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AN APPLICATION OF DIGITAL IMAGE PROCESSING FOR UAV'S AUTOMATIC LANDING SYSTEM AID

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Abstract

This work proposes a cheap and lightweight system based on lasers pointers and digital image processing to estimate height and attitude relative to the ground. The main expected application of the module is small Unmanned Aerial Vehicles (UAVs), where simple and small attitude estimation systems are required by the characteristics of this kind of aircraft. The module shall be capable of providing data with sufficient precision so that an automatic landing system implementation is possible.

1 General Introduction

The recent growth of interest in Unmanned Aerial Vehicles (UAV's) increased at the same time of the development of microelectronics and digital technologies. However, the mission of successfully landing an aircraft without the aid of a pilot is still a challenge. Many civil and military UAV's still use remote piloted strategies for landing procedures. The difficulties behind the landing automation are diverse, and one of these is the lack of a sufficiently good method to estimate the airplane's position and attitude relative to the runway using a cheap and light solution.

The satellite based positioning systems available on the market nowadays for civilian use are known to have a considerable error on the height estimation, what makes this device inappropriate for this use. Other solutions are available but are expensive or overly heavy to embed on small UAV's.

The purposed system consists on a camera and four lasers mounted on a platform. The platform containing the system is to be fixed in the aircraft, pointing downwards as shown in Fig.1.

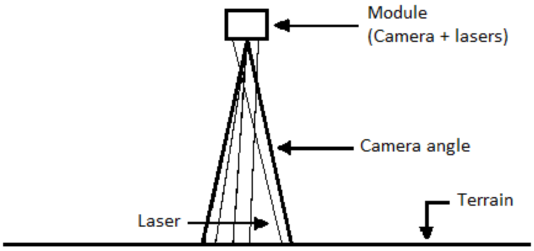

Fig. 1 – Proposed system pointing downwards

Since the four lasers are pointed downwards, the camera capture an image containing the four spots, as can be seen in Fig. 2.

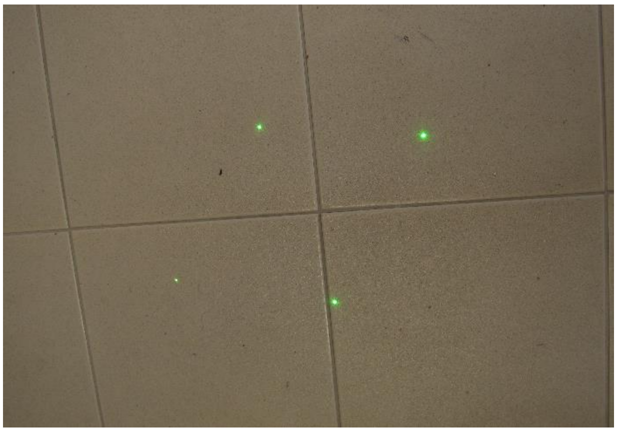

Fig. 2 - Image captured by the camera containing the spots

From digital image processing, the position of the center points of the laser spots can be determined in the image's bitmap, resulting in four pairs of Cartesian coordinates.

By geometry calculations, it is possible to determine the height and attitude of the system using as input the four points on the image.

In order to determine the system outputs, height and attitude angles, several geometrical parameters must be determined with precision. In addition, it is necessary to treat the image applying a camera calibration procedure. In order to accomplish it, camera calibration was adopted and a process of indirect measurement of the geometrical parameters was applied.

Once the lasers and camera's geometrical and optical characteristics are attained with the required precision, the height and the attitude of the aircraft can be determined using the geometrical model.

2 Objectives

The main goal of this work is to propose an effective alternative method to estimate attitude of an aircraft for landing procedures.

In addition, this work aims the description of the setup of the prototype system, the methods used to achieve precision in measurements, the geometrical calculations used to determine the output parameters as well as show results of a test-case.

3 Module

3.1 Overview

The module is the platform that attaches the four lasers and the camera. This way the module provides the necessary geometrical assembly and parameters of lasers and camera. It was built a prototype module in order to develop measurements and tests. This module was constructed aiming accommodating the camera and the lasers and to be fixed in the test platform.

