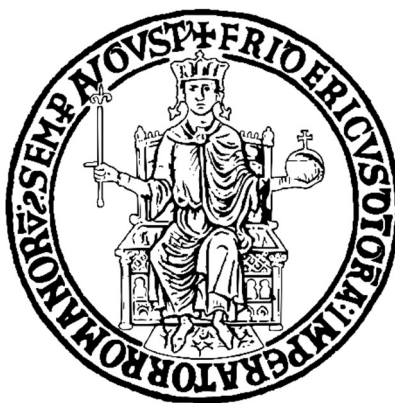




UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

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***

Paolo Veneruso

Relatori

Prof. Giancarmine Fasano
Prof. Roberto Opromolla
Dr. Carlo Tiana
Mr. Giacomo Gentile

Coordinatore

Prof. Michele Grassi



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.

Table of Contents

Keywords	iv
Abstract.....	v
Table of Contents	vii
List of Figures	ix
List of Tables	xiv
Nomenclature and symbology	xvi
Acronyms and abbreviations.....	xix
Acknowledgements.....	xxiii
Chapter 1: Introduction.....	1
1.1 Problem statement	4
1.2 State of the art.....	5
1.3 Dissertation outline and contributions	25
Chapter 2: Operating scenario and sensor requirements	30
2.1 Operating Scenario	31
2.2 Vision system requirements.....	36
2.3 FMCW radar system requirements.....	41
Chapter 3: Camera data processing.....	53
3.1 Camera selection and switch between cameras	57
3.2 CNN-based landing pattern detection and matching	59
3.3 Patterns matching.....	60
3.4 BB tracking logic.....	61
3.5 2D keypoints detection and matching.....	63
3.6 Pose estimation and integrity monitoring	67
3.7 Vision-aided Extended Kalman Filter	70
Chapter 4: FMCW radar data processing.....	74
4.1 Radar antenna system and waveform design.....	74
4.2 Radar signal processing and targets detection	79
4.3 Radar targets matching	81
4.4 2-D cross-correlation to detect and match targets in normalized radar images.....	83
4.5 Radar-aided Extended Kalman Filter	85
Chapter 5: Simulation-based performance assessment.....	90
5.1 Vision-aided EKF	90
5.2 Radar-aided EKF	105

Chapter 6:	Experimental assessment	122
6.1	Experimental Setups	122
6.2	Datasets.....	125
6.3	Results	129
6.4	Planned flight test activities.....	135
Chapter 7:	Conclusions.....	137
7.1	Summary.....	137
7.2	Future work.....	139
List of publications.....		142
Bibliography		144

List of Figures

Figure 1-1.	Examples of multirotor eVTOL aircraft on the left (Volocopter Volocity above [5] and EHang EH216 below [6]), vectored thrust aircraft on the central column (Lilium Jet above [7] and Joby Aviation S4 below [8]), and UAVs for cargo delivery on the right (Wing drone above [9] and Zipline drone below [10]).	2
Figure 1-2	Vertiport aspect foreseen by Volocopter GmbH [5].	3
Figure 1-3	Autonomous runway detection for aircraft landing as part of the DLR project ADVISE-PRO. Left: runway detection on IR image frames through contour extraction and segmentation of the runway corners [41]. Right: runway detection on MMW radar images through shadow correlation with a known pattern [42].	10
Figure 1-4	Collins Aerospace hardware to support EFVS operations. HUD on the left, HMD in the center, and EVS sensor suite on the right. <i>Image credit: Collins Aerospace.</i>	11
Figure 1-5	Development view of Daedalean AG's VLS, providing landing guidance based on AI-aided processing of high-resolution camera images [58].	13
Figure 1-6	3-D volume defined by EASA [14] (on the left) and FAA [13] (on the right) for UAM VFR approach and landing procedures. The aircraft must always fly above the defined volume.	15
Figure 1-7	Landing pattern for TLOF used for UAM VFR landing operations defined by EASA (left) [14] and FAA (right) [13].	16
Figure 1-8	Examples of markers from the 4 main families used in UAV applications: a) ARTag, b) AprilTag, c) ArUco, and d) STag [82].	18
Figure 1-9	Left: UAM landing pattern of 5 lines of lights proposed in reference [107] framed by the selected camera with NIR filter applied. Right: UAM Landing pattern of 3 ArUco markers [109] detected from the IR camera frames.	22
Figure 1-10	Left: FMCW radar-based landing system proposed by [128] with the selected landing area including 3 corner reflectors below an acrylic plane. Right: fixed-wing autonomous landing system aided by radar detections of 4 passive reflectors placed in correspondence of the runway sides adopted in [129].	25
Figure 1-11	Selected onboard multi-sensor navigation architecture.	26
Figure 2-1	OFV defined by EASA [14], in green, and potential approach trajectories in function of the slope angle (ϑ).	32
Figure 2-2	Selected landing pattern with the 4 high RCS targets placed at the corners of the FATO, in orange. The north-East axes of the NED reference frame are reported in yellow.	36

Figure 2-3	Approach trajectory projected on the North-Down plane, and radar beam extended geometry.	42
Figure 3-1	Flowchart of the implemented vision-aided navigation architecture. The sensors utilized for data acquisition are represented by colored rectangle blocks on the left. The light blue box denotes the EKF, while the orange box represents the <i>Camera processing</i> block, encompassing all image processing steps. Visual processing blocks detailed in this Chapter are indicated by dark blue rectangle boxes.	53
Figure 3-2	Mounting configuration of the two cameras onboard the aircraft. The overlap region defined by the two cameras is highlighted in green.	55
Figure 3-3	Proposed landing pattern based on the one defined by EASA in [14]. The selected keypoints of interest are highlighted on the pattern: points 1 2, 3, 4 are the square vertices; points A, B, C are the triangle vertices; AT1, AT2, AT3 are the three AprilTags.	56
Figure 3-4	Example of a critical condition. The full triangle is not enclosed in the collected frame, so its inner vertices are extracted.	58
Figure 3-5	Detection of a pattern that is partially present in the image frame.	61
Figure 3-6	Flowchart for BB detection and tracking in the image frame.	63
Figure 3-7	Features detection and matching applied in a scenario with fog presence.	65
Figure 3-8	Keypoints matching logic applied to a secondary pattern (i.e., Pattern 2). The keypoints reprojected onto the image plane through direct mapping and the vectors connecting the square center to its vertices are shown in red. The keypoints detected within the BBs and their corresponding vectors are depicted in black. The frame is captured at a distance of approximately 163 m.	67
Figure 3-9.	PnP solver and integrity checks flowchart.	70
Figure 4-1	Flowchart of the implemented processing to integrate radar signal in the multi-sensor EKF.	74
Figure 4-2	Airborne radar system - Data acquisition flowchart.	75
Figure 4-3	Antenna system geometry in RRF (in the plane at $z=0$).	76
Figure 4-4	Transmitter antenna array – normalized power pattern – broadside pointing angle.	76
Figure 4-5	Sawtooth radar waveform - Signal frequency vs Time representation.	77
Figure 4-6	Radar signal processing block - simplified workflow.	80
Figure 4-7	Flowchart for radar reflectors matching in radar targets list – Algorithm 1.	82

