Road pavement inspection with UAVs beyond visual line of sight in long-range operations

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Abstract. This article describes the aerial platform developed in the framework of a research project for the improvement and optimization of road maintenance operations. The aerial platform performs road pavement quality inspection in long-range drone flight scenarios. A customized multi-purpose drone adapted to the payloads used, a high-resolution camera to obtain the digital model of the road with photo-grammetry and small, lightweight cameras to Detect And Avoid (DAA) possible threats in the environment while flying in Beyond Visual Line Of Sight (BVLOS) operations have been developed. For photogrammetry, a Sony full-frame camera con-trolled (triggering and metadata management) with a Raspberry Pi is used. DAA processing is carried out onboard on an Nvidia Jetson Orin NX, using Artificial Intelligence (AI) and transmitting real-time video to the Ground Control Station (GCS).

Keywords: UAV, Inspection and Maintenance, Photogrammetry, BVLOS

1 Custom aerial platform development

During the requirements analysis phase of the project, the conditions for the final demonstration of the entire system were defined. Among the most important requirements was the fact that at least 2 Km of road had to be surveyed. This requirement impacts directly on the selection of the aerial platform. Different commercial platforms were analyzed, but several devices had to be mounted, and in some cases the autonomy was not sufficient or in other it was not possible to modify the original layout to fit all the devices.
At this point it was decided to develop a custom aerial platform using the previous knowledge and skills acquired in previous R&D (Research and Development) projects such as Piloting or Aerial Core. Taking advantage of the fact that it is a new development and taking into account that the same platform could be used for other sectors with minor modifications (construction, mining, topography, ...) a design with high flight autonomy and load capacity has been developed. Fig. 1 shows a first design phase of the aerial platform with the photogrammetry payload attached. In this preliminary design, the processing unit, cabling, power electronics and all necessary accessories were laid out.

The final platform specifications are shown in Table 1.

(a) C750 sketch (b) C750 preliminary 3D design (c) C750

Fig. 1. Design development of the C750

Table 1. C750 specifications

Main Engine	T-Motor MN605-KV170
Main rotor propeller	T-Motor 22x6.6 Prop
Speed control of the main motor	(ESC) ALPHA 60A 12S
Motor battery	Tattu Plus 1.0 22000mAh 22.2V 25C 6S1P LiPo
External pilot situation	TBS Tracer 2.4 GHz R/C System - Mission Planner
Autopilot	Cube Orange + Ardupilot
Datalink	Ubiquiti R5AC-Lite
MTOW	25 Kg
OEW	15 Kg
Upper limit Payload weight	10 Kg
Autonomy OEW	25 minutes
Autonomy MTOW	15 minutes
Range	3.5 Km
Ceiling	1524 m
Maximum speed	18 m/s

2 Digital model for quality inspection

From a maintenance operations management point of view, it is crucial to identify the most damaged areas in order to prioritise work orders there.
The proposed system allows the inspection of large areas of pavement without the need to have employees physically inspecting the road, reducing the risk to employees and shortening the time taken to obtain results.
The digital model of the pavement and vertical elements surrounding the road, such as traffic signs or information panels, is obtained by applying photogrammetric techniques. Aerial photogrammetry is used to create two dimensional (2D) or three dimensional (3D) models from aerial photographs, usually it requires photographs of two or more angles of the same area in order to map the image, and it may or may not involve computer software.
The basic principle behind all photogrammetric measurements is the geometrical-mathematical reconstruction of the paths of rays from the object to the sensor at the moment of exposure. The most fundamental element therefore is the knowledge of the geometric characteristics of a single photograph [1].

Similar to the images we perceive with our eyes, a photograph is the result of a central projection, also known as single point perspective. The distances of the central point of convergence (the optical centre of the camera lens, or the exposure station) to the sensor on one side and the object on the other side determine the most basic property of an image, namely its scale.
Fig. 2 shows the triangles established by a ground distance D, and the flying height above ground H_g on the terrain side and by the corresponding photo distance d and the focal length f on the camera side are geometrically similar for any given D and d: the scale S or $1/s$ of the photograph is the same at any point. The relationship between the different distances is described in Equation 1.

