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Advances in Detect and Avoid for Unmanned Aircraft Systems and Advanced Air Mobility

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Preface

- Detect and Avoid / Sense and Avoid as one of the major roadblocks that have hindered civil operations, and thus as a key point for UAS integration

- Starting from the need of "equivalent level of safety", a significant evolution has been experimented… actually leading to different DAA "frameworks"

- Lecture objective:
  - Clarify the main elements of a DAA system and their interfaces
  - Show some technological trends and research experiences*
  - Discuss challenges and perspectives

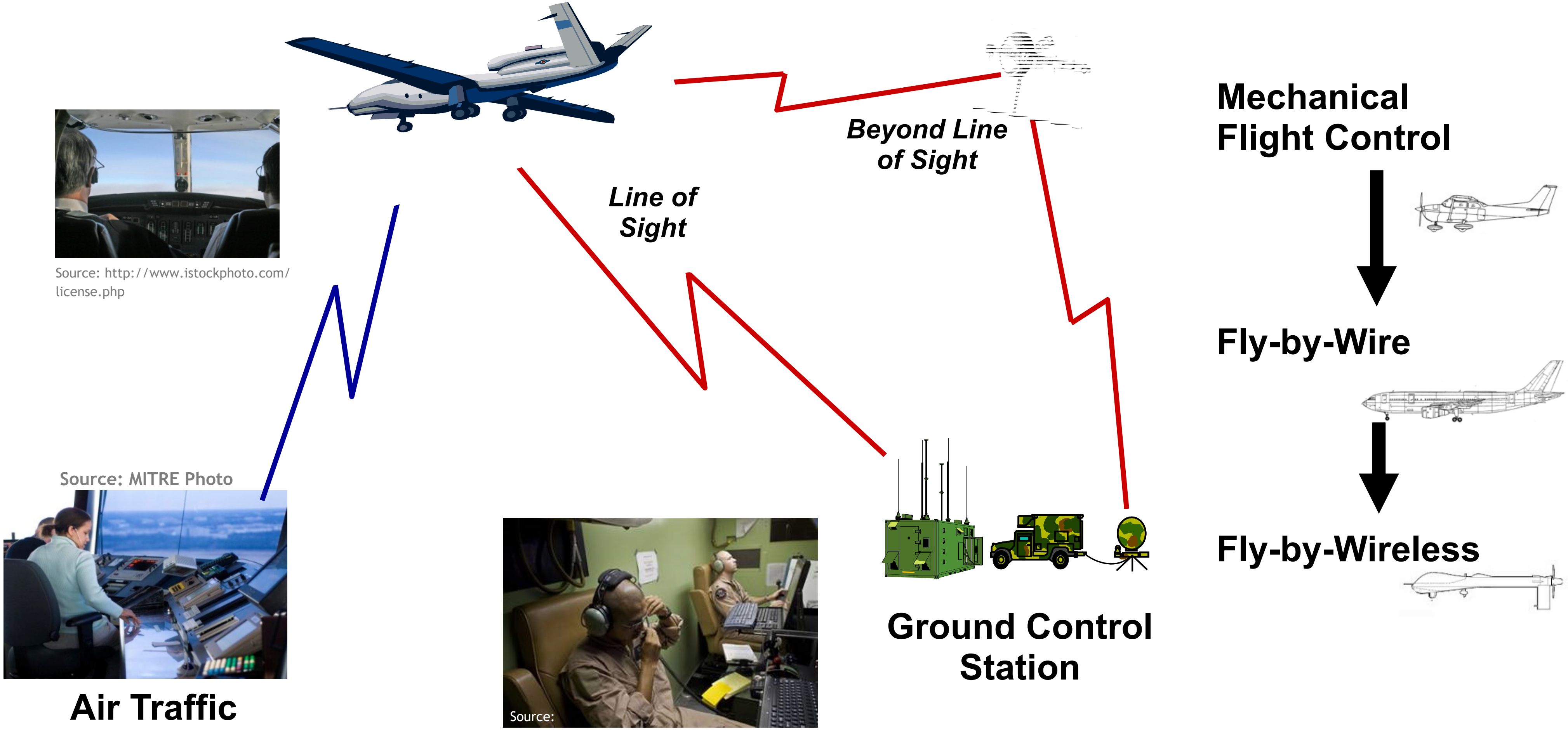
- Terminology
  - "Sense and Avoid" and "Detect and Avoid" used in the technical community and by regulatory entities
  - "See and Avoid" often used for visual architectures. This will not be used here to avoid ambiguities ("See and Avoid" considered as the human pilot capability we need to replace/emulate)

Not meant to be all inclusive

Outline

- Introduction
- Tasks and Taxonomies
- Basics and Trends
  - Sensing for Unmanned Systems
  - Avoidance: remotely operated vs. autonomous
  - AI in Sense and Avoid
- DAA Research @ UniNa
- Perspectives and conclusion

Unmanned Aircraft System



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Line of Sight

Beyond Line of Sight

Source: MITRE Photo

Air Traffic Control

Source:

Crew

Ground Control Station

Mechanical Flight Control

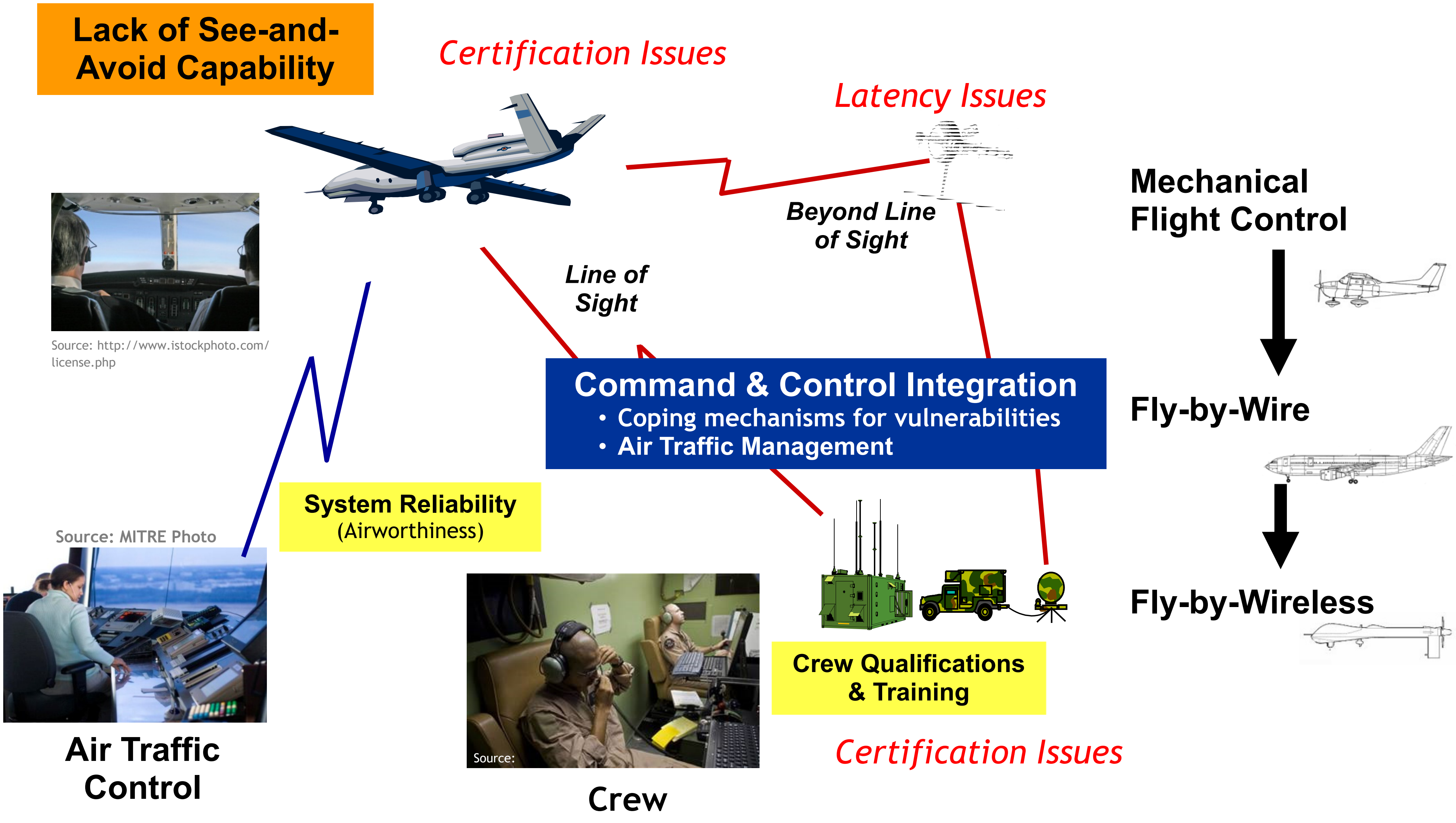
Fly-by-Wire

Fly-by-Wireless

'Approved for Public Release; Distribution Unlimited. 13-3448'

(credit: D. Maroney, MITRE, University of Naples UAS Seminar, 2016)

Key Integration Challenges



Lack of See-and-Avoid Capability

Certification Issues

Latency Issues

Mechanical Flight Control

Beyond Line of Sight

Line of Sight

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Command & Control Integration

- Coping mechanisms for vulnerabilities
- Air Traffic Management

Fly-by-Wire

System Reliability
(Airworthiness)

Source: MITRE Photo

Fly-by-Wireless

Crew Qualifications & Training

Air Traffic Control

Source:

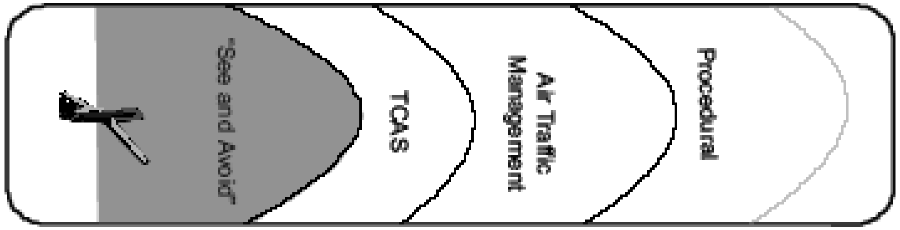
Certification Issues

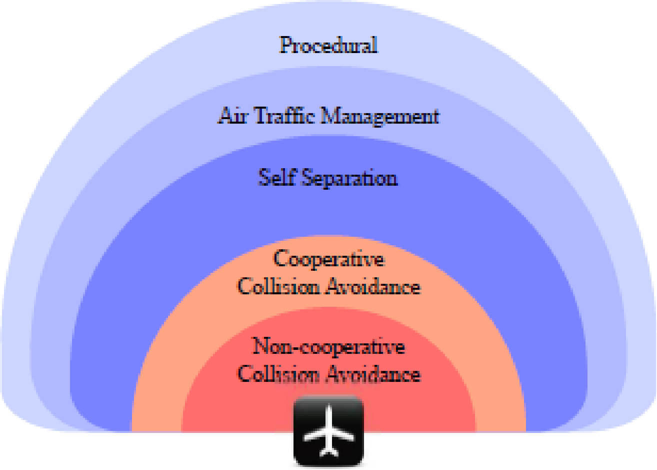
Crew

(credit: D. Maroney, MITRE, University of Naples UAS Seminar, 2016)

Sense and Avoid

- Initial definition of Detect and Avoid closely related to non-cooperative human-like capabilities. It has later evolved to include cooperative technologies (i.e., based on data link among aircraft)





(From: P. Angelov (Ed), *Sense and Avoid in UAS Research and Applications, 2012)*

- «Swiss cheese» model
- The very last level is «providence» - separation minima

Sense and Avoid

- Recent evolution led to different SAA “frameworks”

- Given general objectives

  - Avoiding collisions with other manned aircraft
  - Avoiding collisions with other unmanned aircraft

    +

  - Avoiding weather/clouds
  - Avoiding collisions with obstacles
  - Avoiding collisions with people/property on the ground

The problem is naturally a multi-dimensional one, due to the wide variety of UAS and the different airspace classes in which they operate

- Useful distinction in SAA analyses

  1. SAA for “large” UAS in controlled airspace (“traditional” ATM environment)

  2. SAA at very low-altitudes in minimally or un-controlled airspace (“small” UAS, U-Space, UTM, UAM)

Note: very close range DAA (e.g., indoor) not of primary interest in this talk

SAA in ATM

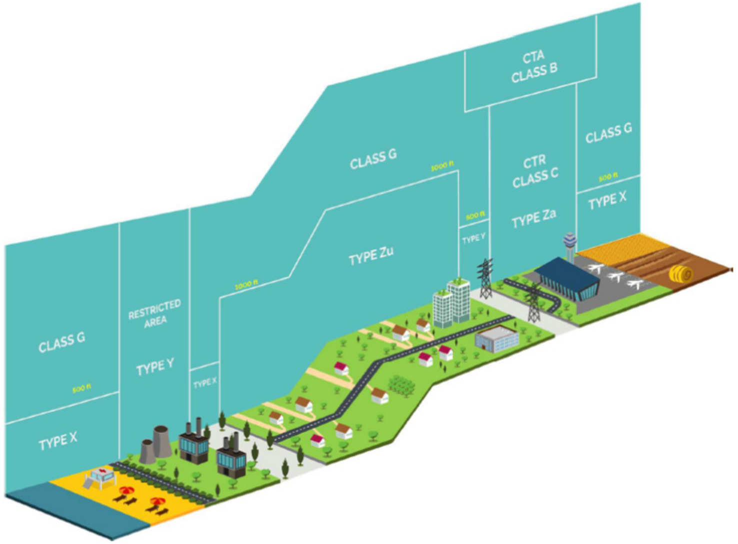
- (Medium/)Large UAS are required to deal with **manned aircraft** operating in the same airspace**, as the main obstacle to avoid**. To be integrated, these UAS need to interact at the levels of separation defined for these airspaces (en route and terminal), operating under appropriate flight rules (usually IFR or VFR).

- The SAA capability will have to react with avoidance maneuvers that are appropriate and expected, to permit the UAS to fly with **equivalent levels of safety** (ELOS) to manned aircraft.

SAA in UTM/U-Space

- More recent framework compared with DAA in “traditional” ATM framework
- Dramatic increase of low altitude small UAS applications (class G airspace) leading to the definition of UTM/U-Space concepts
- New, rapidly changing environment, with new users and various dynamics. Strong link with innovative advanced / urban air mobility concepts (AAM / UAM as new entrants)
- Strong emphasis on automated networked traffic control technology and consequent CNS needs/developments
- SAA also considered as a fundamental component of this framework. It is widely agreed that this should involve both cooperative and non-cooperative technologies

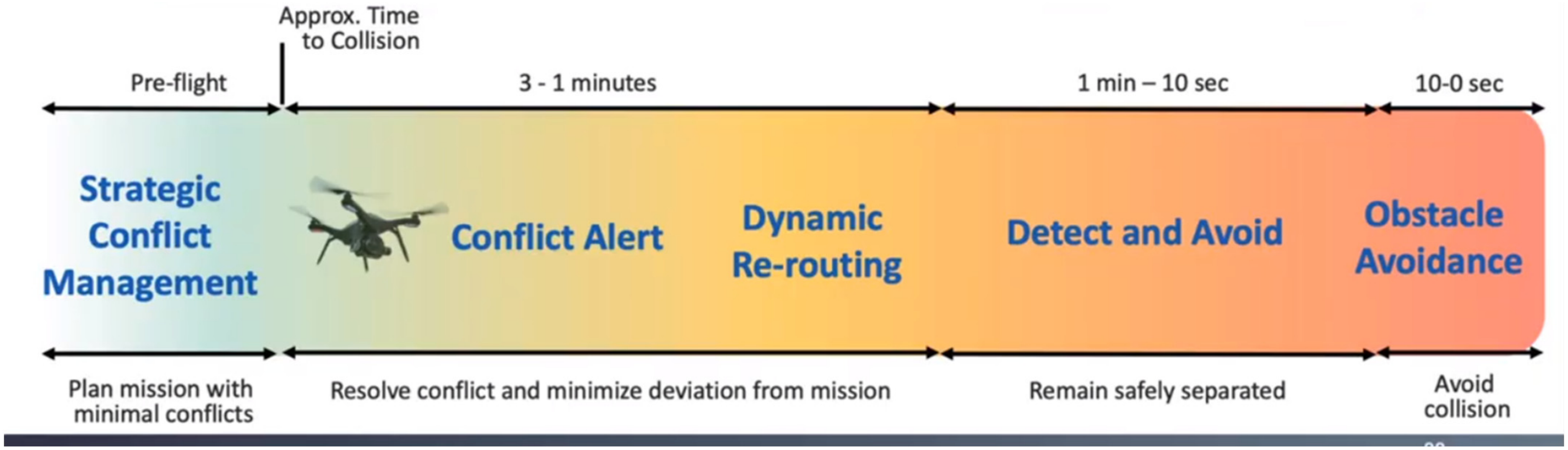
(https://utm.arc.nasa.gov/index.shtml)



(Corus - U-space Concept of Operations, 2019)

SAA in UTM/U-Space

- Open framework resulting in many open areas of investigation
    - Relation among cooperative SAA, non-cooperative SAA and infrastructure-based separation management
    - Sensing requirements, safety levels, flight rules, and their links
    - Sensing and decision-making approaches tailored for small UAS sensors and complex environments
    - Link between obstacle avoidance and navigation challenges in very low altitude operations
- Beyond Visual Line of Sight Operations (BVLOS) for small UAS as near term objective



(NASA UTM Technical Interchange Meeting, 2021)

SAA Basics - Tasks

- Main SAA tasks:
  - **Sense** - methods for surveilling the environment around the aircraft
  - **Detect** - analysis to determine if there are aircraft or obstacles in that environment, and to evaluate if they are, or will be, a threat to the UA
  - **Avoid** - evaluation of the actions that the UA should take to reduce or remove the threat of the detected aircraft or obstacle.

