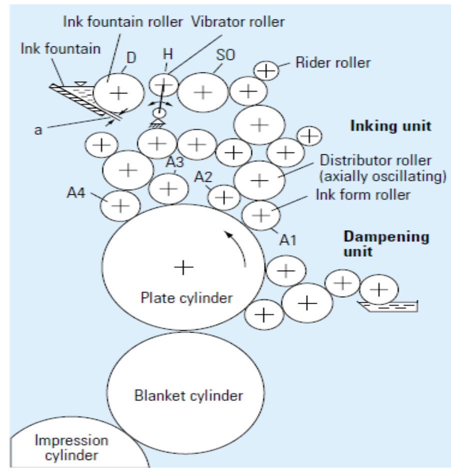

Figure 1
Diagram of an Inking Unit and Dampening Unit

In the offset printing process the printing and nonprinting areas of the plate are practically on one level. The printing areas of the printing plate are oleophilic / ink-accepting and water-repellent, that is, hydrophobic. The non-printing areas of the printing plate are hydrophilic, consequently oleophobic in behavior. This effect is created by physical phenomena at the contact surfaces (Figure 2). [2]

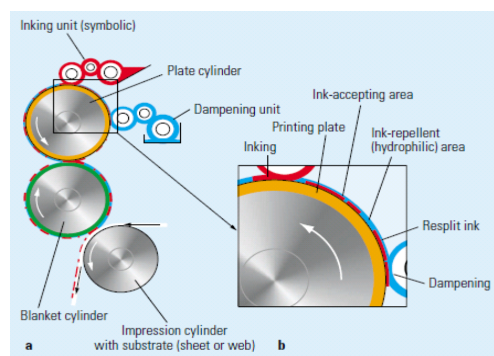

Figure 2
Offset Printing (Lithography). a Components of a Printing Unit; b Basic Principle

The dampening system covers the non-printing areas of the printing plate with a thin film of dampening solution. This dampening solution (water plus additives) spreads over the non-printing areas (Figure 3). [2]

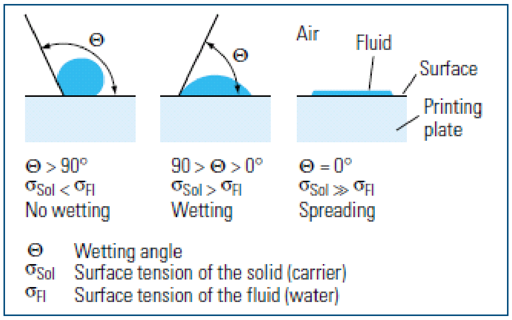

Figure 3
Wettability of Surfaces and Wetting Angles

To achieve good wetting, surface tension has to be reduced by means of dampening solution additives. [2]

Printing Unit

The structure and action of an offset printing unit is presented in a simplified form, a printing unit consists of inking and dampening units (already described), the plate cylinder with the printing plate, the blanket cylinder with the blanket fixed to it, and the impression cylinder. [2]

Paper

Finally, the most important component in the printing industry is the paper. Paper consists of a web of pulp fibers (normally from wood or other vegetable fibers), usually formed from an aqueous slurry on a wire or screen, and held together by hydrogen bonding. Paper may be characterized by moisture content, physical characteristics, strength properties, optical properties, and other criteria depending on its end use. [4]

Process Control

Three basic components of control systems: sensors/transmitters, controllers, and final control elements. These components perform the three basic operations of every control system: measurement (M), decision (D), and action (A). [5]

Most basic process control systems consist of a control loop as shown in Figure 4, having four main components: a measurement of the state or condition of a process; a controller calculating an action based on this measured value against a preset or desired value (setpoint); an output signal resulting from the controller calculation, which is used to manipulate the process action through some form of actuator; and the process itself reacting to this signal, and changing its state or condition. [6]

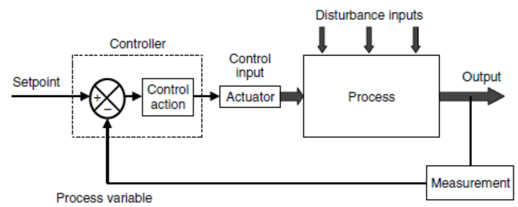

Figure 4
Elements of a Process Control Loop

Two of the most important signals used in process control are called: Process variable (PV) and Manipulated variable (MV). In industrial process control, the PV is measured by an instrument in the field, and acts as an input to an automatic controller which takes action based on the value of it. [6]

