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CLOUD BASE HEIGHT ESTIMATION USING A LOW-COST DIGITAL CAMERA

Fernando M. Janeiro [1], Frank Wagner [2], Pedro M. Ramos [3] A. M. Silva [2]

[1] Instituto de Telecomunicações, Universidade de Évora, Portugal, fmtj@uevora.pt
[2] Centro de Geofísica de Évora, Universidade de Évora, Portugal, frankwagner@uevora.pt, asilva@uevora.pt
[3] Instituto de Telecomunicações, Instituto Superior Técnico, Lisbon, Portugal, Pedro.Ramos@Lx.it.pt

Abstract − Cloud height, wind speed and direction at cloud height play an important role in air safety. This paper presents a low-cost system based on digital consumer cameras to estimate cloud base height. It is shown that both wind speed and direction at cloud level can also be obtained with this system. The method is based on triangulation and uses image registration to identify common cloud features in photographs taken from different positions. The wind speed and direction is obtained from two time-lapsed pictures taken from the same position.

Keywords Cloud height, digital imaging, environmental measurements

1. INTRODUCTION

Cloud base height, wind speed and wind directions at cloud level are important information for weather forecast and air safety [1]. Especially low level clouds and/or high wind speeds at low altitudes influence the safety of aircrafts in the vicinity of airports. Furthermore clouds are one of the major components in the climate system and hence important for climate change [2].

In the past, cloud base height was determined using ceiling light, *i.e.*, a narrow light beam illuminating a cloud. Measuring the inclination angle at a certain distance from the (vertical light beam) gives the cloud base height through triangulation [3]. This method works best during night-time. Cloud base height can also be estimated from radio soundings [4], which are regularly performed by national weather service agencies. In modern times ceilometers are used which can be operated automatically all day round [5]. In these systems, a laser pulse is emitted into the atmosphere and reflected at the cloud base. From the travel time of the laser pulse between the device and the cloud base, its height can be obtained with high accuracy. However these instruments are relatively expensive.

The advent of low-cost high-resolution digital consumer cameras has led to the development of environmental instrumentation based on digital photography. Recently, a digital camera based system was proposed as an easily affordable atmospheric visibility measurement instrument [6].

In this paper, it will be shown, as a proof-of-concept, that cloud base height can be obtained from digital images obtained with low-cost digital consumer cameras. It will be demonstrated that the wind speed and direction at cloud base height can also be estimated with the same system.

2. METHOD AND SETUP

In this section, the method to estimate cloud base height is proposed and described. The procedure is based on triangulation from stereo photography. Angle estimation is needed for the triangulation and knowledge of the camera sensor size is required if the camera is operated at different zooms. Also, to perform the triangulation, the same point or feature must be identified in both pictures. This step is accomplished using image registration.

2.1. Theory

The triangulation procedure used to estimate the cloud base height is depicted in Fig. 1, where two pictures of the overhead sky are obtained from positions A and B on the ground. The distance between the two positions is *d* and the cloud base height to be estimated is *h*.

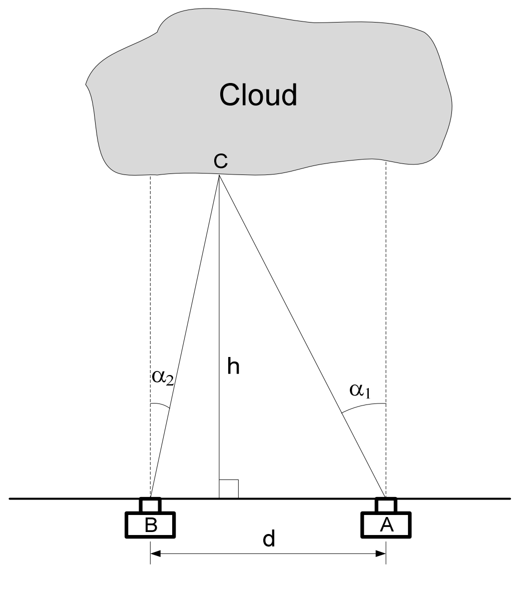

Fig. 1. Triangulation method used to measure distances.

