Control Engineering Practice 75 (2018) 17–25

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Visual estimation of deviations for the civil aircraft landing

V. Gibert [a], F. Plestan [b,*], L. Burlion [c], J. Boada-Bauxell [a], A. Chriette [b]

[a] *Department of Stability and Control, Airbus Operations SAS, Toulouse, France*
[b] *Ecole Centrale de Nantes-LS2N, UMR CNRS 6004, Nantes, France*
[c] *Onera, Toulouse, France*

ARTICLE INFO

Keywords:
Visual estimation
Nonlinear observers
Aircraft landing

ABSTRACT

This paper presents a new scheme for the visual estimation of deviation of a system with respect to an object for which no feature is known (position, dimensions, …). This scheme is based on nonlinear observers and, thanks to an adequate combination of the visual information, requires reduced computation for its design. It is evaluated on a scenario describing the landing of an aircraft on an unknown runway and is validated with synthetic images.

1. Introduction

In future aircraft, Airbus wishes to develop automatic landing "everywhere and every time". The proposed solution based on cameras would allow operation of an aircraft as a pilot would operate it nowadays in case of DGPS loss and ILS unavailability, *i.e.* in visual flight rules. Then, the camera and observation scheme can be considered a sensor in case of failure of other sensors, even if the conditions of visibility are not ideal, thanks to infra-red or multimeter-waves cameras. The camera coupled, in this paper, to an observer (called software sensor) is also very interesting in the frame of data fusion and would appear as an additional redundant sensor. In this case, it could be used to verify readings from other measurement systems (GBAS/SBAS that equipped civil aircrafts, IRS), to re-calibrate them versus camera informations, to detect sensors failure or to ensure redundancy.

Not all airport runways are equipped with ILS (Instrument Landing System) technology, and GPS (Global Positioning System) is not always available; yet both of these systems are required to ensure automatic landing. A solution to overcome the lack of external information consists of using an embedded visual system for retrieving the deviation information of the aircraft versus the runway. Given that camera sensors and image processing algorithms have made large technological leaps in the last few decades, visual informations coupled with *IRS* (Inertial Reference System) measurements could induce a solution to perform automatic landing. Then, the camera provides informations for the control of the aircraft, which is called visual servoing. It consists of using a vision sensor and computer vision algorithms in order to control the motion of the system (see tutorial in Chaumette & Hutchinson, 2006). Note that, in civil aircraft applications, embedded sensors such as accelerometer or gyros provide accurate information so that the attitude (yaw, pitch, roll angles) and the motion of the aircraft can be considered well-known; hence, the use of dynamics of visual features between several images is sufficient to estimate deviations with respect to (*w.r.t.*) the runway.

The first class of visual servoing control is named *PBVS* (Pose Based Visual Servoing) and consists of using visual measurements in order to estimate the pose of the camera, whereas the second class of control, named *IBVS* (Image Based Visual Servoing), consists of controlling the coordinates of visual features in the image plane.

IBVS solutions applied to the automatic landing of an aircraft have been intensively studied during the last decade. Guidance solutions are proposed in Azinheira and Rives (2008) and Le Bras, Hamel, Barat, and Mahony (2009) in order to reach and track the desired trajectory by using only lines coordinates detected in the image of the runway, or in Coutard, Chaumette, and Pflimlin (2011) and Gibert and Puyou (2013) in which the control is based on centerline and touchdown point coordinates. Nevertheless, these scheme imply the development of new guidance laws with a completely new structure (composed of image capture, image processing and guidance algorithms) which might be difficult to certify by the authorities and strongly increases the cost of these solutions. In fact, the use of already certified guidance laws is a key-point for aircraft manufacturers; it is the main reason why the *IBVS* solution is not the "ideal" one. Therefore, it is desired to introduce visual servoing, but without changing the control structure; this is why the *PBVS* described in the sequel presents a great interest.

