# MTX-LAB controlled by Multi-SISO PID controllers

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**Abstract:** The MTX-LAB plant is a didactic laboratory setup based on humidity and temperature sensors for testing control algorithms. The objective is to reproduce an industrial problem with a classroom lab plant. The plant shows multivariable characteristics consisting of two-input two-output system, where air outlet temperature and humidity are controlled variables, and lamp and cooler fan intensity are the manipulated variables. A multi-SISO-PID controller shows one of the possibilities that can be applied to control the system.

*Keywords:* arduino, lab plant, control strategy, simulation, PID, PI.

## 1. INTRODUCTION

With the advent of new technologies, the industry has enlarged the use of automation control systems to obtain efficient production management, searching for better cost-benefit relations. The use of artificial intelligence and instrumentation, such as sensors with data transmission by Wi-Fi, supervisory and human-machine interface applications, as well as control algorithms that simulate actual data are fundamental to ensure the automatic control, aiming for a product with high quality and market competitiveness (Teruel, 2010).

Reproduction of an actual industrial plant within the university environment is not a trivial task, since it involves several issues: industrial equipment has a high cost due to its acquisition, installation, maintenance, and security restrictions that must be taken into account to be safely operated by the students (Pereira, Paladini and Schaf, 2012). Thus, small-scale experiments are an interesting solution to offer the student pragmatic and didactic teaching through the construction and simulation of prototypes that simulate industrial environments and their real problems, as stated by Colón, Teixeira, and Diniz (2009).

In this context, the MTX-LAB didactic plant aims to demonstrate the operation of the various humidity and temperature control loops didactically, avoiding the traditional temperature and level prototypes. Its compact design allows it to be taken to the classroom; it has low cost and low utilities demand, in addition to interesting dynamic behavior. Additionally, this plant also stands out for its low cost, $ 58.

Many researchers have developed low-cost prototypes for practical and pedagogical teaching. Most of them are based on level and temperature control loops. Alves, Brandão, and Oliveira (2018) present a teaching approach known as Project-based learning (PBL), and the developed prototype has temperature, level, and flow control, in addition to monitoring process variables with a supervision system. Torres *et al.* (2017) develop a didactic thermal plant, whose objective is to implement PID to control the output temperature by varying the valve position, while maintaining the constant-power heat source. Gomes, Nicacio, and Tôrres (2017) implement a PI controller, whose tuning method used is Root Locus in order to control the temperature of the mixing tank of the didactic plant SMAR PD3, taking over the temperature, the pressure, the flow, and the level as the process variables. Pruna *et al.* (2018) apply a PID controller to a flow control plant, using three tuning methods: Ziegler-Nichols, Cohen-Coon, Lópes & Miller, also develops a graphical interface in the Matlab software. Weidmann *et al.* (2019) develop a low-cost plant ($ 85) to control the level by PI controllers with anti-windup action and adjusted by the Aström and Hagglünd method (1984).

This present work aims to reproduce an industrial problem with a portable lab plant, called MTX laboratory plant, whose objective is to control humidity and air temperature through different control strategies. It also developed a local didactic interface, which allows viewing the experimental data in real-time.

## 2. MTX-LAB EDUCATION UNIT

The Group of Intensification, Modelling, Simulation, Control, and Optimization of Processes (GIMSCOP) developed the MTX plant, and it aims to define the best temperature and air humidity operating range. The plant was made with equipment and sensors that work with an Arduino Leonardo board, as shown in Figure 1.

MTX-LAB was developed to allow humid air to enter the chamber consisting of a tee PVC pipe component and two parts of recycled bottles (see Fig. 1a). There is a cooler between these parts of bottles, which has the function of moving the air mass from the left side (before it) to the right side (after it). There are also two lamps inside the chamber, which heat the system.

