



Aerospace
and Defense



Close proximity and collision risk assessment of drones and urban air mobility

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11th SESAR Innovation Days



Context and motivation



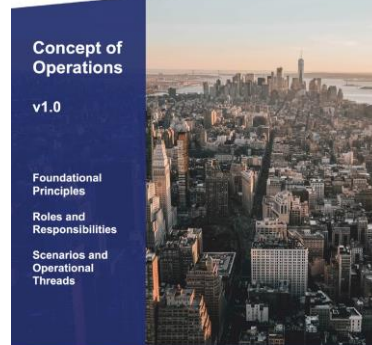
Context

- U-space
- Drone operations
- Urban air mobility
- Risk assessment

Strategic Research and Innovation Agenda



U-space



Urban Air Mobility (UAM)

Assessing the Risks of Integrating Unmanned Aircraft Systems (UAS) into the National Airspace System

ASSESSING THE RISKS OF INTEGRATING UNMANNED AIRCRAFT SYSTEMS INTO THE NATIONAL AIRSPACE SYSTEM

Committee on Assessing the Risks of Unmanned Aircraft Systems (UAS) Integration

Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
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Washington, DC
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Joint Authorities for Rulemaking of Unmanned Systems

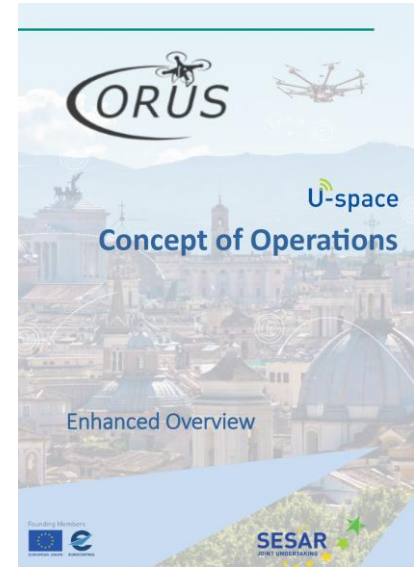
JARUS guidelines on Specific Operations Risk Assessment (SORA)

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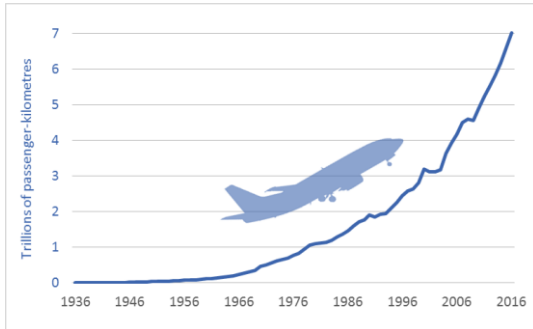
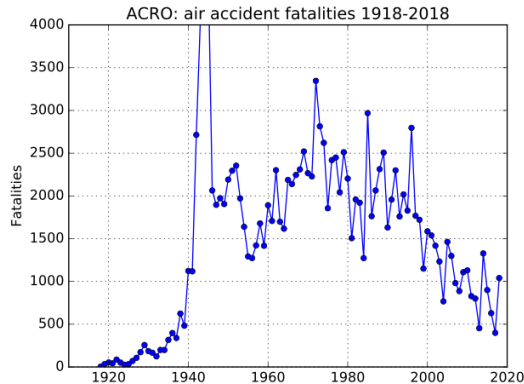


U-space



Towards a new era of aviation safety

(Manned) air accident fatalities



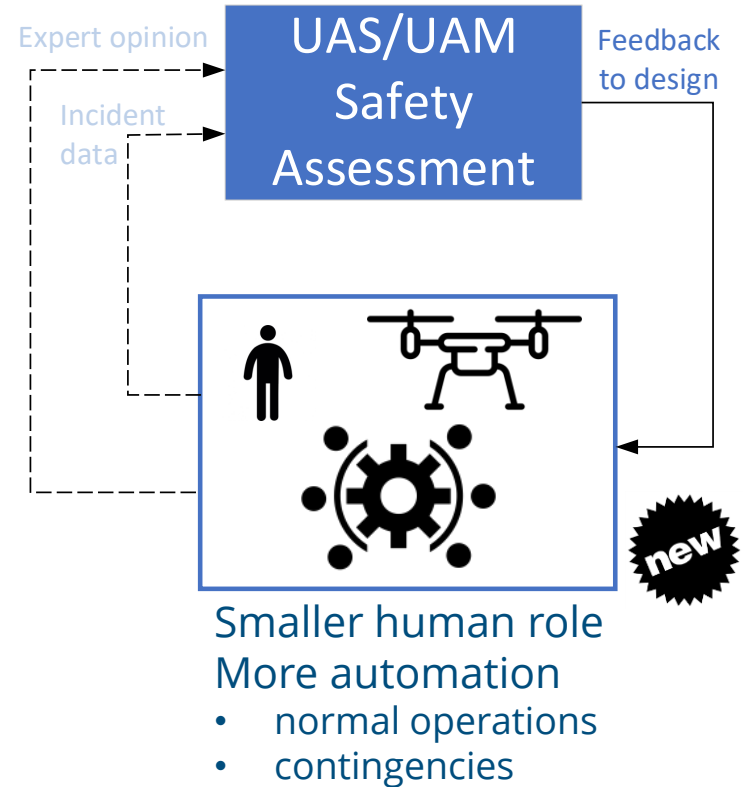
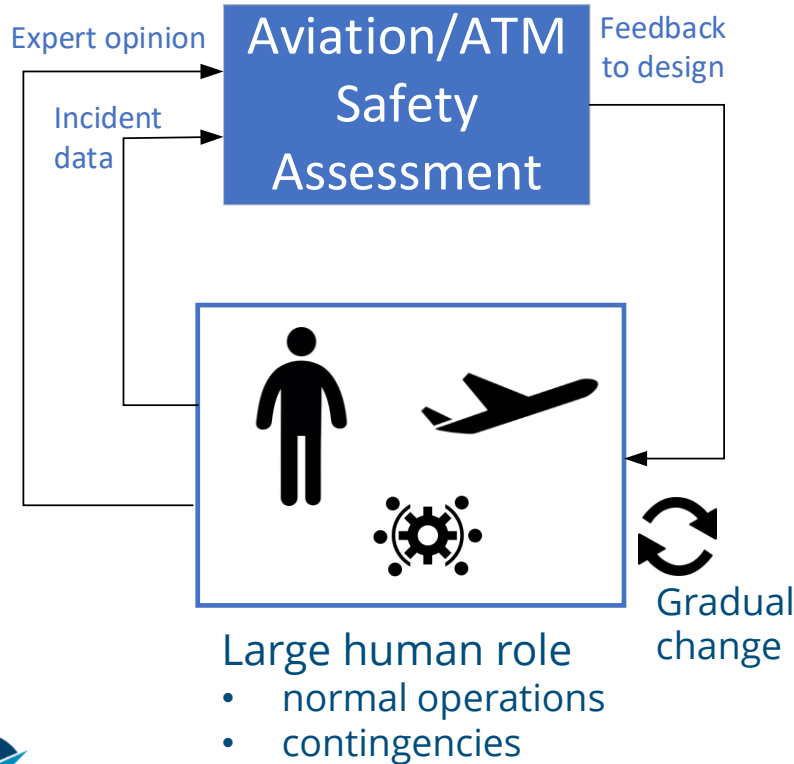
UAS/UAM safety

