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AUTOMATED SYSTEM FOR ACQUISITION AND TRANSMISSION OF THERMAL IMAGES FROM AN ELECTRIC POWER SUBSTATION

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Abstract: Power substations are facilities responsible for carrying out the distribution of electrical energy. Thermographic monitoring systems have obtained satisfactory results by identifying points with anomalous temperatures, anticipating the occurrence of failures. Thus, this article describes a system for acquiring and transmitting images from a thermographic camera, from a power substation to a remote server. A geometric equation for the repeatability errors in the framing of the images is shown. They are obtained through mobile cameras, through self-guided vehicle (AGV) and pan-tilt angles mover. It also presents the main blocks of software developed, as well as the structure of the means of communication used.
Keywords: Automation, motion control, image acquisition, AGV, pan-tilt.

INTRODUCTION

Power substations are facilities responsible for carrying out the distribution of electrical energy. For this, various equipment such as transformers and protection and switching devices are needed, which can suffer damage over time, causing failures. In order to comply with the demands for continuity in energy supply and to follow the quality and availability indexes imposed by the National Electric Energy Agency (ANEEL), it is advantageous for electrical system operators to reduce the failures that may cause service interruption in substations (Pinto et al, 2008; Souza, 2008; Tarrago, 2019).

Thermographic monitoring systems have obtained satisfactory results by identifying points with anomalous temperatures in electrical equipment, anticipating the occurrence of failures. Due to the greater number of substations than qualified labor to carry out thermal inspections, several alternatives have been developed to capture thermal images in an automated way (Guo et al, 2010); as is the case of the project PD 2866-0528/2020 – Development of a Methodology for Automatic Analysis of Thermal Images, carried out by the Universidade Tecnológica Federal do Paraná (UTFPR) in partnership with the company: ‘’Companhia Paranaense de Energia” (COPEL). In this project, in order for the entire monitoring and analysis process to be carried out in an automated way, it was necessary to develop an image acquisition system and a data transmission system.

The developed acquisition system is composed of a FLIR® thermographic camera, an AGV (Automated-Guided Vehicle) and a Pan-Tilt advisor, the latter developed by local manufacturers. The AGV and Pan-Tilt are responsible for positioning the thermographic camera, which must capture separate images of each component of the substation.

Therefore, this article aims to describe the data acquisition and transmission system of the thermographic camera, from a power substation located in the city of Curitiba to a remote server.

In addition to the thermal images, which will contain the radiometric data of the components, optical images must be acquired for their identification by a neural network (see Figure 1). However, these algorithms will not be discussed in this article.

IMAGE ACQUISITION SYSTEM

The image acquisition system is composed of a set of two cameras (CAM: thermographic and optical), equipped with Pan-Tilt angular movement, installed on an AGV, which moves on almost flat terrain, formed by crushed stones.

Due to the irregularity of the ground, it is not possible to easily estimate the path followed by the AGV. Even if a straight-line trajectory is commanded, the AGV will present position and alignment errors, as can be seen in the different poses illustrated in Figure 2.

Figure 1: Example of optical (left) and thermal (right) image of the substation.

Figure 2: Camera movement system.

To improve the framing repeatability of the acquired images, it is necessary to add a closed-loop control to the AGV traction and guidance drive. And, in this case, if there are still small errors in the pose achieved by the AGV, it will be possible to apply an angular compensation in the Pan-Tilt and in the focus distance of the camera lens, as a way to reduce such errors. The geometric equation for this compensation is discussed in the next section.

a) Geometric Analysis

Temperature monitoring in electrical power substation equipment requires several poses: (P_1, P_2, ...P_n) of stop in the AGV, where each pose is composed of the triad of coordinates: $P_n = (x_n, y_n, a_n)$ x_n and y_n, Cartesian coordinates measured from the reference system: P.