Alternatively, the PV can be an input to a data display so that the operator can use the reading to adjust the process through manual control and supervision. The variable to be manipulated, in order to have control over the PV, is called the MV. The ideal value of the PV is often called the target value, and in the case of an automatic control, the term set-point (SP) value is preferred. [6]

Analytical Measurement

The analytical measurements in consideration under this investigation are pH and conductivity.

pH Control

Devices used to measure pH values detect the concentration of Hydrogen ions. pH has a measurement range of 0 to 14 pH units. On the pH scale, a midscale value of 7 pH units represents neutrality values below 7 pH are acidic, and values above 7 pH are alkaline. This parameter can be measured on-line and will therefore permit immediate correction of any variation. However, we must be aware that although pH has a linear measurement scale, it has basically a very nonlinear characteristic. [7]

The selection of controller action is critical. Control system theory can be broadly broken up into two major categories: open loop control and closed loop controls. A closed loop is also known as a feedback control system; it consists of a system whereby the output variable is compared with the input parameter, so that the system may be adjusted in future iterations so that the input and output come closer and closer together.

An open loop system operates without a feedback loop; that is, there is no way for the system to compare its output against its input. Instead, confidence is placed in the correct performance of the actuator. It is generally a less expensive system to implement than a closed-loop system. [8]

There are two types of control: continuous control, and discrete control. In continuous control the variables and parameters are continuous and analogue; in discrete control the variables and parameters are discrete-mostly in binary format. In reality a combination of both control types actually exist in both process and discrete manufacturing industries. Continuous control systems can achieve its control objective in a number of ways. [8]

The objective of the most common control is reviewed: [8]

- The regulatory control has as objective is to maintain process performance at a certain level or within a given tolerance band of that level.
- The Feed-forward control has as objective is to anticipate the effect of disturbances on the system, and to compensate for them before they can occur.
- The Steady-State optimization is an Open-loop control system that uses performance measures, the index of performance, mathematical models of the process, and optimization algorithms to determine input parameters, to drive the process.
- The Adaptive Control has as objective to overcome the disturbances which steady-state optimization is prone to, adaptive control uses feedback control and optimization by combining both practices.
- The On-line search strategies has as objective is to improve the adaptive control decision function, described above. Sometimes the decision function cannot be sufficiently defined; that is, the relationship between the input parameters and the index of performance is not known precisely enough to take action.
- Other control techniques that are specialized techniques that may be used, including: learning systems, expert systems, neural networks, and artificial intelligence methods. [8]

The difficulty in controlling pH stems entirely from its nonlinear relationship to acid and base concentration in a solution. The slope of a single titration curve of pH vs. reagent delivery can vary over several orders of magnitude, and the set point where control is exercised is usually positioned in the steepest region of the curve. [9]

Most practical feedback loops are based on Proportional–Integral–Derivative (PID) control or some minor variations of it. The PID controller is by far the most common control algorithm. Thousands of instrument and control engineers worldwide are using such controllers in their daily work. The PID algorithm can be approached from many different directions. It can be viewed as a device that can be operated with a few empirical rules, but it can also be approached analytically. [10] Equation (1) and (2) are the general transfer functions for PID controller.

$$G(s) = K_P + K_I \frac{1}{s} + K_D s \quad (1)$$

$$G(s) = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \quad (2)$$

where:

K_P = Proportional gain

K_I = Integral gain

K_D = Derivatives gain

T_I = Integral time constant (reset action)

T_D = Derivative time constant (rate action)

The control signal is thus a sum of three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error), and the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain Kp, integral gain Ki and derivative gain Kd. The proportional term is typically the main drive in control loop, which reduces a large part of overall error. The integral term reduces the final error or steady state error in the system. Summing event a small error (instantaneous error) over time, produce a drive signal large enough to move the system toward a smallest error. The last term is derivative term which counteracts the integral term and proportional term when the output change quickly or disturbance enter the system and improving the transient response. [10]

Sometimes typical control schemes are not enough to control a process and advanced control technique and algorithm can help on these situations. Some of these techniques are: PID error squared algorithm, fuzzy logic models, model free adaptive control (MFA), and self-tuning PID.

