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Automating a solar water heating system

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Abstract: The use of solar thermal energy is getting more attention throughout the past few years, providing alternative yet efficient solutions to the energy production challenge across the globe.

Solar thermal collectors are one of the most diversified types of the solar collectors' family, starting from one simple principle: heating water from the sun. The technology used in this area is simple yet reliable. The collector used in the project is a photo thermal converter; the solar radiations are captured by the solar cells, heating the water inside a serpentine and transferring it to the reservoir.

The photo thermal collector is illuminated by a laboratory lamp of 277, 42 Watts (extracted power) and heats the water up to 39°C in 15minuts.

The aim of this work is to study different theories to realize a monitoring and a control approach to uphold the temperature of the reservoir in a specified range and establish better productivity of the system. Therefore, we added two Arduino-based devices, one to monitor temperature, and the other to control the water pump speed based on the values detected from the temperature sensors. The temperature of the water in the reservoir is maintained in the desired range (30°C to 40°C). The communication between the computer and the system in a total is done by serial data transfer.

Keywords: *Electronic devices, Arduino boards, Renewable energy, Solar energy, Photo-thermal, Temperature control,*

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1. INTRODUCTION

Sustainable development, the increase in the energy demand, and the decrease of the use of fossil energies are the three most important factors that made renewable energy the first studied, evaluated and promoted science in the world these days[1]. Solar, wind, hydro and biomass etc, resources are used lately to come hand in hand with fuel, and mostly overcome the challenge of good function through a long period of time. Solar energy however stands as the most varied among others since it is out there anywhere around the globe[1]. Hence scientists developed multiple systems useful in harvesting the energy extracted from the sun radiation and transforming it into electricity, heat or both[1,2]. Among these systems the photo thermal conversion technology stays the most varied within all, however depending on the classical form of the radiation conversion isn't enough to assure the good function of the systems heated[2]. Hence optimization approaches are used[3,4] .In the literature, several works have been published on multiple optimization methods for solar heating systems [3]. Authors started by determining the optimal control strategy for water flow modulation in solar thermal applications using as a starter differential algorithm based on the switch on switch off principal (between 0 and a maximum value of flow rate) [1,5] , thus the controller either starts or shuts down the water flow pump according to the switch on switch off temperature difference. Multiple control strategies exist, and are used along with the differential approach, such as Proportional-Integrated-Differential (PID) controllers, Proportional-Sum- Derivative (PSD) controllers, and fuzzy logic controllers[6]. These methods may certainly be more practical in programming than others, more benefic also considering several aspects. Micro-controllers based systems are wildly used for monitoring physical parameters (temperature, pressure, humidity, etc) and in particular parameters linked to solar energy applications[6]. According to the past research literature implemented control strategies helped improving the energy efficiency of solar thermal facilities[6-8]. Nevertheless the developed electronic devices differ from one work to another according to the specific requirement of every particular application[9]. In this paper, we chose to study two different type of controllers and apply the most adequate one to the heating system to maintain the temperature in a desired range (30°C to 40°C)

2. MATERIAL and METHODS

"*Solar collectors*" is a term used to describe a multitude of different devices designed for harnessing the energy from the sun, which is in the form of solar radiation, by converting it into useful heat[2]. Thus, solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy. It is evident that solar collectors constitute a major component of any solar energy system[2]. Their operation is based on absorbing the incoming solar radiation, converting it into heat, and transferring this heat to a fluid (usually air, water, or a special heat transfer fluid) flowing through the collector [1,2,10]. The solar energy collected in this way is carried from the circulating fluid either directly to a heat-demanding process or to a thermal energy storage tank [2]. This transfer generally needs pumps and valves to get the liquid from one set point to another since we can't only depend on gravitational force.