The *PBVS* scheme could be divided in two steps: the first one is to estimate the deviations of the aircraft *w.r.t.* the runway, and, in the second step, the estimated deviations are used in the certified guidance laws. Note that a single camera provides a 2D view of the scene, but 3D

---

[*] Corresponding author.
E-mail address: franck.plestan@ec-nantes.fr (F. Plestan).

https://doi.org/10.1016/j.conengprac.2018.03.004
Received 19 September 2017; Received in revised form 29 January 2018; Accepted 2 March 2018

deviation estimation is required for the control of a landing aircraft. The estimation of the 3D deviations can be obtained by using more than one camera (Trisiripisal, Parks, Abbott, Liu, & Fleming, 2006). Nevertheless, stereo-vision appears difficult in civil aircraft application because, when the landing operations start, the distance from runway is important; thus, calibration of both the cameras must be very precise which is a hard task in an industrial context. Another solution is based on knowledge of objects (here, the runway) dimensions (Gui et al., 2013). However, this paper considers a generic runway whose size and markers are not known: geometric reconstruction solutions using these informations cannot be applied. The last solution consists in using a monocular camera by taking into account its motion (Dahl, Nyberg, Holst, & Heyden, 2005; Giordano, De Luca, & Oriolo, 2008; Karagiannis & Astolfi, 2005). Note that these preliminary results with such approach are limited to the use of one single point in the image and there is not application with a landing scenario.

This last solution is selected to solve the 3D estimation problem and consists of using state observers. Thanks to this solution, the unknown scale factor can be estimated, and an estimation of the 3D information becomes available. Hence, there is a real interest to develop solutions in order to estimate the deviations of the camera *w.r.t.* the runway. For this purpose, the available information is the knowledge of attitude, velocities and accelerations provided by the Inertial Measurement Unit and visual measurements; *no geometric information of the runway is required.* The visual informations, provided by image processing algorithms, correspond to the perspective projection of the 3D corners of the runway in the image plane. To sum up, the problem remains to estimate a 3D information from 2D measurements. The authors of the current paper have already proposed estimation solutions of the deviations during an aircraft landing scenario. In Gibert, Burlion, Chriette, Boada-Bauxell, and Plestan (2015a), an extended observer solution of Karagiannis and Astolfi (2005) using more than 1 point has been proposed, with a detailed observability analysis of the system. In Gibert, Burlion, Chriette, Boada-Bauxell, and Plestan (2015b), observer solutions based on high gain approach and sliding mode theory have been designed in conditions such that the observability along the landing is guaranteed. However, these solutions do not have formal convergence proof, are quite complex to design and have been tested in simulation but not by using real image processing experiments.

The main contribution of this paper is to propose observation solutions, based on a new simplified formulation thanks to the use of a virtual frame. This new formulation provides a simple dynamic system that makes the design of the observers easy and guarantees the observability all along the landing trajectory. Then, a robust observer based on sliding mode theory is designed and compared to a high gain observer. Realistic results based on synthetic images and real image processing are detailed; the aircraft landing is made assuming that runway features are not known.

The paper is organized as follows. First, the problem under interest is presented with its simplified formulation. Then, the new observation scheme is presented by assuming that two points are tracked in the image; sliding mode and high gain observers are designed. Finally, results in realistic conditions thanks to synthetic images are proposed.

2. Problem formulation

The problem of range estimation based on a standard formulation in the camera frame has been tackled with different observers (Giordano et al., 2008; Karagiannis & Astolfi, 2005). However, it has been shown in Gibert et al. (2015a) that, if the objective is to estimate the deviations of the aircraft with respect to the runway, there are singularities of observability during the landing phase, when only a single point of the image is used. Therefore, a new problem formulation is proposed by introducing a *virtual frame* that allows to simplify the problem formulation and to get some interesting properties.

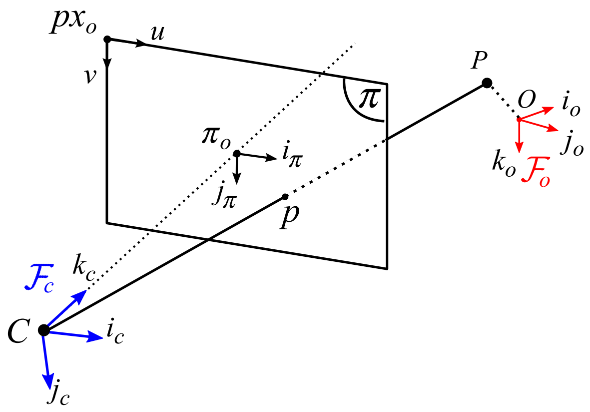

Fig. 1. Perspective projection of a point P in the image plane.