- Little data yet
- High fatality rates from early (manned) aviation would not be acceptable in current society
- Third party risk is more important



Essential to assure high safety standards from the start

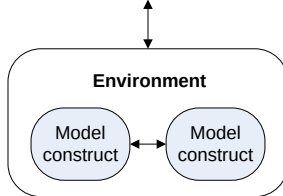
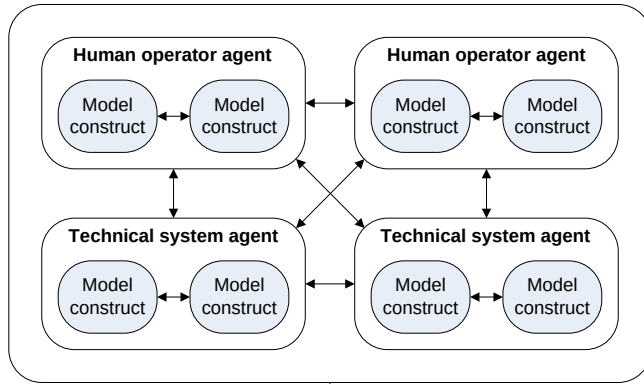
Need for advanced safety assessment approaches



- Systems involving complex dynamic interactions
 - Variety of unmanned aircraft, CNS systems, high levels of automation, human interactions
 - Performance variability in normal conditions
 - Sensor errors, human reaction times, wind,...
 - Performance variability off-nominal/failure conditions
 - System failures, human errors, adverse weather,...
- Need to assess safety of UAS/UAM operations
 - When systems work as intended
 - DAA effectiveness, traffic density, planning,...
 - When there are failures
 - Impact of system failures, planning errors,...



Agent-based dynamic risk modelling



Agent-based models of aircraft, systems, human operators and environment

- Dynamics and stochastic variability in normal conditions
- Dynamics and stochastic variability in off-nominal/failure conditions

Rare event Monte Carlo (MC) simulation

- Interacting Particle Systems MC simulation
- Risk decomposition

Applications/methods

- Blom et al. (2007, 2015, 2018), Stroeve et al. (2009, 2020), Everdij et al. (2014)

Scope

Concept of Operations

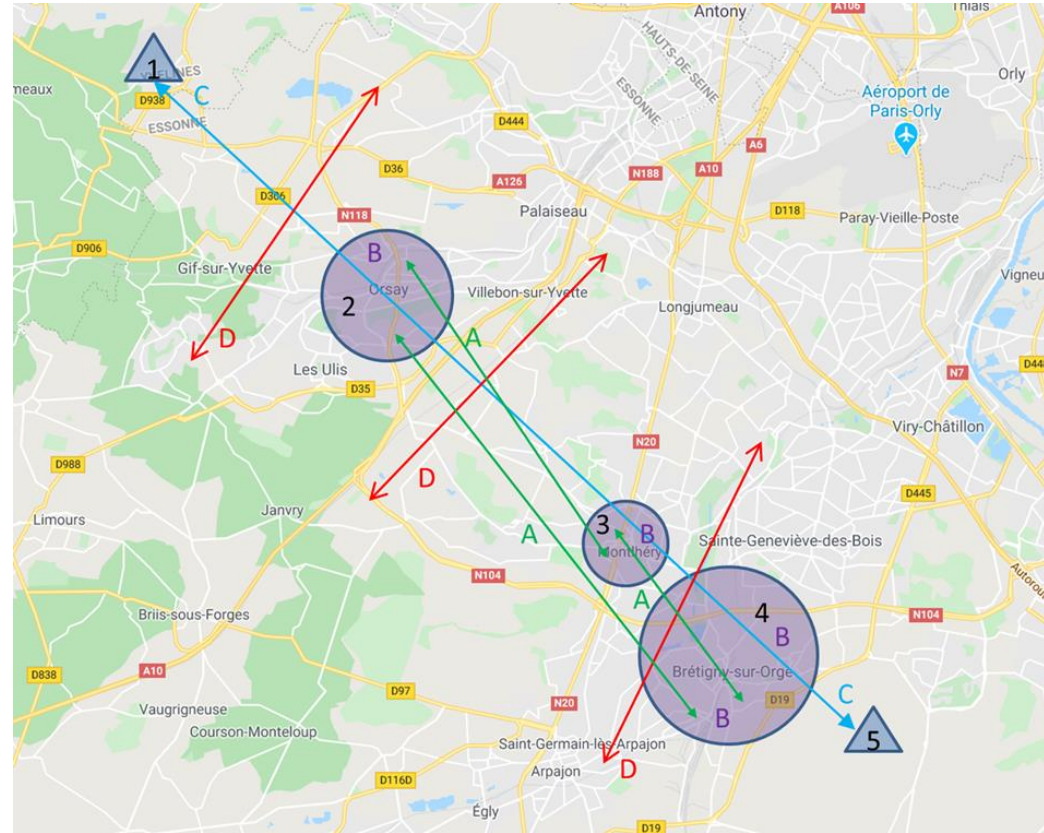
Risk Types and Variability

Areas

- Aerodromes 1, 5 (Toussus-le-Noble, Brétigny)
- Urban areas 2, 3, 4 (Orsay, Monthléry, Brétigny)

Missions

- A. VTOL air taxis between urban areas
- B. VTOL surveillance & loitering in urban areas
- C. Fixed-wing drones between airports
- D. Fixed-wing drones crossing overall area



In scope

- All operations are controlled by pilots-in-command (PICs) in remote pilot stations
- Command-and-control (C2) link systems in UAS, RPS and regional infrastructure
- Navigation data via global navigation satellite system and pressure altimetry
- Automatic dependent surveillance data
- Detect-and-avoid (DAA) system to remain well clear
- Response to DAA is via PIC

Out of the scope

- No strategic deconfliction
- No tactical conflict resolution
- No capacity management
- No geofencing
- No automatic response to DAA
- No manned aviation
- No interface with air traffic control

In scope

Risk of close proximity and mid-air collision of UAS/UAM with other UAS/UAM

Out of the scope

- No third-party risk regarding people, animals, buildings, infrastructure on the ground
- No risk with regard to manned aviation

