Confidence-Based Buffer for Strategic Deconfliction with Probabilistic Operational Intent

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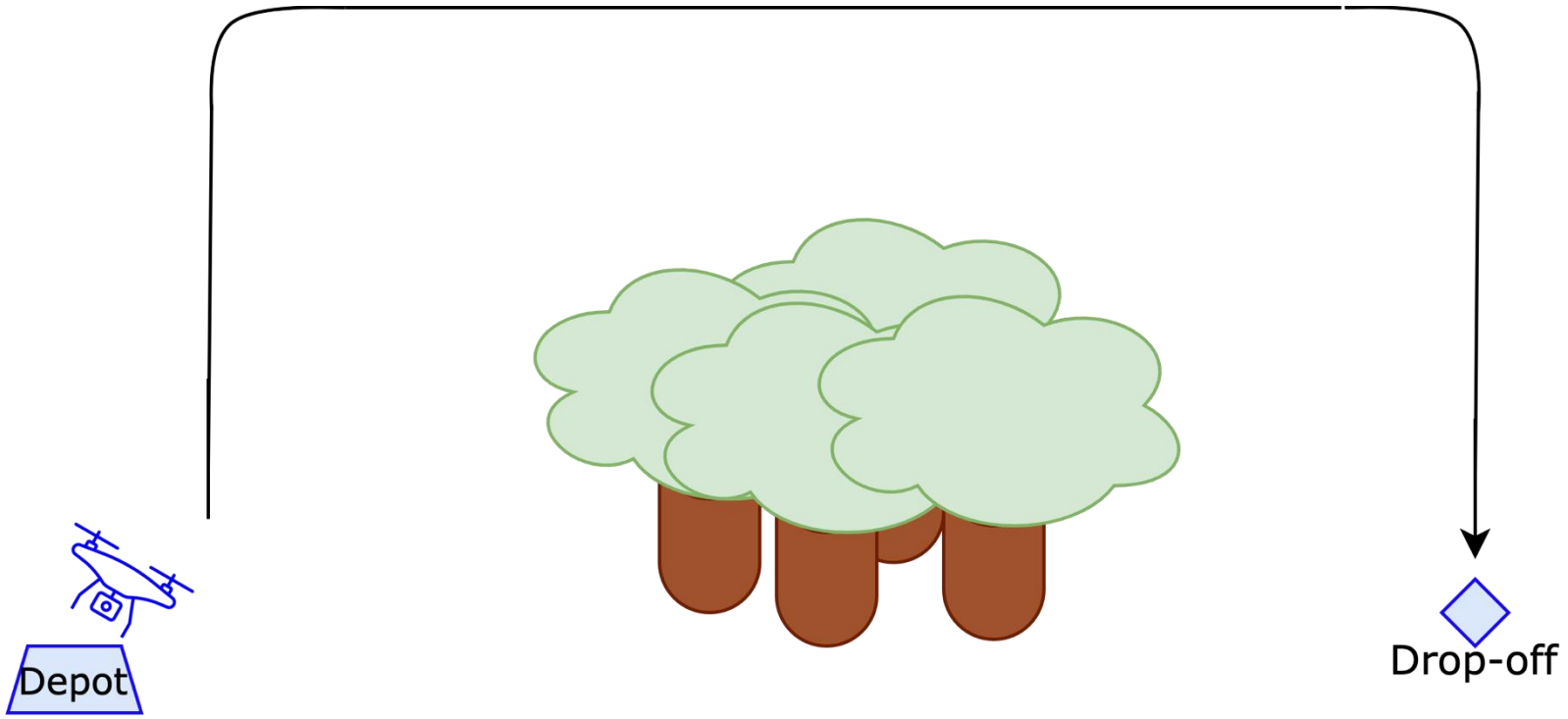
AIAA SciTech Forum 2025