2.1. Standard formulation in the camera frame

Consider the following notations (see Fig. 1)

- $\mathcal{F}_o = (O, \mathbf{i}_o, \mathbf{j}_o, \mathbf{k}_o)$ an inertial frame (in the current application, it will be a frame linked to the runway);
- $\mathbf{P_o} = (P_{o1}, P_{o2}, P_{o3})$ the 3D coordinates of a point P in $\mathcal{F}_o$;
- $\mathcal{F}_c = (C, \mathbf{i}_c, \mathbf{j}_c, \mathbf{k}_c)$ the camera frame whose origin, C, is the optical center of the camera;
- $\mathbf{P_c} = (P_{c1}, P_{c2}, P_{c3})$ the coordinates of P in the frame $\mathcal{F}_c$;
- $\mathcal{F}_\pi = (\pi_0, \mathbf{i}_\pi, \mathbf{j}_\pi)$ the image frame whose origin π_0 has coordinates in $\mathcal{F}_c$, $\pi_0 = (0, 0, f)$ where f is the focal length of the camera.
- $\mathcal{F}_{px} = (px_0, \mathbf{u}, \mathbf{v})$ the pixellic frame whose origin is at the upper-left corner of the image.

The standard expression for the dynamics of the point P (that is fixed in $\mathcal{F}_0$) in the camera frame $\mathcal{F}_c$ is (Dahl et al., 2005):

$$\begin{bmatrix} \dot{P}_{c1} \\ \dot{P}_{c2} \\ \dot{P}_{c3} \end{bmatrix} = \boldsymbol{A_c} \cdot \begin{bmatrix} P_{c1} \\ P_{c2} \\ P_{c3} \end{bmatrix} + \boldsymbol{b_c} \tag{1}$$

with $\boldsymbol{A_c} \in M_{3,3}(\mathbb{R})$ and $\boldsymbol{b_c} = [b_{c1}\ b_{c2}\ b_{c3}]^T \in \mathbb{R}^3$ respectively representing the skew matrix of the known rotational and translational velocities of the camera in the camera frame $\mathcal{F}_c$.

The problem is that the state of (1) is not directly measured. Thanks to the vision system based on perspective projection camera model (Hartley & Zisserman, 2003), the available measurement of the 3D coordinates of the point P is a 2D vector $\boldsymbol{y_c}$ expressed in the image plane π and given by

$$\boldsymbol{y_c} = \begin{bmatrix} y_{c1} \\ y_{c2} \end{bmatrix} = f \cdot \begin{bmatrix} \frac{P_{c1}}{P_{c3}} & \frac{P_{c2}}{P_{c3}} \end{bmatrix}^T \tag{2}$$

with f the focal length of the camera. For the rest of the paper, without loss of generality, the focal length is considered equal to 1.

The objective of the paper is to get an estimate of the state vector $[P_{c1}\ P_{c2}\ P_{c3}]^T$ from the knowledge of $\boldsymbol{A_c}$, $\boldsymbol{b_c}$, and $\boldsymbol{y_c}$.

A necessary condition to design an observer for system (1) is that this latter is observable. Given that observability condition (Karagiannis & Astolfi, 2005) is fulfilled, solutions based on nonlinear observers have been proposed (Chen & Kano, 2002; Dahl et al., 2005; Karagiannis & Astolfi, 2005). However, in Gibert et al. (2015a), it has been shown that, *in the case of aircraft landing*, if the tracked point is the aiming guidance point on the runway, observability is not maintained all along the landing phase.

Then, in order to ensure observability all along the landing phase, a solution consists in using *at least* two points on the runway (*i.e.* which belong to the runway plane). This way, if one of the points is not providing observability, the second guarantees that the whole