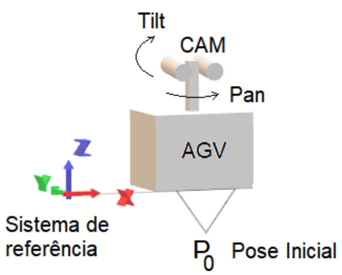


Figure 3: Camera movement system.

In this system: a_n is the azimuth angle, measured with respect to the z-axis of the reference coordinate system. In the initial pose the AGV has coordinates: $P_0(x_0, y_0, a_0)$ known and immutable throughout the process, whenever the AGV returns to it, as illustrated in Figure 3. For the acquisition of the different images, in addition to the AGV seeking various poses, there will also be a set of different pan-tilt-focus coordinates (PT_{n1}, PT_{n2}...PT_{ni}) of the camera associated with each pose: PT_n. These camera coordinates are formed by the angles ap of pan, at of tilt and focal length df, as shown in Figure 4.

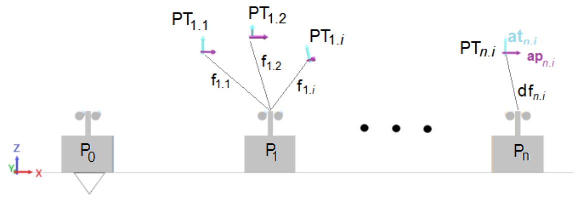


Figure 4: Poses and thermographic image collection points.

The different AGV poses that meet must ideally be positioned along a rectilinear trajectory, however in practice the poses may present deviations making the trajectory quasi-rectilinear, as illustrated in Figures 5 and 6.

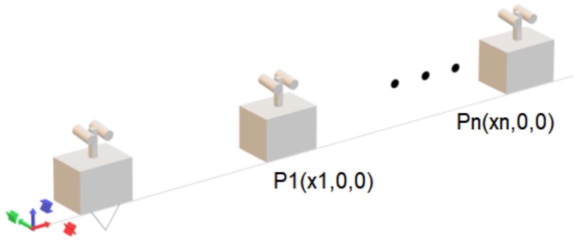


Figure 5: Rectilinear ideal trajectory.

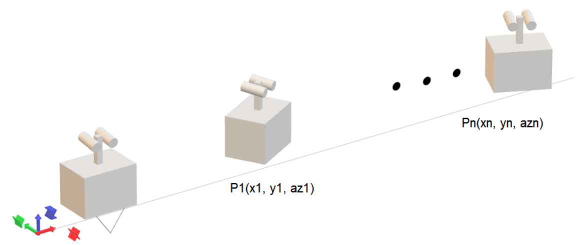


Figure 6: Expected quasi-rectilinear trajectory.

It is recognized and expected that when executing each new search path, by pose: P_n desired, the AGV control system presents deviations, leading it to a set of incorrect and estimated poses such as: $\sim P_n$. The total error of the desired pose: $\delta P_n(\mathcal{E}x_n, \mathcal{E}y_n, \mathcal{E}a_n)$ will cause a deviation in the framing and focus of the image to be obtained, which must be corrected through a compensation in these three parameters of δPT_{ni}. As illustrated in Figure 7.

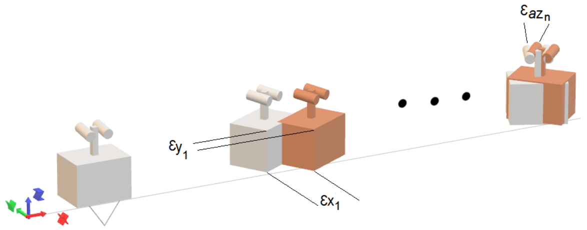
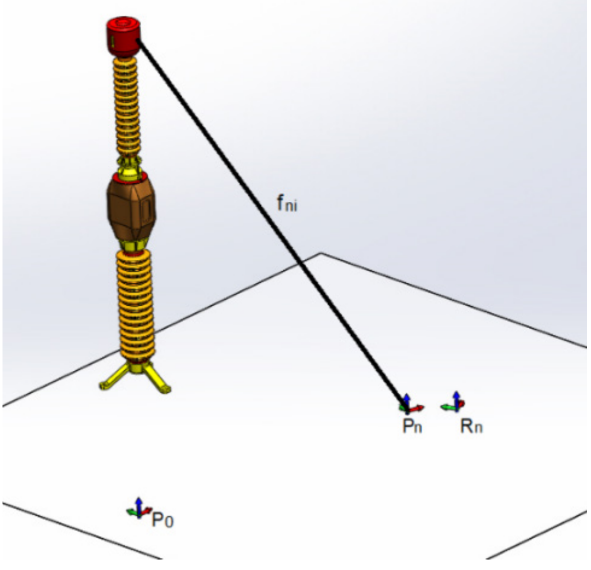