Normal variability

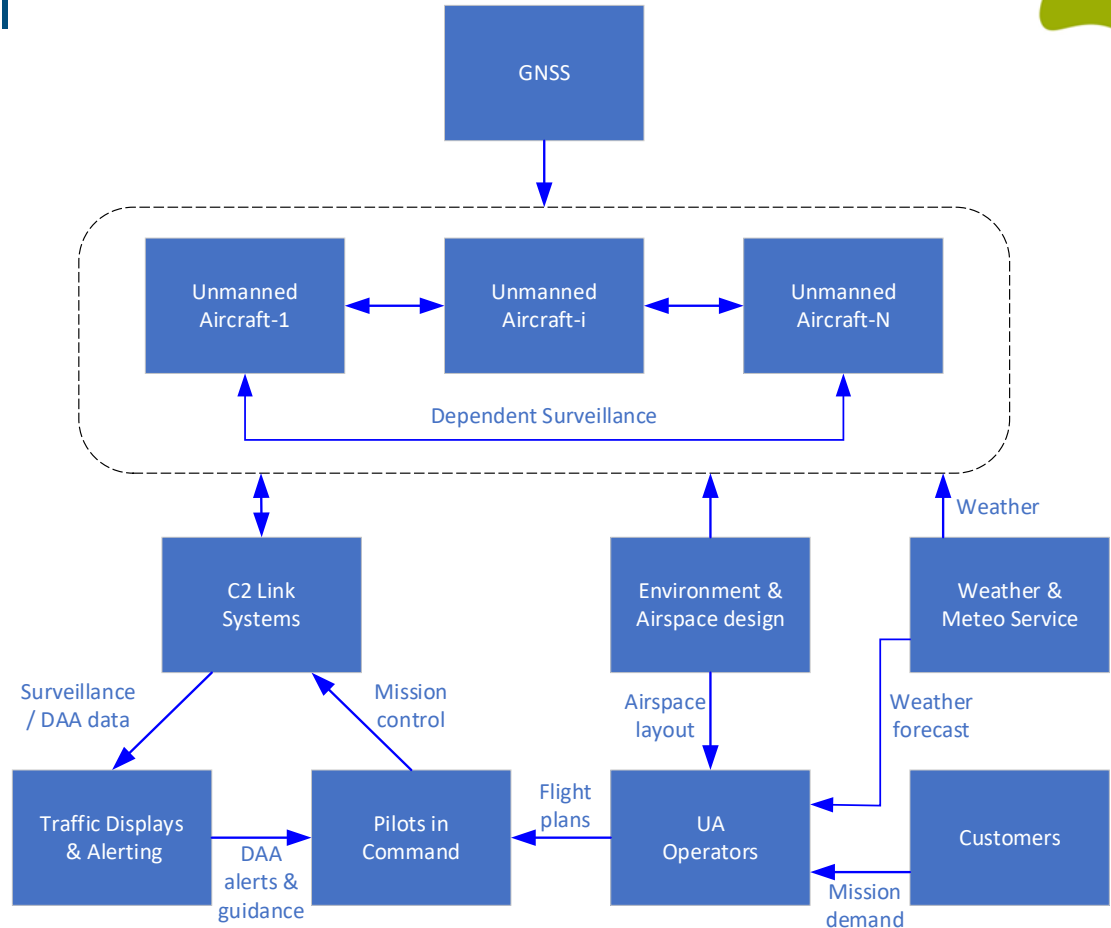
- Wind speed
- Customer demand
- Errors in altitude and vertical speed measurement
- Errors in GNSS-based horizontal position and speed estimates
- Delay in ADS-B transmission
- Delay in C2 link transmission
- Delay in response to DAA alert by PIC
- Rates of turn and climb/descent by PIC in DAA response
- Rates of climb, descent, turn, acceleration, deceleration, cruise speed during nominal flight

Failure modes

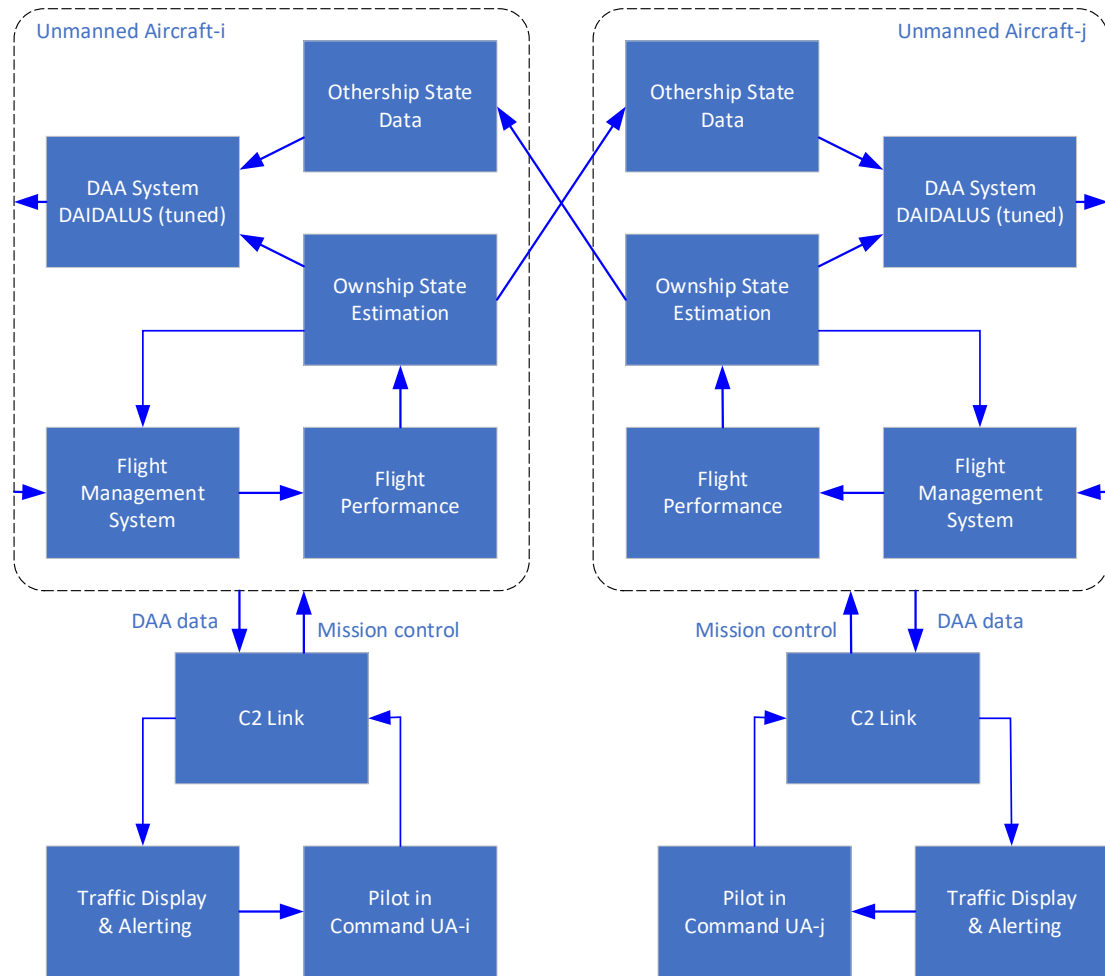
- Adverse weather not predicted
- Wrong altitude in flight planning
- Engines failure
- Reduced accuracy of pressure altimetry
- GNSS-based estimation is not working (aircraft system or in whole region)
- Reduced accuracy of GNSS-based estimation (single aircraft or whole region)
- C2 link not working (aircraft system, RPS, or whole region)
- ADS-B system of aircraft is not working
- DAA system of aircraft is not working
- No/limited response to DAA alert by PIC

Agent-based models

- Customer demand
 - Poisson processes
 - Random mission-dependent positions
- Weather
 - Wind
 - Adverse weather
- Airspace design
 - Free flight / Altitude layers
- UA operators
 - Flight level
- Mission control by PIC
 - Speed/acceleration
- C2 Link systems
 - UAS / RPS / Region



- Ownship state data
 - Pressure altitude & rate
 - GNSS-based horizontal position & speed
- Othership state via ADS-B
- DAIDALUS by NASA
 - DAA reference system
 - Rule-based
 - Parameters tuning
- Response to DAA alerts always via PIC

