Estimation of Aircraft Height and Lateral Deviation With Respect to Runway Using Images from Un-Calibrated Camera

Durgarao Sykam[#], VPS Naidu[*]

[#]*Dept. of ECE, MSR Institute of Technology, Bangalore*
[*]*MSDF Lab, CSIR-NAL, Bangalore-17*

vpsnaidu@gmail.com

Abstract— **Enhanced Synthetic Vision System (ESVS) consisting of several imaging sensors mounted onto the aircraft together with some built-in computing devices for acquiring, storing and displaying the sensor data. This data, provide necessary information to the pilot during flight phases close to terrain like approach and landing. Estimation of aircraft height and lateral deviation with respect to runway using images from an un-calibrated camera is implemented and studied. Studies have shown that error in height is more when the aircraft is away from the runway and error in lateral deviation is more when the aircraft away from the runway and is symmetrical with respect to runway central line.**

Keywords— Camera model, aircraft lateral deviation, vanishing point.

I. Introduction

In the current aircraft operating environment, low visibility approach and landing operations require a combination of aircraft avionics equipage, surface infrastructure, and specific crew training to operate at reduced visibility. These requirements limit low visibility approaches to a relatively small number of runways. In order to improve operational performance and lower the cost operations, it would be desirable to increase the availability of low visibility operations at larger number of runways. These low visibility conditions can be improved by using multi imaging sensors operating in different infrared spectral bands. Fusion of these images can be displayed on head up display (HUD) in front of pilot along with some other flight parameters like altitude and deviation with respect to runway. The information flow diagram of the above mentioned procedure is illustrated in [1] and is being developed at MSDF lab, National Aerospace Laboratories, Bangalore under Integrated Enhanced Synthetic Vision System (IESVS) for national civil aircraft (NCA). Synthetic vision systems (SVS) create a cockpit-centered representation of the external view from precise aircraft position and attitude inputs, and high precision database of terrain and cultural features like runways [2]. The global positioning system (GPS) provides the necessary position data for creation and display of the external scene. There are two significant functions for SVS i.e. Verification of alignment with the landing runway center line [5] and improving pilot visual performance in making the transition from instrument flight to the visual cues required for final alignment, flare and landing. Enhanced vision system (EVS) provides a real time out-the-window (OTW) imagery with the help of vision sensors. It generates huge amount of data and simply present on HUD to improve pilot's situation awareness [6]. In this report, it is planned to process this imagery data to compute some useful information viz., aircraft lateral deviation with respect to the centre of the runway for affective piloting.

II. Height and Lateral Deviation Estimation

Accurate estimation of aircraft lateral deviation from runway centre line is very important during landing phase. It can be done by fusing the data coming from different onboard sensors such as GPS (Global Positioning System) and INS (Inertial Navigation System) etc. GPS is very sensitive to signal dropout and hostile jamming. The use of INS alone produces large localization error as the work time increases. Off course, the integration of GPS and INS which is the general trend in the aircraft navigation may solve these drawbacks. These drawbacks also could be avoided using vision based approaches [1].

Let the runway width be $2d$ on world coordinates and be projected on to the image plane using the camera [1]. The runway strip appears as a trapezium as shown in Fig-1. Let the one side of the raised side of the trapezium is $l1$ whose end points are (x_{1l1}, y_{1l1}) & (x_{2l1}, y_{2l1}) and the other side is $l2$ whose end points are (x_{1l2}, y_{1l2}) & (x_{2l2}, y_{2l2}) in image coordinates. The raised sides $(l1\&l2)$ of the trapezium are crossed at a vanishing point (VP). A line is drawn from this point to the base of the trapezium to form the right angle triangle and whose length (height) is assumed as h and the angles are δ_1 and δ_2 as shown in Fig-1. The vanishing point (x_{vp}, y_{vp}) can be computed as:

$$A_l = \begin{bmatrix} (x_{2l1} - x_{1l1}) & (x_{2l2} - x_{1l2}) \\ (y_{2l1} - y_{1l1}) & (y_{2l2} - y_{1l2}) \end{bmatrix} \quad \text{1a}$$

$$b = \begin{bmatrix} (x_{1l2} - x_{1l1}) \\ (y_{1l2} - y_{1l1}) \end{bmatrix} \quad \text{1b}$$