Figure 4-8	Flowchart for radar reflectors matching in 2D radar images – Algorithm 2.	85
Figure 4-9	Implemented multi-sensor navigation architecture obtained by integrating radar data processing in the architecture reported in Figure 3-1.	88
Figure 5-1	Comparison of synthetic image frames (left) and real helicopter flight test images (right).	91
Figure 5-2	Examples of four created urban scenarios, from top-left in a clockwise direction there are: Portland (OR, USA), Miami (FL, USA), Los Angeles (CA, USA), and London (UK).....	92
Figure 5-3	UE4 simulation of Portland heliport area under different conditions: nighttime (left) and fog (right).....	92
Figure 5-4	Implemented Simulink® model for simulation of camera data, from the <i>UAV Simple Flight Model</i> of the Simulink® UAV Toolbox.....	94
Figure 5-5	Landing pattern seen from different approach directions in two different synthetic scenarios (Portland and London).....	96
Figure 5-6	Positioning errors of the filter and of the LM accepted measurements, with their 3 sigma bounds (dotted lines) along the three directions as a function of the range from the landing pad. Results obtained from an MC analysis on Test Case 4. The plot scale is increased in the last 50 m to better show the errors in the final phase of the approach.....	98
Figure 5-7	Mean of the error and corresponding HPE/VPE of the EKF, and LM error with the 2σ bounds compared with HPL/VPL as a function of the range from the landing pad. Results obtained from an MC analysis on Test Case 4. The plot scale is increased in the last 50 m to better show the errors in the final phase of the approach.	99
Figure 5-8	RMSE along the three directions of the LM algorithm (in black) and the statistical mean of the square root of the corresponding diagonal components of the estimated measurement covariance matrix R (in blue). Results obtained from an MC analysis across all the test cases. The plot scale is increased in the last 50 m to better show the errors in the final phase of the approach.	100
Figure 5-9	Percentage of accepted LM measurements as a function of the range.	101
Figure 5-10	3D histogram showing the EKF and LM mean of the errors along the NED axes in function of the range intervals.....	103
Figure 5-11	3D histogram showing the EKF and LM standard deviation of the errors along the NED axes in function of the range intervals.	104
Figure 5-12	3D histogram showing the EKF and LM RMSE along the NED axes in function of the range intervals.....	104

Figure 5-13	3D histogram showing the EKF and LM maximum errors along the NED axes in function of the range intervals.....	105
Figure 5-14	Flowchart depicting the generation of synthetic sensor data and subsequent processing.	108
Figure 5-15	Scene generated using Ansys AVxcelerate Asset Preparation™ for radar data collection. Left: landing pattern with four corner reflectors placed at the vertices. Right: scenario near the landing area, showing buildings used to simulate radar signal clutter.	109
Figure 5-16	Azimuth-Range map of the received radar signal along the simulation environment. Left: slant range to the center of the landing pad: 311 m, height above the pattern: 142 m, $El=0^\circ$. Right: slant range to the center of the landing pad: 125 m, height above the pattern: 75 m, $El=-12^\circ$. The intensity of the peaks is represented as a function of the SNR. Yellow rings are used to circle the targets' reflections.	110
Figure 5-17	FL camera image frames acquired through MATLAB® + UE4 under varying visibility. Left: first usable frame under dense fog ($R_{max}, Cam = 89$ m). Right: first usable frame under nominal visibility ($R_{max}, Cam = 200$ m).	111
Figure 5-18	Average number of matched detections of the four corner reflectors during each complete elevation scan across all test cases.	113
Figure 5-19	Test Case 1: Mean of the EKF error and HPE/VPE bounds compared with HPL/VPL as a function of the range from the landing pad. Results obtained from an MC analysis. The plot scale is enlarged in the last 30 m to highlight the errors in the final phase of the approach.	114
Figure 5-20	Test Case 2: Mean of the EKF error and HPE/VPE bounds compared with HPL/VPL as a function of the range from the landing pad. Results obtained from an MC analysis. The plot scale is enlarged in the last 30 m to highlight the errors in the final phase of the approach.	115
Figure 5-21	Test Case 3: Mean of the EKF error and HPE/VPE bounds compared with HPL/VPL as a function of the range from the landing pad. Results obtained from an MC analysis. The plot scale is enlarged in the last 30 m to highlight the errors in the final phase of the approach.	116
Figure 5-22	Test Case 4: Mean of the EKF error and HPE/VPE bounds compared with HPL/VPL as a function of the range from the landing pad. Results obtained from an MC analysis. The plot scale is enlarged in the last 30 m to highlight the errors in the final phase of the approach.	117
Figure 5-23	3D histogram of the RMSE along the three axes in function of the range across the four test cases.	118

Figure 5-24	Single shot case 1. EKF-based Positioning Error along the NED axes for all the four test cases.....	119
Figure 5-25	Single shot case 2. EKF-based Positioning Error along the NED axes for all the four test cases.....	120
Figure 5-26	Single shot case 3. EKF-based Positioning Error along the NED axes for all the four test cases.....	121
Figure 6-1.	Setups used for flight test campaigns: 1. DJI Mini 2 (top-left), 2. F550 (bottom), 3. DJI M100 (top-right).....	124
Figure 6-2.	Example of the scaled pattern placed in the flight area.....	125
Figure 6-3	Samples from Dataset 1.1, used to test triangle keypoints detection and matching.	127
Figure 6-4.	Real image frames examples collected from two different flight campaigns. Left: Dataset 3., right: Dataset 2.1, 2.2. Patterns identification successful.	128
Figure 6-5	Samples images from Dataset 1.1 (left) and Dataset 1.2 (right) with the CNN detections and corresponding 2D keypoints identifications (the triangle perimeter is plotted through a red continuous line and its vertices through black dots).	129
Figure 6-6	Height and ground distance relative to the pattern in the LM estimates and GNSS measurements. The landing trajectory is a vertical approach to the pattern in the beach scenario shown in Figure 6-3 (right).	130
Figure 6-7.	LM measurements and EKF position estimates compared with the DJI estimates. Dataset 3. Processing keypoints data derived from the primary pattern only (red, N=1) or both patterns (blue, N=2). Slant distances range from 5.21 m to 3.22 m (scaled by 32) from the center of Pattern 1.....	132
Figure 6-8.	LM measurements and EKF position estimates compared with the DJI estimates. Dataset 2.1. Processing keypoints data derived from the primary pattern only (red, N=1) or both patterns (blue, N=2). Slant distances range from 6.71 m to 4.13 m (scaled by 32) from the center of Pattern 1.....	133
Figure 6-9.	LM measurements and EKF position estimates compared with the DJI estimates. Dataset 2.2. Slant distances range from 6.8 m to 2.8 m from the center of Pattern 1.....	134
Figure 6-10.	EKF position estimates compared with the DJI estimates in NED coordinates along the approach trajectory flown in Dataset 2.2. Scaled ranges to the landing pattern (1:32) between about 218 m and 89 m.	135
Figure 6-11	Picture from the test campaign including the four corner reflectors circled in orange and placed in correspondence of the landing area at a distance of 24 m one from each other.....	136