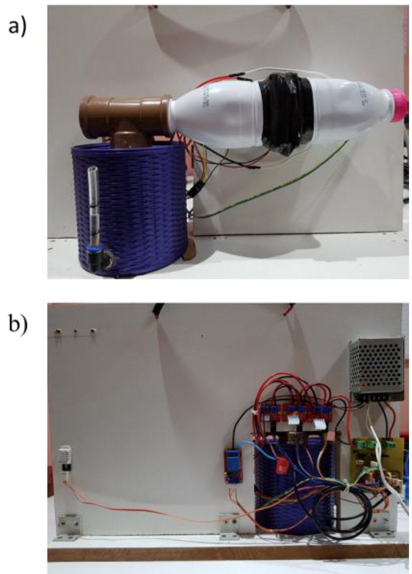


Fig. 1. MTX-LAB plant developed by the GIMSCOP: a) Front side; b) Backside.

The purple tank (Fig. 1a) is filled with water and heated through an electric heater, generating water vapor that mixes with the air mass circulating in the chamber above. Between the connection of this tank and the tee PVC component, there is another cooler.

In addition to the microcontroller, the plant is equipped with sensors to monitor temperature and humidity at the inlet and outlet of the chamber's chamber, temperature, and level of the purple tank. Further details regarding the MTX-LAB components can be seen in Appendix A. Also, the didactic interface developed for plant supervision can be found in Appendix B.

## 3. DYNAMIC MTX-LAB EVALUATION

The MTX_LAB plant is a fascinating plant due to its simplicity and dynamic behavior. As the lamp and cooler power variation, the input variables induce an effect on output variables, as the temperature and relative humidity on the chamber output, in which those effects can be more (or less) intense depending on the system operating point.

Besides, these output variables cause effects in each other because the temperature defines the water vapor's saturation pressure and, consequently, the maximum mass quantity of that vapor in the air. Thus, for a fixed quantity of water vapor mass on the system, the temperature increase or reduction implies relative humidity reduction or increase.

Another interesting feature of the system is water vapor's addition when the electric tank heater is activated. Although the water medium temperature in the environment can differ from the water boiling temperature, the liquid around the heater zone receives a very high thermal load doing this portion of water to reach the boiling temperature quickly and producing extra evaporation.

Additionally, the tank exhaust can potentialize the effect of water mass addiction on the system when it is on. The effect of water mass addiction is the increasing on relative humidity. The opposite is also true for a fixed output temperature.

In order to evaluate the causes and effects of MTX_LAB dynamics, an experiment in open loop was done, in which modifications were done on the system input variables and the effects on the output variables were observed, as can be seen in Fig. 2.

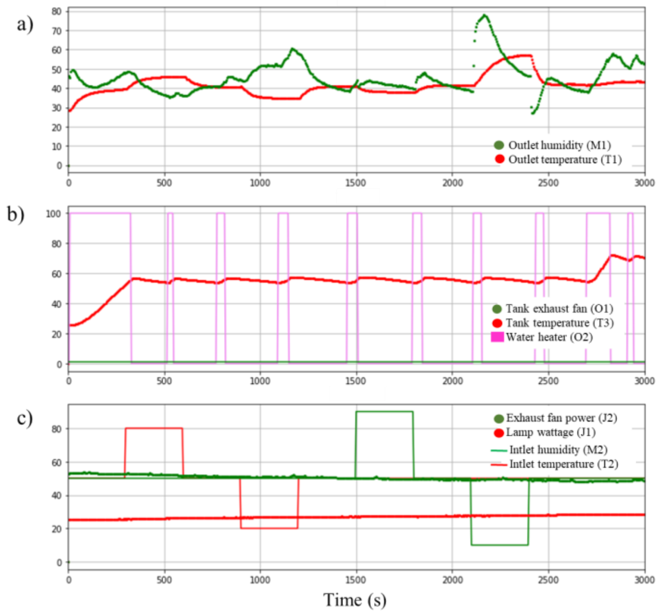


Fig. 2. Dynamic MTX-LAB evaluation in open-loop: (a) output, (b) tank, and (c) input. The temperature units are degrees Celcius (°C), the relative humidity, the power of the lamp, exhaust fan, and electric heater is in percentage (%).

