UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

DOTTORATO IN INGEGNERIA INDUSTRIALE

XXXVII CICLO

Settore Scientifico Disciplinare: IIND-01/E
Impianti e Sistemi Aerospaziali

MULTI-SENSOR-BASED ENHANCED VISION TECHNIQUES TO SUPPORT APPROACH AND LANDING OPERATIONS IN URBAN AIR MOBILITY SCENARIOS

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La borsa di dottorato è stata cofinanziata con risorse del
Programma Operativo Nazionale Ricerca e Innovazione 2014-2020, risorse FSE REACT-EU
Azione IV.4 “Dottorati e contratti di ricerca su tematiche dell’innovazione”
e Azione IV.5 “Dottorati su tematiche Green”

A Zitone

Keywords

Multi-sensor navigation, Urban Air Mobility, Approach and landing procedures, Visual camera, FMCW radar, Data fusion, Extended Kalman Filter, Unmanned Aerial Vehicles, sensing requirements, Artificial Intelligence

Abstract

Approach and landing operations are among the most critical phases in aviation, accounting for a significant proportion of accidents due to challenges as low visibility conditions. These challenges are amplified in the emerging Urban Air Mobility (UAM) context, where Vertical Take-Off and Landing (VTOL) aircraft operate in densely populated urban environments, often with limited space and closer to potential obstacles. Existing navigation systems, such as the Instrument Landing System (ILS) and GNSS augmentation systems, are ill-suited to these scenarios due to their reliance on ground-based infrastructure, susceptibility to signal degradation in urban areas, or limitations in supporting variable approach trajectories. These factors necessitate the development of innovative onboard navigation solutions that minimize infrastructure dependency while ensuring robust, weather-resilient, and safe operations.

To address these challenges, this dissertation proposes a novel multi-sensor navigation architecture specifically designed for UAM approach and landing operations. The architecture integrates a GNSS receiver, an Inertial Measurement Unit (IMU), two visual cameras and an Frequency Modulated Continuous Wave (FMCW) radar. Each sensor complements the others, enabling a navigation solution capable of providing accurate state estimation throughout the approach and landing phases. The radar and cameras design prioritizes compatibility with the operational and regulatory constraints defined by international aviation authorities, such as European Union Aviation Safety Agency (EASA), including the integration of enhanced visual and radar-aiding navigation cues tailored to specific vertiport infrastructure.

The vision system leverages advanced computer vision techniques, including Convolutional Neural Network (CNN) for landing pattern detection and image processing techniques for tracking of the area of interest and keypoints extraction. The visual measurements are validated through integrity monitoring before being incorporated into a loosely coupled Extended Kalman Filter (EKF), ensuring precise pose estimation during critical flight phases. Meanwhile, the radar system complements the vision-based systems providing resilience to adverse visibility conditions and higher operative ranges. Radar data processing involves targets

detection and different matching algorithms exploiting the navigation state prediction of the EKF and the known position of the targets on the vertiport, enabling early and reliable detection of the landing area. The radar data is tightly integrated into the EKF, allowing the filter to extract navigation information even from limited number of targets correctly matched.

The performance of the proposed architecture is assessed through high-fidelity simulations and experimental validation. Simulations emulate realistic urban scenarios, including adverse visibility conditions, to evaluate the contributions of individual sensors and the overall multi-sensor system. The visual measurements prove essential to provide centimeter-level accuracy in the final phase of the approach trajectory, while the radar enables the navigation system to meet the assumed navigation performance requirements even at high ranges from the landing area and in adverse visibility. Experimental validation, conducted via scaled flight tests using Small Unmanned Aerial Vehicle (sUAV), demonstrates the effectiveness of the visual processing pipeline, including the ability to correctly distinguish between multiple landing patterns.

