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Implementation of Condition-Based Maintenance (CBM) in a central air conditioning unit by using microcontroller and open-source monitoring platforms

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***Abstract*—In this work, an online and real-time monitoring system was developed in order to perform Condition-Based Maintenance (CBM). The proposed system named HC 4.0 uses low-cost hardware components such as an Arduino microcontroller and the graphical user interface was designed with the Grafana software, an open-source platform, to measure temperature, relative humidity, compressors currents and motor fan currents in a central air conditioning unit installed at a Brazilian Clinical Hospital named "Hospital das Clínicas da UFG/EBSERH" (HC-UFG/EBSERH). The HC 4.0 solution presents as a result useful information for the maintenance team indicating how to act in a faster, more assertive and effective way regarding the inherent failure modes that are dealt with in a usual work routine.*

A long-time experiment was conducted for 30 days while the Hospital was operating normally and prominent results were obtained. A designed dashboard through Grafana is used to evaluate the conditions required in order to make an early intervention in the equipment. Furthermore, the system is able to send alerts to the maintainer's cellphones by using a message app such as Telegram, when some parameter goes beyond the pre-defined limits. Additionally, a Failure Mode and Effect Analysis (FMEA) for the central air conditioning unit of the hospital is presented alongside the recommendations to each situation for the maintainer. The results encourage the use and further development of the HC 4.0 approach in order to implement low-cost CBM of Hospital equipment's such as the central air conditioning unit focused on this work.

I. INTRODUCTION

One of the great challenges for maintenance teams is to take assertive decisions before the functional failure of an equipment occurs. Acting on the right moment, when the equipment is in the incipient stage of its failure mode may represent the opportunity to reduce both direct and indirect maintenance costs that involve material purchases and maintenance time. At the same time, promptness of service is optimized. Teles (2019) says that a failure mode is the way how the failure is born in an equipment, getting worse with time until it turns to a functional failure when the equipment loses its projected operational functions. This paper proposes the use of a low-cost online monitoring system that was developed, capable of identifying failures in real-time, aiming to detect failures at a certain stage as early as possible. Thus, a monitoring solution to a central air conditioning unit from a Brazilian Clinical Hospital (HC-UFG/EBSERH) with a microcontroller (Arduino) and a monitoring platform (Grafana) was developed.

In the concept of Industry 4.0, there are new technological ways to apply improvements in a hospital. For instance, to achieve certain goals such as performing near real-time online monitoring of the operation of a critical equipment. Industry 4.0 acts as the umbrella term made up of the tools which form its structure, namely, Cloud Computing, Cyber Physical Systems (CPS), Big Data and the Internet of Things (IoT) (CHESWORTH, 2018; KRISHNARAJ, 2021; CARVALHO, 2020). Monitoring variables of equipment, system or environment is not something difficult nowadays, since the production of low-cost sensors and microcontrollers is a reality worldwide that maintenance managers need to know and utilize. With relatively low investments it is possible to turn the maintenance strategy of critical equipment's from Corrective Maintenance or Preventive Maintenance to Condition-Based Maintenance (CBM). This strategy not only helps to reduce the inherent maintenance costs, but also helps to improve the safety of the monitored equipment's or structures (SILVA et al., 2020). Additionally, promptness of service can be optimized with the proper operation of such a system, reducing the chance of inactivity or waiting time for the patients.

In times of Industry 4.0, the term Predictive Maintenance might be confused with CBM. However, it is possible to differentiate between them. Dabrowski and Skrzypek (2018) compare both indicating that, on the one hand, CBM is characterized by being performed after some condition is observed in a certain equipment. It requires monitoring devices and qualified staff. As a result, CBM maximizes the productive time and the useful life of the equipment. Predictive Maintenance, on the other hand, is characterized by the need for high investment in monitoring, prognostic and diagnostic equipment; managing to maximize productivity and equipment life, giving a high possibility of planning. Schmidit and Wang (2016) indicate that Predictive Maintenance is an approach that uses condition monitoring data to predict future machine conditions and make decisions based on that prediction. Lai, Jiang and Jackson (2019) explain that CBM assumes there are indicators which can be used to detect and quantify possible equipment failure before it actually occurs. (Rabelo et al., 2017a) explain that CBM have been evolving constantly and such strategies aim at detecting the presence and severity of damage on a statistical basis.

There are many possible ways to monitor equipment's available in the world market or by self-development. The failure prediction process can be achieved either by using machine learning techniques or without them, being the alternatives implemented according to the need, complexity, cost and severity. Yan et al (2020) have demonstrated an experiment to monitor rotating equipment without sensors, using only audiovisual resources to predict the failure mode, demonstrating the effectiveness and limitations for this type of solution. De Azevedo et al (2017) have used accelerometers to monitor the bearing vibration of real wind turbines, identifying a failure in one of the bearings and verifying that the vibration spectrum changed after the bearing was changed. Rabelo et al., (2017b) have used a low-cost impedance-based monitoring system in order to detect real-time growth of fatigue cracks in an aluminum beam using piezoelectric transducers. Raduenz et al (2018) have demonstrated the possibility of predicting directional valve failures based on the control signal, spool position and supply current, concluding that the online measurement of the data provides faster reaction in the solution. In the context of maintenance 4.0, online monitoring, in its various forms, has become a necessity for critical equipment's. The main limitation in this regard are the costs, which still characterize some advanced technological solutions, as well as the cost and difficulty of finding resources on the market with the necessary analytics and information technology (IT) skills (RODA; MACCHI; FUMAGALLI, 2018).

The main goal of this paper is to propose a low-cost solution to implement a CBM model to monitor failure modes regarding the central air unit of the hospital where it has been deployed. The solution presents results making the maintenance process more assertive, with online monitoring capability of a critical equipment of the hospital.

User monitoring interface with Grafana (Grafana, 2022) also added to HC-UFG/EBSERH the concept of Internet of Things (IoT) in the Physical Infrastructure Sector. Kumar et al (2019) states that the Internet of Things (IoT) is an emerging paradigm that enables communication between electronic devices and sensors through the internet to make our lives easier. Magrani (2018) conceptualizes Internet of Things as the interaction and connectivity between various types of everyday objects, with the possibility of connecting to the internet. In order to perform online monitoring, the developed system uses the Ethernet Shield which, connected to the HC-UFG/EBSERH intranet, transmits the data collected by the sensors. Online monitoring has several advantages, since it is cheaper and easier, no human presence is required, usually the measurement is more accurate, the measurement is independent of the worker's skill, it enables the possibility of programmable alerts and triggers. Also, data storage is easy, allowing for further studies of forecasts and statistical models.