Figure 7: Angular and positioning errors during the execution of trajectories.

This compensation can be estimated through the fc() correction function, which defines a relationship between the deviations in the coordinates PT_{ni} of the camera and the deviations in the Pn coordinates of the AGV. By definition:

$$\delta PT_{ni} \equiv fc(\delta \overline{P}_n).$$

The computation for framing, given by the angles a (pan) and t (tilt), as well as the focal length (f) that will actually be sent to the camera (at the time of image acquisition) can then be calculated from the coordinates: P_n e PT_{ni} (pre-memorized), as shown in Figure 8. Here we consider $R_n = (xr_n, yr_n, ar_n)$ as the actual coordinate of where the AGV actually stopped.



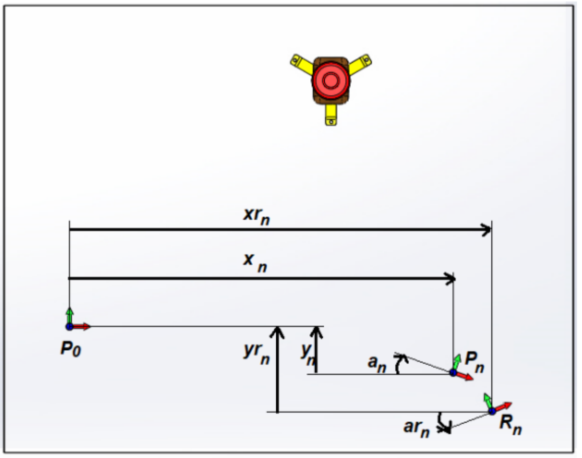


Figure 8: Coordinate system views: perspective (left) and top (right).

Thus, initially the errors must be calculated:

$$\varepsilon x_n = x_n - xr_n$$
$$\varepsilon y_n = y_n - yr_n$$
$$\varepsilon a_n = a_n - ar_n$$

Then the value of the pan angle to send to the camera can be calculated by the expression:

$$p = \mathrm{tg}^{-1}\left(\frac{y_p}{x_p}\right) - \varepsilon a_n \qquad (1)$$

and x_p and y_p the new coordinates of PT_{ni} related to R_n, calculated as:

$$x_p = \mathrm{df}_{ni}.\cos(\mathrm{at}_{ni}).\cos(\mathrm{ap}_{ni}) + \varepsilon x_n$$
$$y_p = \mathrm{df}_{ni}.\cos(\mathrm{at}_{ni}).\cos(\mathrm{ap}_{ni}) + \varepsilon y_n$$

While the tilt angle value to be sent to the camera will be given by the equation:

$$t = \mathrm{tg}^{-1}\left(\frac{\mathrm{df}_{ni}.\mathrm{sen}(\mathrm{at}_{ni})}{\sqrt{x_p^2 + y_p^2}}\right) \qquad (2)$$

where z_p is the height coordinate of the focal point, which does not suffer deviation with the stop error of the AGV, calculated by the expression:

$$z_p = \mathrm{df}_{ni}.\mathrm{sen}(\mathrm{at}_{ni})$$

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as shown in figure 9. And, the new focal length value must also be corrected, changing to the value given by the expression:

