Online Real-Time Water Quality Monitoring and Control System

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ABSTRACT

This research project looks at a novel method for monitoring and control of swimming pool parameters. A National Instruments Compact Rio embedded controller and its software program LabView is used as the basis for this system. A swimming pool model was selected to trial the system due to its similarities with both drinking water and industrial plants. The system monitors the following water parameters: temperature, pH, free chlorine level, oxidation-reduction (redox) potential, total dissolved solids and turbidity. The system controls five chemical dosage pumps, a heating element, an inlet valve, 2 outlet valves, a main pump and a fibre optic system. Currently the system has almost completed its proof of concept phase. The system can monitor water parameters to an accuracy comparable with standard manual techniques and it can control chemical dosages to an accuracy of +/-1.3ml. Tests have been performed using both rated and proportional pump control. Data can be written directly to an Excel worksheet for storage and analysis. The system can publish its display to a webpage which can be accessed for both monitoring and control purposes using a laptop, PDA or mobile phone. Similarly the stored data can be accessed remotely. A fibre optic turbidity sensor is under development using affordable off the shelf components. An optical E. coli detection system using a FRET micro array to detect DNA is being developed in conjunction with Dr. Michael Kane at Purdue University. The aim of this collaboration is to produce a reusable and reliable biosensor capable of detecting low levels of target DNA sequences.

Keywords: Water, Monitoring, Control, LabView, Biosensor, E. coli, FRET.

INTRODUCTION

The need for effective water quality monitoring and control systems is becoming more apparent as demand on water supplies increases. A system, which can provide accurate, real-time, remote monitoring and control capabilities would prove to be a useful tool in safeguarding public health and ensuring quality standards are met. Automatic data logging and analysis features would provide relevant parties with information in a useful format, enhancing the operating performance of the system. Furthermore a system capable of automatically monitoring the presence of pathogens such as Escherichia coli would provide health and environment authorities with peace of mind. Such a system would have many other applications in industrial process control and environmental monitoring.

BACKGROUND

The goal of any pool operator should be to achieve a good water balance. Chemical values must be right for disinfection, safe for swimming and good for pool materials. The main source of pollution in any pool is from the bathers themselves. Pollutants deposited by bathers into the pool include: sweat, urine, mucus from nose and chest, saliva, hair, cosmetics and scales from skin and faecal matter. Such pollutants cause microorganisms to be introduced to the pool. There has been a number of disease outbreaks linked directly to swimming pools including E. coli, Cryptosporidium parvum and Naegleria fowleri.

In order to prevent disease outbreaks it is necessary to continually disinfect the pool water. The most common form of disinfectant used is calcium hypochlorite. The effectiveness of the disinfectant is not solely dependent upon the concentration dosed. Water temperature, pH and turbidity all affect the ability of the disinfectant to destroy microorganisms. Figure 1 shows how pH level affects the availability of disinfectant in the pool water:

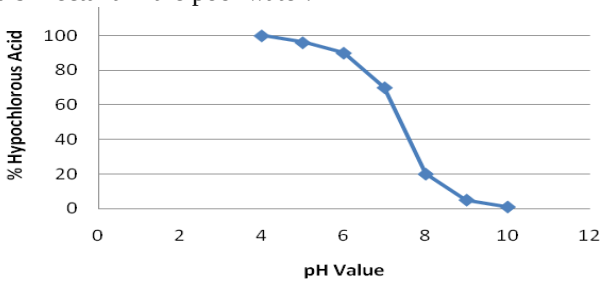

Figure 1 – Graph of Available Disinfectant against pH Level[1]

As water temperature increases the more acidic the water tends to become and vice versa. The more turbid the water the more particles there are to shield microorganisms from the disinfectant. The disinfectant destroys microorganisms by an oxidation reaction. Due to the varying rate of pollutant introduction to the pool a quantitative measure of chlorine level is not sufficient to provide efficient operation. An ORP probe measures the oxidation-reduction potential (redox potential) in the pool. Redox potential gives a qualitative measurement of the effectiveness of the disinfectant. A redox reading of below 700mV indicates poor disinfection in the pool, regardless of chlorine concentration.

Water hardness and total dissolved solids outside of recommended ranges can cause damage to pool materials. A TDS of above 1000mg/l or a hardness value of below 40mg/las $CaCO_3$ can lead to corrosion of pool materials. A hardness level of above 150mg/l as $CaCO_3$ can cause scaling to occur.