List of Tables

Table 1-I	Major characteristics of exteroceptive sensors used to support manned aircraft/UAV approach and landing operations.	7
Table 2-I	Vision system required parameters for airborne vision-aided navigation in UAM approach and landing operations (trajectory first descent slope of 21.9°)	41
Table 2-II	Airborne radar frequency bands characteristics.....	44
Table 2-III	Free-Space Path Loss in different radar frequency bands.	45
Table 2-IV	Atmospheric loss coefficient in different radar frequency bands.....	46
Table 2-V	Rain Loss Coefficient in different radar frequency bands and selected rain fall rates.	46
Table 2-VI	Antenna size for different radar frequency bands - $N_x = 24, N_y = 8, d = \lambda/2$	48
Table 2-VII	Minimum required transmitted power for different radar frequency bands at $R=400$ m.....	49
Table 2-VIII	Summary of the characteristics of the analyzed frequency bands in the UAM approach and landing use case.	49
Table 2-IX	Radar system requirements for airborne radar-aided targets detection in UAM approach and landing operations. *Parameters dependent on the selected center frequency of 32.85 GHz are marked with a double asterisk (**).	50
Table 3-I	Hyperparameters adopted for the training of the CNN-based detector.	60
Table 5-I	Key parameters of the simulated sensors	95
Table 5-II	Simulated approach trajectories	96
Table 5-III	Positioning performance in terms of means and standard deviation of the LM algorithm along three axes of the NED reference frame. The statistics are evaluated at 10 Hz coherently with the camera acquisition frequency.....	102
Table 5-IV	Positioning performance in terms of RMSE and maximum error of the LM algorithm along three axes of the NED reference frame. The statistics are evaluated at 10 Hz coherently with the camera acquisition frequency.....	102
Table 5-V	Positioning performance in terms of means and standard deviation of the filter along three axes of the NED reference frame. The	

	statistics are evaluated at 200 Hz coherently with the filter update frequency.	102
Table 5-VI	Positioning performance in terms of RMSE and maximum error of the filter along three axes of the NED reference frame. The statistics are evaluated at 200 Hz coherently with the filter update frequency.	103
Table 5-VII	Key parameters of the simulated radar system.	107
Table 5-VIII	RMSE on the NED axes computed at different range intervals on the MC analysis. The RMSE is evaluated across the four test cases considered through 100 simulations per test case.	118
Table 6-I	DJI mini 2 camera (video mode) specifications.	122
Table 6-II.	FLIR camera and lens parameters in second and third setups.	125
Table 6-III	Summary of the collected datasets.	128

Nomenclature and symbology

<i>Symbol</i>	<i>Definition</i>
s	Scalar
$\bar{v}$	Vector
$\hat{\bar{v}}$	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
$\bar{H}$	Measurement sensitivity matrix
$\bar{\bar{I}}_{n*n}$	Identity matrix of dimensions $n*n$
$\bar{\bar{J}}(x)$	Jacobian matrix of the variable x
k_B	Boltzmann constant
$\bar{k}_c$	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
Y	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

<i>Acronym</i>	<i>Definition</i>
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 Nearest 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 supportabile 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/IEEE 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/IEEE 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*

(ICUAS),

1184-1191.

doi:

<https://doi.org/10.1109/ICUAS60882.2024.10556929>

- 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>
- E. Miccio, P. Veneruso, G. Fasano, C. Tiana, R. Opromolla, and G. Gentile, “Integrated vision-aided precision navigation and obstacle detection sensing pipeline for UAM approach and landing”, in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–9. doi: <https://doi.org/10.1109/DASC62030.2024.10749415i>

Bibliography

- [1] Q. Long, J. Ma, F. Jiang, and C. J. Webster, “Demand analysis in urban air mobility: A literature review,” *J Air Transp Manag*, vol. 112, p. 102436, 2023, doi: <https://doi.org/10.1016/j.jairtraman.2023.102436>.
- [2] A. P. Cohen, S. A. Shaheen, and E. M. Farrar, “Urban Air Mobility: History, Ecosystem, Market Potential, and Challenges,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 9, pp. 6074–6087, 2021, doi: 10.1109/TITS.2021.3082767.
- [3] National Aeronautics and Space Administration, “Urban Air Mobility (UAM) Market Study,” 2018. Accessed: Nov. 08, 2024. [Online]. Available: <https://ntrs.nasa.gov/api/citations/20190001472/downloads/20190001472.pdf>
- [4] A. Bacchini and E. Cestino, “Electric VTOL Configurations Comparison,” *Aerospace*, vol. 6, no. 3, 2019, doi: 10.3390/aerospace6030026.
- [5] “Volocopter GmbH.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.volocopter.com/en>
- [6] “EHang.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.ehang.com/>
- [7] “Lilium.” Accessed: Nov. 08, 2024. [Online]. Available: <https://lilium.com/>
- [8] “Joby Aviation.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.jobyaviation.com/>
- [9] “Wing drone delivery.” Accessed: Nov. 08, 2024. [Online]. Available: <https://wing.com/>
- [10] “Zipline Drone delivery and logistics.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.flyzipline.com/>
- [11] A. Takacs and T. Haidegger, “Infrastructural Requirements and Regulatory Challenges of a Sustainable Urban Air Mobility Ecosystem,” *Buildings*, vol. 12, no. 6, 2022, doi: 10.3390/buildings12060747.
- [12] P. D. Vascik and R. J. Hansman, “Development of vertiport capacity envelopes and analysis of their sensitivity to topological and operational factors,” in *AIAA Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics Inc, AIAA, 2019. doi: 10.2514/6.2019-0526.
- [13] Federal Aviation Administration, “Engineering Brief No. 105, Vertiport Design,” 2022. Accessed: Oct. 16, 2022. [Online]. Available: <https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf>
- [14] European Union Aviation Safety Agency., “Vertiports - Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN), 2022.” Accessed: Mar. 27, 2022. [Online]. Available: <https://www.easa.europa.eu/en/downloads/136259/en>
- [15] B. I. Schuchardt *et al.*, “Air Traffic Management as a Vital Part of Urban Air Mobility—A Review of DLR’s Research Work from 1995 to 2022,” *Aerospace*, vol. 10, no. 1, 2023, doi: 10.3390/aerospace10010081.
- [16] M. Maly, C. Krammer, M. A. Wechner, J. Jaisle, J. Hoffelner, and F. Holzapfel, “Demonstration of a Procedure-Based Approach to Develop a Concept of Operations for Optionally Piloted Vehicles,” in *AIAA AVIATION 2023 Forum*. doi: 10.2514/6.2023-4195.

