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Embedded System for automating manual inventory survey process of street lighting with a I2C photometric sensor network

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Abstract. Currently, most companies dedicated to managing public lighting infrastructure manually perform the process to determine the quantity, lighting technology and physical condition of luminaires and poles. This process carries some problems inherent to its manual execution such as increased costs in large areas, logistics issues and personnel management, but, mainly, a bad acquisition of the required data derived from the human factor that performs the process (i.e., taking wrong sensor information or incomplete inventory survey) that can cause economic losses due to energy consumption to the electricity companies.

This article presents an alternative proposal that involves hardware and firmware on existing systems to automate the inventory survey of public lighting based on an embedded system with a network of photometric sensors and geolocation focused on the acquisition of ambient light and light color data with a restricted sampling frequency, environmental data and inertial measurement data proposing a certain set of sensors and organizing the data obtained in a log file for further processing. The results obtained in the field tests are presented and discussed.

Keywords: Street lighting, inventory survey, embedded system, microcontroller, photometric sensor

1 Introduction

1.1 Background

Public lighting is an indispensable service in any urban area regardless of its size. Urban development is constantly growing, and street lighting also must grow along with the urban area. Managing this service is not an easy task and for this there are companies whose turn is exclusively the provision of public lighting management services, services that range from keeping an inventory control of the public lighting infrastructure, updating it to modern lighting technologies such as LED luminaires, as well as keeping it in optimal conditions to lighting maps, intelligent lighting, energy saving, among others. These companies carry out a process called inventory survey of public lighting or also known colloquially as census of luminaires that consists of collecting information on the number of luminaires that exist, their location, as well as their physical conditions and such process, at present day, continues to being performed manually by most companies. This process requires organized personnel that are hired in the form of crews of 4 technicians that are given pre-established routes to carry out the inventory survey. The manual process of inventory surveying in general is as follows:

- The zones and routes to be followed by the crews are established to cover the area of interest of the city.
- Crews are given their personal protection equipment, a tablet, a lux meter and a crane to make the journey through the streets.
- Upon arrival at the area of interest, the crew search and stops at each of the luminaires following the previously defined route.
- In each luminaire, the staff identifies the geolocalization of the luminaire, type of light head and pole, type of pick arm, height, physical conditions, lighting technology, makes measurements of the lighting levels and enters all this information in a digital form on the tablet.
- With the tablet, photographs of evidence of the pole and luminaire are taken.
- A stamp is placed to identify that the luminaire has already been checked.
- After the data is taken and in case the luminaire or pole presents any defect or needs its lighting technology to be updated, a report is raised for a maintenance team to carry out the necessary repairs or changes.

This process is complicated as the volume of infrastructure to be managed grows as is the case of large cities and can become a challenge as problems arise in logistics, human resources, costs, time to complete, etc.

With the development of electronic technologies applied to embedded systems and wireless communications, public lighting management companies began applying these technologies to reduce energy consumption through remote monitoring of luminaires in specific areas of a city. This technology typically uses photometric sensors and microcontrollers to acquire sensor data, as well as wireless communication modules to send the information to a remote monitoring terminal or web page.

The present article presents an embedded system with a network of photometric sensors, an environmental sensor, an inertial motion sensor, a high-precision GPS and a real-time clock to automate the manual process of the inventory survey of public street lighting extracting only the variables of interest and organizing the information in a format required format.

2 State of the art

2.1 Commercial solutions

There are systems developed by commercial companies that have the similarity of implementing modules with photometric sensors and a microcontroller, along with wireless communication modules that are mounted on each of the luminaires in the area of interest and allow remote monitoring / control of the luminaires.

One of these systems is based on a microprocessor that runs a Java VM along with an integrated sensor board including a light sensor [1] that was developed for prototyping wireless sensor networks projects could be used for an application in which the module is installed on the lighting pole near the luminaire to acquire real time measurements of the illumination levels and controlling the power on/power off the luminaire remotely for energy saving purposes. The main disadvantages of this system are that it's already discontinued, it was not developed for street lighting monitoring (it's a development module that could be used for anything else), their application approach is monitoring specific areas (such as industrial buildings or shopping centers) and having to install a module for each luminaire which increases the costs in areas with a high number of luminaires.