(Note: while there is a general agreement on the tasks to be carried out, terminology may vary)

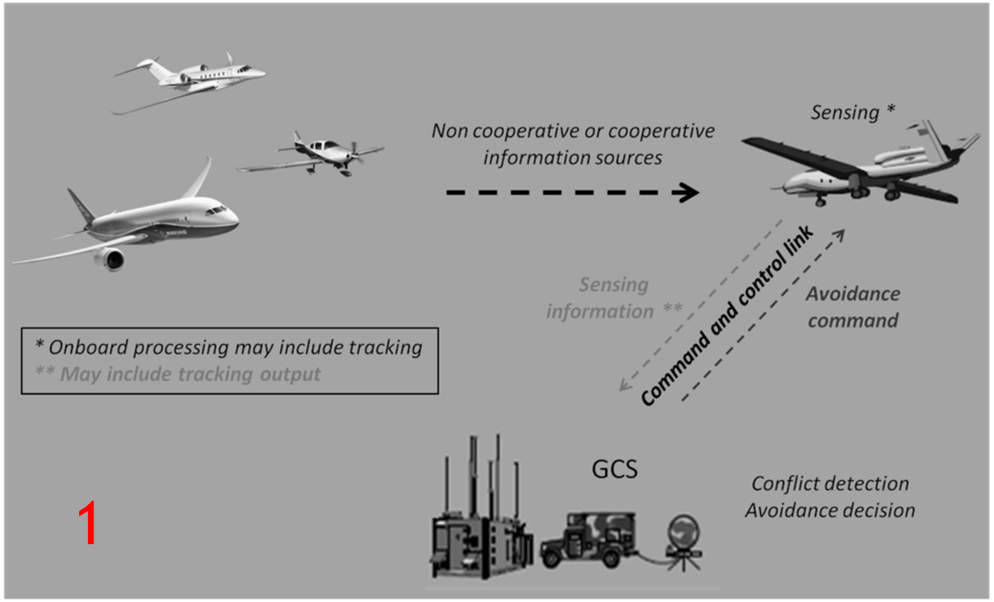
Taxonomy of DAA - 3 scenarios

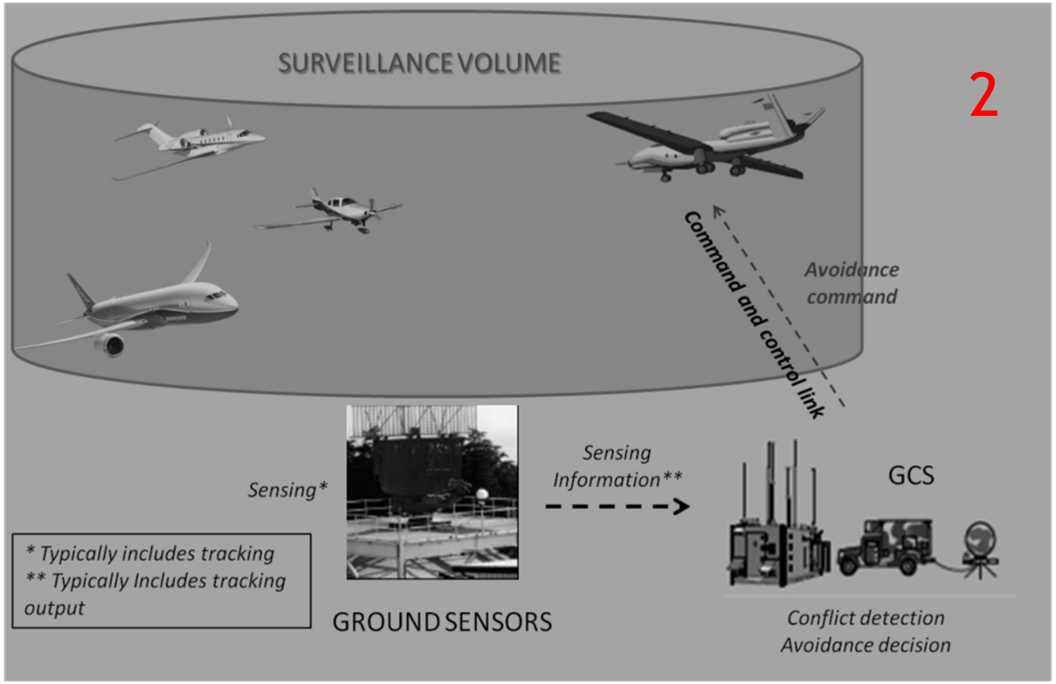
- These three fundamental tasks of an SAA system can be implemented in different ways, giving rise to several architectural and technical solutions. These solutions can then be classified using different taxonomies.

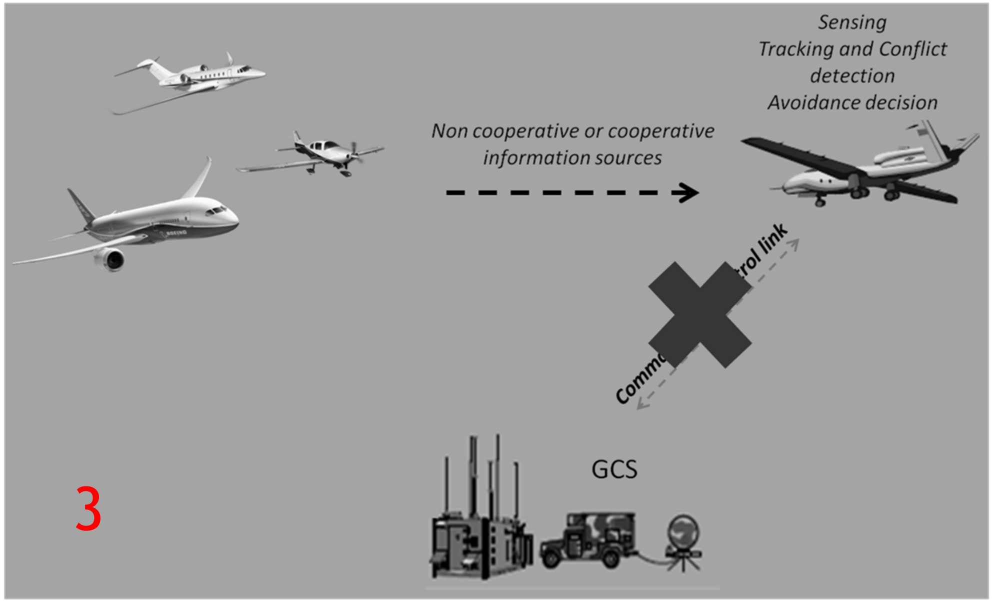
- A general approach for classification that involves all three parts is based on the physical location of information sources and processing/decision making centers.

- These elements can be based onboard the UA, or be located on the ground.

3 Scenarios

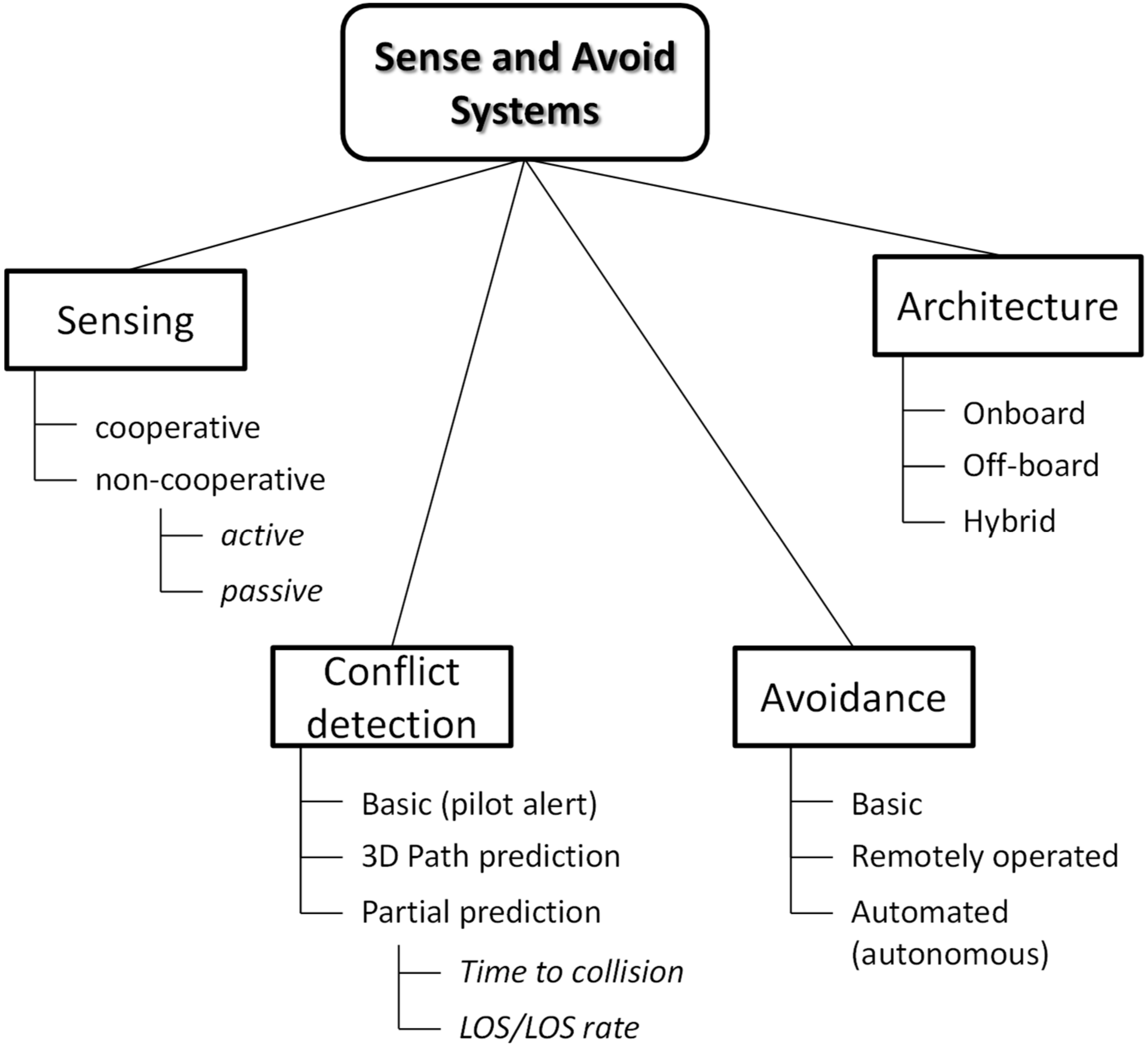






(Fasano et alii, Sense and Avoid for Unmanned Aircraft Systems, IEEE AES Magazine 2016)

General DAA Taxonomy



Sense and Avoid Systems

- Sensing
  - cooperative
  - non-cooperative
    - *active*
    - *passive*
- Conflict detection
  - Basic (pilot alert)
  - 3D Path prediction
  - Partial prediction
    - *Time to collision*
    - *LOS/LOS rate*
- Avoidance
  - Basic
  - Remotely operated
  - Automated (autonomous)
- Architecture
  - Onboard
  - Off-board
  - Hybrid

(Fasano et alii, Sense and Avoid for Unmanned Aircraft Systems, IEEE AES Magazine 2016)

Separation Assurance vs. Collision Avoidance

- **Separation Assurance:** Function that reduces the probability of a collision by ensuring aircraft remaining “well clear” of each other thereby assuring safe separation. Significant work carried out to quantitatively define well clear conditions

- **Collision Avoidance:** Extreme maneuvers just prior to closest point of approach to prevent collisions in cases where safe separation is lost.

- Maneuvering early allows smooth maneuvers
- Sensing range and performance must be adequate

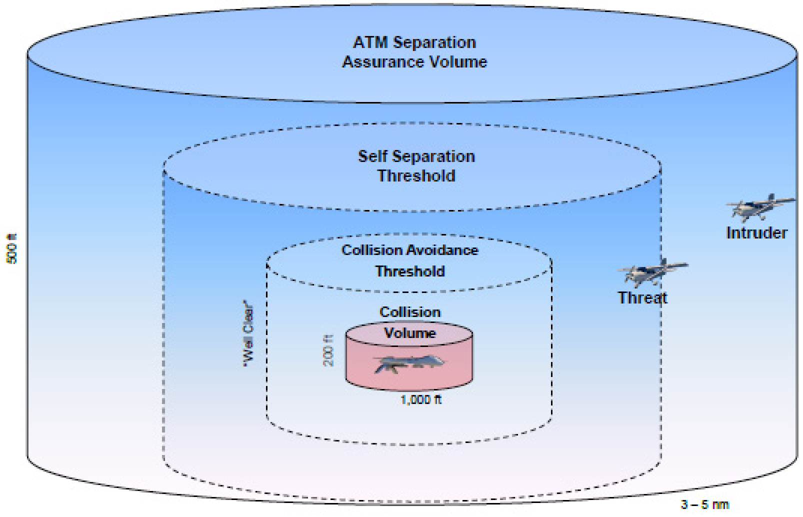
- Non-cooperative sensors usually linked with collision avoidance scenarios

Self Separation

- **Within Minutes**
- **Benign**
- **Multiple Objectives**
  - **Right of Way Rules**
  - **Well Clear**
  - **Etc.**

Collision Avoidance

- **Within Seconds**
- **Aggressive**
- **Single Objective**
  - **Don’t hit!**

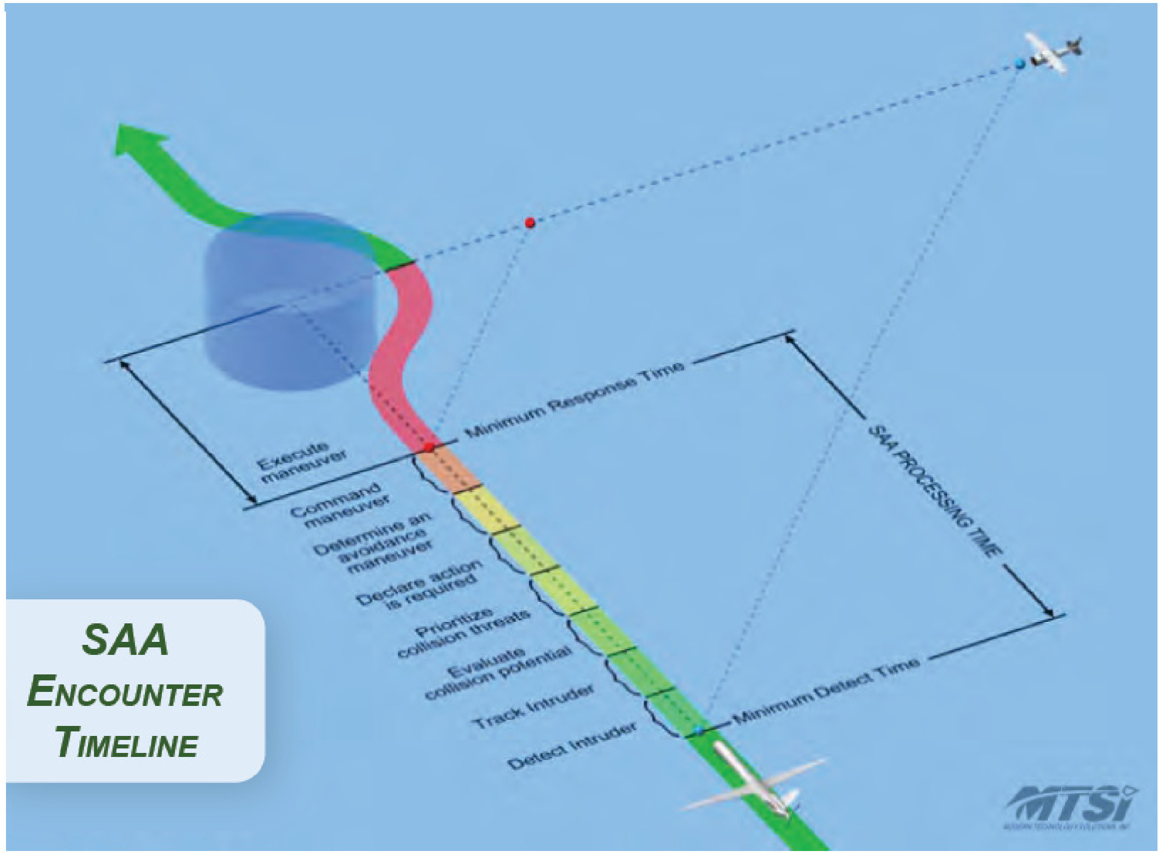


From FAA sponsored SAA Workshops

DAA timeline

- DAA requires several processing steps → a collision maneuver is started in general with a non-negligible latency with respect to sensor detection. This latency has to be taken into account when evaluating sensing requirements

- This makes the problem more challenging especially for non-cooperative information sources



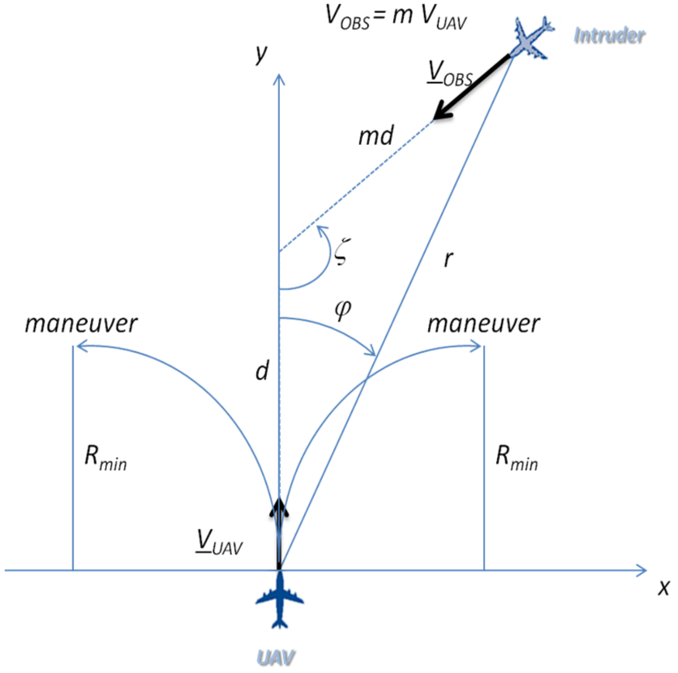
(from FAA sponsored Sense and Avoid Workshop, 2009)

Sensing

- Requirements
- Cooperative sensors
- Non-cooperative sensors and algorithms

Sensing requirements

- Basic requirements
  - Minimum range of initial detection for an obstacle big enough to be considered a non-negligible threat
    - Stochastic perspective – declaration range
    - Encounter geometry, speed, maneuverability, flight constraints
  - Field of View (FOV) to be monitored
  - Sensing accuracy
    - Quality of situational awareness, link with conflict detection and avoidance strategies
  - Measurement rates and latencies
  - Integrity
    - Confidence in sensing information for cooperative and non cooperative sources



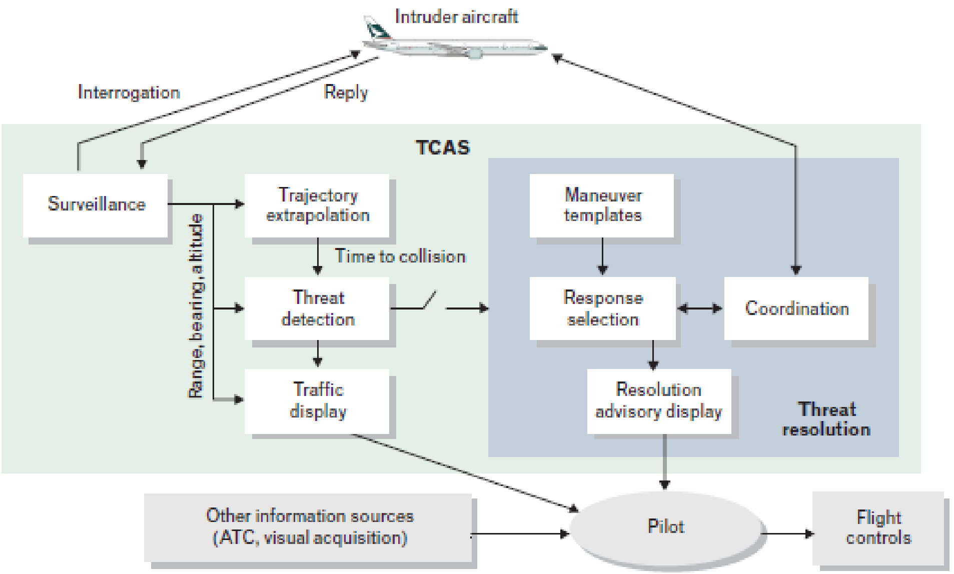
- Need of integrated approach
- Development of Minimum Operational Performance Standards (MOPS – DO-365, DO-366A, DO-381)
- Safety needs, airspace structure, flight rules, technological requirements: links and open points