Throughout the development of this work, some papers were searched to verify if some of them would suggest the proposal of a low-cost monitoring solution focused in CBM to hospital equipment. However, even though some studies have reported the proposal of methodologies to implement CBM to hospital equipment, very few have focused on the development of a low-cost solution to perform online monitoring. The main contribution of this paper is to propose such methodology by using the central air conditioning unit of a clinical Hospital.

This kind of solution is very important to certify that a CT Scanner (Computed Tomography Scanner) environment is kept within the standard operational boundaries. This provides risk mitigation of corrosion in components of equipment of high responsibility in a hospital such as a CT Scanner (shown in Fig. 1), whose costs are significantly high.

Fig. 1: CT Scanner

II. APPLICATION OF ARDUINO FOR DATA COLLECTION WITH SENSORS

For the design of the DAQ (Data Acquisition) system, low-cost hardware components were chosen for the solution, which includes a microcontroller board (Arduino Mega 2560), nine electrical current sensors (SCT-013-000), one temperature and humidity sensor (DHT22), and an infrared sensor (E18). The microcontroller was programmed to collect data of temperature and relative humidity from an environment with a CT Scanner, which requires strict controls on these variables. The data were collected in the return duct. All measurements of electrical currents were performed within the electrical panel at the contactors output, as highlighted in yellow in Fig. 2. The DAQ system was also set to collect the electric currents of two hermetic refrigerant compressors in order to sense the electric currents of an evaporator fan motor as well as the fan rotation.

Fig. 2: Electrical panel and current sensors

It should be noted that although the central air conditioning targeted by this work is used to control the climatization in a tomography room, it also climatizes two other rooms. Due to infrastructure limitations, the measurement could not be performed inside the room. To work around this issue, the return air measurement, which would be sufficient and a correct method if it were only one environment, had to be corrected to achieve the specific desired room setpoint and not the contribution of all three rooms.

Fig. 3: E18 infrared sensor

A calibrated datalogger (Icel HT-4000) was used to perform 439 measurements that were compared to the developed monitoring system measurements, as shown in Fig. 5 and Fig. 6. The points that are darker than others refer to higher frequency of the same correlation between room temperature and return duct temperature (Fig. 5) and it can be seen on bar graphs over the axes, where the bars are bigger when there are more data repeatability. The linear correlation value between temperature values is 0.8665, which shows a strong linearity. On the other hand, Fig. 6 is about the relative humidity values with the same measurement conception. The linear correlation value between relative humidity values is 0.5982, which shows a good linearity as well. Thus, since there is linearity between the data, it was possible to perform a linear regression to calibrate the data measured by the sensor in the microcontroller program.

Fig. 4: Temperature and relative humidity sensor (DHT22)

In order to correct the measurement between temperature and relative humidity in the room and in the air return duct, a linear regression was applied. Fig. 5 and Table 2 illustrate an example with 14 measurements out of 439 performed to generate the linear equation that correlates the value measured inside the room and the value measured on the air return duct to temperature and relative humidity, respectively. In Fig. 5, T_Datalogger and T_DHT_0 represent the temperature measured in the room and air return duct, respectively. In Table 2, UR_Datalogger and UR_DHT_0 represent the relative humidity measured in the room and air return duct, respectively. At both tables a regression column is presented where the regression equation has been applied, generating temperatures values with average percentual difference of 0.744 % in regard to room temperature. Concerning the relative humidity values, an average percentual difference of 1.133% was observed in regard to room relative humidity.

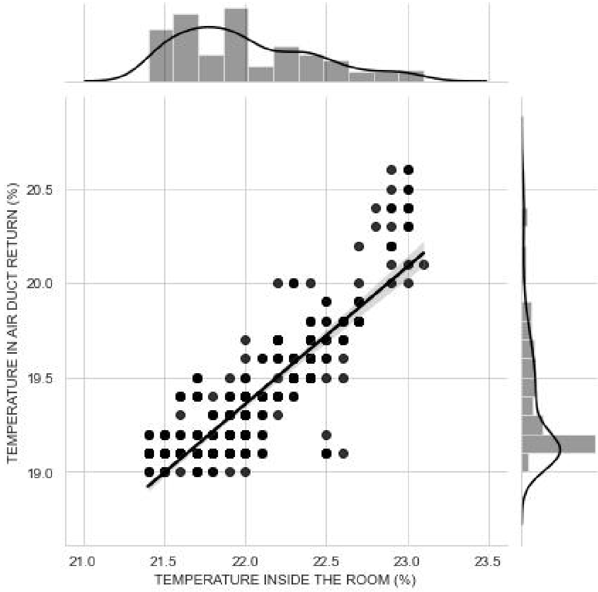

Fig. 5: Correlation between room temperature and Arduino temperature

Table.1: Correlation between room temperature and air return duct

ID	Date	Hour	T_Datalogger	T_DHT_0	Regression
1	10/23/2020	14:52:19	23.00	20.40	23.08
2	10/23/2020	15:02:19	23.00	20.60	23.28
3	10/23/2020	15:12:19	22.90	20.60	23.28
4	10/23/2020	15:22:19	23.00	20.60	23.28
5	10/23/2020	15:32:19	23.00	20.50	23.18
6	10/23/2020	15:42:19	23.00	20.50	23.18
7	10/23/2020	15:52:19	23.00	20.30	22.97
8	10/23/2020	16:02:19	23.00	20.40	23.08
9	10/23/2020	16:12:19	23.00	20.40	23.08
10	10/23/2020	16:22:19	23.00	20.40	23.08
11	10/23/2020	16:32:19	22.90	20.40	23.08
12	10/23/2020	16:42:19	22.90	20.30	22.97
13	10/23/2020	16:52:19	22.90	20.40	23.08
14	10/23/2020	17:02:19	22.90	20.50	23.18

