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A real-time simulation environment for aircraft vision-based autonomous landing system design

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Abstract—In the strive for always more safe and autonomous operations for civil aviation the landing phase remains by far the most challenging. Robustifying the already existing automatic landing system, classically based on exteroceptive sensors, with vision-based solutions have recently demonstrated promising perspectives. Nonetheless, the design and validation of such novel algorithms comes at enormous costs and logistic effort for installation, in-flight data collection and testing. In this paper a novel simulation platform, named SCHEMIN, for rapid conception, prototyping and testing of vision-based control solutions at very low cost and time-scale is presented. The software/hardware architecture is implemented to guarantee tight and high-fidelity coupling between flight dynamics and visual environment models, allowing for state observation, computer vision processing, virtual sensor data fusion and full aircraft control. The system is also able to easily and safely simulate system failures and off-nominal degraded conditions at any level. The platform has been validated in open-loop against real flight-test data recordings. The proposed architecture will also play an important role for conception and testing of learning-based algorithms for autonomous landing in a close future.

Index Terms—Vision Systems for Automation and Robotics, Implantable Sensors for Robotic Applications, Simulation and Modeling of Robotic Systems

I. INTRODUCTION

Among the different flying phases of an aircraft (A/C), the landing remains the most challenging one. Recent studies have focused on finding new robust approaches to either assist pilots or safely and autonomously land a fixed wing aircraft. In case of absence of precise on-ground equipment, such as the Instrument Landing Systems radio-emitters (ILS CAT-III), allowing for flight-path deviations sensing with respect to the ideal descent trajectory, alternatives with exteroceptive sensors have been envisaged to offer flexible solutions. The use of onboard vision sensors have appeared as a natural and low cost solution to provide an estimation of the relative position of the A/C w.r.t. its destination runway during Final Approach Segment (FAS) and landing phase [1], [2]. To reduce prototyping

costs and time for developing new autonomous landing vision-based control strategies, a dedicated simulation platform, able to recreate highly realistic flight conditions, from both flight physics and visual rendering standpoints, has recently been developed at ONERA.

Multiple computer-vision solutions for landing applications have been proposed in recent years ranging from civil aircraft [3], [4] and carrier [5] to general aviation [6] and UAVs [7], mostly based on two different control approaches, *i.e.* either estimating the 3D pose and orientation of the A/C w.r.t the runway or computing relative distances estimated directly from the image [8]. Both methods rely on runway features detection/extraction from the image. This may vary in function of the time of day (daylight/night), camera sensor typology and resolution (color/greyscale - visible/infrared) and mission requirements [9]–[12]. Certainly, the A/C dynamics, and thus the camera motion, affects runway detection and control performances significantly [13]. To that matter, the use of different optical sensors and/or additional sensors have been investigated. In particular, Multisensor Data Fusion (MDF) algorithms hybridizing stereo camera information with GPS/GNSS, inertial measurements (IMU), or thermal sensors have been recently proposed in [7], [14]–[16]. The development of such vision-based data fusion approaches motivates the need for reliable and powerful computing units at a design stage. As presented in [17], time delays are systematically introduced by the image processing software layer that will affect any downstream estimation process. All these findings justify the hardware/software requirements for the proposed real-time simulation platform. Likewise, as demonstrated in [13], the impact of the aircraft dynamics on the runway detection algorithms performance makes the vision-based landing system conception strongly application dependent, impeding the technological transfer among different carriers. This endorses the need for a generic and flexible simulation mean that will enable fast designing and testing phases when developing

any new vision-based control architecture for A/C autonomy. Such platform, unlike existing open-source simulation means, such as Airsim [18], is specifically design for civil aviation use cases and could eventually provide auxiliary data for certification purposes of autonomous systems in critical flight conditions.