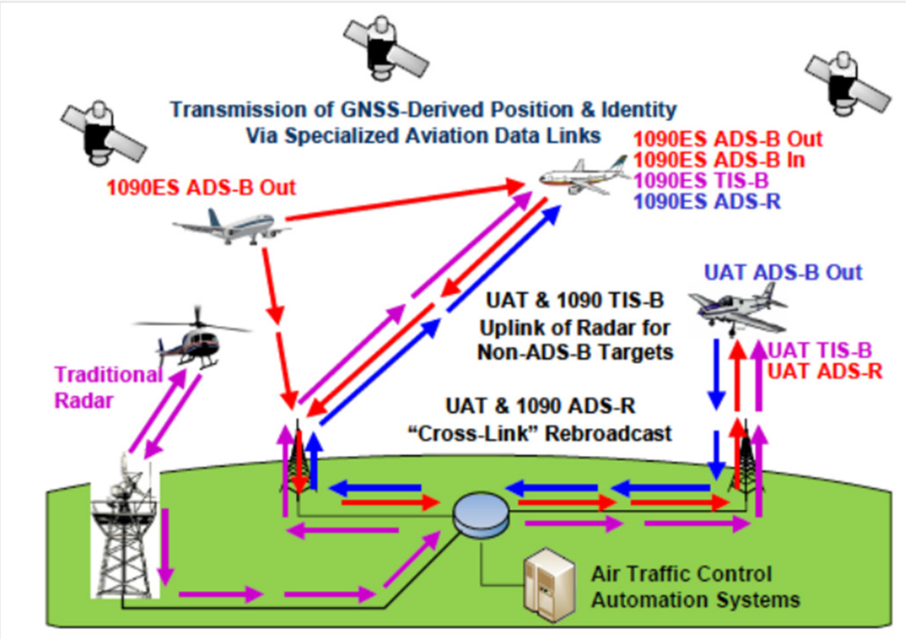
Cooperative systems

- Require an exchange of information between aircraft, do not work for non equipped aircraft

- TCAS and ADS-B
  - Present and future (ACAS) of both manned and unmanned aviation
  - Typically large detection range: both separation assurance and collision avoidance functions

- New perspectives (especially for UTM/U-Space environment): V2V, infrastructure-based (LTE, 5G, …). The key concept is sharing GNSS-based information





(US implementation with dual link strategy, 1090 ES and UAT)

Trends and Concerns

- TCAS
  - of interest for large UAS
  - developed and validated for aircraft with onboard pilots, not to replace see and avoid
  - low maneuverability issues

- ADS-B
  - Available proven technology, minimizes size, weight & power, accuracy and integrity known, simplifies algorithms, reduces development and certification risks
  - General concerns: non-cooperative obstacles, dependance on GNSS and radio link performance (i.e., integrity and availability), vulnerability

- Other ADS-B concerns regarding operation in high density airspaces
  - Motivates the interest in other communication links
  - Can be reduced for ADS-B by working on transmit power (Guterres et alii, 2017)

(from https://uavionix.com/)

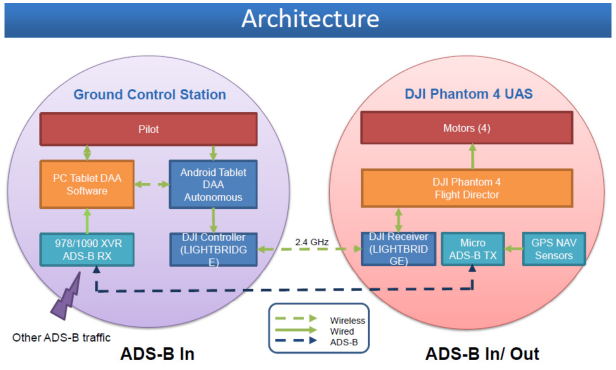
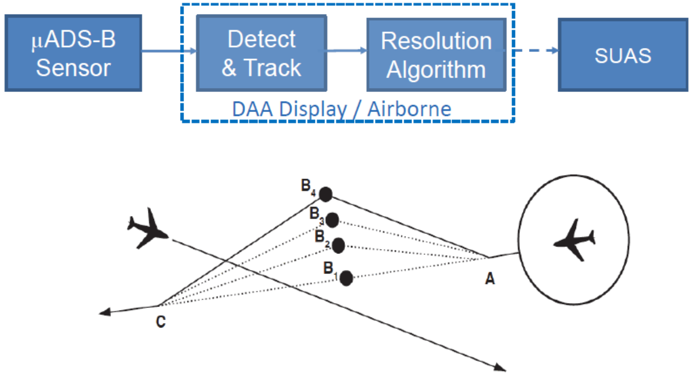
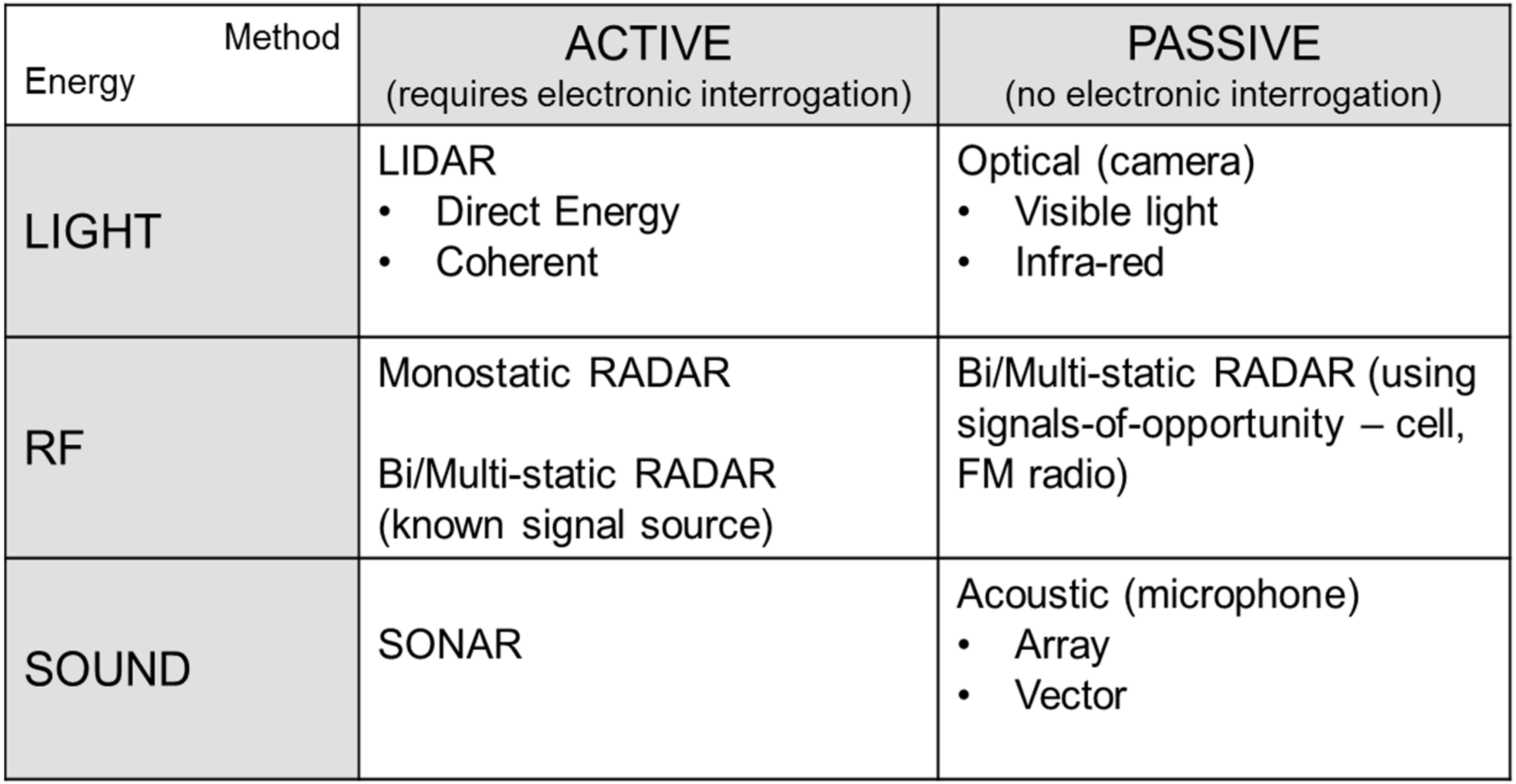


Fig. 2. ADS-B system architecture (US Patent Serial No. 9,405,005).[2]



(R. Arteaga, Automatic Dependent Surveillance Broadcast: µADS-B Detect-and-Avoid Flight Tests, AIAA Scitech 2018)

Non-cooperative Sensing

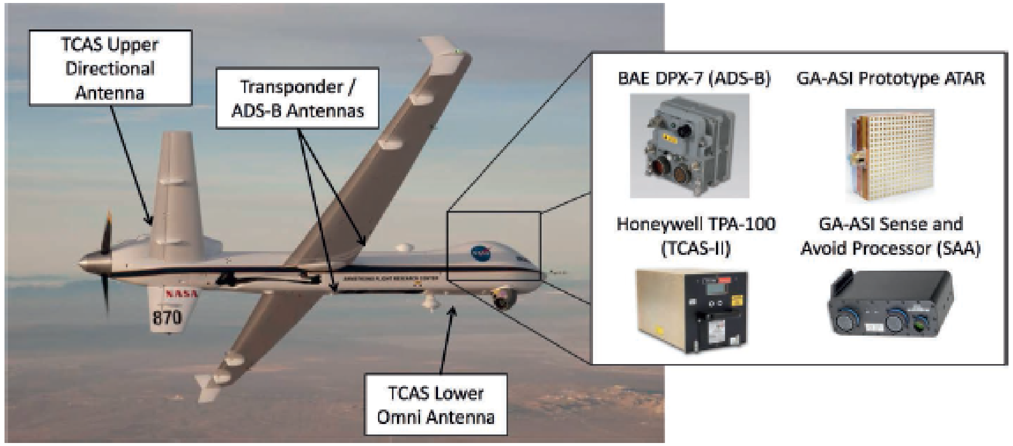


Method Energy	ACTIVE (requires electronic interrogation)	PASSIVE (no electronic interrogation)
LIGHT	LIDAR • Direct Energy • Coherent	Optical (camera) • Visible light • Infra-red
RF	Monostatic RADAR Bi/Multi-static RADAR (known signal source)	Bi/Multi-static RADAR (using signals-of-opportunity – cell, FM radio)
SOUND	SONAR	Acoustic (microphone) • Array • Vector

- Monostatic radars and daylight cameras as traditional options for medium/large and small UAS

Trends in DAA radars for large UAS

- Several companies developing air-to-air radars for large UAS
- C-band and X-band considered, electronic scanning
- Radar as key sensor to enable UAS integration without chase planes and observers (https://www.nasa.gov/press-release/nasa-flies-large-unmanned-aircraft-in-public-airspace-without-chase-plane-for-first)
- Software defined architectures and multi-function options being considered (detect and avoid, weather, landing support, …), need to fulfill different requirements



From: T. Kotegawa, "Proof-of-concept airborne sense and avoid system with ACAS-XU flight test," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 31, no. 9, pp. 53-62, September 2016

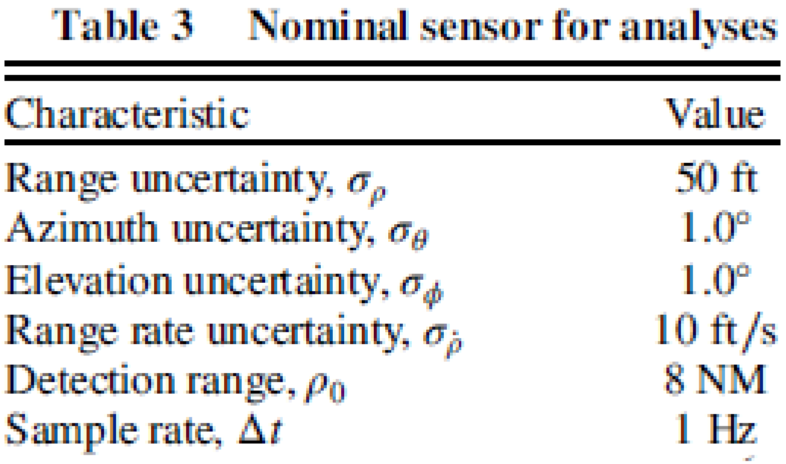


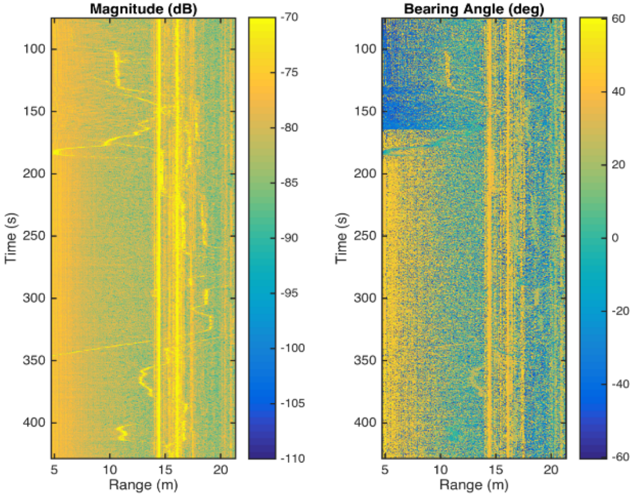
Table 3 Nominal sensor for analyses

Characteristic	Value
Range uncertainty, σ_ρ	50 ft
Azimuth uncertainty, σ_θ	1.0°
Elevation uncertainty, σ_ϕ	1.0°
Range rate uncertainty, $\sigma_{\dot{\rho}}$	10 ft/s
Detection range, ρ_0	8 NM
Sample rate, Δt	1 Hz

Radar specifications, based on MOPS, assumed in: Jamoom, Canolla, Pervan, Unmanned Aircraft System Sense and Avoid Integrity: Intruder Linear Accelerations and Analysis, AIAA Journal of Aerospace Information Systems 2017, Vol. 14, No. 1, January 2017

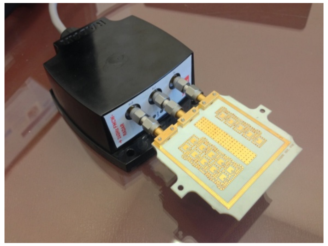
Trends in DAA radars for small UAS / UAM

- (high frequency) FMCW technology to cope with limited onboard power and size/weight budgets, link with automotive technology
- Multi-channel techniques and/or innovative beam steering approaches (metamaterial antennas) to combine wide FOV coverage and degree-level angular accuracy
- Different classes, weight ranging from a few tens of grams to order 1 Kg
- Low target detectability as an issue for low power / low gain solutions in view of moving traffic avoidance
- Measurements: degree-level angular accuracy on two angles (azimuth and elevation) and relatively large detection range only for the largest radars (which are of interest for UAM/AAM)
- Ultralight radar solutions suitable for navigation and fixed obstacle avoidance

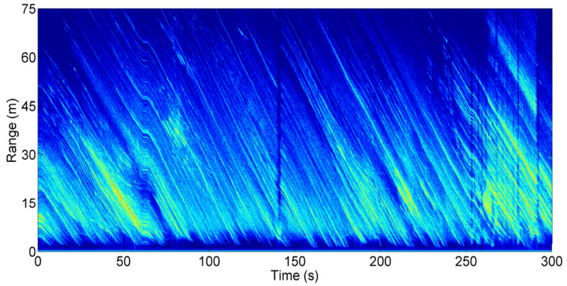


https://echodyne.com/products/echoflight/

https://aerotenna.com/shop/μsharp-patch/



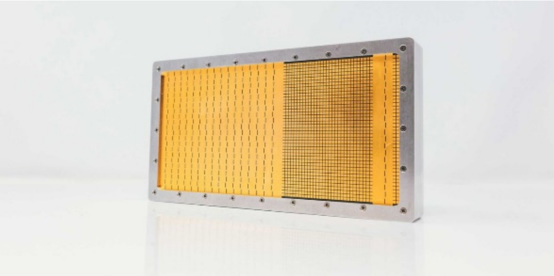
https://shop.imst.de/radar-solutions/



DAA radars for small UAS / UAM - examples of recent developments

- Feb 2022: Honeywell demonstrates IntuVue RDR-84K Band Radar System in drone to drone scenario

  (https://aerospace.honeywell.com/us/en/about-us/press-release/2022/02/honeywell-smart-drone-radar-avoids-collisions-automatically)



KEY CHARACTERISTICS
Weight: 1.5 lbs. (0.7 kg)
Size: 8.9" x 4.9" x 1.7" (226 mm x 125 mm x 43 mm)
Power: 60 watts
Field of view: 110 azimuth x 30° elevation
Packaging: RF and processing in one box

- NASA/Bell Systems Integration and Operationalization (SIO) activities with Echodyne radar (and cameras)
  - Ground clutter challenges: ghost targets
  - Challenges in the trade-off clutter filtering / detection range
  - Cameras used to confirm radar detection

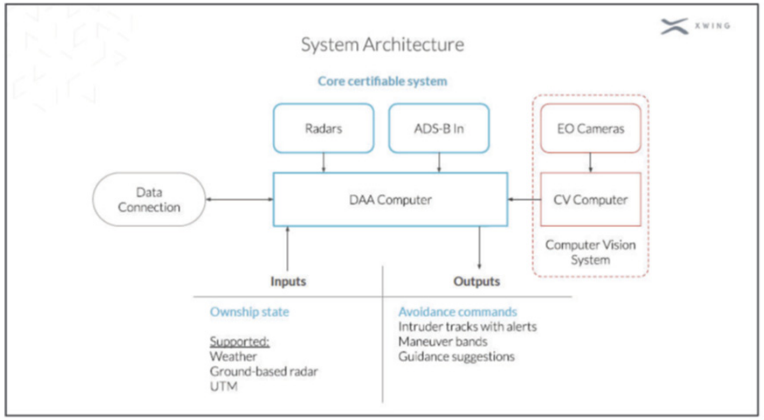
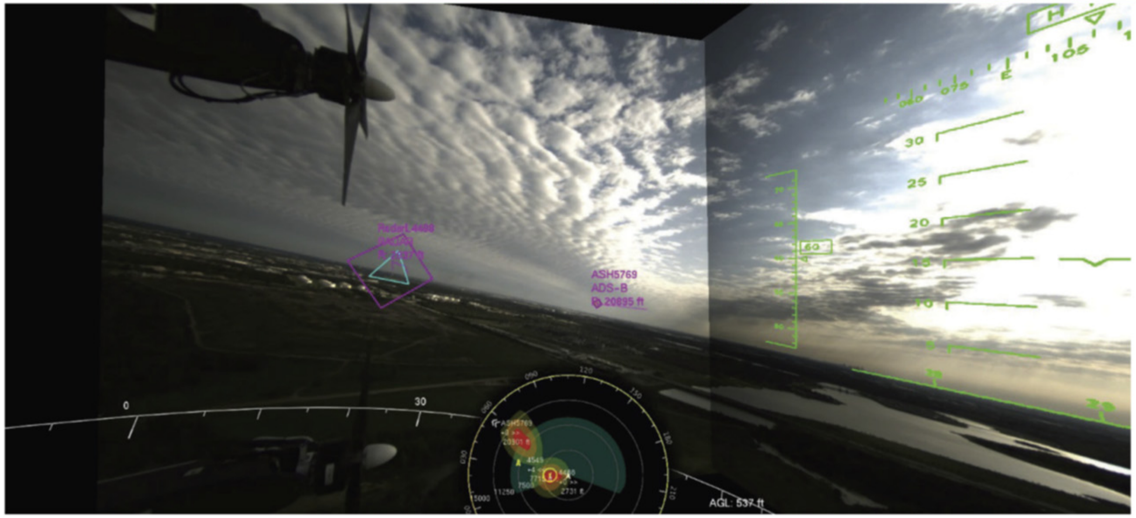


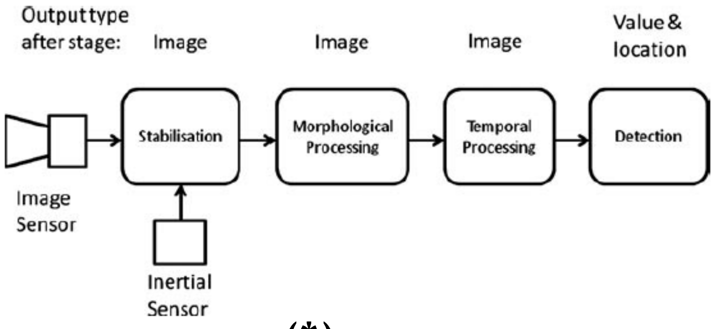
Figure 4. ABDAA System Architecture.