It is necessary to ensure several geometrical characteristics of the module in order to assure the system's capabilities of measuring the attitude height. The angles between the laser and the platform need to assure also that at least three lasers' dots appear in the image for all combinations of height and attitude. This last requirement is justified by the fact that it is necessary at least three dots in the image for the calculation of the values.

In order to accomplish these operational requirements, the camera was fixed in the center of a square plate and the bottoms of the lasers were fixed in the middle of each edge of the plate. The lasers were fixed with an angle of approximately 80 degrees with the respective edges of the plate.

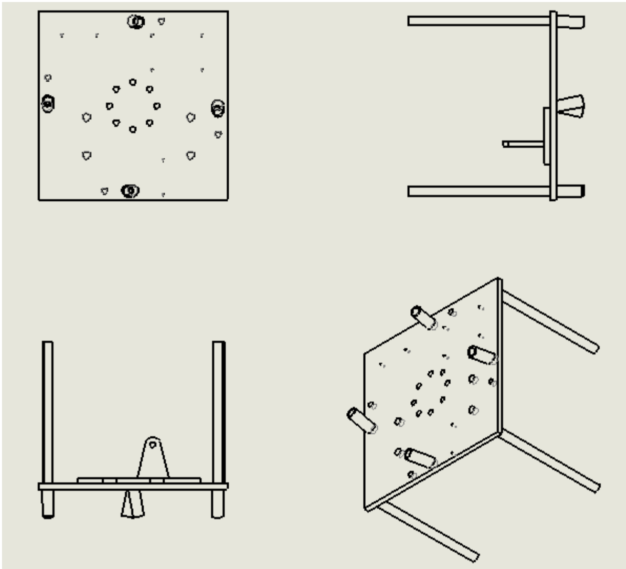

Fig. 3 - Module preliminary design views

3.2 Geometrical parameters definitions

Considering the presented module assembly, it is necessary to define some relevant parameters that are used in the geometrical calculations of the system.

3.2.1 Base

The base is the square plate where the lasers and camera are fixed and the base is supposed to be fixed on the aircraft. As it is the main part of the module, the coordinate system fixed on the base is most important on the system mathematical modeling. The definition of its coordinate frame can be seen at Fig. 4. When any entity is defined using the base coordinate frame, the index *B* is used.

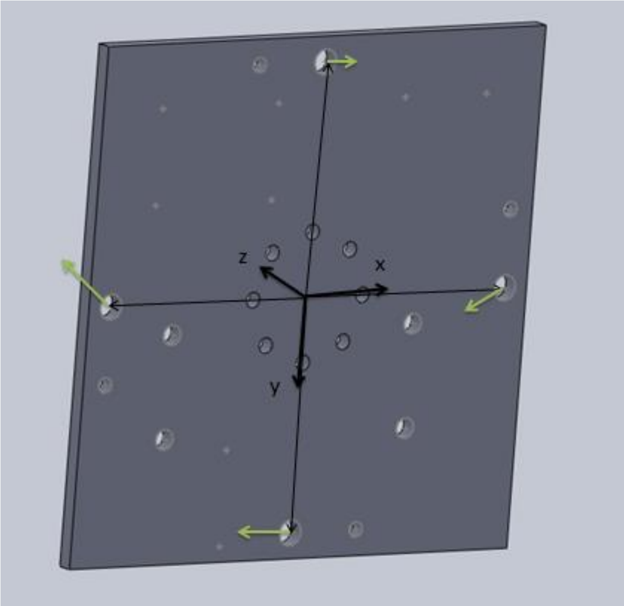

Fig. 4 - Base coordinate system and laser beam vectors

3.2.2 Lasers

The i^{th} laser is defined in the calculation as a unit vector $\hat{l}_i$ and by the point lp_i where the laser beam crosses the base plate. These two entities define the laser beam line.

