IoT-Solar Energy Powered Smart Farm Irrigation System

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Abstract—As the Internet of things (IoT) technology is evolving, distributed solar energy resources can be operated, monitored, and controlled remotely. The design of an IoT based solar energy system for smart irrigation is essential for regions around the world, which face water scarcity and power shortage. Thus, such a system is designed in this paper. The proposed system utilizes a single board system-on-a-chip controller (the controller hereafter), which has built-in WiFi connectivity, and connections to a solar cell to provide the required operating power. The controller reads the field soil moisture, humidity, and temperature sensors, and outputs appropriate actuation command signals to operate irrigation pumps. The controller also monitors the underground water level, which is essential to prevent the pump motors from burning due to the level in the water well. The proposed system has three modes of operations, i.e. the local control mode, mobile monitoring-control mode, and fuzzy logic-based control mode. For the purpose of the proposed system validation, a prototype was designed, built, and tested.

Index Terms—Fuzzy logic, Internet of things (IoT), renewable energy, smart irrigation.

1. Introduction

If a good yield of crops is desired, then irrigation systems require constant monitoring, especially in remote areas where water is scarce. Farming operations may also face challenges related to the energy required for a good yield of crops. Energy efficiency in agriculture has been widely researched from several viewpoints [1], [2].

Technological advances in agriculture may provide answers to controlling the yield of a crop in response to varying climate conditions [3], [4]. Reference [5] has presented the use of instruments to measure soil properties automatically. Following the trend of using technological advances to improve the quality and yield of crops, this work focuses on a smart irrigation system, which can fulfill its energy requirements from renewable energy sources like solar energy.

Farmers usually control the water flow to crops depending on the needs of a crop. Such needs depend on the

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Manuscript received 2019-07-25; revised 2019-08-21.
This work was supported by the American University of Sharjah under Grant ELE/COE 490-491.
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Color versions of one or more of the figures in this paper are available online at http://www.journal.uestc.edu.cn.
Publishing editor: Xuan Xie
surrounding temperature, soil moisture, time of the day, and health of a crop. Excess or insufficient irrigation can lead to a low yield of crops. Water scarcity is serious and makes irrigation difficult. In remote locations, far-away from major water sources, irrigation mostly relies on underground water. In such a situation, water needs to be pumped out from a well using electric motors. Depending on the level of underground water, the pumps used for irrigation need to be monitored and turned off when there is an impending danger of the well running dry. This is because pump motors use the cooling effect of the flowing water to maintain their operating temperature. If no water flows through a pump, it may run dry, and either stop functioning due to overheating, or burn. Besides, due to excessive friction caused by the lack of flowing water, mechanical seals may get damaged. This can increase maintenance and repair costs over time. Also, the motors operating irrigation pumps are mostly water-cooled. So, the operation in low water conditions can cause serious overheating, leading to fires that may destroy the motors and the pump. Therefore, from the above, it is clear that automated monitoring and control of irrigation are critical. Further, a system that can instantly notify a user of abnormal behavior and allow a user to remotely intervene and manage the irrigation process is desirable and is the motivation of this work.

There have been previous works related to the automation of irrigation processes. However, most such works appear focused on the use of specialized techniques towards enhancing a particular aspect of farming. Limited literature focused on the use of vision-based techniques in modern agriculture. Other authors have worked on various aspects of automating drip irrigation. The novelty of the work presented in this paper compared with the previous literature is that, sensing and control of drip irrigation are handled by a single microcontroller-based system that utilizes a fuzzy-logic algorithm for decision-making and control. Further, a source of renewable energy, i.e. a solar cell, is provided for supporting the stand-alone operation to handle the temporary loss of power supplied by the utility company. Also, a wireless monitoring system interface is developed, which can allow a remote user to remotely monitor the status of a farm from the convenience of a mobile phone or a computer.