(https://ntrs.nasa.gov/api/citations/20210009973/downloads/NASA-CR-20210009973.pdf)

Trends in Visual Sensing

- Main trends of interest concern algorithms (and computational power)
- Sky region vs below the horizon sensing
- Several sky region techniques augment morphological filters with multi-temporal techniques to extract slowly moving targets. Morphological filters can be aided or replaced by AI-based detectors
- Below the horizon: frame differencing / image registration concepts – challenges, appearance-based techniques using deep learning



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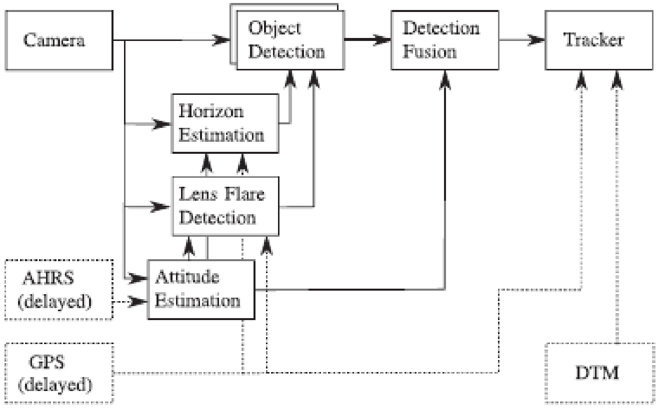

Figure 4.

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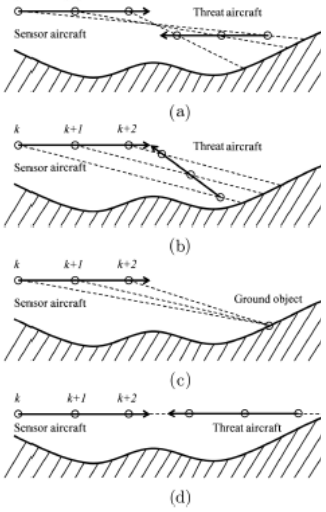
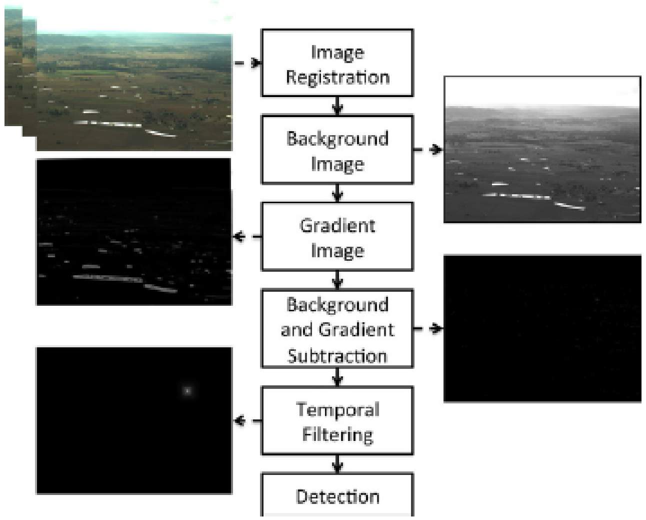


FIGURE 2 Example motion of (a) a potential collision threat, lision threat, (c) a ground object, and (d) a collision threat with relative motion similar to that of a ground object (adapted from Nussberger et al.[4])



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* J. Lai, J. J. Ford, L. Mejias, and P. O'Shea, "Characterization of Sky-region Morphological-temporal Airborne Collision Detection," Journal of Field Robotics, vol. 30, no. 2, pp. 171-193, March/April 2013

** A. Nussberger, H. Grabner, and L. Van Gool, "Aerial object tracking from an airborne platform," Proceedings of the 2014 International Conference on Unmanned Aircraft Systems (ICUAS), Orlando, FL, USA, 27-30 May 2014, 1284-1293

*** T. L. Molloy, J. J. Ford, L Mejias, "Detection of aircraft below the horizon for vision-based detect and avoid in unmanned aircraft systems," Journal of Field Robotics, vol. 34, no. 7, pp. 1378-1391, October 2017

Trends in Visual Sensing

- Deep learning also exploited in commercial solutions (airborne and ground-based)

- Emphasis on detection and tracking of manned aircraft
  - Non cooperative traffic detection to improve safety figures of general aviation

- Very large datasets for training, based on synthetic and flight data

- Airborne visual detection and tracking as test case in EASA – Daedalean project “Concepts of Design Assurance for Neural Networks II” (CoDANN II) aimed at examining the challenges posed by the use of neural networks in aviation
  - https://www.easa.europa.eu/newsroom-and-events/news/easa-publishes-second-joint-report-learning-assurance-neural-networks

(https://www.irisonboard.com/casia/)

(https://daedalean.ai/products/detection)

Trends in Lidar Sensing

- Technological evolution guided by autonomous driving and mobile mapping applications. Compact high resolution solid state LIDAR as promising technology

- Different sensor classes with weight ranging from a few tens of grams to order 1 Kg

- Fine range accuracy, high update rate, fine angular resolution leading to a denser FOV coverage, limited FOV in elevation. Detection range typically below 200 m, larger ranges with mass/FOV trade-offs

- Solution of interest in relatively low speed scenarios / particular flight phases

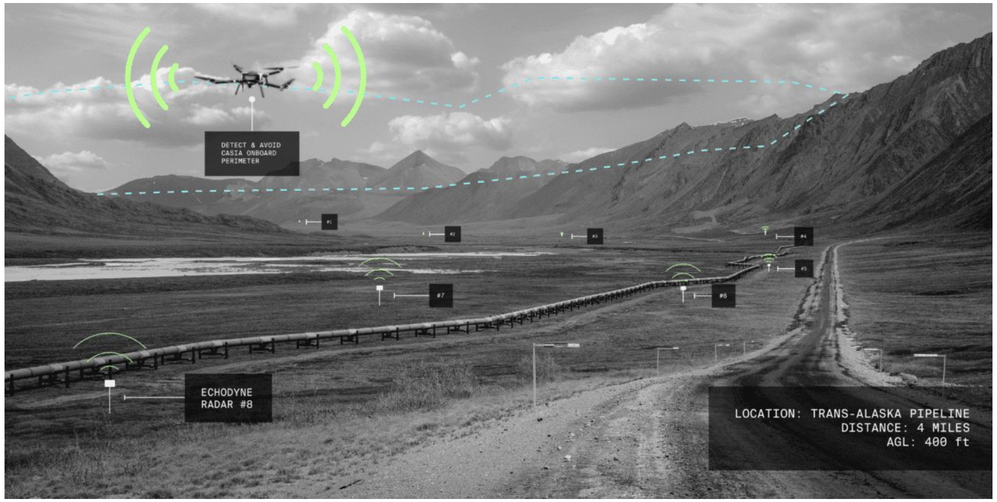
https://velodynelidar.com/

https://innoviz.tech/

https://www.livoxtech.com

Trends in Ground-based sensing for DAA

- Main Technologies
  - Monostatic or traditional radar: existing, repurposed or new sensors
  - Bi-static or multi-static radar
  - EO cameras
  - Passive Acoustic
- Initially conceived as a near term / geographically limited solution → development towards distributed sensing networks
- Less SWaP constraints, limited surveillance volumes with variable sensing accuracy. Link with communications requirements and airspace management concepts

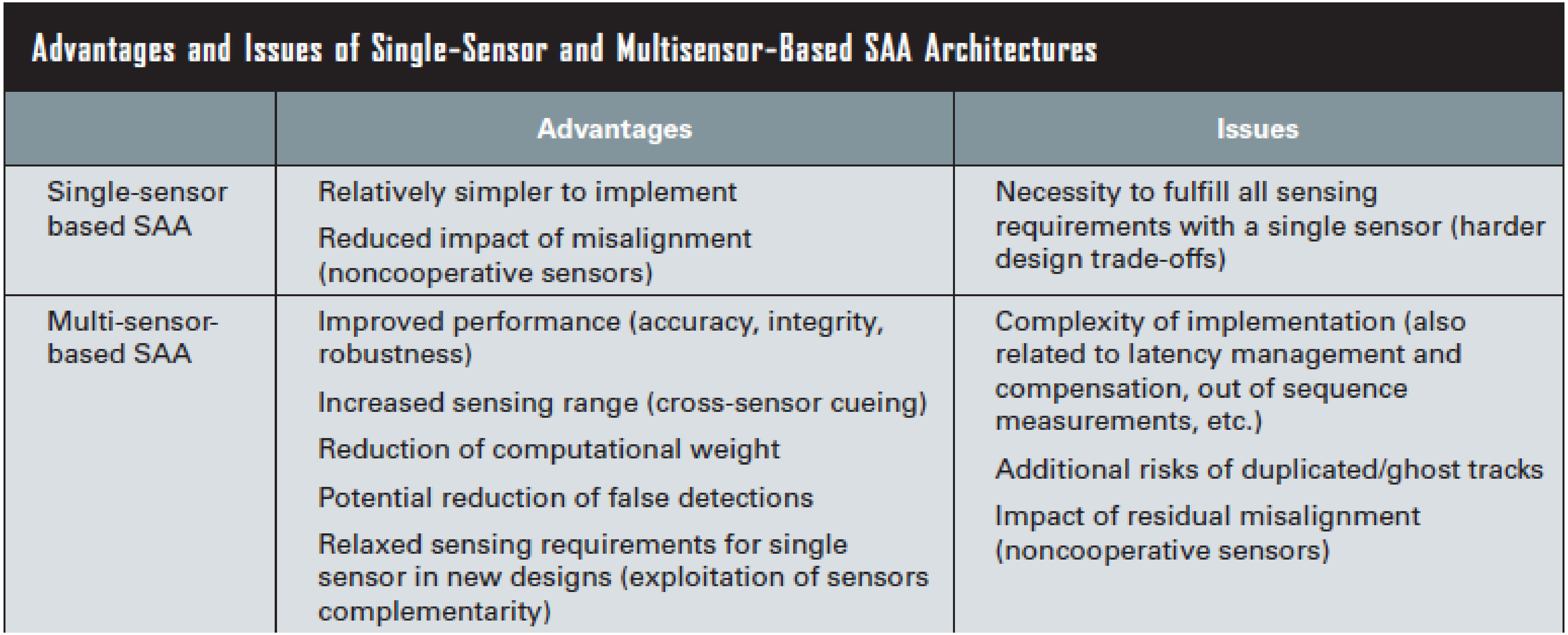


Combination of airborne cameras and ground-based radars (Echodyne Echoguard)
https://dronebelow.com/2019/08/02/first-ever-bvlos-drone-operation-without-visual-observers/

https://www.raytheon.com/capabilities/products/skyler

Potential and challenges of data fusion

- Current developments and trends involve multi-sensor-based architectures and data fusion approaches

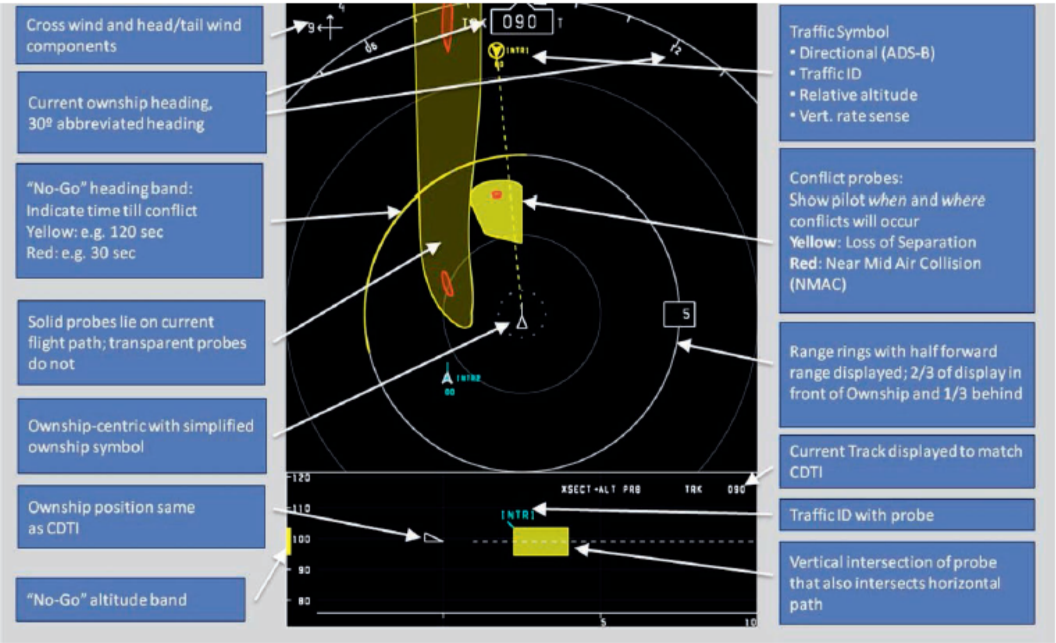


Advantages and Issues of Single-Sensor and Multisensor-Based SAA Architectures

	Advantages	Issues
Single-sensor based SAA	Relatively simpler to implement Reduced impact of misalignment (noncooperative sensors)	Necessity to fulfill all sensing requirements with a single sensor (harder design trade-offs)
Multi-sensor-based SAA	Improved performance (accuracy, integrity, robustness) Increased sensing range (cross-sensor cueing) Reduction of computational weight Potential reduction of false detections Relaxed sensing requirements for single sensor in new designs (exploitation of sensors complementarity)	Complexity of implementation (also related to latency management and compensation, out of sequence measurements, etc.) Additional risks of duplicated/ghost tracks Impact of residual misalignment (noncooperative sensors)

Avoidance: concepts and trends

- Remotely operated vs autonomous avoidance – significant overlap due to limited situational awareness
  - Conflict probing – HMI Aspects
  - Suggested vs commanded maneuvers



Cross wind and head/tail wind components

Current ownship heading, 30º abbreviated heading

"No-Go" heading band: Indicate time till conflict
Yellow: e.g. 120 sec
Red: e.g. 30 sec

Solid probes lie on current flight path; transparent probes do not

Ownship-centric with simplified ownship symbol

Ownship position same as CDTI

"No-Go" altitude band

Traffic Symbol
- Directional (ADS-B)
- Traffic ID
- Relative altitude
- Vert. rate sense

Conflict probes: Show pilot *when* and *where* conflicts will occur
Yellow: Loss of Separation
Red: Near Mid Air Collision (NMAC)

Range rings with half forward range displayed; 2/3 of display in front of Ownship and 1/3 behind

Current Track displayed to match CDTI

Traffic ID with probe

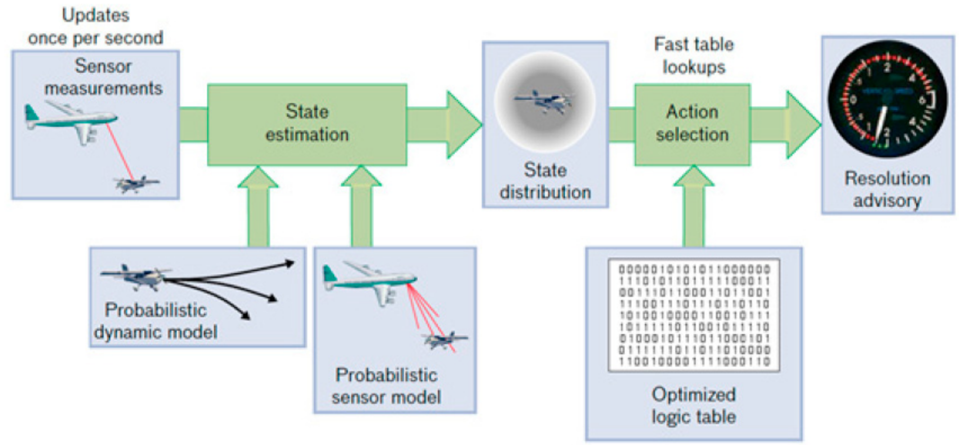
Vertical intersection of probe that also intersects horizontal path

Figure 7.
CPDS horizontal and vertical profile display snapshot.

From: T. Kotegawa, "Proof-of-concept airborne sense and avoid system with ACAS-XU flight test," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 31, no. 9, pp. 53-62, September 2016

Avoidance: concepts and trends

- Probabilistic and deterministic approaches being considered in standard developments. Main examples: ACAS-Xu and DAIDALUS
- Other efforts aimed at new scenarios: ACAS-sXu and ACAS-Xr
- Active research on autonomous avoidance with emphasis on complex environments



Once per second, ACAS X ingests and processes surveillance data and determines the optimal action for every target aircraft.