3.2.3 Camera

As the camera is responsible for the image acquisition, considering the pinhole camera model, all the image calculations are done in the reference system established in the camera center of projection.

The reference system *C* is established in the projection center of the camera initially by a translation from the base frame, this is shown on Fig. 5.

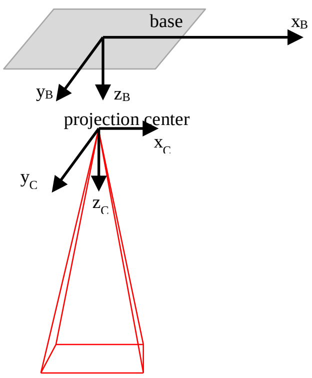

Fig. 5 - Base reference system and camera reference system

It is necessary to consider that the installation of the camera in the base adds errors to the initial position of the *C* reference system. These translation and rotation errors are calculated by the optimization process and used to compensate measurements.

4 Experimental method

In order to test the feasibility and the capabilities of the system, an experiment was set. Four steps composed the experiment and are listed below:

1) Experimental set-up and acquisition of images and its respective attitude values;
2) Image processing in order to determine the positions of the four points and to determine the camera characteristics that needs to be considered in the analysis;
3) Optimization process to have a better estimation of geometrical parameters;
4) Determination of attitude and height using the proposed model combined with previous steps results.

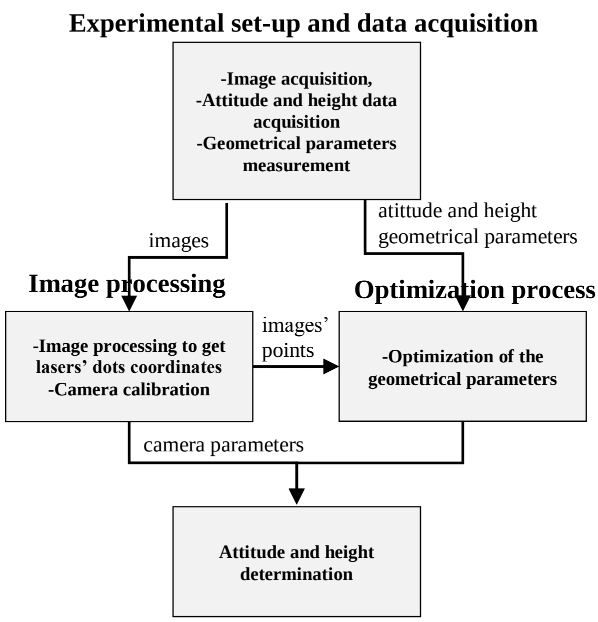

Fig. 6 - Diagram of the methodology used in the experiment

5 Experimental data acquisition

With the purpose of having accurate measurements for comparing the height and attitude obtained with the module estimation and with the actual values it was necessary to acquire experimental data.

The experiment was set fixing the prototype in the mounting flange of a six-axis industrial robot *KUKA KR 16*. Using this configuration, it was possible to precisely position the module and acquire a set of pictures with known attitude and height.

The camera used during the experiments phase was a *CANON PowerShot SX20 IS*. Care was taken when mounting the 16mW laser pointers at the base. Their bases were fixed to the module following the pattern described in section 3. A simple electronic circuit that provided power for the lasers was also installed at the module.

The complete set of the module and robot assemble is shown at Fig. 7.

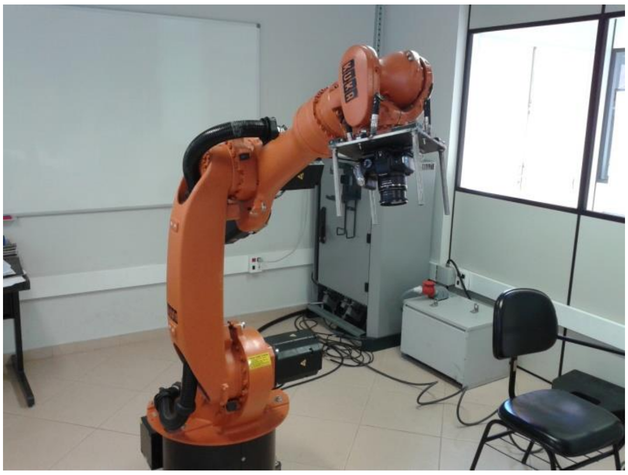

Fig. 7 - Module attached to the robot

Using the robot remote control device for pointing the module downwards a sequence of photos were taken. Image acquisitions were done with three different clarity conditions in the room to validate that the image treatment would not be affect by clarity variations.