In order to counteract the variable pH gain, a PID error squared algorithm is recommended. A loop using the error squared is less responsive than a loop using just the error, however, it will respond faster with a large error. The smaller the error, the less responsive the loop.

A practical fuzzy logic models were introduced in the 1970s. It is suitable for poorly defined nonlinear process control applications, such as pH control. It works by using approximate reasoning similar to the human decision-making process when coping with uncertainty and approximation. [11] Fuzzy Logic Modeling is used for processes that are not fully understood. It is a linguistically interpretable rule-based model, which is based on the available expert knowledge and measured data. [11]. Fuzzy control has been implemented with success on pH control. [12]-[14]

Moreover, Model-free adaptive (MFA) control, is an adaptive control method that does not require process models. An MFA control system is defined to have the following properties: no precise quantitative knowledge of the process is available; no process identification mechanism or identifier is included in the system; no controller design for a specific process is needed; no manual tuning of controller parameters is required; and closed-loop system stability analysis and criteria are available to guarantee the system stability.

Some derivations of the core MFA control technology address specific pH control problems are: MFA pH controller to control pH processes, and Antidelay MFA pH controller for pH processes with varying time delays. [9]

Nonlinear control is one of the most challenging topics in modern control theory. Therefore, it is difficult to develop a single controller to deal with the various nonlinear processes. Traditionally, a nonlinear process has to be linearized first before an automatic controller can be effectively applied. [9]

When combining the time-varying MFA and MFA pH control functions, an antidelay MFA pH controller is generated that can control a pH process with large and varying time delays. When a pH process has large varying time delays as well as large inflow rates and pH changes, the difficulty for this control loop quadruples. The antidelay MFA type pH controller has the combined power of being predictive, adaptive, and robust. It is adaptive to compensate for the large gain changes, predictive to deal with large time delays, and robust enough to handle inflow changes, titration curve moves, and other uncertainties. [9]

Conductivity Control

The form of the conductivity controls is similar to that used on the pH loop, although no control valves are directly involved with the dosing. [7] Conductivity cells and measuring range change according to the number of poles and whether they are platinized or not influence the measurement.

The measurement range over which the cell stays linear gets broader as the number of poles increases. Platinized poles also contribute to increasing the measurement span in which the cell is linear.

PROJECT METHODOLOGY

A five color printing Press Heidelberg SM102FP is being used to develop a dampening solution control and monitoring system that can maintain the concentration level of the parameters during the normal printing production run. The research study follows an approach of an Engineering Design process which is composed of the following steps: recognizing the need, defining the problem, planning the project, gathering information, conceptualizing alternatives, evaluating the alternatives, selecting the preferred alternative, communicating the design, and guidance for application implementation of the preferred design.

The first step in the engineering design process is to fully understand what the customer needs are:

Know the "Customers' Needs."

ABC Pharma Printing (ABCPP) as many other printing industries has been dealing with printing defects related to the chemical solution, usually called the dampening or fountain solution. ABCPP has rejected a total of 368,000 printed sheets by problems related with dampening solution during this FY 2012 which has had a cost $22,159.

Define the Problem

The science of offset printing involves many variables. The Conductivity and pH on a dampening solution affects ink transfer efficiently and the quality of the final product. Increasing conductivity can lead to problems due to a disturbed ink / water balance: ink piling, poor ink drying, too high dot gain, poor print quality. While low pH conditions cause water to be corrosive. High pH conditions cause scaling: minerals precipitate out of the water and those minerals will block filters and pipes. Depending on the pH value, calcium carbonate contained in the paper will react or not react with the fountain solution.

Various companies are sharing the printing accessory market of the dampening solution circulation and control. They offer dampening solution control systems that ensure consistent and reproducible conditions. This type of dampening system is costing around $60,000 in the global market. One of the objectives of this engineering design is to design a low cost "custom made" automated system to monitoring and control pH and Conductivity concentration of the Dampening Solution on a Heidelberg Press SM102FP with 5 colors to reduce printing defects related to dampening solution at least by 30%.

There are two important process variables that need to be monitor and keep in control to avoid printing quality issues: these are pH and conductivity. The only parameter that is being measured manually is temperature.