Another commercial solution is based on the integration of consumer electronics modules: a conventional luxmeter, a high precision vehicular GPS and digital cameras mounted on the top of a car fixed on a tower-form mechanical structure [2]. However, this solution does not implement a microcontroller to acquire and organize the data and it's not processed by a specialized software to generate a virtual map of the street lighting infrastructure, instead, all the acquired data that is delivered to the client is inside of Excel spreadsheets with links to the photographs taken and AutoCAD files containing the map plot of the lighting infrastructure.

2.2 Related papers

In 2014, Sumeet Kumar of the Massachusetts Institute of Technology (MIT) in his PhD thesis [3], developed a mobile prototype to map the lighting levels in the streets and public lighting infrastructure of a city automatically using an embedded system based on the Arduino Mega development card, TEMT6000T ambient light sensors, an inertial motion sensor and a high-precision GPS, along with another system based on high-definition cameras with wide-angle lenses. He also developed a software that can identify the "hot spots" of lighting by filtering the noise of other light sources and discarding false positives in the measurements to finally build a map where you can visualize the lighting levels and the lighting infrastructure based on the measurements of both systems that integrate the complete system called "CASP" (Car-mounted Autonomous Street light scanning Platform). He also explored the distribution of photometric sensors throughout the system.

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The mechanical structure of the system is a bar on which both sensors and cameras are mounted. This bar is installed on the roof of a vehicle that is driven through the areas of interest to be mapped.

Although the prototype was successfully tested, it did not escalate to the point of developing the system beyond a prototype, it was not commercialized and there are still areas of future work and exploration to improve the system:

1. Analyze other photometric sensor options than can obtain more information. In the same way, explore the use of other types of sensors that provide extra information to guarantee the reliability of the system.
2. Change the microcontroller to another that offers better performance or fits better for the application, as well as modify the overall architecture of the system.
3. Design a new structure that will house the system to protect it from the environment but won't interfere with measurements.
4. Modify the way in which the data obtained by the sensors will be transferred to a custom developed software to process this data and map the inventory of public lighting, either by means of and wireless protocol, direct USB connection to a laptop and / or by SD memory storage.

In 2015, a team in association with a local electricity company developed a mobile system for automating the manual process of detecting and classifying street lighting infrastructure combining hardware and software based on a neural network [4]. The version presented on the paper consists of an electronic board with the light sensors and a DSP that communicates via Bluetooth to a tablet managed by an operator for transferring the acquired sensor data. This tablet also communicates via USB to a digital camera for taking pictures of the luminaires of interest. This information is then downloaded to a PC via a wireless communication.

This article does not focus on the data acquisition of the sensors, instead, it explains in more details the software that processes the data with a neural network and the data acquisition interface developed for the tablet (Android OS).

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3 System Architecture

3.1 System requirements

According to the functional requirements for this prototype's version, the system has a restricted sample rate of minimum 4 to 5 photometric measurements per second. In order to comply with this requirement, each board of the sensor network is controlled by an Atmega328 microcontroller that obtains the required measurements and store them on its internal memory until the main board sends a digital signal that triggers an event to send the information to the Raspberry Pi. This information also needs to be stored in a log file since it will be an entry file for the software that will process the acquired data.

Log file storage is not required to be stored in an external memory unit, it can be extracted directly from the Raspberry Pi or by any means.