2. Assumptions

It is assumed that the farms irrigation system has 5.5 hours of constant bright sunshine per day with an average ambient temperature of about 25 °C. It is understood that this is not an assumption that will hold globally, however for such farms that are not within the scope of assumptions, the separate maximum power point tracking (MPPT) solar system may be required. MPPT systems ensure that the height and angle of a solar panel can be changed to track the sun throughout the day; this ensures that the maximum possible amount of the sun’s energy is captured and converted to electricity. This has been the core focus of a few authors in [18] and [19], but is not the focus of this work. Also, the irrigation system presented in this paper is designed for a miniature farm, this allows us to simulate and prototype on a smaller scale of the proposed irrigation system. The miniature farm used for this work is built based on a rectangular plastic tub, which has the following dimensions 50 cm (width), 70 cm (length), and 10 cm (height). The reason for choosing a miniature farm is to develop a prototype which clearly helps understand the intended operation, and captures the main ideas proposed as a part of the smart irrigation system developed in this paper.

3. System Design

The overall proposed system design is described in Fig. 1. On the left-hand side of Fig. 1, there are various power sources and a charge controller. Power is supplied from the solar panel, during the hours of sunshine, to the charge controller, which is responsible for delivering power to the smart irrigation system and for charging the battery. At night, or during the time of a day when there is low sunlight, the charge controller powers the smart
irrigation system using the battery. The heart of the system is the National Instruments controller, myRIO, which consists of a dual-core ARM® Cortex™-A9 real-time processor and an Artix-7 field programmable gate array (FPGA). FPGA has gained popularity due to its speed of operation, a relatively lower cost compared with traditional microprocessor units, reliability, and ease of long-term maintenance.

The controller has 10 analog input channels, 6 analog output channels, 40 digital I/O lines, 3 embedded accelerometers, and a Wi-Fi adapter. The controller digital and analog inputs are used to interface with the float switches, soil moisture sensor, humidity and temperature sensor, and flow rate sensors, which are connected to the controller. The relay board is used to interface the diaphragm pump and a bilge pump that control the irrigation process. The relay board works at a supply voltage level of 5 V. This 5 V signal is provided to the relay board, by a buck converter, which steps down the 12 V supply voltage from the charge controller to the desired 5 V level.

A prototype is designed and built for testing purposes. The upper part is a dual-layer rectangular tub that is filled with soil, and the lower part is fully or partially filled with water to simulate an underground water table. The plastic layer, which separates the top and bottom layers, has holes that allow the water, which has not been absorbed by the soil to flow into the lower layer (i.e. the underground water table). A bilge pump is submerged into the underground water table, which extracts water and stores it in the reservoir (water storage tank). The bilge pump inlet is fitted with a filter so that dissolved soil or other particulate material is not sucked into the pump. This overall design is chosen to mimic the operation of farms that may have access to ground water but may have little or no access to other sources of water. A diaphragm pump extracts water from the tank and is responsible for irrigating the farm, via a drip irrigation process as shown in Fig. 2. The flow rate of water through the diaphragm pump can be controlled, which controls the rate of water fed to the soil via drip irrigation.

3.1. Data Acquisition Sensing Unit (DAQ-Sen)

The DAQ-Sen unit consists of several sensors and actuators, each of which is considered as an object (thing) and has a unique Internet access sub-address that enables farmers to access it via a mobile application. This is where the IoT concept has been implemented in this project.
A class consisting of a set of functions is developed to enable users and the system to read any sensor and enable any actuator. For example, an instance of this class is responsible for reading the environment variables, i.e. the temperature, humidity, and soil moisture.

Another instance of the class is the flow rate sensor read; it is used to measure the water flow rate in the pipes. In response to the sensor reading and the water flow rate in the pipe, an output instance of the class is invoked. It controls the actuator to turn on or off the pumps to avoid the damage to the pumps by running in dry conditions, i.e. when the water available in the water table or the storage tank is not sufficient. Fig. 3 shows the details related to the connections of the DAQ-Sen unit to the controller.

The soil moisture sensor, temperature sensor, flow sensor, and humidity sensor provide analog inputs to the controller. The digital inputs include the high and low water level float switches, which monitor the maximum and minimum required water levels in the water storage tank. The top float switch is essential to turn off the bilge pump before the storage tank overflows. Similarly, the bottom float switch is essential to turn off the diaphragm pump before the storage tank is completely empty.

3.2. Proposed System Renewable Energy Requirement Calculation

This section presents the calculations required to estimate the power needed to operate the proposed smart irrigation system. As mentioned earlier, for this prototype farm design, it is assumed that the farm will have 5.5 hours of constant bright sunshine a day, i.e. $H_{\text{SD}} = 5.5$ h.