This paper details and analyses the new SCHEMIN platform developed at ONERA in the TRT (Trusted and Resilient Trajectory) project framework, led by AIRBUS UpNext and cofunded by the DGAC organization (Civil Aviation General Directorate). To illustrate some of the functionalities offered by the platform and its overall representativeness, a novel vision-based control strategy for autonomous landing is proposed. This latter is fed by flight-path deviations w.r.t. a reference descent trajectory that are estimated through time from an original implementation of an Extended Kalman Filter (EKF) that accounts for both “classical” (GPS/GNSS, IMU, air data probes, radio altimeter, etc.) and vision-based measurements issued from synthetic image processing.

The paper is organized as follows: Section II presents the SCHEMIN platform hardware/software architecture; Section III describes an example of vision based-control strategy for the autonomous landing of an airliner; Section IV assesses the performances of global algorithmic pipeline by comparing some results obtained in simulation with real flight data recordings; Section V ends the article with some conclusions and perspectives.

II. SCHEMIN SIMULATION PLATFORM

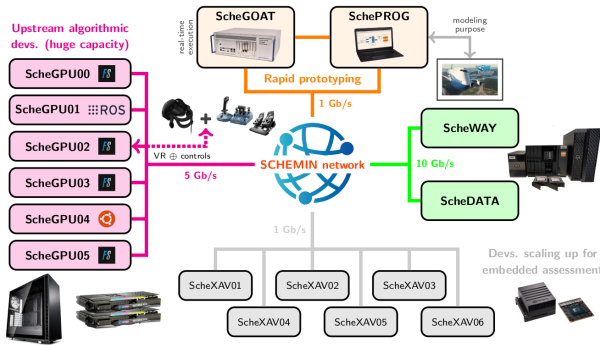


Fig. 1: SCHEMIN platform architecture

SCHEMIN is an ONERA simulation platform which has the ambition of simulating realistic flight conditions in order to design, test and validate a new generation of autopilots accounting for vision-based information. Figure 1 illustrates the overall SCHEMIN architecture and the available units. The structure is advantageously modular which offers a large variety of applications. All units communicate by an UDP protocol through an internal network provided by ScheWAY, which serves as a global orchestrator and access-point for batch processing, represented on the right side of Figure 1. A data storage unit, ScheDATA, provides 240 TB to gather real flight data and record simulated flight in order to facilitate debugging and analysis of simulation results.

On the left-hand side the high-performance processing units, referred as ScheGPU0X are gathered. Each ScheGPU0X are equipped with an AMD Ryzen 9 3900XT 12-core processor with 128Go of RAM and NVIDIA GeForce RTX 3090 graphic cards. The architecture has voluntarily multiple operating systems and middlewares: ScheGPU01 and ScheGPU04 runs on Linux with a ROS (Robot Operating System) Noetic and ROS2 Foxy distribution, and are mainly used to run the computer vision algorithms; the other ScheGPU0X runs on Windows 10 computers with ROS2 Foxy distribution, and are employed to couple the realistic world rendering of Microsoft Flight Simulator 2020 (MSFS) to an external flight dynamic model. At the moment, MSFS provides the best rendering on the market as well as an infinite possibility of customization as illustrated by the comparison in Figure 2. MSFS offers with its *simconnect* API the possibility of overwriting the aircraft’s state and impose pose and orientation from external sources. A Virtual Reality (VR) headset and a set of joystick, throttle and rudder pedals controllers of an Airbus complete the architecture and are connected to ScheGPU02 for human in-the-loop testing.



Fig. 2: Visual comparison between a real image (left) and its representation in MSFS (right)

On the center-top of Figure 1 the rapid prototyping computer set is illustrated. It is composed of a programming unit, SchePROG (a 64 Bits Windows 10 with an Intel Core i7-10850H processor), allowing for building and deploying on a Speedgoat real-time target machine Matlab/Simulink code. It is specifically employed for fully nonlinear aircraft dynamics modeling and low level controllers implementation. This set-up complies with the platform generality requirement allowing for simulating any aircraft or Unmanned Aerial Vehicle (UAV) and any ad-hoc controllers. For embeddability evaluation of any conceived algorithms the architecture is equipped with NVIDIA®Jetson AGX Xavier™ illustrated on the center-bottom of Figure 1 and refereed as ScheXAV0X.

