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Position Reference by Automatic Threshold Detection with a Camera System

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ABSTRACT

Position reference for approach flight and level run flight inspection procedures are normally determined by using optical instruments, such as theodolites, laser trackers, or by differential GPS techniques.

These methods require an additional operator on the ground or, as a minimum requirement, an extra landing to set up the optical or GPS equipment before operations start. Nowadays, with an increasing demand to keep costs down, but at the same time having to flight check more complex procedures, it is necessary to employ tools which enable flight inspection crews to make most efficient use of flight hours.

This paper describes a camera system installation in the flight inspection aircraft to determine position reference on approach flight procedures as well as on level run procedures. Additionally, en-route positioning is possible with land mark updates.

After a brief explanation of the camera system components, the techniques for image correction and threshold detection will be explained. Examples will show the impressive potential of the camera system. First results of camera system supported inspection flights demonstrate the reliability of the system, in comparison to Precise Differential GPS (P-DGPS) supported flights.

INTRODUCTION

General

The camera system is part of the AD-AFIS-400 position reference system and serves as position update system for the calibration of approach navigation aids (ILS, MLS, PAR, PAPI). The camera system comprises a Charge Coupled Device (CCD) line scan camera and a CCD area scan camera. Additionally a laser altimeter is installed as height reference for low altitude flights. See figure 1 for a drawing of the cameras and laser altimeter locations at the aircrafts compartment. Figure 2 shows the sensor head with integrated equipment installed in the aircrafts fuselage.

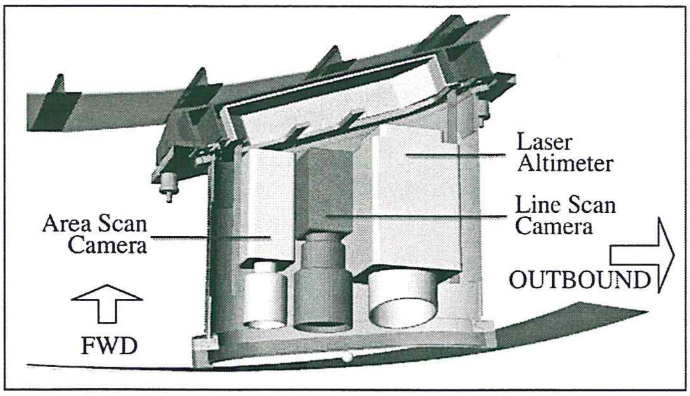

Figure 1: Sensor Head

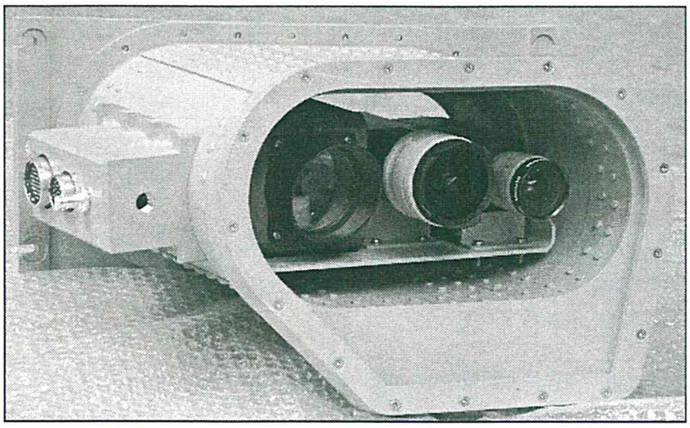

Figure 2: Cameras and Laser Altimeter Installed in Sensor Head

A dedicated camera computer is used for image processing. The AFIS combines results from the image processing unit with the data from the supplementary Inertial Reference System (IRS) and a high accuracy air data sensor.

The CCD sensors offer high sensitivity and a high dynamic range, both corresponding very well to the broad range of different illumination conditions from bright sunlight to twilight. Moreover, they operate over a wide spectral range such that all features together guarantee good results for different visibility conditions.

The line scan camera is equipped with a fisheye lens so the area recorded during the overflight and hence the appropriate accuracy is adjusted to the requirements of runway mark updates. Furthermore it offers automatic runway mark update up to 600 m altitude. The area scan camera allows manual updating based on landmarks up to 2000 m altitude. The line scan camera operates with a scanning frequency of 300 Hz. Assuming 140 kts ground speed a resolution of 25 cm in flight direction will be achieved.

CAMERA SYSTEM COMPONENTS

Line Scan Camera

The line scan camera is used for automatic threshold detection in a self computed area-of-interest (AOI) from the flight position data in low and high altitude flights (15 … 50 m; 200 … 600 m) and for interactive marking of landmarks in low level flights (below 200 m). The resolution is 2048 pixel (14 _ 14 µm) and the gain is up to eightfold remote controlled.

The line scan camera is equipped with a 180° fisheye lens.

Area Scan Camera

The area scan camera is used for interactive marking of VOR symbols, TACAN transmitter or landmarks in high level flights (above 200 m). The resolution 656 _ 492 pixel (9.9 _ 9.9 µm).

The area scan camera is equipped with a fixed focus lens.

Laser altimeter

The laser altimeter is the height reference for low altitude approaches.