$$f = \sqrt{x_p^2 + y_p^2 + z_p^2} \tag{3}$$

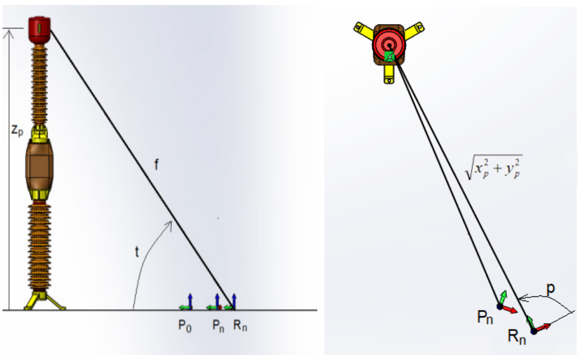

Figure 9: Visualization of zp, t and f (left) and angle p (right).

b) Sensing by LiDAR

Preliminary tests carried out on site at the substation proved the impossibility of the AGV performing ideally rectilinear trajectories. The main factor that prevented this behavior is related to the inhomogeneity and the low friction coefficient of the tires with the ground, characterized by crushed stone.

The measurement of trajectory errors using LiDAR sensors was one of the main alternatives of use, mainly taking into account the impossibility of using odometry through encoders on the wheels (given the constant loss of adhesion of these due to the soil constituted by gravel). The use of LiDAR proved to be adequate for this purpose, where along the trajectory performed the device was able to measure with precision better than 0.01m not only the position and orientation of the AGV, but also mapping points of interest in the environment (such as it is possible to visualize in the highlighted area in Figure 10, the presence of metallic structures presented in the substation).

IMAGE TRANSMISSION SYSTEM

Exploratory research was carried out for the development of the system's communication architecture. And, in this aspect, the different ways of extracting data and controlling the thermographic camera were investigated.

The company Teledyne FLIR® provides technical documentation regarding its SDKs

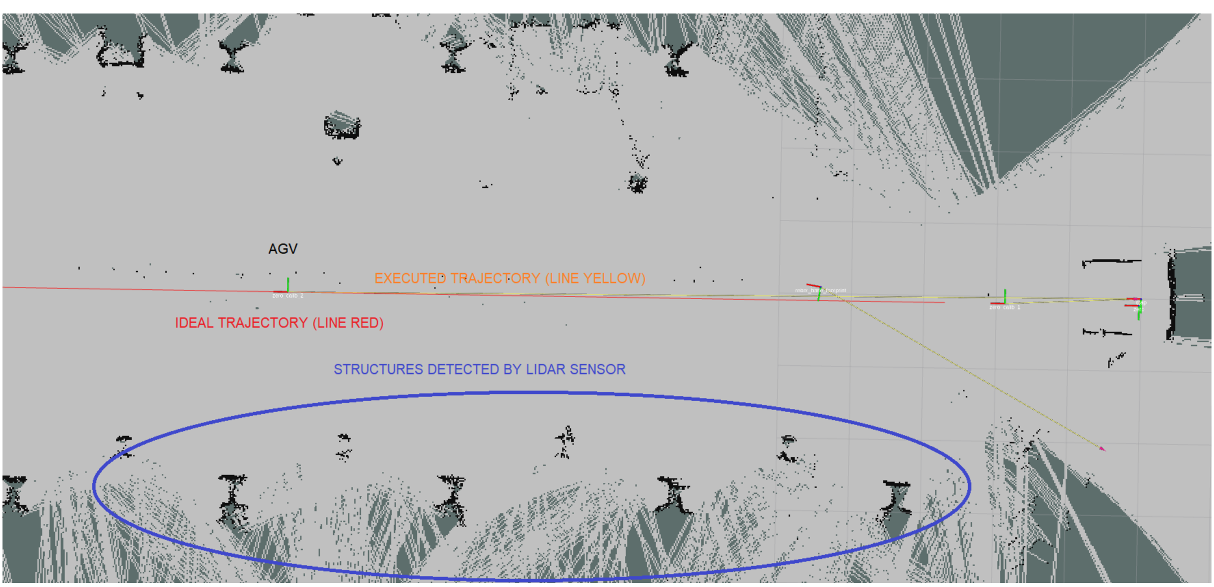

Figure 10: Mapping of the environment through sensor: LiDAR.