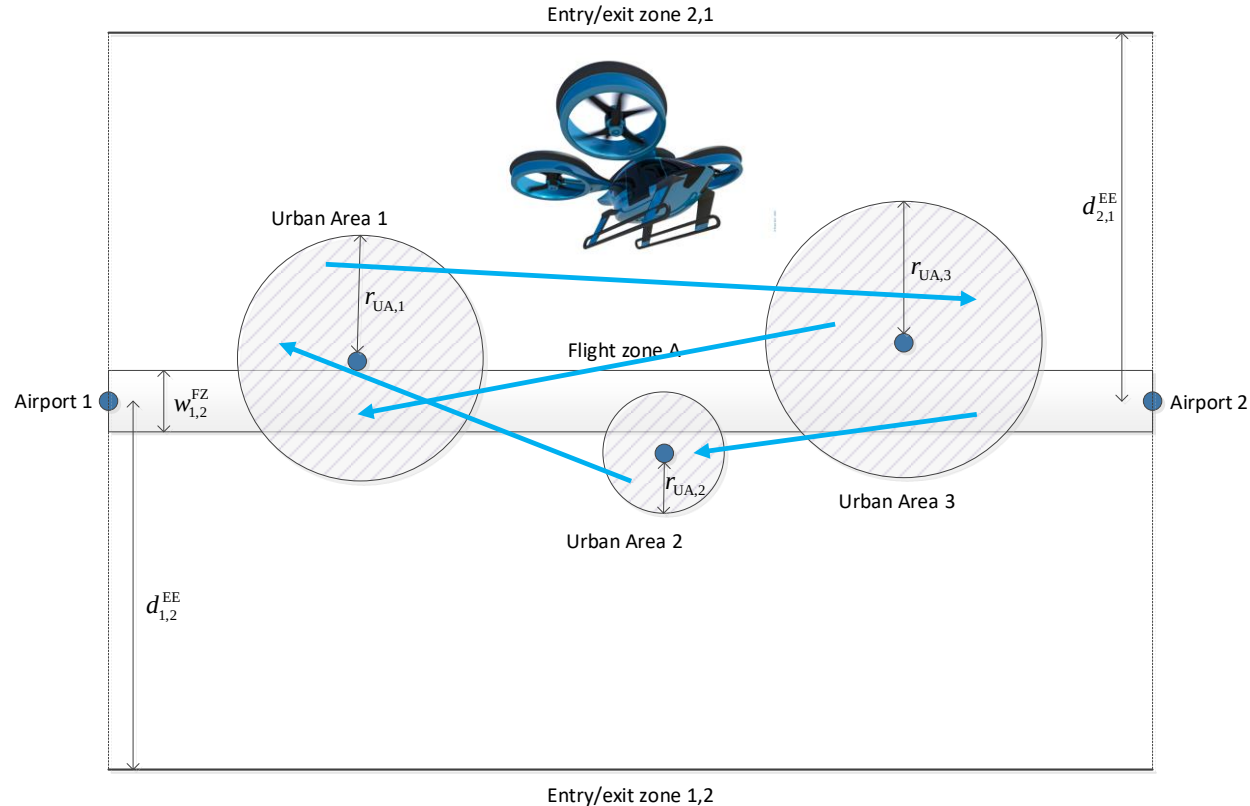


Between arbitrary points in different urban areas

Flight phases

- Vertical take-off to flight level
- Accelerate
- Cruise
- Decelerate
- Vertical landing