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Nomenclature and symbology

Symbol	***Definition***
s	Scalar
$\bar{v}$	Vector
$\bar{\hat{v}}$	Predicted value of a vector
$\bar{v}^-$	Variable estimated by the prediction step of the filter (a priori)
$\bar{v}^+$	Variable estimated by the correction step of the filter (a posteriori)
$\bar{\bar{M}}$	Matrix
A_s	Area illuminated by the main radar beam
$\bar{a}_s$	Spatial steering vector
$\bar{\bar{A}}$	Hessian matrix of iterative PnP solver
B	Radar signal bandwidth
c_0	Speed of light in vacuum
d	Distance along the horizontal axis to the center of the landing pad
F	Radar receiver noise figure
f	Frequency (of a radar signal)
$\bar{f}$	Focal length (camera sensor)
f_c	Central frequency (of a radar signal)
G	Antenna gain
h	Height above to the center of the landing pad
$\bar{\bar{H}}$	Measurement sensitivity matrix
$\bar{\bar{I}}_{\boldsymbol{n*n}}$	Identity matrix of dimensions *n*n*
$\overline{\overline{J(x)}}$	Jacobian matrix of the variable x
k_B	Boltzmann constant
$\overline{k_c}$	Distortion coefficients (camera intrinsic parameters)
$\bar{\bar{K}}$	Kalman gain
L	Sum of the sources of radar loss

L_{BS}	Beam-shaping loss
L_{FATO}	Dimension of the side of the FATO area
L_{TLOF}	Dimension of the side of the TLOF area
$\overline{\overline{M_A^B}}$	Rotation matrix from reference frame A to reference frame B
N_x	Number of antenna elements along *x* direction
P	Power (Tx: transmitted, Rx: received)
p	Air pressure
$\bar{p}$	Vehicle Position
$\bar{\bar{P}}$	Predicted state covariance matrix
$\overline{pp}$	Principal point
R	Slant range to a specific target or to the landing pattern
$\bar{\bar{R}}$	Measurement covariance matrix
r_r	Rain rate
res	Residual of the PnP solution
S_c	Chirp slope
T	Air temperature
t_x	Time of the x radar chirp parameter
Thr_x	Threshold on the parameter *x*
$(u,v)_x^i$	Pixel coordinates in the image plane of the points *x* at the frame acquired at instant *i*
v	Target radial velocity
$\bar{v}$	Vehicle velocity
$\bar{x}$	vehicle navigation state
β	Exteroceptive sensor mounting angle with respect to the horizontal body plane
Υ	Loss (related to radar signal)
δ	Grazing angle
$\delta\bar{x}$	Error vector corresponding to the vector $\bar{x}$
Δ	Resolution of a variable
ϑ	Slope of the first phase of the approach trajectory

Θ_{az}	Azimuth beamwidth of the radar antenna
Θ_{el}	Elevation beamwidth of the radar antenna
λ	Signal wavelength
μ	Mean of a statistical distribution
ν	Water vapor density
$\bar{\rho}$	Attitude error vector
σ	Standard deviation of a statistical distribution
σ_t	Radar Cross Section of a target
$\bar{\Psi}$	Vehicle attitude

Acronyms and abbreviations

Acronym	*Definition*
AAM	Advanced Air Mobility
ADC	Analog-to-Digital-Converter
AI	Artificial Intelligence
AoA	Angle of Arrival
ARNS	Aeronautical Radio Navigation Service
AT	AprilTag
Az	Azimuth
BB	Bounding Box
CAAC	Civil Aviation Administration of China
CA-CFAR	Cell Averaging Constant False Alarm Rate
CASA	Civil Aviation Safety Authority
CDGNSS	Carrier Phase Differential GNSS
CNN	Convolutional Neural Network
COPOSIT	COplanar Pose from Orthography and Scaling with ITerations
CRF	Camera Reference Frame
CVS	Combined Vision System
DL	Down Looking
DLR	German Research Center
DNN	Deep Neural Networks
DVE-M	Degraded Visibility Environment Mitigation
EASA	European Union Aviation Safety Agency
EFVS	Enhanced Flight Vision System
EHVS	Enhanced Helicopter Vision Systems
EKF	Extended Kalman Filter
El	Elevation
EM	Electromagnetic
EVS	Enhanced Vision System

eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FATO	Final Approach and Take Off
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FL	Forward Looking
FMCW	Frequency Modulated Continuous Wave
FOV	Field Of View
FPSL	Free-Space Path Loss
GBAS	Ground-Based Augmentation Systems
GNN	Global Nearet Neighbor
GNSS	Global Navigation Satellite System
HFOV	Horizontal Field of View
HMD	Helmet-Mounted Display
HPA	High-Power Amplifier
HPE	Horizontal Positioning Error
HPL	Horizontal Protection Level
HSV	Hue-Saturation-Value
HUD	Head Up Display
ICAO	International Civil Aviation Organization
IF	Intermediate Frequency
IFOV	Instantaneous Field Of View
IFP	Instrument Flight Procedure
ILS	Instrument Landing System
IMU	Inertial Measurement Unit
IR	InfraRed
LED	Light Emission Diodes
LiDAR	Light Detection And Ranging
LM	Levenberg-Marquardt
LNA	Low Noise Amplifier
LPF	Low Pass Filter

MAP	Missed Approach Procedure
MC	Monte Carlo
ML	Machine Learning
MLS	Microwave Landing System
MMW	Millimeter Wave
MTI	Moving Target Indicator
NASA	National Aeronautics and Space Administration
NED	NED
NIR	Near-Infrared
NL	Nadir-Looking
NN	Neural Network
OFV	Obstacle-Free Volume
OPV	Optionally Piloted Vehicle
PAPI	Precision Approach Path Indicator
PLA	Polylactic Acid
PnP	Perspective-n-Point
radar	Radio Detection And Ranging
RCS	Radar Cross Section
RF	Radio-Frequency
RGB	Red-Green-Blue
RIO	Radar-Inertial Odometry
RMSE	Root Mean Square Error
RNP	Required Navigation Performance
ROI	Region of Interest
ROS	Robot Operating System
RRF	Radar Reference Frame
RSS	Root Sum Square
SAA	Sense-and-Avoid
SBAS	Satellite-Based Augmentation Systems
SCR	Signal-to-Clutter-Ratio
SNCR	Signal-to-Noise-plus-Clutter-Ratio

SNR	Signal-to-Noise -Ratio
SVS	Synthetic Vision System
sUAV	Small Unmanned Aerial Vehicle
SWaP	Size Weight and Power
SWIR	Short-Wave Infrared
TLOF	Touch down and Lift-Off
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
UE4	Unreal Engine 4
UKF	Unscented Kalman Filter
VFOV	Vertical Field of View
VFR	Visual Flight Rules
VLS	Visual Landing System
VPE	Vertical Positioning Error
VPL	Vertical Protection Level
VRS	Vortex Ring State
VTOL	Vertical Take-Off and Landing
XSV	eXternal Vision System

Acknowledgements

Scrivere questa tesi mi ha dato l'opportunità di ripercorrere gli ultimi tre anni, un periodo intenso e formativo, probabilmente il più significativo della mia vita fino a oggi. Sono stati anni di cambiamento profondo, sia sul piano professionale che personale, in cui ho imparato che dedizione e costanza possono aprire porte impensabili e rendere possibile anche ciò che sembrava irraggiungibile. Ho scoperto che ogni sfida affrontata con coraggio ed entusiasmo – e persino ogni ostacolo superato con fatica – ha contribuito a costruire una versione di me più consapevole e determinata.

Ogni passo avanti che ho compiuto in questi anni, ogni successo, grande o piccolo, e ogni trasformazione che ne è derivata non sarebbero stati possibili senza le persone che mi hanno accompagnato lungo il cammino. Sono stati un sostegno continuo, sia nei momenti di difficoltà che in quelli di slancio, aiutandomi a superare le difficoltà e a celebrare i traguardi. A loro voglio dedicare poche parole, ma sincere e sentite, per esprimere tutta la mia gratitudine. Senza di loro, affrontare questo percorso sarebbe stato molto più difficile, se non impossibile.