Experimental Setup

Solar energy is considered the most efficient in terms of clean exploitation and conversion processes, including photovoltaic, photochemical, and photo thermal conversion, converting sun radiation to electricity, chemical and thermal energy respectively. Nevertheless, the energy conversion efficiency remains low in photovoltaic and chemical applications compared to the thermal conversion approach. The photo thermal conversion process is considered the traditional conversion method transforming solar radiation into heat as thermal energy; it is quite simple and effective like the system used in this study: The water inside the collector is heated due the radiations absorbed and then transferred to the water tank via tubes made of a special kind of plastic.

Image 1. Experimental setup

The materiel used to setup the solar system is given by table 1:

Table 1. Laboratory equipment list

Equipment	Properties
Photo thermal collector	(42 cm * 30,5 cm) made of black and total absorbance material with a thermal emissivity of 0,35
Lamp atelier	1000 Watts
Temperature Sensor	Two temperature probes to measure the temperature and an analogical device to visualize the values and transfer the data to computing systems using RS232 cable
DC Voltage source	Up to 20 Volts
Water Reservoir	filled with distilled water to prohibit limestone sediments in the tubes and inside the collector

Parameters and System Control

Solar furnaces provide generally a large set of machineries, storage tanks, motors, pumps, valves sensors etc. hence applying control methods to assure the best function of our renewable plant is the challenge nowadays, the literature is rich by different control strategies and methods, these methods may certainly be more practical in programming than others, beneficial also considering several aspects. The objective of this study was focused on controlling a water pump that circulates water from a solar collector to storage tank.

Pumps are usually based on DC motors so basically controlling the flow rate through a water pump means by far controlling a DC Motor speed.

Control theory

Solar furnaces are generally controlled manually by trained operators considering the huge size of solar plants, however scientists have been more than keen on developing new control strategies to design robust control systems, thus, solar applications can be seen as a benchmark to test new control approaches[6,11].

Differential control

Several works have been published in the literature on different optimization strategy for solar systems, using optimal control strategy for each furnace. However, for a solar heating system (extracting solar radiation to heat a storage tank) we found that the most used controllers are based on differential theory. A differential controller consists in automating the heat collection system by sensing a difference between two temperature probes and activating a relay (switch on/ switch off) when the differential value is ample. It is quite simple as an algorithm if the solar radiation collected is stable (which is the case in our study) but in case of varying radiation (large solar systems) it needs to be improved to meet the required data.

The differential algorithm developed in our study is illustrated by figure 1:

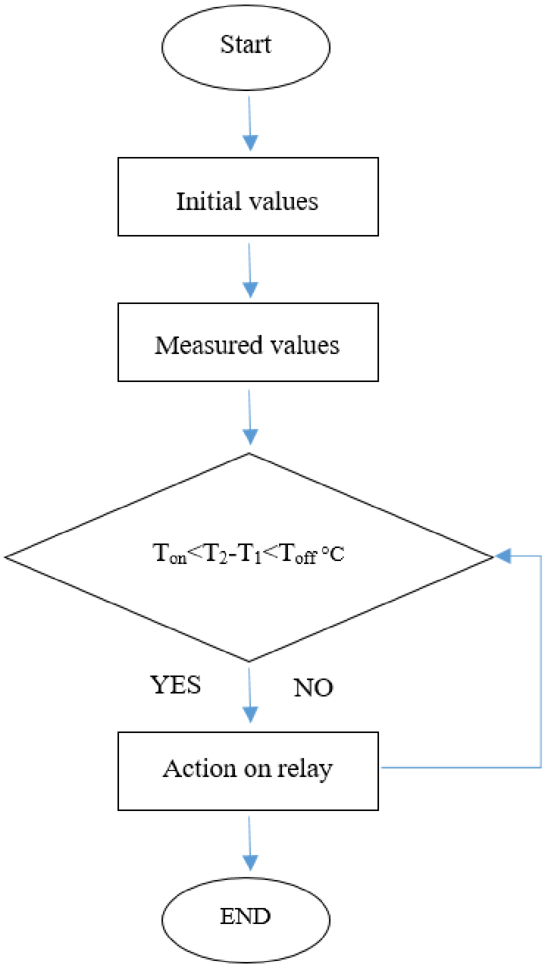

Figure 1. Differential Controller

PID Control

Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. As the name suggests, PID algorithm consists of three basic coefficients; proportional, integral and derivative which are varied to get optimal response[6,7].