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = A_l^{-1} b \quad \text{2}$$

The VP is computed as:

$$\begin{bmatrix} x_{vp} \\ y_{vp} \end{bmatrix} = \begin{bmatrix} x_{1l1} \\ y_{1l1} \end{bmatrix} + \lambda_1 \begin{bmatrix} (x_{2l1} - x_{1l1}) \\ (y_{2l1} - y_{1l1}) \end{bmatrix} \quad \text{3}$$

And the angle at VP is:

$$\delta = \cos^{-1}\left(\frac{\begin{bmatrix}(x_{2l1}-x_{1l1})\\(y_{2l1}-y_{1l1})\end{bmatrix} \bullet \begin{bmatrix}(x_{2l2}-x_{1l2})\\(y_{2l2}-y_{1l2})\end{bmatrix}}{\left\|\begin{bmatrix}(x_{2l1}-x_{1l1})\\(y_{2l1}-y_{1l1})\end{bmatrix}\right\| \left\|\begin{bmatrix}(x_{2l2}-x_{1l2})\\(y_{2l2}-y_{1l2})\end{bmatrix}\right\|} \right) \quad 4$$

where $\bullet$: dot operation

$\|V\|$: norm of vector V

The height h and lateral deviation A can be computed from the simple geometry as [3]:

$$h = \left(\frac{2d}{\tan(\delta_1) + \tan(\delta_2)} \right) \quad 5$$

$$A = d - h\tan(\delta_2) \quad 6$$

δ_2 and δ_1 can be obtained from the Fig-1, using trigonometry. $\delta_2 = 90 - \tan^{-1}\left(\frac{y_{2l2} - y_{1l2}}{x_{2l2} - x_{1l2}} \right)$ 7

$$\delta_1 = 90 - \tan^{-1}\left(\frac{y_{2l1} - y_{1l1}}{x_{2l1} - x_{1l1}} \right) \quad 8$$

From the above equation one can observe that the aircraft lateral deviation A is depends only on the known runway width d and the angle δ_2 height h computed from the image data. It does not depend on the camera parameters and hence camera calibration is not required. The accuracy in the computations of h depends on the accuracy of the computed δ_2. The accuracy of the δ_2 depends on the camera resolution.

III. RESULTS AND DISCUSSION

To test the lateral deviation estimation, a rectangular runway strip is taken whose corner points in 3D world coordinates are presented in Table-1A (2nd column). These points are viewed through the camera model [4] and the resultant image coordinates are also shown in Table-1A (3rd column). The camera parameters used in this study are shown in Table-1A (1st column). The computed δ_1 & δ_2, h and A are shown in Tbale-1B. From Table-1A&B, it is observed that rounding of pixel coordinates produces more error.

The true and estimated height and lateral deviation with and without round off pixel coordinates are shown in Table-2. The test is done for different deviation values from runway center line (*cpx*) while keeping the camera at a height *(cpz*) 4000m and away (*cpy*) -2000m. The algorithm computes the deviation very accurately as shown in Table-2 (2nd and 4th column). It is observed that there is an error (5th & 6th columns in Table-2) in the estimation while we considered the pixel coordinates. It is because of corresponding world coordinates in 2D image plane are floating points. In reality, this is not the case where the pixel locations are represented by integers. Rounding of these floating values causes some error in height and deviation estimation. These errors can be minimized by using high resolution camera and/or zooming facility.

The effect of camera deviation on vanishing point (*VP*) without rounding pixel coordinates and with round off pixel coordinates are shown in Fig-2a and 2b respectively by keeping camera height (*cpz=4000m*) and distance from the runway (*cpy=-2000m*) fixed and deviation from the center of runway (*cpx*) varying from -500m to 500m. Estimation of height and lateral deviation with camera position CP=[*cpx, cpy=-500m, cpz*] as shown in Table-3A for different cpx and cpz. Similarly for camera position CP=[*cpx, cpy=-1000m, cpz*] with different cpx and cpz are shown in Table-3B. It is observed that the error in height and the lateral deviation are increases when the camera is move away from the runway. Error in height estimation is almost constant for different camera heights. There is a fixed pattern in lateral deviation error.

Estimated height error with different aircraft (camera) position cpy and cpx and with constant cpz as shown in Fig-3a. The mean height error (mhex) with respect to lateral deviation and mean height error with repect to forward disatnce to runway are also shown in Fig-3a.