3.2 System components

The architecture was developed based on the functional requirements and the previous research/development. Each set of photometric sensors are controlled by an Atmega328 microcontroller using the I2C communication protocol and the sensors of the main board are controlled by a Atmega2560 microcontroller using the I2C and UART communication protocols. All the system's boards are connected to Raspberry Pi for organizing the collected data in a specific required format via the UART protocol. The system is composed of 2 types of boards, 5 boards containing photometric sensors and a microcontroller to acquire data named "Photometric sensor boards", and a board named "Main Board" that contains an ambiental sensor, an inertial movement unit, a high-precision GPS, a Real-Time Clock and a microcontroller to acquire data. In figure 1, the components of each board are displayed in more details:

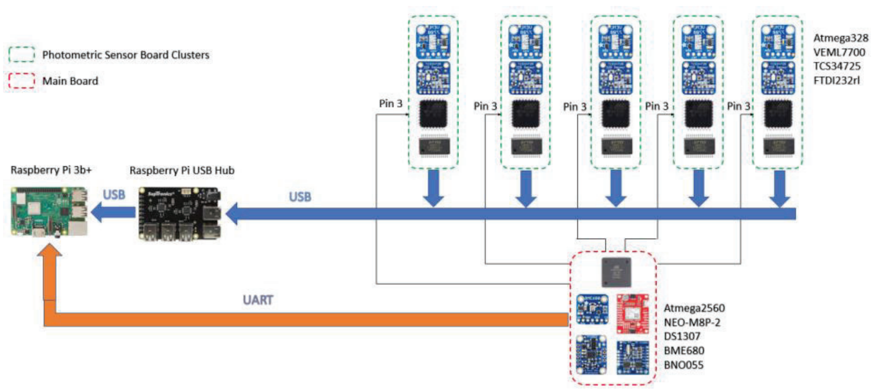


Fig. 1. System's general architecture

The system is contained by a wooden case prototype mounted over the roof of the car. This case holds the Raspberry Pi, the USB hub and the cables that connect the system altogether with the systems boards, the main board and 5 photometric sensor boards distributed along the case. The reason why it is mounted over a car is to receive directly the light generated by the streetlighting while the car is on movement, thus, automating the manual survey process. In figure 2, there's a 3D model representing of how the system's case is mounted over a vehicle.

Fig. 2. 3D representation of the system mounted on a car

3.3 Main Board Architecture

The ATmega2560 microcontroller controls and acquires data of the GPS, Real-Time Clock, BME680 and BNO055 sensors and store the information in its internal memory. After acquiring the data, it organizes and sends it to the Raspberry Pi which triggers a digital control sequence on the photometric boards to make them send their acquired data to the Raspberry Pi. A block diagram representing the general architecture of the main board is presented in figure 3 as well as table 1 describing the components and measurements.

