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Abstract—**The inspection of high voltage power transmission lines is mainly carried out by manned aerial vehicles or foot patrol. However, these maintenance methodologies for inspection are somehow inefficient and expensive. Moreover, helicopter assisted inspection endangers the human life. Recently, unmanned aerial vehicles have been under development in several research centers all over the world due to its potential applications. In this paper, we present an unmanned aerial system based on the quadrotor helicopter for high voltage power line inspection. Our interest is to equip the quadrotor helicopter with the necessary payload in order to be able to carry out a qualitative inspection, therefore the hardware architecture of the aerial robotic system is presented. Finally, some experimental results are shown to demonstrate the feasibility of the proposed system.**

I. INTRODUCTION

One of the aspects that characterized the development of a society is its energy consumption in all of its forms, particularly its electrical power consumption. The distribution lines are the link between the power plants and the points of consumption, through substations and transformation centers, providing as far as possible the redundancy required due to its mesh structure. Given the great distance that may exist between the main central and users, the tension of electric distribution lines is set to different values in the substations. At the end of May 2013, the electrical network in Mexico reached a length of 51091 km, according with the Federal Electricity Commission (CFE, for its acronym in Spanish), having transmission lengths of 23627, 26915 and 549 km for 400, 230 and 161 kV lines, respectively. The high voltage transmission lines have an important role in the overall performance of the electrical network as they are the intermediate process between production, distribution and sale of electricity. The failures in this process has very high implicit costs in its three main processes; generation, transmission and distribution of electricity.

The maintenance methodologies that several electrical institutions are using to keep under control the performance indicators of the transmission process, involves four main directions: foot patrol, manned aerial vehicles, climbing robots and unmanned aerial vehicles (UAVs).

A. Foot Patrol Inspection

In the foot patrol inspection, a team of usually two people walk from pylon to pylon and inspect the power line. Visual inspection is carried out with the help of binoculars and sometimes with infrared (IR) and corona detection cameras. Such an inspection can be highly accurate but only for the surfaces of power line equipment that can be well seen from the ground [1]. The patrolling of transmission lines with personnel movement across roads are not easy given the national terrain. Therefore it is slow, tedious, monotonous and subjective, therefore larger defects can sometimes be overlooked.

B. Manned Aerial Vehicles - Helicopter Assisted Inspection

High-speed aerial transmission line inspections have been conducted by either fixed or rotor winged airframes staffed by a team of three people, the pilot, the inspector, and the recorder. The effectiveness of these inspections in determining damage conditions and defects has generally been rated low. Aerial inspection clearly offers advantages in speed and accessibility, however given the high costs involved in such inspections, its use should be rented in quick inspection of large networks or in places where the accessibility by land present difficulties. There have been several studies using this method, as in [3], [4], and [5], focusing in the sensor fusion. Despite the good results and efforts this methodology highly endangers the human life, therefore other alternatives has begun to be explored as climbing robots or UAVs.

C. Climbing Robots Inspection

An alternative approach to power line inspection is by means of a climbing robot. This mobile robot can move along the conductor and overcome various obstacles on the power lines. The main advantage of this concept is the inspection accuracy that comes with its proximity to the line. On the other hand, development and construction of a robot mechanism for overcoming obstacles on the line is the main research problem due to its extremely difficulty. Moreover, due to the electromagnetic field of the power line the electronics and sensors on the robot have to be protected. See [6], [7], and [8].

D. UAV Inspection

Robotic aerial systems represent an alternative to piloted systems, both reducing the risk to personnel and cutting costs, for a wide range of activities related to monitoring transmission lines and other types of strategic infrastructure.