Error in height estimation is more when the aircraft is away from the runway and is symmetric with respect to runway central line. Estimated height error with different aircraft (camera) position cpz and cpy and with constant cpx as shown in Fig-3b. The mean height error with respect to height from the runway is also shown in Fig-3b. Error in height estimation increases when the height (*cpz*) of the aircraft is increases and the height error is symmetric with respect to center line of the runway as shown in Fig-3c. Estimation of deviation error with respect to runway centreline by changing the cpy &cpx and keeping cpz constant as shown in Fig-4a.

Error in estimation of lateral deviation increases when the Aircraft moving away (*cpy*) from the runway and the lateral deviation error is symmetric with respect to center line of the Runway. Estimation of lateral deviation error with respect to runway centreline by varying cpz & cpy and keeping cpx constant as shown in Fig-4b. Deviation error is same for different heights of an aircraft (*cpz*), and the deviation error increases when the aircraft moving away (*cpy*) from the runway. Estimation of deviation error with respect to runway by varying cpz & cpx and keeping cpy constant as shown in Fig-4c. Deviation error is same for different heights (*cpz*) of an aircraft. The deviation error decreases and increases (fluctuation) when it is deviated from the runway center line and the error is symmetric with respect to runway center line.

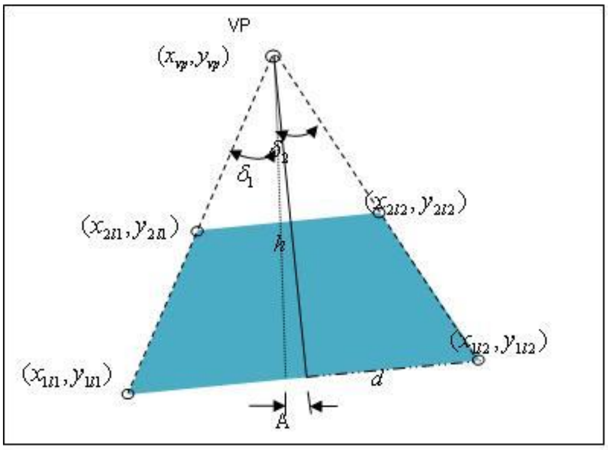

Fig-1: Perspective projection of runway strip in image plane

TABLE IA

3D WORLD COORDINATES AND CORRESPONDING IMAGE COORDINATES WITH GIVEN SET OF CAMERA PARAMETERS

Camera Parameters	Runway in world coordinates $W_c = [x_w \quad y_w \quad z_w]_{(m)}$	Runway in 2D image plane $I_c = [x_i \quad y_i]_{(pixels)}$
$[x_c \quad y_c \quad z_c] = [500 \quad -2000 \quad 4000]$ $f = 100$ $\theta = 0^0$ $\alpha = -90^0$	$W_{c1} = [0 \quad 500 \quad 1]$ $W_{c2} = [1000 \quad 500 \quad 1]$ $W_{c3} = [1000 \quad 3500 \quad 1]$ $W_{c4} = [0 \quad 3500 \quad 1]$	$I_{c1} = [20.8333 \ -166.6250]$ $I_{c2} = [-20.8333 \ -166.6250]$ $I_{c3} = [-9.2593 \ -74.0556]$ $I_{c4} = [9.2593 \ -74.0556]$

TABLE IIB

TRUE AND ESTIMATED VP ANGLE, HEIGHT AND DEVIATION

Parameters	True	estimated	
		Without round off pixel coordinates	With round off pixel coordinates
Angle (δ_1)	7.1250^0	7.1268^0	7.3524^0
Angle (δ_2)	7.1250^0	7.1268^0	7.3524^0
Height (h)	4000m	3999m	3875m
Deviation (A)	0m	0m	0m

TABLE II

THE TRUE AND ESTIMATED HEIGHT, DEVIATION (CPY=-2000M)