It is further assumed that only 80% of this 5.5-hour span produces usable power, i.e. $\eta_{\text{usable}} = 0.8$. Note that the numbers for $H_{\text{SD}}$ and $\eta_{\text{usable}}$ are not chosen completely arbitrarily. This can be seen by performing the following computation. Consider that a day has 12 hours of sunlight (regardless of brightness), and then compute the ratio $(5.5 \times 0.8)/12 = 36.67\%$.

This shows that even if a solar panel is set out in the sun for the entire day, only about 37% of the hours of the entire day contribute to usable electrical energy, which may be a conservative figure giving the state of currently continuing technological advancements related to solar panels, and hence the above assumptions seem reasonable. For our work, we assume that the ambient temperature is 25 °C. Because the smart irrigation system uses a battery to store charges, the loss of energy when charging the battery from the solar panel, followed by the eventual discharge of the battery to supply the pumps, needs to be considered. This loss of energy accounts for
the fact that no realistic battery-charge controller pair can possibly convert all the energy received from the solar panel into stored chemical energy. A term known as the round-trip efficiency is used to capture this loss of energy. A reasonable estimate for the round-trip efficiency ($\eta_{\text{batt}}$) of a battery is around 80%, i.e. in the process of charging and then discharging the battery, about 20% energy loss occurs. Another factor considered is the charge controllers' efficiency itself, i.e. a factor accounting for how much of the energy available to the charge controller gets from the inputs of the charge controller, to the outputs. This factor, also known as the de-rating factor of a charge controller ($D_{\text{CC}}$) is usually around 85%. Finally, the maximum allowable depth of discharge for a battery needs to be known. Batteries are known to run into issues when discharges to below 10% of their capacity. As a result, the maximum depth of discharge (DOD) selected for this work is 75%, i.e. the battery should begin to charge with 25% of the remaining capacity.

Table 1 below indicates the approximate energy required by each function.

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
<th>Operations (hours/day (h/d))</th>
<th>Wh/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>myRIO</td>
<td>14.0</td>
<td>24.00</td>
<td>336.00</td>
</tr>
<tr>
<td>Bilge pump</td>
<td>42.0</td>
<td>0.25</td>
<td>10.50</td>
</tr>
<tr>
<td>Diaphragm pump</td>
<td>33.0</td>
<td>0.25</td>
<td>8.25</td>
</tr>
<tr>
<td>Relay poard</td>
<td>0.1</td>
<td>24.00</td>
<td>2.40</td>
</tr>
<tr>
<td>Sensors</td>
<td>0.5</td>
<td>24.00</td>
<td>12.00</td>
</tr>
<tr>
<td>Total energy per day ($E_{\text{tot}}$)</td>
<td>—</td>
<td>—</td>
<td>~369</td>
</tr>
</tbody>
</table>

It is to be noted that the time of the operation for the pumps, i.e. 0.25 hours per day, is chosen after running the pumps repeatedly for many trials. It was observed that for the small size of the prototype farm, and due to the pumps being of a sufficiently high flow rate capacity, the 15 minutes of operation per day at a full flow rate is enough for the farm to be irrigated. Of course, for a full-scale implementation on an actual farm, these numbers need to be revised.

The following calculations provide details related to the selection of the battery required for the proposed prototype of the smart irrigation system. The power required to be generated by the solar (photovoltaic) panel ($P_{\text{PV}}$) to meet the total of 369 Wh/d mentioned in Table 1 is calculated as

$$P_{\text{PV}} = \frac{E_{\text{tot}}}{H_S D_{\text{CC}} \eta_{\text{usable}}} = \frac{369}{5.5 \times 0.8 \times 0.85} = 98.66 \text{ W.} \quad (1)$$

As seen in (1), the total power needed from the solar panel is 98.66 W. Now we have this number as the amount of power required to be generated by a solar panel, and it is easy to pick a solar panel that meets the input voltage ratings of the charge controller, and produces at least 98.6 W of power. For our prototype, we have opted for a 100 W solar panel, as this rating is larger than the calculated 98.6 W rating. It is worth to note that the power calculated is the power required for the one-day operation, and not instantaneous power required. This is the reason why the efficiency of solar panels is not considered, and the 98.6 W requirement already factors in the hours of sunlight reasonably available, as mentioned above. The following computations relate to the sizing of the battery. The daily energy required to be supplied/stored by the battery $E_{\text{batt}}$ can be computed as the ratio the energy required per day divided by the battery efficiency, i.e.