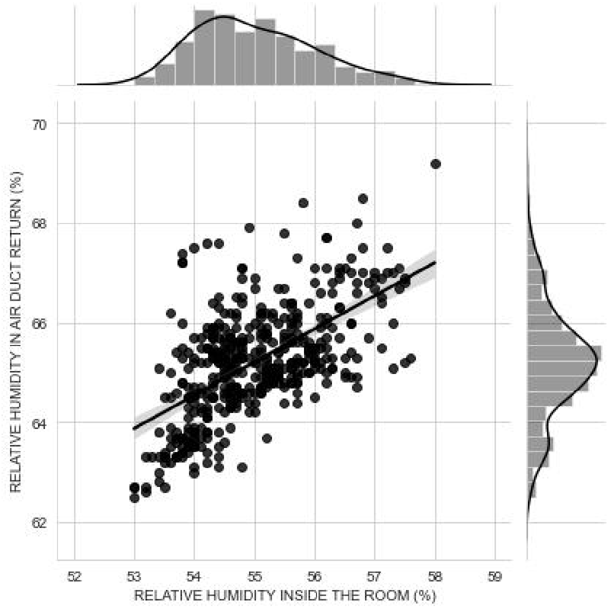

Fig. 6: Correlation between room humidity and Arduino relative humidity

Table.2: Correction analysis of relative humidity measurements

ID	Date	Hour	UR_Datalogger	UR_DHT_0	Regression
1	10/23/2020	15:02:19	58.00	69.20	57.19
2	10/23/2020	15:12:19	57.10	66.40	55.66
3	10/23/2020	15:22:19	56.60	66.00	55.44
4	10/23/2020	15:32:19	56.30	65.30	55.06
5	10/23/2020	15:42:19	55.10	65.10	54.95
6	10/23/2020	15:52:19	56.00	64.50	54.62
7	10/23/2020	16:02:19	56.20	65.50	55.17
8	10/23/2020	16:12:19	56.00	65.50	55.17
9	10/23/2020	16:22:19	56.20	66.00	55.44
10	10/23/2020	16:32:19	55.90	65.60	55.22
11	10/23/2020	16:42:19	55.50	65.50	55.17
12	10/23/2020	16:52:19	56.20	65.00	54.89
13	10/23/2020	17:02:19	55.30	65.60	55.22
14	10/23/2020	17:12:19	55.00	64.60	54.68

The variables measured by the monitoring system developed have been represented graphically in Grafana. Fig. 7 shows the complete dashboard that has been developed in this work.

A section with the instantaneous measurements of temperature, relative humidity and fan rotation speed is shown in Fig. 8. This type of graphical representation is called a Gauge, with visual warnings that indicate whether or not the variable is within acceptable limits. If the value displayed is in the green color, it is in the expected condition. If it is in the yellow color, it is out of range, but not in critical condition yet. The yellow temperature range was considered 19-20°C or 24-25°C, while the relative humidity yellow range was considered 35-40% or 60-65%. Lastly, if it is in the red color, it is in the unwanted critical condition. The limits were established by using the CT Scanner manual and maintainers experience.

III. DEVELOPMENT OF AN INTERFACE WITH GRAFANA

In this work, a graphical interface has been made with Grafana dashboard. The software Grafana provides a highly customizable interface, and allows templated queries for the desired variables (BRATTSTROM; MORREALE, 2017).

Fig. 7: Work Dashboard using Grafana

Fig. 8: Represents temperature, relative humidity and rotation instantaneous reading

Fig. 9 shows a histogram of electric currents. Since all values are green, the dashboard displays a safe operation occurring. In case the upper limit is crossed, the bars start to show red colors.

Fig. 9: Compressors and fan currents instantaneous reading

Fig.10-Fig. 15 present time domain plots of the temperature, relative humidity, fan rotation speed, compressors 1 and 2 electrical currents and fan currents, respectively. This is the dashboard part that is programmed to send alarms through a mobile message application when the variables values reach the region red for more than 10 minutes. For this experiment, the application Telegram was used.

