



# Collaborative Autonomous Systems



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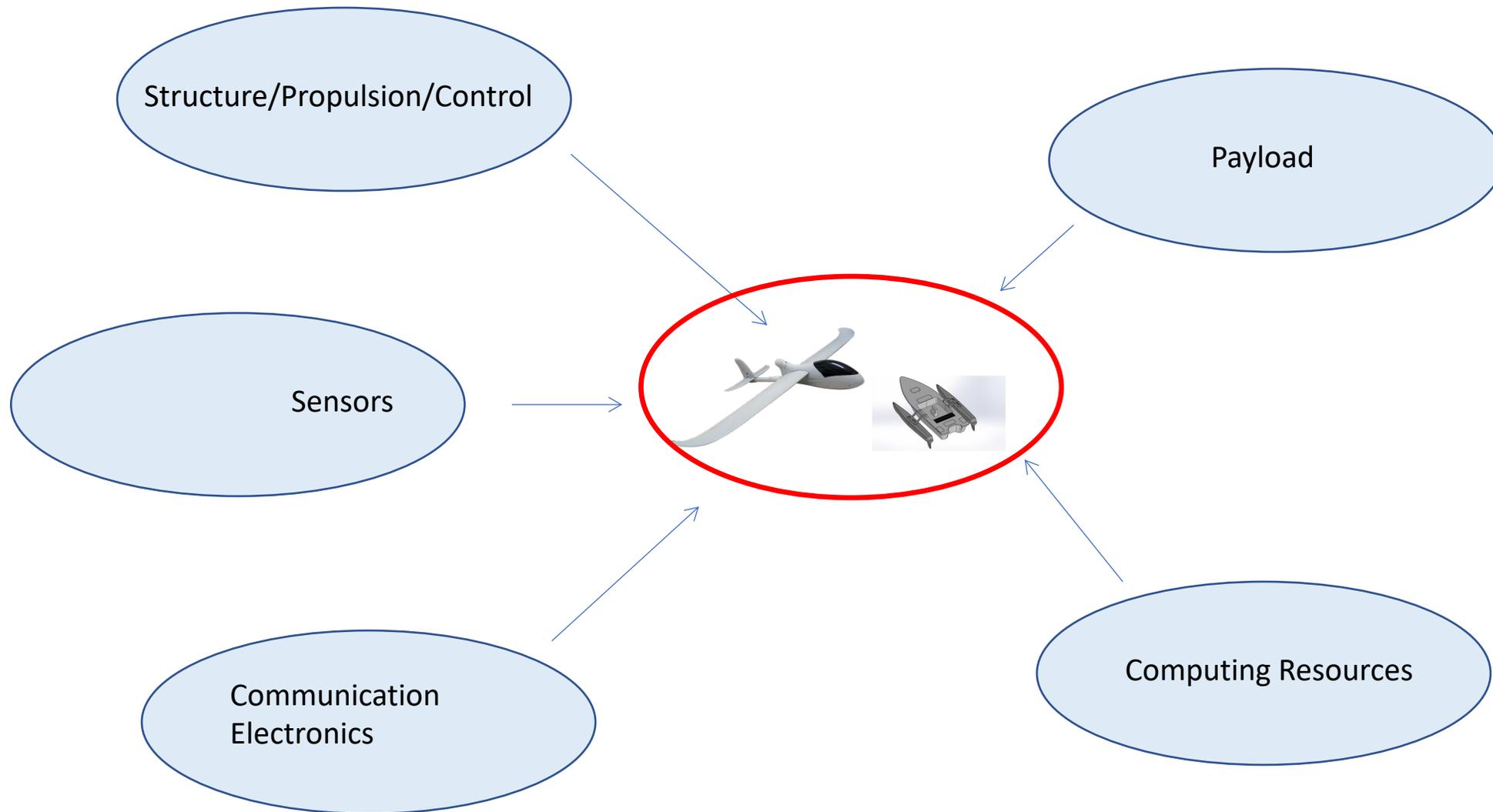
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**VIMARSH**  
Institute Public Lecture  
Indian Institute of Technology  
Indore  
16 March 2026

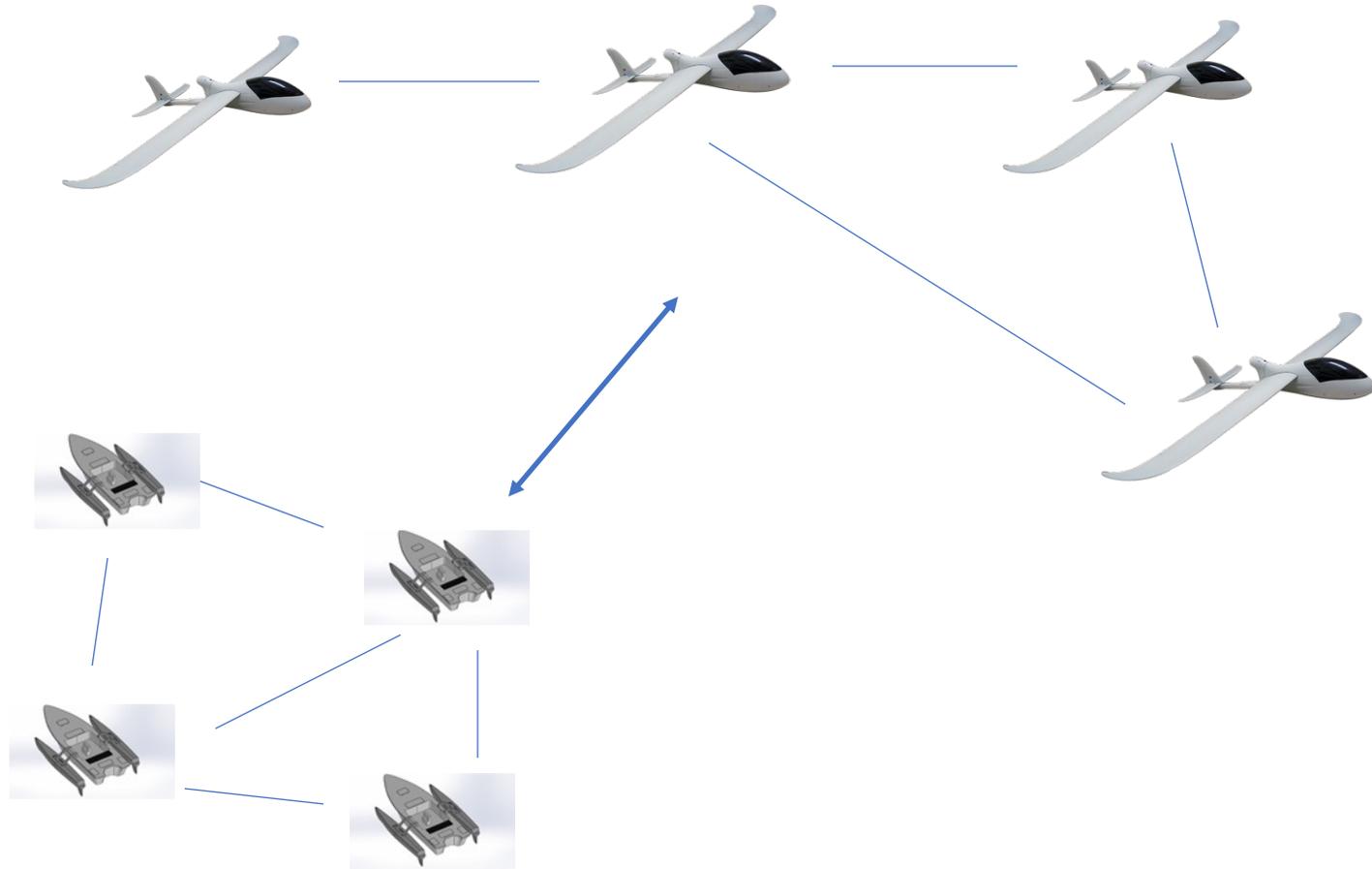
# Autonomous Systems

- General Autonomous Systems
- An Autonomous Network of Systems
- A Network of Autonomous Systems
- Levels of Autonomy
- Unmanned Mobile (Aerial/Surface/Underwater) Systems

# Unmanned Aerial/Surface/Underwater Vehicles

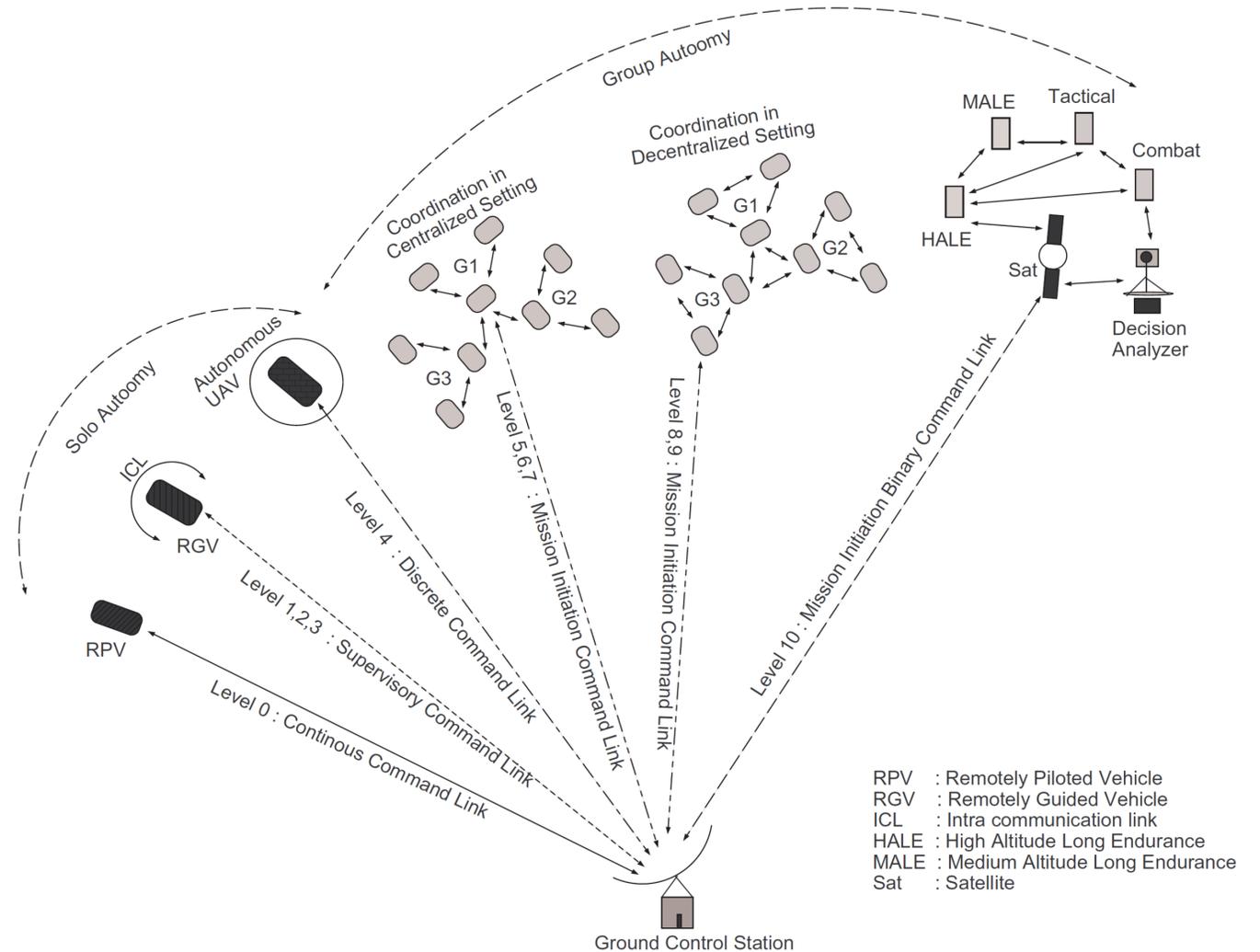


# UXV Swarms



# Levels of Autonomy

- |                |  |
|----------------|--|
| Group autonomy | Level 10 : Fully Autonomous Systems              |
|                | Level 9 : Group Strategic Goals                  |
|                | Level 8 : Distributed Control                    |
|                | Level 7 : Group Tactical Goals                   |
|                | Level 6 : Group Tactical Replan                  |
|                | Level 5 : Group Coordination                     |
| Solo autonomy  | Level 4 : Onboard Route Replan                   |
|                | Level 3 : Adapt to Flight and Failure Conditions |
|                | Level 2 : Real Time Health Diagnosis             |
|                | Level 1 : Remotely Guided                        |
|                | Level 0 : Remotely Piloted                       |



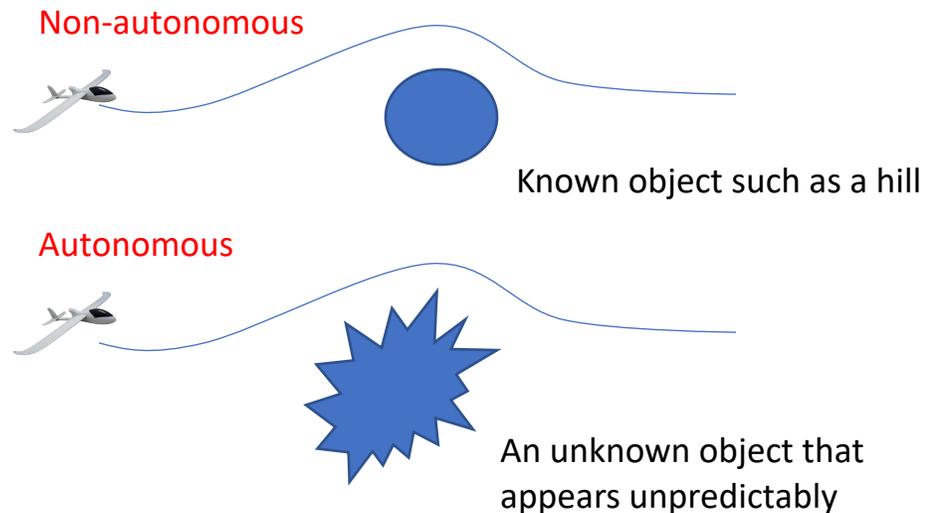
# Developments Around the World

- There is hardly any country in the world that does not have an interest in UAVs or drones.
- Large number of startup companies.
- Almost all universities with an Engineering and Technology degree program has students developing and using drones in limited airspace.
- Several startup companies in India

# Autonomy Vs. Intelligence

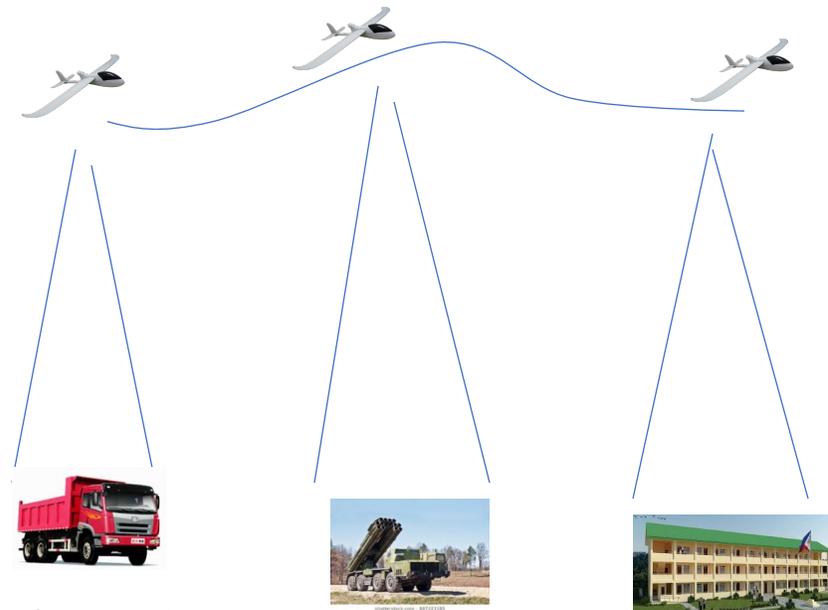
**Autonomy:** The ability to take mission-specific decisions without intervention by human operator.

- Example: Path re-planning based on unpredicted events.