Il primo e più sentito ringraziamento va alla mia ampia squadra di supervisori, che hanno rappresentato per me dei sensori fondamentali: integrando le loro "misure" con saggezza e competenza, hanno trasformato quella che inizialmente sembrava una discesa incerta e turbolenta di un ingenuo tesista in una traiettoria di atterraggio sicura e, soprattutto, indimenticabile. Giancarmine, ci sarebbero troppe ragioni per cui dovrei ringraziarti, e nessuna parola riuscirebbe davvero a esprimere quanto ti sia grato per aver creduto in me sin dall'inizio e per avermi dato l'opportunità di vivere questa esperienza. Più di tutto, però, voglio ringraziarti per aver sempre anteposto il rapporto umano a qualsiasi altra cosa: la tua infinita bontà e la tua capacità di tranquillizzarmi in ogni situazione hanno reso ogni sfida più semplice da affrontare, sempre accompagnata da preziosi consigli e infiniti aneddoti. Roberto, grazie per il tuo supporto instancabile, che tra una battuta e una revisione "senza pietà", mi ha spinto a non fermarmi mai di fronte alle difficoltà, a migliorare me stesso e credere nelle mie idee senza paura e, soprattutto, a riconoscere il mio valore, aiutandomi a costruire una

sicurezza che all'inizio faticavo a trovare. Carlo, grazie per tutto quello che mi hai insegnato in questi anni, sempre con l'inconfondibile tocco di ironia che rende ogni confronto stimolante e difficile da dimenticare. Ma, più di ogni altra cosa, grazie per esserti battuto affinché potessi vivere l'esperienza più straordinaria della mia vita - e con questo non mi riferisco solo ai voli in elicottero, ma a tutti i tre mesi a Portland, che porterò con me per sempre. Giacomo, grazie per essere stato sempre presente e per essere stato la mia guida verso il mondo aziendale. So bene che dall'esterno alcuni traguardi potrebbero sembrare piccoli, ma noi due sappiamo quanta fatica sia servita per raggiungerli e quanto ti sia battuto contro tutti affinché diventassero realtà. Infine, grazie Luca, supervisore (e motivatore) acquisito, per avermi trasmesso la tua infinita conoscenza e passione per la ricerca, contribuendo con entusiasmo al nostro progetto e credendo in noi più di chiunque altro.

Un grazie immenso a tutti i ragazzi del GNC Lab, per avermi accolto dal primo giorno di questo percorso ed averlo reso indubbiamente più ricco, più sopportabile nei momenti difficili e ancora più entusiasmante in quelli di successo. Abbiamo condiviso insieme la soddisfazione per ogni traguardo raggiunto e la frustrazione per ogni ostacolo incontrato, costruendo un ambiente che è andato ben oltre il semplice lavoro di ricerca. Non è possibile esprimere il senso di vuoto che mi porta il pensiero di poter salutare l'atmosfera familiare, le infinite discussioni tecniche (e non), l'ansia e la frenesia del campo volo, le serate gioco ed i momenti di puro divertimento vissuti insieme. Se porterò per sempre con me un ricordo straordinario di questi anni di dottorato, è anche merito vostro. Un ringraziamento speciale a Enrico, per l'inesauribile entusiasmo e determinazione che sei riuscito a trasmettermi in questi anni di amicizia, rendendo indimenticabili le tante esperienze (e viaggi) che abbiamo avuto la fortuna di condividere e mostrandomi sempre piena fiducia in ogni scelta.

Il pensiero più profondo e sentito va alla mia famiglia, la fonte inesauribile di amore e forza da cui attingo ogni giorno. Ai miei genitori, per il loro supporto costante e la capacità di guidarmi con saggezza e comprensione, anche quando il mio carattere riservato mi ha reso difficile condividere preoccupazioni legate al lavoro. A Martina, la mia più grande sostenitrice silenziosa, che con uno sguardo sa riconoscere ogni giornata negativa e con poche parole riesce sempre a distrarmi e a farmi ritrovare leggerezza, riportandomi alle passioni che ci legano. E a Zitone, il mio faro e modello di vita, che ogni giorno continua a risplendere nel mio cuore. So che sarebbe orgogliosa di vedermi crescere e realizzarmi, e questo pensiero mi accompagna sempre.