(Software Development Kit) and its APIs (Application Programming Interface). Both are used to control cameras. Several tests were carried out with the camera; comparing the Atlas SDK, the Rest API and the camera's web interface, for the automated acquisition of thermal images. Tests included focus control, camera calibration and thermal and optical image capture.

Focus control (f) is essential since in practice the components will be at different distances from the camera (as already shown in Figure 9), and therefore it is necessary to perform autofocus before capturing each image.

In order to allow the command, monitoring and automation of image acquisitions, it was necessary to develop a web interface to present all important information to the system operator.

Thus, the following sections discuss the means of communication used, as well as the modeling of the main blocks of software developed.

a) Media

4G is the acronym for the fourth generation of mobile telephony. This technology has presented significant advances in data transmission compared to previous generations. With it, it is possible, for example, to play videos in high definition and carry out video conferences with great stability. When using a 4G modem, it is possible to use the 4G channel not only for cell phones, but for computers or other devices, dispensing with cable internet.

A VPN (Virtual Private Network) is a virtual private network that establishes a secure connection by encrypting data. Through the VPN tunneling system, data can be sent without other users having access. In addition, because it is built on the infrastructure of a public network, it is a cheaper privacy solution.

The MikroTik equipment is a router that features features for configuring VPN (Virtual Private Network), Proxy, Hotspots, Bandwidth Control, QoS and Firewall. In fact, MikroTik is a network device manufacturer based in Latvia. Among these devices, it also has RouterBoard series routers, which combine a Linux-based operating system called MikroTik RouterOS with its own hardware line.

The data transmission system has a local network that works with the IP protocol. Figure 11 illustrates the equipment present in the system.

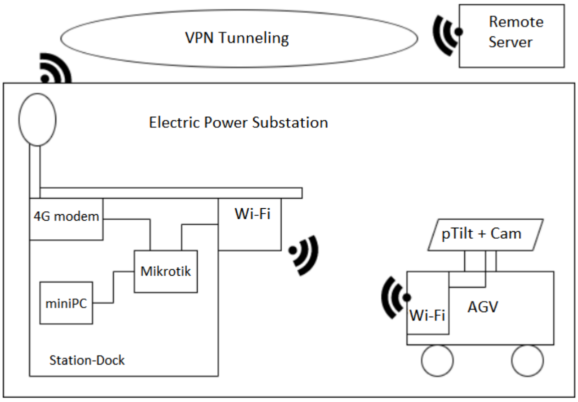

Figure 11: Image transmission system architecture.

The local network uses a VPN to communicate with the remote server. To use VPN tunneling, it is necessary to provide a local network connection to the internet, which was done with 4G technology. Access to the virtual private network is granted by a MikroTik.

b) Main blocks of software developed

With the StreamingCamera class, present in the Atlas SDK, it was possible to capture optical images. The ThermalCamera class and the other classes that inherit its characteristics – DualStreaming-ThermalCamera, ThermalGigabitCamera and Thermal-SpinnakerCamera – enabled the acquisition of thermal images, containing the radiometric metadata. With the VideoOverlay-Camera class it was possible to capture the image being displayed in the web interface. DualStreamingThemalCamera was the class that proved to be the most promising, as it allows obtaining both a thermal image and an optical image, which can be done in Python language and with the Python.NET library, according to the SysML activity diagram, illustrated in Figure 12.