Fig. 2 shows that between 0 and 250 s, the process has startup with temperature and environment relative humidity equal to approximately 28 ºC and 53%, respectively. The input variables (lamp power and cooler) were set to 50% about their range. The tank has the temperature setpoint next to 60 ºC and the exhauster in 0% (off).

In the next period, from 250 to 600 s, a step of 30% in the lamp power was applied, increasing the output temperature from 40°C to approximately 46 °C, that causes a decrease in output relative humidity from 45% to 35% (Fig. 2), as expected. In this same period, past 500 s, it is possible to notice a relative humidity peak. It was caused by tank electric heater activation, which adds water vapor to the chamber above the tank.

Between 600 and 900 s of Fig. 2, the power lamp returns to startup value, decreasing the output temperature and increasing the output humidity. In the following period, between 900 and 1300 s, a step of -30% in the luminous intensity was applied, decreasing the output temperature and increasing the output humidity. Then, between 1200 and 1500 s, the luminous intensity returns to startup conditions, and the output variables return to the same value reached in the period between 700 and 800 s.

In the second half of the test, in the period between 1500 and 1800 s, a step of 40% was applied in the cooler power, increasing the airflow in the chamber, causing an increase in the output relative humidity and a decrease in the output temperature (Fig. 2). In that period, the reduction in temperature is expected due to chamber cooling caused by an air mass renewal. Analyzing the relative humidity individually, the effect caused by the change in the input variable is the opposite of the expected. The air mass's residence time is not favorable to increasing water vapor concentration in the system output. However, as was previously mentioned, the water vapor saturation pressure in the air depends on the temperature in an inversely proportional relationship. So, the effect caused in relative humidity due to a change in output temperature was higher than the effect caused by changes in the residence time of air mass in that part of the experiment.

When returning the initial experiment setting, between 1800 and 2100 s, the output variables return to the same setting's previous level. In the period between 2100 and 2400 s, a step of -40% in the cooler power was applied, and in parallel, the tank heater has started operation unloading a big water vapor mass in the system, as seen through the relative humidity peak in this period beginning. Past this first moment, an increase in output temperature and relative humidity (from 40 °C to approximately 58 °C for temperature, and from 40% to approximately 48% for relative humidity), as expected, knowing the individual effects on each variable. However, it was observed that although the temperature increase has an inverse effect in output relative humidity, the effect of the increase of water vapor mass concentration in the air, due to a less residence time of the air in the chamber, was superior in this part of the experiment. Following, the system returns to the initial setting, and the output variables levels return to previous levels.

Finally, in the period between 2700 and 3000 s, the tank temperature is set to a higher level, from approximately 60 °C to 70 °C, transferring more thermal energy to the system chamber causing a slight rising in output temperature, and transferring more water vapor mass quantity due to heater tank activation causing an increase in output relative humidity.

**Table 1: MTX-LAB cause and effect matrix**

| Input variables | | Variables at the exit of the chamber | | |
|---|---|---|---|---|
| | Configuration | Temperature (T1) | Relative humidity (M1) | Tank temperature (T3) |
| Lamp wattage (J1) | High | ++ | -- | 00 |
| | Low | -- | ++ | 00 |
| Chamber exhaust fan power (J2) | High | -- | -- | 00 |
| | Low | ++ | ++ | 00 |
| Eletric heater (OY2) | On | + | + | ++ |
| | Off | 0 | 0 | 00 |

(+): Increase (-): Decrease 0: slight variations or null

Thus, it is evident the MTX_LAB unique static and dynamic behavior, since the effects of output temperature and residence time of air mass in the system are competitors, and depending on the operating point, one effect can be higher than the other one. Moreover, the output temperature is a variable that imposes operational limits to the output relative humidity and the external environment temperature and relative humidity. It is also important to highlight that beyond the effect of water vapor addition in the chamber, the tank temperature also influences the chamber thermally.