$$E_{\text{batt}} = \frac{E_{\text{tot}}}{\eta_{\text{batt}}} = \frac{369}{0.8} = 461.25 \text{ Wh/d.} \quad (2)$$

The usable Ampere-hour (Ah) capacity of the required battery can be calculated by dividing $E_{\text{batt}}$ by the rated terminal voltage of the battery, i.e.
From (3), the usable capacity required for the battery, to maintain the operation for a day is simply $C_{\text{batt/day}}=38.44 \text{ Ah}$. Dividing this by the max allowed depth of discharge gives the actual battery capacity, i.e.

$$C_{\text{actual-batt/day}} = \frac{C_{\text{batt/day}}}{\text{DOD}} = \frac{38.44}{0.75} = 51.26 \text{ Ah}. \quad (4)$$

The battery should not be discharged completely since it will shorten its lifespan; hence, the depth of discharge is taken into consideration in (4). Using a battery of this capacity will power the system for an entire day if the solar panel fails or does not receive sunshine for the whole day, assuming the battery was charged to the full capacity on the earlier day.

According to the above calculations, it is decided to use a 100 W PV solar panel as mentioned before, and a deep cycle, lead-acid battery of the capacity of 55 Ah rated at 12 V. A deep cycle battery is used, because its design enables it to be charged and discharged numerous times without significantly affecting the overall battery health. Also, just as for the solar panel, the battery is chosen to be of higher rating than actual calculations, because there might be a few additional losses which may have not been completely accounted for.

3.3. Charge Controller and Pumps

The charge controller used in this work is responsible for managing the overall power flow. It handles the charging of the battery from the solar panel, and handles the supply of power to the load from the battery.

During the day when the sunlight shines on the solar panel, because of which if the terminal voltage of the solar panel is greater than 12 V, then the charge controller begins to charge the battery via the current output from the solar panel, and the current from the solar panel supplies the smart irrigation system components. The value of the charging current for the battery is small, so in bright sunlight, the solar panel may produce a current large enough to simultaneously charge the battery and drive the smart irrigation system. If at any time, the pumps require to be switched on and the solar panel cannot supply enough current, the charge controller switches the battery out of the charging mode, then the battery can supply power to the smart irrigation system. In addition, if the solar panel voltage drops below 12 V, or the battery is completely charged then the battery charging process is stopped. In severely low light conditions, when the solar panel voltage decreases far below the 12 V mark, power is supplied from the battery to the load. According to specifications, the charge controller chosen can handle a current up to 30 A with a maximum solar panel voltage of 48 V DC. The charge controller also works in temperatures ranging from $-10 \degree C$ to $60 \degree C$, and can supply 12 V or 24 V battery-based systems.

The following paragraph provides details related to the pumps used with the smart irrigation system. The bilge pump is responsible for extracting water from the underground water table (simulated by the lower half of the tub), and storing it in a water tank. The flow rate of the bilge pump used is 1100 gallons of water per hour when receiving a 12-V DC supply. In addition, it has a rated current of 3.5 A, making the rated power of the bilge pump 42 W.

The diaphragm pump is connected to the water storage tank, which is responsible for irrigating the farm. The pump selected has a rate of 1.2 Gallons per minute at a pressure of 241.33 kPa. The diaphragm pump requires a 12-V supply, and draws a max current of 2.7 A, thus consuming a max power of 33 W for working.

3.4. Overall Design

Fig. 4 below shows the entire smart irrigation system. The left-hand side of Fig. 4 shows the prototype farm, which contains the drip irrigation pipe, simulated water table, and submerged bilge pump. The bilge pump supplies
water to the water reservoir, which stores water for future usage, which is shown on the right-hand side of Fig. 4. The smart sensing unit (see the top center of Fig. 4) controls the pumps, which has the controller, charge controller, buck converter, and relay board in it. This smart sensing unit performs all the fuzzy logic-based pump control operations. Power is supplied to the entire system from the power supply unit (see the bottom center of Fig. 4), which contains the solar panel, battery, and charge controller.

