# Project "ELEVAR" – Study of Vertical Structures with Robotized Aircrafts

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## SUMMARY

The “Project ELEVAR– Study of Vertical Structures with Robotized Aircrafts”, has as its main objective the development of an aircraft for the autonomous photogrammetric surveys of vertical surfaces, namely of dam walls, bridge, pillars, and facades of buildings and monuments. The photographs obtained will support the visual inspections carried out in the scope of monitoring and safety control of civil engineering works. The aircraft will navigate through stereoscopic cameras, sensors and dedicated algorithms that allow the autonomous positioning and three-dimensional reconstruction of the structures without the aid of GNSS systems in areas of poor signal coverage or where high precision is required. The photographic surveys will be carried out with a distinct, high-definition camera, aided by a system that allows to acquire images at the desired moment. The system is being developed by a consortium of three entities the company TEKEVER ASDS (leader), integrating the Institute of Systems and Robotics of Instituto Superior Técnico and the National Laboratory for Civil Engineering. This paper presents the project and the results achieved.

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## 1. INTRODUCTION

The safety control of civil engineering works is supported by a set of monitoring activities that include the analysis of the records of visual inspections and of data measured by instruments and tests. Due to the large size of civil engineering structures, direct visual inspections (where the specialist stands by the structure without the need for ancillary means) are limited to small areas. Scaffolding, suspended platform and digital cameras with zoom are some of the auxiliary means that can be used to obtain information of the areas normally inaccessible. Remotely controlled unmanned aerial vehicles (UAV), and more specifically multicopters carrying digital cameras, allow very short-range photographs at a relatively low cost, and, for this reason, is an equipment that should be considered by the experts in visual inspection.

When the photographic survey is carried out observing rules of Photogrammetry, the processing of photographs by suitable software allows the generation of clouds of points and orthomosaics (orthos), two supports that allow the measurement of lengths, areas or volumes and, in the case of the orthos, it enables the use of digital image processing techniques to enhance surface characteristics. A good photographic coverage demands several requirements - including high overlap of photographs and distances to the photographed surface with short variations - which are easily reached when the flight is autonomous. To achieve this in-flight autonomy, aircrafts use signals from GNSS satellites to determine their position. When there are obstructions to the reception of these signals the only option is to carry out flights in manual mode, totally controlled by the operator, a situation that should be avoided.

In order to overcome the limitations of the current aircrafts, namely to be able to perform autonomous flights in places where there are partial obstructions to the reception of GNSS signals, three entities - TEKEVER ASDS (leader), the Institute of Systems and Robotics of Instituto Superior Técnico and the National Laboratory of Civil Engineering - formed a consortium to develop a multicopter for the autonomously perform photo surveys of vertical surfaces, namely facades of dams, buildings and monuments, or pillars of bridges. The navigation will be performed with the aid of cameras, sensors and dedicated algorithms when the positioning by GNSS does not have the necessary integrity. The project, named "ELEVAR - Study of Vertical Structures with Robotized Aircraft", that had a financial support of the program COMPETE, also proposes the creation of a service that involves not only the use of the aircraft and also the generation of photogrammetric products, to be used by those who are responsible by the safety of civil engineering structures. This paper is intended to present the developments achieved by the consortium.

## 2. THE CONSORTIUM OF THE ELEVAR

The project ELEVAR (Henriques et al., 2018 and 2019) is being developed by three entities: TEKEVER ASDS (project leader), Institute of Systems and Robotics of Instituto Superior Técnico (IST / ISR) and National Engineering Laboratory Civil (LNEC). Given its relevance, this section presents the involvement of the three members of the consortium.

The company TEKEVER ASDS, of the TEKEVER group, develops technologies and new products for aerospace, defense and security, until these reach a level of maturity that justifies a marketing strategy. To this end, TEKEVER ASDS has focused on research activities that accelerate the development of technologies such as space communications systems and unmanned aerial platforms.