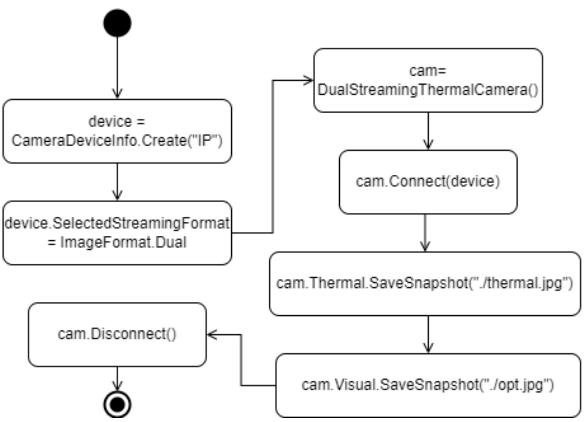

Figure 12: SysML activity diagram for image capture via Atlas SDK.

Rest API made it possible to capture 640x480 resolution thermal image, 1280x960 resolution optical image and 2592x1944 resolution optical image, which provided a wider field of view. It is also possible to obtain a 640x480 resolution optical image that has the same field of view as the thermal image. To acquire a thermal image via Rest API using Python, proceed according to the diagram illustrated in Figure 13a, where IP (Internet Protocol) refers to the IP address of the camera and snap_name to the name of the file where the image will be recorded.

A token attribute of the class is inserted in the header of functions that use the POST method, having an authentication role. This token must be generated in the camera's web interface. The focus () and calibrate () methods are represented, respectively, in Figures 13b and 13c. It is possible to observe in these the use of the POST method with the requests library, where the data sent in the data parameter and the authentication token in the header (header).

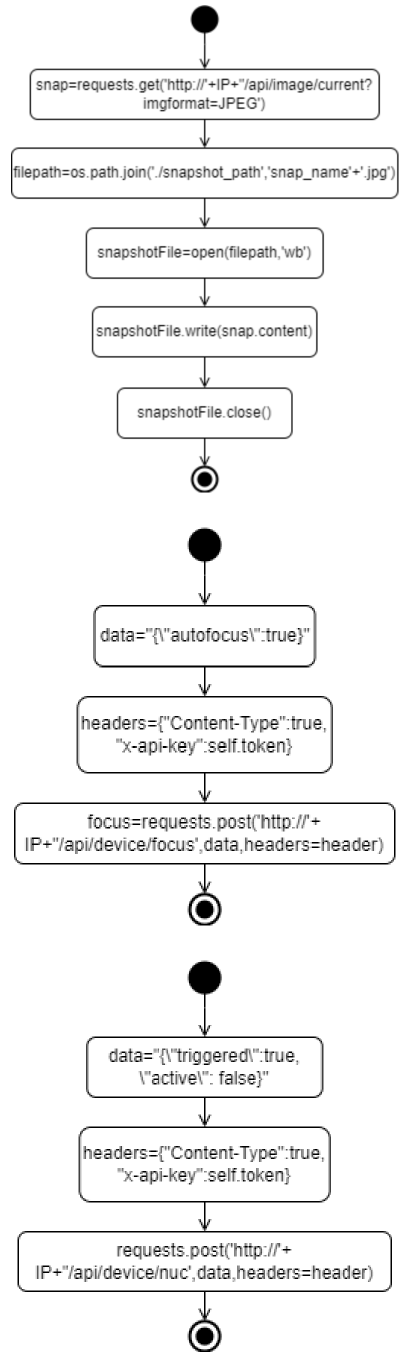

Figure 13: SysML activity diagrams: 13a-(left) thermal image capture; 13b-(center) focus () method performing autofocus; 13c-(right) calibrate() method of calibration.