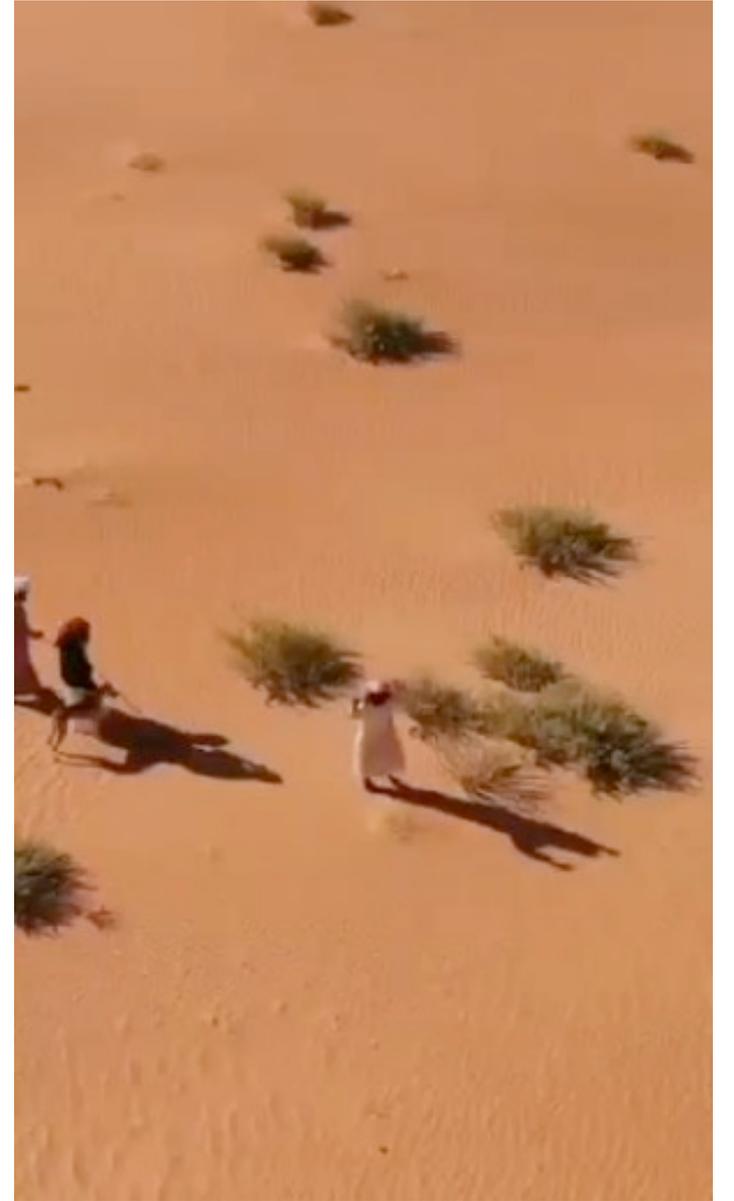


**Intelligence:** The ability to reason with sensory data inputs.

- Example: Identifying objects in the environment



# A Lesson in Collaborative Control from the Real World



# Footage of a pursuit evasion game



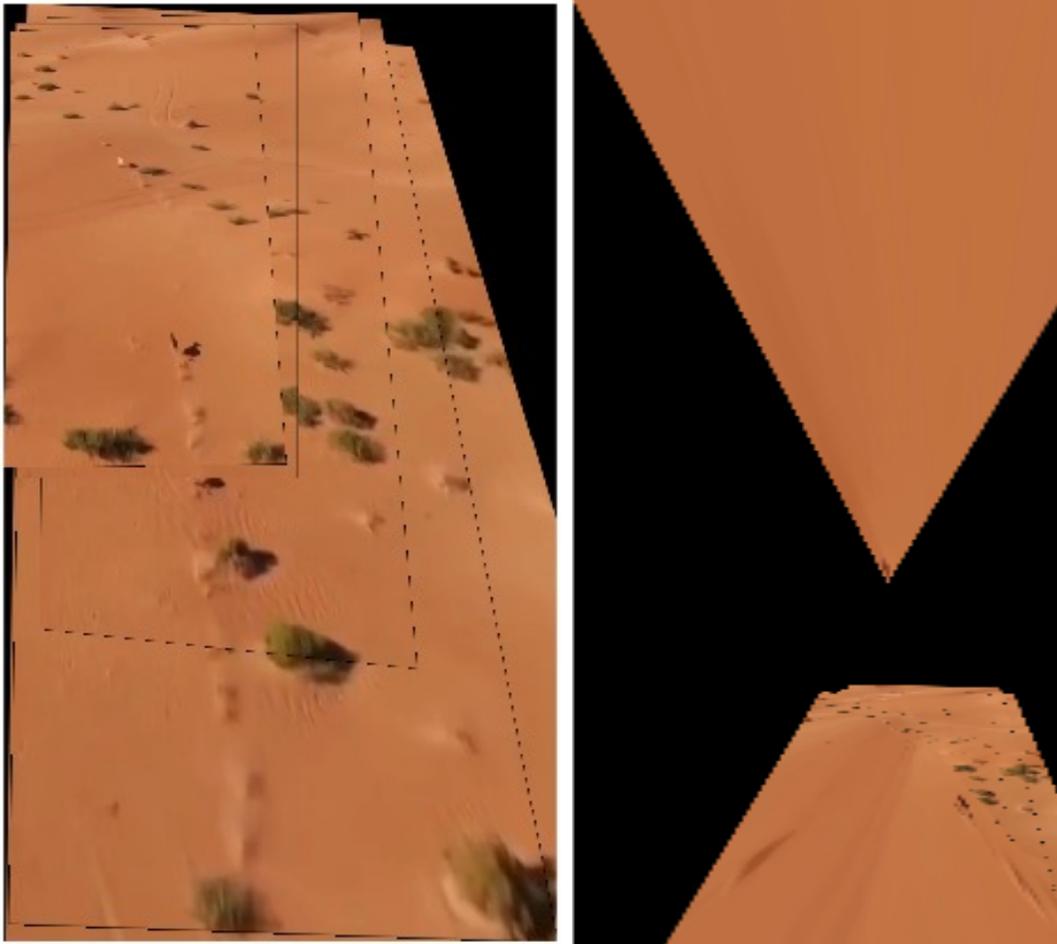
- A rabbit is being chased by two saluki dogs.
- A chase footage of 171s at 30 fps captured from a drone.
- Dogs have higher speed compared to the rabbit but less agile.

# Footage of a pursuit evasion game



- A rabbit is being chased by two saluki dogs.
- A chase footage of 171s at 30 fps captured from a drone.
- Dogs have higher speed compared to the rabbit but less agile.
- **The Good News: The Rabbit Escaped!!!**

# Stitching of frames



Stitching using standard libraries

Why stitch the frames?

- Generate trajectories of the rabbit and the dogs.
- Trajectories will help in analysing the maneuver strategies.

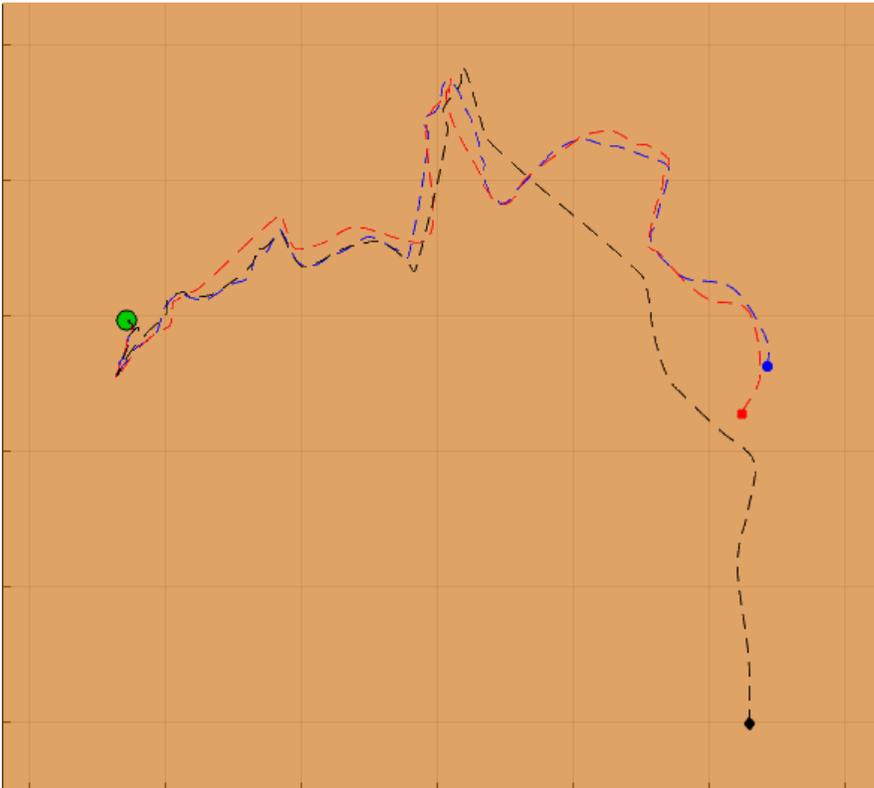
Problems with using standard stitching libraries

- Camera frame is rotating as well as translating.
- The stitched results obtained cannot be used for practical purposes.
- We do not obtain trajectories of moving objects like the rabbit or the dogs.

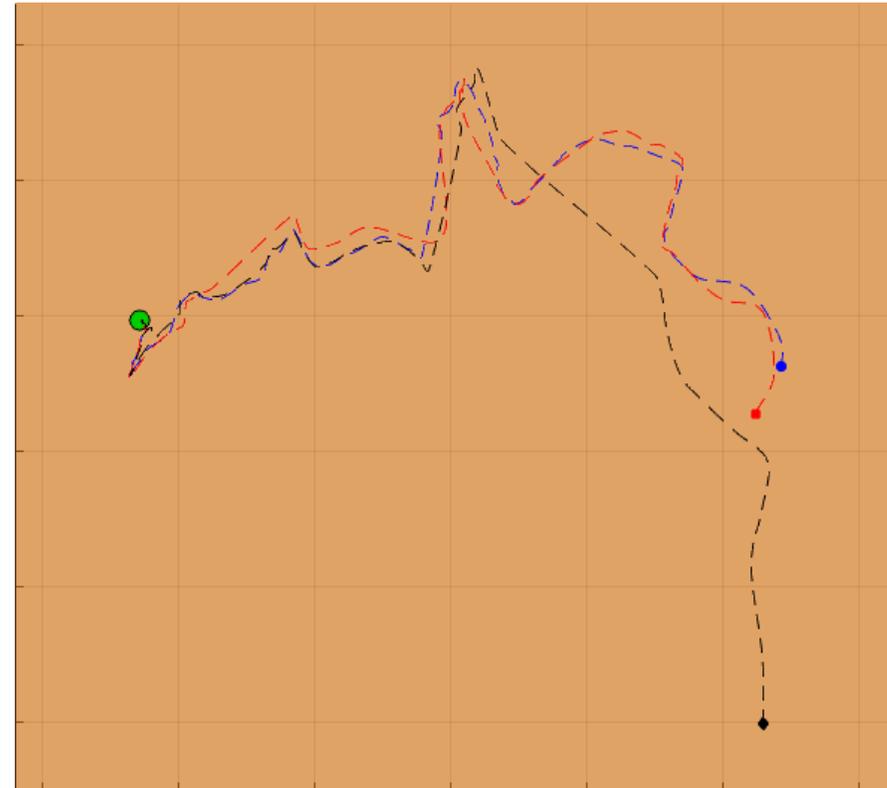
Manual stitching of the frames has to be done

# Stitched results

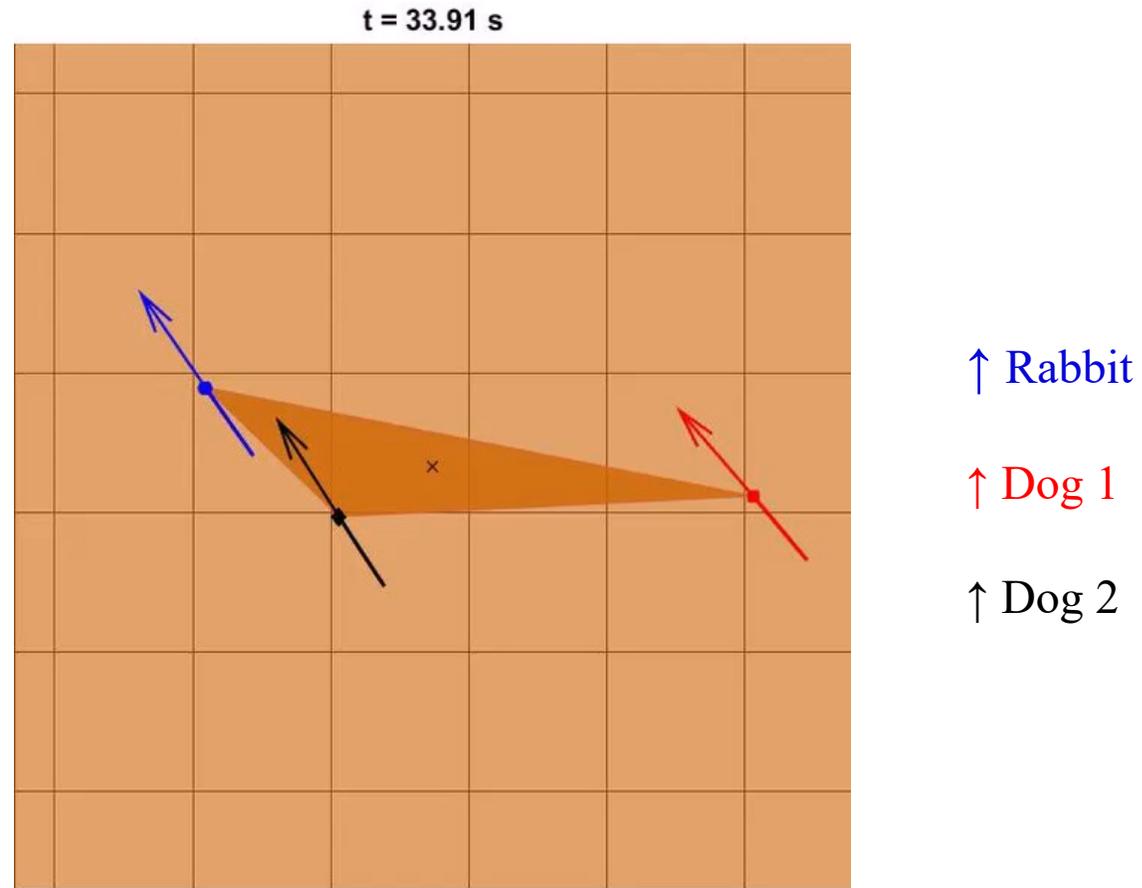
View from a fixed reference frame



A close-up view

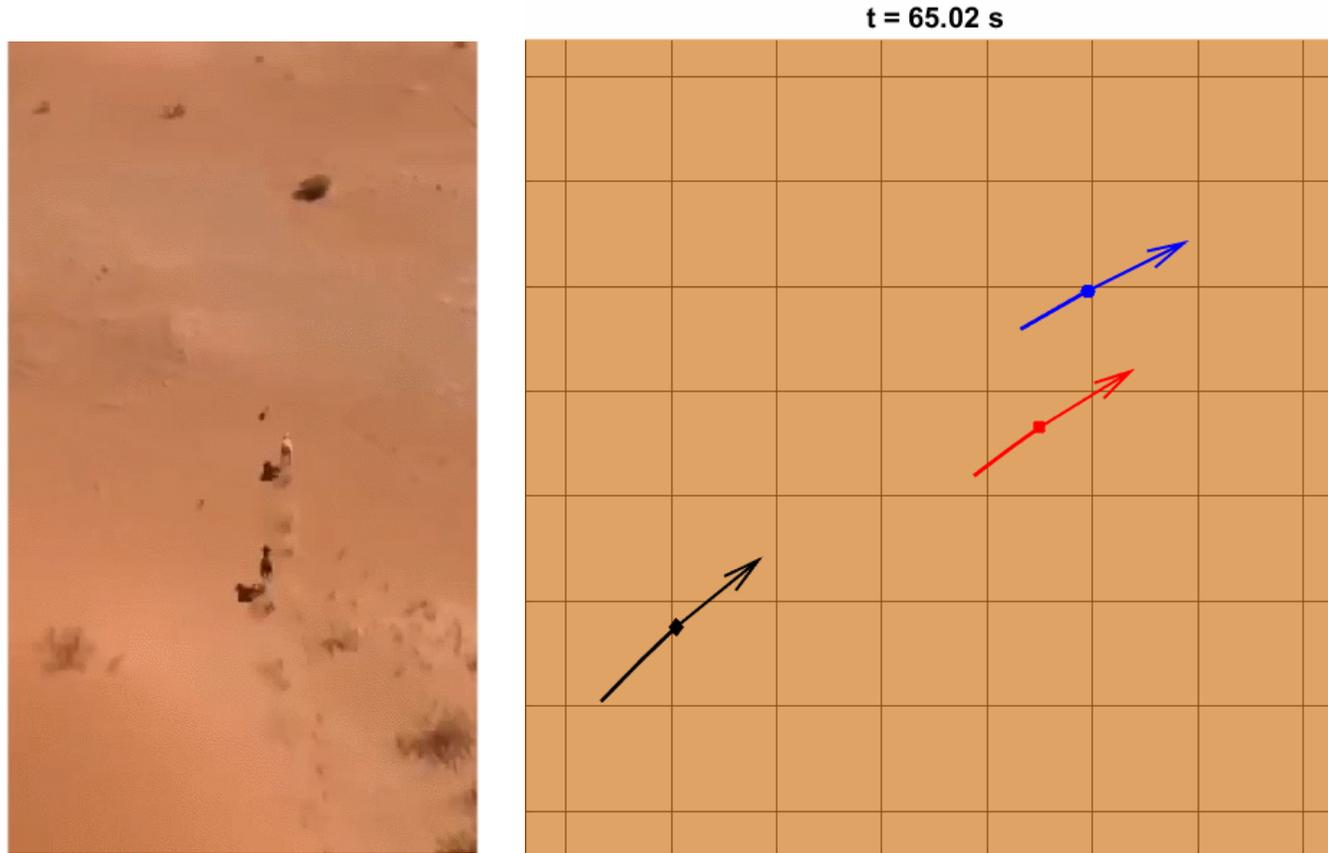


# Stitched results



Video of motion of the players and the variation in their relative geometry

# Stitched results- Comparison with actual footage



Actual footage

After stitching

↑ Rabbit   ↑ Dog 1   ↑ Dog 2

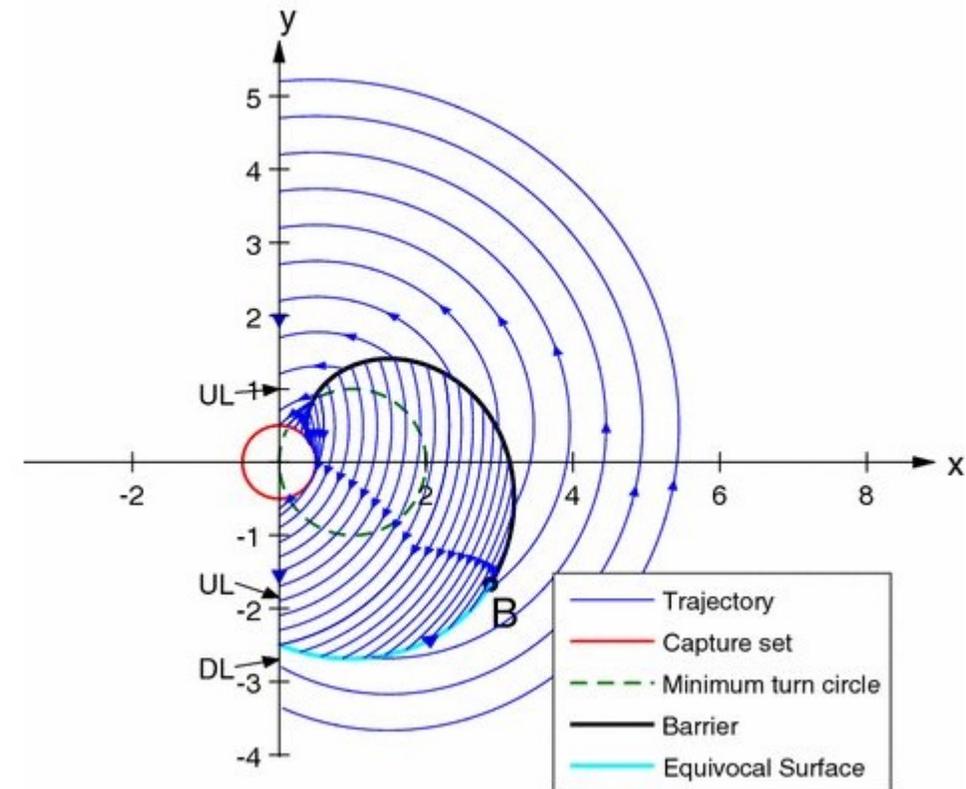
- The comparison shown is for the window from 65.02s to 75.02s
- The time window also shows instances where the players get out of camera view.
- Cubic spline fitting helped in interpolating for the missing locations.