As the lead entity of the project, TEKEVER ASDS was responsible for the management and coordination of tasks, in order to ensure a coherent development among them within the expected time, being also responsible for the activities of communication and dissemination of results of the project. In a more technical perspective, TEKEVER ASDS was responsible for developing the operating concept of the ELEVAR platform and the aircraft to be used. In addition, the company was also responsible for testing, integrating and verifying the systems and conducting test flights that will culminate in a real-world demonstration for interested and relevant entities in the area whose problem is addressed by ELEVAR.

The ISR is an IST research unit where advanced multidisciplinary research activities are developed in the areas of Robotics and Information Processing, including Systems and Control Theory, Signal Processing, Computer Vision, Optimization, Artificial Intelligence and Intelligent Systems as well such as Biomedical Engineering. In this project, a team from ISR's Computer Vision laboratory focused on the research and development of systems and algorithms for navigation through visual and inertial odometry. At the same time, it has developed tools for 3D reconstruction of structures, for the navigation of nearby vehicles avoiding collisions and for the creation of photogrammetric products for the detection of anomalies. It has also contributed to the specification and definition of image acquisition, processing and control systems used in the project.

The mission of LNEC is to undertake, coordinate and promote scientific research and technological development, with a view to the continuous improvement and good practice of civil engineering. It has as its priorities the creation, development and dissemination of research in fields related to civil engineering. The LNEC intervention in project ELEVAR has focused predominantly on the initial and final phases of the project. In the initial phase of the project, it has supported the definition of the requirements to be met by the aircraft and, in the final phase, it is performing the tests need to check the quality of flights and products generated.

## 3. NEED FOR AN AIRCRAFT TO AUTOMATICALLY CARRY OUT PHOTO SURVEYS VERTICAL SURFACES

When there are obstructions - partial or total - to the propagation of the GNSS signals it is not possible to perform an autonomous flight in safety, so the aircraft must be operated manually. In this type of flight, it is more difficult to comply with the flight plan, and the solution is to perform the flights at slow speed, which decreases the area lifted per flight because the duration of the flight is limited by the battery charge. At the same time is usual to take a very high number of photographs, much more than needed, often excessive.

Another drawback of manually operated flights is the unforeseen alteration of the trajectory due to the influence of the wind, being the bursts the atmospheric element that most interferes with the flight. Another element that makes flying near surfaces especially dangerous is the changes in the direction of wind propagation by the obstacles it encounters.

Finally, an element important that makes flights near structures very risky is the time of reaction of the person that operates of the aircraft, usually too long when compared with automatic systems. During pre-programmed flights when the system detects that an unexpected change of position or of attitude have occurred, the software that automatically controls the aircraft corrects instantaneously the flight direction, speed and/or attitude.

## 4. CHARACTERISTICS OF THE AIRCRAFT

### 4.2 - Physical characteristics

The aircraft is being developed by TEKEVER ASDS, the project leader. It consists of a quadrirotor 86 cm in diameter (between rotors) and 46 cm in height, which can reach an autonomy of 18 minutes for a payload of 1 kg using a battery of 20000 mAh. This aircraft has been subjected to several internal tests during its development period until it is ensured that the system is navigating and behaves under the desired conditions. After completion of the internal tests, the aircraft was tested in an operational environment near a concrete dam in June 2018. In Figure 1 it is possible to observe the aircraft in the moments preceding one of the tests performed in this dam. These tests were still carried out without the integration of the navigation system by vision. This test allowed to validate the manual navigation of the aircraft next to dams, already having as payload the camera of high resolution necessary for the acquisition of images of high quality.

Figure 1 - ELEVAR platform aircraft in the first work environment test

After the successful tests the next step was to integrate several systems needed to allow autonomous flights without GNSS signals.