Background – UTM BVLOS

UTM BVLOS

- Trajectory-based operation



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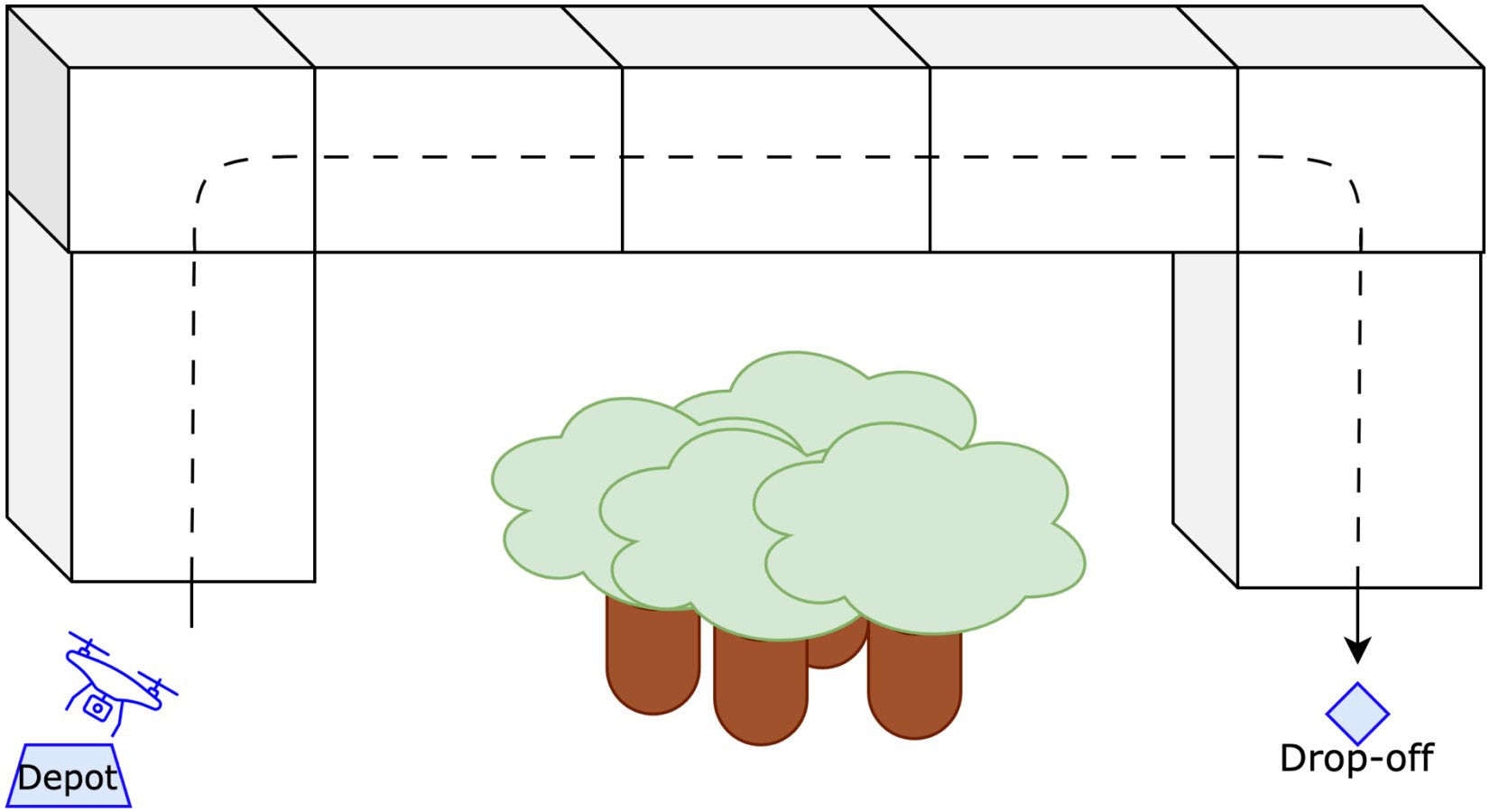
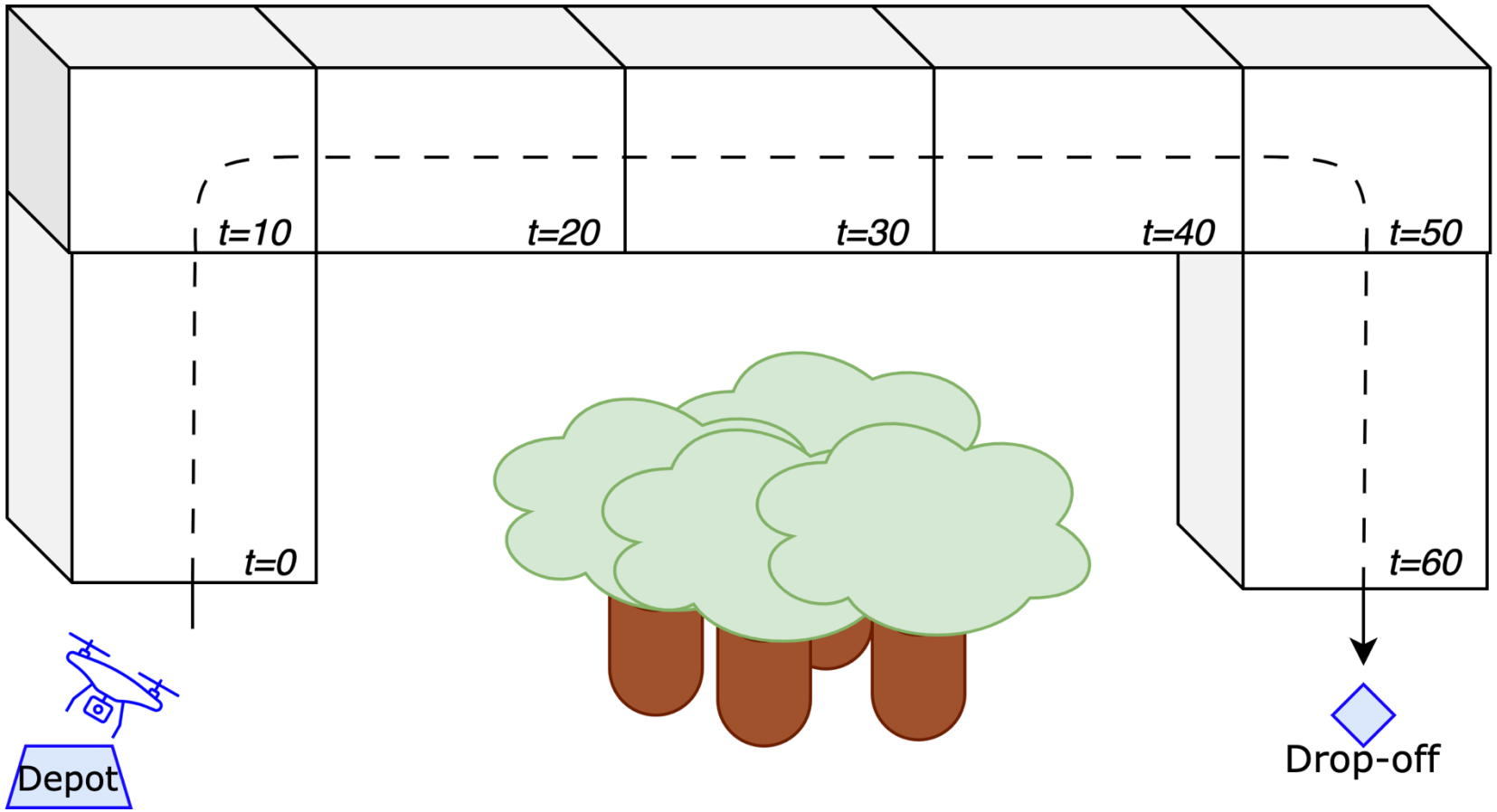
- Trajectory-based operation
- 4D Operational Volume Blocks (OVBs)