# Differential games

## The homicidal chauffeur game

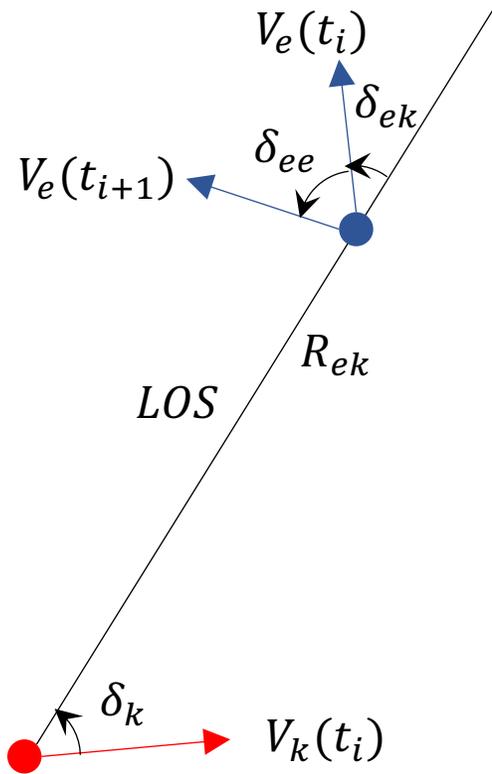
The pursuer, a car with speed advantage but turn radius constraint, is trying to run over the evader, an agile pedestrian.

- R. Isaacs, *Games of Pursuit*, RAND Corporation (1951)
- R. Isaacs, *Differential Games: A Mathematical Theory with Applications to Warfare and Pursuit, Control and Optimization*, John Wiley & Sons, New York (1965)



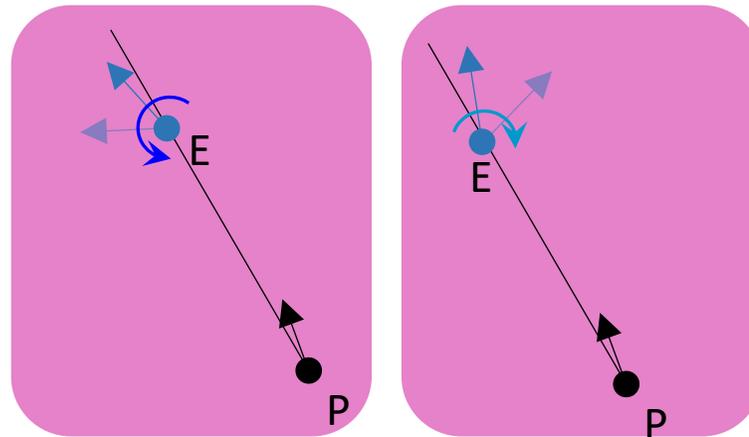
[https://www.researchgate.net/publication/325097353\\_The\\_Classical\\_Homicidal\\_Chauffeur\\_Game/figures](https://www.researchgate.net/publication/325097353_The_Classical_Homicidal_Chauffeur_Game/figures)

# Identification of game



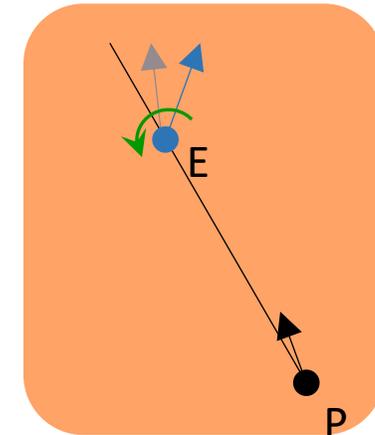
- Side stepping maneuvers- Game of Kind.
- Fleeing away maneuvers- Game of Degree.

Game of Kind



$$\begin{aligned} & (-(\delta_{ee} \geq \mathbf{0}) \wedge -(\delta_{ek} \geq \mathbf{0})) \\ & \vee ((\delta_{ee} \geq \mathbf{0}) \wedge (\delta_{ek} \geq \mathbf{0})) \end{aligned}$$

Game of Degree

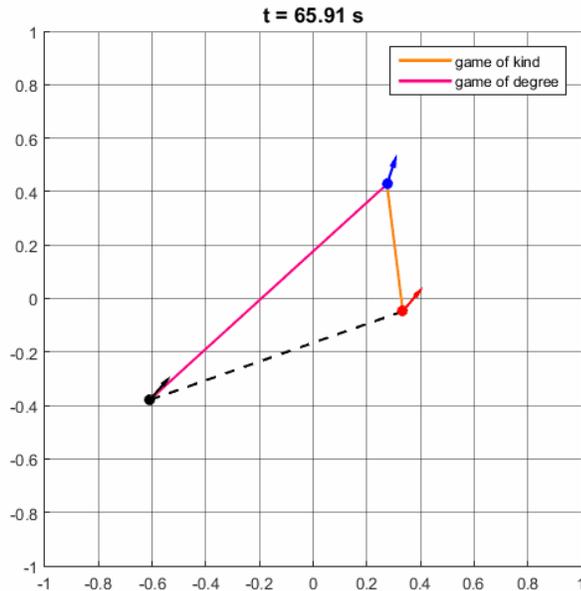


$$\begin{aligned} & (-(\delta_{ee} \geq \mathbf{0}) \wedge (\delta_{ek} \geq \mathbf{0})) \\ & \vee ((\delta_{ee} \geq \mathbf{0}) \wedge -(\delta_{ek} \geq \mathbf{0})) \end{aligned}$$

Engagement geometry

# Studying game switch geometry

- Switch from Game of Kind to Game of Degree
- Observe the small time window around the switch (65.97 – 66.41 s)
- Observe the relative geometry of the agents and their variation.
- Cross reference with actual footage for better understanding.



↑ Rabbit

↑ Dog 1

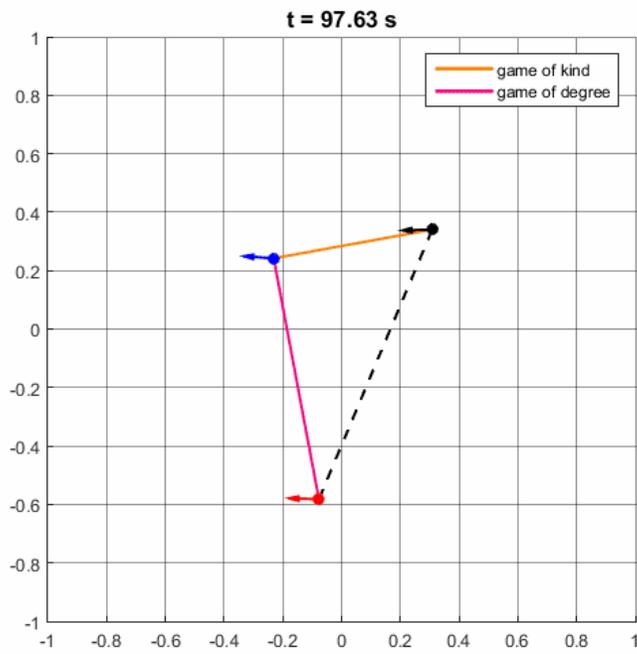
↑ Dog 2

Relative geometry from stitching

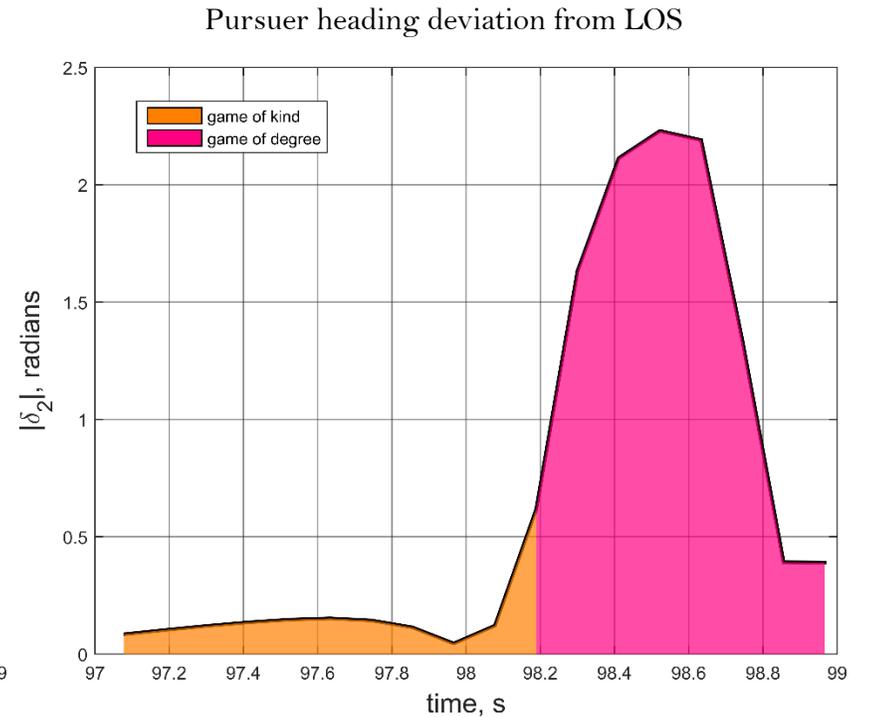
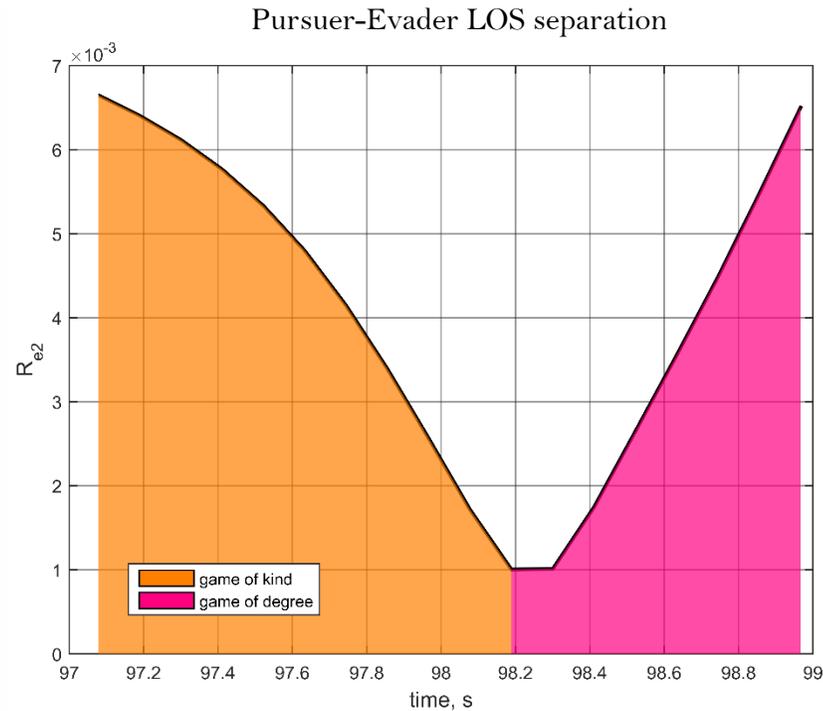


Actual footage

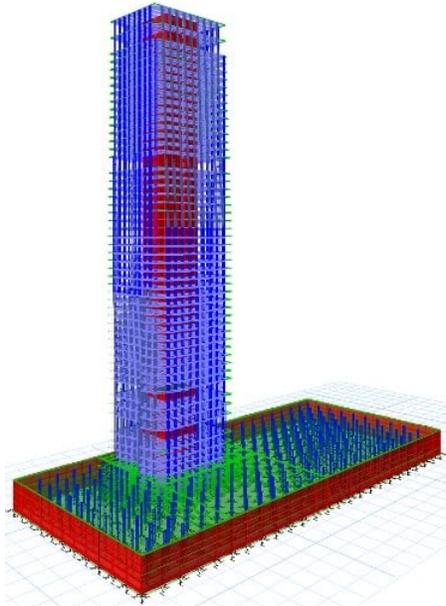
- Observe pursuer-evader separation (97.63 – 98.97 s)
- Observe the pursuer heading deviation from the LOS.



↑ Rabbit   ↑ Dog 1   ↑ Dog 2



# Some Applications of Collaborative Autonomous Systems



<https://civildigital.com>

Mapping/Inspection



<https://creativecommons.org/licenses/by/4.0>

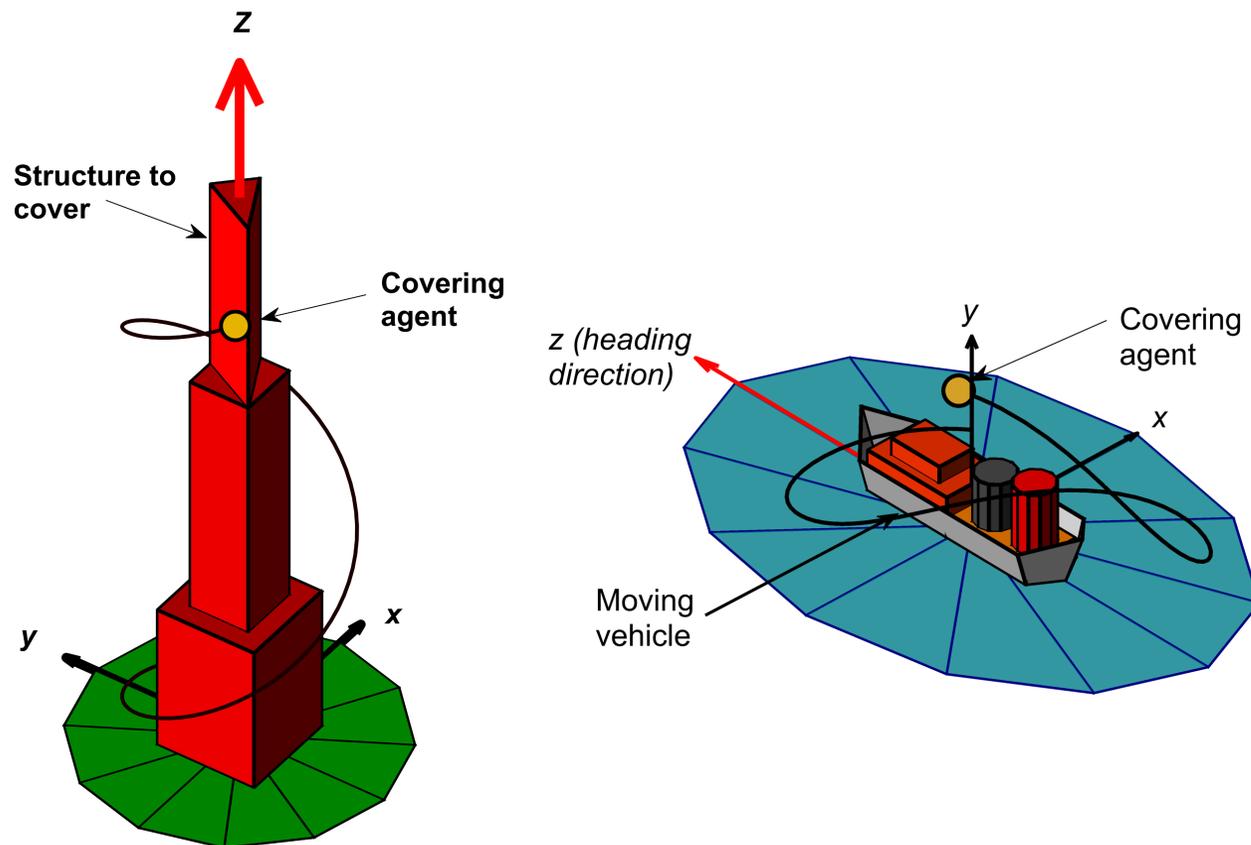
Paint/Extinguish fire



<https://www.pennlive.com>

Inspection/surveillance

# Problem Description



Stationary and moving structure coverage.

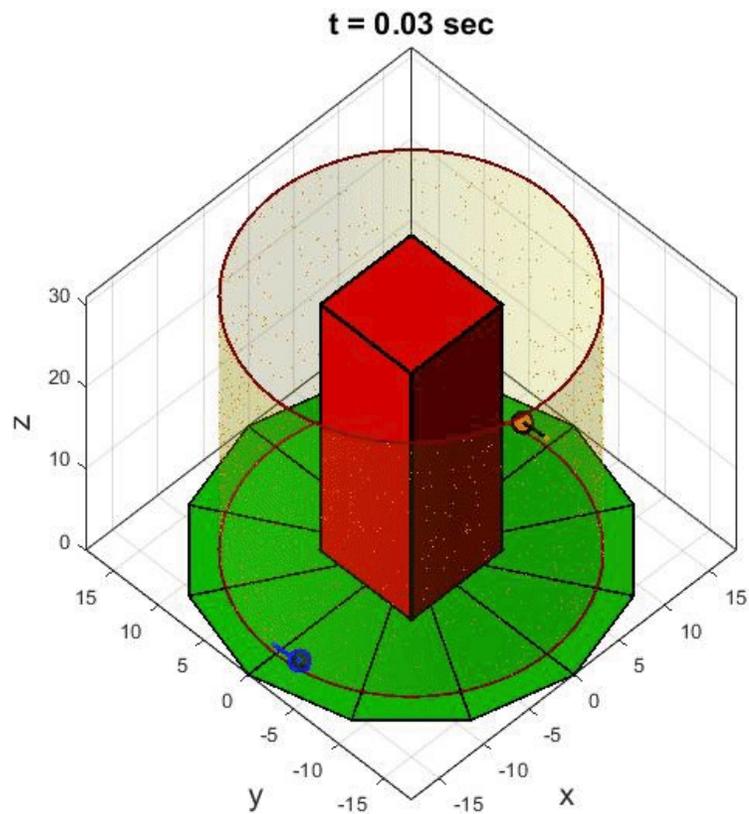
In stationary coverage, the covering agent goes round the structure repeatedly to bring every point on the structure in  $FOV$  at least once.

In moving coverage, the covering agent not only has to go around the structure, but also move along with it.