Table 1 summarizes the effect between the process variables. Now, grounded in these analyses, it was proposed a controlling alternative for MTX_LAB, based on Multi-SISO PID controllers strategy, as can be seen in the next section.

## 4. MTX-LAB CONTROLLED BY MULTI-SISO PID CONTROLLERS

This session discusses a control proposal for the MTX-LAB plant, evaluating the performance of different configurations for this strategy through performance criteria and the system identification stage for the controller design.

### *4.1 Multi-SISO controller*

The multi-SISO PID controllers' strategy proposed for MTX-LAB is a simplified approach to multivariable controllers, which approximates the MIMO (multi-input multi-output) system by several SISO (single-input single-output) loops.

In this approach, based on information from the cause-effect matrix (Table 1), a SISO loop has the wattage lamps as input and the output temperature as output. In another SISO loop, the wattage of the chamber exhaust fan is the manipulated variable. The output relative humidity is the controlled variable, both of which are loops with PID controllers.

Also, an auxiliary loop was closed with an ON-OFF controller, in which the tank temperature is controlled from the actuation of the tank electric water heater. Figure 3 is a schematic representation of MTX-LAB with the identification of the proposed control loops.

In loops 1 and 2 (see Fig.3), different combinations of PID controllers were evaluated, as shown in Table 2.

The PID controller algorithm used was the discrete version in positional form, given by:

$$\mathrm{u(kh) = ubias + P(kh) + I(kh) + D(kh)} \quad (1)$$

where $h$ is the sampling time, u(kh) is the control signal, P(kh), I(kh) and D(kh) are respectively the proportional, integral, and derivative actions that are calculated according to Equations (2-4).

$$\mathrm{P(kh)} = \mathrm{K_p}(\mathrm{y_{set}(k)} - \mathrm{y(k)}) \quad (2)$$

$$\mathrm{I(kh + h)} = \mathrm{I(kh)} + \frac{\mathrm{K_p h}}{\tau_\mathrm{I}}(\mathrm{y_{set}(kh)} - \mathrm{y(kh)}) \quad (3)$$

$$\mathrm{D(kh)} = \frac{\tau_\mathrm{D}}{\tau_\mathrm{D} + \mathrm{Nh}}\mathrm{D(kh - h)} - \frac{\mathrm{K_p}\tau_\mathrm{D}\mathrm{N}}{\tau_\mathrm{D} + \mathrm{Nh}}(\mathrm{y(kh)} - \mathrm{y(kh - h)}) \quad (4)$$

In Equations (2-4), $K_p$, $\tau_I$, and $\tau_D$ are the PID tuning parameters. Parameter N is related to the derivative control action filter.

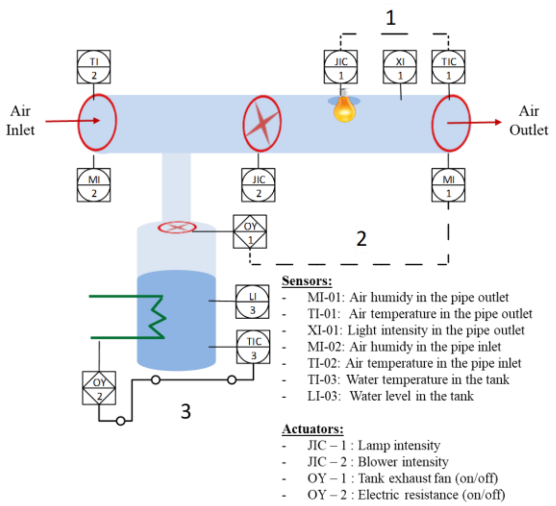


Fig. 3 MTX plant schematic representation with its variables and closed-loop control strategies developed.