4. Modes of Operations

The smart irrigation system designed above is programmed to run under the following three modes.

· Local control mode: In this mode, the user can control the water pumps manually via the Start/Stop switches presented on the controller. This mode has the highest priority and will halt the operation in any other mode (described below), so the user can manually control the water pump. Once the user has ended the manual control, the system resumes the operation in the mode it was in earlier.

· Mobile monitoring and control mode: In this mode, the user can view the status of the sensors on the farm and make a decision to control the water pump remotely using a smart phone or a laptop over the Internet. This mode makes use of a web/mobile application stored on a server to send a control signal to the controller. Therefore, the user can monitor and control the water pump(s) over the Internet while she/he is on the move.

· Fuzzy logic based control mode: In this mode, no manual input or monitoring by the user is required. The controller makes decisions to turn on/off water pumps based on sensor readings and a fuzzy-logic based control algorithm. Details related to this mode are described in the next section.

5. Software Interfaces

5.1. Fuzzy Logic Based Irrigation Control

The smart irrigation system uses a fuzzy logic-based control algorithm, which is described below. The
crisp values from the sensors, i.e. the actual sensor readings, are fuzzified to linguistic terms and the member functions are created accordingly. In this case, the sensor values of the humidity, temperature, and soil moisture are taken as inputs and membership functions are created using four linguistic terms for the temperature, three for the humidity, and three for the soil moisture. The terms were named as “High”, “Medium”, and “Low” for the humidity and soil moisture sensors, and “Very hot”, “Hot”, “Cold”, and “Very cold” for the temperature sensor. The number of linguistic terms and their names are completely up to the preference of the user. The membership functions for each of the inputs are shown in Figs. 5 to 7. Then, a set of “if-then” rules are created, based on the number of linguistic terms for each input, and the number of inputs. In this case, we generate 36 conditions, a few can be seen below in Table 2, since we have 4 fuzzy terms for the first sensor and 3 fuzzy terms each for the subsequent two sensors.

Based on the fuzzy values of the input, and the fuzzy algorithm, which is implemented via the standard fuzzy logic toolkit in LabView, the fuzzy values for the outputs are created and defuzzified into actual outputs. In this case, the center of the area method is chosen for defuzzification of the output, which controls the diaphragm pump by turning it on, or off based on the output function, which can be seen in Fig. 8. For details related to the fuzzy logic, readers can refer to [24]. A practical guide for fuzzy logic can also be found in [25].
5.2. Mobile Application

The proposed smart irrigation system needs to be accessible and controllable from anywhere at any time, in case the user decides to take complete control of the system. This is done using a remote web server with a structured query language (SQL) database to store the sensor measurements, which the user can view by accessing a webpage as shown below in Fig. 9.

5.3. Programming the Controller

The software running the system is developed using LabView in a single virtual instrument (VI) file. This software contains various loops running in parallel inside of a flat sequence. The flat sequence has three frames in it. In the first frame there is a fuzzy system loader which loads the fuzzy system (input/output membership functions and the rule sets) from a ‘.fs’ file, and assigns required initial values before the program goes to the second frame, which contains the main body of the control logic. The last frame contains the reset function, which stops the controller safely.

The first loop, as shown in Fig. 10, gets the analog readings from the analog voltage output sensors connected to the controller, averages them, and displays them. In our case, there are two soil moisture sensors (SM), a humidity sensor (HUM), a temperature sensor (TEMP), and an auxiliary light detecting sensor (LDR). And LDR is simply used to determine whether the system is operating in daylight conditions. This loop also has the fuzzy logic controller, which takes as arguments—the output of the fuzzy system loader and the input sensor values as an array, and returns a crisp output from the fuzzy logic system. Since a binary (on or off) control of the motor is required, this crisp output of the fuzzy system is compared with the high value threshold and low value threshold to turn on/off the diaphragm pump accordingly. If the output exceeds the high value threshold, a flag (FL) is set to turn on the diaphragm pump (active low); if the value is less than the low value threshold, the pump is simply turned off.