The accuracy of the distance measurement is better than $\pm$ (10 mm + 20 $\times$ 10^{-6} $\times$ distance).

Camera Computer AD-PAC125-0100

The computer of the camera system (see figure 3) is a rugged PC/AT compatible computer.

The four (4) PCI slots and three (3) ISA slots contain:

- A watchdog board,
- A real time clock,
- A 100 BaseTx/Fx Ethernet interface,
- Analog area scan camera interface,
- Digital line scan camera interface,
- 4-Channel opto-isolated digital output.

The computer's power supply is 19-30 VDC at 120 W.

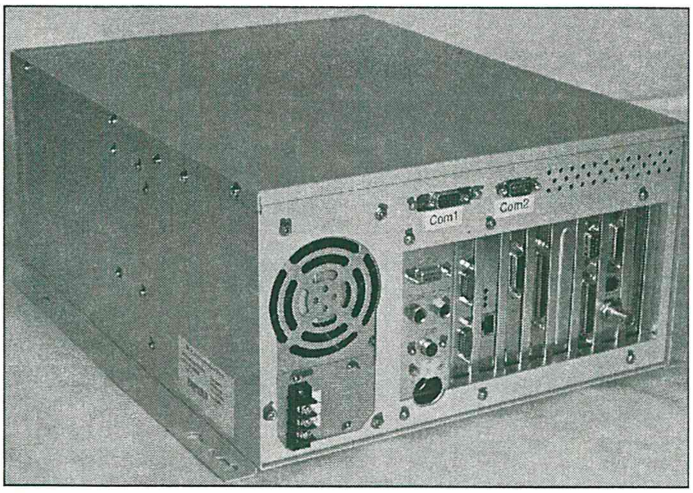

Figure 3: Camera Computer

PRINCIPLE OF OPERATION

The image raw data are stored on the camera computer's hard disk prior to the processing which is performed by the AFIS computer in a multi-step approach.

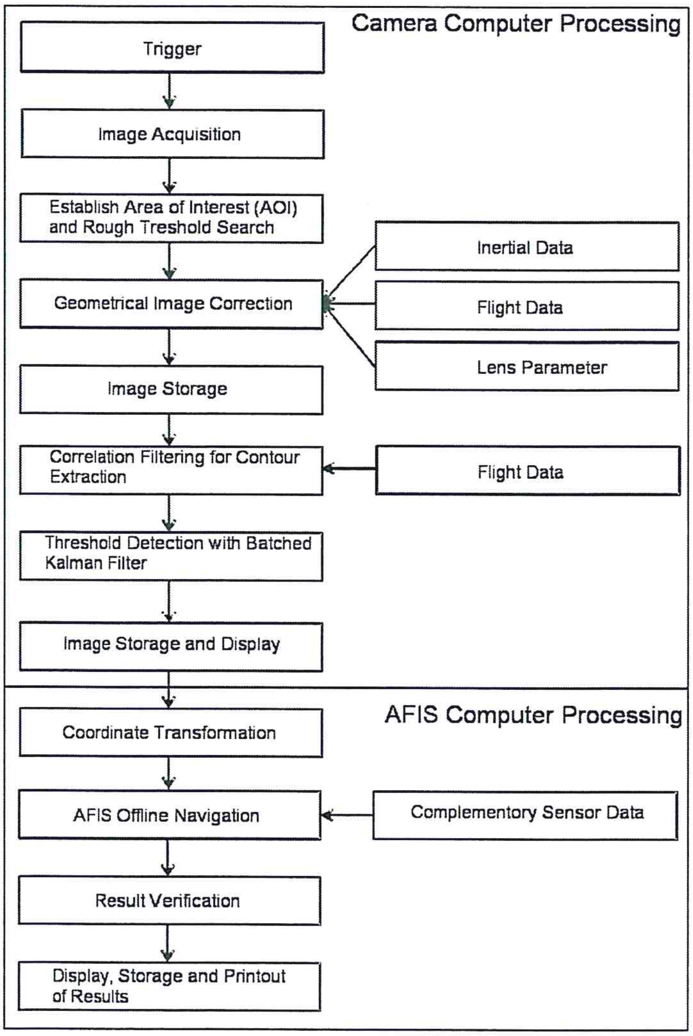

Figure 4: Image Processing of the Camera System

The procedure for camera updating is divided into the following steps (see also figure 4):

- Acquisition of camera data during threshold crossing,
- Post-processing of camera data,
- Estimation of IRS, and barometric altimeter errors,
- Backward integration for the horizontal and vertical channel.

As shown in figure 5, the reference point (origin of the threshold coordinate system) is located at the beginning of the approach threshold and at the end of the departure threshold. The deviation of the current aircraft position relative to the reference point is calculated and the absolute position of the aircraft is determined. These position data are time tagged by the navigation processor and so precisely match with the unaided position data for backward integration.