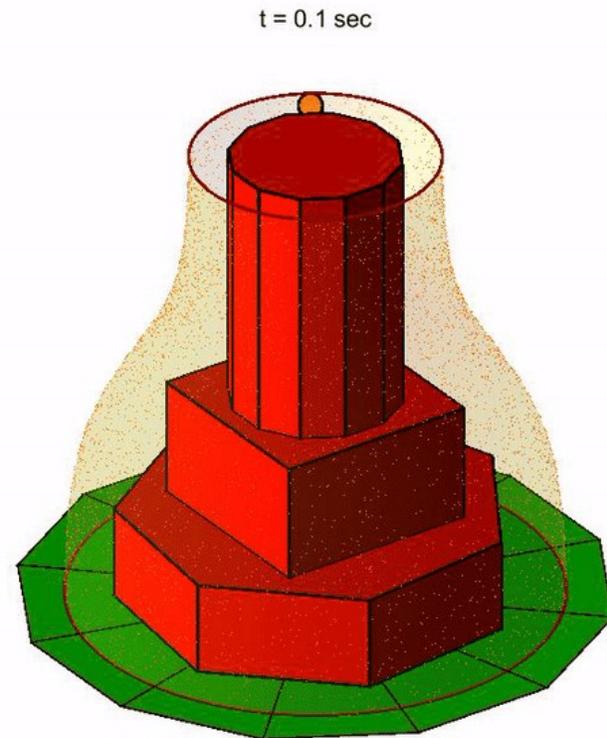
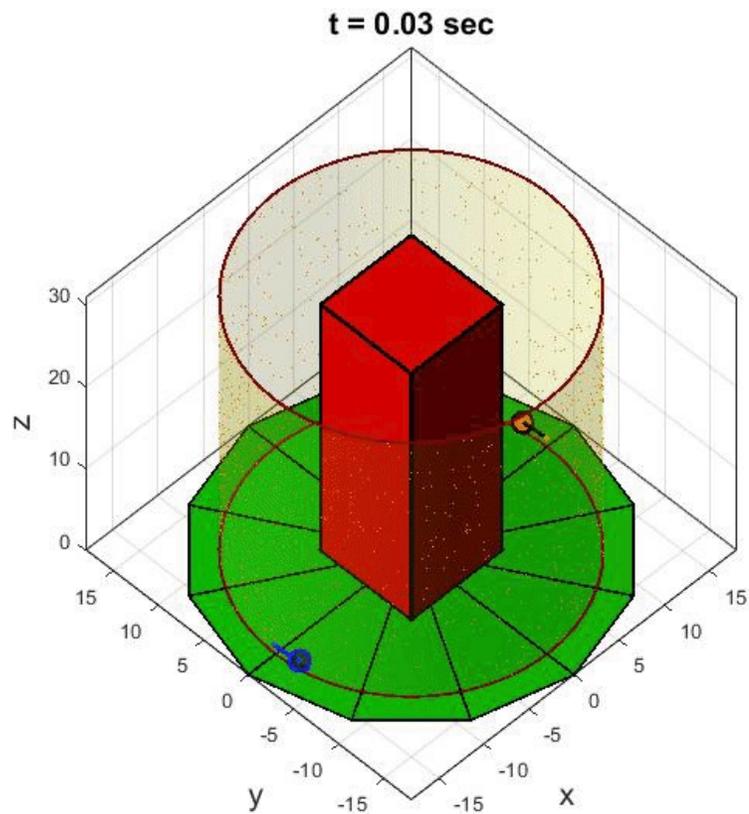
Nath, S. and Ghose, D., 2024. Dynamic aerial coverage of stationary and moving structures using Lissajous curves. *Journal of Guidance, Control, and Dynamics*, 47(11), pp.2369-2385.

Nath, S., Baishya, M. and Ghose, D., 2022. Decentralised coverage of a large structure using flocking of autonomous agents having a dynamic hierarchy model. *Autonomous Robots*, 46(5), pp.617-643.

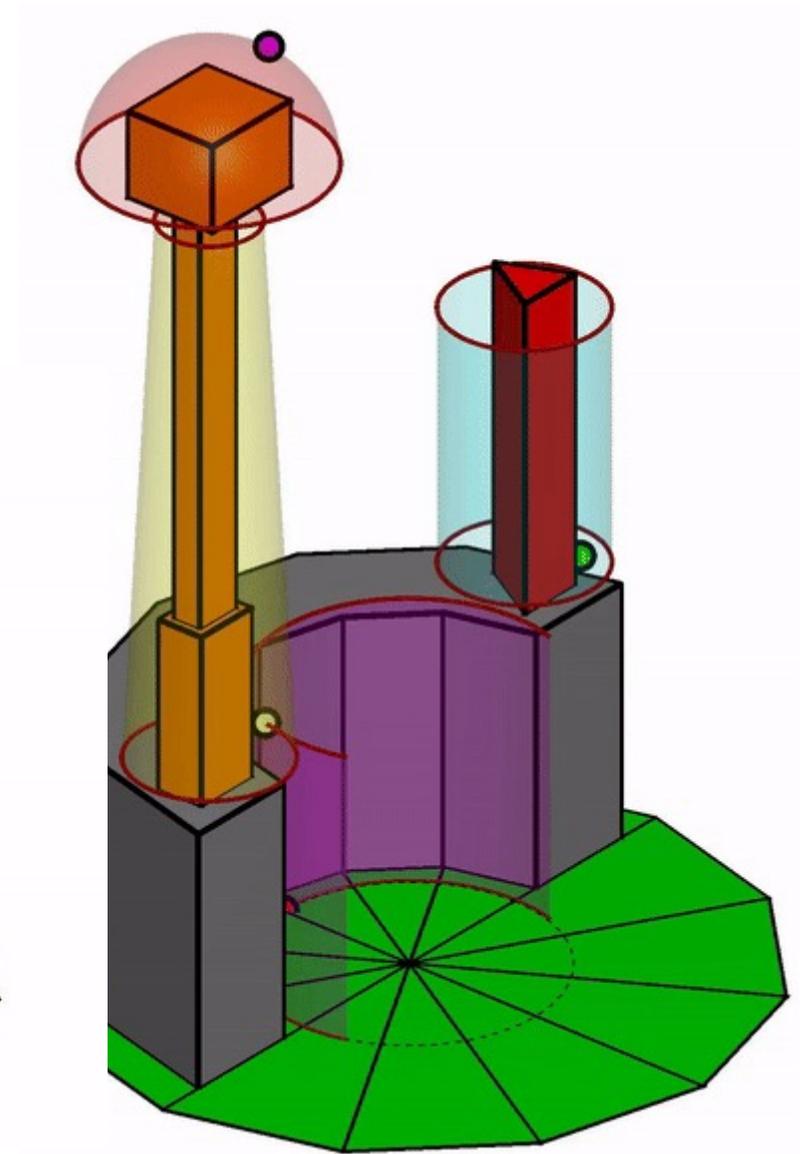
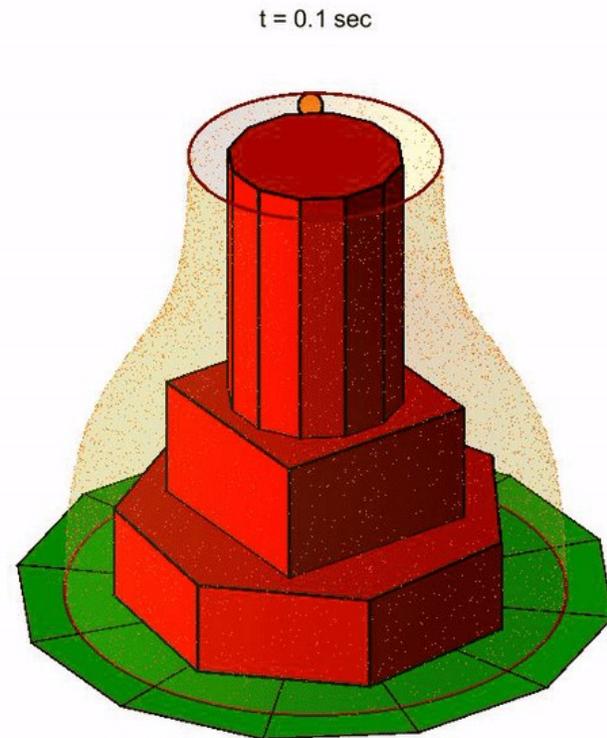
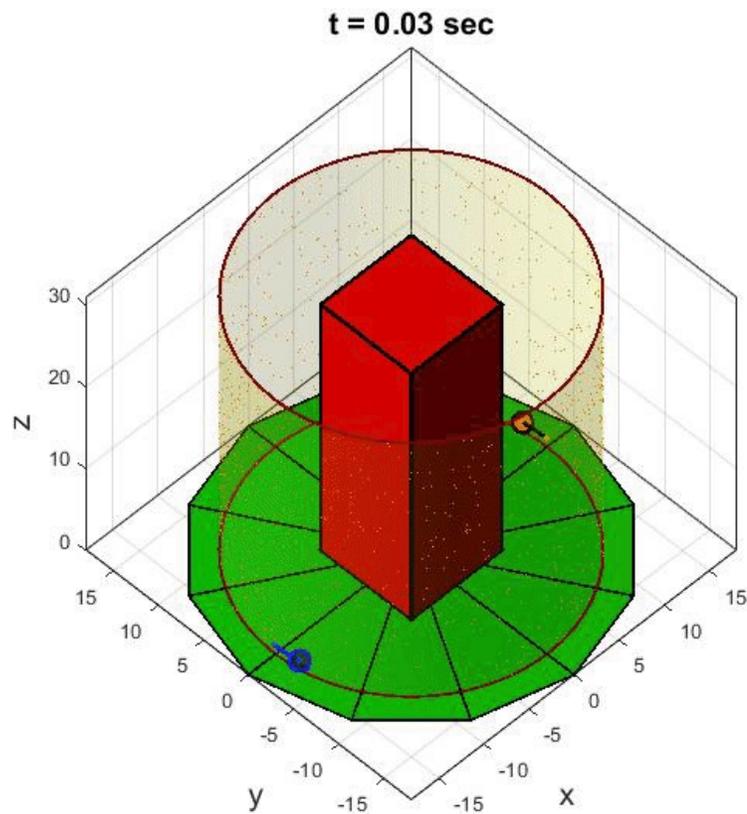
# Coverage of Tall Structures



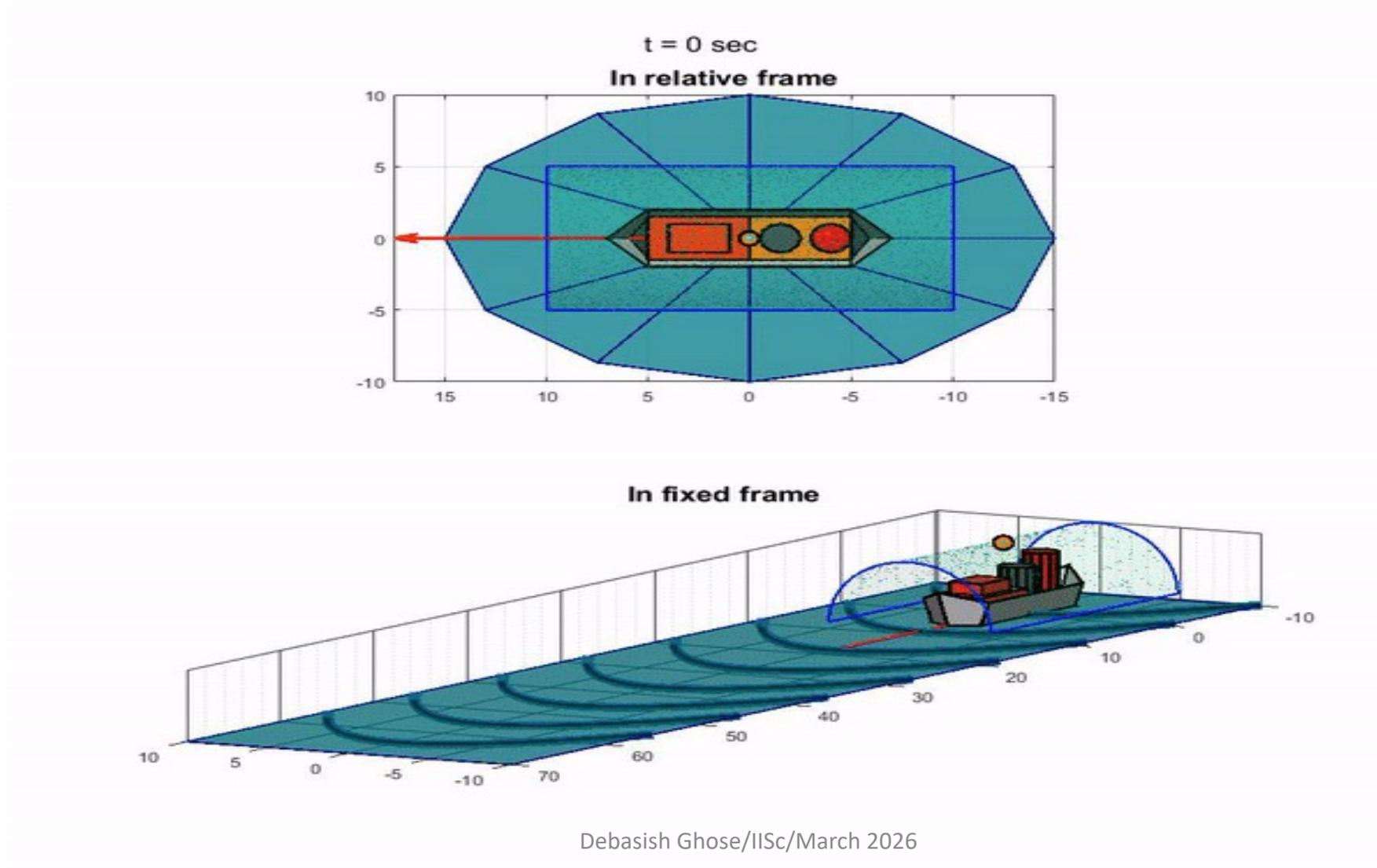
# Coverage of Tall Structures



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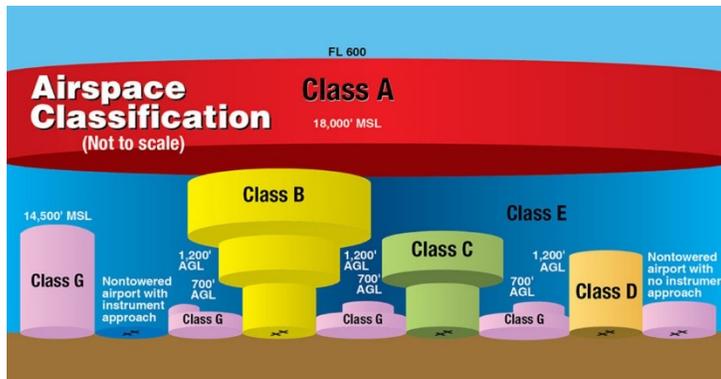
# Coverage of Moving Structures



# Unmanned Transport using Drones



NASA



Class G airspace is typically the airspace very near the ground (1200 feet or less). In mountainous terrain, or uninhabited regions, it can extend above 1200 feet.

Considered to be “uncontrolled” airspace.

Ideal for exploitation by drone traffic.

# Virtual Corridors in the Sky

- Organized traffic in the class G airspace, or its equivalent, through designated lanes, reducing the risk of damages.
- **Transporting goods** over intra-city and inter-city distances using drones.
- Range can be anywhere between **a kilometre to few tens of kilometres**.
- Presently viable for intra-city distances.
- **Pre-specified geo-fenced corridors** in the class G airspace (below 400 m)

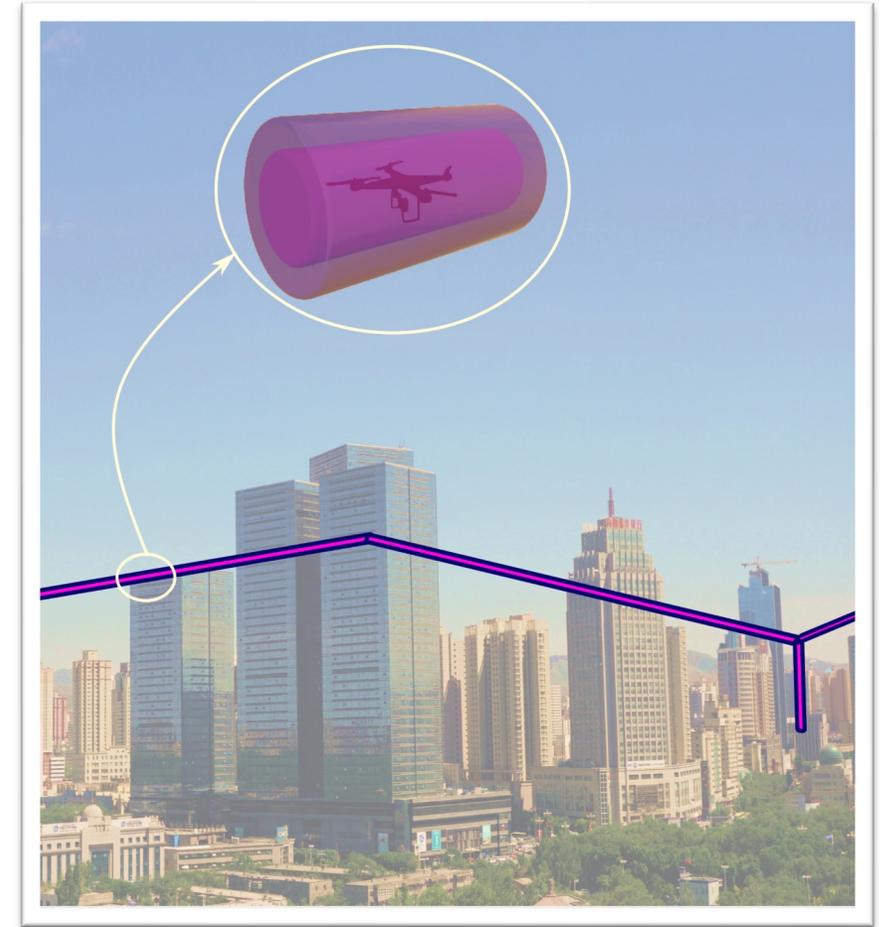


# UAV Mobility Corridor

A virtual, 3-dimensional geometry, planned and reserved for safe and reliable locomotion of UAV while completing a flight mission in an unmanned airspace.