This aircraft responds to the concept of operation, which consists of an autonomous navigation based on stereoscopic vision using algorithms to assist the navigation of the autopilot when the GNSS signal is weak or cannot provide the required integrity. The concept of operation allowed to define the following features of the platform ELEVAR:

- Path Following - Predefined Coordinate Tracking;
- Geofencing - autonomously maintain the aircraft within pre-established geographic boundaries;
- Return to Home - Autonomous and safe aircraft guidance for a predefined landing coordinate;
- Obstacle Avoidance - maintain a safe distance between the aircraft and the structure;
- Detection of system anomalies - continuous monitoring of aircraft status and signalling on alert.

### 4.2 - Image acquisition system for navigation

In order to perform visual-inertial navigation, a sensor setup of this type was developed. The initial prototype, shown in Figure 2, included two global shutter monochromatic cameras (Point Grey BlackFly) and an inertial measurement unit (XSens MTi), which contains 3D accelerometers, gyroscopes and magnetometers. These sensors were hardware-synchronized by a trigger signal generated by a microcontroller (Arduino Nano), also used for the user interface composed by the switches and LEDs on the outside of the enclosure. The system also contains a single-board computer (Nvidia Jetson TX2), responsible for onboard processing, and a 3S LiPo battery to power to the setup.

Figure 2 - Prototype of the sensor system

In the June 2018 Fagilde dam test, this system was used to record a dataset which was used as a proof of the applicability of a platform of this type for vision-based navigation. Seen as this was prior to the integration with the UAV, these trajectories were recorded by transporting the platform by hand. Afterwards, some more exhaustive testing was performed under a controlled laboratory setting, as show in Figure 3. The environment was treated so as to control the overall illumination and texture, by placing objects all through the testing zone. This indoors dataset, recorded in the ISR offices, also included measurements from a motion capture system, which was used as ground truth for the quantitative assessment of the precision of the estimated trajectories. The results of the testing process are described in the following section.

Figure 3 – Indoors testing environment

Later this system was adapted (reduction of weight and electrical integration with the aircraft) to be incorporated into the UAV platform. In Figure 4 is presented a photo of the aircraft. On the top a GNSS receiver, under a LiDAR sensor for obstacles avoidance (to keep the aircraft at a security distance from the wall), as well the single-board computer. On the front is the visual-inertial sensor setup, including the IMU (orange box) and the stereo camera pair. Under the carbon-fibre fixation bar are a high-resolution commercial photo camera and a low-latency video camera (for real-time video transmission).

Figure 4 – Aircraft developed under the project Elevar

### 4.3 - Navigation Algorithm

Real-time visual-inertial navigation is typically performed in an incremental fashion, by calculating the transformation between consecutive capture instants. In sparse, feature-based algorithms, this starts with the detection of salient points in an isochronous image pair. These are then subsequently associated which, together with the precise information about the geometric transformation between cameras (i.e., extrinsic parameters), ideally allow for the triangulation of observation pairs, resulting in a 3D point position. This generates a point-cloud whose tracking through redetection in consecutive frames allows for the estimation of the rotation and the translation that the set of cameras endured between the two frames, under a static environment assumption. The concatenation of these transformations yields the sensor trajectory from the start-up point, while the 3D point cloud corresponds to a sparse map of the observed environment.

However, there are some limitations inherent to stereoscopic vision systems. Should the distance between cameras be significantly smaller than the distance to the observed environment, the images captured by the stereo pair would be practically the same, there being no disparity between them. In this situation, the points detected are effectively not triangulable since the optical rays would be approximately parallel. In this case, the scale (or depth) of the environment (and therefore of the trajectory) would be rendered unobservable - the stereo system is said to degenerate to the monocular case. The parallel use of inertial sensors not only solves this limitation but also contributes to an overall increase in the accuracy of the estimated trajectory.

As part of the proof of concept, the open-source algorithm code proposed by Mur-Artal and Tardós (2017) was applied to part of one of the trajectories recorded in the Fagilde dam test, corresponding to climbing of a set of stairs. The result is obtained in two views in Figure 5, where the sparse mapping is represented in black and the estimated trajectory in blue.