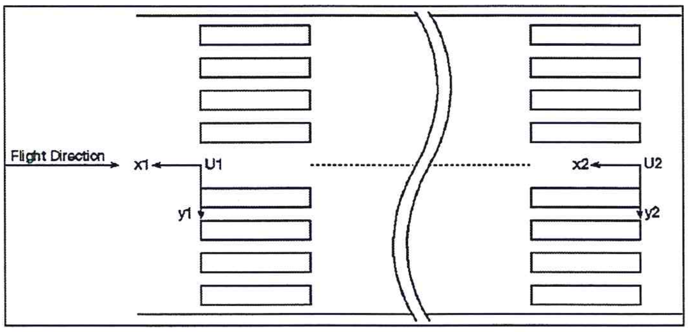

Figure 5: Reference Points

During this operation the attitude data provided by the navigation processor are used to compute the necessary geometrical corrections for the image data.

At the beginning and the end of the runway mark the position in flight direction can be determined additionally.

As the image data are stored before processing, a position update at the second runway threshold can be performed even in case of very short runways.

The whole procedure is executed completely automatic. Therefore, no starting or stopping or any interactive search of a region of interest has to be done by the flight inspector. Also the flight deck crew may fully focus their activities on their primary functions due to the fact, that no operator interaction is requested during this important phase of the approach.

Acquisition of Image Data

The scanning process of the camera is triggered by the actual on-line position solution, e.g. computed from GPS/IRS information. The scanning starts 150 meters in front of the threshold and stops 150 meters behind the threshold. Maximum data acquisition time is 10 seconds. The data are stored locally on the camera computer's hard disk and are time-tagged by the time management hardware of the AFIS computer.

In addition to the data acquisition, the camera interface unit controls the integration time of the CCD sensor to adapt the image acquisition process to different illumination conditions. Furthermore, the CCD data are filtered to reduce signal noise.

For the threshold detection the line scan camera has been selected because of the higher resolution and sensitivity compared to a standard CCD video camera. However, the opening angle of the fisheye lens limits the maximum altitude to use the line scan camera for landmark updates. Therefore, the area scan camera is used on high level flights.

The following description of post-processing, image correction and threshold detection will exemplified on the line scan camera.

Geometrical Correction of Image Data

After the acquisition of an image the attitude and position data of the aircraft are considered for the geometrical correction of the image. This method provides the capability of the system to correct the image data not only in the direction of the scanned lines, but also to introduce a linear 2D geometrical correction, modifying the original orthogonal structure of the lines and generating a new "artificial" image.(refer to figure 6).

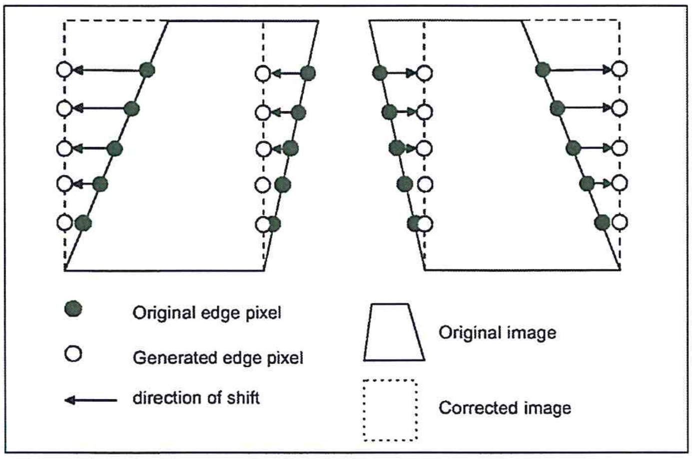

Figure 6: Principle of Geometrical Correction

As the attitude data are available for every measurement cycle of position data, this will allow to split up one image into several sub-images corresponding to the respective position data. Every sub-image than can be corrected independently from each other. Therefore, the system is able to correct deflections due to rolling and yawing of the aircraft for the complete image. Changing of the roll and/or yaw angle during the flight over the runway mark is considered to correct each section of one image separately. Moreover, interpolation is possible using original pixel data from two or even more sub-images. This procedure offers proper geometrical correction also of larger deflections.

The integration time of the CCD sensor will be controlled by the system itself and will be adjusted automatically.

Threshold Detection

Initially, an automatic search for the runway mark is done to establish an Area of Interest (AOI) for the subsequent processing. Hereafter, the processing is reduced to the AOI. The threshold structure is defined by the parameters of the AFIS facility database. This data support the AOI search algorithm.

The centre of the runway mark is identified by image detection algorithms. Hereby, the alternating bright and dark areas of the threshold pattern are analyzed.

AFIS Offline Navigation

The AFIS navigation solution is mainly influenced from the IRS. Due to the structure of the IRS internal sensors, is the specified IRS accuracy for the horizontal component of the position 2 NM/h, what corresponds to approximately 1 m/s (95%).

The camera system is providing a highly accurate position (designed as camera position) at both thresholds of the runway. The accuracy of the camera positions is better than 0.5 m.

With the camera position at the first threshold the IRS horizontal velocities are integrated until the second threshold. The positioning error at the second threshold results from the difference between the integrated position and the achieved camera position. A velocity error is calculated with the flight time interval between the thresholds. In a last step, the reference position is calculated for the complete approach by means of the integration of the IRS velocities corrected by the velocity error.

The horizontal positions of the IRS solution and the single GPS solution are corrected by the achieved camera positions. The vertical position solution is improved by the aid of the laser altimeter.

The camera position updates of both thresholds are used to estimate the errors of the various sensors required for the backward integration. This includes the estimation of the IRS errors and the errors of the barometric, radar and/or laser altimeter.