- [17] National Aeronautics and Space Administration., “UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4, 2021,” NASA/Deloitte Consulting LLP. Accessed: Jan. 10, 2022. [Online]. Available: <https://ntrs.nasa.gov/api/citations/20205011091/downloads/UAM%20Vision%20Concept%20of%20Operations%20UML-4%20v1.0.pdf>
- [18] A. Mathur *et al.*, “Paths to Autonomous Vehicle Operations for Urban Air Mobility,” in *AIAA Aviation 2019 Forum*, Nov. 2019. doi: 10.2514/6.2019-3255.
- [19] K. Schweiger and L. Preis, “Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations,” *Drones*, vol. 6, no. 7, 2022, doi: 10.3390/drones6070179.
- [20] D. Thipphavong *et al.*, “Urban Air Mobility Airspace Integration Concepts and Considerations,” in *2018 Aviation Technology, Integration, and Operations Conference*, Nov. 2018. doi: 10.2514/6.2018-3676.
- [21] International Civil Aviation Organization, “ICAO accident statistics.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.icao.int/safety/iStars/Pages/Accident-Statistics.aspx>
- [22] European Union Aviation Safety Agency., “Annual Safety Review 2024,” 2024. Accessed: Nov. 08, 2024. [Online]. Available: <https://www.easa.europa.eu/en/document-library/general-publications/annual-safety-review-2024#group-easa-downloads>
- [23] C. Ippolito *et al.*, “Concepts for Distributed Sensing and Collaborative Airspace Autonomy in Advanced Urban Air Mobility,” in *AIAA SciTech Forum and Exposition*, 2023.
- [24] E. R. Stefanescu, V. Chekh, A. Shastry, and T. Biresaw, “Advanced Air Mobility (AAM) Aircraft Precision Landing Design for Instrument Meteorological Conditions (IMC) Operations,” in *AIAA AVIATION FORUM AND ASCEND 2024*. doi: 10.2514/6.2024-3654.
- [25] E. Kawamura, C. Dolph, K. Kannan, T. Lombaerts, and C. A. Ippolito, “Simulated Vision-based Approach and Landing System for Advanced Air Mobility,” in *AIAA SCITECH 2023 Forum*, 2023.
- [26] S. Bijjahalli, R. Sabatini, and A. Gardi, “GNSS performance modelling and augmentation for urban air mobility,” *Sensors (Switzerland)*, vol. 19, no. 19, Oct. 2019, doi: 10.3390/s19194209.
- [27] F. Causa and G. Fasano, “Multiple UAVs trajectory generation and waypoint assignment in urban environment based on DOP maps,” *Aerosp Sci Technol*, vol. 110, p. 106507, 2021, doi: <https://doi.org/10.1016/j.ast.2021.106507>.
- [28] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*. 2011.
- [29] G. Gallego *et al.*, “Event-Based Vision: A Survey,” *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 44, no. 1, pp. 154–180, Jan. 2022, doi: 10.1109/TPAMI.2020.3008413.
- [30] M. Dreissig, D. Scheuble, F. Piewak, and J. Boedecker, “Survey on LiDAR Perception in Adverse Weather Conditions,” *2023 IEEE Intelligent Vehicles Symposium (IV)*, pp. 1–8, 2023, [Online]. Available: <https://api.semanticscholar.org/CorpusID:258108386>
- [31] UBER Elevate, “Fast-Forwarding to a Future of On-Demand Urban Air Transportation,” 2016. [Online]. Available: <http://inrix.com/scorecard/>

- [32] Federal Aviation Administration, “AC 90-106B - Enhanced Flight Vision System Operations,” 2022. Accessed: Nov. 08, 2024. [Online]. Available: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_90-106B.pdf
- [33] European Union Aviation Safety Agency, “Acceptable Means of Compliance (AMC) and Guidance Material (GM) to Annex IV Commercial air transport operations [Part-CAT],” 2017. Accessed: Nov. 08, 2024. [Online]. Available: <https://www.easa.europa.eu/en/official-publication>
- [34] International Civil Aviation Organization, “Annex 6 to the Convention on International Civil Aviation - Operation of Aircraft,” 2018. Accessed: Nov. 08, 2024. [Online]. Available: https://www.icao.int/publications/Documents/2018/Annex_6_Operations_of_Aircraft_Part_I_International_commercial_air_transport.pdf
- [35] Federal Aviation Administration, “AC 20-167A - Airworthiness Approval of Enhanced Vision System, Synthetic Vision System, Combined Vision System, and Enhanced Flight Vision System Equipment,” 2016. Accessed: Nov. 08, 2024. [Online]. Available: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-167A.pdf
- [36] Collins Aerospace, “Collins Aerospace - Vision Systems.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.collinsaerospace.com/what-we-do/industries/business-aviation/flight-deck/vision-systems>
- [37] A. Brailovsky *et al.*, “REVS: a radar-based enhanced vision system for degraded visual environments,” in *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions 2014*, J. J. Güell and J. Sanders-Reed, Eds., SPIE, 2014, p. 908708. doi: 10.1117/12.2053084.
- [38] L. Prinzel and L. Kramer, “Synthetic Vision Systems,” 2009. Accessed: Nov. 08, 2024. [Online]. Available: <https://ntrs.nasa.gov/api/citations/20090007635/downloads/20090007635.pdf>
- [39] Collins Aerospace, “Collins Aerospace receives milestone certification for CVS.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.collinsaerospace.com/news/news/2022/10/collins-receives-milestone-certification-for-combined-vision-systems>
- [40] J. Kerr, “Enhanced detection of LED runway/approach lights for EVS,” *Proceedings of SPIE - The International Society for Optical Engineering*, Nov. 2008, doi: 10.1117/12.764684.
- [41] H.-U. Doehler and B. R. Korn, “Autonomous infrared-based guidance system for approach and landing,” in *Enhanced and Synthetic Vision 2004*, J. G. Verly, Ed., in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 5424. Aug. 2004, pp. 140–147. doi: 10.1117/12.547107.
- [42] B. R. Korn, “Enhanced and synthetic vision system for autonomous all weather approach and landing,” in *Enhanced and Synthetic Vision 2007*, J. G. Verly and J. J. Güell, Eds., SPIE, 2007, p. 65590A. doi: 10.1117/12.722434.
- [43] B. Foote and J. Melzer, “A history of helmet mounted displays at Rockwell Collins,” in *Display Technologies and Applications for Defense, Security, and Avionics IX; and Head- and Helmet-Mounted Displays XX*, D. D. Desjardins, P. L. Marasco, K. R. Sarma, P. R. Havig, M. P. Browne, and J. E. Melzer, Eds., in Society of Photo-Optical Instrumentation Engineers (SPIE)