**Table 2: Combinations of PID controllers evaluated in multi-SISO strategy**

| Setting | Controlled variable | Controller |
|---|---|---|
| A | Humidity | PID |
| | Temperature | PI |
| B | Humidity | PI |
| | Temperature | PI |
| C | Humidity | PI |
| | Temperature | PID |
| D | Humidity | PID |
| | Temperature | PID |

### *4.2 Closed-loop performance criteria*

The metric used to evaluate the performance comparison was the Integrated Absolute Error (IAE) criteria, which is given by

$$\mathrm{IAE} = \int_0^{\infty} |y_{set}(t) - y(t)|dt \quad (5)$$

where $y_{set}(t)$ is the setpoint and $y(t)$ is the present value of the controlled variable.

In addition to the IAE performance index, the Control Effort (CE) was also assessed, which is given by

$$\mathrm{CE} = \int_0^{\infty} (u_{k-1}(t) - u_k(t))^2 dt \quad (6)$$

where $u_k(t)$ is the present value of the manipulated variable and $u_{k-1}(t)$ is the value before $u_k(t)$.

### *4.3 System identification and controller design*

In order to design PID controllers, the system identification was performed by transfer functions. For this, the experiment presented in Fig. 2 was used. It must be observed that due to the strong correlation presented by the relative humidity variable with the outlet temperature, a simple transfer function was not possible to explain the nonlinear behavior that involves the power of the exhaust fan/outlet temperature/outlet relative humidity, discussed in detail in section 3.

For the relationship between the lamp power (J1) and output temperature (T1) variables, the following transfer function was identified:

$$G(s) = \frac{\Delta T1}{\Delta J1} = \frac{0.22}{70s+1} e^{-2s} \quad (7)$$

The result of the transfer function identified (Eq. 7) with the experimental results can be seen in Figure 4.

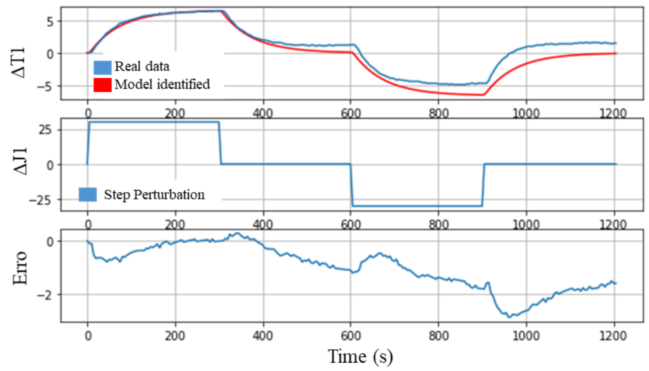


Fig. 4. Identification of T1 response to J1 in order to obtain the transfer function.

In Figure 4, it can be observed that for the identification of the transfer function (Eq. 7) was selected the part of the experiment in which only the power of the lamps is manipulated, the period between 0 to 1200 s (Fig. 2). Furthermore, the identified model has captured the system's transient response.

Although it was not possible to identify a simple model that captured the humidity behavior, some insights could be treated as a stationary state gain, and from that, adjust classic linear controllers for this loop. For the temperature loop, knowing the identified model (Eq. 7), was used the Internal Model Control (IMC) method, developed by Rivera, Morari, and Skogestad (1986), as the starting point, with slight adjustments being made *a posteriori*. The tunings to the settings, which were presented in Table 2, are shown in Table 3.

**Table 3: Tuning of the evaluated controllers for each setting**

| Setting | PID Controller's Parameters | | |
|---|---|---|---|
| | **$K_p$** | **$\tau_I$ [min]** | **$\tau_D$ [min]** |
| **A** | -0.5 [%/%] | 10 | 5 |
| | 12 [%/ºC] | 50 | - |
| **B** | -0.6 [%/%] | 8 | - |
| | 12 [%/ºC] | 50 | - |
| **C** | -0.6 [%/%] | 8 | - |
| | 12 [%/ºC] | 30 | 3 |
| **D** | -0.6 [%/%] | 10 | 5 |
| | 12 [%/ºC] | 30 | 3 |

### *4.4 Evaluation of the MTX-LAB in closed-loop*

The results of the closed-loop evaluations for each set of PID controllers evaluated, based on the IAE and CE performance criteria of temperature (Temp.) and humidity (Hum.), are shown in Table 4.