6 Images treatment and calibration

6.1 Treatment and points' coordinates acquisition

The position of the four laser dots on the image are the input for the attitude and height estimation model. Therefore, a reliable method to determine these coordinates is necessary. The following image treatment routine was developed to identify the dots' coordinates:

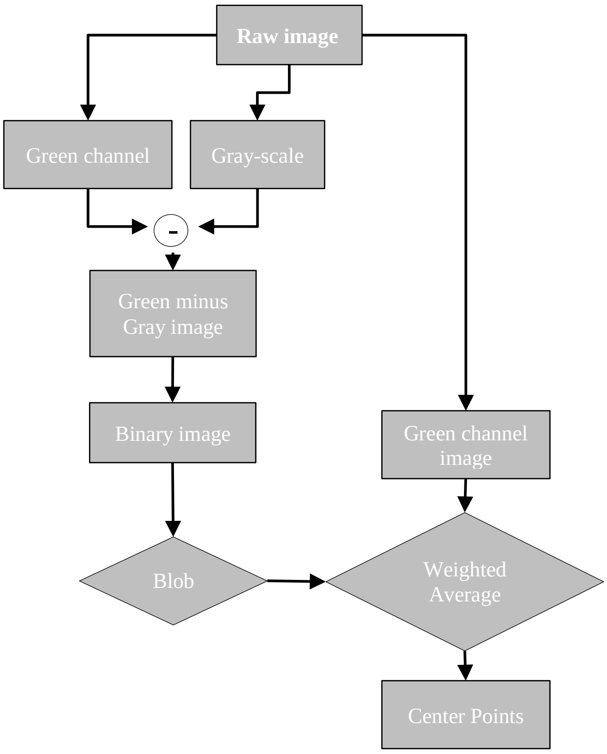

Fig. 8 - Dots' coordinates acquiring method

The calculation of the center point of each dot was made by a weighted average calculation, considering the region of the dot in the green color channel image.

To do so, it was necessary to estimate an initial guess for the dot center and its diameter. These estimations were done using a blob detection algorithm applied to a binary image.

The binary image was obtained by applying a threshold operation for values higher than 90% of the full scale to the image result of the subtraction of the gray scale from the green channel, both extracted from the raw image, as can be seen in Fig. 8.

6.2 Camera calibration

Cameras, as every instrument, have their inherent errors and specifications. Once the performance of the system is dependent on the resulting images, it is necessary to compensate them to extract metric information from 2D images [1]. The process of determination and compensation of errors is known as calibration process.

The final goal of the camera calibration process is to determine a set of camera parameters that can describe the points' transformation from the 2-D camera image to a line in the 3-D space described on the camera frame[2]. Several calibration methods are available on the literature[3][4] but the Caltech Camera Calibration Toolbox for Matlab® developed by Bouguet J. was applied in this work.

Once the process of calibration is done, a direct set of image point place correction is obtained. After this correction is done an inverse mapping is applied at the now corrected pixel position to transform a 2-D image point onto a normalized vector x_n which is a pinhole image projection. In other words, once a point is detected at the image trough the image treatment, it is corrected for lens distortion to another pixel coordinate and afterwards a camera frame based normalized vector pointing from the center of projection of the camera to the real place where the laser is reflected on the ground plane is obtained.

An illustration of vectors along their given names can be seen at Fig. 9.