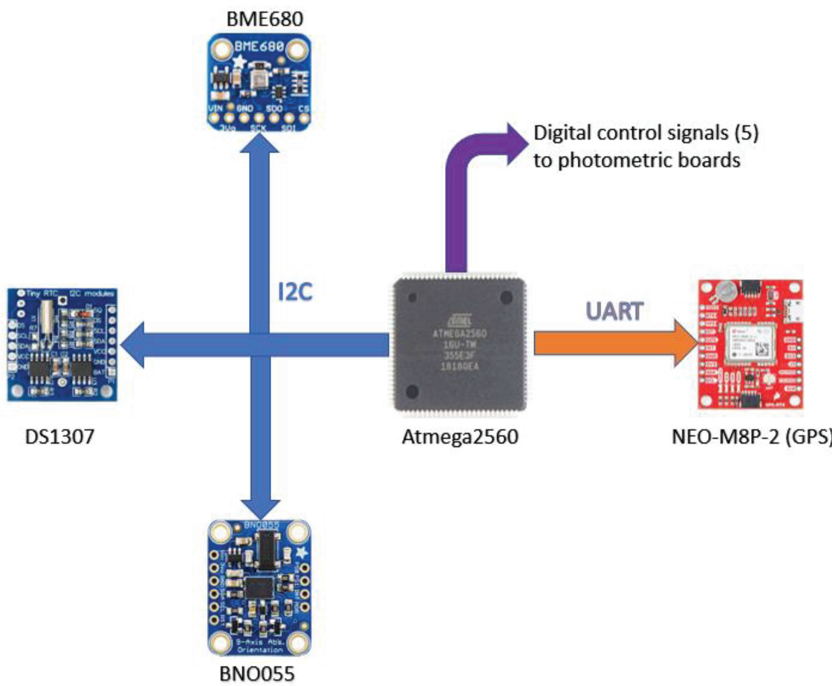


Fig. 3. Main board architecture block diagram

Table 1. Sensor and components of the main board

Sensor/Component	Description	Measurements
NEO-M8N-2P	High precision GPS	Geolocalization
DS1307	Real-Time Clock	Timestamp
BME680	Ambiental Sensor	Temperature, Pressure, Humidity
BNO055	Inertial Movement Unit	X, Y and Z orienta-

		tion
ATmega2560	Microcontroller	Data Acquisition

3.4 Photometric Sensor Board Architecture

It consists of a ATmega328 microcontroller that controls and acquires data of the VEML7700 and TCS34725 sensors. It sends its obtained information to the Raspberry Pi when the main board sends a digital control signal. In figure 4, it's represented the general photometric board architecture in a block diagram. Also, in table 2 the components and measurements of this board are listed.

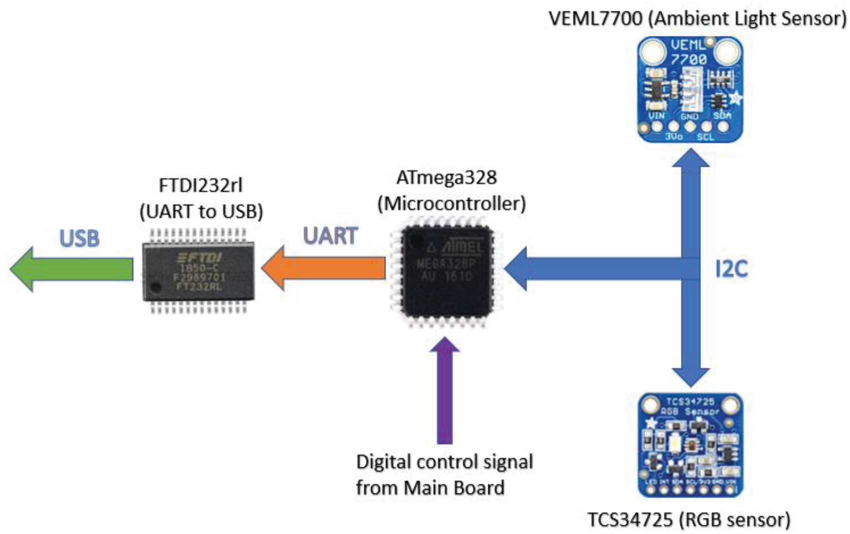


Fig. 4. Photometric sensor board architecture block diagram

Table 2. Sensor and components of the photometric sensor board

Sensor/Component	Description	Measurements
VEML7700	Lecture Notes	Lux, White
TCS34725	RGB Sensor	Red, Green, Blue, Clear
ATmega2328	Microcontroller	Data Acquisition

4 Automation of the manual inventory survey process

4.1 System's Algorithm

As the system is composed of several components, each of the boards have their own source code which allows them to acquire and organize data in a parallel way. The general steps or algorithm the system follows is represented in the figure 5 and later described in steps.