The following table summarizes the chemicals and control methods selected for each of the pool parameters:

Parameter	Increase	Decrease
Temperature	Heater on	Heater off
Chlorine Level	Add $Ca(OCl)_2$	Dilute with source water
Redox Potential	Add $Ca(OCl)_2$	n/a
pH Level	Add $NaHCO_3$	Add HCl
TDS Level	n/a	Dilute with source water
Turbidity	n/a	Add $Al_2(SO_4)_3$
Hardness	Add $CaCl_2$	Dilute with source water

Table 1 – List of Pool Water Parameters

Where: $Ca(OCl)_2$ – Calcium Hypochlorite
$NaHCO_3$ – Sodium Bicarbonate
HCl – Hydrochloric Acid
$Al_2(SO_4)_3$ – Aluminium Sulphate
$CaCl_2$ – Calcium Chloride

SYSTEM AND TEST RIG OVERVIEW

An overview of the monitoring and control system is shown in Figure 2 at the end of the paper. The system currently has a total of 9 inputs and 9 outputs. The pool circulation system has been mimicked by the use of a scaled rig. An image of the test rig is shown in Figure 3 at the end of the paper. Due to the low flow rate of the rig circulation system it was decided to not include a filter in the rig. However the use of the system to control filter backwashing will be simulated using a series of switches. A National Instruments Compact Rio 9023 embedded controller was selected to operate the test system.

Five modules were selected to be used with the controller – a 32 channel analog input module, a 16 channel analog output module, an eight channel digital input module, an eight channel digital output module and a 4 channel thermocouple module. The Compact Rio once programmed in LabView can function independently of a P.C. Data can be downloaded periodically to free up memory or continually via an Ethernet link. Variable pump speed control is currently being achieved by using the pulse width modulation feature of the digital output module. The peristaltic pumps chosen run off a 12Vdc supply, well within the operating range of the digital output module. In real world operation, especially in larger public pools, dosage pumps generally run off mains power meaning that this form off variable speed control will need to be altered. The analog output module can be used to provide a variable control voltage for a mains supplied dosage system. Due to the binary nature of their operation in a swimming pool environment, mains powered valves for water inflow and outflow control can be controlled by the system using a digital output module and a set of relays. The main circulation pumps in nearly all pools operate in a similar manner meaning a relay control can also be employed.

An aquarium heater is being used to heat the relatively small volume of water in the test rig. The large volume of water associated with pools means large scale heaters are required to maintain an amiable water temperature for bathers (and an optimum temperature for disinfection). Modifications to the on/off control currently employed may be necessary depending on the design of such heaters.

SYSTEM MONITORING

Table 2 below shows the sensor specifications being used to monitor the swimming pool parameters:

Parameter	Sensing Method	Accuracy	Output Range
Temperature	Thermocouple	+/- 0.1°C	41µV/°C
Chlorine	Amperometric Probe	+/- 0.1 ppm	0 – 20mA
Redox Potential	Electrode	+/- 15 mV	0 – 1V
pH	Electrode	+/- 0.05 pH	+/- 0.5V
Total Dissolved Solids	Amperometric Probe	+/- 20 ppm	0 – 20mA
Turbidity	Fiber Optic	0.1 NTU[NB]	0 – 10V
Hardness	Manual (Colorimetric)	+/- 10mg/l $CaCO_3$	n/a
Biosensor	Optical	n/a	Boolean output

Table 2 – System Monitoring Specifications

NB: Expected accuracy at time of paper submission

The thermocouple, electrodes and amperometric probes have different response times to register accurate readings. Also, the TDS probe must be 'fired' alternately to the other probes as it produces a small voltage which can affect the other probe measurements in our test rig setup. This is not a problem in real world set ups as each probe is isolated. To optimise the data collected it is required that

parameter measurements be logged at the same time. The chlorine probe possesses the longest response time (15mins) and so sets the time interval between logging points at 15 mins + 30secs, to allow the TDS probe to fire (TDS variation in 30secs is sufficiently small to be of no consequence). Water hardness will be monitored manually due to the prohibitive cost of an automated probe. The wide range of acceptable hardness levels requires monitoring only every two hours.

As with most automated sensing systems sensor accuracy diminishes over time as sensor fouling occurs. To counteract this a weekly cleaning and recalibration regimen is in place. With regard to signal noise the variable input levels on the C series analog input module (+/- 200mV, +/- 1V, +/- 10V) allow monitoring to be 'tailored' to each sensor thus minimizing the error incurred.