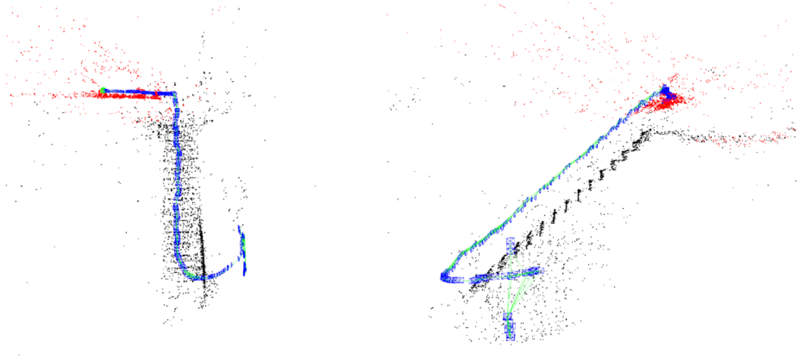

Figure 5 - Estimated trajectory and mapped region (two views - frontal and lateral) in the test carried out in the Fagilde dam

This evaluation, although apparently positive, is only qualitative because in the test carried out at the dam it was impracticable to obtain direct measurements of position to compare with the obtained results (ground truth). This motivated the following tests performed in the ISR laboratory, where a motion capture system was used for this end.

For these tests, a series of trajectories based on a 2x2m square were recorded. This dataset included several variants of the same trajectories, both with and without rotation, as well as facing different directions. As an illustrative example, the results for the forward-facing case are shown in Figure 6, with the computed trajectory in yellow and the mapped points in grey. For these tests, as well as the successive integration, the algorithm proposed by Leutenegger et al (2015) was used.

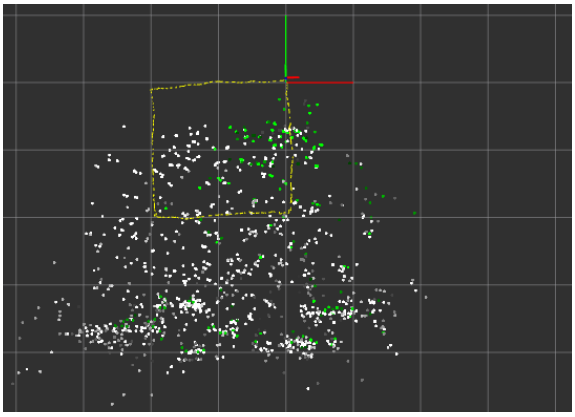

Figure 6 – Test trajectory results in the indoors ISR dataset

With the system performance completely validated, the integration of the visual-inertial payload with the onboard autopilot was pursued. In order for its internal estimator to use this information, the VIO output was transformed to WSG-84-based NED coordinates. Since visual-inertial algorithms are typically local, and thus not globally georeferenced, this step required the initialization of both the setup position and attitude. For this end, information from the onboard GPS receiver and the IMU internal attitude estimator was used.

After completing the integration, the system was tested further in outdoors conditions. As such, Figure 7 shows the results of one of these tests, where the georeferenced visual-inertial estimates are in green, the GPS estimates in blue, and the overall autopilot estimator results in red.

Figure 7 – Outdoors testing results

Further outdoors tests in a more realistic scenario nearby a motorway bridge were performed and some of the results are shown in Figure 8 for two linear trajectories.

a) b)

Figure 8 - Flight test trajectories nearby a bridge. a) N/S b) E/W

The VIO algorithm could successfully reconstruct the UAV trajectories although with some imperfections that were apparently mitigated by the integration with the GPS data at the autopilot. However, due to technical limitations, current tests cannot fully assess the trajectory estimation precision and further tests need to be done in that regard.