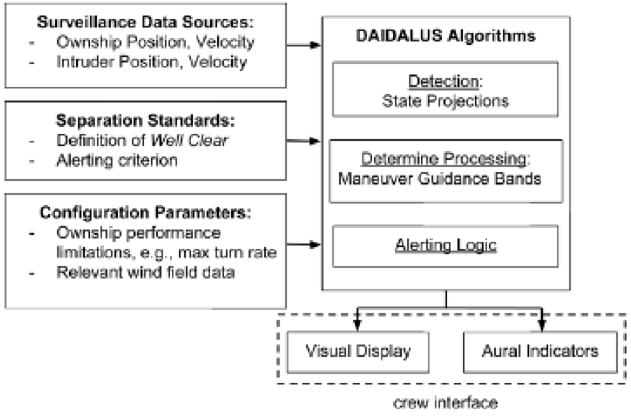


Figure 1. High-Level Architecture of DAIDALUS

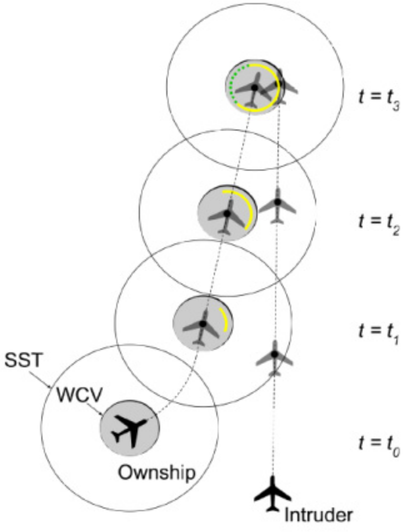


Figure 4. Maneuver Guidance Bands

(Olson, W. A.: Airborne Collision Avoidance System X. , Massachusetts Institute of Technology, Lincoln Laboratory, June 2015. Tech Notes)

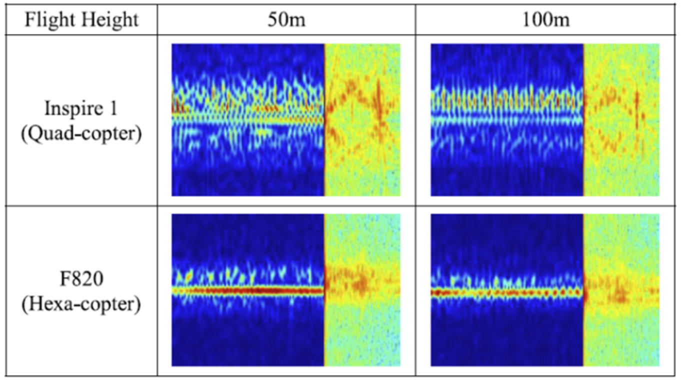
(C. Muñoz et al., “DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems,” 2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC))

AI in Sense and Avoid

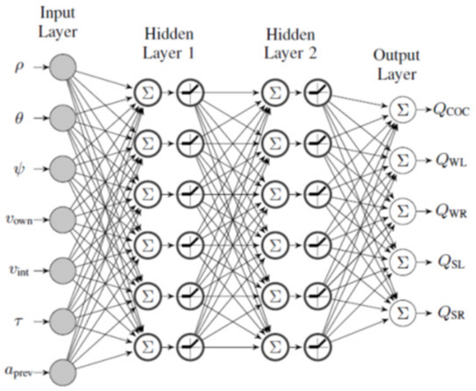
- AI potential is being investigated in the whole SAA pipeline

- Sensing
  - Visual
  - Information extraction by CNNs from raw radar and acoustic data

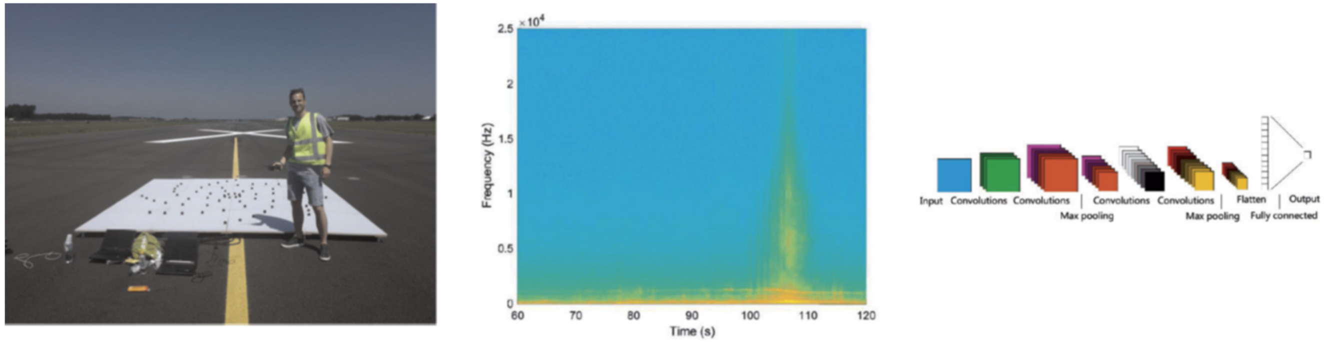
- Decision-making
  - Neural networks to compress look-up tables in ACAX-sXu
  - Reinforcement learning
  - End-to-end AI-based solutions
  - Many recent approaches are relevant to Micro Aerial Vehicles and agile flight in cluttered environments



(Kim et al., Drone Classification Using Convolutional Neural Networks With Merged Doppler Images, IEEE GRSL 2016)



(Julian et al., Deep neural network compression for aircraft collision avoidance systems, JGCD 2019)



(Wijnker et al., Hear-and-avoid for unmanned air vehicles using convolutional neural networks, Int. J. of Micro Aerial Vehicles, 2021)

AI/ML in SAA - Perspectives and Challenges

- AI/ML approaches represent well assessed techniques, especially considering visual sensing
- Research perspectives and upgrades concern the entire SAA pipeline
- Dataset availability
  - Experimental tests in relevant environments
  - Challenges
- Combination of real and synthetic data
  - Generalization, performance/computational trade-offs
  - Datasets for new operating environments
- Certification
  - dataset characterization
  - stochastic nature of non cooperative sensing
  - multi-stage processing pipelines → system level perspective

UniNa research paths on Detect and Avoid

- First activities carried out in collaboration with the Italian Aerospace Research Center (CIRA)
- Main focus on onboard non-cooperative sense and avoid with multi-sensor architectures (radar/EO)
- Experimental dataset exploited for studies about vision-based sense and avoid

- More recent research focus on low altitude DAA for small UAS and UAM/AAM

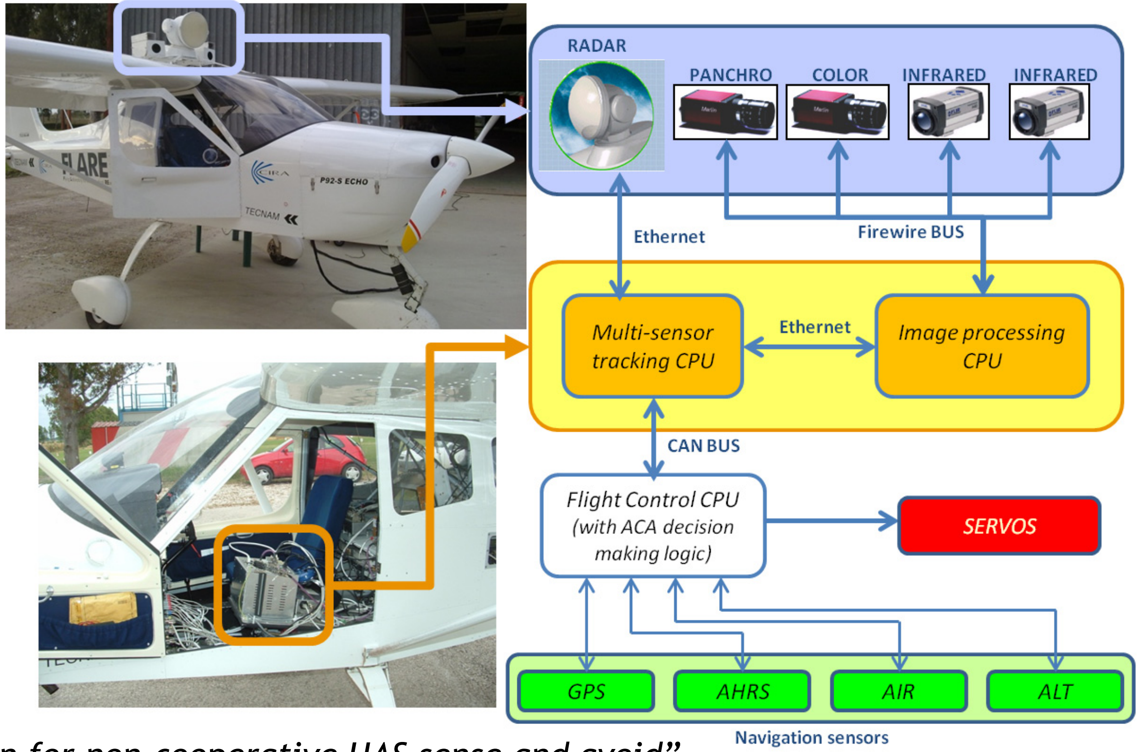
- Increasing interest for ground-based sensing and for air/ground interaction in airspace surveillance

DAA: project TECVOL

- Radar/EO data fusion architecture based on:
  - Sensors’ hierarchy (radar as main sensor)
  - Central-level fusion (minimally pre-processed measurements)
  - Extended Kalman filter
  - Cross-Sensor cueing

- COTS-based approach for flight demonstration

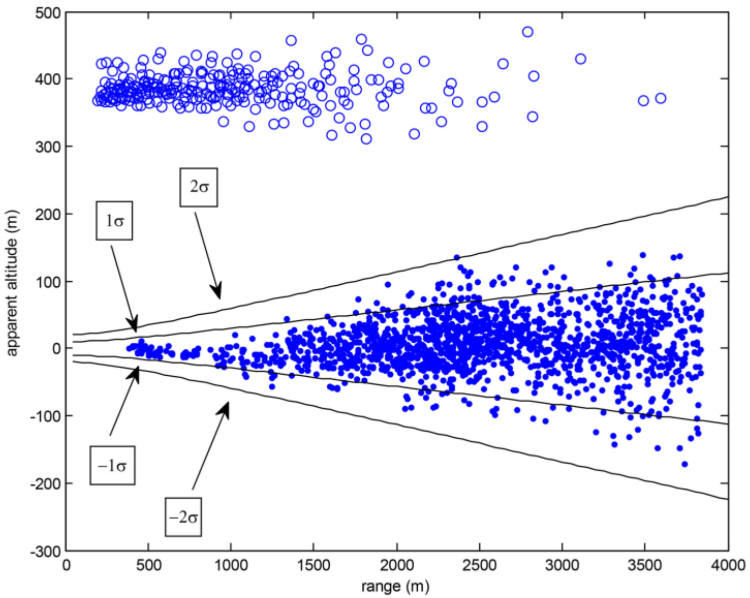
- Flight demonstration of:
  - Real time radar-based detection and tracking
  - Real time multi-sensor-based detection and tracking
  - Autonomous non-cooperative collision avoidance

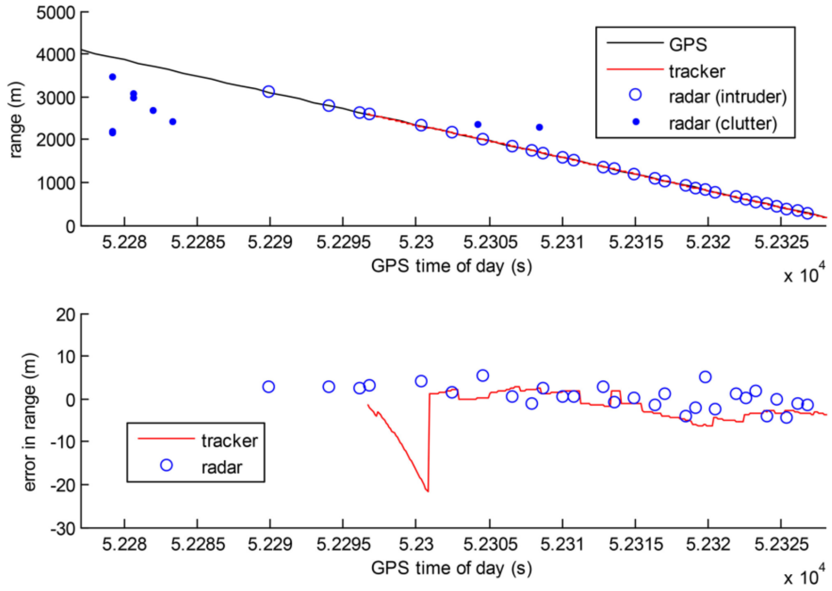


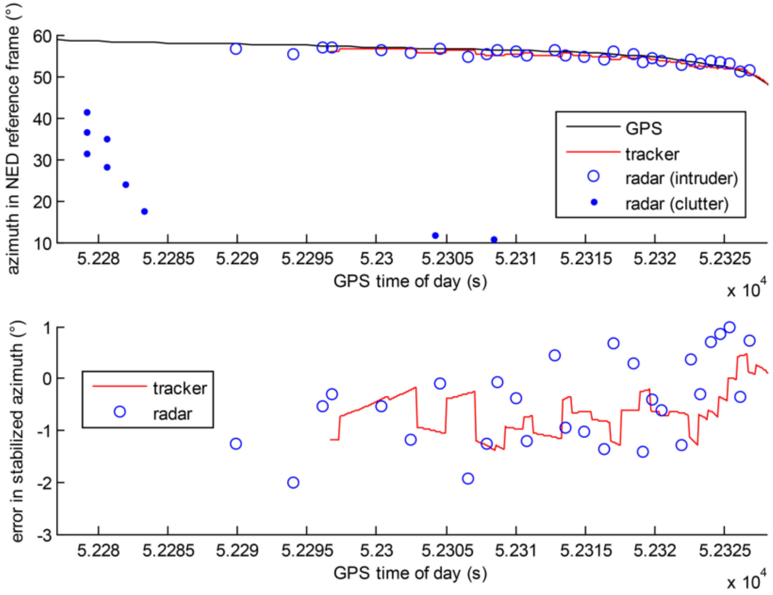
(G. Fasano et alii, “Radar/electro-optical data fusion for non-cooperative UAS sense and avoid”, Aerospace Science and Technology, vol. 46, pp. 436-450, October–November 2015)

Flight results: radar-only tracking

- Radar as a reliable source of information (need for ground clutter filtering)
- Limits of radar-only tracking related to rough angular accuracy



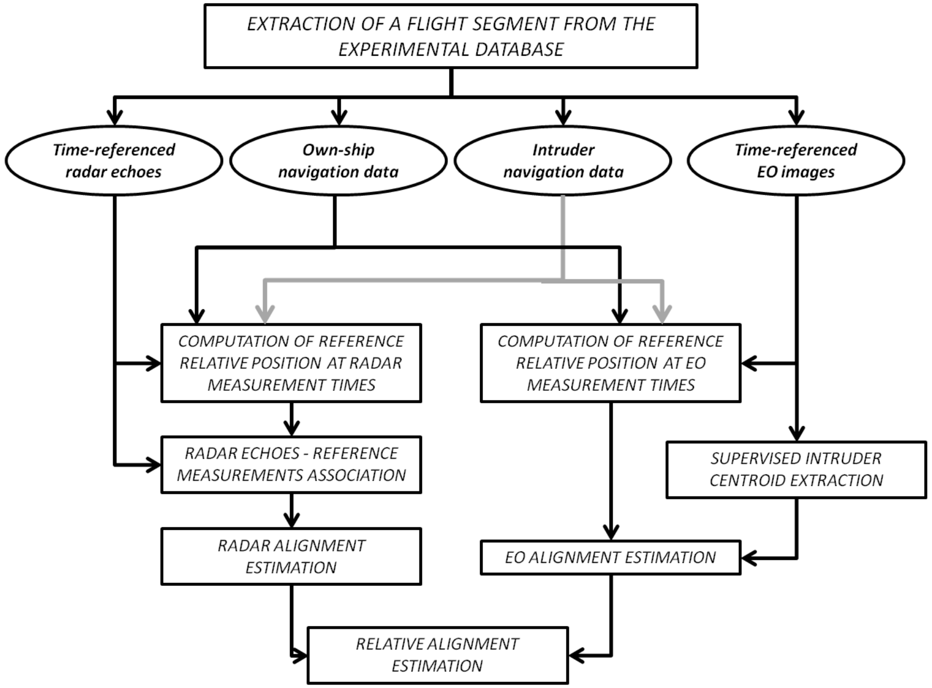




D. Accardo et alii, "Flight Test of a Radar-Based Tracking System for UAS Sense and Avoid", IEEE Trans. on Aerospace and Electronic Systems, vol.49, no.2, pp.1139-1160, April 2013

Flight results: multi-sensor fusion

- Need of data fusion to improve tracking accuracy and thus conflict detection performance
- Usage of cross-sensor cueing to enhance real time EO detection performance reducing sensitivity to weather/illumination
- Role of ownship navigation system
- Data fusion implementation aspects, such as out of sequence measurements and relative sensors alignment



EXTRACTION OF A FLIGHT SEGMENT FROM THE EXPERIMENTAL DATABASE

Time-referenced radar echoes

Own-ship navigation data

Intruder navigation data

Time-referenced EO images

COMPUTATION OF REFERENCE RELATIVE POSITION AT RADAR MEASUREMENT TIMES

COMPUTATION OF REFERENCE RELATIVE POSITION AT EO MEASUREMENT TIMES

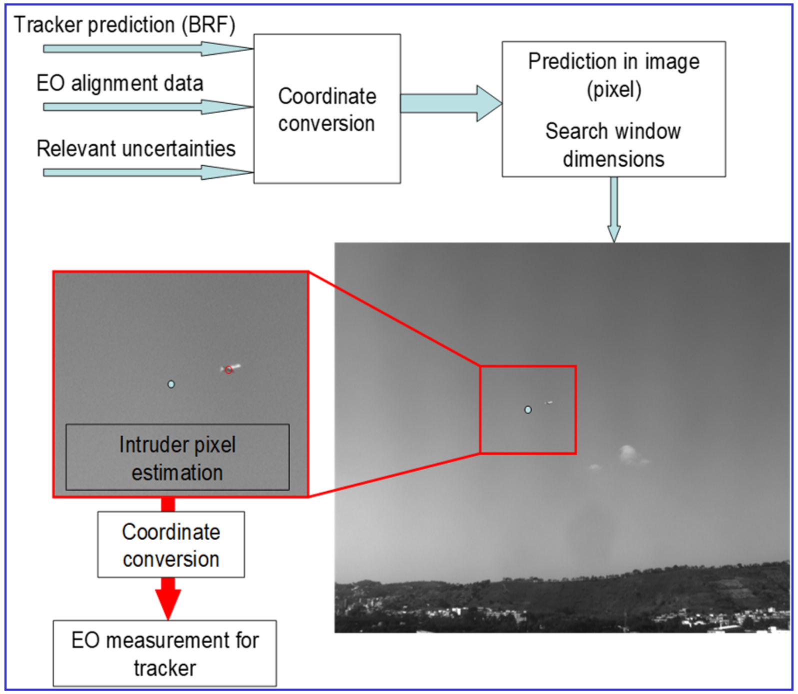
RADAR ECHOES - REFERENCE MEASUREMENTS ASSOCIATION

SUPERVISED INTRUDER CENTROID EXTRACTION

RADAR ALIGNMENT ESTIMATION

EO ALIGNMENT ESTIMATION

RELATIVE ALIGNMENT ESTIMATION



Tracker prediction (BRF)

EO alignment data

Relevant uncertainties

Coordinate conversion

Prediction in image (pixel)