Background – UTM BVLOS

UTM BVLOS

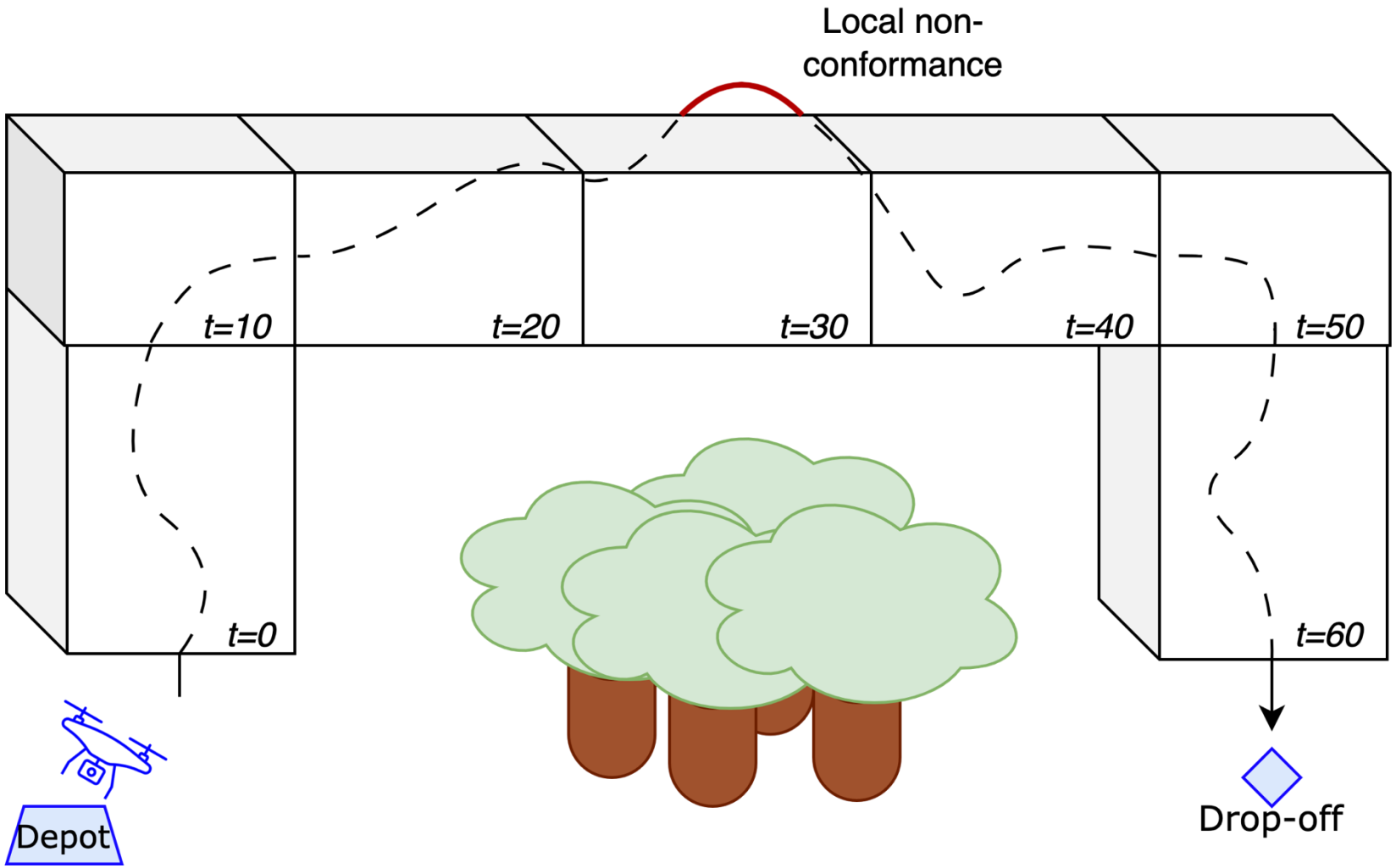
- Trajectory-based operation
- 4D Operational Volume Blocks (OVBs)
- Fixed in space and specified entry and exit times



Background – UTM BVLOS

UTM BVLOS

- Trajectory-based operation
- 4D Operational Volume Blocks (OVBs)
- Fixed in space and specified entry and exit times
- ASTM International: 95% conformance