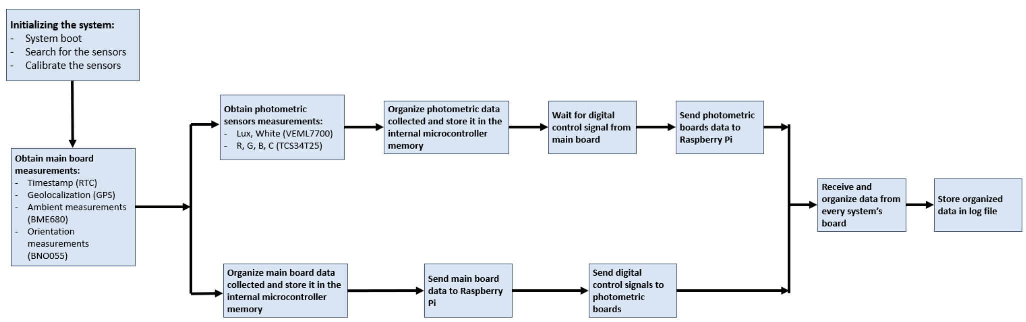


Fig. 5. System's general algorithm block diagram

- At system's power up, the Raspberry Pi starts its booting process.
- Initialization of main board and photometric boards (sensor calibration).
- Raspberry Pi executes logger script and waits for incoming data.
- Main board and photometric boards data acquisition in parallel.
- Main board sends its data to Raspberry Pi.
- Main board sends trigger signal to photometric boards.
- Photometric boards send its information to Raspberry Pi.
- Raspberry Pi organizes data received.
- Data saved in log file.

4.1.1 Main Board Data Acquisition

The main board communicates with its sensors via the I2C and UART (for the GPS) protocols. It accesses specific registers of the sensors by sending them a command (specified in the sensor's datasheet) to acquire timestamp, geolocalization, temperature, pressure, humidity, X orientation, Y orientation and Z orientation. Each sensor has its own address and specific registers to retrieve the required measurements and they are partitioned in the MSB and LSB registers to obtain the complete information. The I2C communication is set to function in the fast mode which has a 400 Kbit/s speed.

With the GPS it's different, since the communication protocol is UART, once it has connected to the mobile network, it will start sending all its information in the NMEA (National Marine Electronics Association) protocol. The microcontroller then filters only the required information from the NMEA output string.

After completing data acquisition from all the sensors and GPS, it will reorganize them in a string with a specific order (table 4) and send it to the Raspberry Pi. The last step is to send a digital control signal to each photometric board so they can send their acquired data.

```
Hour:Minutes:Seconds,Day/Month/Year;$GNRMC,$GNVTG,$GNGGA,
$GNGSA,$GPGSV,$GLGSV,$GNGLL;Temperature,Pressure,Humidity
;X_orientation,Y_orientation,Z_orientation;
```

4.1.2 Photometric Boards Data Acquisition

Each sensor has its own address and registers to retrieve the required data. After the microcontroller is done obtaining the required data and arranging them in a string with a specific order which can be seen in the string below and it's the same for every photometric board.

```
ClusterNumber,Lux,White,ColorTemperature,R,G,B,C;
```

4.1.3 Connection of Photometric Sensor Boards and Main Sensors Board

The digital control signal generated by the main board in order to communicate with the photometric boards and indicate them it's time to send their information, consists of pulling 5 digital pins (table 7) from low to high in a sequential way starting with the first photometric cluster, passing through clusters 2, 3, 4 and finally cluster 5. The main board will then pull the 5 digital pins from high to low and start obtaining again its data.

4.1.4 Connection of Raspberry Pi with The Main Board and Photometric Boards

The way the main board and the photometric boards communicate with the Raspberry Pi is via an USB port connected to a hub. The reason for using USB ports to communicate is because the Raspberry Pi does not have all the necessary UART or I2C modules to connect with the 5 photometric boards. It has 4 USB ports, but they can be extended using a USB hub as seen in figure 6.