Search window dimensions

Intruder pixel estimation

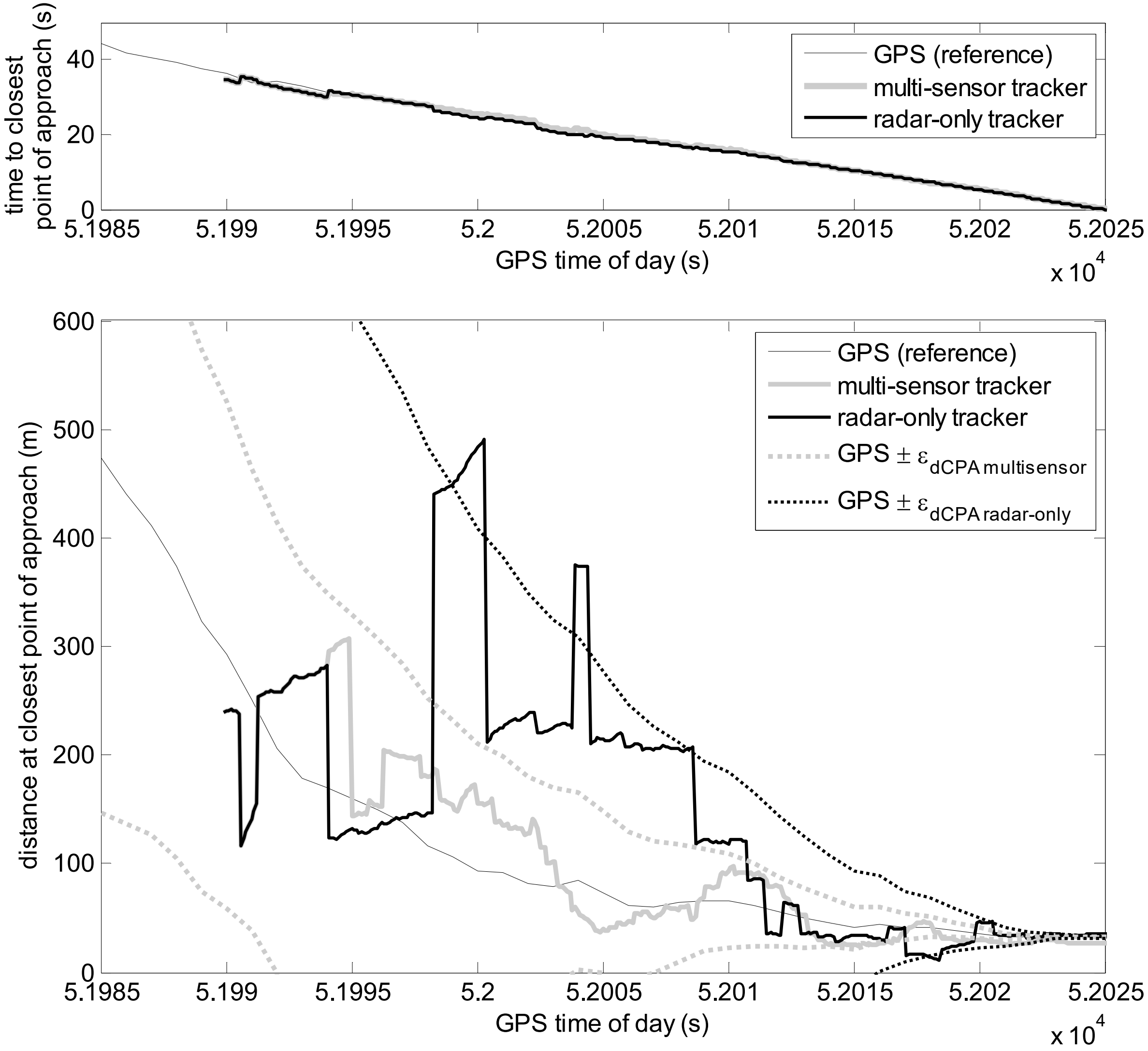
Coordinate conversion

EO measurement for tracker

(G. Fasano et alii, "Radar/electro-optical data fusion for non-cooperative UAS sense and avoid", Aerospace Science and Technology, vol. 46, pp. 436-450, October-November 2015)

SAA: flight results
Multi-sensor-based detection and tracking

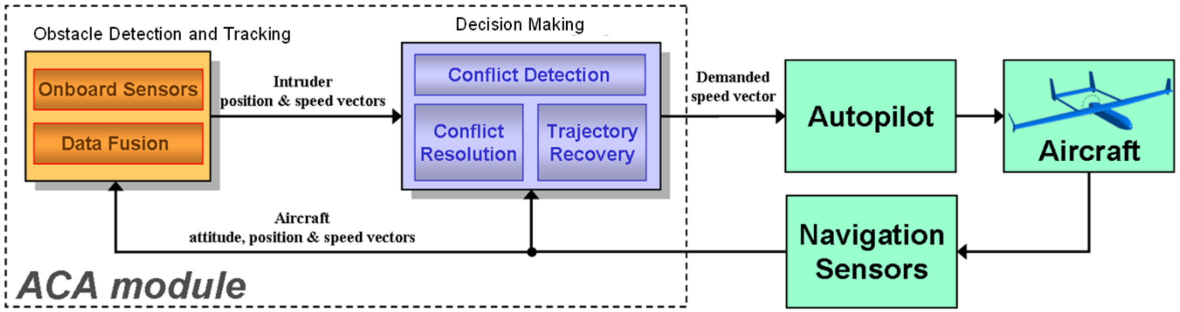
- Compared with radar-only tracking, a more accurate estimate of angular rates, and thus of the distance at closest point of approach, can be provided



(G. Fasano et alii, “Radar/electro-optical data fusion for non-cooperative UAS sense and avoid”, Aerospace Science and Technology, vol. 46, pp. 436-450, October-November 2015)

SAA: flight results
Autonomous non-cooperative collision avoidance

- Carried out in radar-only configuration
- Smooth (mostly horizontal) maneuvers
- Increase of ground clutter and degradation of valid measurement rate during avoidance maneuver



Obstacle Detection and Tracking

Onboard Sensors

Data Fusion

Intruder position & speed vectors

Decision Making

Conflict Detection

Conflict Resolution

Trajectory Recovery

Demanded speed vector

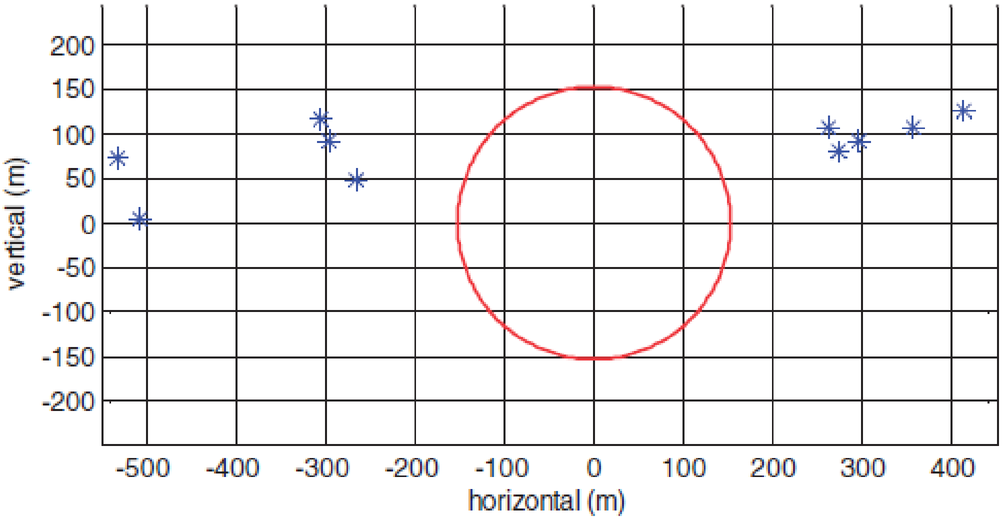
Autopilot

Aircraft

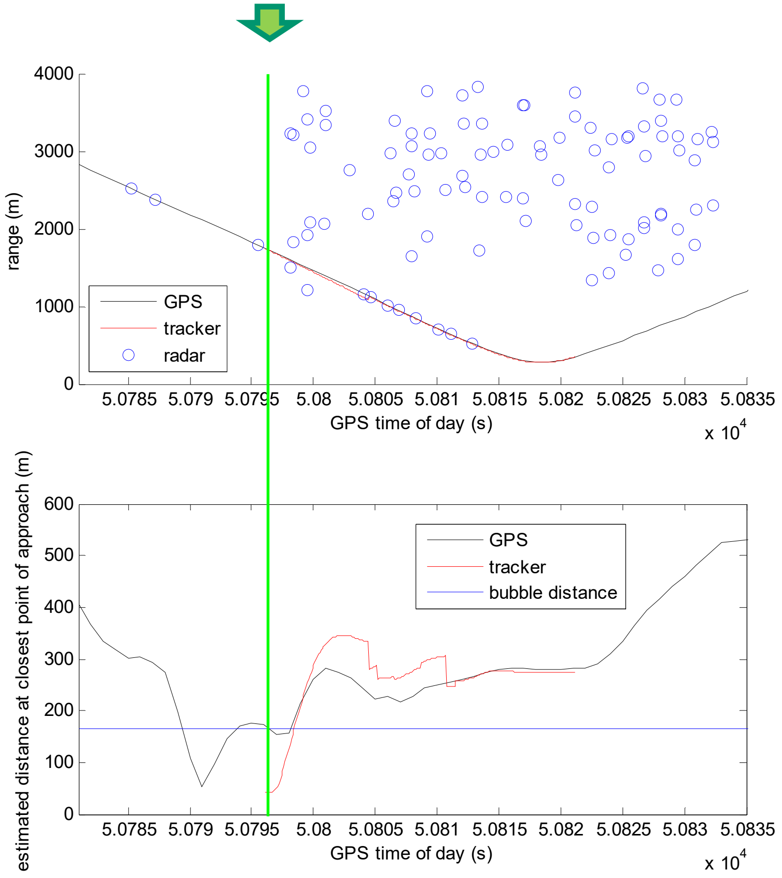
Navigation Sensors

Aircraft attitude, position & speed vectors

ACA module

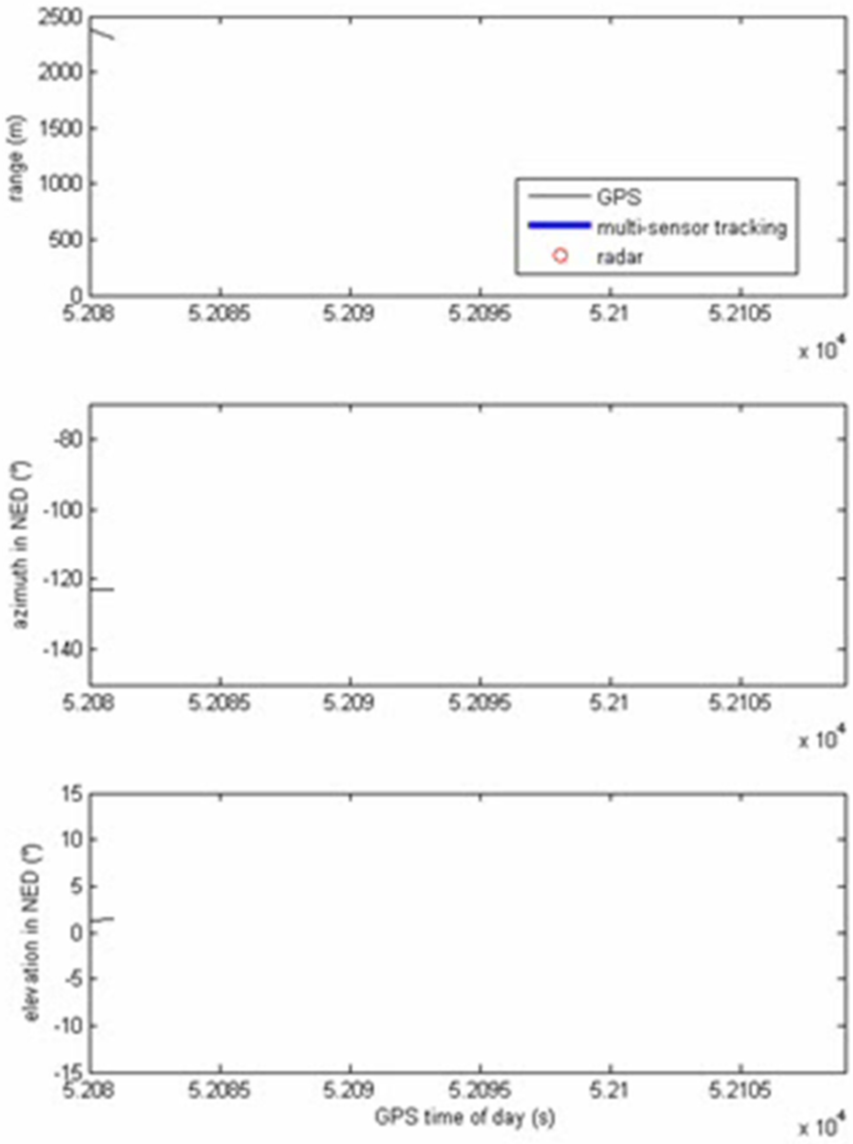


AVOIDANCE MANEUVER INITIATED

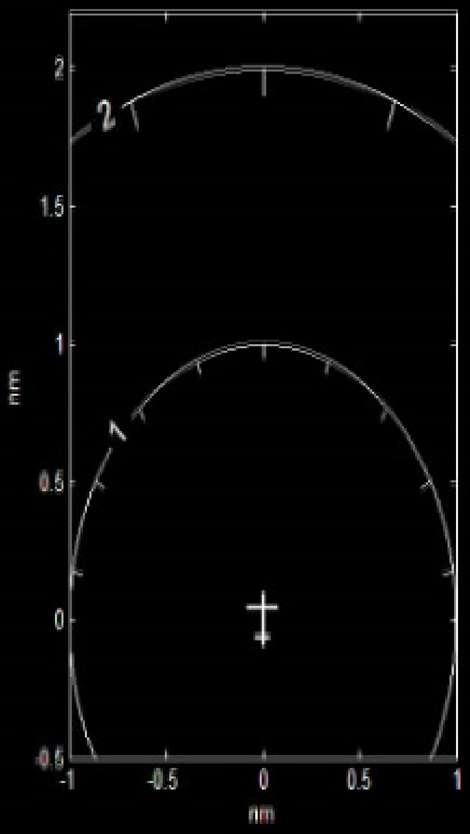


(Fasano et al., In-Flight Performance Analysis of a Non-cooperative Radar-based Sense and Avoid System, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering July 2016)

Flight results: multi-sensor fusion

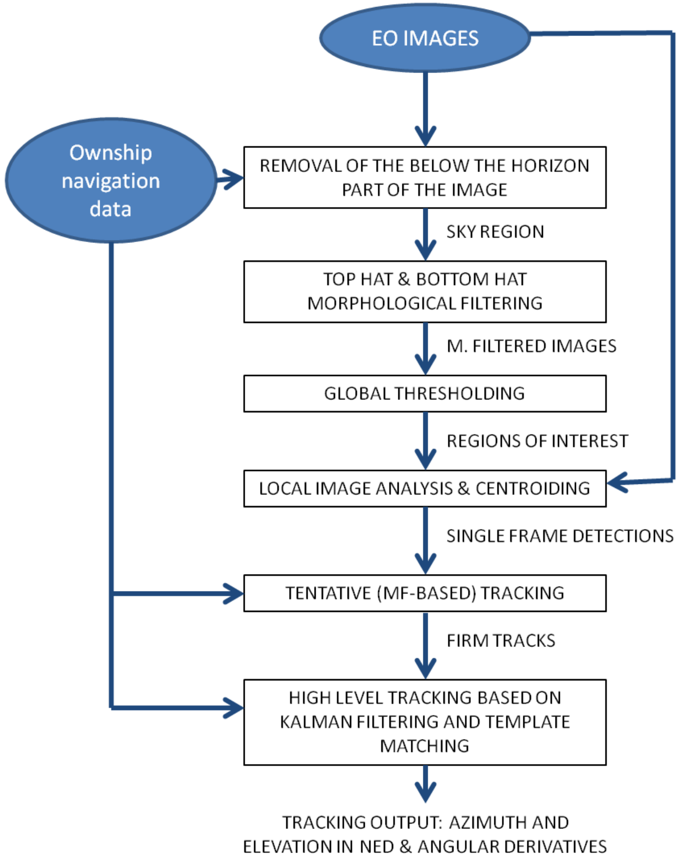


SAA - TCAS-like output video



Vision-based SAA

- Multi-step detection and tracking strategy based on morphological filters (above the horizon)
- Conflict detection based on adaptive threshold for line-of-sight rate including ownship motion, intruder azimuth, and worst case assumption about intruder velocity and range



EO IMAGES

Ownship navigation data

REMOVAL OF THE BELOW THE HORIZON PART OF THE IMAGE

SKY REGION

TOP HAT & BOTTOM HAT MORPHOLOGICAL FILTERING

M. FILTERED IMAGES

GLOBAL THRESHOLDING

REGIONS OF INTEREST

LOCAL IMAGE ANALYSIS & CENTROIDING

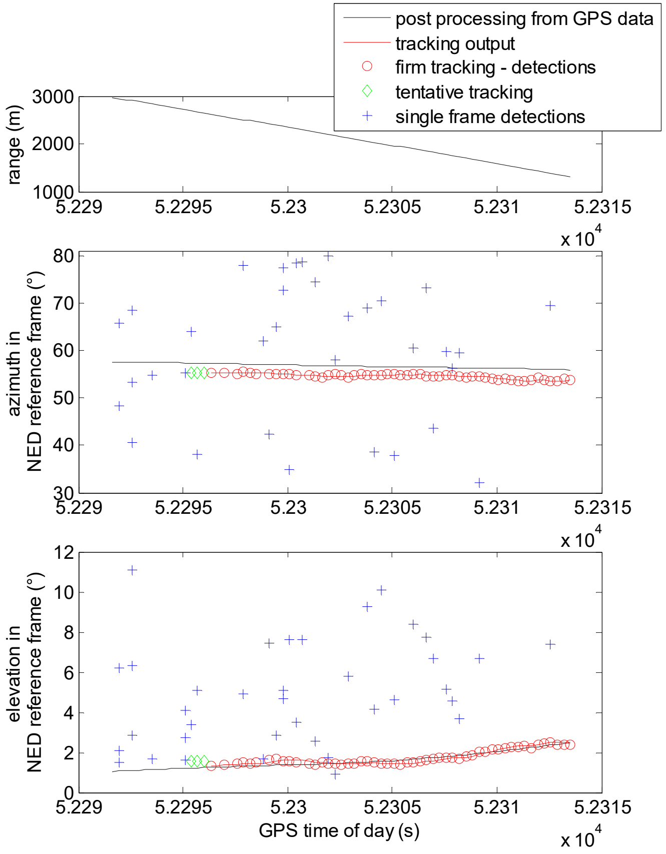
SINGLE FRAME DETECTIONS

TENTATIVE (MF-BASED) TRACKING

FIRM TRACKS

HIGH LEVEL TRACKING BASED ON KALMAN FILTERING AND TEMPLATE MATCHING

TRACKING OUTPUT: AZIMUTH AND ELEVATION IN NED & ANGULAR DERIVATIVES



- Declaration range sensitive to illumination and environmental conditions
- Tracking accuracy impacted by AHRS performance

G. Fasano et alii, "Sky region obstacle detection and tracking for vision-based UAS sense and avoid," Journal of Intelligent & Robotic Systems, vol. 84, no. 1-4, pp. 121-144, December 2016.