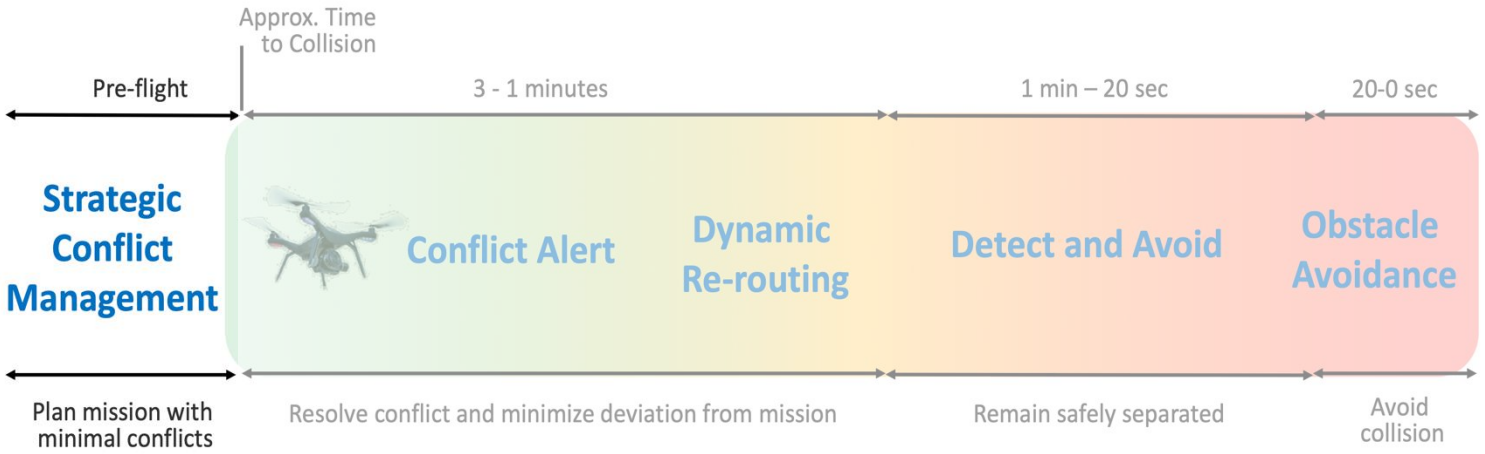
Background – Strategic Deconfliction

UTM BVLOS

- Multi-layer conflict management model

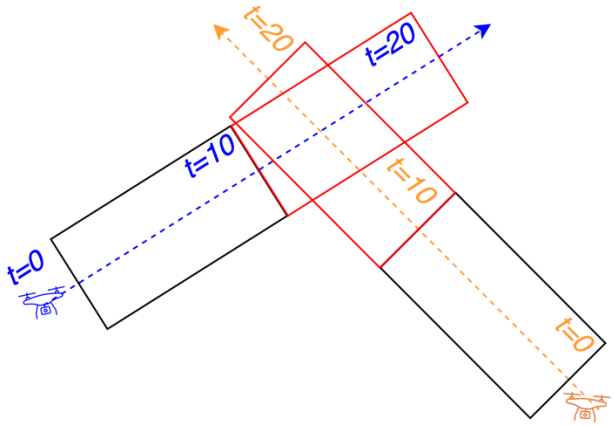
Strategic deconfliction

- Time, Velocity, Altitude, Heading



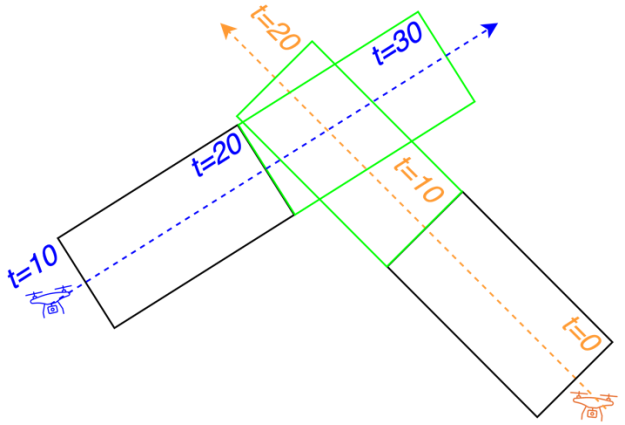
[1]

Conflict scenario