Speeds / accelerations from uniform distributions



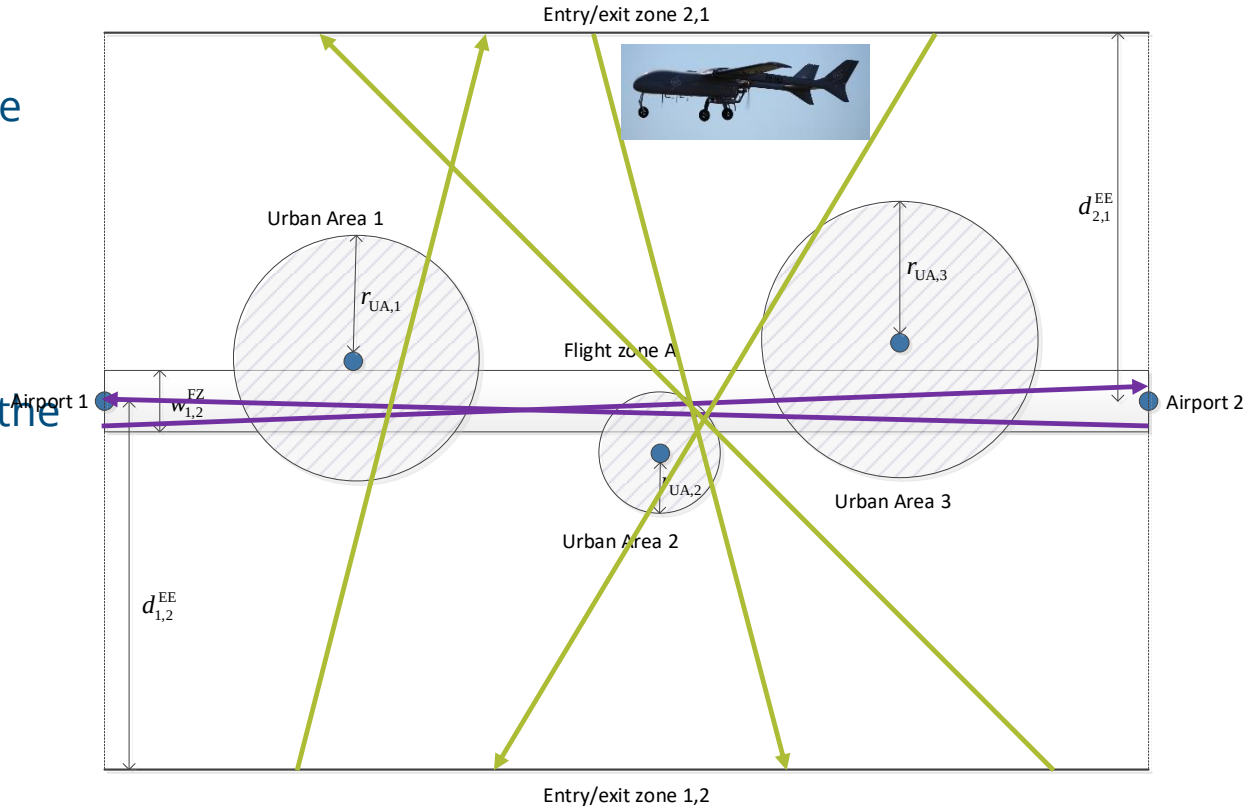
En-route Airport

- In the flight zone between the airports
- Constant flight level

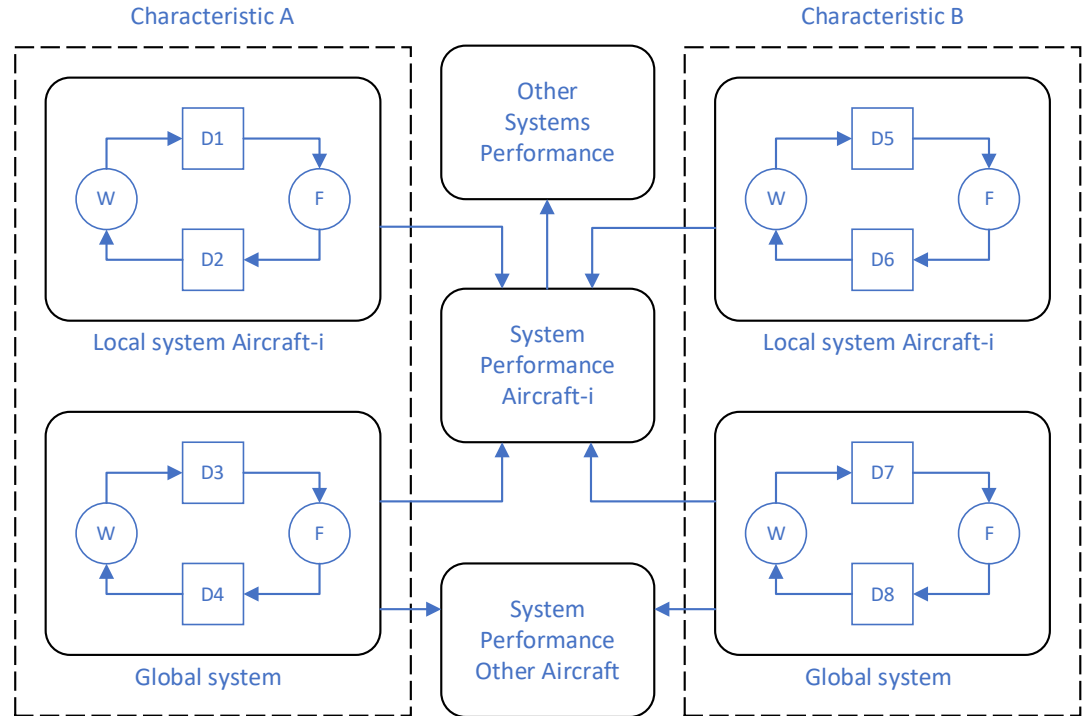
En-route Crossing

- Between arbitrary points on the entry/exit zones
- Constant flight level

Cruise speed from uniform distribution



- Working mode (W)
 - System is working normally
 - High likelihood, long duration
- Failure mode (F)
 - System fails
 - Small likelihood, limited duration
- Local system
 - Affecting single UAS
- Global system
 - Affecting multiple UASs
- Multiple system characteristics
 - e.g. availability, accuracy level
- System performance impact
 - e.g. navigation performance, dependent surveillance



DAIDALUS

Detect and Avoid Alerting Logic for Unmanned Systems

- Reference system of DAA MOPS (RTCA DO-365)
 - For large UAS
 - Not designed for low altitude / VTOL
- C++ software (NASA Open Source Agreement)
- Rule-based alerting logic
 - Settings are adaptable for types of operation
- Remain Well Clear functionality
 - Alerts & guidance to remain or regain well clear
 - Direction and altitude guidance

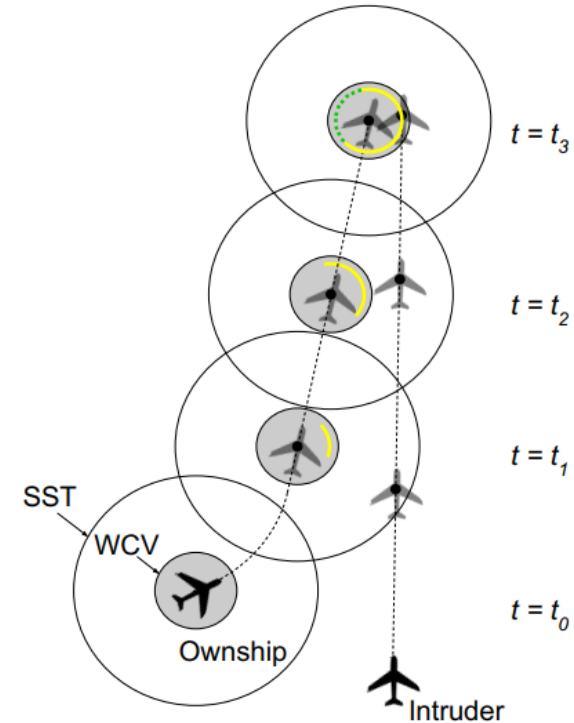


Figure from (Munoz et al., 2015)

Rare event Monte Carlo simulation

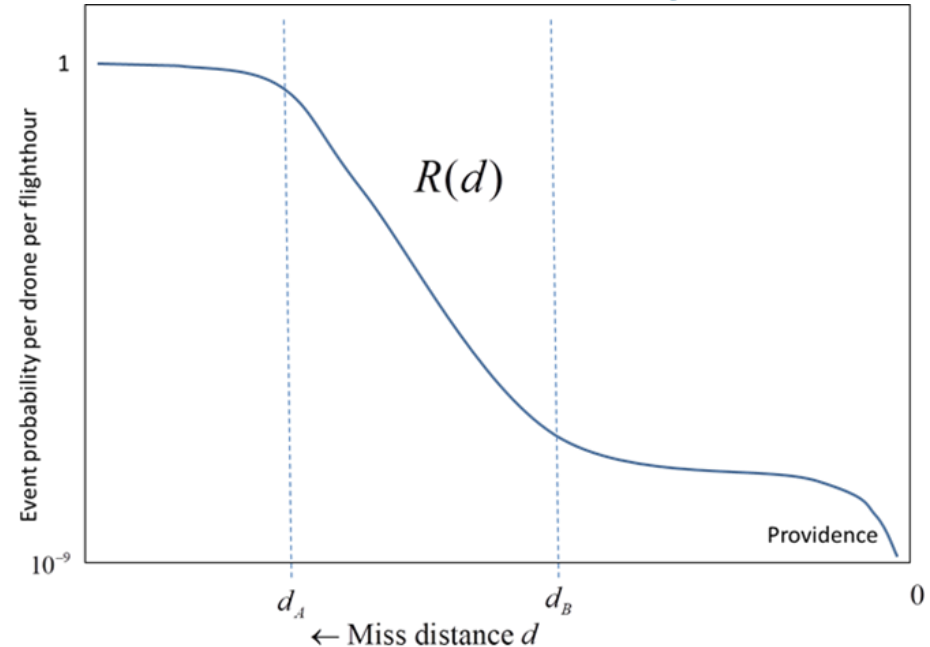
Objective

To effectively estimate low probabilities of miss distance events up to collisions