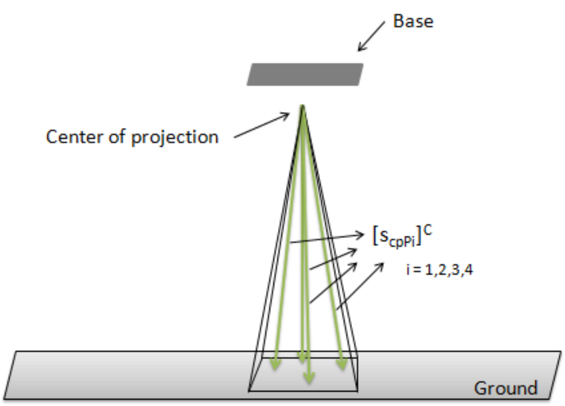

Fig. 9 - Vectors determined from image point by the camera calibration process

7 Geometrical parameters optimization

Every manufacturing process has inherent deviations from the actual designed part and increasing precision makes the production process more expensive and time consuming. Once the final performance of the proposed system is highly dependent on the geometry of the module, it is necessary to determine the final configuration of the assembly with suitable precision.

The optimization process consists of distinct phases.

The first one consists on measuring the final assembly with usual metrology equipment.

The second is a steepest descent method applied to the problem model using as inputs some of the experiment images and their respective height and attitude measured data. The values to be optimized are the position of the lasers' bottoms Lp^B, the lasers' unit vectors Lv^B, the position of the camera projection center Cp^B and the orientation of the camera coordinate system Ca^B, all of them w.r.t B

$$Lp^B = [lp_1^B \quad lp_2^B \quad lp_3^B \quad lp_4^B] \tag{1}$$

$$Lv^B = [\hat{l}_1^B \quad \hat{l}_2^B \quad \hat{l}_3^B \quad \hat{l}_4^B] \tag{2}$$

$$Cp^B = [xp^B \quad yp^B \quad zp^B] \tag{3}$$

$$Ca^B = [\theta a^B \quad \varphi a^B \quad \psi a^B] \tag{4}$$

In order to perform this optimization, it is necessary to establish the function that takes the attitude and height values as inputs and outputs the dots on image coordinates.

The function that simulates this behavior is basically a geometrical problem and is approached using the following algorithm[5]:

1)Using the attitude values provided by the measurement, a rotation matrix from the base to the ground frame is generated

2)Using the estimated values of the camera orientation, a rotation matrix from the base to the camera frame is calculated.

3)Each of the laser position points and laser beam unit vectors on the base frame is transformed to ground coordinates

4)The laser position and unit vector define the line that represent the laser beam, using this, the intersections point of the plane and the lines are calculated on ground coordinates.

5)The intersection points are converted to the base coordinate system. In sequence, they are converted to the camera coordinate system.

6)Using the camera calibration results, determine the dots position on the image.

With this relation established the steepest descent optimization adjusts the geometrical parameters to minimize the distance between the estimated points and the experimental image points.

The optimization was ran using as initial guess the measured values for the lasers position and angles and an estimated value for position and orientation of the camera frame. After 4600 iterations, the optimization reached convergence. The initial values measured and the results of the optimization d for the angles of the lasers with the base are shown in Tab. 1.

Tab. 1 - Measure and optimization values for the lasers' angles

		Lasers			
		1	2	3	4
Measured Values	Azimuth (°)	252.58	7.19	90.68	173.99
	Elevation(°)	80.98	80.56	82.06	79.10
Optimized Values	Azimuth(°)	265.01	5.11	97.92	167.00
	Elevation(°)	82.54	80.57	81.61	80.68

The initial measured and optimized values for the position point of the lasers' bottom in the module are shown on Tab. 2.