Planning the Project

The project planning begins gathering all supportive information to define process needs, and problem statement during the first two weeks. After determine process variables, needs, and constraints, it is necessary to establish a schedule to complete the engineering design. The schedule was established in the third week. The next three steps of the process were scheduled to be completed in a month. On these steps is necessary to explore possible process control alternatives for pH and conductivity.

The alternative selected is communicated and the guidance for the implementation process is the process that takes more time due to some expected delays due to the non-availability of the equipment on production hours. The whole engineering design process should not take longer than fourteen weeks.

Gathering Information

Dampening Solution on a printing press should keep pH level between 4.8 to 5.5 and conductivity lower than 1800 µS/cm to sustain printing quality. The fountain solution tank is cleaned every week and fills with a new fountain solution formulation. Fountain Solution is composed of 40% (8 gals) of Prisco 2451 and 60% (12 gals) of reverse osmosis water.

This fountain solution tanks has two divisions. The main tank capacity is 35 gals and the first stage tank capacity is 7 gals. This first section of the tank is a reserve of fountain solution already mixed with water. It is used a as fountain solution additive named Prisco 2451. This product is a mixture of following the substances: 111-76-2 2-butoxyethanol (10- 20%), 107-21-1 ethylene glycol (5-10%), 10377-60-3 magnesium nitrate (2.5-5%), 872-50-4 N-methyl-2-pyrrolidone (≤2.5%), and 112-59-4 2-(2-hexyloxyethoxy) ethanol (≤2.5%).

The conductivity and pH are measured by the operator during fountain solution mixing and replacing process at the beginning of the week. Additional measurements may be taken during the printing process but measurements have not been taken and recorded on daily bases.

This situation complicates any troubleshooting on the equipment due to printing defects because tracking pH level and conductivity values of the last production runs is almost impossible. This situation increase troubleshooting cost and delay final actions to fix the problem. Employees recommend install a similar control and monitoring system installed on the new printing press to control pH and conductivity. ABCPP would like to install a pH and conductivity control on each printing press but it is too expensive.

ABCPP as many companies authorize design project where the return on investment (ROI) can be reached on less than 1.1 years. The objective of this engineering design project is to design a low cost "custom made" automated system to monitoring and control pH and Conductivity concentration.

RESULTS AND DISCUSSION

The following sections describe in details the analysis perform to determine and select the alternative to be implement on the Heidelberg Press.

Conceptualize and Evaluate the Alternatives

The conceptualization of formal design to control pH and conductivity begins establishing the three basic operations components of the pH control system and the three basic operations components of the conductivity system. The three basic components of a pH control system are: measurement [(M) – pH electrode, level], decision [(D) – pH controller]; and action [(A) – peristaltic pump, mixer motor, and control valve]

And the three basic operations of a conductivity control system are: measurement [(M) – conductivity electrode, level], decision [(D) – conductivity controller], and action [(A) – peristaltic pump, mixer motor, control valves]

The conceptualization of the pH control system and conductivity control system has begun determine the appropriate analytical measurement equipment. And the appropriate control strategy to avoid overshoot and undershoot. A control strategy is selected from the non-linear control methodologies.

There are three methodologies that were compare to select the most appropriate to control pH and conductivity: PID error square control, pH fuzzy logic control, and Model-Free Adaptive.

The PID error square is efficient and respond faster with a large error. The smaller the error, the less responsive the loop. pH level and conductivity values on a fountain solution usually change slowly. Both parameters gradually increase during the production. The implementation of this methodology requires create a mathematical algorithm and integrate the system with the software because it is not available to purchase on the market.

pH fuzzy logic control can be used for processes that are not fully understood. It is necessary to create a interpretable rule-based model. The main issue to implement this methodology is requires create a computer algorithm and the integration with the system.

The Model Free Adaptive methodology has been proven on the market for many years. It has as advantage that does not require precise knowledge of the system under study. It is available on the market. Foxboro, Cybosofts, and Allen Bradley are some of the companies that offer this type of non-linear control.

Selecting the Preferred Alternative and Communicating the Design

It was selected a MFA system control pH and conductivity of the fountain solution on a Heidelberg. The implementation of a Model-Free adaptive system will require the following equipment for measure, control, and act.

The equipment recommended for measure are the following:

A two pole platinized conductivity probe was selected for our application. This selection assures that the operational range of the conductivity probe is from 500 μS/cm to 1800 μS/cm. The conductivity transmitter should have automatic temperature compensation operate at least on the same range of the probe.