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The use of robotic aerial platforms for observation represents a field of increasing interest for companies and institutions. The inspection with UAVs is very similar to the automated helicopter inspection, sharing some common problems as camera stabilization, pole tracking and automatic defect detection. An evaluation of using an UAV for power line inspection indicated that this approach could be faster than foot patrol and would yield the same or even better accuracy than costly helicopter inspection [9]. The Electric Power Research Institute (EPRI) has promoted the development of a more cost-effective airborne inspection method for the inventory and inspection of electric power lines. High-speed aerial patrols have typically only been used to identify the most visible (i.e., of sufficient size and severity) conditions on transmission lines. The problem of detection and tracking of power lines in complex environments is presented in [10], where a Kalman filter is used to track the power lines in the Hough space, based on the continuity of a video sequence. Moreover, in [11] a novel UAV terrain contour match method of multi-path terrain matching based on 2D plane laser radar is proposed. Those studies are focused on the surrounds of the power lines but they do not mention anything about the status of the power lines. The AggieAir-TIR remote sensing platform, presented in [12], encompasses a foam glider and a thermal infrared (TIR), they provide a low-cost TIR camera calibration experiment. Despite de good results the gliders are not a suitable aerial platform for performing a detailed power lines inspection since they do not offer the capability of hover. To overcome this issue, UAV helicopter is used in [13], where a combination of an autonomous helicopter and a inspection system is carried out. The complete aerial system is based on a single rotor helicopter which has a TIR camera, a color camera, and a laser altimeter. The good performance of the mentioned system is shown, however it is still a good challenge to specifically design and build an UAV quadrotor helicopter for performing the task of power line inspection.

E. *Objectives and motivation*

The main goal of this project is to design and build an unmanned aerial system (UAS) based on the quadrotor helicopter for monitoring the power lines. The quadrotor must be equipped with the payload necessary to perform a qualitative inspection and have the possibility to extend it to perform a quantitative inspection. Moreover, the vision algorithms designed and developed for this project should be running in the ground control station (GCS), in order to report any anomalies in real time. The payload encompasses a TIR camera and a color camera, the combination of both images will be helpful for detecting hot spots and other damages. Furthermore, the quadrotor helicopter must be capable of performing three flight modes: manual flight, GPS fixed location, and GPS navigation. The flight control has to withstand the effects of wind disturbances since the inspection are carried out mostly in environments involving high wind speeds.

The paper is organized as follows. Section II gives the description of the unmanned aerial system. In Section III, the description of the vision system and one example of a qualitative inspection are introduced. The conclusion are presented in Section IV.

II. DESCRIPTION OF THE UNMANNED AERIAL SYSTEM

An unmanned aerial system comprises a number of subsystems which include [2]:

- the GCS which houses the system operators, the interfaces between the operators and the rest of the aerial system
- the quadrotor carrying the payload
- the system of communication between the aircraft and the GCS; which transmits control inputs to the aircraft and returns the information from the payload and other data from the aircraft to the GCS

The whole system is designed as a complete UAS for power line inspection. The hardware architecture of the whole aerial robotic system can be seen in Fig. 1. The aerial robotic system consists of two sub-systems: the flight control system and the payload for achieving power line inspection. The quadrotor helicopter encompasses the flight control system and the payload. The flight control system is responsible for the task management, signal fusion and translating the flight control instructions into a robust and safe flight, moreover it also contains the communication system based on radio frequency. The payload is comprised by a video transmitter and two cameras; a color camera and a TIR camera. The above mentioned parts will be described in detail in the following sub-sections.

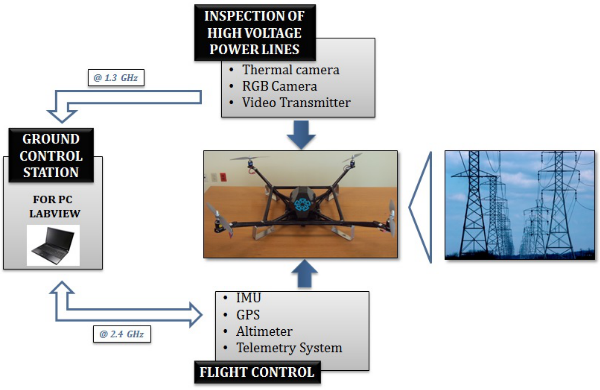


Fig. 1. Hardware architecture for achieving power lines inspection.