**Table 4: Performance index for each set of evaluated controllers**

| Setting | Performance Index | | | |
|---|---|---|---|---|
| | $IAE_{Hum.}$ | $CE_{Hum.}$ | $IAE_{Temp.}$ | $CE_{Temp.}$ |
| A | 10277.8 | 21646 | 2538.3 | 40488.6 |
| B | 8226.7 | 12218.2 | 3477.3 | 54160.3 |
| C | 8105 | 12953.8 | 2862 | 230869.7 |
| D | 13080.2 | 292060.3 | 2815.8 | 224210.3 |

Analyzing each loop individually, it is observed that the best controller, in terms of IAE, was the PIs from C and A settings for the humidity and temperature loops, respectively, because both have lower IAE values, as observed in Table 4. In contrast, when those two controllers were used together (setting B), they had underperformed, especially the temperature loop (37% upper IAE compared to better performance). That evidences the multivariable characteristic of the system, wherein one loop behavior interferes in another, mutually.

Besides evaluating the IAE criterion, it is also necessary to evaluate the CE criterion, because it indicates how much sudden movement is being made in the manipulated variable. That way, it was identified that the best controllers were the PIs from B and A settings for the humidity and temperature loop, respectively, because both have lower CE values, as observed in Table 4. It was also observed that when PIDs controllers were used in both loops (setting D), the control effort was higher.

Based on these observations, if there is a priority of control between one of the controlled variables and also taking into account a non-excessive control effort of both loops, the most suitable setting when prioritizing humidity control is setting B. For the case of temperature priority, setting A is the most suitable. For example, the experimental result of the system under setting B is shown in Figure 8.

In Fig. 8, it is noted that the system has been achieved the setpoints, except for the sampling interval between 250 and 750 in the temperature control loop. For this reason, the largest IAE criterion among the configurations can also be justified. However, if the system had started from a slightly more favorable condition, this setpoint would have indeed been reached, as happened in the other experiments. Although there was a great effort to start the experiments in the closest possible condition for comparative analysis, there are variables that cannot be controlled, such as the day's temperature and humidity.

The same figure shows how sensitive the humidity is to any change in the system's other variables. For example, when the tank's electrical heater is turned on, due to the existence of a more significant transfer of water vapor to the chamber, the outlet humidity suffers an additive disturbance in its value, moving it away from the setpoint. It was also observed that the variability of the controlled variables managed to be transferred to the manipulated variables, which was translated into smooth control actions for both loops.

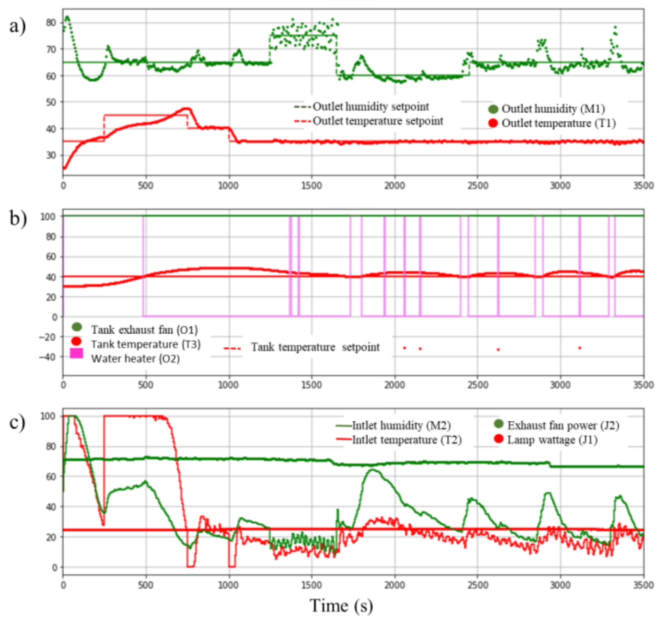


Fig. 5. Dynamic MTX-LAB evaluation in closed-loop experiment with setting B: (a) output, (b) tank, and (c) input. The temperature units are degrees Celcius (°C), the relative humidity, the power of the lamp, exhaust fan, and electric heater is in percentage (%).