The biosensor, which is detailed in a later section, will provide a Boolean input to the monitoring system. It is hoped that the biosensor will produce readings on an hourly basis. Should E. coli be detected an alarm will be triggered in the monitoring system, alerting staff and relevant authorities.

SYSTEM CONTROL

A series of experiments were performed to confirm that the calculated chemical dosages were correct and to deduce their effects on relevant water parameters and each other. It was decided not to include aluminium sulphate in these tests as it will only be dosed occasionally. These tests confirmed the calculated dosages were correct and also highlighted no unexpected interactions between chemicals. The graph in Figure 4 shows the relationship between calcium hypochlorite dosage and chlorine level in tap water. It is clear from the graph that the relationship is linear.

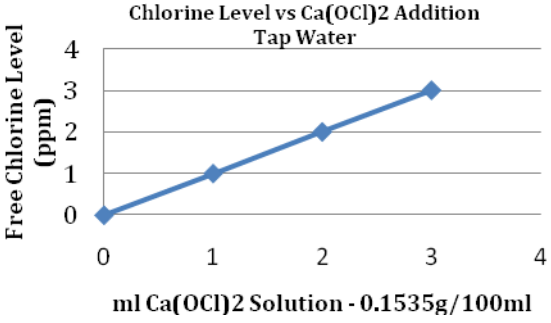

Figure 4 – Chlorine Level vs Calcium Hypochlorite Addition

The graph in Figure 5 highlights the effect of calcium hypochlorite addition on water pH. For each 1ppm increase in chlorine level there is approx 0.2 increase in pH level. This increase can be negated by one of two options: 1) dosing HCl in conjunction with calcium hypochlorite to lower pH or 2) dosing sodium bicarbonate to buffer the water against pH change. The decision on which option to choose will be based on the existing water pH, chlorine and alkalinity levels.

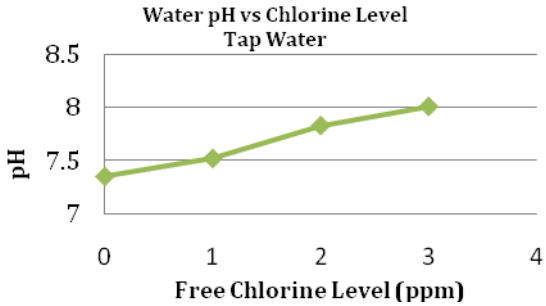

Figure 5 – Water pH vs Chlorine Level

A set of pump tests were then performed to find the volumetric flow rates of each of the peristaltic dosing pumps when operating individually and together. These tests highlighted some differences in pumps dosage rates in both operating modes, as shown in Table 3, which were factored into the control algorithm.

Power Level (%)	Vol. Pump 1 (ml)	Vol. Pump 2 (ml)	Vol. Pump 3 (ml)	Vol. Pump 4 (ml)	Vol. Pump 5 (ml)
100	46	46	45	45	46
90	46	45	45	42	46
80	42	41	41	41	42
70	42	40	40	40	41
60	36	36	36	35	36
50	35	32	33	33	33
40	30	24	25	26	26
30	22	20	15	17	16
20	9	7	0	2	3
10	0	0	0	0	0

Table 3- Pump Dosage Results **1min** Runtime

To simplify the control algorithm a detailed study of the source water was performed. Measurements of source water temperature, chlorine level, pH, alkalinity, TDS, ORP, hardness and turbidity were noted from a number of source water samples and averaged. This allowed a timed loop to be employed at startup to bring the above parameters to approximately within the operating range of the system, thus minimizing the time taken to refine the pool parameters. Other factors that were required to implement the control algorithm were: total water volume held in test rig, test rig water turnover period, test rig water circulation time and inlet and outlet valve flow rates. Figure 5 shows an example of the control method employed to dose chlorine into the system for a target concentration of 2ppm.

Due to the longer dosage times and circulation period in a real world implementation of this system, the parameter under control may be monitored 2 – 4 times before the control action is completed, providing the control system with improved feedback. This will

allow for proportional control to be used reducing the risk of response overshoot in the system.