A. *Quadrotor Helicopter*

The quadrotor helicopter is classified as a powered rotary wing vertical take-off and landing aircraft. The quadrotor has been developed from scratch in our laboratory to meet the requirements for power line inspection. It is equipped with an autopilot which consists of a microprocessor, an inertial measurement unit (IMU), a GPS, an altimeter and a communication system. The quadrotor flight controller must be able to perform three flying modes according with the inspection task: manual flight, GPS fixed location and GPS navigation. These flight modes are defined as follow:

- Manual flight: the quadrotor is piloted by the user. In this flight mode the pilot can flight the rotorcraft having line of sight.

- GPS fixed location: in this flight mode while the user is flying in manual flight it attempts to maintain the current attitude and GPS location.
- GPS navigation: the quadrotor performs autonomous flight following a GPS coordinates path defined by the user in the GCS.

The quadrotor is an underactuated and highly nonlinear dynamic system, thus an appropriate model ideally includes the gyroscopic effects resulting from both the rigid body rotation in space and the four propulsion groups of rotation [14]. The equations describing the dynamics of the quadrotor, can be expressed in the earth- fixed reference frame E_E as

$$\begin{array}{rcl}\ddot{X}_E & = & \frac{1}{m}R(\Theta)[F_{prop} - F_{aero}] - G \\ \ddot{\Theta} & = & [IM(\Theta)]^{-1}\left[\begin{array}{c} T_{prop} - T_{aero} - T_{gyro} - \\ M(\Theta)\dot{\Theta} \times IM(\Theta)\dot{\Theta} \\ -I\left(\dfrac{\partial M(\Theta)}{\partial \theta}\dot{\theta} + \dfrac{\partial M(\Theta)}{\partial \phi}\dot{\phi}\right)\dot{\Theta} \end{array}\right]\end{array} \tag{1}$$

where $X_E = [x, y, z]^T$ is the absolute position of the quadrotor and $\Theta = [\psi, \theta, \phi]^T$ represents its attitude by the Euler angles. Several robust flight controllers have been carried out for the quadrotor aerial platform [16], [17]. A common flight trajectory in the inspection of power lines is shown in Fig. 2.

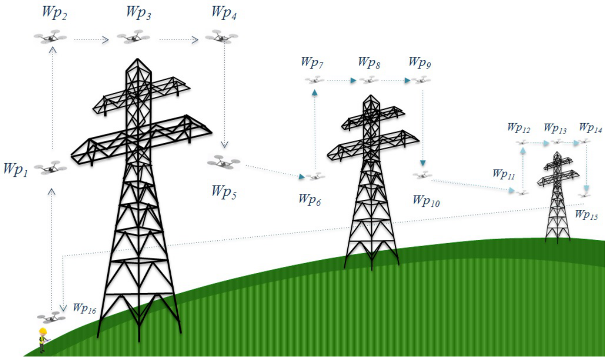


Fig. 2. UAV used for power line inspection.

Moreover, the helicopter is equipped with a vision system based on a color camera and a TIR camera. The aerial video taken during flight is transmitted to the GCS where the image processing is carried out in order to offer important features to the user.

B. Ground control station

Monitoring the quadrotor during flight represents a key point in the development of this work. The GCS serves as the graphical user interface since it allows the manipulation of several flight parameters (See Fig. 3). The GCS software is primarily responsible for monitoring and sending data to the helicopter. Due to this fact, a ground station has been designed and implemented in our laboratory. The GCS is for managing flight plans and tasks, manually controlling the helicopter and displaying the instrumentation (physical parameters) of the helicopter. The graphical user interface of the GCS for PC is shown in Fig. 3, it has been carried out using the programming development environment LabVIEW. The PC ground station receives the telemetry string from the air vehicle containing GPS location, altitude, and attitude data through a radio modem. In addition, the GCS has a user friendly interface for setting up a flight path mission.