The overall communication synchronization, for real-time performances, is handled with TCPROS and UDPROS protocols inside the SCHEMIN network. ROS2 is preferred for communications with and between Windows computers while ROS runs on Linux machines for guaranteeing stability of some open-source packages, i.e. *libuvc_camera* to process the MSFS video stream captured with a Flint 4K Pro game device. Matlab ROS toolbox guarantees correct interface and communication of the Speedgoat real-time machine in the overall closed-loop architecture.

SCHEMIN allows to potentially simulate any aircraft, design and test a large variety of autopilot logic (with and without the pilot in the loop), reproduce with a high level of realism any weather and visual conditions anywhere in the world. The feasibility and performance assessment of new vision-based control algorithms can be advantageously done at a low human and financial costs.

III. VISUAL-BASED CONTROL STRATEGY

For validation purposes, a visual-based control strategy for aircraft landing needed to be implemented and compared with real flight data available. In this section, the main algorithm and its sub-functions are presented. An accurate and validated Boeing 747 mathematical model [19] is chosen as use case for the simulation environment and implemented on SchePROG.

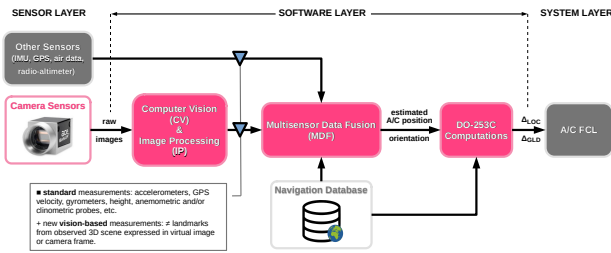


Fig. 3: Vision-based autonomous landing function architecture.

Visual servoing consists in using a vision sensor and computer vision algorithms in order to control the motion of the system [8]. Two control strategies can be distinguished, the Pose Based Visual Servoing (PBVS) and the Image Based Visual Servoing (IBVS). While the first method relies on a relative knowledge of the target to estimate the pose and attitude of the camera with respect to the target, the second one offers more flexibility on the target's characteristics knowledge as its features can be expressed in relative terms in the image [13]. PBVS solutions are more advantageous allowing separation of estimation and guidance control problems. The estimation of the aircraft deviations w.r.t the reference descent path and the guidance law, computing reference pitch, roll rate and vertical speed can hence be conceived and implemented separately [4], [20]. Such approach tend to facilitate integration and certification process for aviation authorities. For all these reasons, a PBVS solution has been chosen for implementation in SCHEMIN to mimic an ILS-like function enriched with camera sensor.

For the validation use case, the virtual camera is positioned above the pilots cockpit behind the windshield, for consistency with the available real flight-data available. As proposed in [17], [21], and illustrated with Figure 3, visual information are treated as additional measurements inputs in an original EKF globally improving the aircraft states estimation performance while guaranteeing robustness against other sensors' failure.

The software lawyer in Figure 3 is composed by an Image Processing (IP) block providing a measure of the runway

center-line to the Multisensor Data Fusion (MDF) filter required for the A/C state estimation. This is done with a Region Of Interest and Runway Detection (ROI+RuDe) algorithmic pipeline which combines both image area tracking (ROI) and runway centerline detection (RuDe) capabilities. The IP is an adaptation of the works led by D. Dickmanns [22] and K. Schertler [23]. This tracking technique is an adaptation of the MEDIANFLOW tracker of the OpenCV library which appeared to be the most suitable solution for processing a video stream. The ROI is initialized with a GPS measurement and, taking advantage of the known camera intrinsic and extrinsic calibration, allows for image cropping around the runway and a more accurate and robust center-line detection. This also prevents undesirable correlation effects in the EKF.