A pH sensor will flat profile sensing surface and ruggedized glass membrane last longer.

The pH transmitter should operate on the range of 0 to 14pH, accuracy: ±0.1 pH, automatic temperature compensation, and output of 4-20mA.

The equipment recommended for control are: Control logix PLC (Backplane, Analog 4-20mA Input Card, Analog 4-20mA Output, DC Output Card, Ethernet card, Prosoft PC56, CyboCon, and Cybolink software.

And finally the equipment performing the actions are: peristaltic proportional dosing pump (4-20mA), peristaltic pump (4-20mA), dc flow control valves, data acquisition chart recorder, and motor of the static mixer. Figure 5 shows the P&ID of the MFA controller integrated with fountain solution tank as a system.

Guidance for Application Implementation of the Preferred Design

This design implementation requires installing firstly pH probe and conductivity probes with their transmitter in an open loop configuration. Equipment should be calibrated according to manufacturer operational manual.

The installation of the pH and conductivity probes requires some modifications of the fountain solution pipes. At this time level switches should be installed with its transmitters. The next step on the implementation is installing and programming the PLC and CyboSoft's software.

At this stage it should be tested all inputs and outputs. Then it is required to install all final elements to control the process: peristaltic pumps, motor, etc. A close loop implementation requires not only entering setup points. It is necessary to enter MFA configuration parameters. This is broadly explained on the CyboSoft's User Manual. In addition, a data acquisition chart recorder shall be used to record pH and conductivity measures as part of the open loop stages. This chart recorder is being connected to 4-20mA output from the controller. A qualification protocol should be performed as the final step of the implementation.

CONCLUSION

The proposed design will fulfill the necessity of control pH and conductivity of the fountain solution. The Modern-Free Adaptive control selected on the design is considered as reliable to control non-linear parameters as pH and conductivity and the steady state condition of the process should be reached is less time compared PID control. This project was limited to design an automated process control further investigations should determine the appropriate operational ranges of each parameter.

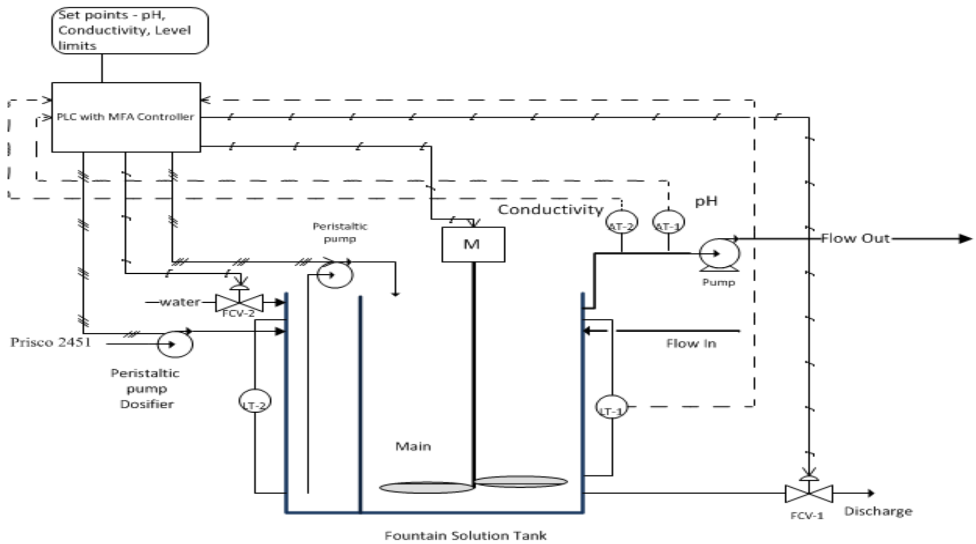

Figure 5
P&ID of the MFA Controller

The automation control of the dampening solution balances of pH and conductivity contribute to reduce quality issues during the printing process ensuring consistent and reproducible conditions on a short and long term. Maintain an accurate fountain (dampening) solution concentration through an automate control system will help to establish the best setting parameters for pH and Conductivity on the Dampening Solution of this Heidelberg Press respect to other process variables studies (ink, paper, ink unit adjustment, etc.).

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