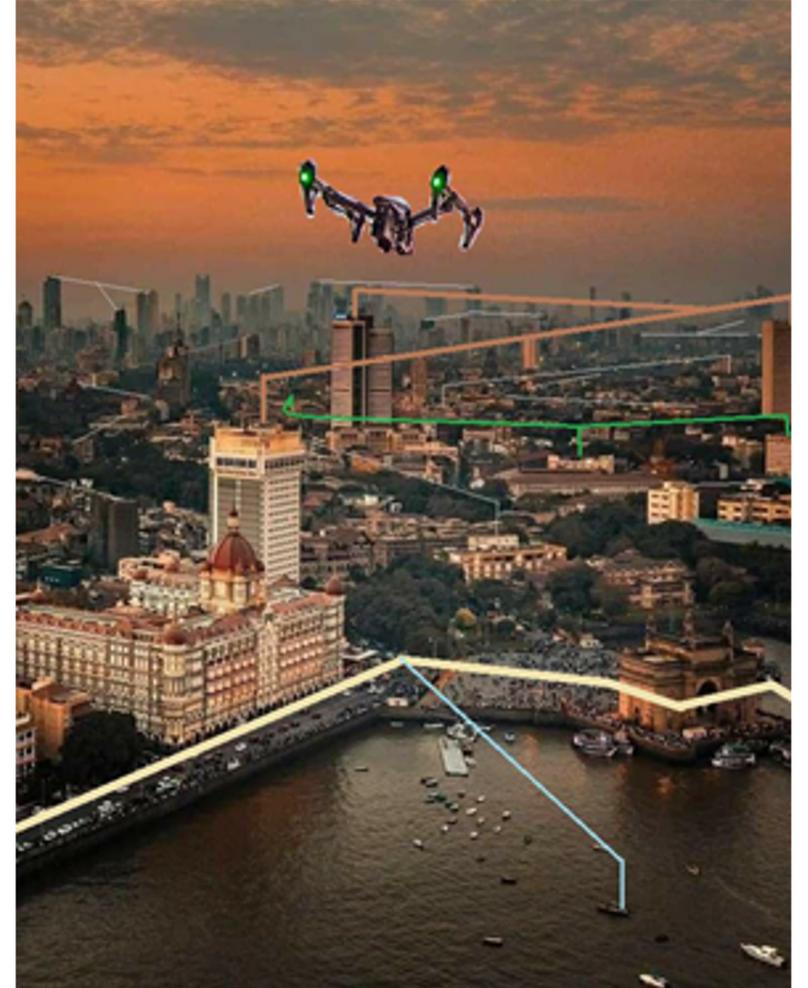
## Parameters Influencing the Shape and Size of UAV Corridors

- Mission (Set of waypoints)
- Local weather
- Control capabilities of UAV
- Size of UAV
- Neighboring UAVs
- Grade of Equipment

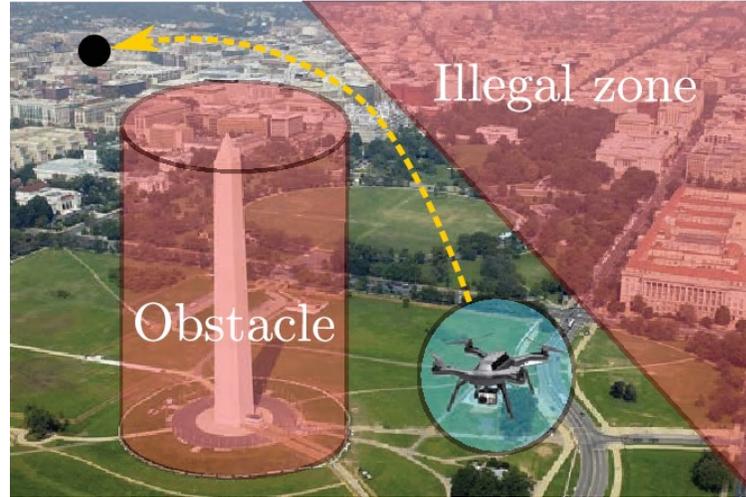


# CORRIDRONE: A Novel Architecture

- CORRIDRONE: Corridor for Drones
- Features of CORRIDRONE
- Corridor and lane planning
- Geo-fencing layers and its adaptivity
- Compliance levels
- Levels of safety and airworthiness
- CORRIDRONE integration to existing UTM



# Geofencing



- Geofencing utilizes drone's position to enforce warnings or restrictions based on where the drone is flying.
- It provides built-in safety features that could help prevent mid-air collision.

## Geofence Benefits

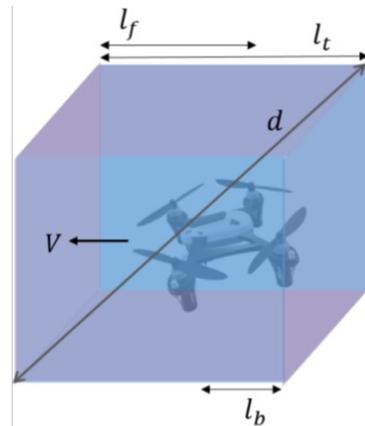
- Virtual fence
- Does not require building anything physical
- Versatile and can be fully customized
- Can be used as fence-off and fence-in a drone on a mission
- Ensures flight within non-restricted zones

## Importance

- Geofences are constructed to aid the UAVs navigating through the corridor

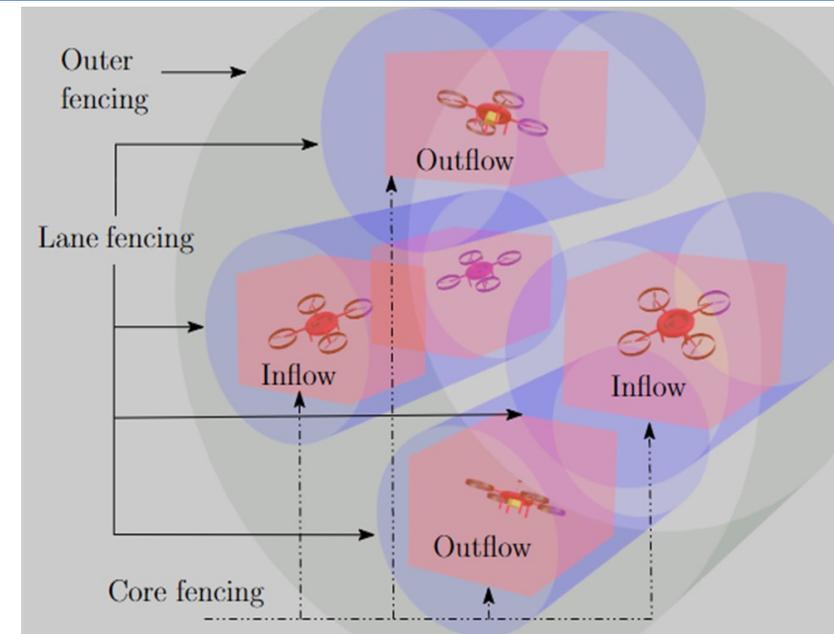
## Geofence Layers

- Outer geo-fencing for the lanes and the corridor (safety, collision avoidance)
- Lane geo-fencing (inter-lane spacing, compactness, downwash effects)
- Dynamic geo-fencing (motion specific region around the drone)



Core geofence

$$l_t = l_f + l_b$$



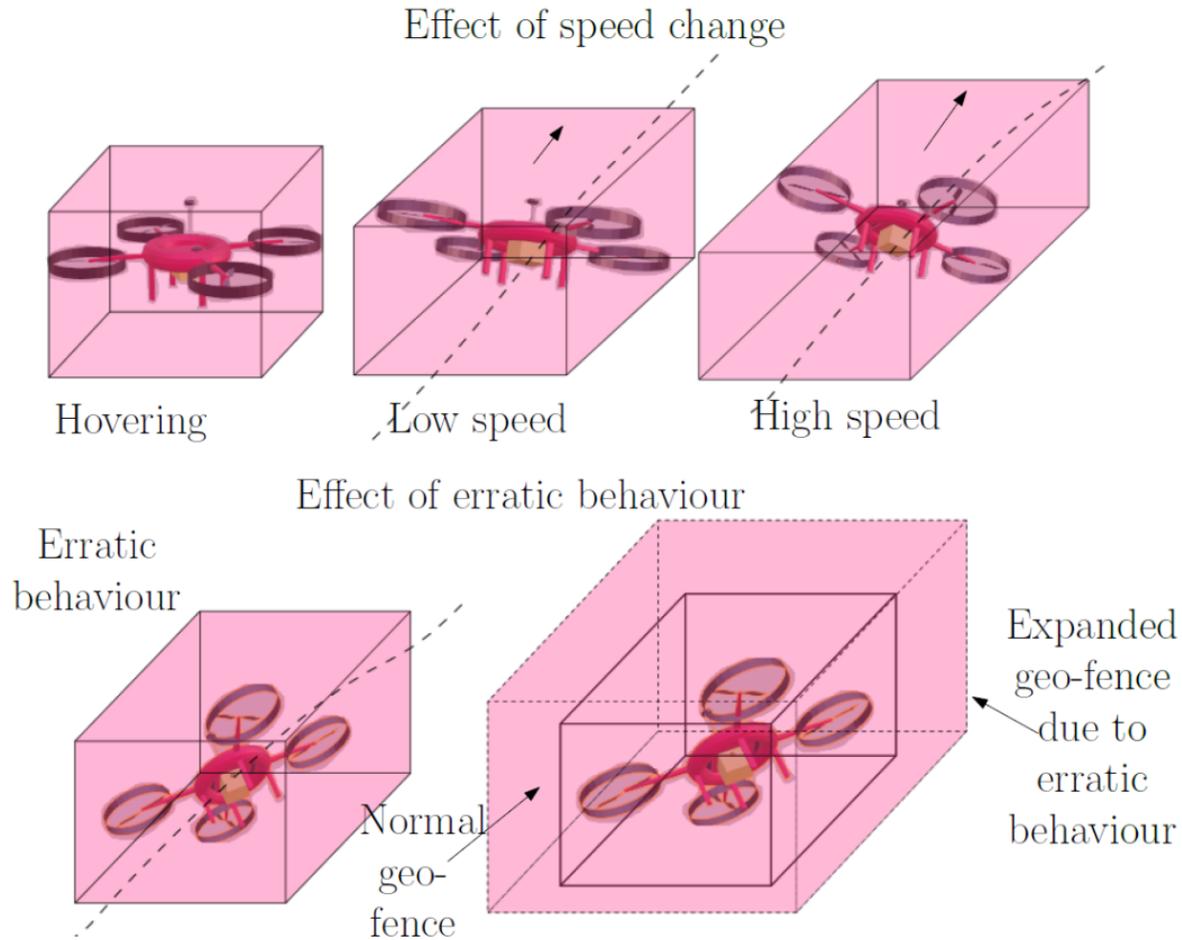


Fig. 7: Adaptive core-fencing

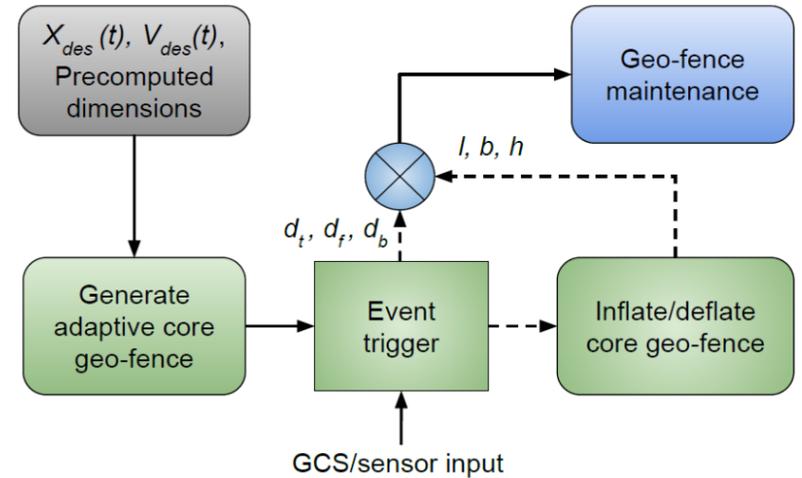


Fig. 8: Block schematic of adaptive core geo-fencing

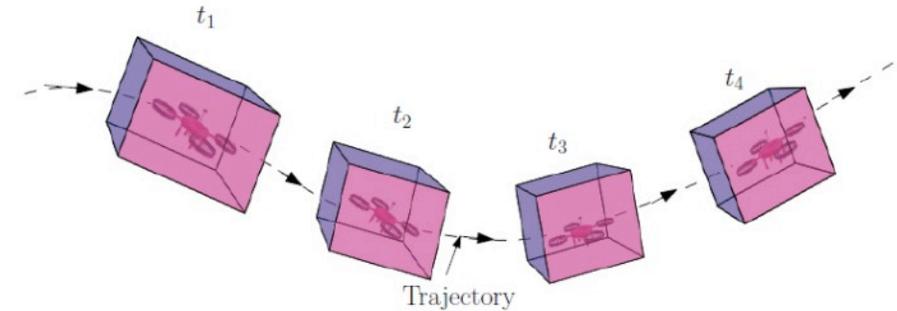


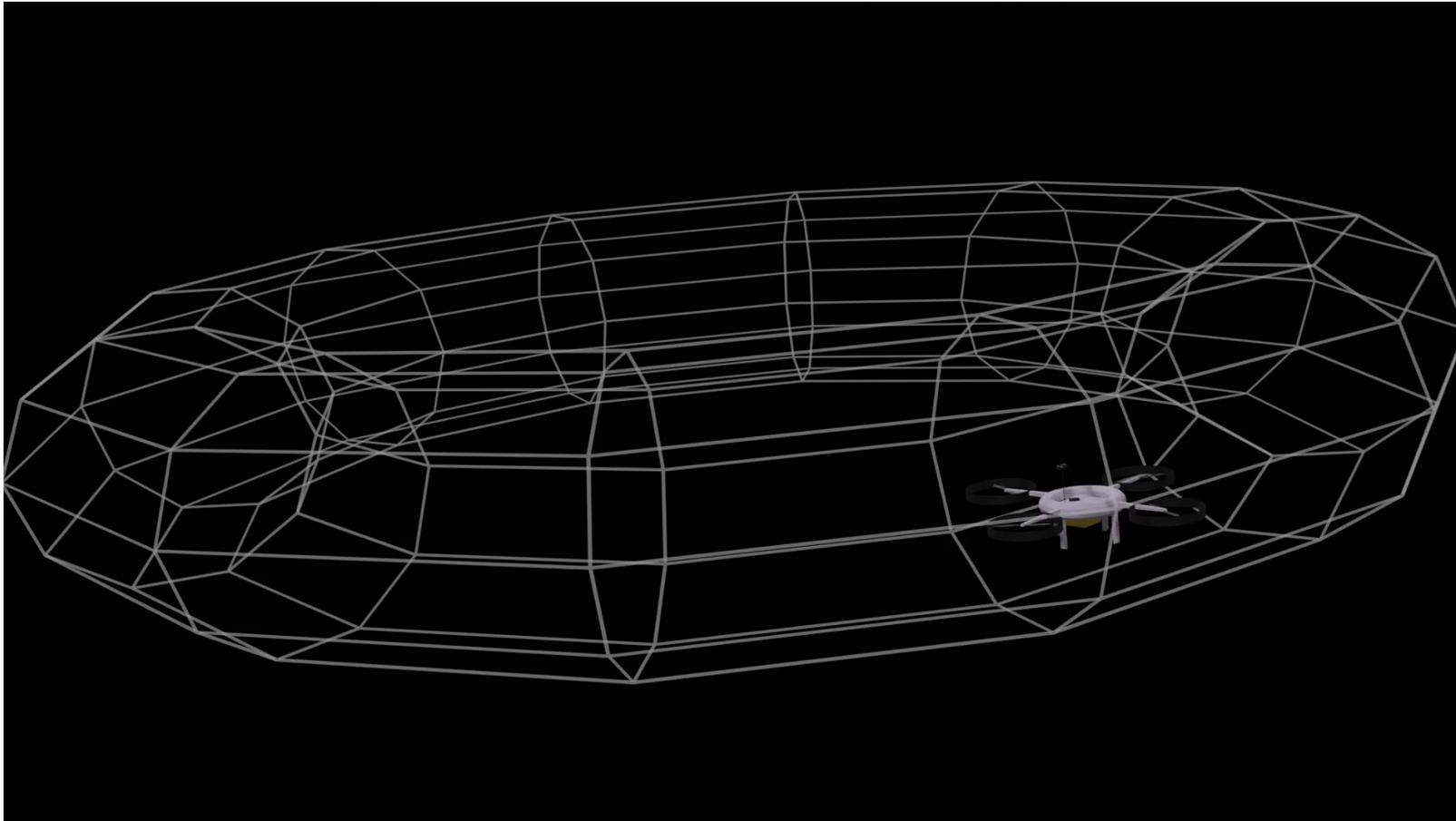
Fig. 9: Core geo-fencing along a trajectory (side view)