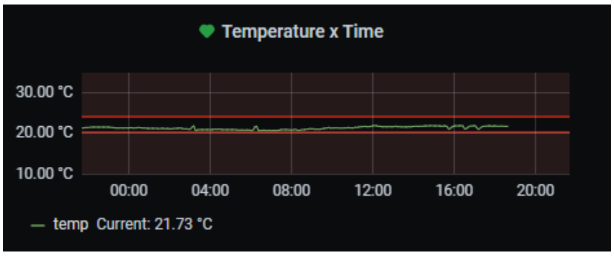

Fig. 10: Temperature along the time

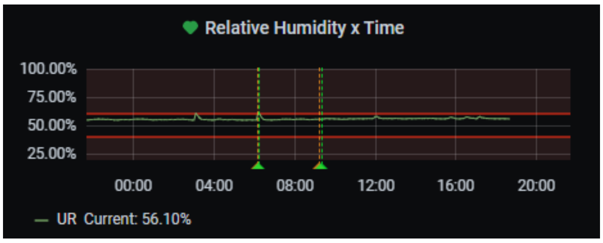

Fig. 11: Relative humidity along the time

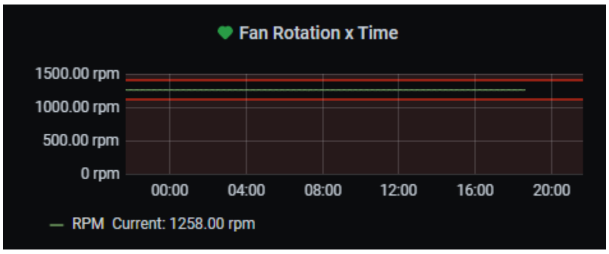

Fig. 12: Fan rotation along the time

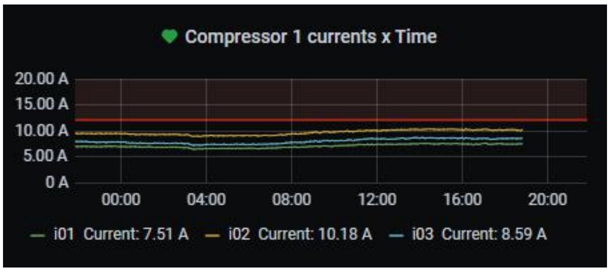

Fig. 13: Compressor 01 currents along the time

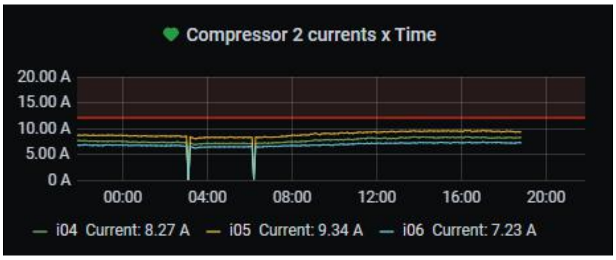

Fig. 14: Compressor 02 currents along the time

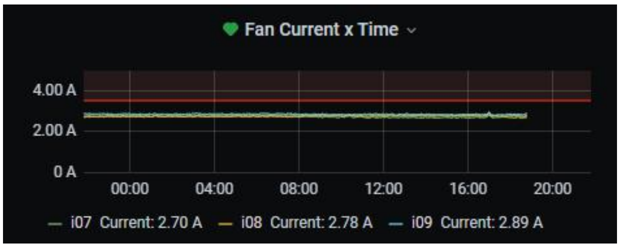

Fig. 15: Fan currents along the time

On the last dashboard line (Fig. 16) a line of time versus equipment total availability is presented. The line will be reduced in case the rotation speed value becomes zero. In addition, Fig. 16 presents a table showing which relays responsible for triggering components of the central air conditioning are switched either on, off or in last status. At the moment when Fig. 17 was captured, the fan relay (VT) was on and all others components were in last status.

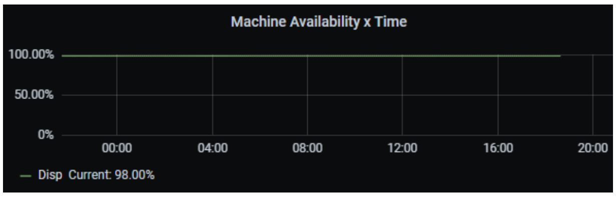

Fig. 16: Machine availability along the time

OPERATION	ID
VT: ON / ALL IN LAST STATUS	22104
VT: ON / ALL IN LAST STATUS	22103
VT: ON / ALL IN LAST STATUS	22102

Fig. 17: Type of operation

IV. SOLUTION PLANNING AND EXECUTION

This work has been developed in order to create a solution for the benefit of the Maintenance Team (SIF) from HC-UFG/EBSERH, a federal public hospital. The solution proposed is to deploy a pilot project of a critical equipment managed by a CBM strategy.

For the experiment design, a period of 30 days was established for continuous online monitoring and verification of the system. During this time, data was collected to analyses whether the measurements presented satisfactory results while the equipment's were in operation. Data has been carefully checked during the tests and were verified using appropriate instruments. Fig. 18 shows a fan rotation speed measurement where the data collected was satisfactory providing 0.89% of variation in relation to a calibrated instrument.

Fig. 18: Rotation measurement

For comparing the temperature inside de CT Scanner room and the temperature in the air conditioning duct outlet, it was utilized a datalogger to collect the data inside the room, as shown in Fig. 19. In this figure is possible to see 3 curves with three different colors:

- Yellow: Relative humidity (RH %);
- Red: Temperature (ºC);
- Green: Dew point.

Fig. 20 (Temperature) and Fig. 21 (Relative humidity) represent the same moment of measurement (from 10-30-2020 to 11-03-2020), however using the sensor DHT22. The results were satisfactory comparing with the measurement inside the room.

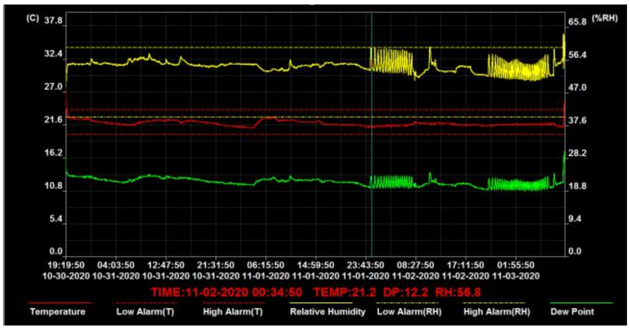

Fig. 19: Temperature and relative humidity from 10/30/2020 to 11/03/2020 using datalogger inside the room before of starting this work

The electrical currents were tested as well by comparing with a current measurement with a plier ammeter (basic precision of 2%) and it has been observed an average difference from 2.2% to 2.5% for all phase currents. For the scope of the proposed application, the measurements have been considered satisfactory.

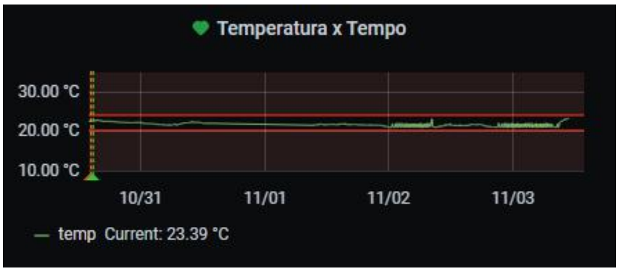

Fig. 20: Temperature from 10/30/2020 to 11/03/2020 in the air conditioning duct outlet

Fig. 21: Humidity from 10/30/2020 to 11/03/2020 in the air conditioning duct outlet

4.1. CBM applied to the fan

The possible failures in the fan electric motor can be resulted from the transmission belt failure mode, the bearing or the electric motor, and all these conditions can generate other more expensive failures if not corrected in an early stage.

On the one hand, in case of failure of the electric fan motor or failure of the fan bearing, the electric currents tend to increase as the failure becomes more severe. On the other hand, the fan rotation tends to decrease and vibration tends to increase as the problem gets worse.

This situation can be seen on Fig. 22, which shows the bearing problem during some days (from 06/02/2020 to 06/08/2020) until the electric motor breaks. This situation has occurred during the development and installation of the HC 4.0. At the time, the team did not know the behavior, and, on this period, it did not have yet the measurements of electric currents. This event shows that even with online monitoring, it is necessary to study and learn about the failures behavior in order to create the right alerts in the system. As can be seen in this failure, the alert trigger was lower than the necessary level to call the maintenance team to go to the site to act before the break. The setpoint was set to 800 RPM, however the failure could be alarmed at the 1100 RPM level. As shown in Fig. 12, the lower threshold for fan rotation has been adjusted to 1100 RPM and it is possible to see too that rotation speed is normally stable in 1258 RPM.