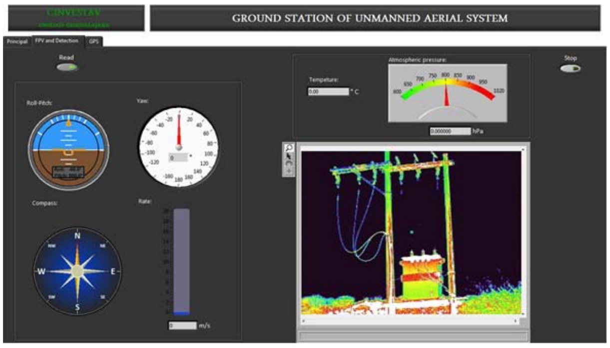


Fig. 3. Ground control station for PC.

III. DESCRIPTION OF THE VISION SYSTEM

The vision system is composed by a TIR camera and a color camera. The video transmitter sends the images to the GCS. This scheme is shown in Fig. 4.

The vision algorithm, which is implemented in the GCS, processes these images in order to perform the qualitative inspection of the joints in the power lines. The qualitative inspection is related to the relative temperature of the joints of the power line. The increase of the electrical resistivity at the joints of the power lines is directly proportional to the temperature at the joint. Therefore, detecting a difference of temperature at the three joints of the power line is enough for the qualitative fault diagnosis [18]. In order to compare the temperature in the joints, these must be spatially located in the images. This is done in two steps, first the background of the thermal image is removed, and then the joints of the power lines are located in the foreground. After that, the temperature comparison is performed, if the temperature is the same in the three joints then there is no fault. But, if there is one different temperature, a fault is detected. The vision algorithm for qualitative inspection is depicted in Fig. 5.

On the other hand, the quantitative inspection could determine the exact temperature of the joint if a fault is detected from the qualitative inspection. However, further development and sensor fusion are still carrying on in our lab to fulfill the requirements for quantitative inspection since a climatological station. The reflected temperature is directly retrieved from the TIR camera but the environment variables like the wind speed, temperature, among others have to be considered in order to estimate the real temperature in the joints of the power line.

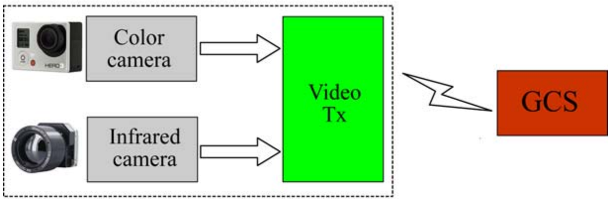


Fig. 4. Vision System Scheme.

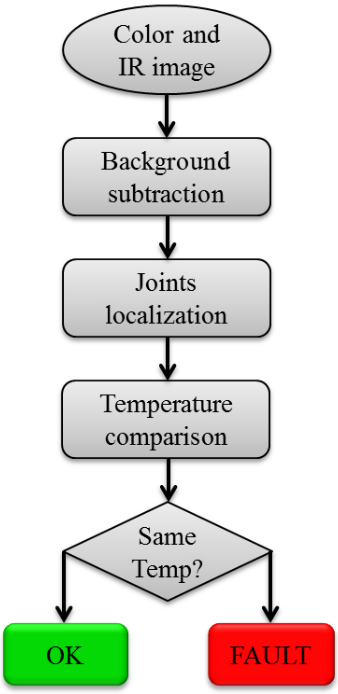


Fig. 5. Vision algorithm for qualitative inspection.

A. Background Subtraction

Due to the nearness of the UAS from the electric tower, the joints of the power lines belong to the foreground of the IR image. Therefore, the first step in the vision algorithm is to discard the background from the image. This is done by means of a stereo calibration of the stereoscopic system (TIR camera + color camera). The calibration process used here is based on the OpenCV libraries [19]. This permits to retrieve 3D information from the environment, so the background (which is geometrically far from the UAS) can be discarded. Fig. 6 shows the original images (color and IR) and the resulting foreground image.