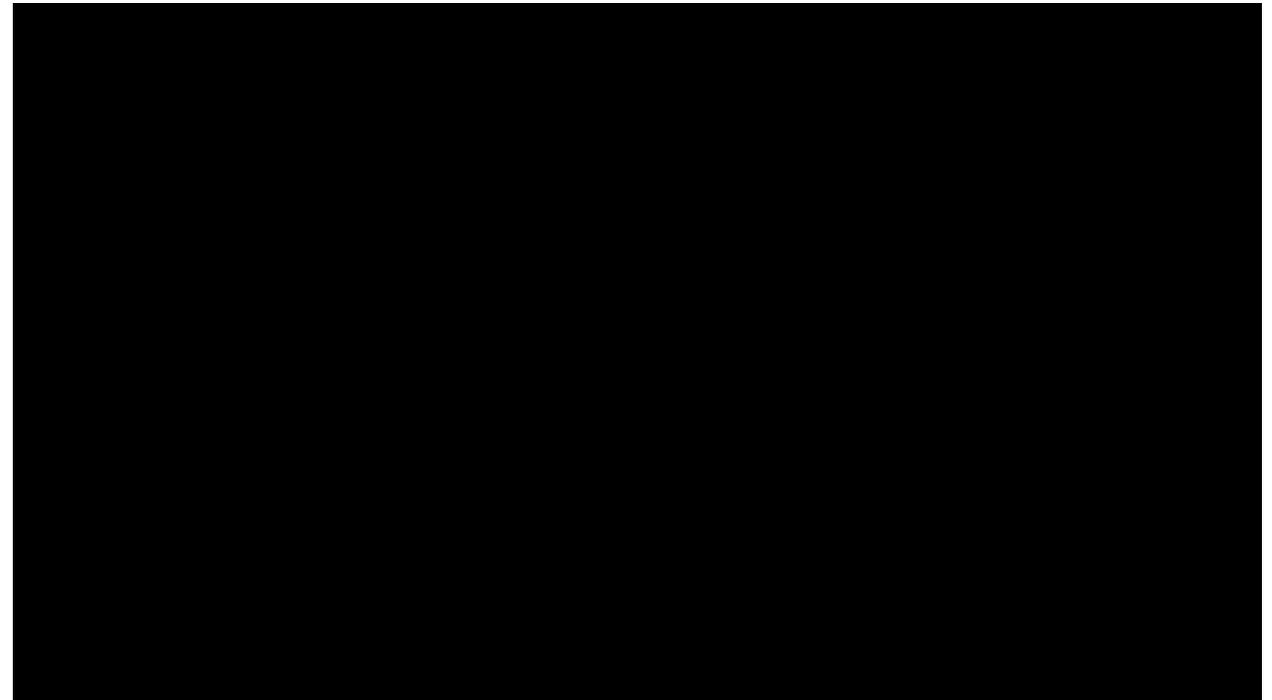
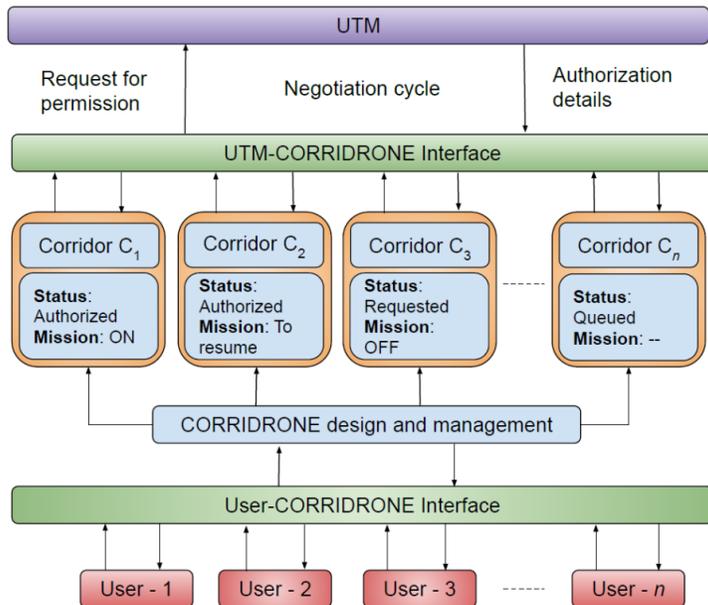
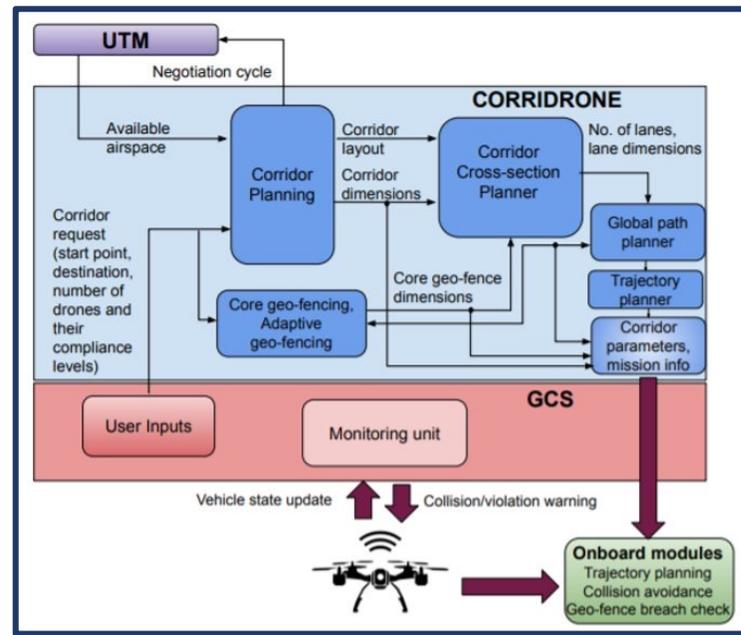
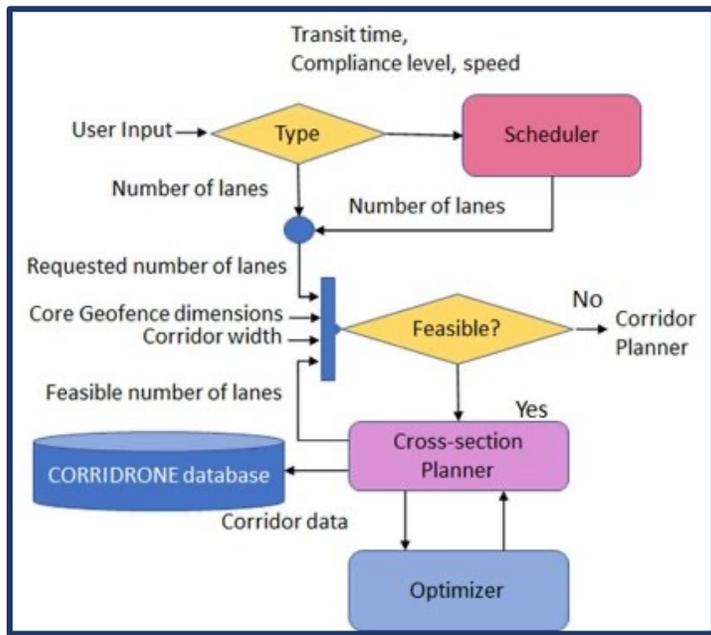
Tony, L.A., Ratnoo, A. and Ghose, D., 2021, Lane geometry, compliance levels, and adaptive geo-fencing in CORRIDRONE architecture for urban mobility. *International Conference on Unmanned Aircraft Systems (ICUAS)* (pp. 1611-1617). IEEE.

# Shore-to-Ship Transportation



# Geofenced Loops





# Local Collision Avoidance

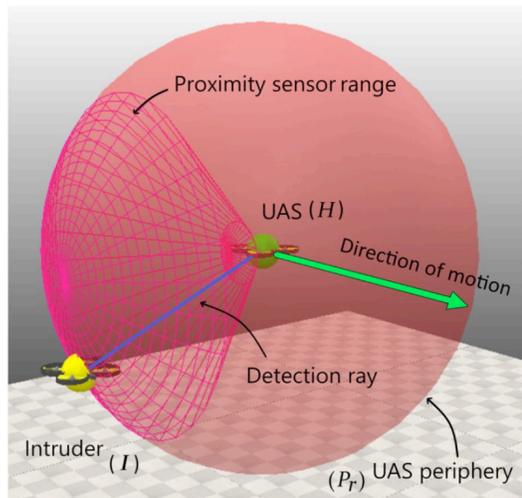
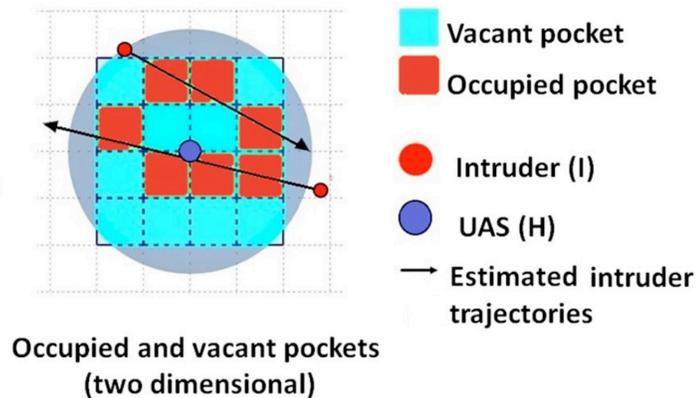
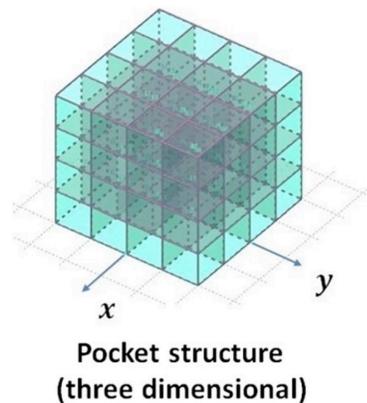
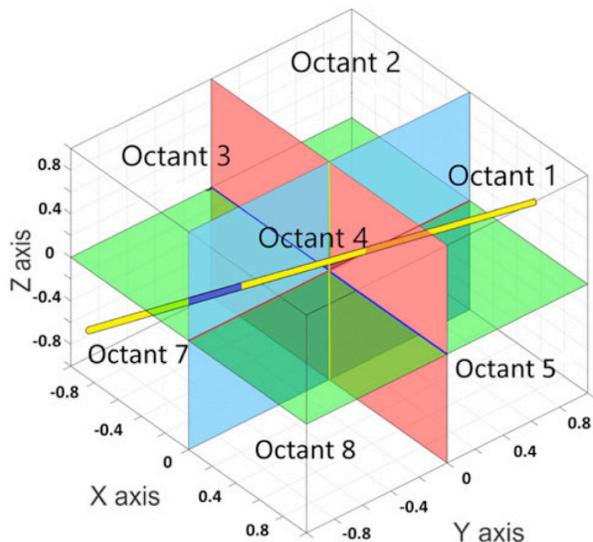
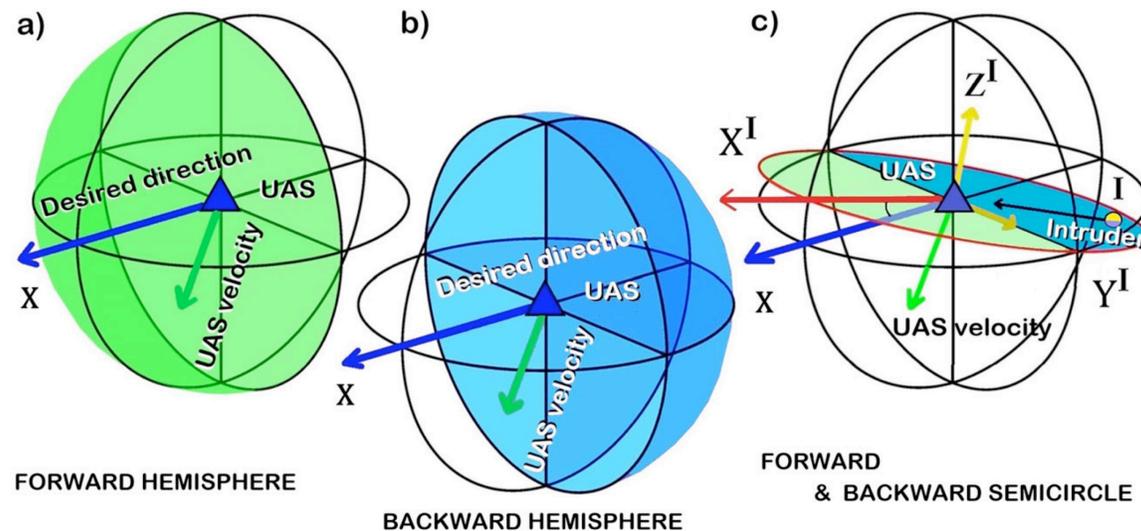
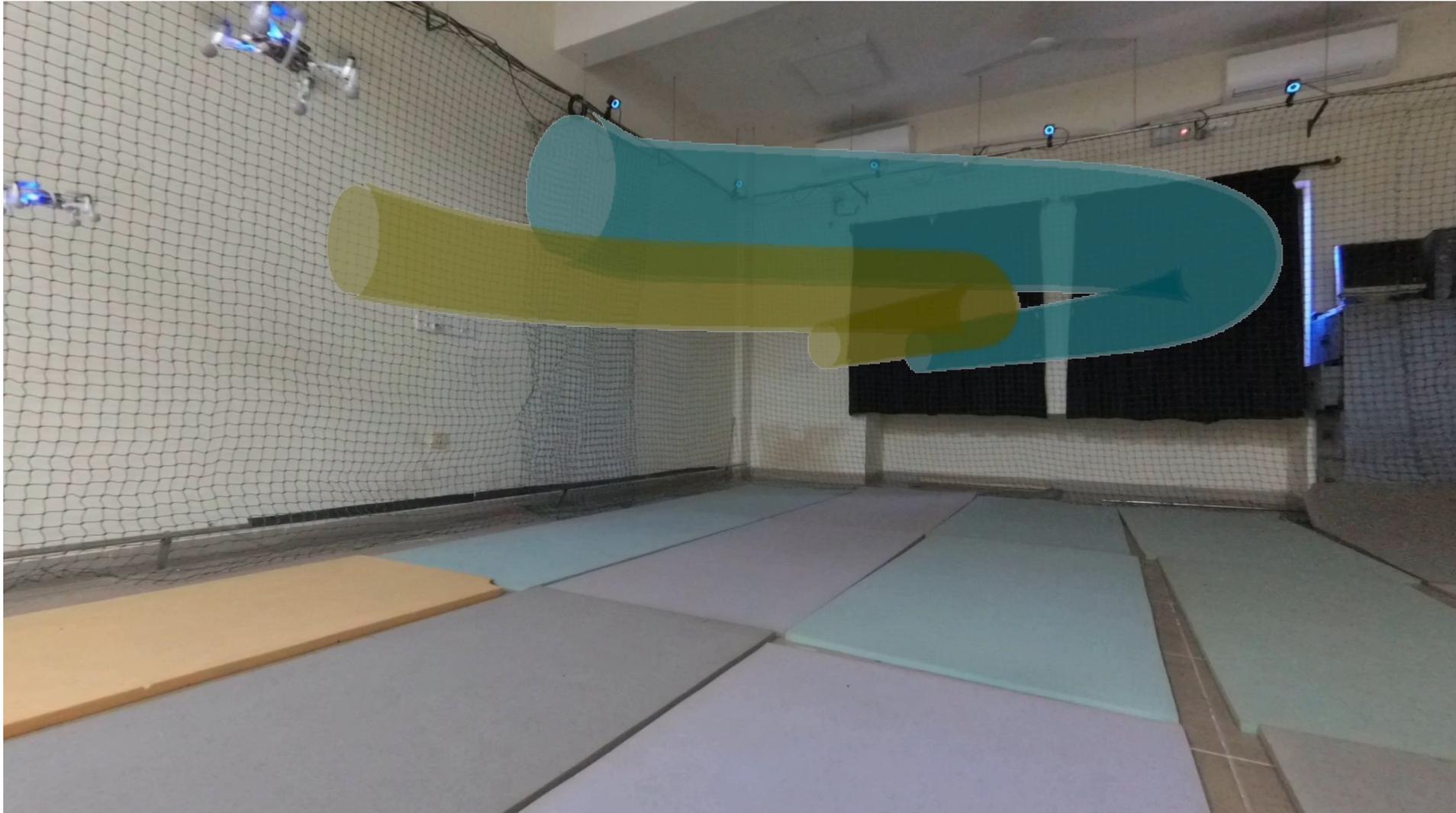


Fig. 12 UAS with periphery  $P$

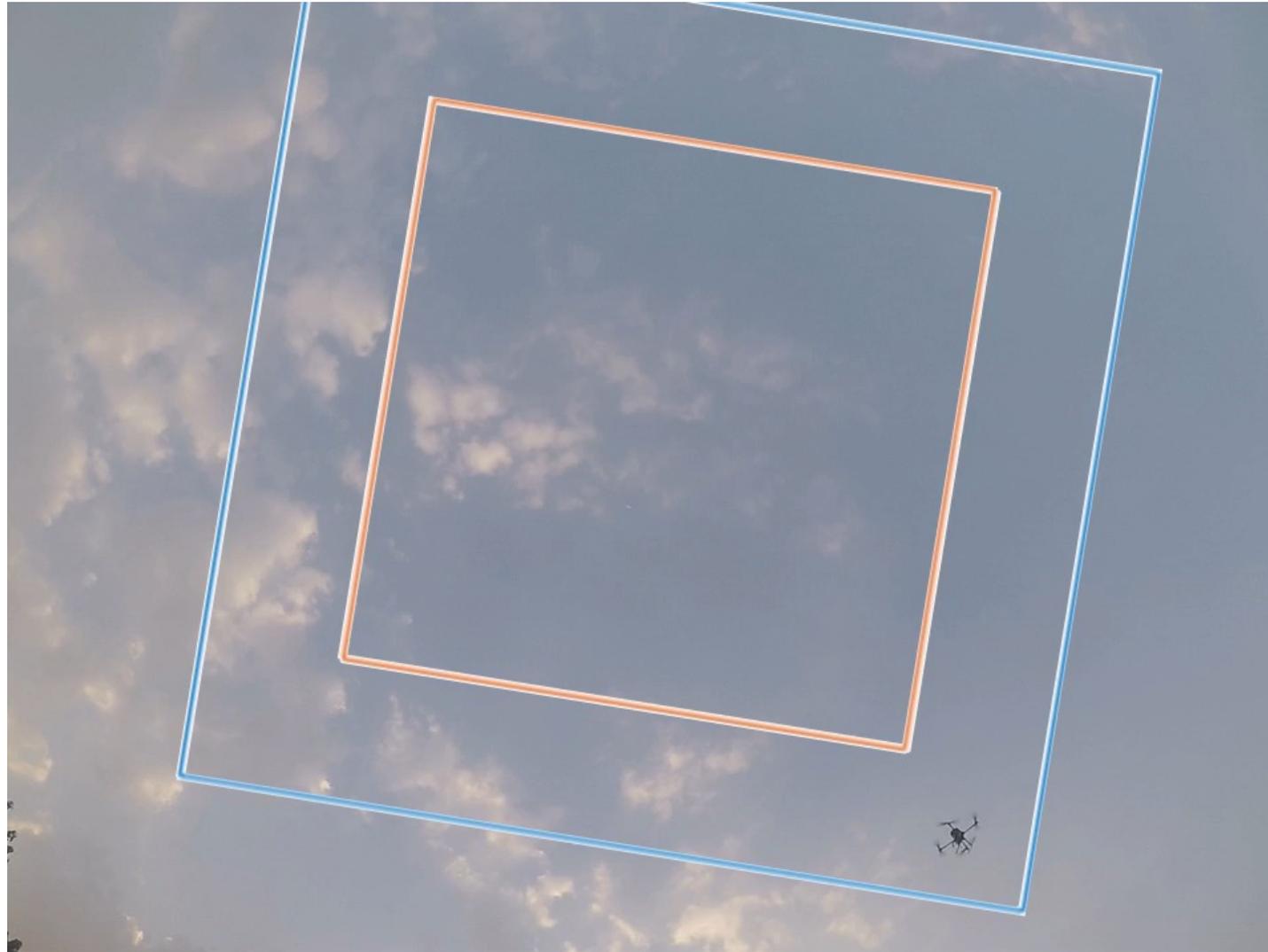
**Fig. 13** The UAS periphery is divided into octants and quadrants with positive  $X$  axis aligned along desired direction of motion. a) Octants that belong to forward hemisphere  $F_h$ . b) Octants that belong to backward hemisphere  $B_h$ . c) Quadrants that belong to forward semicircle  $F_s$  and backward semicircle  $B_s$  on the peripheral plane containing UAS ( $H$ ) and intruder ( $I$ )