Tab. 2 - Measure and optimization values for the lasers' positions

		Lasers			
		1	2	3	4
Measured Values	x(m)	-0.0923	0.0063	0.0927	0.0018
	y(m)	0.0020	-0.1025	0.0037	0.1097
Optimized Values	x(m)	-0.0815	0.0205	0.1146	0.0208
	y(m)	0.0244	-0.0784	0.0205	0.1286

The initial and optimized values for the position and orientation of the camera coordinate system are shown in Tab. 3

Tab. 3 - Measure and optimization values for the camera's center of projection position and orientation

Camera's center of projection					
	Position			Orientation	
	Estimated Values	Optimized Values		Estimated Values	Optimized Values
x(m)	0.0000	0.0220	Θ(°)	180.00	181.675
y(m)	0.0000	0.0220	φ(°)	0.000	0.157
z(m)	0.0600	0.0720	Ψ(°)	0.000	-0.950

Using these calibrated values it is possible to proceed with the geometrical calculation of the final measurements. As these values were optimized using images taken from the final module, a more reliable behavior of the model is expected using them.

8 Estimation model

The estimation of the attitude and height using as input the image points is done by using basic geometrical relations.

The following algorithm is used to estimate the plane position w.r.t. the base frame:

1)Using the assembly optimization results, a rotation matrix from the camera frame to the base coordinate system is calculated

2)Using the dots of the image and the normalization algorithm provided by camera calibration, a unit vector from the projection center pointing to the points on the ground is determined on camera coordinates.

3)The unit vector and the projection center position are transformed to the base frame.

4)Using the lasers origin and the lasers unit vectors from the optimization results, the laser beam lines are determined

5)The lines defined by the laser beams and the camera dots are grouped in pairs

6)The mean points on the line of minimum distance between each pair of lines are calculated (Approximation to line-line intersection)

7)The four mean points are used for a plane fitting using least squares regression, where the distances from the points to the plane are used as reference.

8)The resulting plane is represented in base coordinates, the attitude is calculated using the normal vector components.

9)The height (h) is determined solving the following vector equation, where v_1 and v_2 are a basis of the plane and P_0 is a point on the plane:

$$P_0 + a\,v_1 + b\,v_2 + h\,n = (0,0,0) \qquad (5)$$

9 Results

In order to test the model applicability and precision, it was used a set of seven images captured during the trial phase and its respective values of height and attitude angles.

The set of pictures chosen to test the model is completely different from the images used to optimize the geometrical parameters. The results are summarized on Tab. 4.

Tab. 4 - Results of the method using a set of images as input

Image	Experimental Measurements			Model Estimated Values		
	Θ(°)	φ(°)	Height (m)	Θ(°)	φ(°)	Height (m)
1	0.03	-0.03	1.0929	-0.1464	-2.0676	1.0860
2	0.03	-0.03	0.9929	-0.0530	0.0234	0.9941
3	0.03	-0.03	0.8929	0.1706	2.6660	0.8940
4	0.03	-0.03	0.7929	1.2552	4.5255	0.7951
5	15.01	-0.11	1.4256	13.6420	1.1728	1.4014
6	15.01	-0.11	1.3256	13.1973	1.3128	1.3159
7	15.01	-0.11	0.9280	19.8567	2.6726	0.9150

Analyzing the result it is possible to notice that the errors were significantly high in the estimation of the attitude angles, while the estimation of the height presented satisfactory results. The higher error in the height estimation was found on image 4, with the magnitude of 1.7%.

10 Conclusions

Considering the results provided by the estimation model, it is noticed that the proposed model consists in a good tool to height estimations, achieving high precision on the estimations of this parameter. As the attitude estimation is more sensitive to error in the model, future work will be done in order to improve its determination.

As the tests were held with image samples in order to validate the calculation model, it is necessary to test the capabilities of the algorithm when using instantaneous images. This test will permit the evaluation of the dots recognition method. Considering the importance of determining correctly the position of the center points of the dots, it is important to test the recognition method with several conditions in order to find a more robust and reliable method.

As the determination of the dots' center points position, the determination of the geometry of the module is crucial. On this work, these problem was addressed using an optimization strategy using low precision measurements as initial guess. In order to achieve a more robust model and more accurate results, it is necessary to adopt better construction process and perform high precision measurement on the final module assembly.

Considering all the difficulties involved on the model and the experiment, and the results precision obtained, the system consists in a good and cheap solution to estimate height and attitude using image processing.

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