Methods

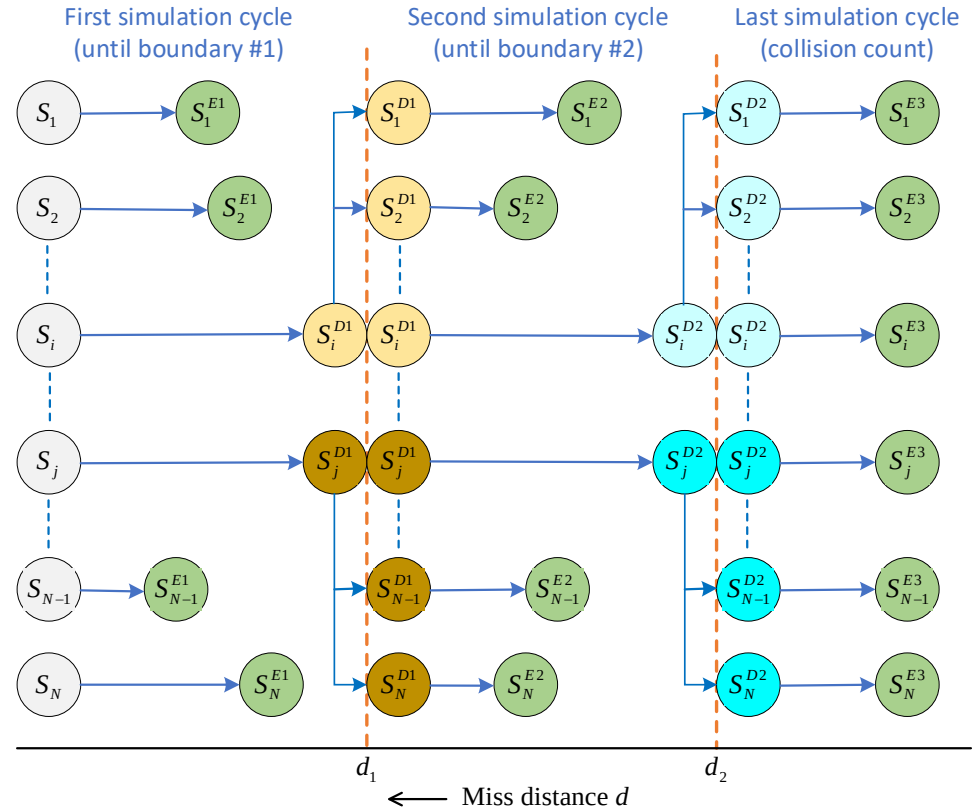
- Monte Carlo simulation with Interacting Particle Systems (IPS)
- Risk decomposition

Schematic risk diagram



IPS Monte Carlo simulation

- Each particle is the complete hybrid state space of the agent-based model
- Simulation is done until miss distance boundaries (e.g. HMD=50m, VMD=15m)
- Resampling and continued simulation is done for particles that reached boundaries
- This provides efficient estimation of small probabilities up to collision events



Global failure conditions

- Weather: *Favourable Weather / Unexpected Adverse Weather*
 - Availability C2 Link Region: *Working / Lost*
 - Availability GNSS Region: *Working / Lost*
 - Accuracy GNSS Region: *Normal / Reduced*
- } 16 combi's

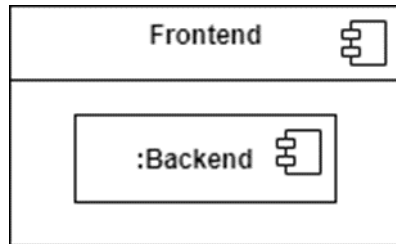
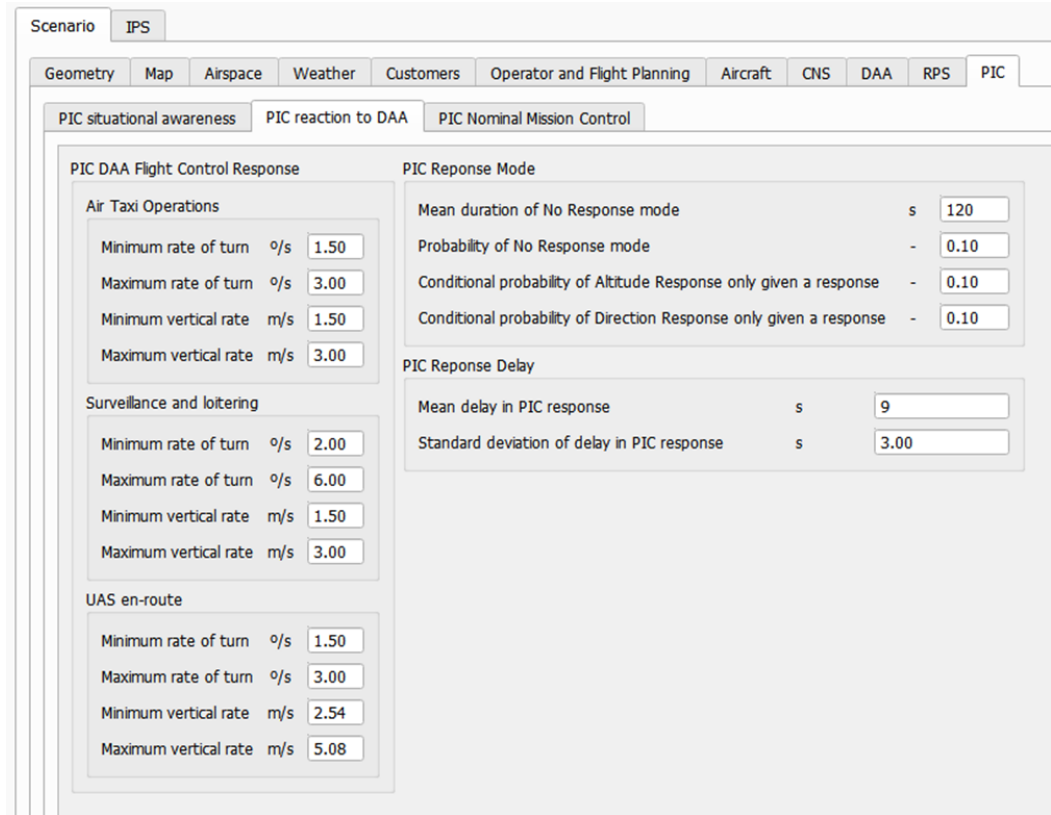
Risk decomposition

- To impose the occurrence of a combination of conditions in a particle
→ Conditional risk given combination of conditions
- To combine with probabilities of combinations of conditions

D(emo)-CRAT software

Frontend

- Windows OS
- C++ QT framework
- Allows to set all (about 220) parameters of the agent-based model
- Allows to configure and follow MC simulations
- Allows to visualize simulation results