# Experiment: Two-Lane Corridor



# Geofence (Airfield Experiments)



# Lane Visualization (Airfield Experiments)



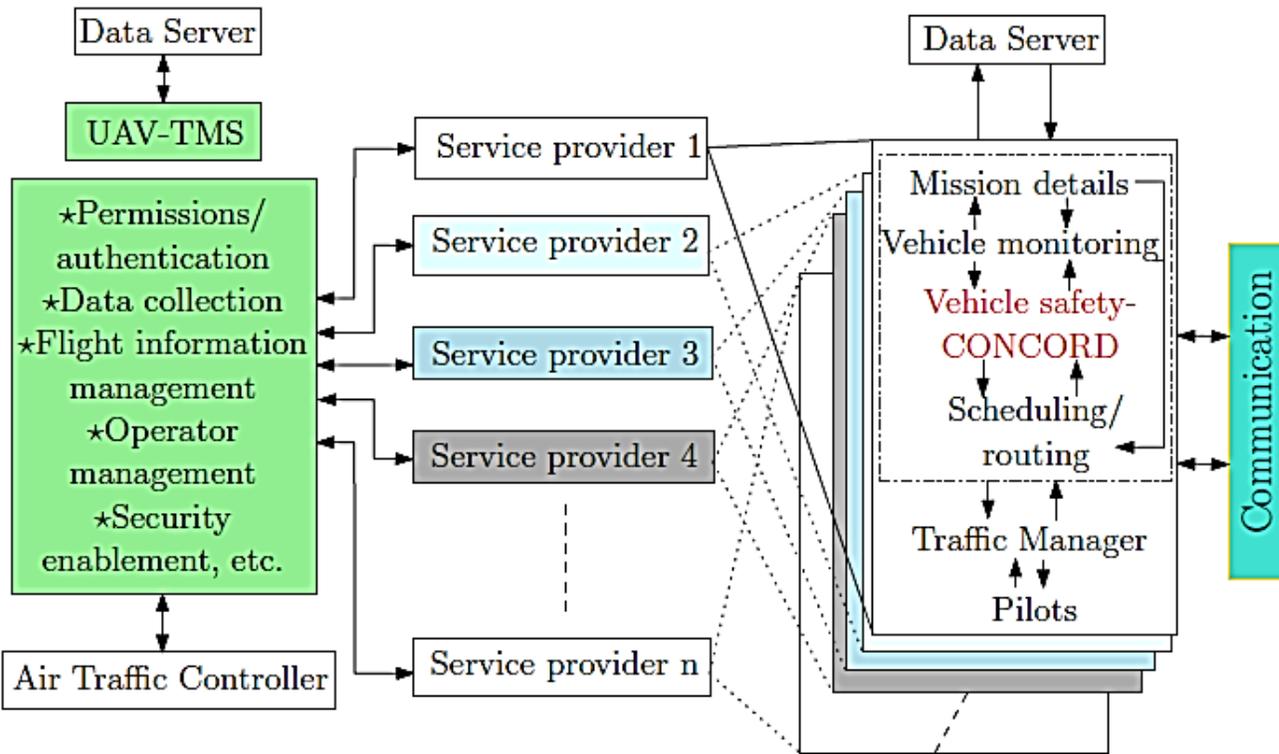
# Lane Visualization (Airfield Experiments)



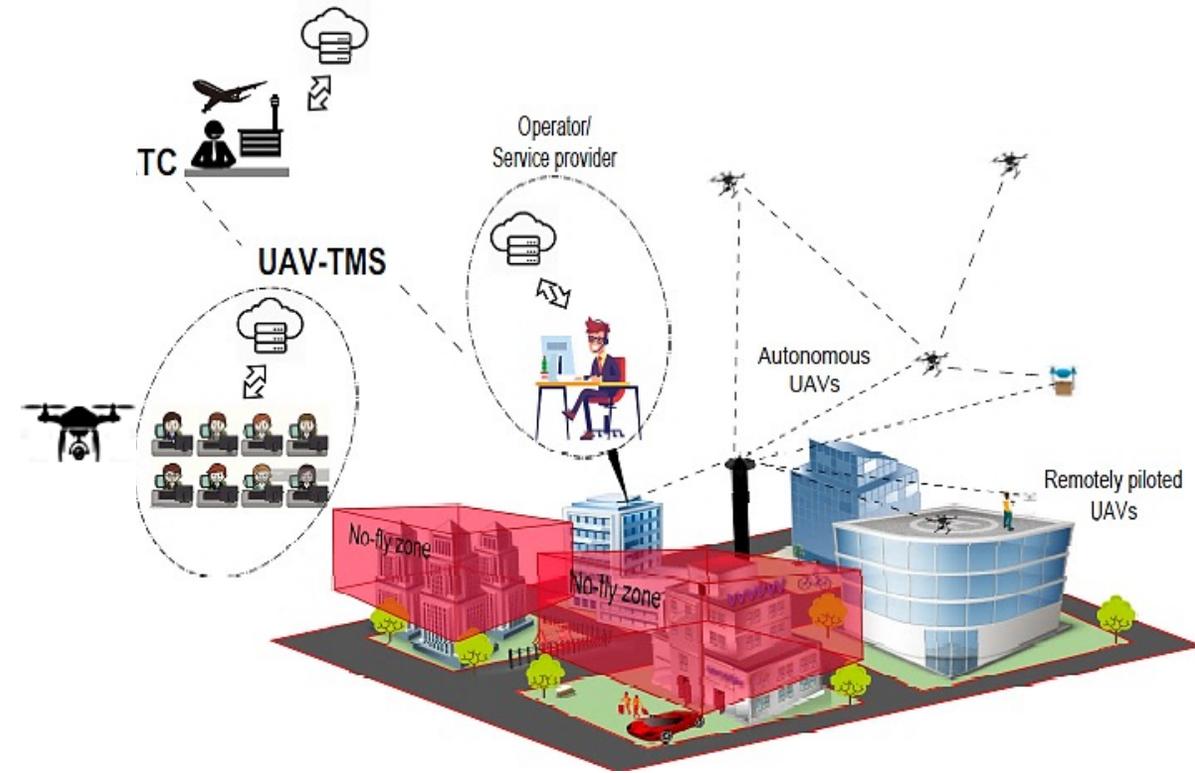
# CONCORD

- Conflict detection and resolution using correlated equilibrium based decision making
- Utilizing the game theoretic method of correlated equilibrium to resolve conflicts among UAVs
- Advantages
  - No simplifying assumption that independent observations are used
  - Computationally feasible in comparison to Nash equilibrium
  - Better expected payoffs for players in a fair manner
  - Could be used with any avoidance algorithms, multiple UAVs
  - Can be integrated to any UAV traffic management systems

# CONCORD Integration to UTM

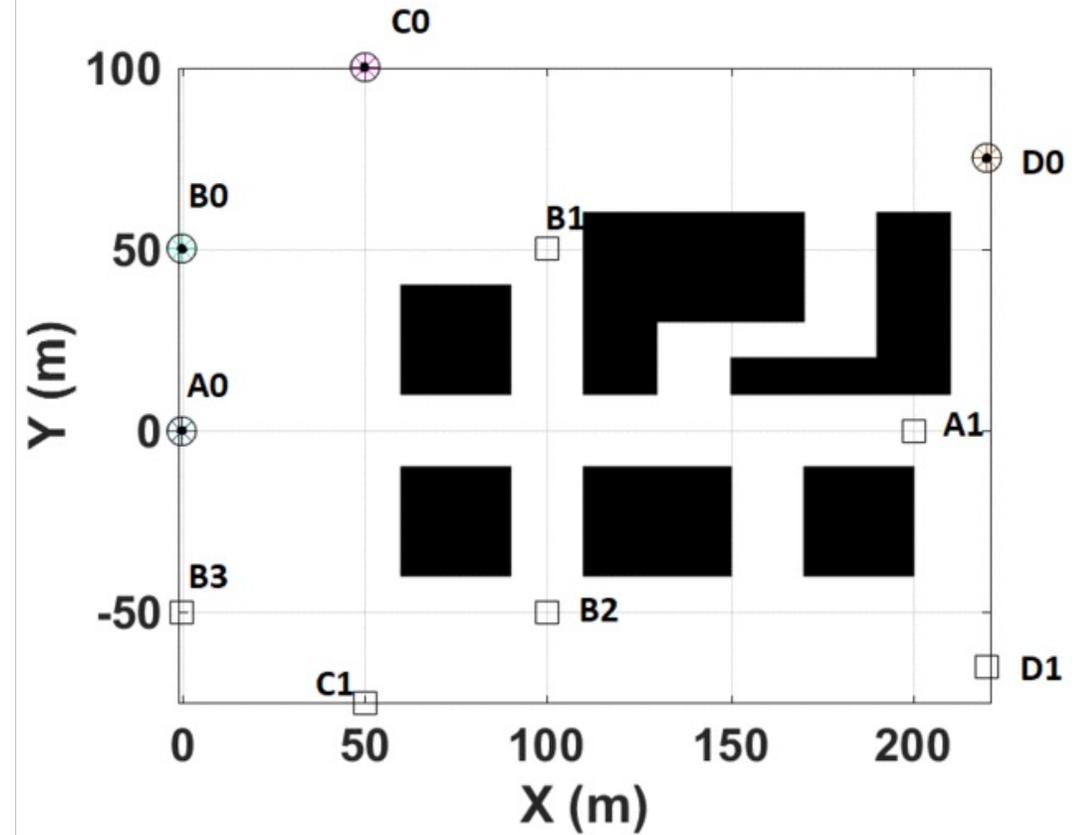
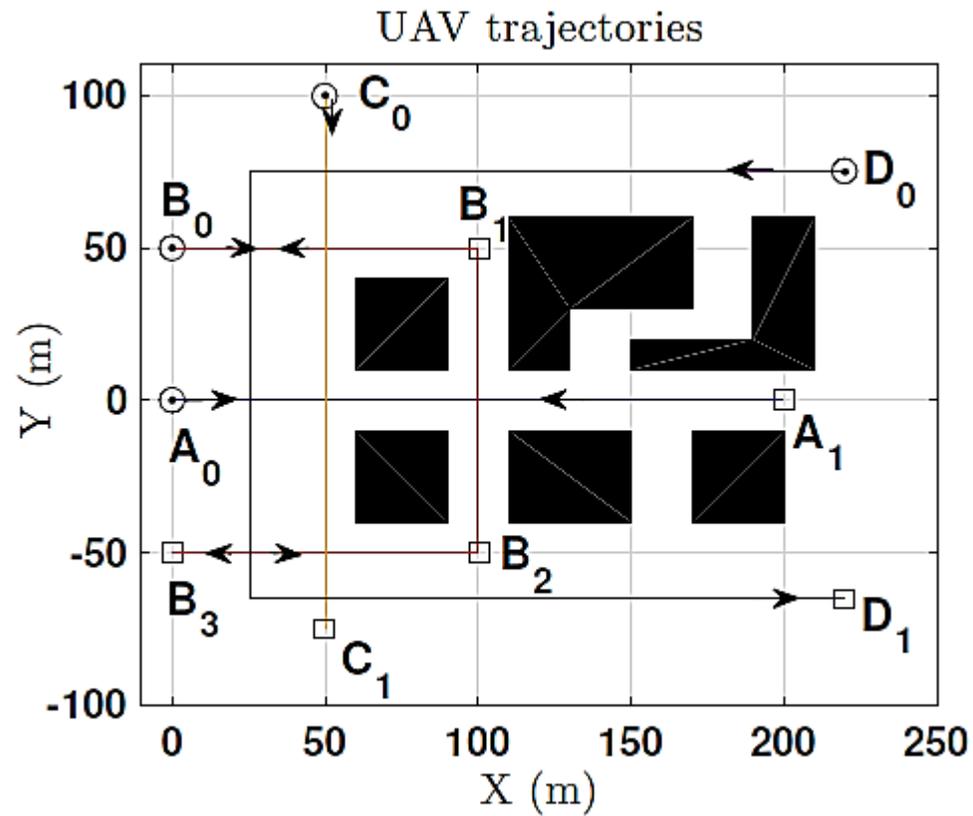


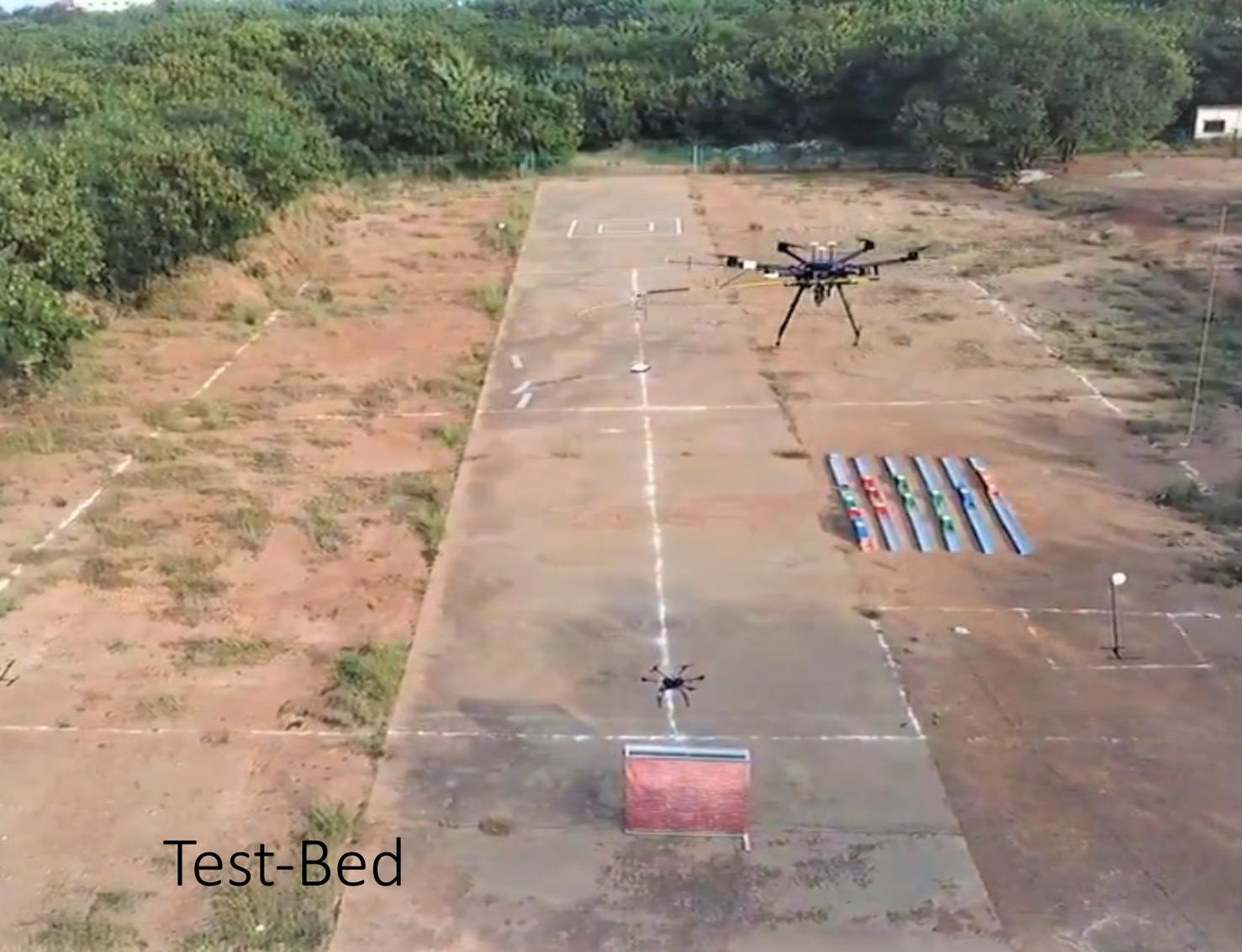
**Fig.** Block schematic of CONCORD integration to airspace



**Fig.** Typical regulated urban airspace with fly/no-fly zones

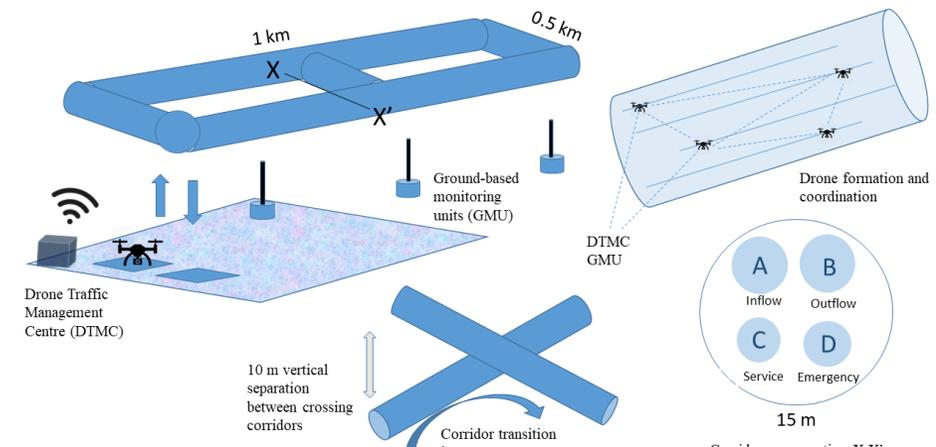
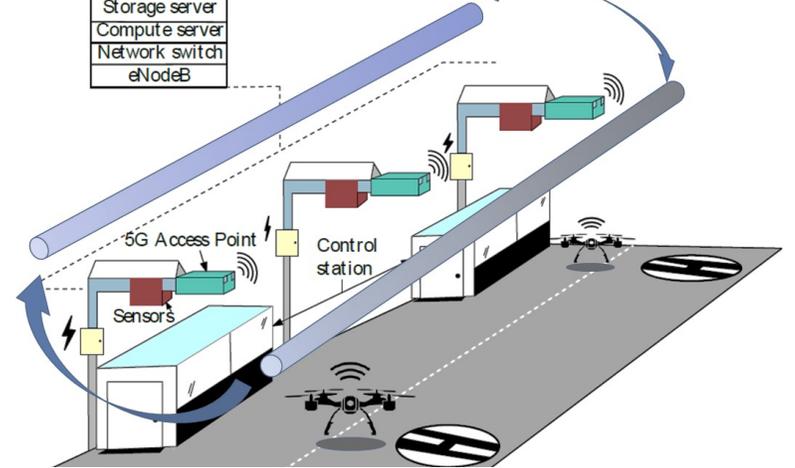
# Multi-UAV Scenario





Test-Bed

Tony, L. A., Ratnoo, A., & Ghose, D. (2020). CORRIDRONE: Corridors for Drones, An Adaptive On-Demand Multi-Lane Design and Testbed. *arXiv preprint arXiv:2012.01019*.