- Conference Series, vol. 9470. May 2015, p. 94700T. doi: 10.1117/12.2181337.
- [44] M. Zimmermann, M. Gestwa, C. König, J. Wolfram, S. Klasen, and A. Lederle, “First results of LiDAR-aided helicopter approaches during NATO DVE-mitigation trials,” *CEAS Aeronaut J*, vol. 10, no. 3, pp. 859–874, 2019, doi: 10.1007/s13272-018-0354-8.
 - [45] J. M. Ernst, S. Schmerwitz, T. Lueken, and L. Ebrecht, “Designing a virtual cockpit for helicopter offshore operations,” in *Proc.SPIE*, May 2017, p. 101970Z. doi: 10.1117/12.2262482.
 - [46] J. M. Ernst, L. Ebrecht, and B. Korn, “Virtual Cockpit Instruments—How Head-Worn Displays Can Enhance the Obstacle Awareness of Helicopter Pilots,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 36, no. 4, pp. 18–34, 2021, doi: 10.1109/MAES.2021.3052304.
 - [47] J. M. Ernst, N. Peinecke, L. Ebrecht, S. Schmerwitz, and H.-U. Doehler, “Virtual Cockpit: an immersive head-worn display as human–machine interface for helicopter operations,” *Optical Engineering*, vol. 58, no. 5, pp. 1–15, Jan. 2019, doi: 10.1117/1.OE.58.5.051807.
 - [48] Z. Szoboszlay *et al.*, “3D-LZ Flight Test of 2013: Landing an EH-60L Helicopter in a Brownout Degraded Visual Environment,” in *American Helicopter Society Annual Forum*, Nov. 2014. doi: 10.13140/2.1.4978.7525.
 - [49] J. D. Miller, M. Godfroy-Cooper, and Z. P. Szoboszlay, “Degraded Visual Environment Mitigation (DVE-M) Program, Bumper RADAR Obstacle Cueing Flight Trials 2020,” *Proceedings of the Vertical Flight Society 77th Annual Forum*, 2021, [Online]. Available: <https://api.semanticscholar.org/CorpusID:252948051>
 - [50] T. Dogaru, “Synthetic aperture radar for helicopter landing in degraded visual environments,” 2018.
 - [51] T. Dogaru, “Polar Format Algorithm for 3-D Imaging with Forward-Looking Synthetic Aperture Radar,” 2020.
 - [52] C. S. Kenyon, “Exploration of Ground Obstacle Visibility in a Degraded Visibility Environment by an Airborne Landing Radar,” 2021.
 - [53] United States Helicopter Safety Team, “Enhanced Helicopter Vision Systems Output Report Helicopter Safety Enhancement No. 91,” 2023. Accessed: Nov. 08, 2024. [Online]. Available: https://ushst.org/wp-content/uploads/2023/02/USHST_H-SE-91_Enhanced_Helicopter_Vision_Systems.pdf
 - [54] R. E. Bailey, S. J. Wilz, and J. J. Arthur, “Conceptual Design Standards for External Visibility System (Xvs) Sensor and Display Resolution,” 2013. [Online]. Available: <https://api.semanticscholar.org/CorpusID:106723097>
 - [55] K. J. Shelton, S. P. Williams, L. J. Kramer, J. J. Arthur, L. P. I. I. I, and R. E. Bailey, “External Vision Systems (XVS) proof-of-concept flight test evaluation,” in *Proc.SPIE*, Jun. 2014. doi: 10.1117/12.2048395.
 - [56] Collins Aerospace, “Enhanced Vision System: EVS-3600.” Accessed: Nov. 08, 2024. [Online]. Available: <https://www.collinsaerospace.com/landing/enhanced-vision-system-3600>
 - [57] R. E. Bailey, S. Williams, K. Kibler, and T. Arthur, “eXternal Vision System Development and Testing for X-59 Low Boom Flight Demonstrator,” in *AIAA AVIATION 2020 FORUM*. doi: 10.2514/6.2020-3087.

- [58] G. Balduzzi *et al.*, “Neural Network Based Runway Landing Guidance for General Aviation Autoland,” 2021.
- [59] Daedalean AG and European Union Aviation Safety Agency, “Concepts of Design Assurance for Neural Networks (CoDANN),” 2020. Accessed: Nov. 08, 2024. [Online]. Available: <https://www.easa.europa.eu/en/downloads/112151/en>
- [60] Daedalean AG and European Union Aviation Safety Agency, “Concepts of Design Assurance for Neural Networks (CoDANN) II,” 2021. Accessed: Nov. 08, 2024. [Online]. Available: <https://www.easa.europa.eu/en/downloads/128161/en>
- [61] Daedalean, “Daedalean’s Roadmap - Situational Awareness for Co-piloting and Autonomous Flight Control,” 2022.
- [62] Y. Li, Y. Xia, G. Zheng, X. Guo, and Q. Li, “YOLO-RWY: A Novel Runway Detection Model for Vision-Based Autonomous Landing of Fixed-Wing Unmanned Aerial Vehicles,” *Drones*, vol. 8, no. 10, 2024, doi: 10.3390/drones8100571.
- [63] Q. Wang, W. Feng, H. Zhao, B. Liu, and S. Lyu, “VALNet: Vision-Based Autonomous Landing with Airport Runway Instance Segmentation,” *Remote Sens (Basel)*, vol. 16, no. 12, 2024, doi: 10.3390/rs16122161.
- [64] D. Bharti, C. Prachand, and K. S. Venkatesh, “VLS-FWA: Real-time end-to-end neural network pipeline of vision-based landing system for fixed-wing aircraft,” in *2024 14th International Conference on Pattern Recognition Systems (ICPRS)*, 2024, pp. 1–7. doi: 10.1109/ICPRS62101.2024.10677823.
- [65] J.-G. Durand, A. Dubois, and R. J. Moss, “Formal and Practical Elements for the Certification of Machine Learning Systems,” in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference*, 2023, pp. 1–10.
- [66] K. S. Wasson and R. Voros, “Deobfuscating Machine Learning Assurance and Approval,” in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–10. doi: 10.1109/DASC62030.2024.10749638.
- [67] D. Nowak, G. Kopecki, D. Kordos, and T. Rogalski, “The PAPI Lights-Based Vision System for Aircraft Automatic Control during Approach and Landing,” *Aerospace*, vol. 9, no. 6, 2022, doi: 10.3390/aerospace9060285.
- [68] Federal Aviation Administration., “AC 150/5390-2C - Heliport Design, 2012.” Accessed: Jan. 07, 2022. [Online]. Available: https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf.
- [69] D. Zahn, R. Naru, A. Guion, and S. Eggum, “UAM Instrument Flight Procedure Design and Evaluation in the Joby Flight Simulator,” 2023.
- [70] D. Zahn, G. Patterson, E. Williams, S. Eggum, and T. Fettrow, “Flight Test Evaluation of Autonomous Descending-Decelerating Precision Point-in-Space Approach to the Ground,” in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–8. doi: 10.1109/DASC62030.2024.10749268.
- [71] Australian Government - Civil Aviation Safety Authority, “Guide to vertiport design,” 2024. Accessed: Nov. 08, 2024. [Online]. Available: <https://www.casa.gov.au/sites/default/files/2024-05/guide-to-vertiport-design.pdf>

- [72] EHang, “EHang’s Pilotless eVTOL Air Operator Certificate Application Accepted by CAAC.” Accessed: Nov. 08, 2024. [Online]. Available: <https://ir.ehang.com/news-releases/news-release-details/ehangs-pilotless-evtol-air-operator-certificate-application>
- [73] S. Shin and K. Lee, “Assessment of Approach and Departure Paths for Vertical Takeoff and Landing Aircraft,” *Journal of Aerospace Information Systems*, vol. 20, no. 12, pp. 917–922, Nov. 2023, doi: 10.2514/1.I011278.
- [74] M. Zintl *et al.*, “An Augmented Reality Pilot Assistance Concept for Advanced Air Mobility Aircraft Employing Simplified Vehicle Operations,” in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–9. doi: 10.1109/DASC62030.2024.10749170.
- [75] M. Zintl and F. Holzapfel, “A Landing Display Concept with an Augmented Reality Enhanced Camera View for Advanced Air Mobility Vehicles,” in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–7. doi: 10.1109/DASC62030.2024.10749461.
- [76] M. Zintl, S. Kimura, and F. Holzapfel, “A Mixed Reality Research Flight Simulator for Advanced Air Mobility Vehicles,” in *AIAA AVIATION FORUM AND ASCEND 2024*. doi: 10.2514/6.2024-4651.
- [77] L. Xin, Z. Tang, W. Gai, and H. Liu, “Vision-Based Autonomous Landing for the UAV: A Review,” *Aerospace*, vol. 9, no. 11, 2022, doi: 10.3390/aerospace9110634.
- [78] R. O. Prakash and C. Saravanan, “Autonomous robust helipad detection algorithm using computer vision,” in *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 2599–2604. doi: 10.1109/ICEEOT.2016.7755163.
- [79] C. Patruno, M. Nitti, A. Petitti, E. Stella, and T. D’Orazio, “A Vision-Based Approach for Unmanned Aerial Vehicle Landing,” *J Intell Robot Syst*, vol. 95, no. 2, pp. 645–664, 2019, doi: 10.1007/s10846-018-0933-2.
- [80] S. Lin, L. Jin, and Z. Chen, “Real-time monocular vision system for UAV autonomous landing in outdoor low-illumination environments,” *Sensors*, vol. 21, no. 18, Sep. 2021, doi: 10.3390/s21186226.
- [81] J. Shi, N. Schlautmann, X. Fang, M. Zintl, J. Dambeck, and F. Holzapfel, “Landing Pad Design for Optical-aided Automatic Vertical Take-off and Landing,” in *Proceedings of the 2024 CEAS EuroGNC conference*, Bristol, UK, 2024.
- [82] M. Kalaitzakis, B. Cain, S. Carroll, A. Ambrosi, C. Whitehead, and N. Vitzilaios, “Fiducial Markers for Pose Estimation,” *J Intell Robot Syst*, vol. 101, no. 4, p. 71, 2021, doi: 10.1007/s10846-020-01307-9.
- [83] L. Jayatilleke and N. Zhang, “Landmark-based localization for Unmanned Aerial Vehicles,” in *2013 IEEE International Systems Conference (SysCon)*, 2013, pp. 448–451. doi: 10.1109/SysCon.2013.6549921.
- [84] Z. Zhao, J. Lee, Z. Li, C. Hyuk Park, and P. Wei, “Vision-based Perception with Safety Awareness for UAS Autonomous Landing,” in *AIAA SCITECH 2023 Forum*, 2023.
- [85] F. V. Benitez, A. Rutherford, J. Van Hilst, E. Babcock, M. Schlieff, and L. Markussen, “A Vision-Based Approach to Autonomous Landing of an eVTOL Aircraft in GPS-Denied Environments,” in *2023 AIAA/IEEE Digital Avionics Systems Conference*, 2023.