4D overlap

Departure time adjustment



3D overlap - no temporal overlap

* Top-down view of cruise flight phase

Background – Strategic Deconfliction

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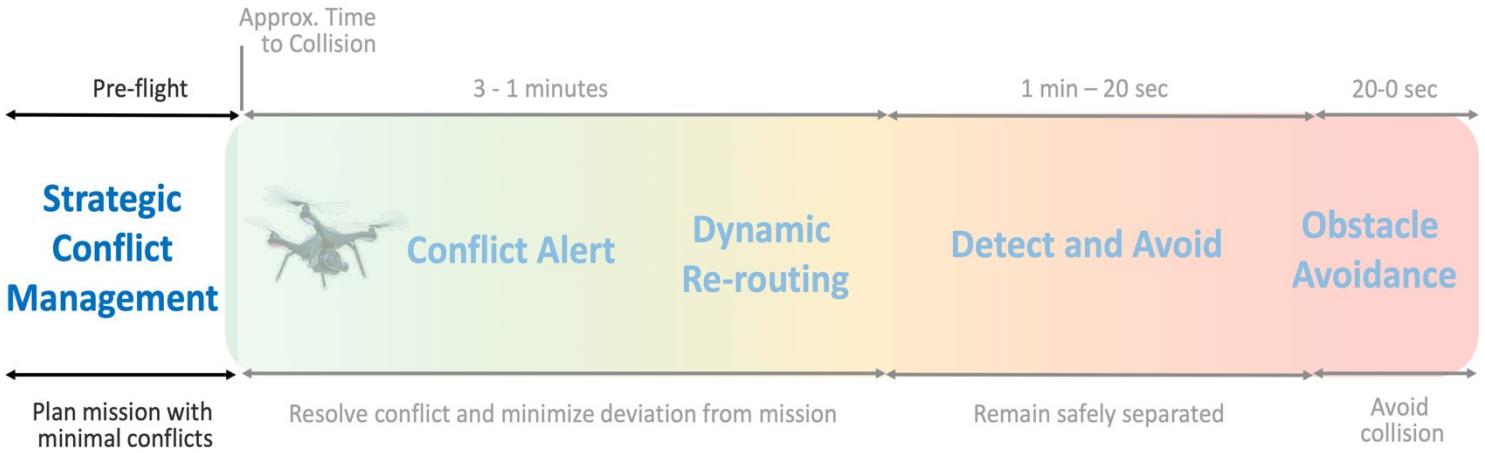
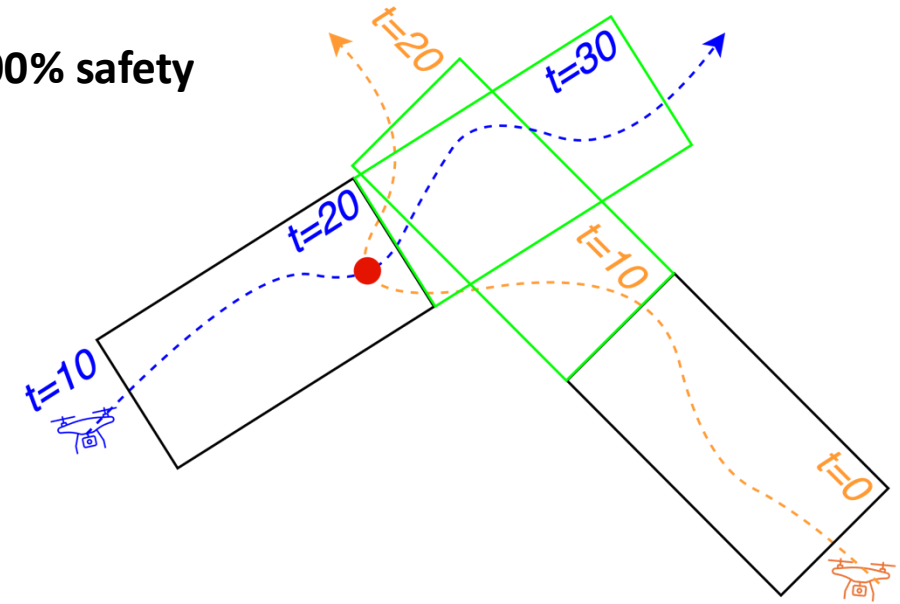