True height[Z](m)	True deviation[X](m)	without round off pixel coordinates		with round off pixel coordinates	
		Estimated height (m)	Estimated deviation(m)	Estimated height (m)	Estimated deviation(m)
4000.00	500.00	3999.00	-500.00	4043.48	-500.00
4000.00	100.00	3999.00	-100.00	3875.00	-83.33
4000.00	50.00	3999.00	-50.00	3875.00	-41.67
4000.00	10.00	3999.00	-10.00	4043.48	-21.74
4000.00	0.00	3999.00	0.00	3875.00	0.00
4000.00	-10.00	3999.00	10.00	4043.48	21.74
4000.00	-50.00	3999.00	50.00	3875.00	41.67
4000.00	-100.00	3999.00	100.00	3875.00	83.33
4000.00	-500.00	3999.00	500.00	4043.48	500.00

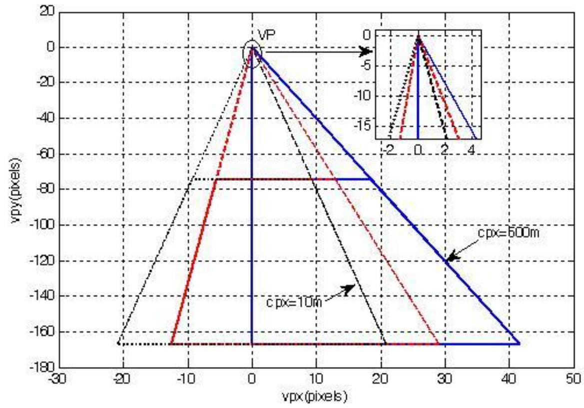

Fig-2a: Effect of camera deviation on vanishing point without rounding pixel coordinates

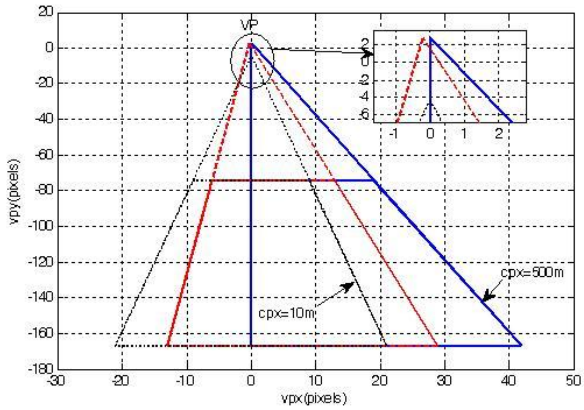

Fig -2b: Effect of camera deviation on vanishing point with rounding pixel coordinates