- [86] J. Wubben *et al.*, “Accurate landing of unmanned aerial vehicles using ground pattern recognition,” *Electronics (Switzerland)*, vol. 8, no. 12, 2019, doi: 10.3390/electronics8121532.
- [87] O. Araar, N. Aouf, and I. Vitanov, “Vision Based Autonomous Landing of Multirotor UAV on Moving Platform,” *J Intell Robot Syst*, vol. 85, no. 2, pp. 369–384, 2017, doi: 10.1007/s10846-016-0399-z.
- [88] F. Hübner, S. Wolkow, A. Dekiert, M. Angermann, and U. Bestmann, “Assessment of Optical Markers for On-Board Autonomous Localization of eVTOLs during Landing,” in *2020 9th International Conference on Research in Air Transportation*, 2020. [Online]. Available: <https://api.semanticscholar.org/CorpusID:231631440>
- [89] F. Hübner, R. Haupt, U. Bestmann, and P. Hecker, “Navigation Augmentation for Landing on Vertipads Utilizing Optical Detection of Standard ICAO Circular Markings,” in *Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024)*, 2024, pp. 2031–2045.
- [90] J. Lee, S. Y. Choi, and T. Bretl, “The Use of Multi-Scale Fiducial Markers To Aid Takeoff and Landing Navigation by Rotorcraft,” in *AIAA SCITECH 2024 Forum*, 2024. doi: 10.2514/6.2024-0338.
- [91] A. Shastry and R. Stefanescu, “Fundamental understanding of vision in fog/low visibility conditions,” in *AIAA SCITECH 2024 Forum*, Nov. 2024. doi: 10.2514/6.2024-0335.
- [92] S. Xiang, M. Ye, S. Zhu, J. Gu, A. Xie, and Z. Men, “A Multi-stage Precision Landing Method for Autonomous eVTOL Based on Multi-marker Joint Localization,” in *2022 IEEE International Conference on Robotics and Biomimetics, ROBIO 2022*, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 2015–2020. doi: 10.1109/ROBIO55434.2022.10011837.
- [93] E. Kawamura, K. Kannan, T. Lombaerts, and C. A. Ippolito, “Vision-Based Precision Approach and Landing for Advanced Air Mobility,” in *AIAA SCITECH 2022 Forum*, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jan. 2022. doi: 10.2514/6.2022-0497.
- [94] K. Kannan *et al.*, “A Simulation Architecture for Air Traffic Over Urban Environments Supporting Autonomy Research in Advanced Air Mobility,” in *AIAA SciTech 2023 Forum*, 2023, p. 895.
- [95] D. Oberkampf, D. F. DeMenthon, and L. S. Davis, “Iterative Pose Estimation Using Coplanar Feature Points,” *Computer Vision and Image Understanding*, vol. 63, no. 3, pp. 495–511, 1996, doi: <https://doi.org/10.1006/cviu.1996.0037>.
- [96] E. Kawamura, C. Dolph, K. Kannan, N. Brown, T. Lombaerts, and C. A. Ippolito, “VSLAM and Vision-based Approach and Landing for Advanced Air Mobility,” in *AIAA SCITECH 2023 Forum*, in AIAA SciTech Forum. , American Institute of Aeronautics and Astronautics, 2023. doi: 10.2514/6.2023-2196.
- [97] N. Brown *et al.*, “Visual & Inertial Datasets for an eVTOL Aircraft Approach and Landing Scenario,” in *AIAA SCITECH 2024 Forum*, in AIAA SciTech Forum. , American Institute of Aeronautics and Astronautics, 2024. doi: 10.2514/6.2024-1386.
- [98] H. Wei, B. Lou, Z. Zhang, B. Liang, F.-Y. Wang, and C. Lv, “Autonomous Navigation for eVTOL: Review and Future Perspectives,” *IEEE Transactions*