It is worth mentioning, the SCHEMIN platform allows for integrating any image processing pipeline and hybridizing techniques with any simulated sensors. The MDF layer aims at estimating with a sufficient precision the absolute position of the A/C (see Figure 3), which plays a pivotal role for aircraft navigation in many close-to-the-ground operations. Referring to A/C landing flight phase, it is noteworthy that standard DO-253C [24] allows to mathematically reconstruct both lateral DEVLOC and vertical DEVGLD deviations with respect to destination runway as:

$$DEVLOC = K_{LOC} \times \tan^{-1} \left(\frac{\mathbf{u}_{lat} \cdot (\mathbf{r}_{A/C}^{ECEF} - \mathbf{r}_{LOC}^0)}{|\mathbf{u}_{rwy} \cdot (\mathbf{r}_{A/C}^{ECEF} - \mathbf{r}_{LOC}^0)|} \right)$$

$$DEVGLD = K_{GLD} \times \tan^{-1} \left(\frac{\mathbf{u}_{ver} \cdot (\mathbf{r}_{A/C}^{ECEF} - \mathbf{r}_{GLD}^0)}{\sqrt{D}} \right) - \Delta_0,$$

$$D = [\mathbf{u}_{rwy} \cdot (\mathbf{r}_{A/C}^{ECEF} - \mathbf{r}_{GLD}^0)]^2 + [\mathbf{u}_{lat} \cdot (\mathbf{r}_{A/C}^{ECEF} - \mathbf{r}_{GLD}^0)]^2$$

In previous equations, the orthogonal triplet $(\mathbf{u}_{rwy}, \mathbf{u}_{lat}, \mathbf{u}_{ver})$ defines the destination runway frame whose origin coincides with destination runway Landing Threshold Point (LTP). Factors (K_{LOC}, K_{GLD}) , as well as parameters \mathbf{r}_{LOC}^0 , \mathbf{r}_{GLD}^0 and Δ_0 , correspond to known quantities that can be computed easily from the navigation database available on board, see Figure 3. Therefore, the problem of reconstructing accurate reference inputs, DEVLOC and DEVGLD, for aircraft guidance during FAS relies entirely on the knowledge of $\mathbf{r}_{A/C}^{ECEF}$ i.e., the absolute position of the A/C expressed in the Earth-Centered Earth-Fixed (ECEF) frame.

Thereafter, the estimation of the absolute positioning vector $\hat{\mathbf{r}}_{A/C}^{ECEF}$ is performed by means of Vision-Aided Extended Kalman Filtering (VAEKF) techniques. An augmented non-linear state space representation of A/C navigation dynamics, denoted by \mathcal{M}_{NL} in the sequel, is derived from both navigation kinematic relationships and most relevant sensors errors to be estimated (e.g., accelerometers/gyrometers biases, misleading cameras calibrations, air data probes inconsistencies, etc.). Such a dynamic modeling can be mathematically formulated as follows:

$$\mathcal{M}_{NL} : \begin{cases} \dot{\mathbf{X}}(t) = f(\mathbf{X}(t), \mathbf{Y}_m(t)) \\ \mathbf{Y}(t_k) = g(\mathbf{X}(t_k)) \end{cases}$$