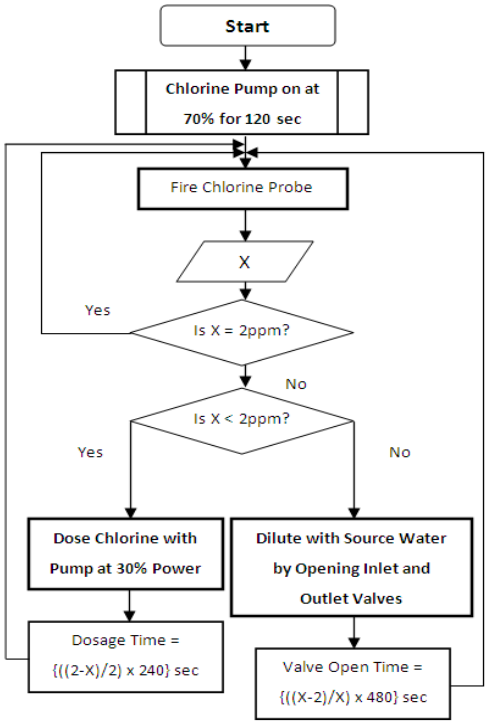

Figure 5 - Chlorine Dosage Control Method

Proper backwashing of pool filters is essential for good pool operation. Backwashing is performed at regular intervals or if filter pressure rises above a predetermined value. The low flow rate of the test rig prohibits including a filter. To demonstrate the systems ability to perform automated backwashing a series of input switches representing differing pressure levels were incorporated. Triggering of these switches will cause a 'virtual' valve system to operate and alert the user. Each backwashing cycle together with system pressure can be logged.

DATA LOGGING AND ANALYSIS

The Compact Rio controller has 256MB of memory allowing data to be logged and collected periodically from the device. This approach to data collection may be useful for applications such as environmental study. Other Compact Rio models have a USB port that allows on board memory to be expanded considerably, thus increasing the time interval between data downloads. Alternatively data can be read from the device in real-time, which is the case with the test rig setup. This requires connection to a PC, either directly or over a network via an Ethernet connection. Data either downloaded periodically or continuously can be read directly into Microsoft Excel allowing for automated analysis. As stated previously, monitored parameters will be time stamped enabling a clear picture of the pool operation to be created. The data along with the analysis outputs (graphs, charts, alert summaries) can then be published online for the use of relevant authorities. User input fields on the LabView interface will allow for other parameters to be noted and factored into the pool analysis. These inputs will be finalized after meeting with relevant parties, but may include bather loading, average age/age range, session length etc.

REMOTE MONITORING AND CONTROL

There are numerous methods of monitoring and controlling the pool system with this setup. The controller can be connected directly to a PC on site allowing pool staff to monitor and control in situ. The web publishing feature within LabView allows the system front end, an example of which is shown in Figure 6, to be accessed externally on another PC, a PDA or mobile phone. This allows authorities such the HSE and EPA to monitor several sites from one location. External users can view the system solely in a monitoring capacity or request full control of the system from staff on site. Logged data can be requested at any time and delivered over an internet connection reducing the need for inspections. The automated nature of data storage and analysis will provide uniform information from different installations, enabling better comparisons of operational standards across many different sites.

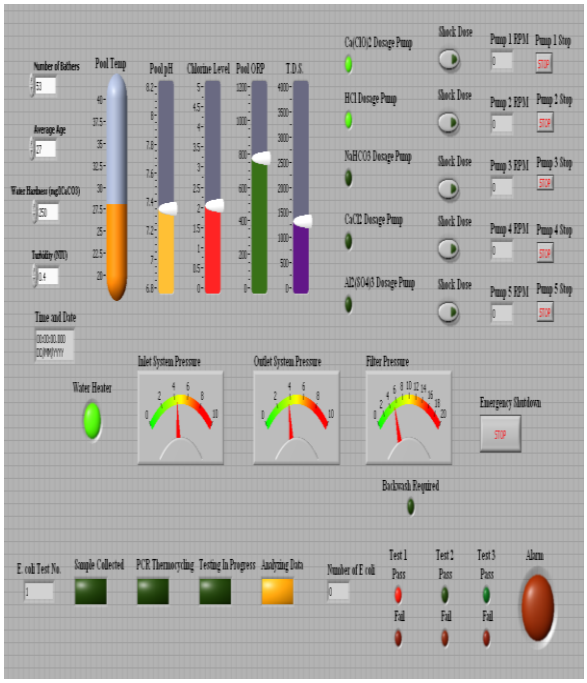

Figure 6 - LabView Frontend

FIBER OPTIC TURBIDITY SENSOR

Turbidity is an important pool water parameter. Not only does turbid water look unappealing to the bather but it can also cause a decrease in the effectiveness of the disinfectant agent. Turbid water can be an indicator of increased water pollution and of poor filtration. Currently manual tests are carried out for turbidity in most pools with the maximum recommended turbidity level being 0.5 NTU (nephelometric turbidity units). Preliminary work is being carried out on the design of a turbidity sensor for

swimming pools. The system will work on a catch and release basis consisting of an LED light source, a feed and a return fiber and an analyzer. The intensity of the light transmitted through the sample will be measured and correlated to a turbidity value. This system is being designed with affordable off the shelf components with the aim of producing a sensor with a greatly reduced cost compared to that of a bench top turbidity meter.