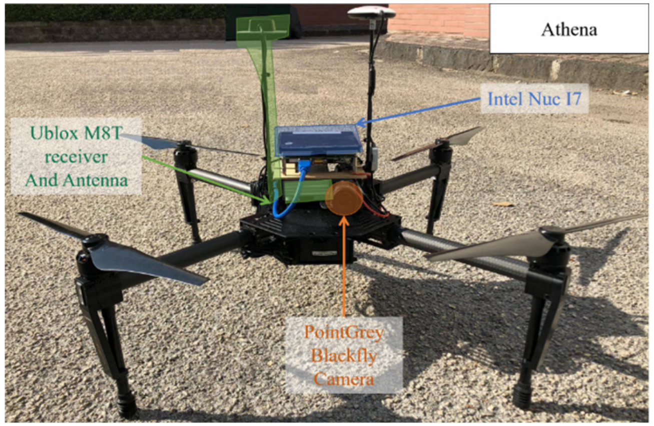
Recent/current activities on DAA

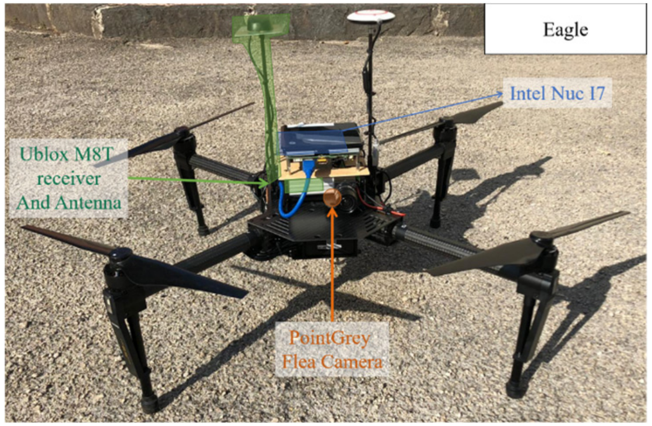
- Innovative airborne vision-based techniques
- Radar-based sense and avoid with low SWaP radars
- Radar/EO fusion on small flight platforms

- Conflict detection and sensing requirements analysis for very low altitude DAA

- Ground-based sensing and air/ground interaction

- Emphasis on flying obstacles

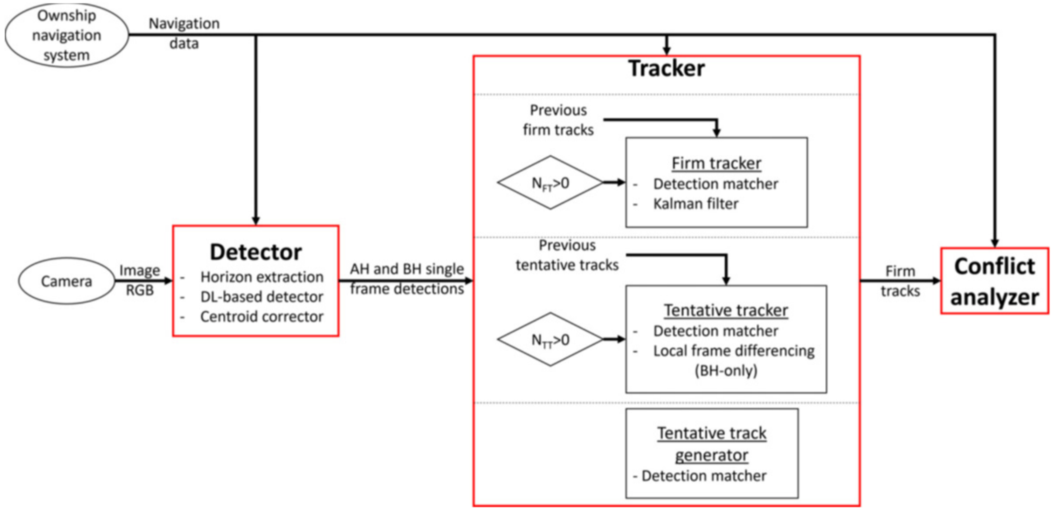




Visual Detection and Tracking

Ideas:

1. Develop an architecture for both above the horizon (AH) and below the horizon (BH) conditions
2. Exploit deep-learning-based detection concepts in whole image: i.e., work with appearance-based techniques also below the horizon
3. Keep a multi-temporal processing structure for transition to firm tracking



Pre-processing

Horizon detection and image segmentation

Deep Learning (DL)-based detection (different detectors for different image regions)

Single-frame object detection

Multi-Temporal algorithm

To carry out tentative tracking, firm track confirmation, angular rates estimation. Local frame differencing for Below the Horizon processing

Conflict detection

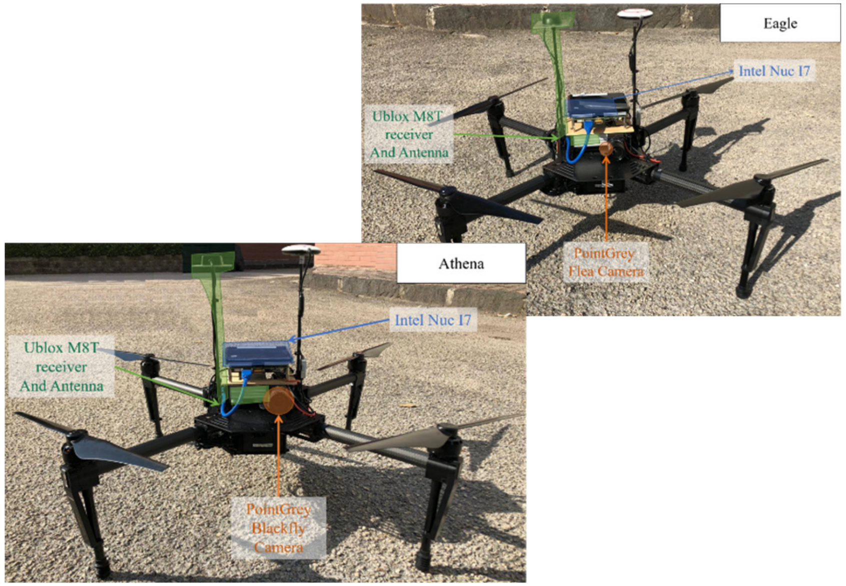
Range-less criteria (angle-based, long range)

(Opromolla and Fasano, "Visual-based obstacle detection and tracking, and conflict detection for small UAS sense and avoid", Aerospace Science and Technology 2021)

Experimental setup and air-to-air tests

- Two customized drones are used, which can simultaneously act as intruder and ownship

- Flight tests carried out at a model aircraft airfield
- Several low-altitude, near-collision encounters
  - initial range of about 300 m;
  - variable speeds.
  - Slight differences in altitude (30 m above ground on average), both above and below the horizon conditions were obtained.



Example flight results

- Large declaration range (order 300 m – 5 pixels) and fine angular/angular rate accuracy in AH encounters
- Multi-temporal strategies fundamental in BH processing to avoid ground-based false targets (lower detection range)

Example AH encounter

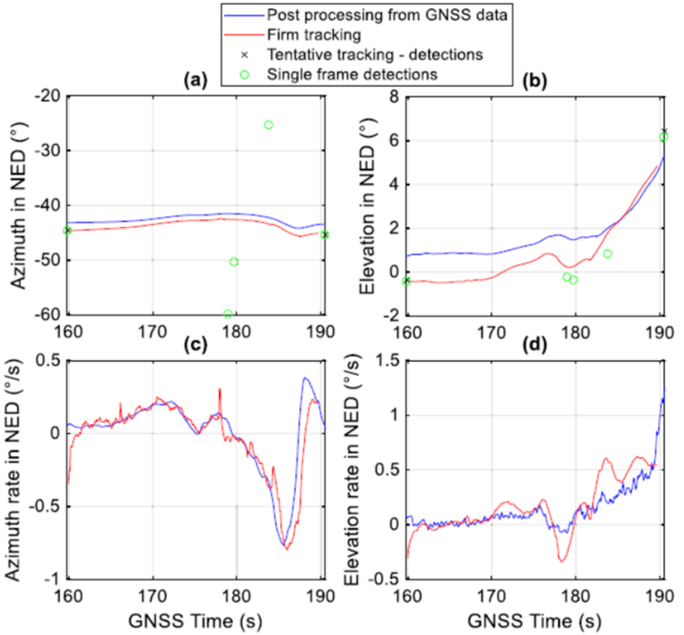


Fig. 10. Output of the firm tracker (red) compared with the reference GNSS-based solution (blue) for the first AH encounter. (a) Azimuth in NED. (b) Elevation in NED. (c) Azimuth rate in NED. (d) Elevation rate in NED.

Local frame differencing for BH processing

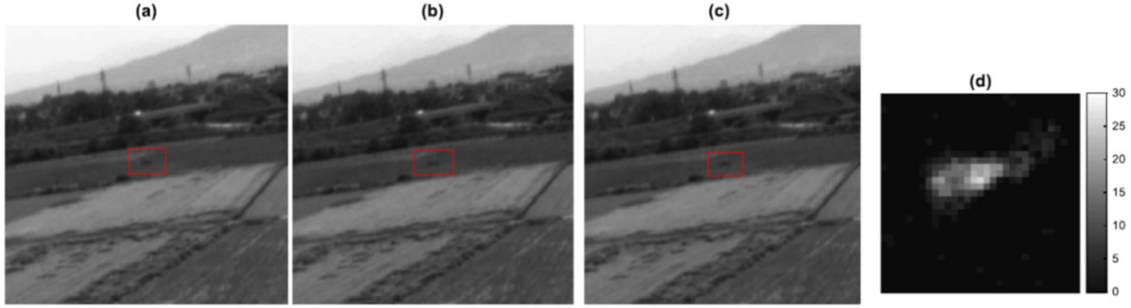


Fig. 4. Example of implementation of the *Local frame differencing* function with $W_{fr\text{-}diff}$ equal to 150 pixels, W_{peck} equal to 20 pixels and $\tau_{fr\text{-}dif}$ equal to 20. (a) Image window cropped from the previous frame, J_{k-1}, centered around the position contained in the tentative track. (b) Image window cropped from the current frame, J_k, centered around the position of the DL-based detection matched with the track prediction. (c) Current image window registered to the previous one, $J_{k,reg}$. (d) Zoom of the difference image window, J_{diff}, around the intruder: P_{reg} is equal to 30 (thus being larger than $\tau_{fr\text{-}dif}$) In (a), (b), and (c), the intruder is enclosed by a red rectangular box for the sake of clarity.

(Opromolla and Fasano, “Visual-based obstacle detection and tracking, and conflict detection for small UAS sense and avoid”, Aerospace Science and Technology 2021)

Non-cooperative low altitude SAA with low SWaP radar

RESEARCH GOALS

- Gather and analyze data from **low SWaP radar** and **visual camera** during **low altitude flight tests.**
- Assess **detection** and **tracking** performance of different sensor fusion strategies.

EXPERIMENTAL RESEARCH PLAN

PHASE 1

✓ Preliminary tests with ground-based radar [1]

✓ Ground-to-air tests with multi-sensor setup
  - assessment of radar and visual standalone tracking strategies [2]
  - assessment of radar/visual fusion strategies [3]

PHASE 2

○ Air-to-air tests with airborne multi-sensor setup

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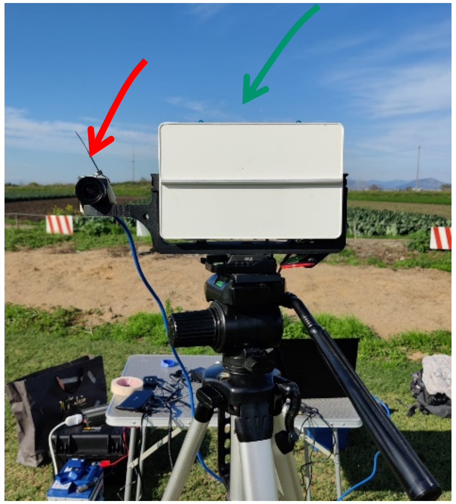
[1] - Vitiello et alii. "Improved Sensing Strategies for Low Altitude Non-Cooperative Sense and Avoid," 2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC).

[2] – Vitiello et alii. "Detection and tracking of non-cooperative flying obstacles using low SWaP radar and optical sensors: an experimental analysis" 2022 International Conference on Unmanned Aircraft Systems (ICUAS).

[3] – Vitiello et alii. "Ground-to-air experimental assessment of low SWaP radar-optical fusion strategies for low altitude Sense and Avoid," 2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC).

Non-cooperative low altitude SAA with low SWaP radar



Echoflight MESA radar

FLIR Blackfly visual camera

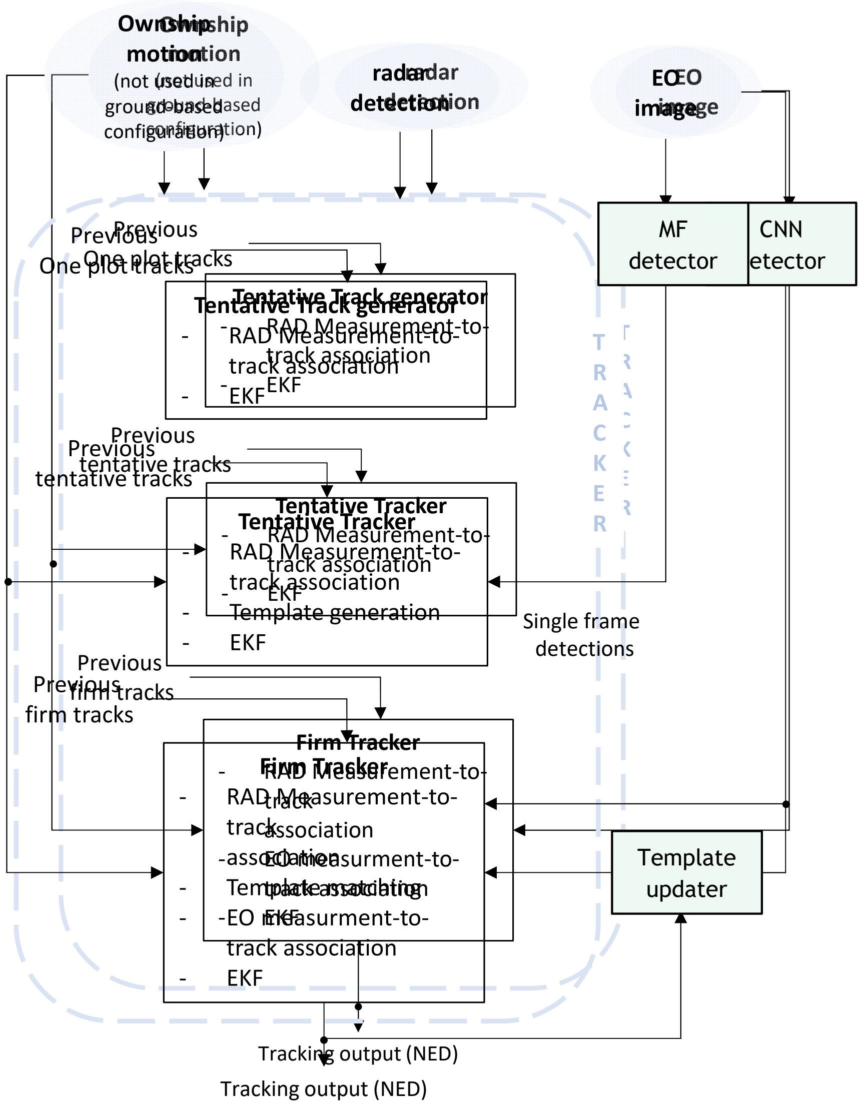
uBlox LEA-6T receiver with patch antenna

Customized DJI M100

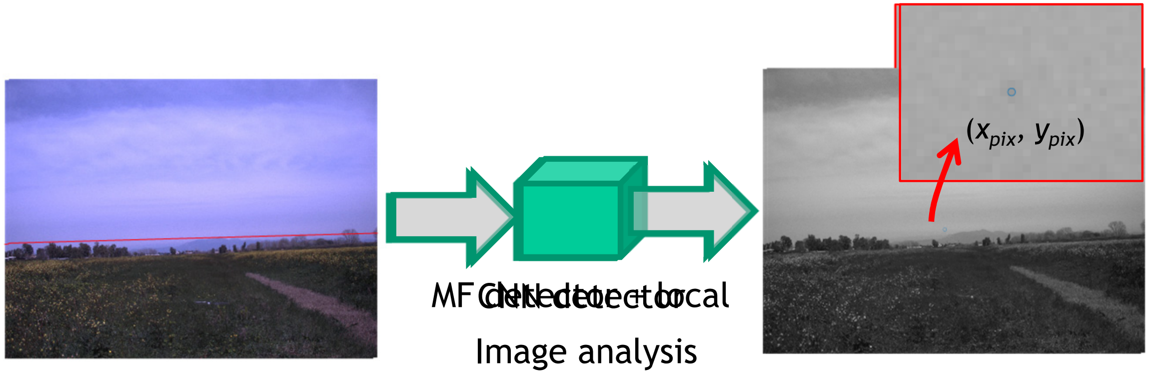
Manually piloted to perform **encounters** (approaching maneuvers)

Non-cooperative low altitude SAA with low SWaP radar

Tested RADAR/VISUAL fused strategies



VISUAL DETECTOR



TEMPLATE UPDATER

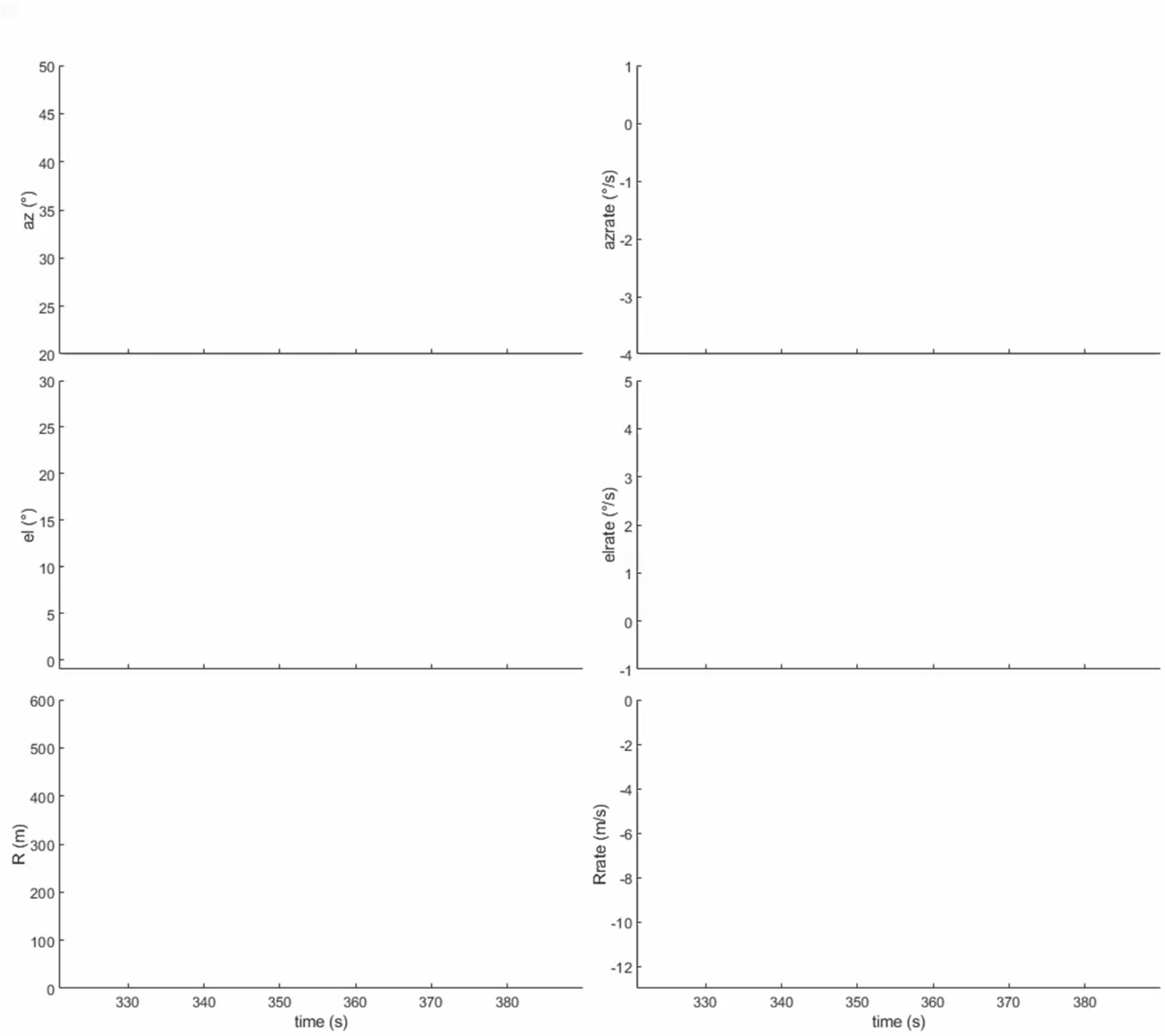
Adaptive method to account for variation in the dimensions of target on the image plane.