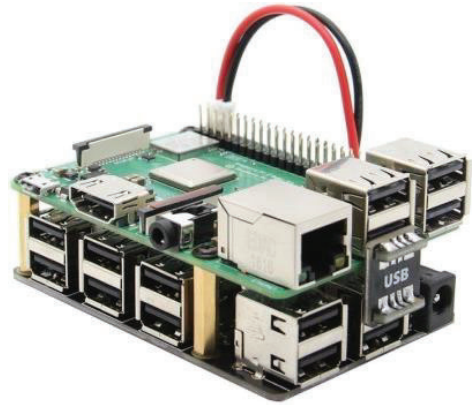


Fig. 6. Raspberry Pi USB hub [5]

4.1.5 Format of Acquired Data

Every measurement is separated by a comma and every sensor is separated by a semi-colon. The only measurement that is separated with a different character is the timestamp which uses a colon. The following string represents the acquired data:

```
20:07:21,24/11/2020;$GNRMC,061944.40,A,2038.49005,N,10325
.56848,W,1.973,,241119,,,A*77$GNVTG,,T,,M,1.973,N,3.654,K
,A*35$GNGGA,061944.40,2038.49005,N,10325.56848,W,1,07,1.1
0,1604.0,M,16.8,M,,*4F$GNGSA,A,3,30,17,19,06,13,07,01,,,,
,,2.14,1.10,1.83*1E$GPGSV,4,1,13,01,15,041,12,02,10,204,2
1,03,03,092,,06,42,182,19*73$GLGSV,2,1,07,76,35,113,,77,5
9,029,,78,20,335,,81,20,216,19*6C;BME680,30.48,849.62,49.
14;BNO055,359.94,21.31,26.38;Cluster1,4178.53,7898.11,226
7,80,101,113,140;Cluster2,4783.96,8139.91,2538,90,97,107,
200;Cluster3,4929.44,9029.8,2600,100,98,109,219;Cluster4,
4800,8564,2526,117,104,100,220;Cluster,5024.7,8998,2636,1
12,102,120,215;
```

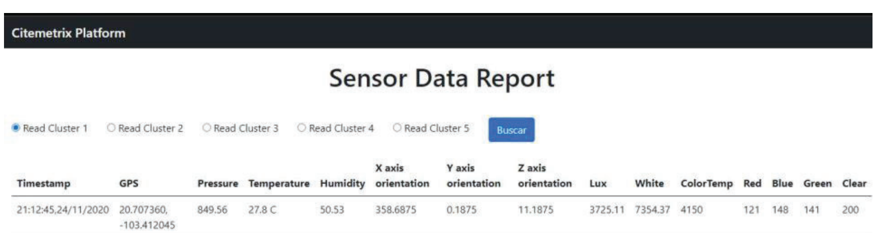
4.1.6 Organizing Data in Raspberry Pi

In order to receive and organize the incoming data from all the system's boards, a python script was developed to read data from the USB port connected to the USB hub. This script reads the strings received and store them in the log file with a line break at the end. The script is executed every time the Raspberry Pi finishes its booting process with the help of a crontab, but it can be executed directly from the terminal whenever it's necessary. The Raspberry Pi is connected to a laptop via an ethernet cable using the VNC software so the operator of the system can visualize in real time the logging process. When the automated street lighting survey process of a specific area is terminated, the operator stops the execution of the python script and extracts the log file for further processing.

5 Results

This prototype was tested outside the laboratory by mounting it in a car and taking a special route that was selected based on the street lighting infrastructure of the zone. The results were uploaded to a web platform to validate the GPS data of the followed route and to visualize in an organized way the data acquired from the sensors as it can be seen in figure 7 and figure 8. The platform converts the NMEA GPS data to a format used in online map services like google maps for a more comfortable visualization.

Fig. 7. GPS data represented in a map



Timestamp	GPS	Pressure	Temperature	Humidity	X axis orientation	Y axis orientation	Z axis orientation	Lux	White	ColorTemp	Red	Blue	Green	Clear
21:12:45,24/11/2020	20.707360, -103.412045	849.56	27.8 C	50.53	358.6875	0.1875	11.1875	3725.11	7354.37	4150	121	148	141	200

Fig. 8. Sensor's data visualized in web platform

According to an interview with a former technician that worked performing this manual process, the routes they follow are divided by zones in which there's a street limitation similar to a geofence. Each zone takes up 3 to 4 days to be mapped and they approximately map 80 – 100 luminaires every work day of 8 hours. Depending on the size of the zone, a combination of 2 or 3 zones results in a neighborhood and a combination of several neighborhoods results in a municipality. So, in urban areas like big cities, the higher the number of municipalities, the higher the time that will take to get the complete inventory survey of street lighting infrastructure. In figure 9 there's a chart representing the comparison of time taken by the manual process vs the automated process based on field tests performed.