[1]

No overlap ≠ 100% safety



* Top-down view of cruise flight phase

Background – Fix Size Buffer

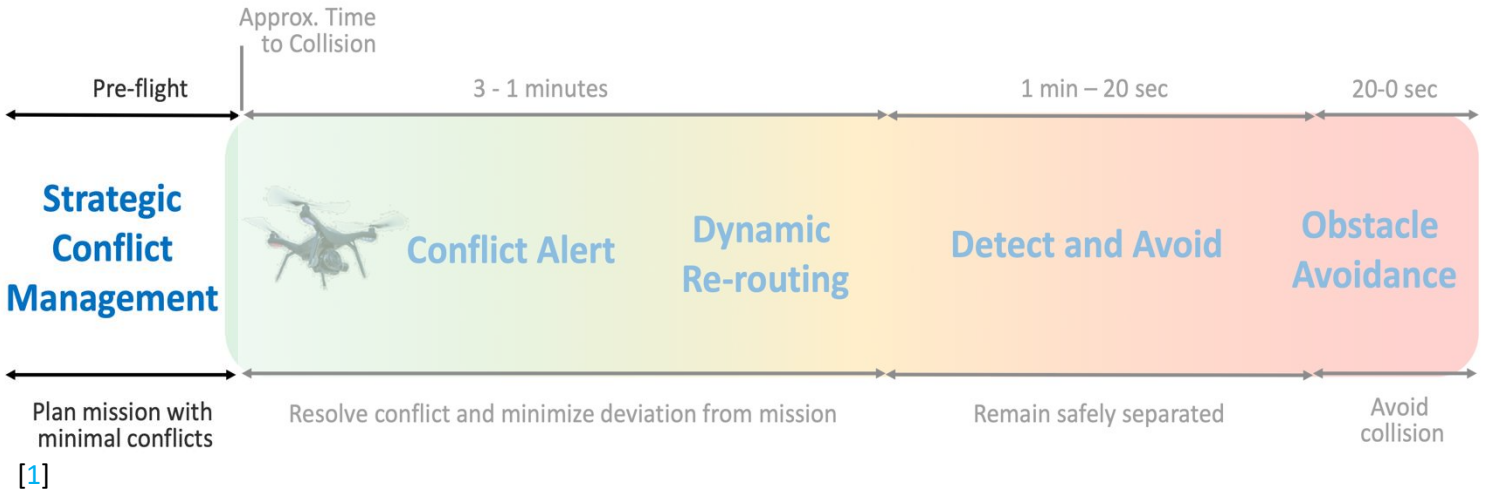
UTM BVLOS

- Multi-layer conflict management model

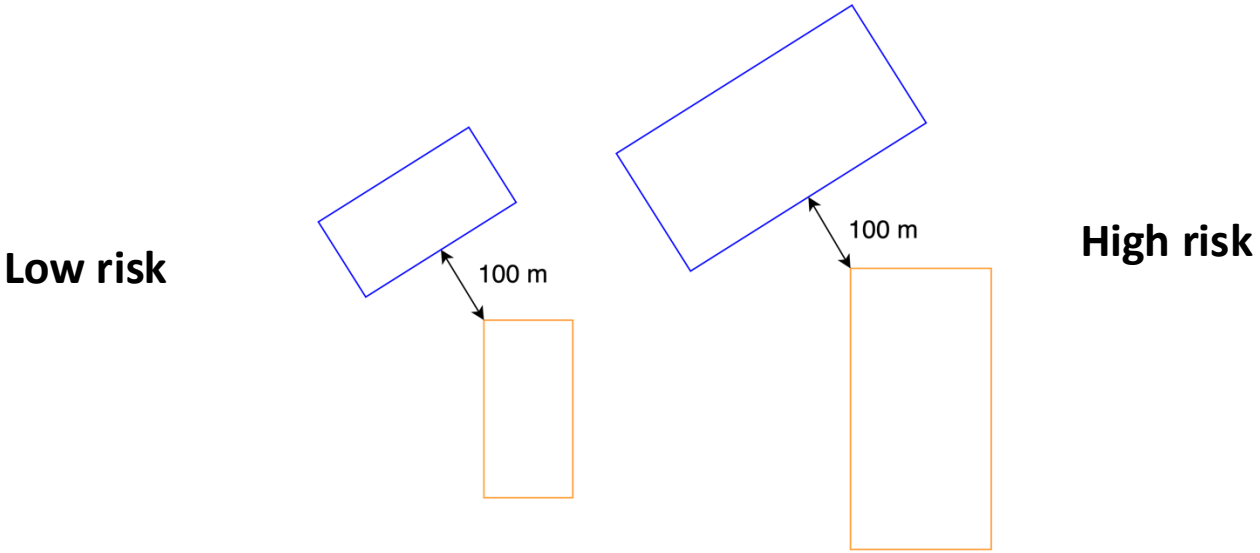
Strategic deconfliction

- Time, Velocity, Altitude, Heading

Fix size buffer



[1]