The second and third loops as shown above in Fig. 11 are similar to the first loop, and perform a function to calculate the flow rate measured from the two flow rate sensors (one attached to each pump). The fourth loop, shown in the left two-thirds of Fig. 12, is used to calculate the average of the flow rates. And the loops containing motor logic (manual modes on and off) are shown in Figs. 13 and 14, respectively.
The last loop as shown in Fig. 15 is responsible for storing the data to get results and generate required plots. The readings for the soil moisture, temperature, humidity, fuzzy logic output, flow rates, and pump
status are sampled every half a second and stored in a 2-dimensional array. After the stop button is pressed (i.e. the operation of the smart irrigation system is halted), this array gets stored in a ".txt" file which can be used for examining the data recorded. In addition, Fig. 16 shows an overall layout of the front panel designed to monitor the sensor readings and control the pumps.

![Fig. 14. Loop containing motor logic (manual mode "off").](image)

![Fig. 15. Loop for storing data.](image)

![Fig. 16. Front panel.](image)

6. Testing and Results

Two tests were carried out to check the operation of the designed smart irrigation system. For these two tests,
the high-level and low-level thresholds for the fuzzy logic output were set to 50 and 35, respectively, which means if the fuzzy logic output exceeded the high-level threshold, the pump motor turned on. Moreover, if the fuzzy logic output decreased below the low-level threshold, the pump motor turned off.

For the first test, the soil moisture was slowly decreased by drying the soil in the prototype farm, and the outputs were observed. Fig. 17 shows the plots of the average soil moisture readings from two SMs, HUM, TEMP, the fuzzy logic output, and the state of the diaphragm pump. These were plotted roughly for an hour. The temperature and humidity were maintained constant to observe the effects of soil moisture change. The x-axis represents the sample number of the data; each sample arrives after a 0.5-second interval so the sampling time is 0.5 s. From Fig. 17, it is seen that when the soil moisture drops, the fuzzy logic output increases more than the high-level threshold of 50 and the diaphragm pump turns on. When soil moisture rises, the fuzzy logic output value decreases below the low-level threshold value of 35, and the motor turns off. This matches the expected behavior of the system.

Fig. 17. Effect of varying soil moisture: (a) soil moisture, (b) humidity, (c) temperature, (d) fuzzy output, and (e) diaphragm pump.

In the second test, the soil moisture was kept approximately constant when the values of the temperature and humidity were varied. The results can be seen in Fig. 18. The results show for increasing the temperature and decreasing humidity, that the fuzzy logic output increases, and the pump turns on. Due to this, the soil gets watered through the drip irrigation system, and the soil moisture reading increases. This causes the fuzzy logic output to decrease and the pump motor turns off.
The prototype was implemented and tested in the lab environment to validate the overall system design from the point of view of the sensors interface, pumps interface, and fuzzy logic rules. The system operated as desired in all modes including the remote access mode.

Upscaling the prototype to actual agricultural environments may require larger diaphragm and bilge pumps which lead to the need of the larger solar panels and battery storage system as well as larger driving circuits for the pumps. The sensors chosen for the prototype have ranges, which are suitable for the real-time agricultural environments.

A distributed irrigation system may be constructed using multiple up-scaled prototypes to irrigate larger or multiple farms. The operating modes, as well as the fuzzy logic system rules, will not be affected by upscaling the system; however, a server must be installed with a gateway to receive the status of each farm. In addition to that, further software development is needed to perform data analysis to optimize the irrigation schedule according to each farm environmental status.

7. Conclusions

An IoT-based renewable energy system for smart farm irrigation was successfully developed. The solar energy requirement has been calculated and the right size solar energy cells were installed. Farmers can operate the system using three different operation modes. The fuzzy logic algorithm was developed to analyze the
environmental and soil conditions to decide when it should irrigate the farm. The prototype system was tested when isolated from a utility power supply, and the operation was completely dependent on solar power. The remote monitoring website makes the system very accessible, and it can be monitored through the web via a computer, or a mobile phone. In future, this design can be scaled up to suit actual farm sizes, and support their operations without requiring human intervention.

Acknowledgment

The authors acknowledge the support from the Department of Electrical Engineering and the Department of Computer Science and Engineering, American University of Sharjah.

References


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