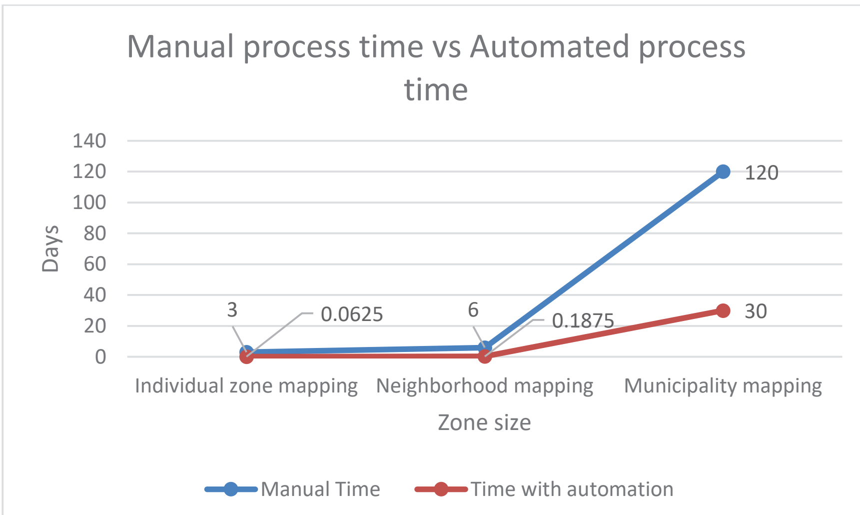


Fig. 9. Manual process vs Automated process time graph

Even though the field tests were only individual zone mapping (the rest of the mapping was calculated based on the individual zone markers), the automated process performed by the prototype is much faster than the manual process performed by technicians since it's mounted over a vehicle with a 50km/hr. average speed, no stopping and the results will later be processed to get the same information the technicians obtain.

6 Conclusion & Discussion

6.1 Conclusion

The manual process of street lighting inventory survey requires data acquisition of every single luminaire of interest in a determined zone which makes it a repetitive and a very time-consuming process as well as facing problems that are inherent from the human intervention. Implementing this solution can not only help to reduce the amount of time taken to map a zone but also reduce the amount of the human resources required by half.

For example, by having a precise map of the street lighting infrastructure, the quality of the public street lighting service improves by enabling faster decisions making regarding on predictive and corrective maintenance of luminaires that need it which can help reduce the insecurity levels of zones with deficient illumination. Energy efficiency is another plus that this solution gives since it maps with precision the actual luminaire infrastructure with illumination technology and thus, helps electricity companies to calculate a more precise energy consumption marker that could help implementing energy saving controls and reduce electricity shortages in zones with higher volume of luminaires. Implementing embedded applications to automate the manual street lighting survey process is a big contribution to the development of smart cities since it goes hand in hand with improvements in public services area, specifically in the street lighting infrastructure that will give this service a better quality for the citizens and will lead updating outdated lighting technologies to smart LED urban lighting and consequently a beneficial environmental impact

6.2 Future work

This prototype presented is still on development and there are improvements to be made. Some of the future work (but not limited to) is listed next:

- Add a Human-Machine Interface like a touchscreen on the Raspberry Pi and/or a web interface for better control of the system and interaction with the operators.
- Add digital cameras to take pictures of the pole and luminaire.
- Faster data acquisition frequency. (add percentage or quantitative marker)
- Wireless communication module to send the log file / sensor measurements to the web platform.
- Improve the materials of the mechanical case to make them water and vibration proof.

This a proposal for automating the manual survey process of street lighting, at the end, another proposal can be implemented.

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