B. Joints Localization

Once the background is removed from the image, we must to locate the joints of the power lines. Due to the electric nature of the system, the joints of the power line exhibit the highest temperature of the tower. Then, locating hot spots in the images is equivalent to locate the joints of the power lines. Let $\Phi(x,y)$ be the foreground of the IR image, the maximum and minimum temperatures from the foreground are obtained as

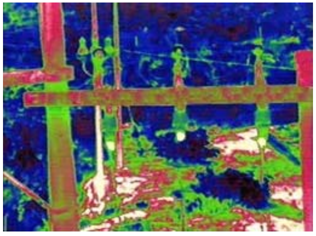
$$T_{max} = \max_{(x,y)\in\Gamma} \Phi(x,y) \quad (2)$$

$$T_{min} = \min_{(x,y)\in\Gamma} \Phi(x,y) \quad (3)$$

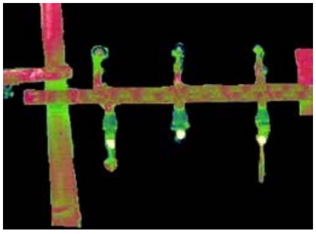
with $\Gamma = \{(a,b) \in a \times b \mid 0 \le a < w, 0 \le b < h\}$ where w and h are the width and height of the image in pixels, respectively. Then we can obtain an initial image of the hot spots as

$$\Psi_0(x,y) = \begin{cases} 1, & \text{if } \Phi(x,y) \ge \hat{T}_t \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

(a) Original color image



(b) Original IR image



(c) IR image without the background

Fig. 6. Background subtraction from the IR image.

where $\hat{T}_t$ is the threshold value for each frame obtained by the Otsu method [20]. After that, the initial hot spots are grown by recursive dilations defined by

$$\Psi_k(x,y) = (\Psi_{k-1}(x,y) \otimes Z) \cap C(x,y) \quad (5)$$

where Z is a neighborhood mask of 8×8, and $C(x,y)$ is a constraint image defined as

$$C(x,y) = \begin{cases} 1, & \text{if } \Psi_{k-1}(x,y) > T_{max} - 0.5(T_{max} - T_{min}) \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

The dilation operation is recursively implemented until we reach a stable image when $\tilde{\Psi}(x,y) = \Psi_k(x,y) = \Psi_{k-1}(x,y)$. Each connected region in $\tilde{\Psi}(x,y)$ represents a hot spot. Finally, the mean of the temperatures in each hot spot is obtained for comparison. The final step of the vision algorithm is the result of the qualitative inspection. If the temperatures obtained from the joints (retrieved from the hot spots in the previous step) are the same, then there is no fault. If there is a difference, then there is a potential fault and the power tower must be investigated. An example of the hot spot obtained from the TIR image is depicted in Fig. 7.

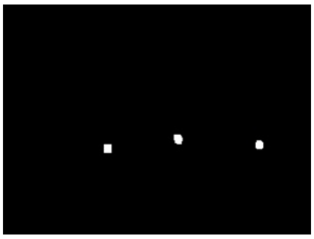


Fig. 7. Hot spots found by the vision algorithm.

IV. CONCLUSION

Performing the inspection of power line corridors using an UAS based on the quadrotor helicopter has several obvious advantages: more efficient, lower cost and safer. In this paper, we present an aerial robotic system for power line inspection implemented from scratch, including the flight control system, the payload required for achieving the inspection task and the GCS. The flight control system and the payload are on-board of the UAV. The payload for inspection system makes use of a color camera and a TIR camera to inspect the devices and components in power line corridors. The TIR camera can take thermal images, which can help us find out the devices and components which are over temperature. This qualitative inspection is enough to determine some common faults.

The research presented here is a good start point for applying UAS in the power industry. Moreover, UAS may also serve to this industry in logistics engineering and construction design. The presented aerial robotic system can be extended or adapted for a more advanced task, such as quantitative infrared inspection of power lines.

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