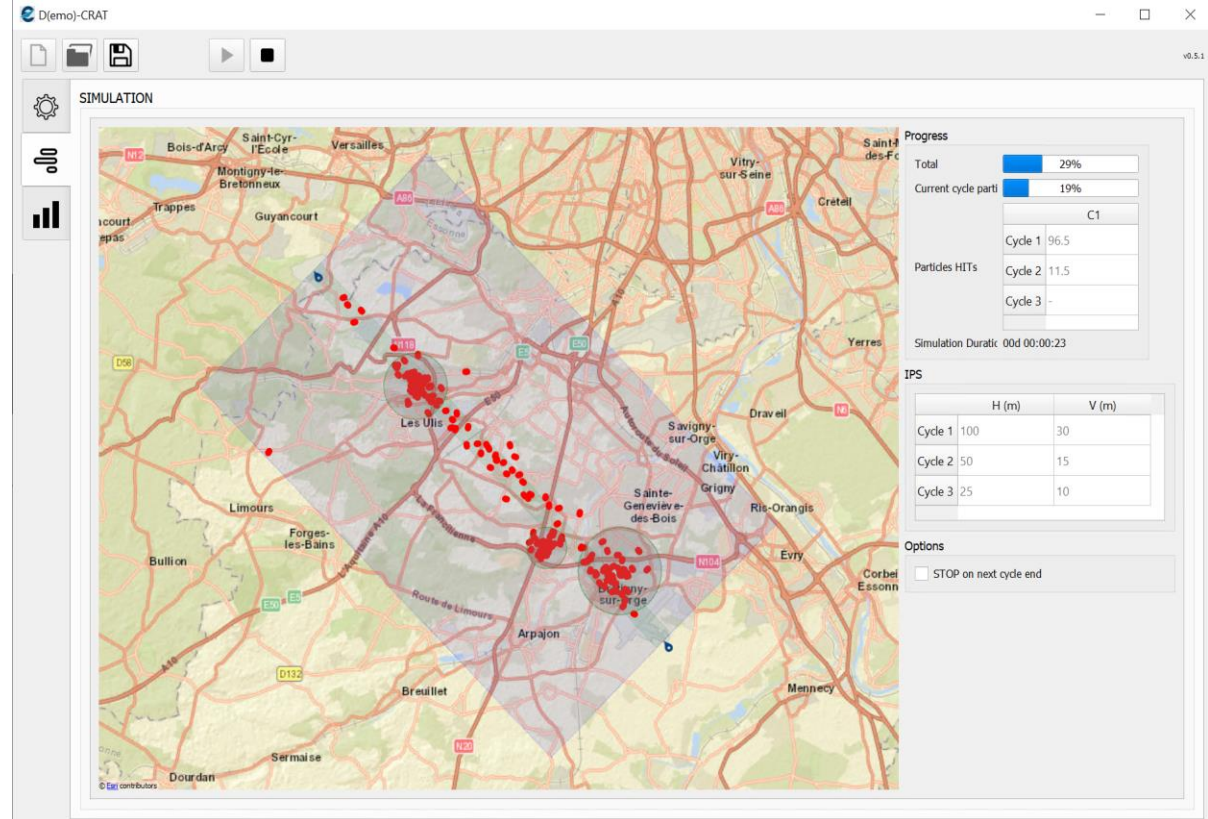
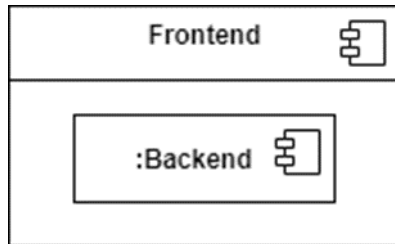



The screenshot shows the D(emo)-CRAT software interface. At the top, there is a 'Scenario' tab and an 'IPS' tab. Below these are several sub-tabs: 'Geometry', 'Map', 'Airspace', 'Weather', 'Customers', 'Operator and Flight Planning', 'Aircraft', 'CNS', 'DAA', 'RPS', and 'PIC'. The 'PIC' tab is currently selected. Under the 'PIC' tab, there are three sub-sections: 'PIC situational awareness', 'PIC reaction to DAA', and 'PIC Nominal Mission Control'. The 'PIC reaction to DAA' sub-section is active, showing parameters for 'Air Taxi Operations', 'Surveillance and loitering', and 'UAS en-route'. The 'Air Taxi Operations' section includes parameters for 'Minimum rate of turn' (0/s, 1.50), 'Maximum rate of turn' (0/s, 3.00), 'Minimum vertical rate' (m/s, 1.50), and 'Maximum vertical rate' (m/s, 3.00). The 'Surveillance and loitering' section includes parameters for 'Minimum rate of turn' (0/s, 2.00), 'Maximum rate of turn' (0/s, 6.00), 'Minimum vertical rate' (m/s, 1.50), and 'Maximum vertical rate' (m/s, 3.00). The 'UAS en-route' section includes parameters for 'Minimum rate of turn' (0/s, 1.50), 'Maximum rate of turn' (0/s, 3.00), 'Minimum vertical rate' (m/s, 2.54), and 'Maximum vertical rate' (m/s, 5.08). The 'PIC Response Mode' section includes parameters for 'Mean duration of No Response mode' (s, 120), 'Probability of No Response mode' (-, 0.10), 'Conditional probability of Altitude Response only given a response' (-, 0.10), and 'Conditional probability of Direction Response only given a response' (-, 0.10). The 'PIC Response Delay' section includes parameters for 'Mean delay in PIC response' (s, 9) and 'Standard deviation of delay in PIC response' (s, 3.00).

D(emo)-CRAT software

Backend

- C++
- Encapsulates DAIDALUS library from NASA
- Executes the agent-based simulation objects
- Controls the IPS MC simulations & risk decomposition
- Stores results



Illustrative simulation and risk results

Air taxies

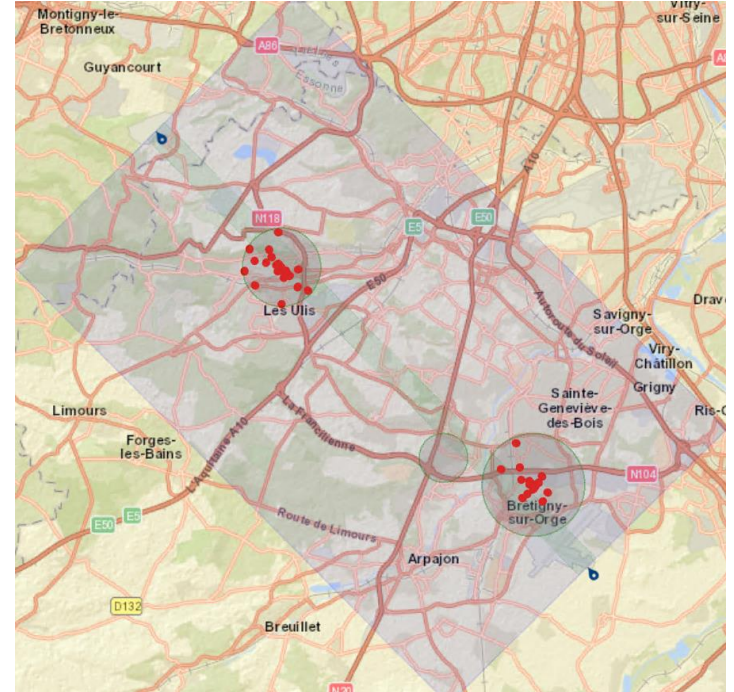
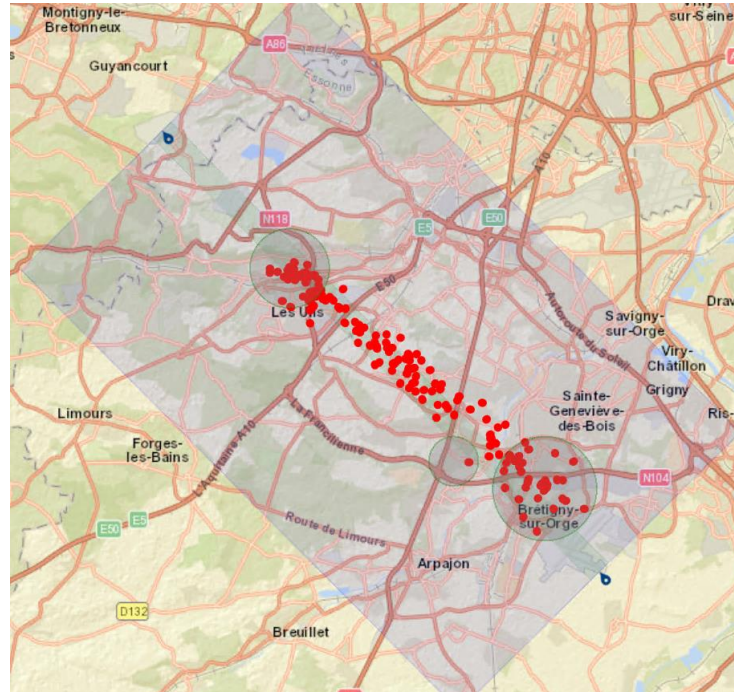