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The same cloud feature (point C in Fig. 1) is identified on the pictures obtained from the two sites and the angles α_1 and α_2 between the camera axis and the line connecting the sites to point C can be measured. If the cameras axes are perpendicular to the ground, the cloud base height is given by

$$h = \frac{\cos(\alpha_1)\cos(\alpha_2)}{\sin(\alpha_1 + \alpha_2)} d \,. \qquad (1)$$

2.2. Camera characterization

The digital camera used is a 6 MPixel Olympus SP-500 UZ with 10 × optical zoom (focal distance from 6.3 mm to 63 mm). The pictures were captured at maximum resolution 2816 × 2112.

The triangulation procedure involves the determination of angles relative to the camera axis (see Fig. 1). This can be done by counting the number of pixels that point C is offset relative to the center of the picture. However, to convert pixels to an angle, the horizontal and vertical angles of view must be determined. Since these angles change with the cameras focal distance *F*, it is best to determine the effective sensor size. The zoom can then be automatically adjusted for different cloud heights, thus optimizing the system resolution. Fig. 2 illustrates this procedure for the vertical dimension. An object with known length *L* is located at a known distance *D* from the camera. For a given focal distance *F* the sensors y length can be determined.

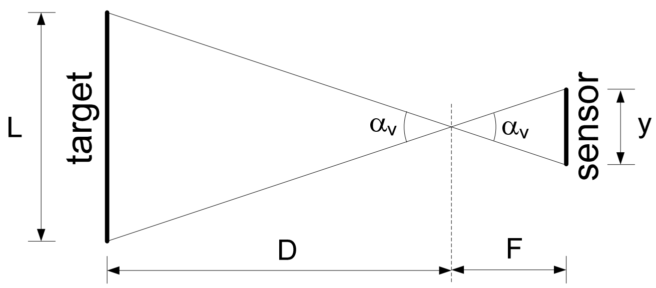

Fig. 2. Sensor size and angle of view definition.

The target shown in Fig. 3 was used as the object for the sensors size determination. It has tick mark spacing of 5 mm and circles with radius that are multiples of 25 mm. The target was placed at a distance *D* = 2.51 m and a picture was obtained with a focal distance *F* = 63 mm. The viewable area of the target as shown in Fig. 3 has dimensions 27.1 cm × 20.3 cm which gives an effective sensor size of 6.8 mm × 5.1 mm.

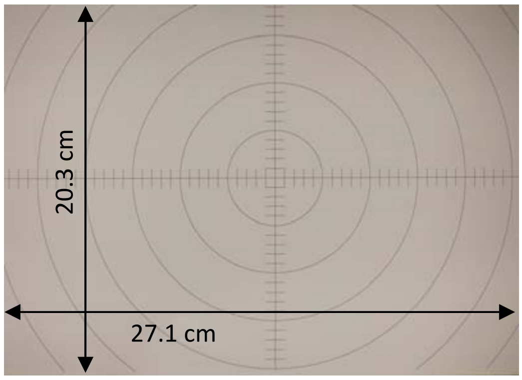

Fig. 3. Target with 5 mm spaced ticks used to determine the effective sensor size.

The horizontal and vertical angles of view α_h and α_v can then be determined as a function of the focal distance through

$$\alpha_h = 2\tan^{-1}\left(\frac{x}{2F}\right), \quad \alpha_v = 2\tan^{-1}\left(\frac{y}{2F}\right) \qquad (2)$$

where *x* and *y* are the effective horizontal and vertical size of the camera sensor. Table 1 presents the horizontal and vertical angles of view for the two focal distances used in this paper. It also presents the angles per pixel α_{ph} in the horizontal and α_{pv} in the vertical directions.

Table 1 – Angles of view and angles per pixel for different focal distances. Picture resolution is 2816 × 2112.

F [mm]	α_h [°]	α_v [°]	α_{ph} [°/pixel]	α_{pv} [°/pixel]
6.3	56.7	44.0	20.1×10^{-3}	20.8×10^{-3}
63.0	6.2	4.6	2.19×10^{-3}	2.19×10^{-3}

Under ideal conditions the angles per pixel for different focal distances should be proportional. The small deviations shown in Table 1 are related to measuring errors.

2.3. Image registration

For the triangulation method to work, the same point or feature needs to be identified in the pictures taken from sites A and B. This is done by image registration which is used to find the translation needed to align both images. The images are initially transformed from the RGB system to YUV system and only the intensity component Y is used. The 2-D cross-correlation between the two intensity images is obtained and its maximum corresponds to the translation needed to align the original images. Since this operation can be very time consuming, it is only applied to a subset of the full pictures. Image A is centered and cropped to 1300 × 1100 pixels and image B to 800 × 600 pixels.