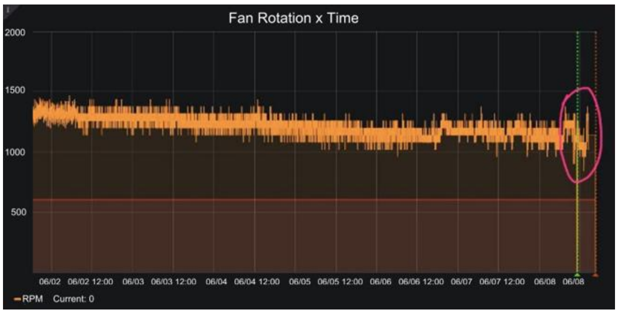

Fig. 22: The fan electric motor failure and break from 06/03/2020 to 06/08/2020

Another failure linked to the fan has been observed during the experiment time: the transmission belt breakage, which is shown on Fig. 23. This behaviour observed was very different from the bearing failure, since there is first a kind of vibration that increases the rotation speed measurement (moment "A"). Different from the bearing failure, in which the rotation speed decreases instantly from 1258 RPM to 1000 RPM (moment "B"). After some hours the transmission belt has broken at exactly 7 a.m. and the equipment automatically turned off (moment "C"). At this specific instance, unfortunately no maintenance maintainer was available before 7 a.m. Nevertheless, the transmission belt changing (moment "D") lasted only 18 minutes. Without an online monitoring strategy, this kind of activity would be dependent on the perception of the CT Scanner operation team about how hot the room temperature would be in that time, thus becoming susceptible to human error. Several problems could have happened if an early intervention had not occurred. For instance, the evaporator could freeze and generate a lot of consequences like gas refrigerant in liquid state inside the compressor, increasing the mechanical efforts, reducing the central air conditioning compressor useful life. Additionally, the CT Scanner could be shut down in case of high temperature.

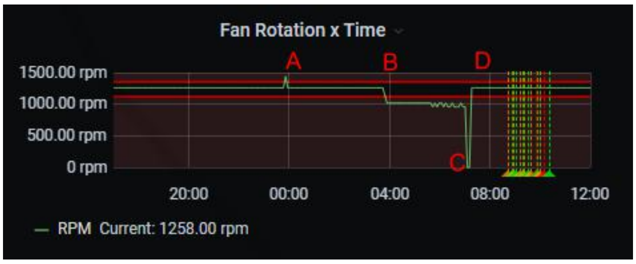

Fig. 23: Detection of transmission belt breakage

It is important to analyze that the machine vibration behavior, when the transmission belt breakage occurs (Fig. 23), is different of the bearing failure mode (Fig. 22), the vibration occurs only between moment "B" and "C" in the first one.

4.2. CBM of the compressors

Like the motor-fan, some conditions can be observed in the graph that cause the failure or the compressor's failure mode. Compressors in a refrigeration system tend to have their currents increased when their mechanical efforts increase. Some possible causes are listed below:

- A dirty condenser prevents the fluid heat exchange which increases its average temperature, expanding the fluid and increasing the system pressure. Consequently, this requires more mechanical effort from the compressor. In this way, the maintainer carrying out the equipment cleaning will be able to check if there is any other condition that is keeping the current high or if only the cleaning was sufficient for the correction;
- If the compressor is in failure mode due to any mechanical component, its electrical currents will also increase. However, because it is a hermetic compressor, the only way to work around this is to change the compressor, as the continuity with it until the break can cause greater damage such as fire risk;
- In the event of a lack of refrigerant in the system, the electric current will tend to reduce, as there will be less mechanical effort, with the visual consequence of freezing the evaporator and the environment temperature increasing. Therefore, with low electric current in the compressor and an increase in temperature in the room, the maintainer must evaluate the system pressure and replace refrigerant gas if necessary;
- If the operation table (Fig. 17) indicates that some compressor should be operating, but the electric currents are indicating value zero, the compressor is already broken. A case that can occur in moments that there is no maintenance team in the hospital to act before the breakage. Another possibility is that some electric protection might be disabled, or some cable might be disconnected;
- Another problem can be seen by analyzing the three electric currents of compressors or fan. If at least one electric current is different than zero and at least one other is equal to zero, there's a problem of phase loss. The maintainer needs to go to the equipment to verify if some electrical terminal is disconnected after the phase failure relay;
- The last problem that can be seen is unbalanced electric current, this is visual on the graphical interface (Grafana) and it will must be necessary to evaluate the equipment on site.

4.3. CBM of the electrical resistors

In case of electrical resistors, devices responsible of controlling the relative humidity that do not have sensors for performance monitoring, it may give rise to failure or failure mode if the system sends a relative humidity alert above the upper limit, for a long time.

4.4. FMEA

The Table 3 from Attachment A shows a part of the central air conditioning FMEA from CT Scanner I room, that shows the main equipment failures. Some actions should be instructed by the FMEA. This table has been developed by using the engineer and technician's maintenance interdisciplinary knowledge. One can see that there are some suggested actions for a specific kind of failure. These instructions help the technician to better understand the alerts that are emitted by the online monitoring system developed.

V. RESULTS AND DISCUSSIONS

The online monitoring developed in this work is in action for more than 30 days, considering commissioning and tests. The HC 4.0 has been stable during this period to measure and has been adding knowledge about the equipment. It also has helped the team to act in a faster and more assertive course of action.

As already introduced from Fig. 19 to Fig. 21, the temperature and relative humidity, main variables to be monitored in this work for having direct impact in the CT Scanner useful life, were satisfactory and mirrored very well the datalogger data.

During the monitoring period, it was possible to verify the exactly moment when there was a leak in one of the compression systems due to the drop in electrical current from one of the compressors. The team went to the site with a manifold, a refrigeration tool to measure the pressure of refrigeration equipment, and the system pressure was checked and there was a leak in one of the copper tubes connection flanges. The team replenished the gas before the drop was significant, preventing loss of refrigerant gas R-410a.

It was also possible to verify that one of the central air conditioning covers had fallen down and the engine room door was open, as the fan motor electric current increased. And in order to check if there was a problem in the electric motor, the team discovered this new fan electric current behavior. After closing the lid and door, the electric current normalized.