Previous formulation describes a continuous-time process modeling with discrete-time output observation. In function of the available measurements and their related sensors errors, to be estimated, different state vector formulations can be adopted within SCHEMIN VAEKF scheme. For instance, for the proposed use case, the following state vector has been considered:

$$\mathbf{X} = (V_N \ V_E \ V_z \ \delta_E \ \lambda_E \ z \ b_{n_{x_m}} \ b_{n_{y_m}} \ b_{n_{z_m}} \ b_{\psi_{cam}} \ b_{\theta_{cam}} \ b_{\varphi_{cam}})^T$$

where $(V_N \ V_E \ V_z)$ refers to the North-East-Down (NED) velocities of the aircraft; $(\delta_E \ \lambda_E \ z)$ corresponds to its latitude, longitude and geodetic altitude (polar positioning coordinates in ECEF frame); $b_{n_{x_m}}, b_{n_{y_m}}, b_{n_{z_m}}$ are accelerometric biases; and $(b_{\psi_{cam}} \ b_{\theta_{cam}} \ b_{\varphi_{cam}})$ models bias uncertainties on extrinsic camera calibration (orientation) that will be estimated through time.

IV. SCHEMIN VALIDATION THROUGH LANDING REPLAY

The SCHEMIN simulator is finally validated by replaying real flight data (FAS and landing) and comparing the deviation (DEVLOC, DEVGLD) computed by the PBVS in the synthetic environment against those computed on board based on GPS/GNSS signal, namely the baseline.

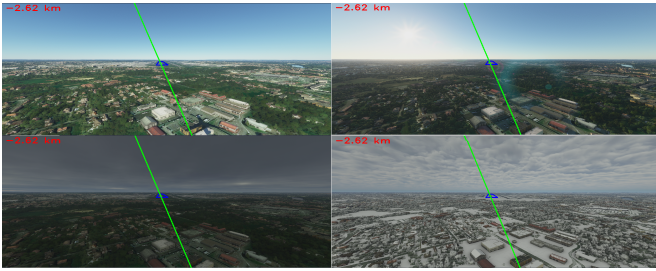


Fig. 4: Illustration of ROI+RuDe outputs for different weather conditions. From top-left clockwise: clear, sun-facing, snowy, cloudy.

Multiple landings at different airports have been replayed, however an example of a single batch of validation on Toulouse airport (LFBO) is hereafter reported for sake of brevity.

A single validation batch consists in replaying a real flight under several weather and time-of-the-day (for sunlight exposure) conditions, monitoring and recording the PBVS output. In its minimal configuration, for monocular camera use case, SCHEMIN operates by generating a synthetic video stream on ScheGPU00, coupled to the real-time aircraft pose evolution streamed by the Speedgoat, while SCHEGPU01 captures the images and executes the VAEKF. Figure 4 displays the outputs of ROI+RuDe algorithms on the synthetic images under various visual conditions. The ROI is represented as a blue parallelepiped, while the center-line is depicted as a green line. A valid center-line detection triggers the estimation of DEVLOC and DEVGLD deviations, upon reaching a distance of approximately 12km from the LTP, provided that a sufficient

number of pixels fall within the ROI. Figure 5 presents the deviations estimation over time and the corresponding errors against the on-board recorded baseline for the same visual condition of Figure 4. The lateral error (DEVLOC), has zero mean distribution and a standard deviation of about 0.1m, while the vertical error (DEVGLD) has a 0.8m mean and a 0.5m standard deviation. The greatest discrepancy occurs during a flight maneuver initiated at a distance of 6km from the LTP, resulting in a 3m lateral estimation error, while both errors tend to zero as the A/C to runway distance reduces. Satisfactory and consistent results are achieved across all visual conditions, proving the validity of the simulation architecture as well as the effectiveness of the PBVS method implemented.

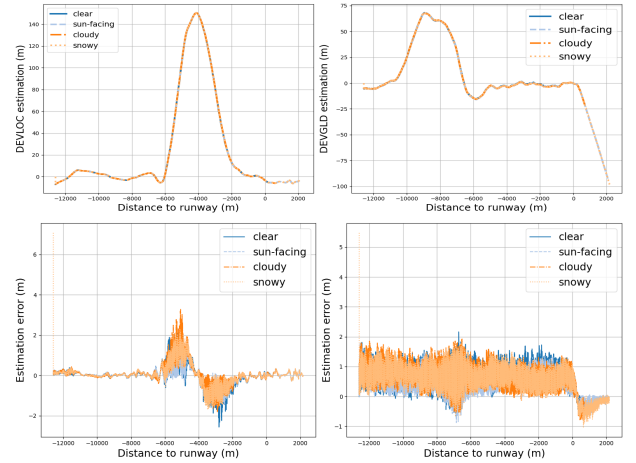


Fig. 5: Comparison of estimated deviations DEVLOC and DEVGLD (top subplots) with the associated estimation error (bottom subplots) for visual conditions illustrated in Figure 4.