3. EXPERIMENTAL RESULTS

This section presents the experimental results of the proposed approach. Two kinds of targets were used: an artificial target in a controlled setup inside the laboratory; and a cloud under natural atmospheric conditions.

3.1. Laboratory measurements

The distance estimation using stereo digital photographs was first tested in a horizontal test-bed. This experiment had the objective of validating the approach by estimating a distance that could be measured. The target shown in Fig. 3 was placed at a distance of h = 2.51 m from the camera location. The distance between sites A and B was set at 4 cm. The pictures were obtained using full optical zoom which corresponds to a focal distance of F = 63 mm.

The pictures obtained from the two different locations are presented in Fig. 4. From the image registration procedure on the two pictures, resulted the 2D normalized cross-correlation shown in Fig. 5.

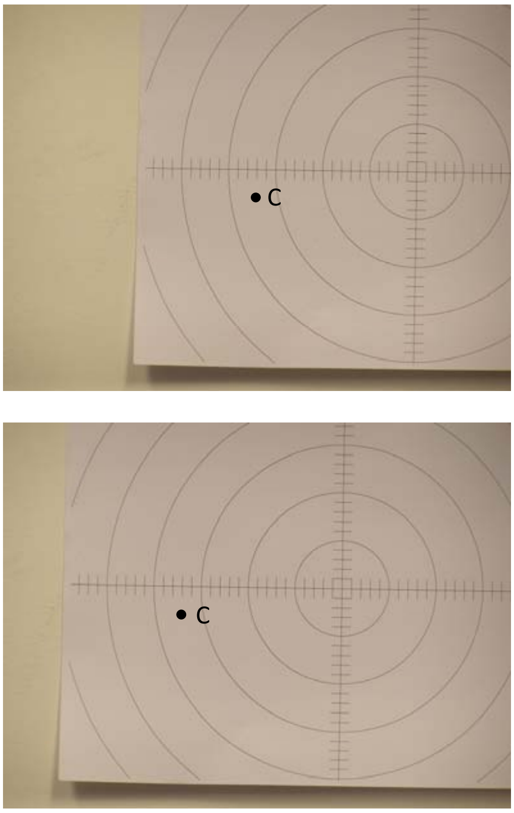

Fig. 4. Target pictures taken from different positions. Point C is horizontally offset by 414 pixels between the two pictures.

The maximum location yields a translation of 414 pixels in the horizontal direction. Therefore, if the center point of image A is chosen as point C, the corresponding point in image B is horizontally offset by 414 pixels. This corresponds to $\alpha_1 = 0^{o}$ and $\alpha_2 = 0.91^{o}$ which according to (1) gives a distance of h = 2.52 m between the camera and the target. The error between the estimated distance and the real distance is within the expected measurement errors for the current setup.

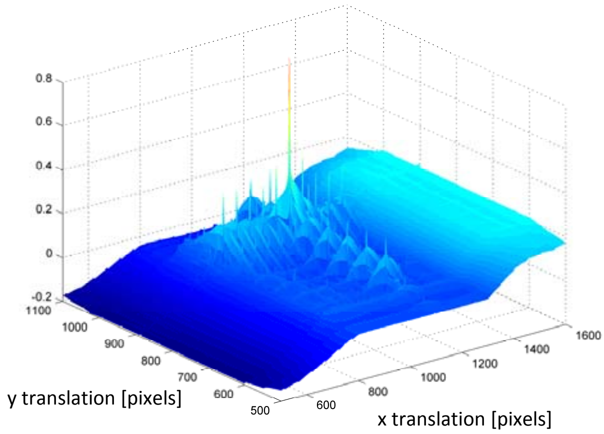

Fig. 5. Normalized cross-correlation between the pictures of Fig. 4. The maximum location yields the translation needed to overlap the two images.

3.2. Field measurements

This subsection describes the actual cloud base height measurement using stereo digital photography. The test was performed in Évora, Portugal at 2009-01-21 16:43 UTC with a partially overcast sky. In this case, the distance d between sites A and B was 18.0 m. The focal distance used in the camera was F = 6.3 mm resulting in minimum zoom and consequently the widest field of view.