- on *Intelligent Vehicles*, vol. 9, no. 2, pp. 4145–4171, 2024, doi: 10.1109/TIV.2024.3352613.
- [99] O. A. Yakimenko, I. I. Kaminer, W. J. Lentz, and P. A. Ghyzel, “Unmanned aircraft navigation for shipboard landing using infrared vision,” *IEEE Trans Aerosp Electron Syst*, vol. 38, no. 4, pp. 1181–1200, 2002, doi: 10.1109/TAES.2002.1145742.
 - [100] Y. Meng, W. Wang, H. Han, and J. Ban, “A visual/inertial integrated landing guidance method for UAV landing on the ship,” *Aerosp Sci Technol*, vol. 85, pp. 474–480, 2019, doi: <https://doi.org/10.1016/j.ast.2018.12.030>.
 - [101] L. Zhang, Z. Zhai, L. He, P. Wen, and W. Niu, “Infrared-Inertial Navigation for Commercial Aircraft Precision Landing in Low Visibility and GPS-Denied Environments,” *Sensors*, vol. 19, no. 2, 2019, doi: 10.3390/s19020408.
 - [102] X. Chen, F. Lin, M. R. A. Hamid, S. H. Teo, and S. K. Phang, “Real-Time Landing Spot Detection and Pose Estimation on Thermal Images Using Convolutional Neural Networks,” in *2018 IEEE 14th International Conference on Control and Automation (ICCA)*, 2018, pp. 998–1003. doi: 10.1109/ICCA.2018.8444340.
 - [103] I. Kalinov, E. Safronov, R. Agishev, M. Kurenkov, and D. Tsetserukou, “High-Precision UAV Localization System for Landing on a Mobile Collaborative Robot Based on an IR Marker Pattern Recognition,” in *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, 2019, pp. 1–6. doi: 10.1109/VTCSpring.2019.8746668.
 - [104] X. Chen, S. K. Phang, and B. M. Chen, “System integration of a vision-guided UAV for autonomous tracking on moving platform in low illumination condition,” in *Proceedings of the Institute of Navigation Pacific Positioning, Navigation and Timing Meeting, Pacific PNT*, The Institute of Navigation, 2017, pp. 1082–1092. doi: 10.33012/2017.15022.
 - [105] J. S. Wynn and T. W. McLain, “Visual Servoing for Multirotor Precision Landing in Daylight and After-Dark Conditions,” in *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2019, pp. 1242–1248. doi: 10.1109/ICUAS.2019.8798020.
 - [106] M. Faessler, E. Mueggler, K. Schwabe, and D. Scaramuzza, “A monocular pose estimation system based on infrared LEDs,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 907–913. doi: 10.1109/ICRA.2014.6906962.
 - [107] D. Akagi, T. McLain, and M. Joshua, “Robust IR-Based Pose Estimation for Precision VTOL Aircraft Landing in Urban Environments,” in *2024 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2024.
 - [108] L. Scholz, A. Dekiert, F. Hübner, and U. Bestmann, “Concept for Sensor and Processing Equipment for Optical Navigation of VTOL during Approach and Landing,” in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, 2022, pp. 1–7. doi: 10.1109/DASC55683.2022.9925802.
 - [109] A. Dekiert, F. Hübner, L. Scholz, and U. Bestmann, “Nonlinear Temperature Mapping for Infrared-Based Landing Site Detection,” in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, 2022, pp. 1–7. doi: 10.1109/DASC55683.2022.9925755.
 - [110] B. J. P. Hordijk, K. Y. W. Scheper, and G. C. H. E. de Croon, “Vertical landing for micro air vehicles using event-based optical flow,” *J Field Robot*,

- vol. 35, pp. 69–90, 2017, [Online]. Available: <https://api.semanticscholar.org/CorpusID:5946333>
- [111] G. Ebmer *et al.*, “Real-time 6-DoF Pose Estimation by an Event-based Camera using Active LED Markers,” in *2024 IEEE/CVF Winter Conference on Applications of Computer Vision (WACV)*, 2024, pp. 8122–8131. doi: 10.1109/WACV57701.2024.00795.
 - [112] Z. Jin, L. Nie, D. Li, Z. Tu, and J. Xiang, “An Autonomous Control Framework of Unmanned Helicopter Operations for Low-Altitude Flight in Mountainous Terrains,” *Drones*, vol. 6, no. 6, 2022, doi: 10.3390/drones6060150.
 - [113] M. Shah Alam and J. Oluoch, “A survey of safe landing zone detection techniques for autonomous unmanned aerial vehicles (UAVs),” *Expert Syst Appl*, vol. 179, p. 115091, 2021, doi: <https://doi.org/10.1016/j.eswa.2021.115091>.
 - [114] J. Castagno and E. Atkins, “Roof Shape Classification from LiDAR and Satellite Image Data Fusion Using Supervised Learning,” *Sensors*, vol. 18, no. 11, 2018, doi: 10.3390/s18113960.
 - [115] F. Liu, J. Shan, B. Xiong, and Z. Fang, “A Real-Time and Multi-Sensor-Based Landing Area Recognition System for UAVs,” *Drones*, vol. 6, no. 5, 2022, doi: 10.3390/drones6050118.
 - [116] M. Schurwanz, J. Mietzner, M. De Muirier, T. Tiedemann, and P. A. Hoehner, “Compressed Sensing-Based Obstacle Detection for Future Urban Air Mobility Scenarios,” *IEEE Sens Lett*, vol. 7, no. 11, pp. 1–4, 2023, doi: 10.1109/LSSENS.2023.3323867.
 - [117] K. Tan, T. Yin, H. Ruan, S. Balon, and X. Chen, “Learning Approach to FMCW Radar Target Classification With Feature Extraction From Wave Physics,” *IEEE Trans Antennas Propag*, vol. 70, no. 8, pp. 6287–6299, 2022, doi: 10.1109/TAP.2022.3175716.
 - [118] H. Arroyo *et al.*, “Segmentation of drone collision hazards in airborne RADAR point clouds using PointNet,” *IEEE Transactions on Intelligent Transportation Systems*, 2024.
 - [119] C. Miliadis *et al.*, “UAS-Borne Radar for Autonomous Navigation and Surveillance Applications,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 7, pp. 7215–7229, 2023, doi: 10.1109/TITS.2023.3254582.
 - [120] X. Cai, M. Giallorenzo, and K. Sarabandi, “Machine Learning-Based Target Classification for MMW Radar in Autonomous Driving,” *IEEE Transactions on Intelligent Vehicles*, vol. 6, no. 4, pp. 678–689, 2021, doi: 10.1109/TIV.2020.3048944.
 - [121] M. R. Ozdemir, A. F. Kucuk, G. Inalhan, B. Baspinar, and S. Ertekin, “Machine Learning Based Radar Cross-Section Clustering Towards Enhanced Situational Awareness for Next-Generation Fighter Aircraft,” in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–8. doi: 10.1109/DASC62030.2024.10749317.
 - [122] J. Michalczyk, R. Jung, and S. Weiss, “Tightly-Coupled EKF-Based Radar-Inertial Odometry,” in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2022, pp. 12336–12343. doi: 10.1109/IROS47612.2022.9981396.

- [123] Y. Almalioglu, M. Turan, C. X. Lu, N. Trigoni, and A. Markham, "Milli-RIO: Ego-Motion Estimation With Low-Cost Millimetre-Wave Radar," *IEEE Sens J*, vol. 21, no. 3, pp. 3314–3323, 2021, doi: 10.1109/JSEN.2020.3023243.
- [124] C. Doer, J. Atman, and G. F. Trnmmer, "GNSS aided Radar Inertial Odometry for UAS Flights in Challenging Conditions," in *2022 IEEE Aerospace Conference (AERO)*, 2022, pp. 1–10. doi: 10.1109/AERO53065.2022.9843326.
- [125] S. Wu, S. Decker, P. Chang, T. Camus, and J. Eledath, "Collision Sensing by Stereo Vision and Radar Sensor Fusion," *IEEE Transactions on Intelligent Transportation Systems*, vol. 10, no. 4, pp. 606–614, 2009, doi: 10.1109/TITS.2009.2032769.
- [126] T. Pavlenko, M. Schütz, M. Vossiek, T. Walter, and S. Montenegro, "Wireless Local Positioning System for Controlled UAV Landing in GNSS-Denied Environment," in *2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2019, pp. 171–175. doi: 10.1109/MetroAeroSpace.2019.8869587.
- [127] Y. Dobrev *et al.*, "Radar-Based High-Accuracy 3D Localization of UAVs for Landing in GNSS-Denied Environments," in *2018 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility, ICMIM 2018*, Institute of Electrical and Electronics Engineers Inc., Aug. 2018. doi: 10.1109/ICMIM.2018.8443483.
- [128] C. Doer, R. Koenig, G. F. Trommer, and E. Stumpf, "Radar Based Autonomous Precision Takeoff and Landing System for VTOLs in GNSS Denied Environments," in *2020 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2020, pp. 922–931. doi: 10.1109/ICUAS48674.2020.9213925.
- [129] D. Yasentsev, T. Shevgunov, E. Efimov, and B. Tatarskiy, "Using Ground-Based Passive Reflectors for Improving UAV Landing," *Drones*, vol. 5, no. 4, 2021, doi: 10.3390/drones5040137.
- [130] M. Brunelli, C. C. Ditta, and M. N. Postorino, "New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity," *J Air Transp Manag*, vol. 112, p. 102460, 2023, doi: <https://doi.org/10.1016/j.jairtraman.2023.102460>.
- [131] Webber D and Zahn D, "FAA and the National Campaign [Powerpoint]." Accessed: Feb. 20, 2022. [Online]. Available: <https://nari.arc.nasa.gov/aam-portal/recordings/>
- [132] "eVTOL Aircraft Directory." Accessed: Mar. 31, 2022. [Online]. Available: <https://evtol.news/aircraft>
- [133] E. Yilmaz, M. Warren, and B. J. German, "Energy and Landing Accuracy Considerations for Urban Air Mobility Vertiport Approach Surfaces," *AIAA Aviation 2019 Forum*, 2019.
- [134] M. Bahr, E. Ferede, and F. Gandhi, "Flight Characteristics of AAM/UAM-Scale Quadcopters Under Atmospheric Turbulence," in *Vertical Flight Society 78th Annual Forum & Technology Display*, 2022.
- [135] S. Zelinski, "Operational analysis of vertiport surface topology," in *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, Institute of Electrical and Electronics Engineers Inc., Oct. 2020. doi: 10.1109/DASC50938.2020.9256794.