The cell phone alerts by Telegram has worked very well. An example may be seen in Fig. 24 when the central air conditioning room door was open. It was a new behavior that occurs when some professional does not close the door and a lot of hot air enters through the evaporator. In this case it was human error, but when the problem is in the equipment, usually it is the case when some heat exchanger is dirty, that is the main purpose of the displayed alert message.

As already mentioned in this paper in Fig. 23, the transmission belt breakage event shows 3 failure mode moments:

- A false increase of rotation speed;
- The real decrease of rotation speed;
- The transmission belt breakage.

The broken belt is shown in Fig. 25 representing the mapped event.

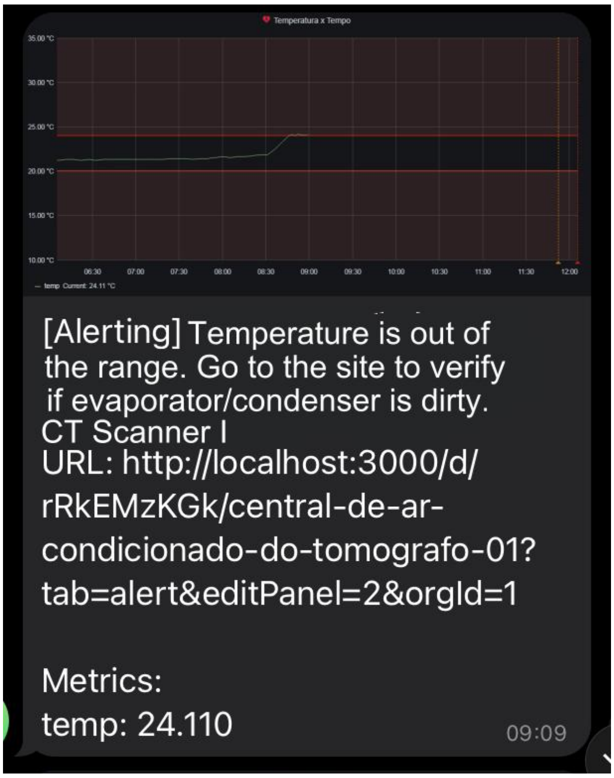

Fig. 24: Cell phone alert

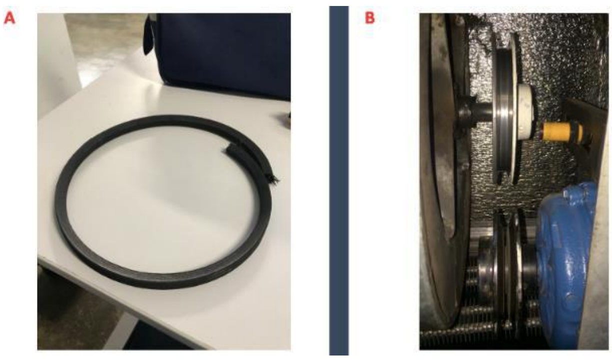

Fig. 25: The broken belt

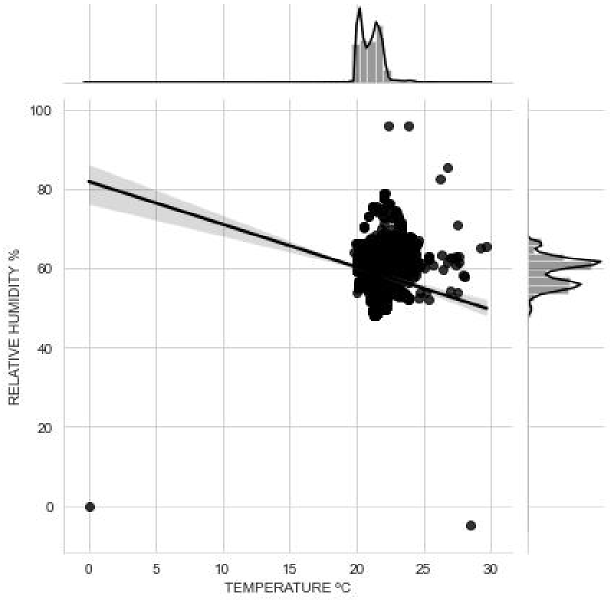

Fig. 26: Correlation between Temperature and Relative Humidity, showing that a system with electric resistances is non-linear

The online monitoring gave the opportunity to analysis the collected data, total of 21,063 rows in the data base. This data base has allowed to infer that the average CT Scanner room temperature is 21.039 ± 0.824 ºC and average relative humidity is 59.080 ± 3.941%. These pieces of information are too difficult to know without a kind of online monitoring. There is a weak negative linear correlation between temperature and relative humidity of -0.225, this correlation graph can be seen in Fig. 26. The linearity occurs only when there is no resistance working. If the system did not have electric resistances and humidificator, this linear correlation could tend to be stronger. The central air conditioning has 22 operations modes (Table 4 from Attachment B). Given the same temperature variation, different operations could be taking place, some of them could be doing the relative humidity to increase (humidification operation) and others could be doing the relative humidity to decrease (dehumidification operation). About these 22 operation modes, the Fig. 27 shows that the mode 7 was more usual during the experiment time (30 days). This operation occurs when the temperature approaches 20ºC and the relative humidity approaches 60%, keeping turned on two group of resistances and both compressors.

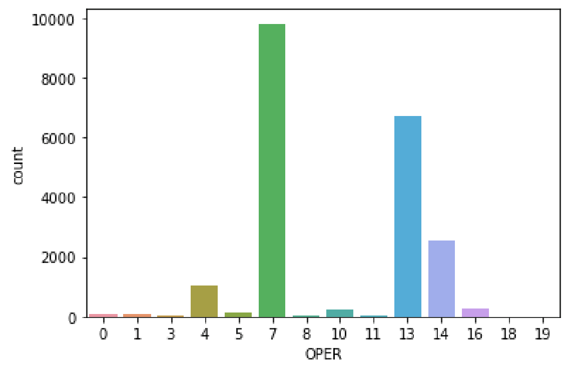

Fig. 27: Operation modes

The Fig. 28 shows the linear correlation between main HC 4.0 variables:

- TEMP: Temperature;
- UMID: Relative humidity;
- COR01: One current of the compressor 1;
- COR04: One current of the compressor 2;
- COR07: One current of the fan.