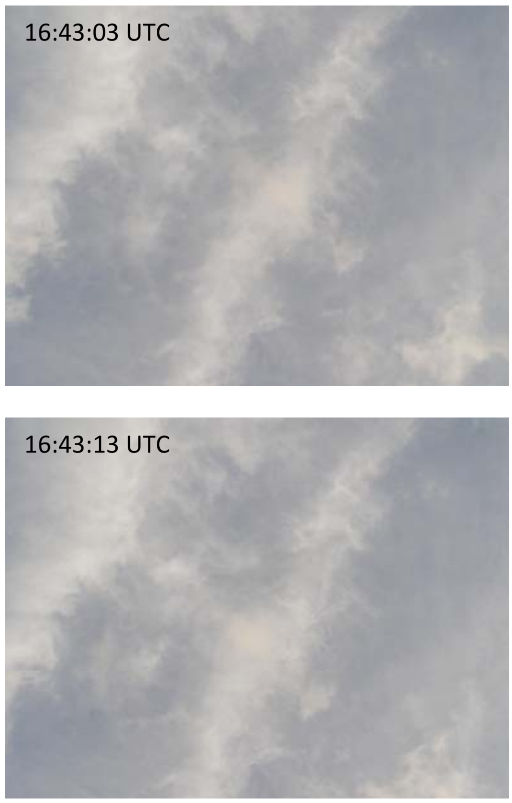

Fig. 6. Cloud pictures taken from position A with a time lapse of 10 s.

At the time of this work only one camera was available therefore the two pictures were not taken simultaneously. Since the clouds are moving due to the wind, the cloud feature of the second image must be corrected for this effect. This can be done taking two time lapsed pictures at point A before moving the camera to point B. From these, the wind speed and direction (at cloud height) can be determined and used to correct the image taken at site B. Note that after this correction, the pictures from the two sites only exhibit a displacement along the direction of the line connecting the two sites.

Figure 6 shows the two pictures obtained at site A with a time lapse of 10 s. The image registration algorithm gives a translation of 110 pixels in the y direction and 2 pixels in the x direction, corresponding to an angle of 2.3º. The effect of the wind on the clouds presents itself as a displacement of 11 pixels per second in the y direction. This result will be used to correct the cloud displacement during the time lapse that occurs while moving the camera from site A to site B.

The picture taken from site B is shown in Fig. 7 and was obtained 18 s after the second picture from site A. The translation obtained from the image registration procedure is 53 pixels in the x direction and 185 in the y direction. After the time-lapse wind correction the translation becomes 50 pixels in the x direction. Choosing point C as the center of the second image at site A, as was done in the horizontal test-bed, results in $\alpha_1 = 0^o$ and $\alpha_2 = 1.01^o$ (corresponding to the 50 pixel offset). Through (1) the estimated height of the clouds is 1.0×10^3 m.

Fig. 7. Cloud picture taken from position B with a time lapse of 18 s relative to the picture taken from position A.

From the cloud height and the pixel displacement obtained from the two pictures taken from site A it is now also possible to estimate the wind speed at cloud base height. An angle of 2.3º at 1.0×10^3 m corresponds to an arc length of 40 m. This is the displacement of the clouds in the 10 seconds between the two photographs, resulting in a speed of 4.0 m/s. The wind direction showed up in the pictures as a y displacement. Since the two sites were aligned in along 80º and the clouds, in this particular day, were moving in a perpendicular direction to this alignment, it can be concluded that the wind direction was 350º.

4. CONCLUSIONS

This paper describes a new method to estimate cloud height based on triangulation using digital photography. Two pictures of the overhead sky are taken from two different locations and a common feature in the clouds is identified, by image registration, in the two pictures. The angle of the feature relative to the cameras axis is computed using the known focal distance and the cameras sensor size. These angles are then used in the triangulation to estimate the cloud base height. The method was validated with laboratory measurements.

Since only one digital camera is used, the two pictures are not obtained simultaneously and the clouds positions need to be corrected due to wind speed. This was accomplished by taking two time-lapsed pictures from one of the locations. Both the wind speed and direction at cloud height were therefore estimated.

Future work involves improving the accuracy of the setup. Two cameras will be used and aligned with greater accuracy. Also, the time-lapse between consecutive pictures, needed for wind speed estimation, will be determined more accurately.

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