The inline design of the sensor will allow for regular monitoring of turbidity as opposed to the intermittent sampling regimen currently in place. This technique is especially suitable for application in drinking water monitoring, where turbidity is a primary indicator of the efficacy of water filtration. A comparison of the fiber optic system against an off the shelf vision system is also being made. While it is expected that the sensitivity of the vision system will be lower than the fiber optic system its ability to produce an image for analysis may prove useful for some applications. Preliminary results of experimentation with the vision system show an effective range of 10 – 50 NTU with a resolution of 5 NTU. Further refinement of the experimental set up should increase resoluton toapprox 1 NTU.

BIOSENSOR

Regular micorbiological testing of pool water is essential for safe operation. The task of a producing a sensitive, low cost, durable biosensor with high rerpeatability is very challenging. Table 4 below summarises some biosensing techniques employed to detect E. coli.

Method	L.O.D.	Detection Time	Ease of Use
Glassy Carbon Electrode[2]	2 cfu/100ml	~ 20 min	Good
Bio-Optical Signature[3]	10 – 100 cfu/ml	~ 5 min	Excellent
Tapered Optical Fiber with SYBR 101 dye[4]	35ng of ssDNA	> 2 min	Extremely Poor
8 Channel Bulk Acoustic Wave Impedance Physical Biosensor[5]	100 cfu/ml	~ 900 min	Average
Cartridge Based UV Fiber Optic Spectrophotometry[6]	< 1 cfu/100ml 10^3 cfu/100ml	1080 min ~ 690 min	Excellent
Antibody Immobilized Biconical Tapered Optical Fiber[7]	70 cells/ml	~ 10 min	Average

Table 4 – Summary of a Selection of E. coli Detction Methods

Although some of the detection times and sensitivities listed in the above table look reasonable they are quoted for samples in which no other pollutants are present. Also the majority are single shot systems and those which are not are prohibitively expensive for the end user.

The detection method[8] developed by Dr. Michael Kane of Purdue University to test for the presence of E. coli O157:H7 (a human pathogen) is a multiple use technique which has very low susceptibility to background contaminants. It can be constructed mostly form off the shelf components minimizing costs. The sensor targets a DNA sequence specific to E. coli O157:H7. This target sequence is amplified using the PCR (polymerase chain reaction) process outlined in the flowchart in Figure 7. This process amplifies by approx 10^9 the target DNA present in the sample. The amplified sample is deposited onto a microarray containing the exact opposite DNA sequence. If the target DNA is present in the sample the two sequences bond together.

When the microarray is then subjected to laser light a 532nm red light is emitted due to FRET (Förster Resonance Energy Transfer) between two fluorophores indicating the presence of E. coli O157:H7. To verify this result the microarray is heated to 60°C to break open the two opposite DNA strands. The laser is fired again and green light should then be emitted from microarray. This is because the two fluorophores molecules are now too far apart for FRET to occur. If a colour change does not occur the test is declared void and the microarray replaced. The system is fully disinfected with deionized water after each test run.