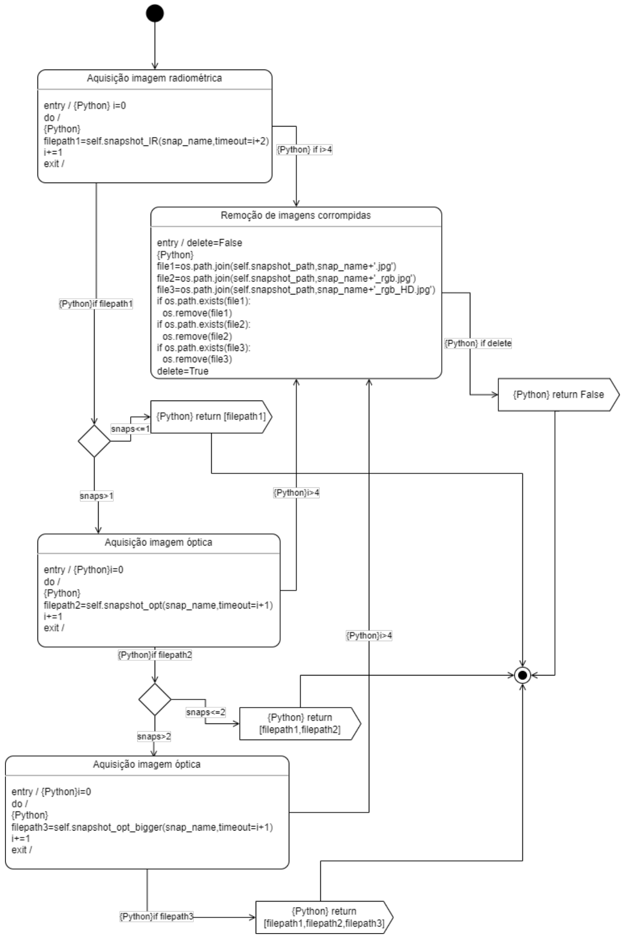

Figure 14: SysML state machine diagram for the snapshot () method.

The snapshot () method present in the class captures all images – thermal, optical and optical with higher resolution; in addition to handling possible connection issues that delay sending the HTTP request and receiving its response, as illustrated in Figure 14.

Rectangles with rounded corners represent states that the system may experience. In each state, entry activities (entry/), state activities (do/), which occur all the time, and exit actions (exit/) are performed. Activities described in Python language are presented with "{Python}" at the beginning of the text. In addition, the arrows indicate transitions between states (Friedenthal et al, 2015).

A miniPC is responsible for controlling the entire system. Thus, it performs an HTTP request for the thermal camera to perform the image capture. This image is then written to a file on the miniPC, as shown in figure 15.

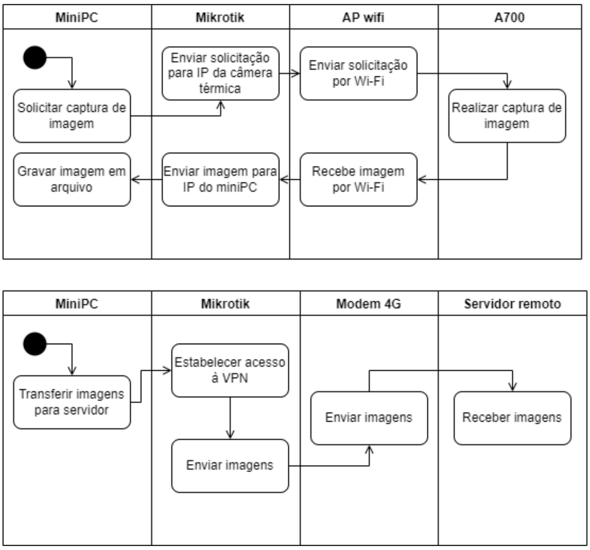

Figure 15: Transmission system activity diagram.

When the miniPC requests the transfer of files to the remote server, MikroTik grants access to the VPN, and through the 4G channel the images are sent to the server.

The company that develops the AGV has provided an API in Python, through which it is possible to control the position of the AGV, the position of the pantilt, and obtain various system statuses. Integrating the Python class, developed for camera control via Rest API with the AGV API, a script was developed to perform automated image capture missions, which is represented in Figure 16 by a state machine diagram.