The basic idea behind a PID controller is to read a sensor (temperature), then compute the output (pump speed). A sensor is used to measure the process variable and provide feedback to the control system. The set point is the desired or command value for the process variable, such as 47 degrees Celsius in the case our temperature control system. At any given moment, the difference between the process variable and the set point is used by the control system algorithm (compensator), to determine the desired actuator output to drive the system. For instance, if the measured temperature process variable is 50 ºC and the desired temperature set point is between 35°C and 47 ºC, then the actuator output specified by the control algorithm might be to drive a change in the pump speed and the flow rate [11]. This is called a closed loop control system, because the process of reading sensors to provide constant feedback and calculating the desired actuator output is repeated continuously and at a fixed loop rate as illustrated in figure 2.

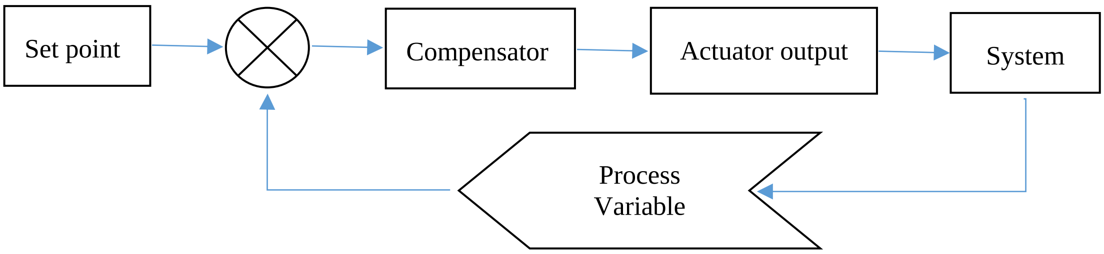

Figure 2. Block diagram of a typical closed loop system.

The textbook version of the PID algorithm is described by:

$$u(t) = T_p(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}) \quad (1)$$

Proportional response T_p or G
The proportional component depends only on the difference between the set point and the process variable. This difference is referred to as the Error term. The proportional gain (T_p) determines the ratio of output response to the error signal[6,7].
Integrated response T_i:
The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the Steady-State error to zero. Steady-State error is the final difference between the process variable and set point. A phenomenon called integral windup results when integral action saturates a controller without the controller driving the error signal toward zero.
Derivative response T_d
The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the process variable. Increasing the derivative time (T_d) parameter will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response[6,7]. Most practical control systems use very small derivative time (T_d), because the Derivative Response is highly sensitive to noise in the process variable signal. If the sensor feedback signal is noisy or if the control loop rate is too slow, the derivative response can make the control system unstable [6,7].

PID Algorithm
The basic idea of the PID controller is to calculate an error value as the difference between a desired set point and a measure process variable and apply a correction based on the three coefficients P, D and I flowing the algorithm:
The controller attempts to minimize the error over time by adjustment of a *control variable*, to a new value determined by a weighted sum [11].
Generally, a PID algorithm accepts changes according to the desired control application, or what is called *tuning*, since not all the terms in the PID equation are necessarily used to fit the approach applicable to a control problem, it is really important to decide on which terms to or not to include and determine what the gains should be for those terms [11].
There are many ways to write a PID algorithm, reason why Arduino developers spent much time making a standard PID algorithm as solid as any found in the industry, however such codes are only valid in some cases and others not, which brings us back to the tuning tenet into developing our own PID controller following the parameters and needs in our case study[9][Figure 3].