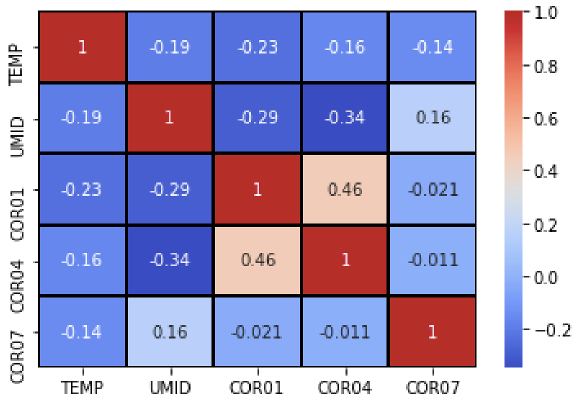

Fig. 28: Linear correlation between the main variables

It is observed that the value of the electric currents of the compressors have higher negative linear correlation with the relative humidity and temperature, but it is not strong as the others too.

VI. CONCLUSION

The solution proposed in this work to perform online monitoring of critical variables of a central air unit in the hospital has provided satisfactory results. It should be noted that the proposed system can be customized for different equipment's, with low cost and high efficiency. The union of Grafana with Arduino has shown results with a good quality of analysis, creating a condition for carrying out Condition-Based Maintenance of the central air conditioning.

The application of linear regression to correct the reading of temperature and relative humidity was efficient, generating satisfactory results when compared with the datalogger inside the controlled room.

The data collection has provided greater correlations knowledge between the variables of the system in studying, giving greater ability for the maintenance team from HC-UFG/EBSERH to make decisions when analyzing different central air conditioning modes of operation conditions.

This paper has also presented a detailed analysis of failure modes related to central air conditioning which is very useful in addition with the online monitoring that has been implemented.

In addition, this work has shown that it is possible to use Arduino and open-source platforms to develop professional, reliable, low-cost and user-friendly solutions.

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Attachment

A. Attachment A

Table 3 - FMEA

Equipment	Equipment's function	Component	Failure Mode	Cause of failure	Recommended preventive actions
Fan	Vent the cooled air from the evaporator	Bearings	Elevation of electric current Excessive noise Rotation speed reduction	Excessive vibration; Damaged belt; Fan unbalance; Misalignment of the electric motor.	Check that the belt is intact; Perform Fan sirocco cleaning; Check that the pulley of the electric motor is aligned with the pulley of the Fan.
Fan	Vent the cooled air from the evaporator	electric motor	Low insulation resistance (according to measurement history / manufacturer's manual) Tripping of thermomagnetic electrical protections Variations in electric current and torque Engine heating	Internal engine contamination; Wire insulation enamel failure; Impregnation varnish failure; Rapid fluctuations in the supply voltage.	Check equipment voltage and current; Check insulation resistance; Rearm protections; Check equipment temperature
Fan	Vent the cooled air from the evaporator	electric motor	Low insulation resistance (according to measurement history / manufacturer's manual) Tripping of thermomagnetic electrical protections Variations in electric current and torque Engine heating	Internal engine contamination; Degradation of insulating material by drying, caused by excess temperature; Insulation material failure.	Check equipment voltage and current; Check insulation resistance; Rearm protections; Check equipment temperature
Fan	Vent the cooled air from the evaporator	electric motor	Low insulation resistance (according to measurement history / manufacturer's	Internal engine contamination; Insulating material failure; Connection overheating due to bad contact.	Check equipment voltage and current; Check insulation resistance; Rearm protections; Check equipment temperature

Equipment	Equipment's function	Component	Failure Mode	Cause of failure	Recommended preventive actions
			manual) Heating of electrical connections Tripping of thermomagnetic electrical protections		
Fan	Vent the cooled air from the evaporator	electric motor	Low insulation resistance (according to measurement history / manufacturer's manual) Variations in electric current and torque Engine heating Tripping of thermomagnetic electrical protections	Internal engine contamination; Degradation of insulating material by drying, caused by excess temperature. Wire insulation enamel failure; Impregnation varnish failure; Insulating material failure; Rapid fluctuations in the supply voltage	Check equipment voltage and current; Check insulation resistance; Rearm protections; Check equipment temperature
Fan	Vent the cooled air from the evaporator	electric motor	Disarming the protections	Violent fluctuation in the supply voltage, for example, lightning strikes;	Check the quality analyzer measurements
Fan	Vent the cooled air from the evaporator	electric motor	Electric current unbalance	Voltage and / or current imbalance between phases; Bad contacts in connections, switches, contactors, circuit breakers, etc .; Voltage fluctuations in the three phases.	Retighten the terminals; Check for loose terminal; Check the measurements of the quality analyzer; Check the quality analyzer measurements.
Fan	Vent the cooled air from the evaporator	electric motor	Elevation of electric current	Excessive difficulty in starting the engine, due to high voltage drop, very high inertia and load torque; Locking the load axis.	Check electrical currents; Change engine bearings.

Equipment	Equipment's function	Component	Failure Mode	Cause of failure	Recommended preventive actions
Fan	Vent the cooled air from the evaporator	electric motor	Wire and / or motor heating	Very long and / or very thin power cables; Incorrect connection of the motor connection cables; Excessive number of matches in short time; Excessive load on the shaft end (permanent or occasional / periodic); Overvoltage or undervoltage in the supply network (permanent or occasional / periodic); Poor ventilation (defective or damaged baffle cover, dirt on the housing, high ambient temperature, etc.).	Check cable connection; Check if the motor fan is working; Check the motor temperature with thermal imager.
Fan	Vent the cooled air from the evaporator	electric motor	voltage and current loss in at least one of the phases	Bad contact in switch, contactor or circuit breaker; Bad contact in connections; Blowing a fuse; Breaking a power cable	Check terminal connections and protection and control devices; Check the integrity of the fuses.
Fan	Vent the cooled air from the evaporator	electric motor	Does not start	Circuit breaker tripped; Burnt winding;	Reset circuit breakers; Rewind electric motor.
Fan	Vent the cooled air from the evaporator	Transmission belt	Excessive vibration and atypical noise Rotation speed reduction	Belt wear; Wrong belt; Pulley damaging the belt.	Change belt; Align pulleys; Machining pulley.
Fan	Vent the cooled air from the evaporator	Fan Palettes	Excessive vibration and atypical noise	Unbalance of the palettes; Breaking of a palette; Detaching a palette.	Balance Fan.
Compressor	Compress refrigerant gas	Compression system	Elevation in electrical current Hot pipes.	Contactor does not work; Broken mechanical components such as bearings; Loose wires from loose terminals.	Check if a signal is arriving at the contactor; Check electrical current; Retighten wires;