Without support, a position error of approximately 200 m for a 200 s approach's duration (12 km) occurs. This error is outside the CAT-III tolerances for the complete approach. However, the correction of the position calculation by using the above described algorithm brings an improvement with a factor of about 10.

Runway Requirements for Threshold Detection

The threshold detection algorithm, which relies on the calculation of the intersection between the front line of the runway stripes and an imaginary centre line of the runway mark. The image must contain several stripes, including the larger distance between the two inner stripes of the runway mark and the inner edge of the adjacent stripe (refer to figure 7).

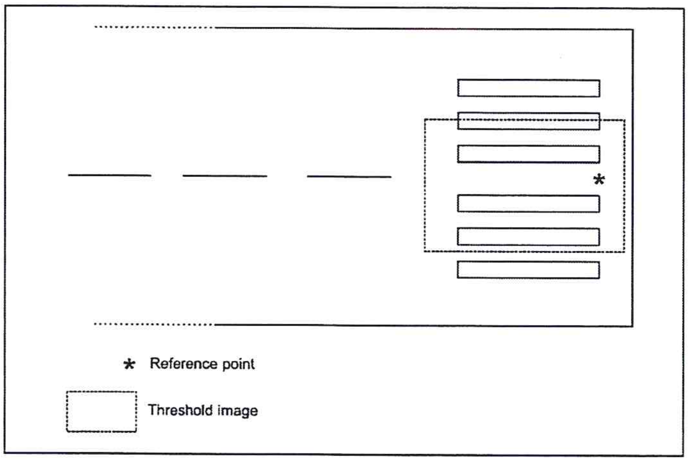

Figure 7: Runway Requirements

However, it should be mentioned, that the imaginary centre line as well as the front line of the stripes will not be calculated from the two inner stripes exclusively. The computing is based on all stripes visible in the image and on their shape. Critical are runway marks, where the painting is quite poor due to rubber stripes and especially where the edges of the painting are no longer clearly visible.

Interactive Position Update

The AFIS operator controls the automatic threshold detection on the AFIS Graphical User Interface (GUI). He may manually select the target, which shall be used for the position update. The acquired line scan or area scan image will be displayed on the GUI and the operator has to move the cursor with the trackball to the reference position in the image. Confirmation of this position is done by pressing a key. The system will use these position data for the update and backward integration similar to the automatically calculated position data of the runway threshold.

As landmarks for update purposes are generally related to the respective navigation aids, position data of the landmarks are included in the data base entries of those particular facilities.

FLIGHT PROCEDURES

Approach Flight Procedures

The camera system uses the line scan camera for the following approach flight procedures:

- ILS localizer approach flights
- ILS glide slope approach flights
- ILS localizer offset approaches
- ILS glide slope offset approaches
- PAR approach flight
- PAPI approach flight

Height over the runway mark	15 ... 50 m
Approach speed	80 ... 180 kts
Roll angle	-10° ... +10°
Pitch angle	-10° ... +10°
Yaw angle	-20° ... +20°
Displacement between runway mark and aircraft	10 m

Table 1: Approach Flights Procedures Operational Limits

Level Run Flight Procedures

The camera system uses the line scan camera for level run flights.

Height over the runway mark	200 ... 600 m
Approach speed	80 ... 200 kts
Roll angle	-5° ... +5°
Pitch angle	-5° ... +5°
Yaw angle	-20° ... +20°
Displacement between runway mark and aircraft	100 m

Table 2: Level Run Flights Procedures Operational Limits

Landmark Update

The camera system uses the best suited camera for landmark updates. In case of low level flights (e.g. below 200 m) the line scan camera will be used. In case of higher level flights (e.g. above 200 m) the area scan camera will be used. Position updates are possible over TACAN and VOR stations or other defined reference points like bridges or crossings.

Height over the landmark	50 ... 2000 m
Approach speed	140 ... 350 kts
Roll angle	-5° ... +5°
Pitch angle	-5° ... +5°
Yaw angle	-10° ... +10°
Displacement between land mark and aircraft	30 m or 15% of altitude whichever is larger

Table 3: Land Mark Updates Operational Limits

EXAMPLES

Example of Geometrical Correction

Figure 8 and figure 9 show recorded threshold pictures and results of the geometrical correction of runway EDVE 26 at Braunschweig airport. The recording was performed under daylight conditions in low approach.