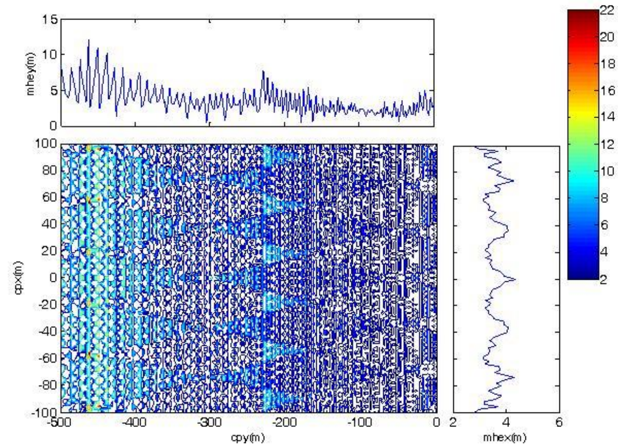

Fig3a: Estimated height error by varying cpy and cpx with constant cpz

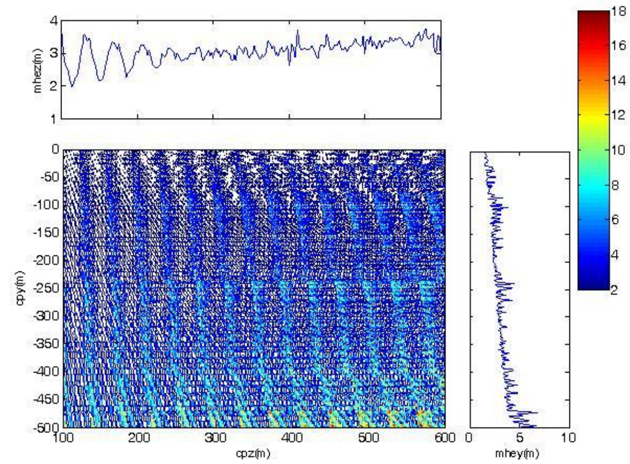

Fig3b: Error in height estimation by varying cpz and cpy with constant cpx

TABLE IIIA

AIRCRAFT POSITION WITH RESPECT TO RUNWAY WITH FIXED CPY=-500M AND VARYING CPX AND CPZ

True		Estimated		Error=(true-estimated)	
cpz (m)	cpx (m)	Height(m)	Deviation(m)	Height(m)	Deviation(m)
1000	500	1000.00	-500.00	0	0
1000	200	1000.00	-205.88	0	-5.88
1000	100	988.37	-104.65	11.63	-4.65
1000	50	1000.00	-52.94	0	-2.94
1000	10	1000.00	-17.65	0	-7.65
1000	0	988.37	0.00	11.63	0
1000	-10	1000.00	17.65	0	-7.65
1000	-50	1000.00	52.94	0	-2.94
1000	-100	988.37	104.65	11.63	-4.65
1000	-200	1000.00	205.88	0	-5.88
1000	-500	1000.00	500.00	0	0
2000	500	2011.76	-500.00	-11.76	0
2000	200	2011.76	-205.88	-11.76	-5.88
2000	100	1988.37	-104.65	11.63	-4.65
2000	50	2011.76	-52.94	-11.76	-2.94
2000	10	2011.76	-17.65	-11.76	-7.65
2000	0	1988.37	0.00	11.63	0
2000	-10	2011.76	17.65	-11.76	-7.65
2000	-50	2011.76	52.94	-11.76	-2.94
2000	-100	1988.37	104.65	11.63	-4.65
2000	-200	2011.76	205.88	-11.76	-5.88
2000	-500	2011.76	500.00	-11.76	0
3000	500	3011.76	-500.00	-11.76	0
3000	200	3011.76	-205.88	-11.76	-5.88
3000	100	2976.74	-104.65	23.26	-4.65
3000	50	3011.76	-52.94	-11.76	-2.94
3000	10	3011.76	-17.65	-11.76	-7.65
3000	0	2976.74	0.00	23.26	0
3000	-10	3011.76	17.65	-11.76	-7.65
3000	-50	3011.76	52.94	-11.76	-2.94
3000	-100	2976.74	104.65	23.26	-4.65
3000	-200	3011.76	205.88	-11.76	-5.88
3000	-500	3011.76	500.00	-11.76	0

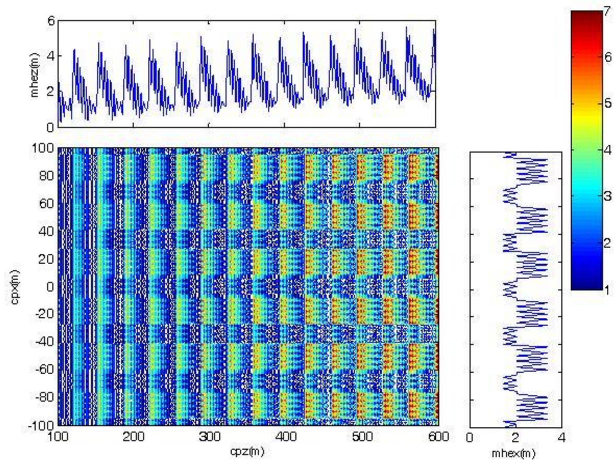

Fig3c: Estimated height error by varying cpz and cpx with constant cpy

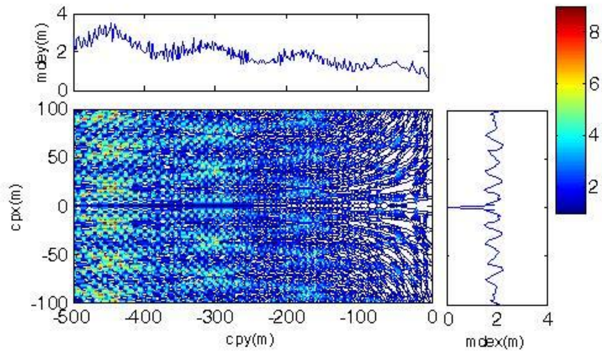

Fig4a: Estimation of deviation error with respect to runway by varying cpy & cpx and keeping cpz constant