Equipment	Equipment's function	Component	Failure Mode	Cause of failure	Recommended preventive actions
Compressor	Compress refrigerant gas	Compression system	Low electric current; Frozen line.	Lack of refrigerant gas in the system; System leak.	Check for leakage; Repair leaks; Reset refrigerant gas.
Compressor	Compress refrigerant gas	Contactors	Contactor does not work	Burnt coil; The signal from the switchboard contactor is not being sent; Arduino relay problem.	Check if the Arduino relay is working; Check if the wires are connected correctly; Check if the signal is being sent to the contactor.
Exhaust fan	Make the air exchange heat with the condenser	Bearings	Elevation of electric current; Excessive noise; Increased system temperature.	Excessive vibration; Damaged belt; Fan unbalance; Misalignment of the electric motor.	Change bearing; Check electrical currents.
Exhaust fan	Make the air exchange heat with the condenser	electric motor	Fan does not work. Compressor current 2 low or equal to zero	Burned capacitor; Capacitor disconnected; Phase loss.	Check capacitor capacitance; Change capacitor; Check if there was a phase loss.
Exhaust fan	Make the air exchange heat with the condenser	Helix	Excessive vibration and atypical noise	Fan with broken propeller palette; Propeller unbalanced; Fan with clearance in the fixation.	Balance propeller palettes; Retighten screws.
Evaporator	Receive heat from the air	Serpentine	System pressure drop; Freezing evaporator.	Dirty evaporator; Punctured evaporator.	Clear Evaporator; Check for gas leakage and correct.
Condenser	Remove heat from the air	Serpentine	System pressure drop; Freezing evaporator.	Dirty condenser; Bored condenser.	Clean condenser; Check for leaks in the condenser and correct.
Resistance bench	Add heat to dehumidify relatively	Electrical resistance	Electrical resistance	Burnt electrical resistance; Phase loss; Wrong wire connection; Loose wire in electrical resistance	Check if the resistances are heating up; Check if voltage is coming; Check the connection of the wires.

Equipment	Equipment's function	Component	Failure Mode	Cause of failure	Recommended preventive actions
Switchboard	Control the equipment	Controller board	Temperature and relative humidity measurement with NAN value	Loose jumper wire; DHT22 sensor problem; Some loose suppressor filter; Electronic board problem.	Test if there is a contactor generating noise on the Arduino when it is released; Check for loose jumper wire; Check if there is a problem with DHT22.
Switchboard	Control the equipment	Controller board	Some frame contactor does not activate	Loose jumper wire; Problem in the relay module; Arduino problem.	Check that all contactor connections are correct; Check if there is a problem in the relay module; Check if there is a problem with the Arduino.
Switchboard	Control the equipment	Controller board	Does not send data to Grafana	Problem with ethernet shield; Blocking the Firewall system; Loose ethernet wire; Error reading DHT22.	Check for network infrastructure problems; Check if the ethernet cable is connected; Check if there is a problem with the ethernet shield; Check blocking in the Firewall; Check for loose jumper wire.

B. Attachment B

Table 4 – Table of truth

ITEM	INPUT											OUTPUT					
	INFRA.	DHT										RELAYS					
OPERATION	ROTATION	TEMPERATURE TOO HIGH	TEMPERATURE IN TOO HIGH OFFSET	TEMPERATURE IN HIGH OFFSET	TEMPERATURE OK	TEMPERATURE IN LOW OFFSET	TEMPERATURE IN TOO LOW OFFSET	TEMPERATURE TOO LOW	RELATIVE HUMIDITY HIGH	RELATIVE HUMIDITY OK	RELATIVE UMIDITY LOW	RELE_VENT	RELE_RES1	RELE_RES2	RELE_COMP1	RELE_COMP2	RELE_UMID
0	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	GREEN	RED	RED	RED	RED	RED
1	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	BLUE	RED	RED	RED	RED	RED	RED
2	GREEN	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	GREEN	RED	RED	RED	RED	RED
3	GREEN	GREEN							BLUE	BLUE	BLUE	GREEN	RED	RED	GREEN	GREEN	RED
4	GREEN			GREEN					GREEN			GREEN	GREEN	RED	GREEN	GREEN	RED
5	GREEN			GREEN						GREEN		GREEN				GREEN	
6	GREEN			GREEN							GREEN	GREEN	RED	RED		GREEN	GREEN
7	GREEN					GREEN			GREEN			GREEN	GREEN	GREEN	GREEN	GREEN	RED
8	GREEN					GREEN				GREEN		GREEN				RED	
9	GREEN					GREEN					GREEN	GREEN	RED	RED		RED	GREEN
10	GREEN		GREEN						GREEN			GREEN	GREEN	RED	GREEN	GREEN	RED
11	GREEN		GREEN							GREEN		GREEN			GREEN	GREEN	
12	GREEN		GREEN								GREEN	GREEN	RED	RED	GREEN	GREEN	GREEN
13	GREEN				GREEN				GREEN			GREEN	GREEN				
14	GREEN				GREEN					GREEN		GREEN					
15	GREEN				GREEN						GREEN	GREEN	RED	RED			GREEN
16	GREEN						GREEN		GREEN			GREEN	GREEN	GREEN		RED	RED
17	GREEN						GREEN				GREEN	GREEN		RED	RED	RED	GREEN
18	GREEN						GREEN			GREEN		GREEN			RED	RED	
19	GREEN							GREEN	GREEN			GREEN	GREEN	GREEN	RED	RED	RED
20	GREEN							GREEN		GREEN		GREEN	GREEN	GREEN	RED	RED	
21	GREEN							GREEN			GREEN	GREEN	GREEN	GREEN	RED	RED	GREEN

INPUT AND OUTPUT				
TYPE	GREEN	RED	BLUE	UNFILLED
INPUT	Reached condition	FAILURE	REGARDLESS OF CONDITION	DID NOT REACH THE RANGE
OUTPUT	ON	OFF	NOT APPLICABLE	MAINTAINS THE LAST STATUS