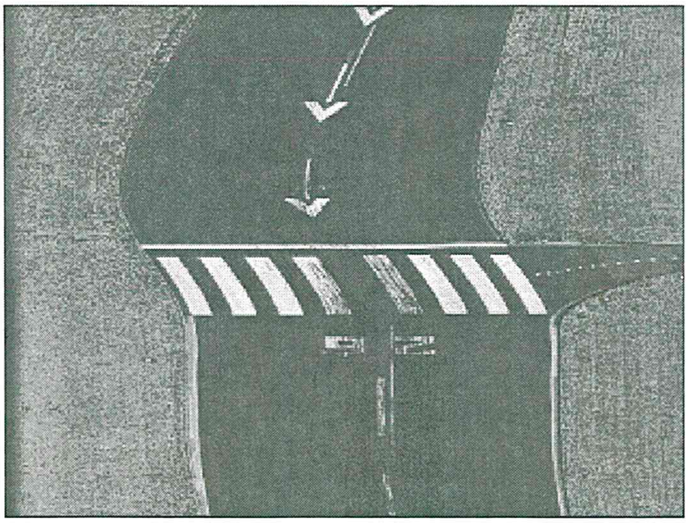

Figure 8: Uncorrected Image

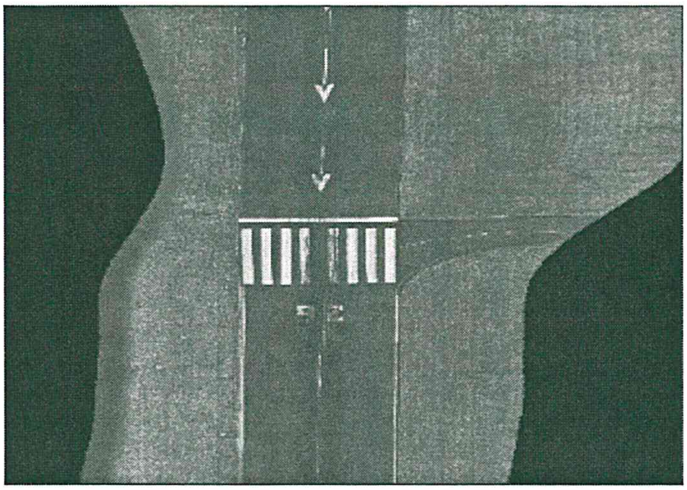

Figure 9: Geometrically Corrected Image

Example of Threshold Detection

Figure 10 shows a recorded threshold picture and the result of the threshold detection of runway EDVE 26 at Braunschweig airport in the AFIS GUI window.

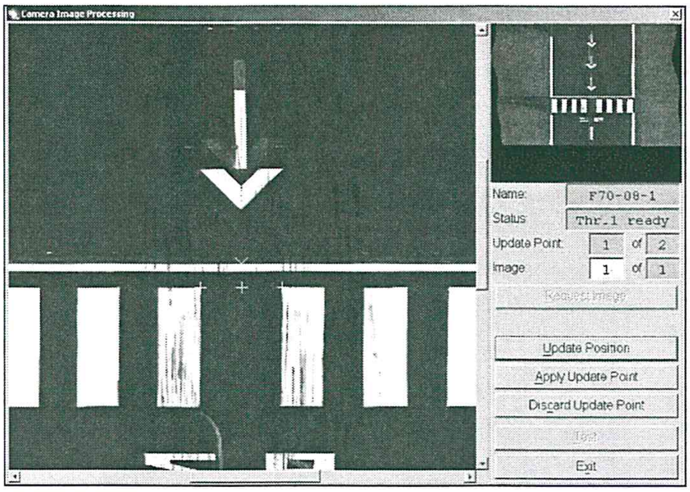

Figure 10: Threshold Detection shown in AFIS GUI

Figure 11 shows the result of the same threshold detection zoomed for a detailed view.

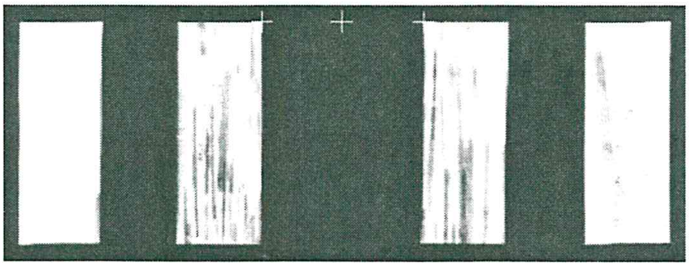

Figure 11: Threshold Detection (Zoomed)

Example of Landmark Update

Figures 12 to 14 show recorded images for manual landmark updates.