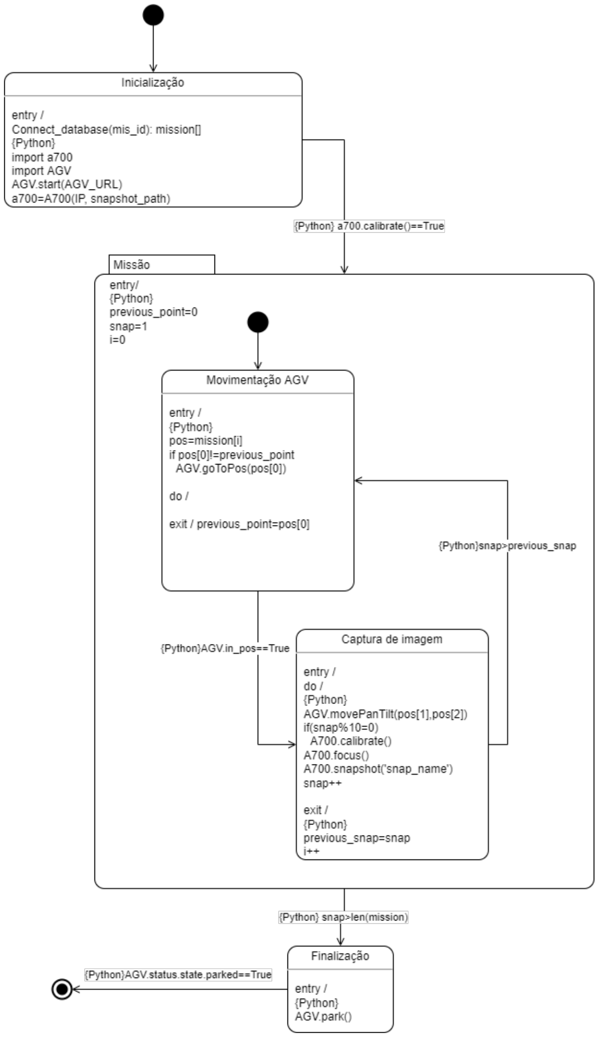

Figure 16: SysML state machine of an automated mission.

Initially, the script connects to the mission database and obtains the AGV stop positions and pantilt positions for the mis_id identifier mission. The Connect_data-base(mis_id) activity returns a list called mission []. A Python list contains a sequence of objects and can be modified by inserting or removing items. In this case, the list will be formed by several tuples. A tuple in Python is also a sequence of objects, but it is immutable. Each tuple present in mission will represent an image capture position, that is, it will present three values: coordinate of the AGV stop point (x), pantilt azimuth angle (azi) and pantilt elevation angle (ele).

After the list of positions is formed, the connection between the miniPC, where this script will be running, with the AGV and with the camera is initialized.

Then the capture mission begins; the AGV moves to the breakpoint described by the tuple of index 0 in the mission list. Upon reaching the point, the pantilt is positioned, the camera performs autofocus, and the snapshot () method is called to capture the highest resolution, both for thermal and optical images. The AGV then moves to the stop point present in the index tuple 1. If this point is equal to the previous point, the AGV remains at the same coordinate. The pantilt is then positioned according to the tuple's values; focus and image acquisition are performed.

The described process is repeated until all the mission acquisitions are carried out. After completion, that is, when the size of the mission list is smaller than the snap variable (image number), the AGV is commanded to park at the dock via the AGV.Park() method.

CONCLUSIONS

Movement systems based on AGV technology have been well applied for several decades, both in the simplest cases indoors (eg in industries) and in outdoor applications, for example in driverless cars (currently researched by Tesla, Google, Apple etc).

In the case of using an AGV to move a thermographic camera in a power substation, the challenge of achieving very high positioning accuracies must be considered, mainly due to the unevenness of the ground, characteristic of the use of crushed stone. However, this unfavorable factor is mitigated when taking into account the fact that positioning errors in the camera can be compensated by adjusting the pan and tilt angles, as well as the focal length. With the use of sensing through LiDAR technology, it was possible to reach precision levels in the order of 1 cm.

In developing a methodology for automatic analysis of thermal images, an automated data acquisition and transmission system is necessary. This article presented the acquisition and communication system developed to automate the collection of thermal images.

In the link https://vimeo.com/689850544, the reader will be able to see a video related to one of the preliminary tests of the project.

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