Ai miei amici, di vecchia data e di nuove avventure, vicini e lontani, quelli che hanno condiviso con me serate di leggerezza e quelli che, anche a distanza, hanno saputo farmi sentire il loro supporto nei momenti più intensi. Grazie per aver reso più sopportabili le follie delle scadenze e meno pesanti i silenzi dovuti alle difficoltà, bilanciando ogni ansia con il conforto e la spensieratezza della vostra compagnia. La vostra presenza è stata tante volte il mio rifugio, e non potrei sentirmi più fortunato ad avervi al mio fianco.

Infine, il ringraziamento più speciale va alla mia compagna della parte finale di questo viaggio, il cui sostegno ha reso più leggera la fase decisamente più intensa di questo percorso. Federica, non ci sono parole che possano davvero rendere giustizia alla tua pazienza infinita, alla tua dedizione incrollabile e alla straordinaria capacità con cui sai starmi accanto e comprendermi nonostante le mie poche parole. Sei stata il mio punto fermo anche quando tutto sembrava in movimento, la mia certezza quando ogni altra cosa sembrava incerta.

List of publications

- Articles published in scientific journals:
  - P. Veneruso, R. Opromolla, G. Gentile, C. Tiana, and G. Fasano, “Sensing Requirements and Vision-Aided Navigation Algorithms for Vertical Landing in Good and Low Visibility UAM Scenarios”. *Remote Sensing*, *14*, 3764. 2022 doi: https://doi.org/10.3390/rs14153764

- Articles submitted to scientific journals:
  - P. Veneruso *et al.*, “FMCW radar-aided navigation for unmanned aircraft approach and landing in AAM scenarios: system requirements and processing pipeline” *Sensors* - Submitted
  - E. Miccio, P. Veneruso, R. Opromolla, G. Fasano, G. Gentile, and C. Tiana, “Vision-aided Sensing Pipeline with AI-based vertiport detection for Precision Navigation in UAM Approach and Landing Scenarios” *Aerospace Science and Technology* – Submitted. doi: http://dx.doi.org/10.2139/ssrn.5059951

- Patents submitted with Collins Aerospace colleagues (details about the technical content are intentionally omitted in this dissertation):
  - C. Tiana, E. Miccio, P. Veneruso, and B. Helfrecht, “Real-time airfield identification and ground accurate incursion positioning system and method” submitted on 08/2024
  - B. Helfrecht, P. Veneruso, E. Miccio, and C. Tiana, “Navigation from sensors in GNSS-denied environments” submitted on 08/2024

- Articles published in conference proceedings:
  - P. Veneruso, E. Miccio, R. Opromolla, G. Fasano, C. Tiana, and G. Gentile, “Analysis of ground infrastructure and sensing strategies for all-weather approach and landing in Urban Air Mobility”, in *AIAA SCITECH 2023 Forum*, 2023. doi: https://doi.org/10.2514/6.2023-2225
  - P. Veneruso, E. Miccio, R. Opromolla, G. Fasano, G. Gentile, C. Tiana, "Vision aided approach and landing through AI based vertiport recognition", in *International Conference on Unmanned Aircraft Systems (ICUAS),* 2023, 1270-1277. doi: https://doi.org/10.1109/ICUAS57906.2023.10155914
  - P. Veneruso *et al.*, “Radar-visual navigation for all-weather approach and landing to vertiports”, in *2023 AIAA/IEE Digital Avionics Systems Conference*, 2023, pp. 1–10. doi: https://doi.org/10.1109/DASC58513.2023.10311212
  - E. Miccio, P. Veneruso, G. Fasano, C. Tiana, R. Opromolla, and G. Gentile, “AI-powered vision-aided navigation and ground obstacles detection for UAM approach and landing”, in *2023 AIAA/IEE Digital Avionics Systems Conference*, 2023, pp. 1–10. doi: https://doi.org/10.1109/DASC58513.2023.10311321
  - E. Miccio, P. Veneruso, G. Fasano, C. Tiana, R. Opromolla, and G. Gentile, “Vision-aided navigation for UAM approach to vertiports with multiple landing pads”, in *International Conference on Unmanned Aircraft Systems*

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- P. Veneruso *et al.*, “Assessing radar-aided navigation for UAM approach and landing through high-fidelity simulations and flight testing”, in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–9. doi: https://doi.org/10.1109/DASC62030.2024.10749214
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