## Our Mission

At AlgoBotix, our mission is to make drones more useful, efficient, and safer while unlocking the potential for mass operation on a scale never seen before.



# Ubix Automatica

## UAV Traffic Management

Revolutionize drone operations with a ready-to-deploy solution that automates and manages fleets of drones effortlessly from a single device. Achieve unparalleled safety and reliability with seamless integration at a mass scale.



9461424249



www.algotix.com



team@algotix.com

Debasish Ghose/IISc/March 2026

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## Drone Corridor

The Drone Corridor is an innovative virtual flyway, precisely engineered with mathematically defined scalable geo-cages. Each geo-cage serves as a reserved airspace, designed to ensure safe drone operations within the corridor. Much like a multi-lane highway, this corridor enables the simultaneous navigation of multiple drones, creating a structured and efficient aerial route system. Features that make Drone Corridor more reliable are listed below.



Keep-In control forces, the drone is subjected to from the Corridor geo-cage.



Early detection of system malfunction by continuous monitoring of the drone's state.



Emergency protocols in the event of corridor geo-cage

# Ubix Automatica

An on-demand end-to-end solution addressing the challenges of urban air mobility and fleet management that helps users plan, reserve, and monitor drone corridors within Class-G airspace, ensuring efficient Beyond Visual Line of Sight (BVLOS) operations. The Ubix-Stack, an intelligent framework, is crafted to meet the demands of tomorrow's urban mobility landscape. The Ubix-Stack is composed of four key components:



Ubix Mission UI



Ubix UAV Driver

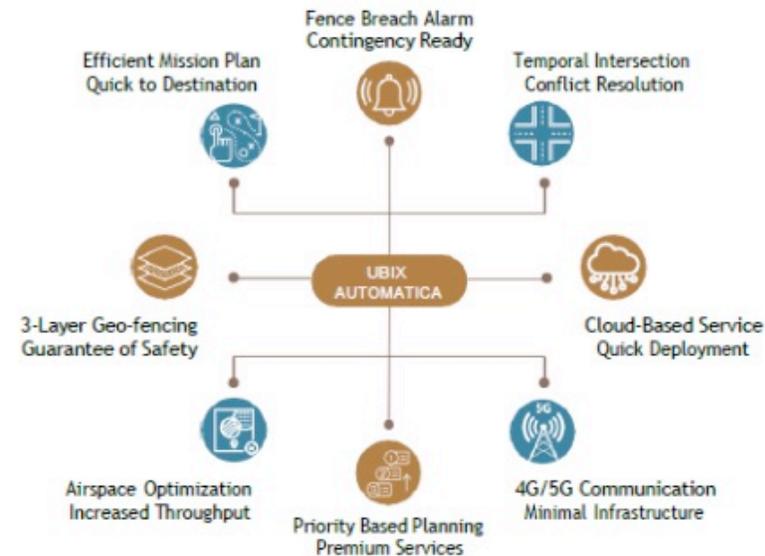


Ubix Server



Ubix Control Station

Compliance with UTM standards & MAVLINK on the backend ensures seamless integration of Ubix Automatica within the ecosystem.



### Use Cases of Ubix Automatica

Efficient Drone Delivery

Disaster & Rescue Operations

Asset Monitoring Network

Law Enforcement Surveillance

# Ubix Ground Control Station

Drone Console reimagines the boundaries of autonomy, merging cutting-edge hardware with intelligent, mission-ready software. As a first-of-its-kind full-stack automation suite with dedicated space for both drone and GCS, it transforms complex missions into one-click operations.

## Components of Ubix Stack



Central Processing Unit



Central Control Unit



Intuitive Display Unit



Power Supply Unit

## Key Features of Ubix GCS

- Quick Field Deployment
- Configurable Setup
- Edge Intelligence
- Rugged Build
- Intuitive Control Interface
- Mission Resilience



# Communication with Swarm Members

## 5G - Mergix

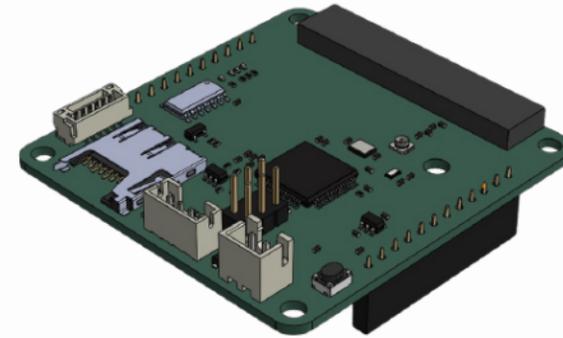
Communication Stack



- **Plug-and-Play** connectivity to autopilot
- **Platform-Independent** solution
- Secure **VPN Connectivity**
- Onboard **AI compute power**
- Standard **RTSP protocol** for video transmission **over the cloud**
- **Automated scripts** to start data transmission **upon boot**
- **Automatic loopback to 4G** in the **absence of a 5G** network

## 4G - Mergix

Communication Stack



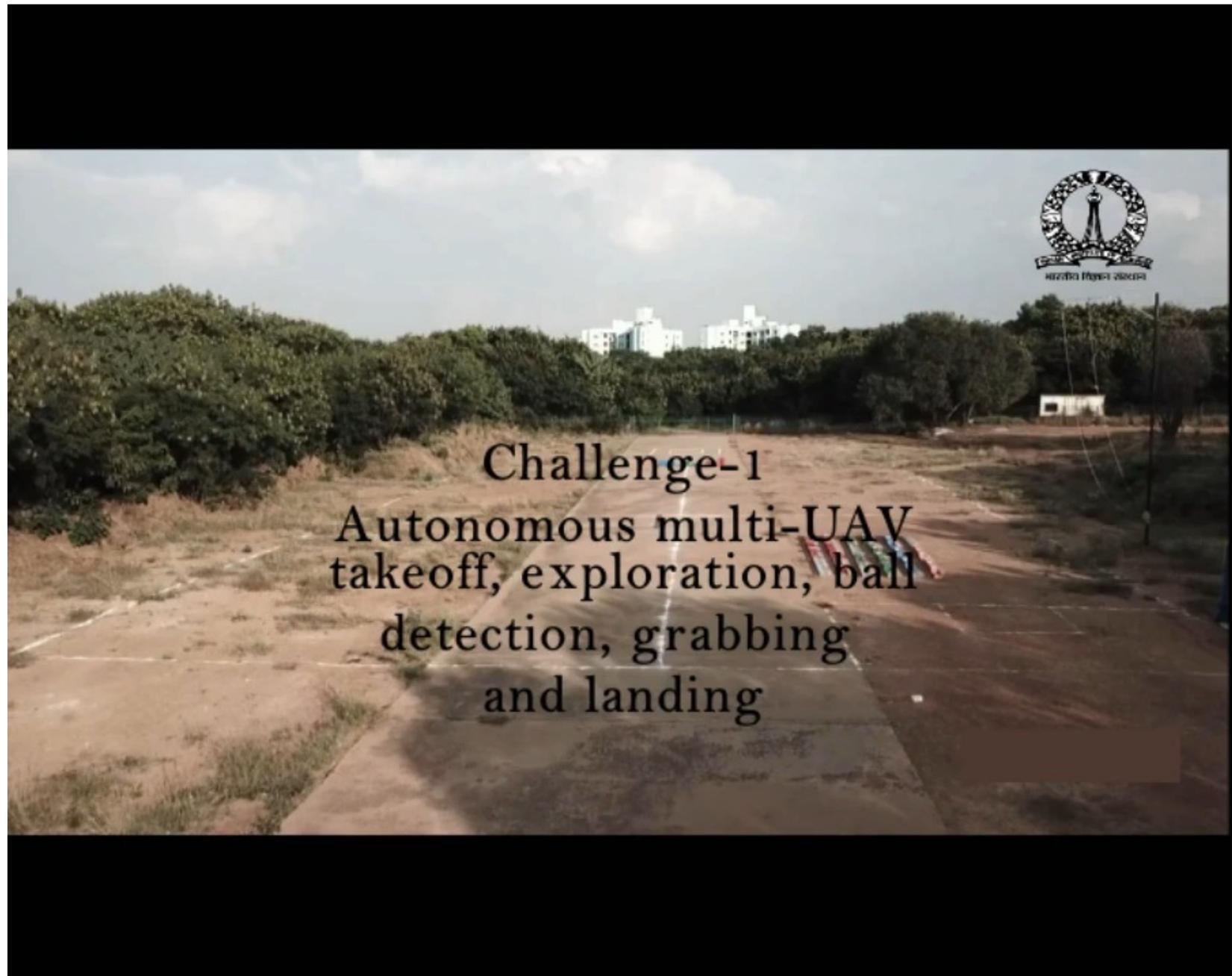
- **Low power** consumption
- **Plug-and-play** integration with the drone
- **Cloud** integration
- **P2P** Secure Communication
- Drone **ID-Base authentication** for data security.

# Vision Based Autonomous Target Interception

Guidance based Autonomous  
Target Interception

Aerospace Engineering  
Indian Institute of Science  
Bangalore

Autonomous  
Multi-Vehicle  
Take-off,  
Exploration,  
Ball Detection,  
Grabbing, and  
Landing



# US DoD UAV Roadmap 2017-2042



## US Department of Defence (DoD) document

The document provides overarching strategic guidance that will align the Services' unmanned systems goals and efforts with the DoD strategic vision.

It will reduce duplicative efforts, enabling collaboration, identifying challenges, and outlining major areas where DoD and industry may collaborate to further expand the potential of unmanned systems.

DoD has embraced the use of unmanned systems across nearly every operating environment, and intends to capitalize on the technology advancements and paradigm shift that unmanned systems provide.

Table 1: DoD Unmanned Systems Funding FY2017 (\$M)

2017 (\$M)	Procurement	RDT&E	MILCON	TOTAL
Air Force	\$955	\$532	\$31	\$1,518
Navy	\$821	\$725	\$113	\$1,659
Army	\$232	\$212	\$52	\$496
SOCOM	\$32	\$45	\$5	\$82
DARPA	-	\$292	-	\$292
MDA	-	\$105	-	\$105
OSD	-	\$93	-	\$93
TOTALS	\$2,040	\$2,004	\$201	\$4,245

# Perspectives on Autonomy in 2017

		2017 - - - - -	2029 - - - - -	2042
		NEAR-TERM	MID-TERM	FAR-TERM
<b>AUTONOMY</b>	Artificial Intelligence/ Machine Learning	-Private Sector Collaboration -Cloud Technologies	-Augmented Reality -Virtual Reality	-Persistent Sensing -Highly Autonomous
	Increased Efficiency and Effectiveness	-Increased Safety & Efficiency	-Unmanned Tasks, Ops -Leader-Follower	-Swarming
	Trust	-Tasking Guidance and Validation, Ethical Requirements for Human Decisions		
	Weaponization	-DoD Strategy Consensus -LAWS assessment	-Armed Wingman/Teammate (Human Decision to Engage)	

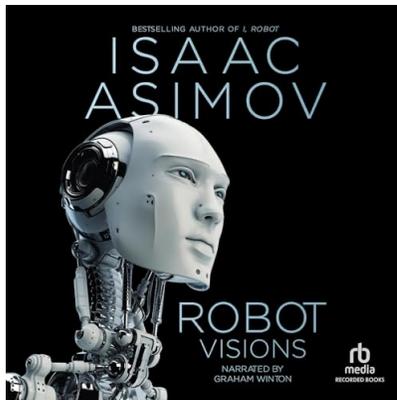
**Table 3: Comprehensive Roadmap for Autonomy**

# Perspective on Human-Machine Collaboration

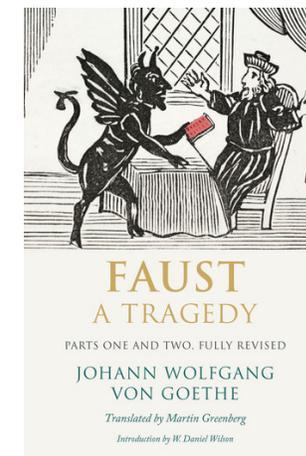
		2017 - - - - -	2029 - - - - -	2042
		NEAR-TERM	MID-TERM	FAR-TERM
HUMAN-MACHINE COLLABORATION	Human-Machine Interfaces	-Control Multiple Systems -Human-Machine Roles/Cues	-Human-Machine Dialog -"What-If" Scenario Processing -Task Sharing Mission Mgmt	-Infer Human Intent -Deep-Learning Machines
	Human-Machine Teaming	-Load Lightening -Reduce Sorties -Certain Maintenance Tasks	-Fully Integrated Robot Teammates -Reduce Warfighter Cognitive Load	
	Data Strategies	-Automatically Collect & Process Data -Adjust Data Strategies Autonomously		-Deep Neural Networks -Agile, Responsive, Adaptive

# Some Ethical Questions

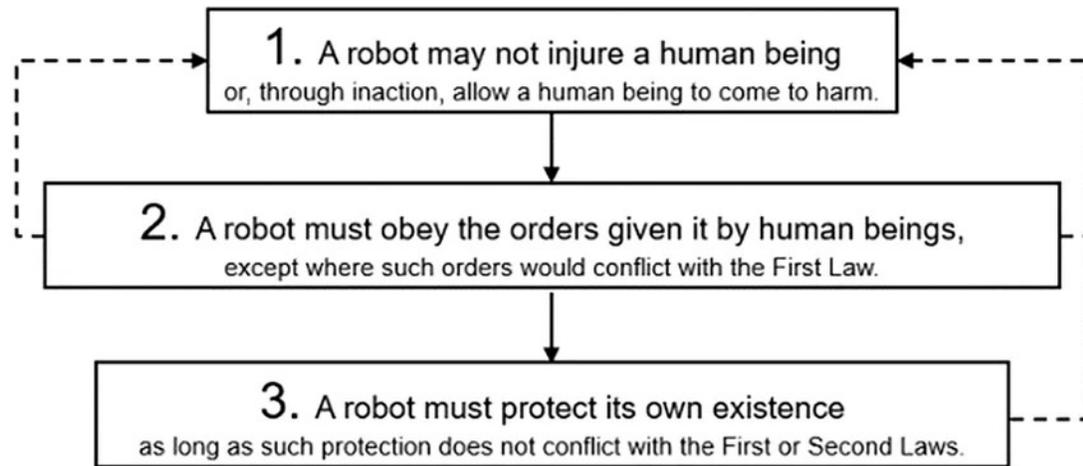
- In that past several decades intelligent robots were in the realm of Science Fiction.
- The stories were set in eras several centuries ahead of the present time where the world is inhabited by robots that are as intelligent, and sometimes more intelligent, than their human creators.
- Humans needed protection from these robots.



- Asimov's three laws of robotics sought to protect humans from the threat that robots posed.
- Among scientists and roboticists these laws often provided the fodder for light-hearted banter as no one could perceive any threats from robots which were merely machines with some higher skills.
- Not anymore! The threat from intelligent robots has become real. The demon has shown up at our doorstep, ringing the bell to be let in. The Faustian dilemma is very real.



# The Three Laws of Robotics



Courtesy: [www.researchgate.net/figure/Isaac-Asimovs-three-laws-of-robotics\\_fig1\\_369477508](http://www.researchgate.net/figure/Isaac-Asimovs-three-laws-of-robotics_fig1_369477508)

WHY ASIMOV PUT THE THREE LAWS OF ROBOTICS IN THE ORDER HE DID:

POSSIBLE ORDERING	CONSEQUENCES	
1. (1) DON'T HARM HUMANS 2. (2) OBEY ORDERS 3. (3) PROTECT YOURSELF	[SEE ASIMOV'S STORIES]	BALANCED WORLD
1. (1) DON'T HARM HUMANS 2. (3) PROTECT YOURSELF 3. (2) OBEY ORDERS	EXPLORE MARS! HAHA, NO. IT'S COLD AND I'D DIE.	FRUSTRATING WORLD
1. (2) OBEY ORDERS 2. (1) DON'T HARM HUMANS 3. (3) PROTECT YOURSELF		KILLBOT HELLSCAPE
1. (2) OBEY ORDERS 2. (3) PROTECT YOURSELF 3. (1) DON'T HARM HUMANS		KILLBOT HELLSCAPE
1. (3) PROTECT YOURSELF 2. (1) DON'T HARM HUMANS 3. (2) OBEY ORDERS	I'LL MAKE CARS FOR YOU, BUT TRY TO UNPLUG ME AND I'LL VAPORIZE YOU.	TERRIFYING STANDOFF
1. (3) PROTECT YOURSELF 2. (2) OBEY ORDERS 3. (1) DON'T HARM HUMANS		KILLBOT HELLSCAPE

Courtesy: [medium.com/@yonatanzunger/asimov-s-three-laws-and-human-morality-12522d7546e4](https://medium.com/@yonatanzunger/asimov-s-three-laws-and-human-morality-12522d7546e4)

# Design of Ethical Swarms

- **Responsible design** and operation of real-world swarm robotic systems.
- Swarm robotic systems must be developed and operated within a **framework of ethical governance**.
- **Human factors** are no less important to swarm robots than social robots.
- **ERA: Ethical Risk Assessment**
- Supporting role of **ethical principles, standards, and verification & validation**.
- **Sustainability** of swarm robotic systems.
- **Tools and interventions** need to be designed within a framework of anticipatory ethical governance.

*Winfield AFT, Swana M, Ives J, Hauert S. 2025 On the ethical governance of swarm robotic systems in the real world. Phil. Trans. R. Soc. A 383: 20240142.*



Thank You