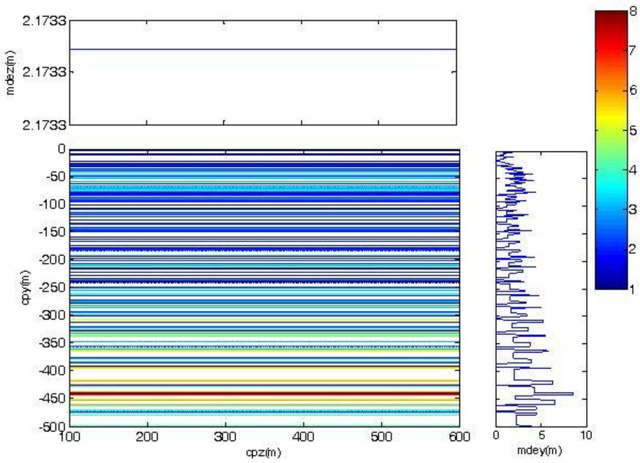

Fig4b: Estimation of deviation error with respect to runway by varying cpz & cpy and keeping cpx constant

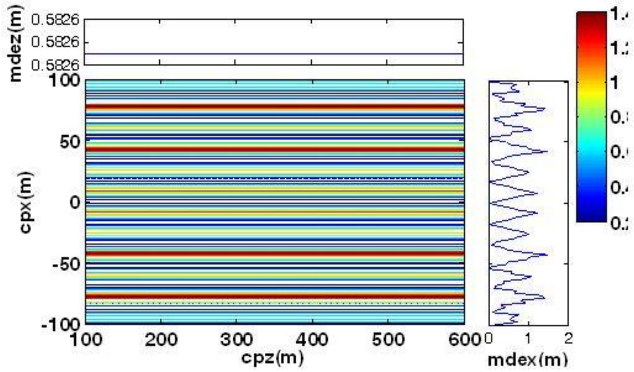

Fig4c: Estimation of deviation error with respect to runway by varying cpz & cpx and cpy constant

TABLE IIIB

AIRCRAFT POSITION WITH RESPECT TO RUNWAY CPY=-1000M AND VARYING CPX AND CPZ

True		Estimated		Error=(true-estimated)	
cpz (m)	cpx (m)	Height(m)	Deviation(m)	Height(m)	Deviation(m)
1000	500	1000.00	-500.00	0	0
1000	200	1000.00	-208.33	0	-8.33
1000	100	979.59	-91.84	20.41	8.16
1000	50	1000.00	-41.67	0	8.33
1000	10	1000.00	0.00	0	10
1000	0	960.00	0.00	40	0
1000	-10	1000.00	0.00	0	10
1000	-50	1000.00	41.67	0	8.33
1000	-100	979.59	91.84	20.41	8.16
1000	-200	1000.00	208.33	0	-8.33
1000	-500	1000.00	500.00	0	0
2000	500	2041.67	-500.00	-41.67	0
2000	200	2041.67	-208.33	-41.67	-8.33
2000	100	2000.00	-91.84	0	8.16
2000	50	2041.67	-41.67	-41.67	8.33
2000	10	2041.67	0.00	-41.67	10
2000	0	1960.00	0.00	40	0
2000	-10	2041.67	0.00	-41.67	10
2000	-50	2041.67	41.67	-41.67	8.33
2000	-100	2000.00	91.84	0	8.16
2000	-200	2041.67	208.33	-41.67	-8.33
2000	-500	2041.67	500.00	-41.67	0
3000	500	3041.67	-500.00	-41.67	0
3000	200	3041.67	-208.33	-41.67	-8.33
3000	100	2979.59	-91.84	21	8.16
3000	50	3041.67	-41.67	-41.67	8.33
3000	10	3041.67	0.00	-41.67	10
3000	0	2920.00	0.00	80	0
3000	-10	3041.67	0.00	-41.67	10
3000	-50	3041.67	41.67	-41.67	8.33
3000	-100	2979.59	91.84	20.41	8.16
3000	-200	3041.67	208.33	-41.67	-8.33
3000	-500	3041.67	500.00	-41.67	0

IV. CONCLUSIONS

Aircraft lateral deviation estimation using images from an un-calibrated camera algorithm is implemented and studied. Camera model is used to simulate the test data. From the results, it was observed that the rounding nature of pixel coordinates effect the vanishing point, hence there is error in height and deviation estimation. The error in height and later deviation are more when the aircraft (camera) is away from the runway.

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