- [136] EUSPA - European Union Agency for the Space Programme, “Report on Aviation and Drones,” 2023.
- [137] O. García Crespillo, C. Zhu, M. Simonetti, D. Gerbeth, Y.-H. Lee, and W. Hao, “Vertiport navigation requirements and multisensor architecture considerations for urban air mobility,” *CEAS Aeronaut J*, 2024, doi: 10.1007/s13272-024-00749-3.
- [138] J. Park, I. Kim, J. Suk, and S. Kim, “Trajectory optimization for takeoff and landing phase of UAM considering energy and safety,” *Aerosp Sci Technol*, vol. 140, p. 108489, 2023, doi: <https://doi.org/10.1016/j.ast.2023.108489>.
- [139] Federal Aviation Administration, “AC 20-167A - Airworthiness Approval of Enhanced Vision System, Synthetic Vision System, Combined Vision System, and Enhanced Flight Vision System Equipment,” 2016.
- [140] N. K. Link, R. v Kruk, D. McKay, S. A. Jennings, and G. Craig, “Hybrid enhanced and synthetic vision system architecture for rotorcraft operations,” in *Proc.SPIE*, Jul. 2002. doi: 10.1117/12.474424.
- [141] G. R. Curry, *Radar System Performance Modeling, Second Edition*. Artech, 2004. [Online]. Available: <http://ieeexplore.ieee.org/document/9101140>
- [142] ITU-R M.2204, “Characteristics and spectrum considerations for sense and avoid systems use on unmanned aircraft systems (UAS).”
- [143] Federal Communications Commission, “Table of Frequency Allocations Chart,” 2015. Accessed: May 13, 2023. [Online]. Available: <https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf>
- [144] A. Goldsmith, *Wireless Communication, 1st ed., Cambridge University*. 2005.
- [145] R. I.-R. P. 676-12 ITU, “Attenuation by atmospheric gases and related effects, (ITU-R P.676),” 2020.
- [146] I.-R. P. 838-3 ITU, “Specific attenuation model for rain for use in prediction model, (ITU-R P.838-3),” 2005.
- [147] R. S. Elliott, “‘Beamwidth and Directivity of Large Scanning Arrays,’ Last of Two Parts,” *The Microwave Journal*, pp. 74–82, 1964.
- [148] C. A. Balanis, *Antenna Theory – Analysis and design, 3rd Edition*. Wiley-Interscience, John Wiley & Sons., 2005.
- [149] “FCC, PETITION OF SIERRA NEVADA CORPORATION FOR RULEMAKING ,” 2018. [Online]. Available: <https://ecfsapi.fcc.gov/file/10216097800681/Petition%20for%20Rulemaking.SNC.pdf>
- [150] Mark A. Richards, *Fundamental of Radar Signal Processing, 2nd Ed*. McGraw Hill Education, 2014.
- [151] T. and R. R. Ch. V. Sohan Mupparaju and Sai Ram, “A Review on YOLOv8 and Its Advancements,” in *Data Intelligence and Cognitive Informatics*, S. and F.-G. P. Jacob I. Jeena and Piramuthu, Ed., Singapore: Springer Nature Singapore, 2024, pp. 529–545.
- [152] “Ultralytics YOLOv8.” Accessed: Nov. 05, 2023. [Online]. Available: <https://docs.ultralytics.com/models/yolov8/#usage-examples>
- [153] “Kaggle.” Accessed: Sep. 04, 2023. [Online]. Available: <https://www.kaggle.com/learn/intro-to-deep-learning>
- [154] 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 on 12/2024, doi:
<http://dx.doi.org/10.2139/ssrn.5059951>.

- [155] E. Miccio, P. Veneruso, R. Opromolla, G. Fasano, C. Tiana, and G. Gentile, "Integrated Vision-Aided Precision Navigation and Obstacle Detection Sensing Pipeline for UAM Approach and Landing," in *2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC)*, 2024, pp. 1–9. doi: 10.1109/DASC62030.2024.10749415.
- [156] "Camera Calibration Toolbox for Matlab." Accessed: Nov. 20, 2023. [Online]. Available:
<http://robots.stanford.edu/cs223b04/JeanYvesCalib/htmls/parameters.html>
- [157] R. Opromolla, C. Vela, A. Nocerino, and C. Lombardi, "Monocular-Based Pose Estimation Based on Fiducial Markers for Space Robotic Capture Operations in GEO," *Remote Sens (Basel)*, vol. 14, no. 18, 2022, doi: 10.3390/rs14184483.
- [158] R. Szeliski, *Computer Vision - Algorithms and Applications*. Springer, 2011.
- [159] C. Van Loan, "Computing integrals involving the matrix exponential," *IEEE Trans Automat Contr*, vol. 23, no. 3, pp. 395–404, 1978, doi: 10.1109/TAC.1978.1101743.
- [160] P. Kelly, M. Majji, and F. Guzmán, "Estimation and Error Analysis for Optomechanical Inertial Sensors," *Sensors*, vol. 21, no. 18, 2021, doi: 10.3390/s21186101.
- [161] P. Groves, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, Second Edition*. Artech, 2013. [Online]. Available:
<http://ieeexplore.ieee.org/document/9101092>
- [162] J. B. Gao and C. J. Harris, "Some remarks on Kalman filters for the multisensor fusion," *Information Fusion*, vol. 3, no. 3, pp. 191–201, 2002, doi: [https://doi.org/10.1016/S1566-2535\(02\)00070-2](https://doi.org/10.1016/S1566-2535(02)00070-2).
- [163] R. Costa and E. Chadwick, "Signal Processing and Range Spreading in FM-CW radar," 1984.
- [164] F. Rosique, P. J. Navarro, C. Fernández, and A. Padilla, "A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research," *Sensors*, vol. 19, no. 3, 2019, doi: 10.3390/s19030648.
- [165] 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.