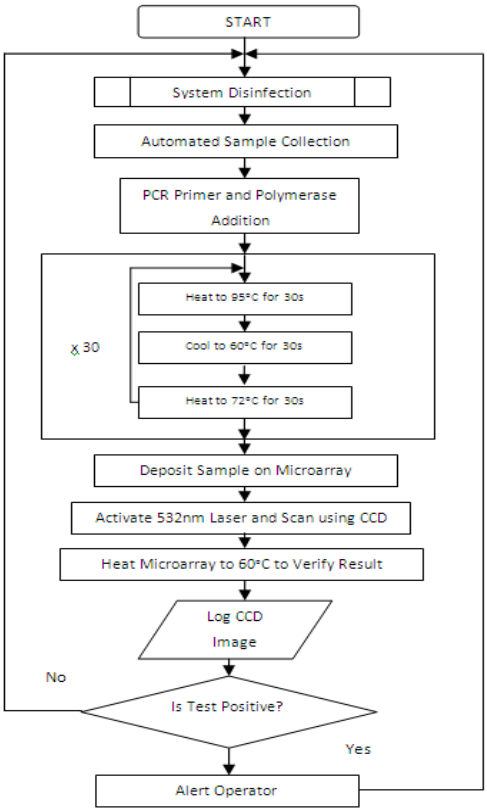

Figure 7 - Flowchart of Biosensing Process

Automated sample collection will be conducted by means of a 2µm filter in a flow through system. Pre-filtering will be used to remove larger waterborne contaminants that would otherwise block the 2 micron filter. After a predefined sampling time the filter will be cleaned by backwashing and the effluent collected for testing.

This detection method is easily altered to detect other microbiological targets such as Cryptosporidium parvum by changing the primers added during the PCR process and the DNA sequence on the microarray used.

FUTURE WORK

At the time of paper submission the test rig is nearing completion and some preliminary testing has been conducted. Extensive testing of the monitoring and control system's response over extended periods of time is required and will be conducted along with testing of the system's response to standard pollutants and shock dosage of chemicals. Dialogue with the relevant authorities has been opened in order to develop the best possible data analysis. A workshop showcasing the completed test rig with industry is scheduled for February 2010. The fiber optic turbidity sensor is currently under development and testing will occur in spring 2010. Initial experimentation with biosensor components and processes will be conducted in parallel with these tests. Upon completion of these experiments the automated biosensor will be built and tested from winter 2010 to summer 2011.

CONCLUSIONS

There are numerous potential applications of the online real-time monitoring and control system outlined in this paper – environmental monitoring, waste water treatment, industrial process control and drinking water monitoring. The incorporation of the biosensor under development in collaboration with Dr. Kane will increase these potential applications and provide the system with market leading monitoring and control capabilities.

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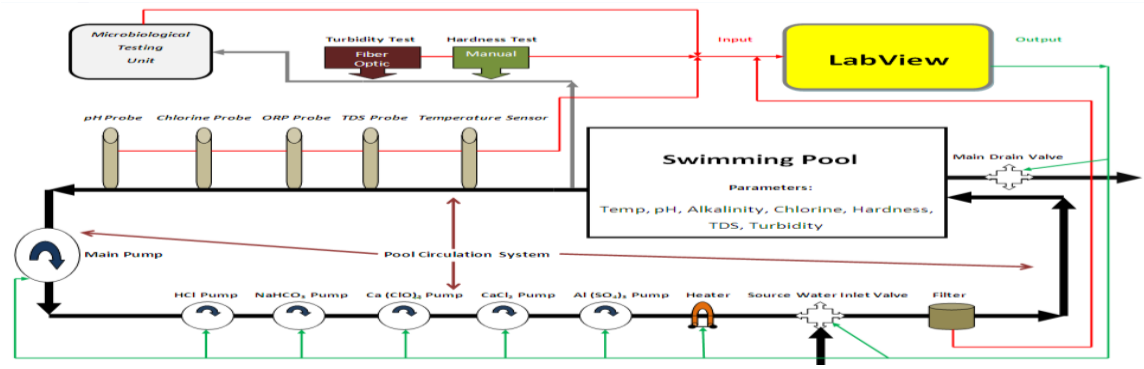

Figure 2 - System Overview

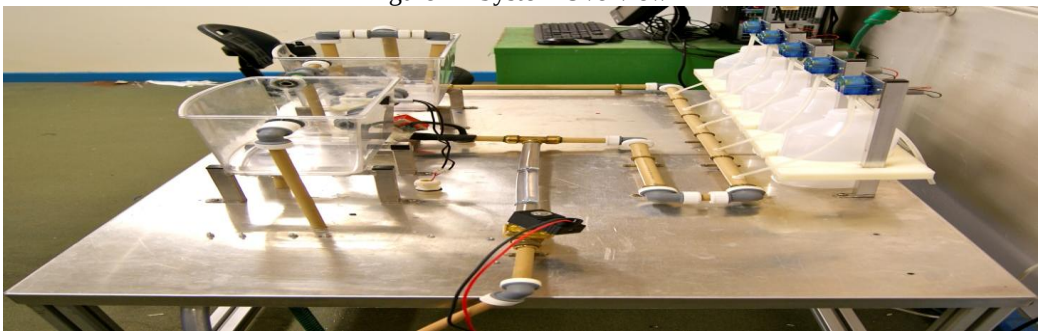

Figure 3 – Image of Test Rig