Close proximity events ($HMD \leq 50m, VMD \leq 15m$)

No DAA: $P=2.2e-2/flhr$ $P=6.7e-3/fl$

1/4.5

With DAA: $P=4.8e-3/flhr$, $P=1.5e-3/fl$



MTBF:
600s

1,000
particles

72,000
flights

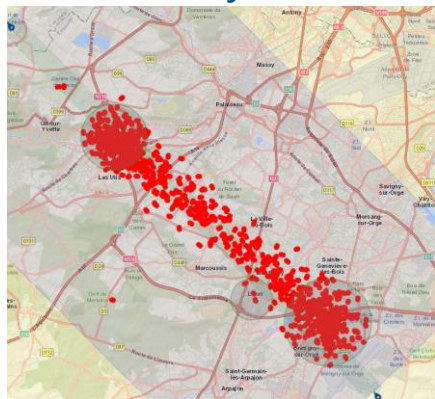
Random
level

00:01:06 ← Simulation time → 1:36:12

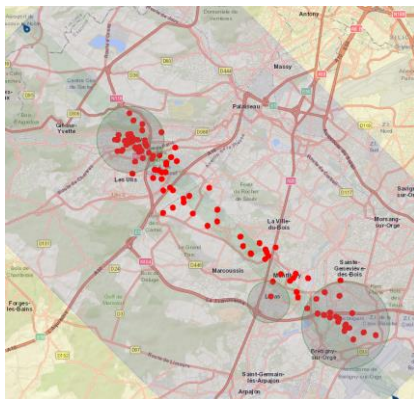
IPS cycles



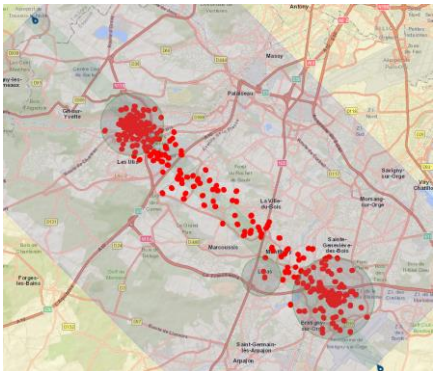
Cycle 1



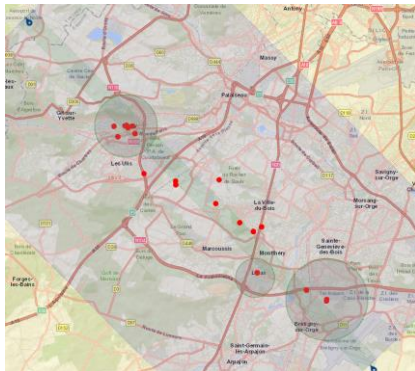
Cycle 3



Cycle 2



Cycle 4 (collision)



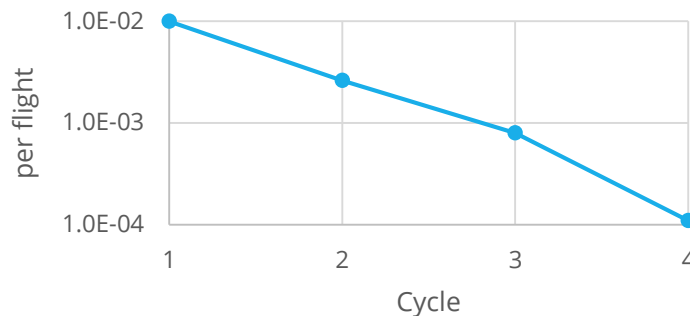
Air taxi scenario

- Middle flight level
- MTCD: 600 s; 360,000 flights
- With DAA, 5000 particles

IPS cycles

1. $HMD \leq 100m$, $VMD \leq 30m$
2. $HMD \leq 50m$, $VMD \leq 15m$
3. $HMD \leq 25m$, $VMD \leq 10m$
4. Collision ($HMD \leq 11.3m$, $VMD \leq 2.5m$)

Close proximity / collision events



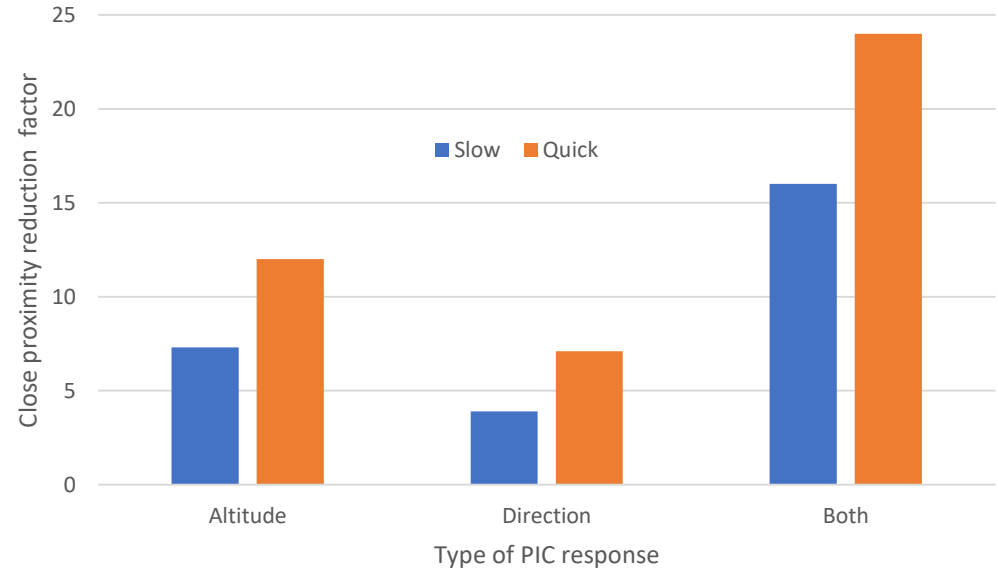
Sensitivity for changes in PIC responses

Type of PIC response

- Altitude response only
- Direction response only
- Both altitude & direction response

	Slow	Quick
Mean delay	9 s	3 s
STD delay	3 s	1 s

UAS en route crossing



Conclusions

- UAS/UAM safety assessment requires advanced modelling and simulation approaches
- Agent-based dynamic risk modelling and rare event Monte Carlo simulation support UAS/UAM quantitative risk assessment
 - Broad scope of agent-based models for UAS/UAM operations
 - Range of stochastic variability for normal and failure conditions
 - State-of-the-art rare event Monte Carlo simulation methods
- Efficient D(emo)-CRAT software tool was developed
- Broader set of results available
 - <https://www.nlr.org/wp-content/uploads/2021/11/NLR-CR-2021-050-RevEd-1.pdf>

Recommendations

- Extend the scope
 - Strategic deconfliction, tactical conflict resolution, capacity management
 - DAIDALUS tuning/extension, ACAS Xu/sXu, collision avoidance function
 - Ground risk, airspace infringement, collision with manned aircraft
- Compare safety of UAS/UAM concepts
 - Understanding of safety implications and feedback to design
- Use for safety assessment of specific UAS/UAM operations
 - Tuning and evaluation of all parameter values and model assumptions

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This research was done as part of the D(emo)-CRAT development (Demonstrator Drone Collision Risk Assessment Tool) under a contract for EUROCONTROL

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- NASA: Cesar Muñoz



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