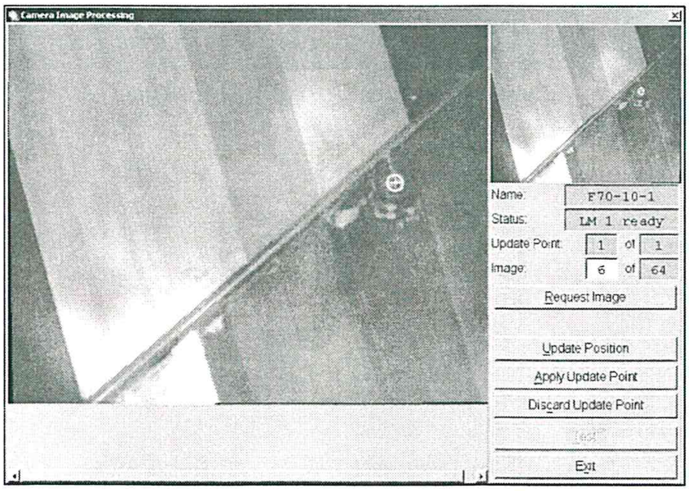

Figure 12: VOR Landmark shown in AFIS GUI

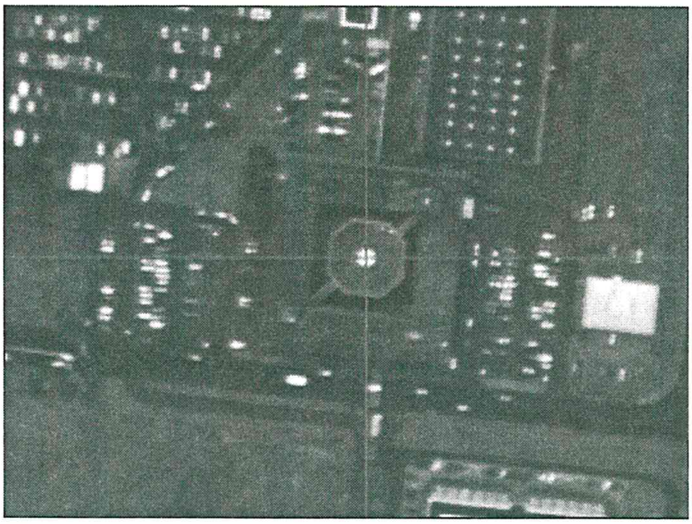

Figure 13: Roof Top Used as Landmark Update

RESULTS

Accuracy Demonstration of the Camera System

Line Scan Camera

The line scan camera position was compared with the offline IRS, P-DGPS and barometric altitude (BaroAlt) coupling solution.

The error in y-direction depends on the height above the threshold and is conditional on the view direction of the camera which is not parallel to the vertical axes of the aircraft.

An error in x-direction occurs mainly from non-parallel mounting of the camera in accordance to the horizontal axes of the aircraft. For the following diagnosis this mounting error was calculated to 0.0265 radian (approximately 1.5°).

After correction of this mounting offset the obtained accuracy of the camera position in y-direction is better than 20 cm. The error of the x-direction is <50 cm for all investigated threshold updates (see table 4 and figure 14).

Flight Height h [m]	Error dx [m]	Error dy [m]
14,6	-0,326	0,195
20,4	-0,114	0,084
23,3	-0,287	0,008
24,7	0,248	0,068
26,0	0,403	0,044
27,0	-0,224	0,003
316,0	-0,465	0,463
324,1	-0,455	-0,506

Table 4: Accuracy of Threshold Updates

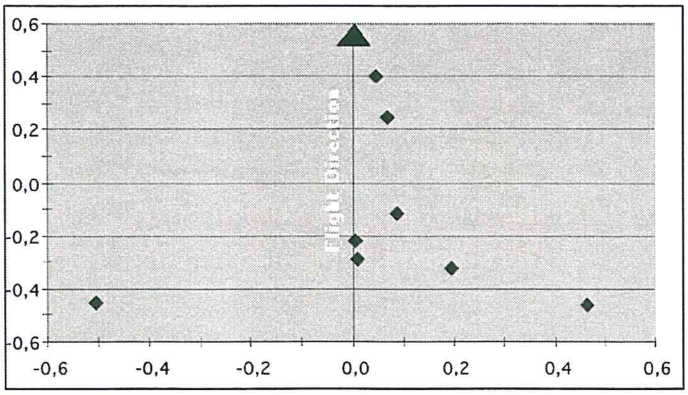

Figure 14: Position Errors of the Line Scan Camera

Area Scan Camera

The area scan camera landmark update was compared with the offline IRS/P-DGPS coupling solution.

The error in y-direction depends on the height above the landmark and is conditional on the view direction of the camera which is not parallel to the vertical axes of the aircraft.

An error in x-direction occurs mainly from non-parallel mounting of the camera in accordance to the horizontal axes of the aircraft. For the following diagnosis this mounting error was calculated to 0.02 radian (approximately 1.1°).

After correction of this mounting offset the obtained accuracy of the camera position in y-direction is better than 5 m. The error of the x-direction is less than 5 m for all investigated camera positions (see table 5 and figure 15).

Flight height h [m]	Error dx [m]	Error dy [m]
408,0	2,377	1,231
503,0	4,870	-1,790
928,1	2,943	3,118

Table 5: Accuracy of Landmark Updates

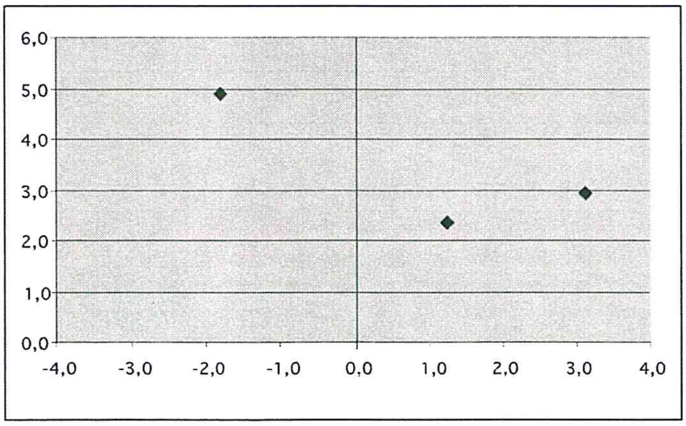

Figure 15: Position Errors of the Area Scan Camera

Position Estimation using Camera System, Single-GPS, IRS and Altitude Sensors

Results Under Typical Conditions

The target is to check the accuracy of the Estimated Position Error (EPE) of the offline position estimation using laser altimeter, camera system, SGPS, radio altimeter, BaroAlt and IRS under typical conditions. The IRS, P-DGPS and BaroAlt coupled offline solution will be used as reference.