Another important feature of the proposed simulation platform is the possibility of imposing arbitrary position offsets to the available flight data with the objective of exploring vision algorithms limitations in a safe and low-cost way. As an example, Figure 6 and Figure 7 showcase the effective performance of the implemented PVBS function for three different values of lateral ($\pm 50m$ and $\pm 200m$) and vertical ($\pm 2m$ and $10m$) offsets. As a result, it is possible to state that accurate vision-based DEVLOC and DEVGLD estimation can be retrieved as long as the runway is visible on the image.

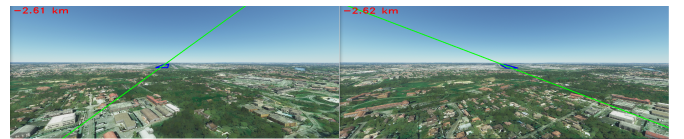


Fig. 6: Illustration of ROI+RuDe outputs for different offsets to the runway.

V. CONCLUSIONS

To conclude, this paper presented a new simulation platform developed at ONERA with the purpose of developing

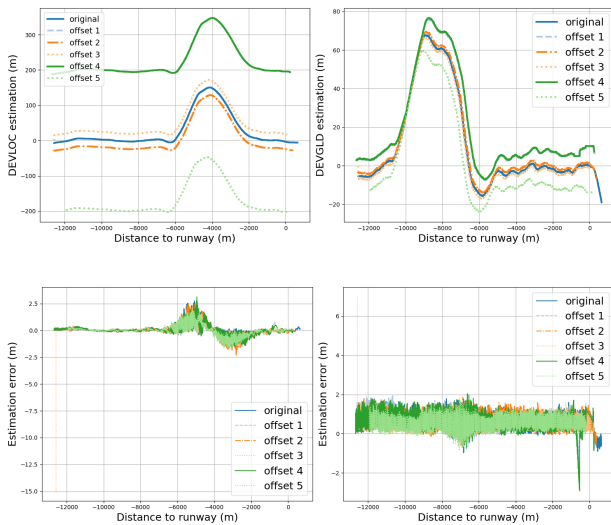


Fig. 7: Comparison of estimated deviations DEVLOC and DEVGLD (top subplots) with the associated estimation error in function of the distance to the runway LTP (bottom subplots) for replayed landings with imposed offsets to the runway.

and testing visual-based autonomous control laws with low logistic efforts and costs. This platform offers high fidelity aircraft behavior and visual environment with an advantageous flexibility of missions and flight conditions. To highlight the interest of the platform in the design and validation process of visual-based autonomous aircraft control, a PBVS strategy is implemented and discussed in this paper. The proposed strategy is decomposed in an ILS-like guidance law supplied by a vision-based multi-sensor data fusion for the aircraft's lateral and longitudinal deviations calculation w.r.t. the runway center-line. Promising preliminary results demonstrated the relevance of the SCHEMIN platform and its high-level of representativeness (when compared against off-line reprocessing of real flight data), as well as the validity of the proposed methodology. They also confirm the important role that such kind of simulation platform could play for pushing boundaries of civil aviation autonomous functions development flight in forthcoming future.

Future work will focus on exploiting the entire set of available machines for stereo vision algorithm development and multi-agent simulations. Likewise, runway detection with artificial neural networks and machine learning strategies will be investigated to reduce the use of geographical knowledge information.

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