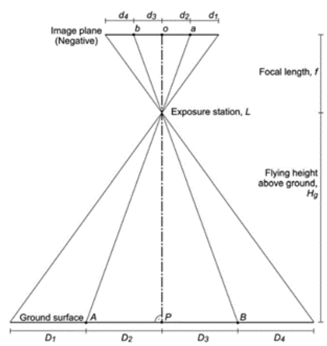

Fig. 2. Vertical photograph take over completely flat terrain [1]

$$S = 1/s = f/H_g = d/D \tag{1}$$

This simplified model becomes more complex when the terrain is not completely flat or the photographs are oblique to the terrain but the basic idea is the same. The geometrical principles and equations mentioned above are sufficient for simple measurements. However, for the precise calculation of the 3D coordinates, it is necessary to mathematically reconstruct the ray paths both inside and outside the camera with high precision. The parameters needed to describe the geometry of the optical paths are given by the inner and outer orientations of the camera.
The inner orientation of an aerial camera comprises the focal length (measured at infinity), the parameters of the radial distortion of the lens and the position of the so-called principal point in the image coordinate system [1][2]. The external orientation includes the X, Y, Z position of the camera in the ground coordinate system and the three rotations of the camera ω, ϕ, κ relative to this system. The elements of exterior orientation can be determined theoretically with modern high-tech GPS/INSS system simultaneous to image acquisition.
Using differential rectification and orthorecfication procedures it is possible to

obtain the correct place for each pixel in its planimetric position [3]. In this manner, the digital model obtained in a laboratory testing is showed in Fig. 3.

Fig. 3. Digital model generation process, the blue rectangles represent each acquired image

3 Detection and avoidance system

In order to inspect long distances (about 2 Km) as proposed in the project, it is necessary to have a system that monitors the environment and is able to send alerts to the pilot in case it detects any kind of threat, as these operations are Beyond Visual Line Of Sight (BVLOS).
BVLOS operations usually require the presence of external observers to communicate any incidents to the UAV pilot, but in sometimes the external observer's point of view is not reliable (Fig. 4).

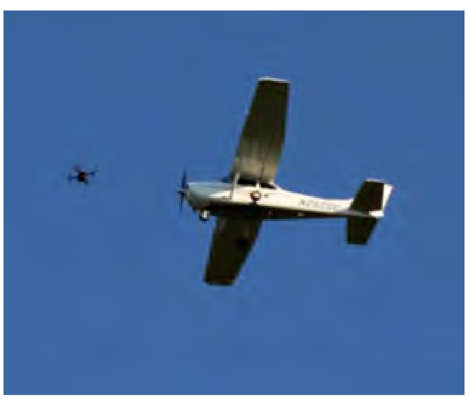

Fig. 4. External observer point of view. UAV (400 feet) and aircraft (600 feet) [4]

Fig. 5. Detail of the detection and avoidance system cameras

There are detection and avoidance systems based on different technologies, such as RADAR, acoustic and optical. In this case, optical systems seem to be

the most appropriate. A camera array can be mounted on top of the UAV, which would not add excessive weight, and image processing can be done on board.
The selected cameras are industrial devices with gigabit Ethernet connections, although USB cameras with the same form factor exist, they have been rejected due to the insufficient number of USB ports on the processing device and the known electromagnetic interference on USB cables when running UAV motors (Fig. 5).
The system developed, besides to obtaining the images from the cameras and processing them with the trained Artificial Intelligence (AI) model, it has the capability to send the image streams in real time to the Ground Control Station (GCS).
On the one hand there is th acquisition of the camera images, where raw frames are modified as needed (rotation, resize, reencoding, . . .) and sent as h264 video streams to the MediaMTX RTSP (Real Time Streaming Protocol) server via GStreamer (open-source multimedia framework) pipelines. From there, these streams serve as input to the threat detection module, as well as to GCS visualization tools without requiring additional processing.
The threat detection module receives and decodes the incoming h264 streams into raw frames and performs object detection on them. These outputs are advertised via ROS (Robot Operating System) communications. A threat status integer indicator is published via a ROS topic, and so are ROI (region of interest) crops of the detected items when a threat is found. After inference, ROI information is painted on the images, which are reencoded into h264 and sent back to the RTSP server, advertised in a different URI (uniform resource identifier).
In the GCS, the pilot can easily identify the threat (Fig. 6), estimate the actual risk and validate or ignore the alert. If the alert is ignored, the exploration mission is continued and if accepted, the autonomous flight mission is modified to avoid the threat and will be resumed when conditions permit.

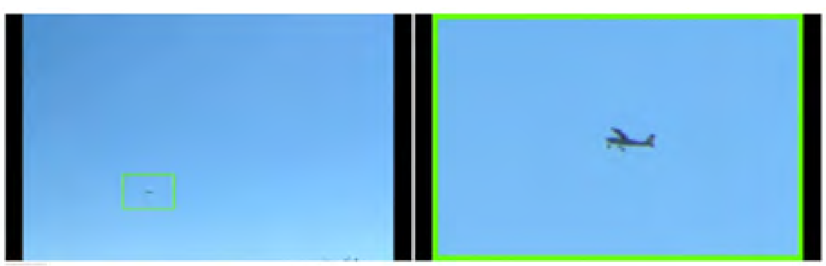

Fig. 6. Threat representation in GCS

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