## 5. CONCLUSIONS

This work presented a laboratory plant that has an interesting multivariable characteristic. The system dynamics observed by the open-loop results showed the influences between controlled and manipulated variables, which lead to the application of a multi-SISO control strategy.

For the closed-loop analysis, among the settings tested, the most suitable for the humidity control is composed of two PI controllers, with parameters $K_p$ of -0.6 %/% and 12 %/°C, $\tau_I$ of 8 and 50 min, performance indexes IAE of 8226.7 and 3477.3, CE of 12218.2 and 54160.3 for humidity and temperature respectively. For the case of temperature priority, the suitable settings present a PID for temperature and a PI for humidity controls, with $K_p$ of -0.5 %/% and 12 %/°C, $\tau_I$ of 10 and 50 min, performance indexes IAE of *10277.8* and *2538.3*, CE of *21646* and *40488.6* for humidity and temperature respectively and also the parameter $\tau_D$ of 5 min for temperature.

For simultaneous control of temperature and humidity, a MIMO control strategy is indicated. Notwithstanding, for educational purposes, the multi-SISO showed significant aspects and topics to be discussed.

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## Appendix A. DIDACTIC PLANT COST

Table 5 shows the components with their cost, being the final prototype cost is estimated to be around $58.00.

**Table 5: Cost to design the MTL_LAB plant.**

| Material | Price |
|---|---|
| 1 Arduino Leonardo | 13.86 |
| 1 12V 15A Switching Power Supply | 5.91 |
| 2 DHT22 Temperature and Humidity Sensor | 10.72 |
| 3 IRF520 MOSFET Module | 2.19 |
| 1 5V 10A Relay Module for arduino | 1.57 |
| 1 220V 830W Water heater | 2.77 |
| 1 DS18B20 water temperature sensor | 3.88 |
| 1 5V Cooler | 3.14 |
| 1 12V Cooler | 5.17 |
| 1 Printed circuit board | 0.37 |
| Pin connectors and bars | 0.74 |
| 10k Ω, 1k Ω, 470Ω Resistors | 0.09 |
| 2 Halogen lamps 12V 50W with support | 1.39 |
| 1 40 mm PVC tees | 1.57 |
| 1 Water tank | 4.62 |
| Wooden support | 0 |

Here are some details:

A) Arduino board Leonardo: it is a microcontroller with digital and analog input/outputs.

B) Temperature and air humidity sensor DHT22:

C) Light intensity sensor BH1750FVI Lux.

D) Water level sensor Arduino-FD10.

E) Waterproof temperature sensor DS18B20.

F) Cooler: it is used two coolers of 12V.

G) Electric Heater: it is used an electric heater of 220V.

H) Lamps: there are two 20W 12V halogen lamps positioned at a 90° angle concerning each other.

## Appendix B. DIDACTIC INTERFACE

The principal idea is to create a local didactic interface, which enables you to see the MTX Plant's experimental data in real-time to evaluate the effect of input variables on output variables. The program chosen to generate the interface is Python (version 3.7), the library used is PYQT5 (PyQt5 Reference Guide, 2020), the design of the window was made by QT Designer software (QT Designer Manual, 2020) and Numpy (Numpy, 2020). Figure 6 presents the interface designed for the system monitoring.


Fig. 6. Graphic interface developed for the MTX-LAB plant.

The "start" button is used to connect the interface to the Arduino and start the experiment, while the "stop" button is used for the system to stop the experiment and save the experiment data. Experimental data are represented by graphs called the input data as "inputs" and the output data as "outputs".