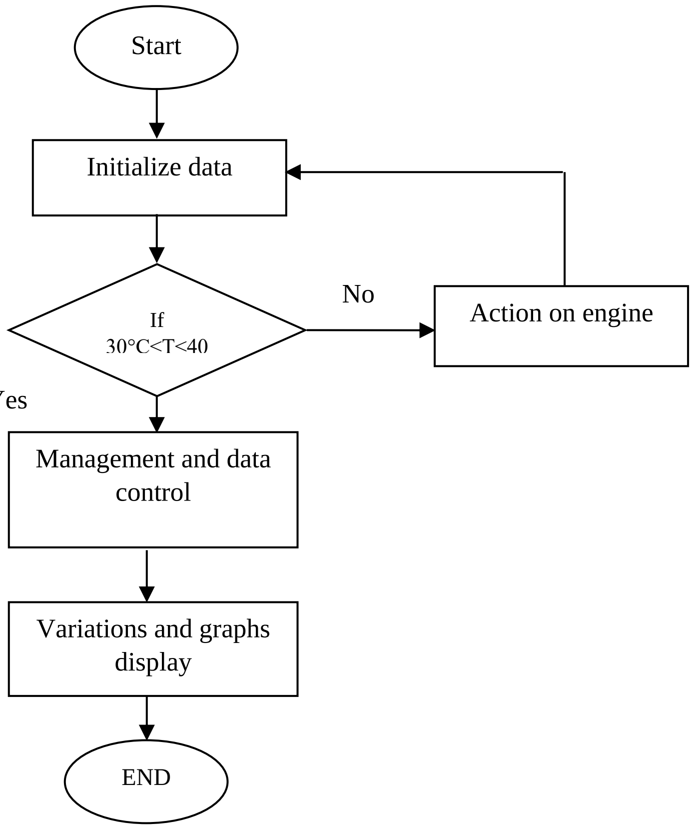

Figure 3. PID control algorithm

PID Tuning methods

Different methods can be used to tune a PID controller such as manual tuning, simulation tuning, or Ziegler-Nichols method tuning.

i. Manual Tuning

Manual tuning means changing the values of the coefficients to get a better response:

Change K_p values in a way that allows the system to reach the set point value as quickly as possible.

Change T_i to get an exact response in a short time period

Change T_d to decrease the system's oscillations

This method can be helpful in some cases however it is time spending and not really helpful in large scale systems.

ii. Ziegler-Nichols method

Also known as ultimate cycle method, it determines the ultimate or critical gain (K_u) and the ultimate period by adjusting the controller gain K_p until the system undergoes sustained oscillations, while maintaining the integral time constant at infinity and the derivative time constant at zero. The time period of oscillations is represented as P_u [12,13]. The values of the PID controller parameters based on the Ziegler-Nichols tuning method are given in the table:

Table 2. Ziegler-Nichols method tuning parameters [13]

Controller type	K_p	T_i	T_d
P	$0.5K_u$		
PI	$0.45K_u$	$1.2T_u$	
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

3. RESULTS and DISCUSSION

Case Study of a DC Motor Speed Control
We tried to simulate the speed and current variations of a classic DC motor connected to a DC voltage source. The results are given by:

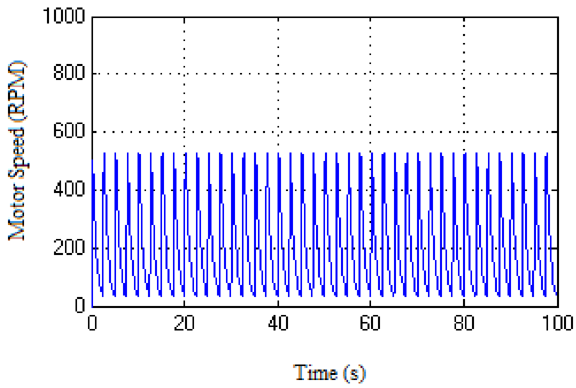

Figure 4. Speed variation

As we can see the speed variations are intense and can't be helpful in assuring a good function of any DC motor based system, reason why adding a controller to adjust its speed seemed like a promising idea.
The figure bellow presents the speed simulation of a DC motor system after adding a PID Controller (P=1, I=1, D=0)
The result of the speed variation control is given by:

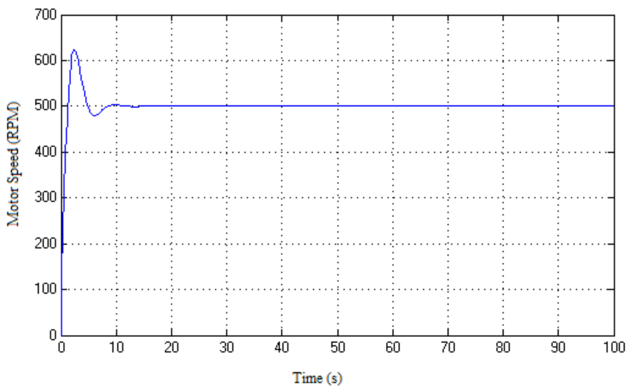

Figure 5. Speed variations using PID controller

The DC motor speed is controlled (fixed) at the set point value given by the instructor [Figure 5]; however, the delay at the beginning of the simulation [0 to 10s] can bring up anomalies when the system is used in high voltage furnaces. Thus tuning the PID controller is the best way to speed up the process and decrease the delay.
Tuning the PID controller mainly means changing the Kp, Ti and Td values in a way that the process responds as quickly as possible to the changes occurred [Figure 6].

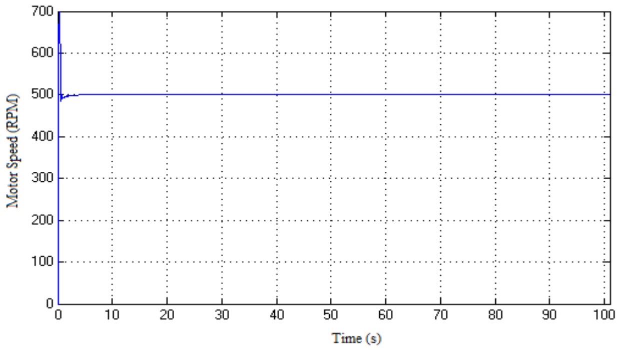

Figure 6: Speed variations after tuning the PID controller

The values of the three different characteristics of the PID controller after tuning are given by:

$$P= 0.009056$$
$$I=0.01465$$
$$D=0.0003771$$

Thus, tuning any type of controller can be helpful in assuring a better performance of electrical based systems as well as good response and almost no delays.

Adding different types of controllers to any physical system helps getting better results at different scales, as seen in solar furnaces, adding a solar tracking system for example gave a better heat and electricity yield since the solar panel follows the sun path all day, assuring a maximum radiation at any time of the day: we were inspired by this kind of technology while developing our study. The system presented in this paper is certainly lab scaled, however the idea of inserting micro-electronic devices into such mega systems is as challenging as new to the application field.

Arduino prototype boards are the trend now, and instead of using really expensive programmable automates, Atmega based microcontrollers are as powerful, less expensive and easy to manipulate.

Using an Arduino board to control the heat flow inside the water tank is quite new to solar applications in terms of the boards used in the automating systems, the algorithms developed or even the monitoring interfaces created to meet the system's need of better function.

Problem occurred

On physical scale controlling a DC motor speed using PID theory requires a digital encoder connected to the motor which we don't have at the laboratory now, so we changed the program using a simpler command: switch on / switch off the pump according to the error given by the controller or in other words we adopted the differential control strategy for now. A strategy that was quite helpful while controlling a mechanic water pump. The results of this approach will be discussed in the future work.

5. CONCLUSIONS

This study was conducted to evaluate the impact of adding any type of controllers to a dynamic system, and control its main parameters. Based on simulated and measured data it can be stated that the control strategy investment into the solar heating furnaces is quite gainful in terms of efficiency, quality and delay. Using PID controllers is certainly more interesting because of its accommodation capability in any solar system, however due to hardware limitations as stated above, a differential controller can be benefic also. This work is yet to be developed to more control strategies and methods based on control theory designed to upgrade solar energy systems.

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