The tests will be performed for a GP Bottom Approach and for an ILS Fly Down. The following data will be used:

Date	Facility	Description
24.05.2002	EDVE 26: GP	GP Bottom Approach
02.07.2002	EDVE 08	ILS Fly Down

Table 6: Used data for position estimation

Figure 16 and figure 17 show the plausibility of the EPE for the GP Bottom Approach. The figures contain the difference (displayed in blue color) between the offline solution and the reference solution. The EPE limits are displayed in red color. Moreover, the difference between the SGPS height and the reference solution has been added in green color for a better analysis of the results.

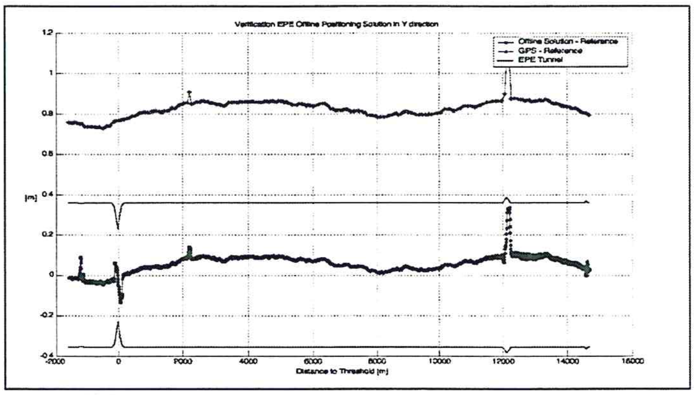

Figure 16: EPE Check of the Position Estimation for a GP Bottom Approach in Y-Direction

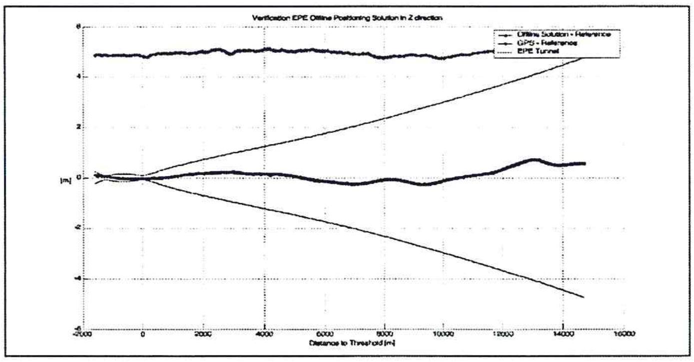

Figure 17: EPE Check of the Position Estimation for a GP Bottom Approach in Z-Direction

Figure 18 and figure 19 show the accuracy of the position estimation for the GP Bottom Approach. The figures contain the required EPE (red curve) as well as the calculated EPE (blue curve).

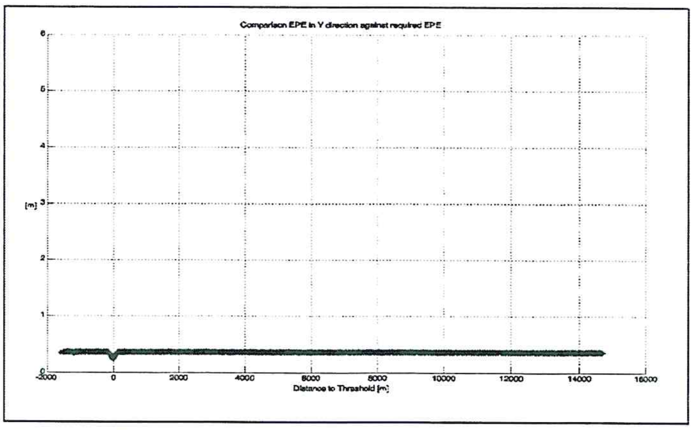

Figure 18: Accuracy Check of the EPE for a GP Bottom Approach in Y-Direction

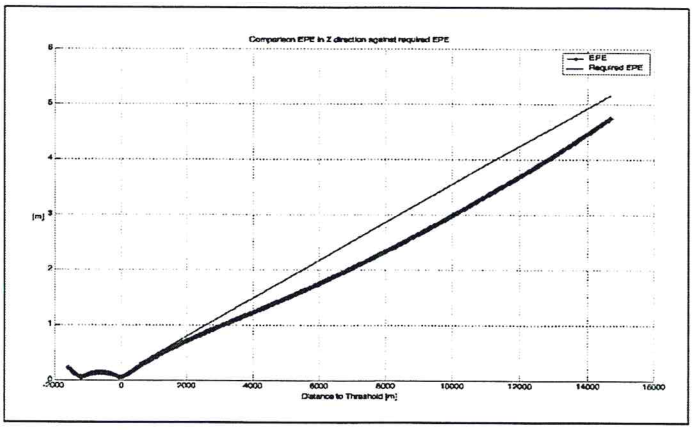

Figure 19: Accuracy Check of the EPE for a GP Bottom Approach in Z-Direction

Figure 20 and figure 21 show the plausibility of the EPE for the ILS Fly Down. The figures contain the difference (displayed in blue color) between the offline solution and the reference solution. The EPE limits are displayed in red color. Moreover, the difference between the SGPS height and the reference solution has been added in green color for a better analysis of the results.