Based on range estimates.

Non-cooperative low altitude SAA with low SWaP radar

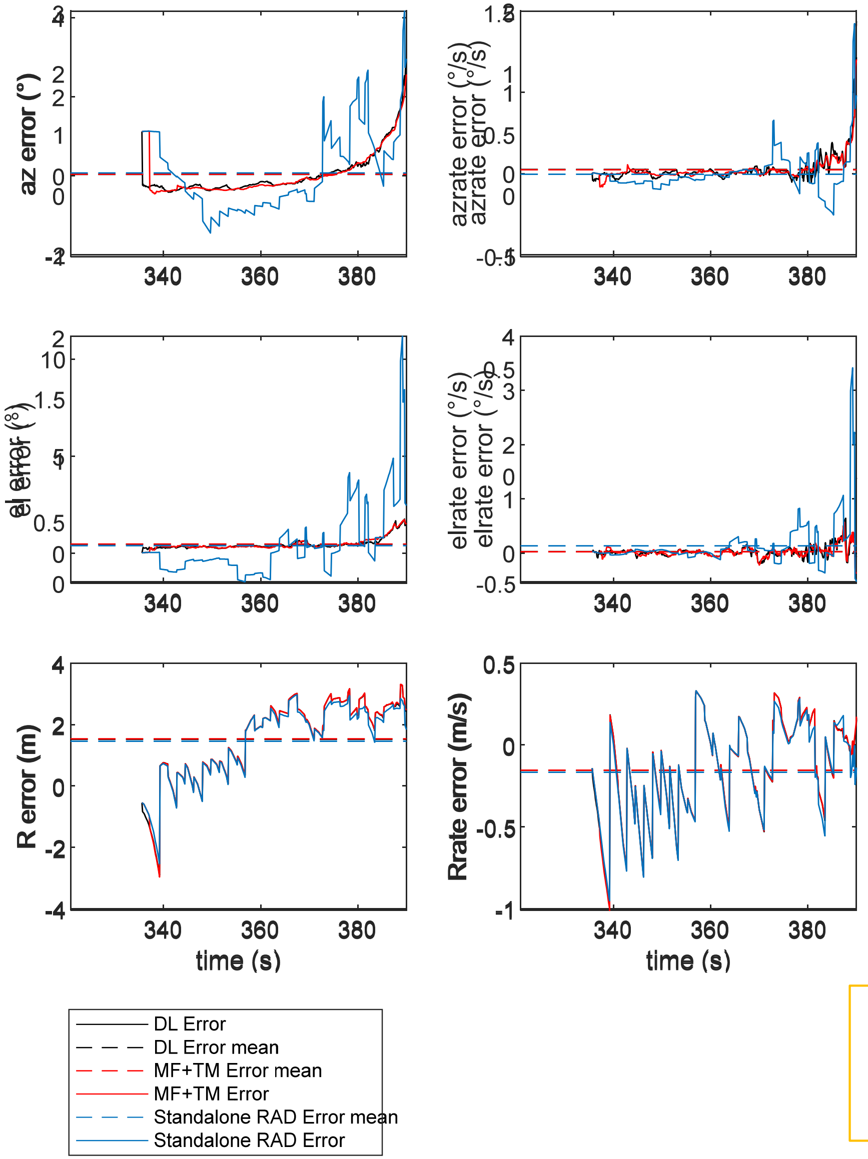
Experimental results

- Ground truth - Firm track ° radar detection



Non-cooperative low altitude SAA with low SWaP radar - results

Experimental results



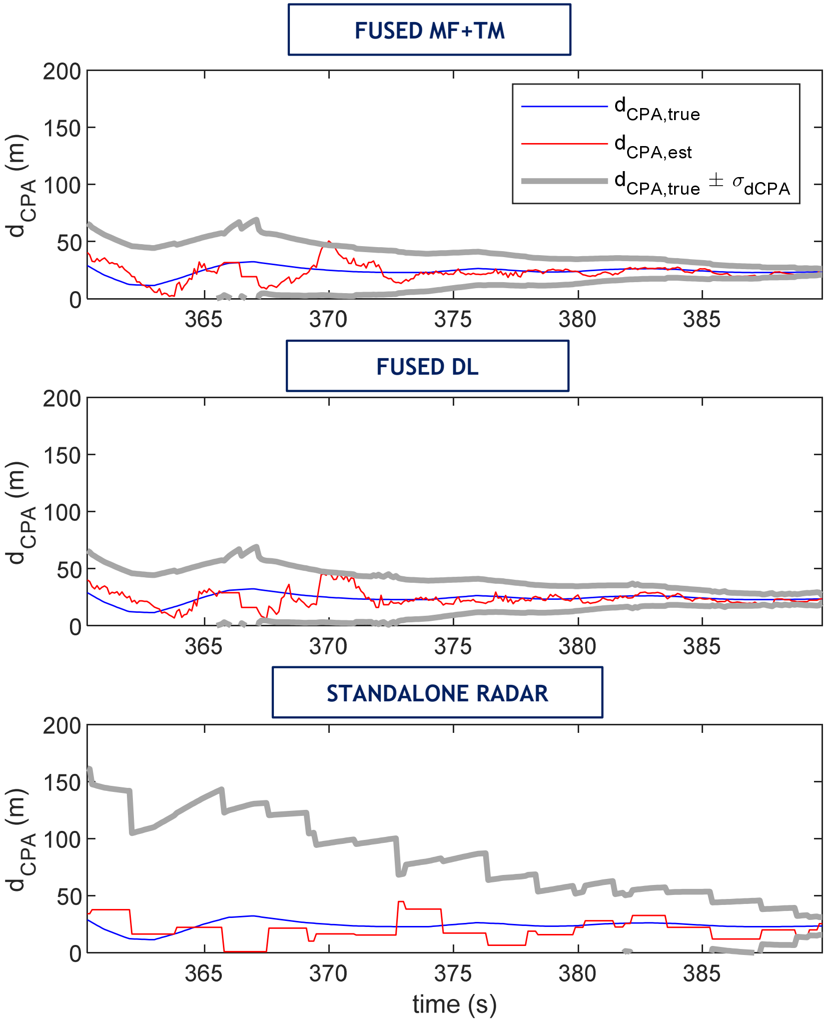
Algorithm	Az RMSE (°)	Az_{rate} RMSE (°/s)	El RMSE (°)	El_{rate} RMSE (°/s)
Fused DL	0.25	0.17	**0.55**	0.11
Fused MF+TM	0.24	0.15	**0.57**	0.19
Standalone RAD	1.01	0.24	**1.85**	0.44

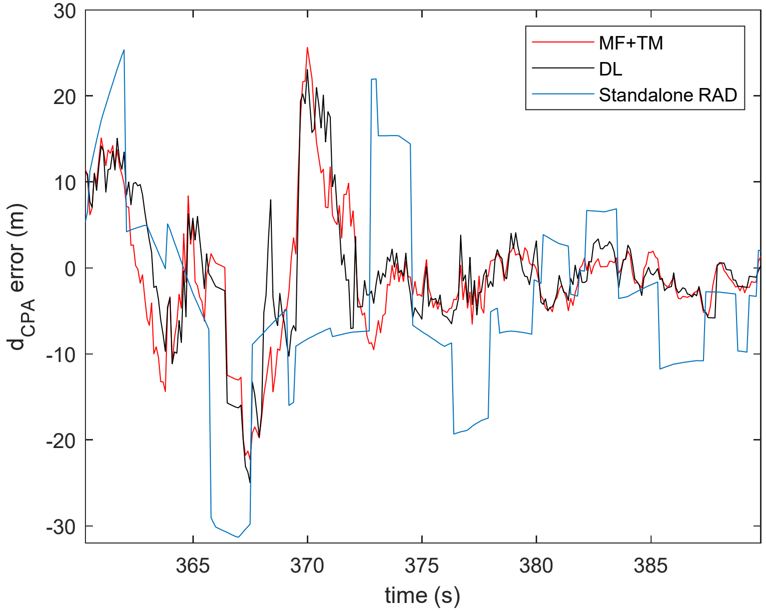
Algorithm	R RMSE (m)	R_{rate} RMSE (m/s)	Firm track range max (m)
Fused DL	1.9	0.3	**520**
Fused MF+TM	2	0.3	**520**
Standalone RAD	1.9	0.3	**520**

- **Improved angular accuracy**
- **Declaration range comparable to encounter max**

Non-cooperative low altitude SAA with low SWaP radar - results

Experimental results on d_{CPA}

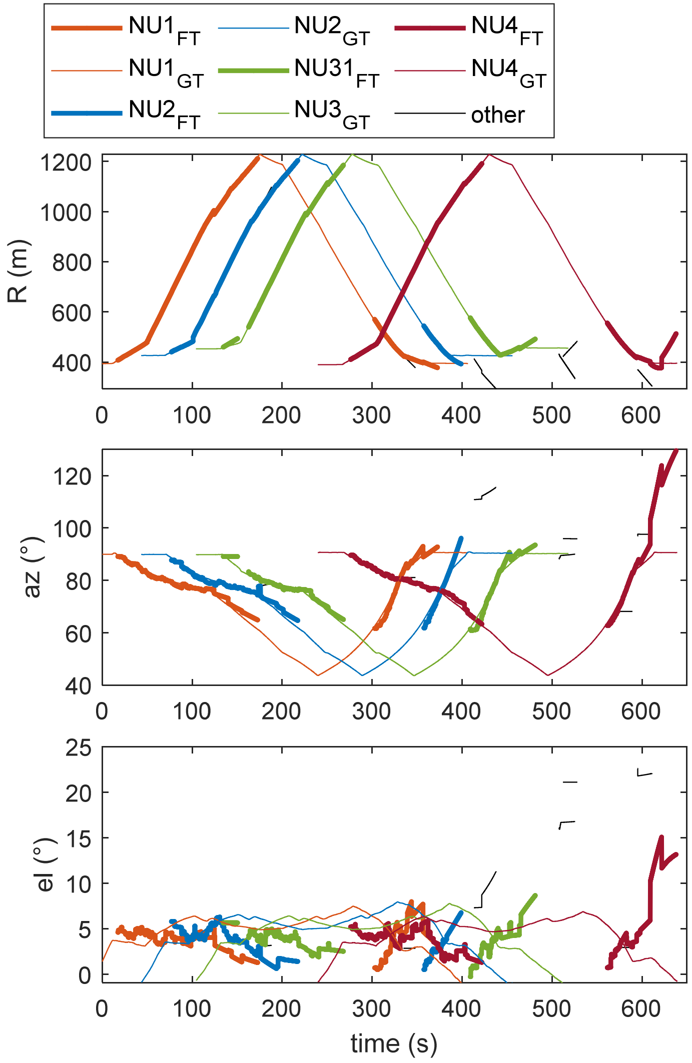


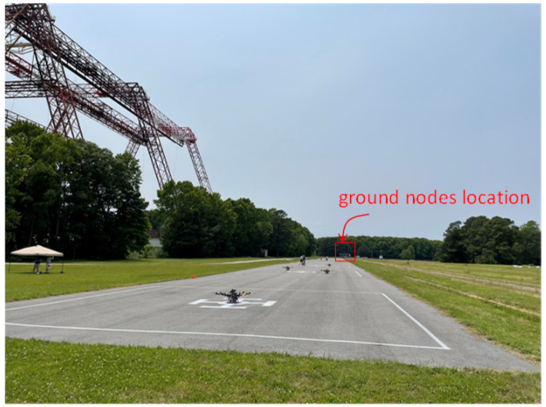


Algorithm	Error mean (m)	RMSE (m)
MF+TM	1	7.5
DL	0.3	7.5
Standalone radar	4	12

Non cooperative SAA with low SWaP radar

- Current cooperation with NASA within the wider framework of distributed ground/air sensing
- Opportunity to
  - Investigate sensing performance in different operating environment
  - Tailor sensing strategies for ground-based nodes
  - Compare and combine sensing approaches
  - Investigate the potential of multi-node fusion exploiting spatial diversity
  - Work on airspace surveillance beyond detect and avoid





(Vitiello et alii, Assessing Performance of Radar and Visual Sensing Techniques for Ground-To-Air Surveillance in Advanced Air Mobility, to be presented at IEEE/AIAA Digital Avionics Systems Conference 2023)

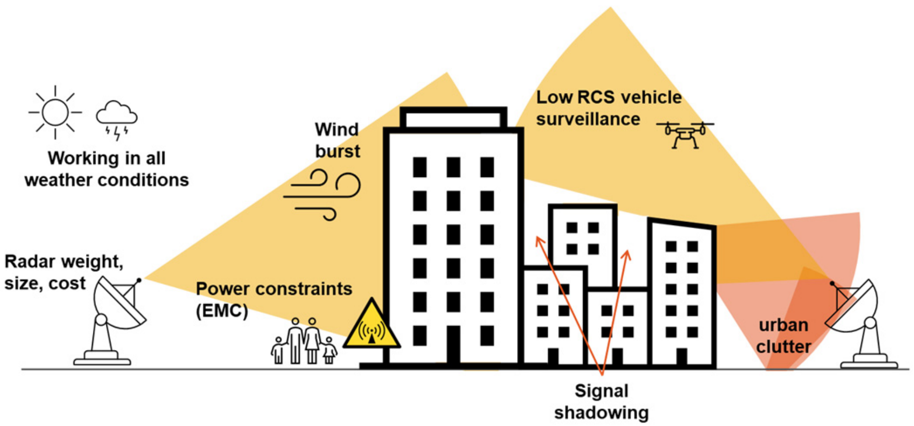
Ground-based radar networks for UAM

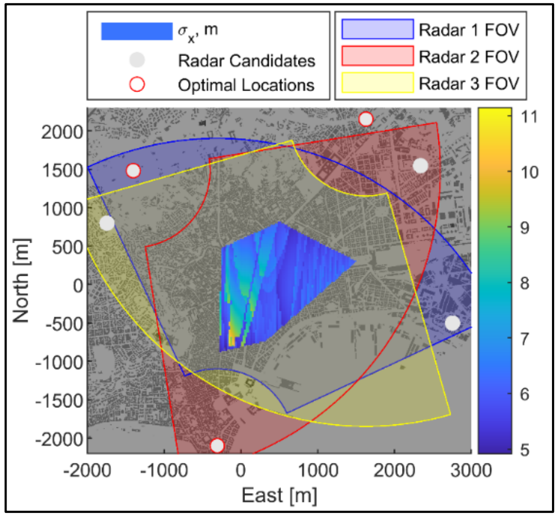
- Theoretical study in collaboration with Raytheon and Collins Aerospace

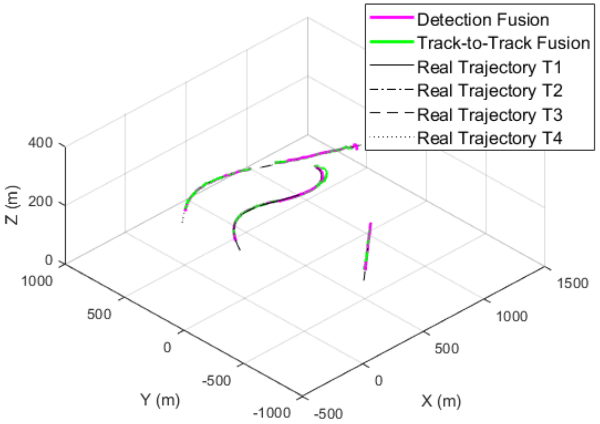
- Research scope: investigate the concept of ground-based sparse medium power radar networks for low altitude surveillance in urban environments
  - Radar requirements
  - Sensor placement optimization
  - Tracking and data fusion algorithms

- Interface with airspace structure and management, communication aspects, navigation performance

- Link with weather sensing







(Aievola et al., «Ground-based Radar Networks for Urban Air Mobility: Design Considerations and Performance Analysis", IEEE/AIAA DASC 2022)

Perspectives

- Lots of on-going activities on DAA in ATM (en-route and terminal areas)
  - Link with enhanced safety for manned aviation (sensing subsystem as a pilot assistance tool, contingency management)
  - Interoperability between DAA and manned aircraft collision avoidance

- Evolution of very low altitude DAA closely related to evolving U-Space/UTM concepts
  - Definition of requirements and standards: how much is enough?
  - Need for integrated and «technology aware» approach
  - Different use cases likely to be accounted for

- UAM/AAM as a new entrant – main players addressing DAA
  - Depending on mission profiles, link between SAA in ATM and UTM/U-Space

Perspectives

(Airbus Vahana program)

https://www.youtube.com/watch?time_continue=33&v=1qyNJElRwfw

Perspectives

- DAA in potentially dense low altitude environments poses specific challenges and encourages a more «tightly coupled» CNS/ATM perspective
  - Ground clutter
  - Link between mobile/fixed obstacle avoidance and navigation issues, both at sensing and decision making level
  - Link between DAA and distributed/centralized cooperation schemes also applicable to multi-drone systems
  - Air/ground interaction

- Very active research community, main non cooperative technology trends deal with
  - artificial intelligence
  - innovative sensors and processing/data fusion architectures
  - avoidance in constrained environments

- Importance of high fidelity simulation environments and (outdoor) flight testing in relevant (complex) environments

- Potential of shared datasets and benchmarks, and flight challenges, to stimulate development of non cooperative solutions

Conclusion

- DAA as an exciting and evolving framework still presenting a number of open issues
- The diversity of UAS, and the related diversity of issues around DAA have contributed to the fact that there is not one accepted answer for DAA for UAS

Way to go for detect and avoid…

How time flies…

Thank you for your attention

Contact information

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