## 5 – Production of Orthomosaics

As mentioned in the introduction, the ELEVAR project also includes the creation of a service designed to generate orthomosaics, which are products of interest to technicians who assess the state and safety of civil engineering structures.

Orthomosaics result from the joining together of several orthorectified images of the same object. For this, the feature-based alignment algorithm (Brown and Lowe, 2007) is used, which consists of the detection of features in each image and the matching of the features in order to obtain information about common points where the images overlap. Obtaining these matches, it is possible to calculate the geometric model that defines the transformation not only of the points of an image for the other but also of all the images for a common reference (the reference of the final mosaic). To improve model estimation, a rather robust optimization method called Bundle Adjustment (Triggs et al., 1999) is still applied. Once optimized, this relative geometric information can be used to transform the coordinates of each image into final mosaic coordinates, thus obtaining a single image with information for all individual photographs.

Figure 9 presents an orthomosaic obtained with photos captured by the aircraft in an operational environment in the dam. As can be seen, the results obtained are quite satisfactory. However, there are still things to improve. It is possible to check small imperfections in the figure such as discontinuities in straight lines, imperfections at the edges of each image, commonly known as seams, and imperfections due to differences in illumination between images that make the final mosaic visually imperfect. To address these problems, algorithms designed to harmonize these links and correct imperfections will be used so that the final image is more visually appealing and closer to reality.

Figure 9 - Orthomosaic obtained with images captured by the aircraft in an operational environment in the dam

Further tests with different datasets are also being performed in order to improve the method presented and, consequently, the result obtained. Among these, another test was performed with a dataset, provided by LNEC that depicts a facade from the back of one of its buildings. Figure 10 represents the result obtained by the algorithm in this scenario. In the first analysis, it can be said that the image presents many errors or imperfections, however, the focus of the algorithm are planar or quasi-planar structures (as in the case of the dam). If the planar section of the image corresponding to the wall of the represented building is evaluated, the algorithm shows no relevant defects and it is possible to make a structural evaluation of the wall. The imperfections, especially in the lower part of the image, are due to the presence of differences in depth creating non-planar surfaces, which are not predicted by the implemented model.

Figure 10 - Orthomosaic obtained using the dataset of LNEC's building facade

Another relevant study carried out with the aid of this dataset was the comparison with the tool previously used by LNEC for the creation of orthomosaics, the MICMAC (Multi Image Correspondances for Methodes Automatiques de Correlation) (see reference MICMAC website). In Figure 11, it is possible to observe the result obtained by this tool for the same dataset, with the final image already cut so that only the relevant region is shown.
It is possible to verify that the result obtained with our algorithm is much more satisfactory than the result obtained with MICMAC. The wave effect in the MICMAC image, especially in the window region, is not present using the proposed method. In addition, the black spot that is visible in the MICMAC result does not exist in our result. This defect is particularly relevant because any imperfection in the region of the structure can be mistaken for a defect, which introduces unnecessary errors in the study of the surface.
This test proves that our approach is a significant improvement over the tool previously used by the LNEC for the creation of orthomosaics. It is also worth noting that the algorithm developed is much easier to use than MICMAC which, perhaps because it is a tool with more functionalities, becomes difficult to use with the need to perform several operations on the dataset to obtain the final result. In addition, this test also demonstrates the robustness of the algorithm for the analysis of several types of structures, showing that it can be very useful for future studies of civil engineering structures.

Figure 11 - Orthomosaic obtained with MICMAC using the dataset of LNEC's building facade

## 6 - CONCLUSIONS

In this work the "ELEVAR" project was presented: it was described the aircraft developed in the scope of the project, as well as the system of sensors for visual navigation as well as the navigation algorithms and of the creation of orthomosaic. The aircraft's capabilities were tested in test flights, some of them in a work environment. With these data the qualitative effectiveness of the algorithms of vision navigation was demonstrated.
The demonstration tests, made to several entities, owners of civil engineering structures, in works with diversified characteristics, are being prepared

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