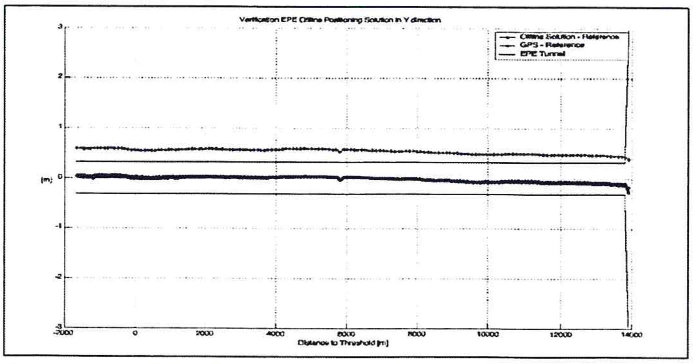

Figure 20: EPE Check of the Position Estimation for an ILS Fly Down in Y-Direction

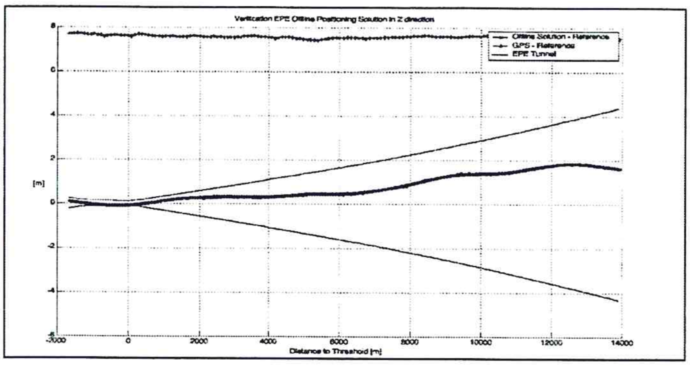

Figure 21: EPE Check of the Position Estimation for an ILS Fly Down in Z-Direction

Figure 22 and figure 23 show the accuracy of the position estimation for the ILS Fly Down approach. The figures contain the required EPE (red curve) as well as the calculated EPE (blue curve).

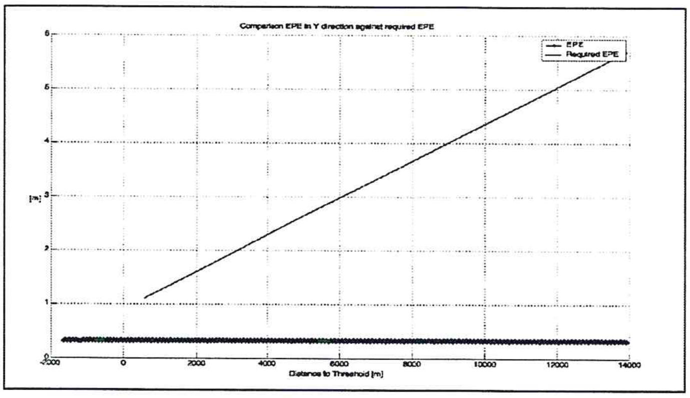

Figure 22: Accuracy Check of the EPE for an ILS Fly Down in Y-Direction

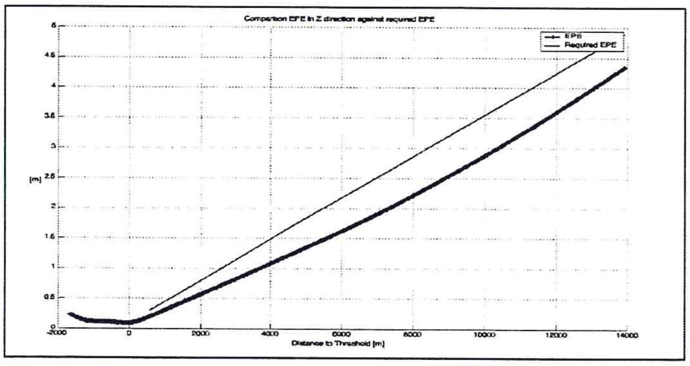

Figure 23: Accuracy Check of the EPE for an ILS Fly Down in Z-Direction

As well for the GP Bottom Approach as for the LLZ Fly Down, the difference between the offline solution and the reference solution is always within the EPE limits. It validates, that the EPE is in the 95% reliability interval. The calculated EPE is always below the required EPE.

The peak that can be observed for the GP Bottom Approach at Y-direction in figure 16 at 12000 m in front of the threshold is due to an outage of the reference data concerning the reference solution.

CONCLUSION

The paper has presented the AD-AFIS-400 camera system for position updates of approach flights and en-route landmark updates. This camera system has been identified as a reliable and accurate position update system.

The integration of a camera system with line scan camera, area scan camera and laser altimeter within the AFIS is able to substitute laser tracker and/or P-DGPS operation. The main benefit results from the renunciation of landings to put down a ground crew for ground station installation and operation.

It is shown, that the camera system in conjunction with the IRS, single GPS solution and subsidiary altitude sensors is suitable for ILS CAT III flight inspection procedures.

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