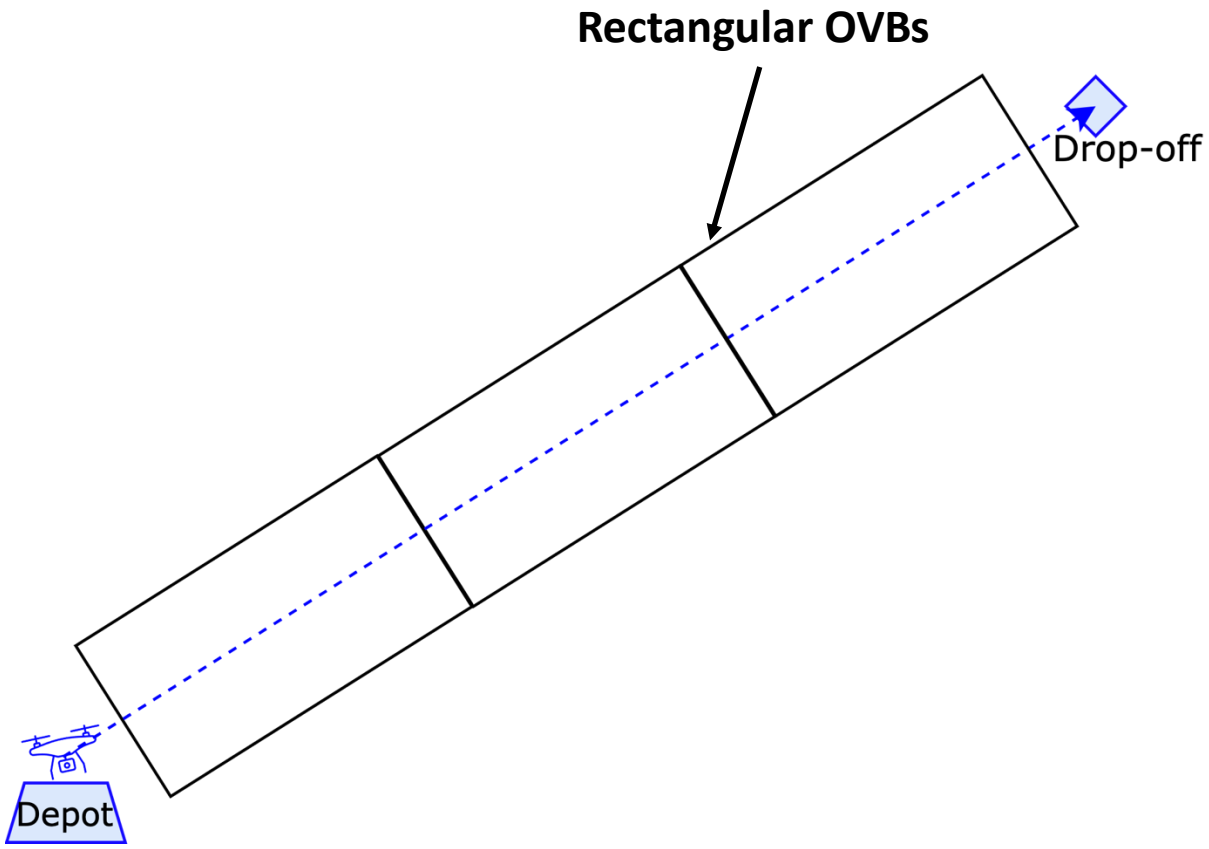


* Top-down view of cruise flight phase

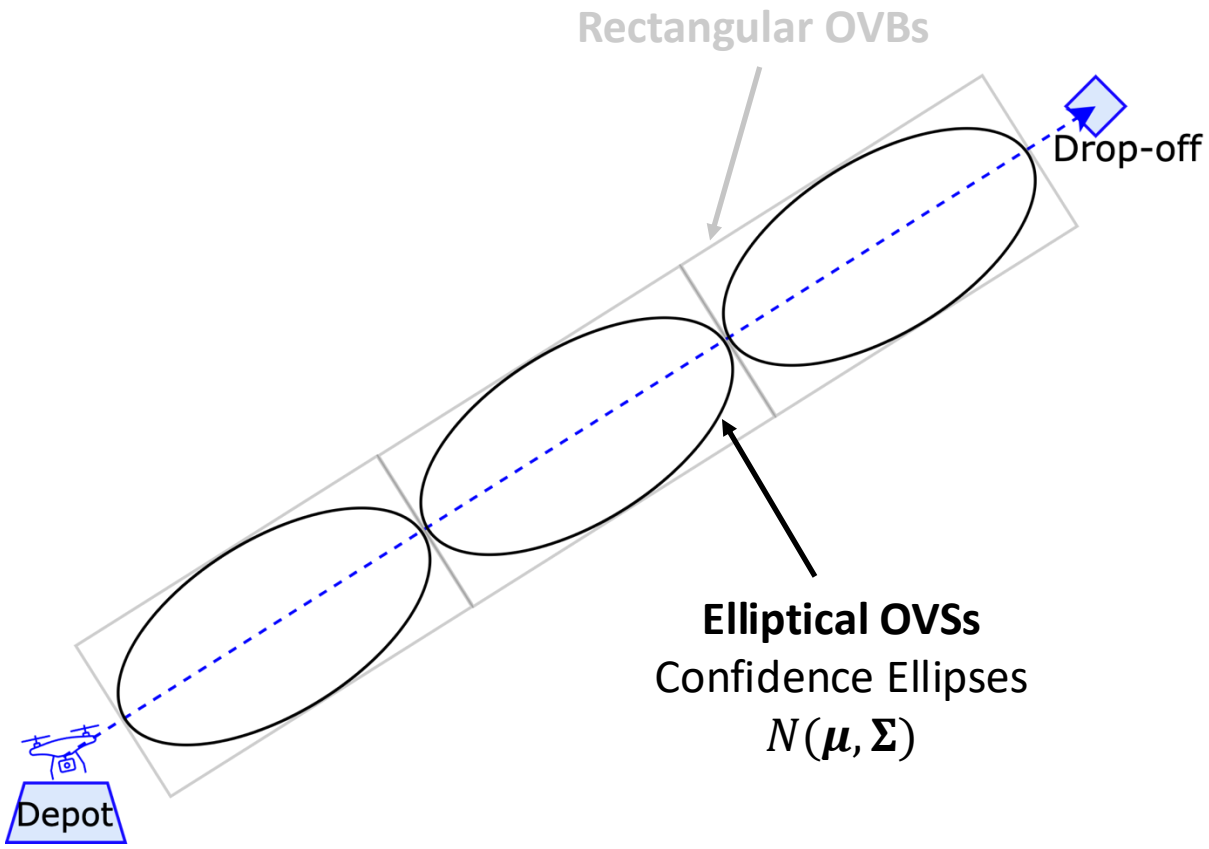
Outline

1. **Paper research contributions**
   - Adaptive buffer 
   - Strategic deconfliction approach 
   - Safety metric 
2. **Simulation scenarios** 
3. **Results** 
4. **Conclusions** 

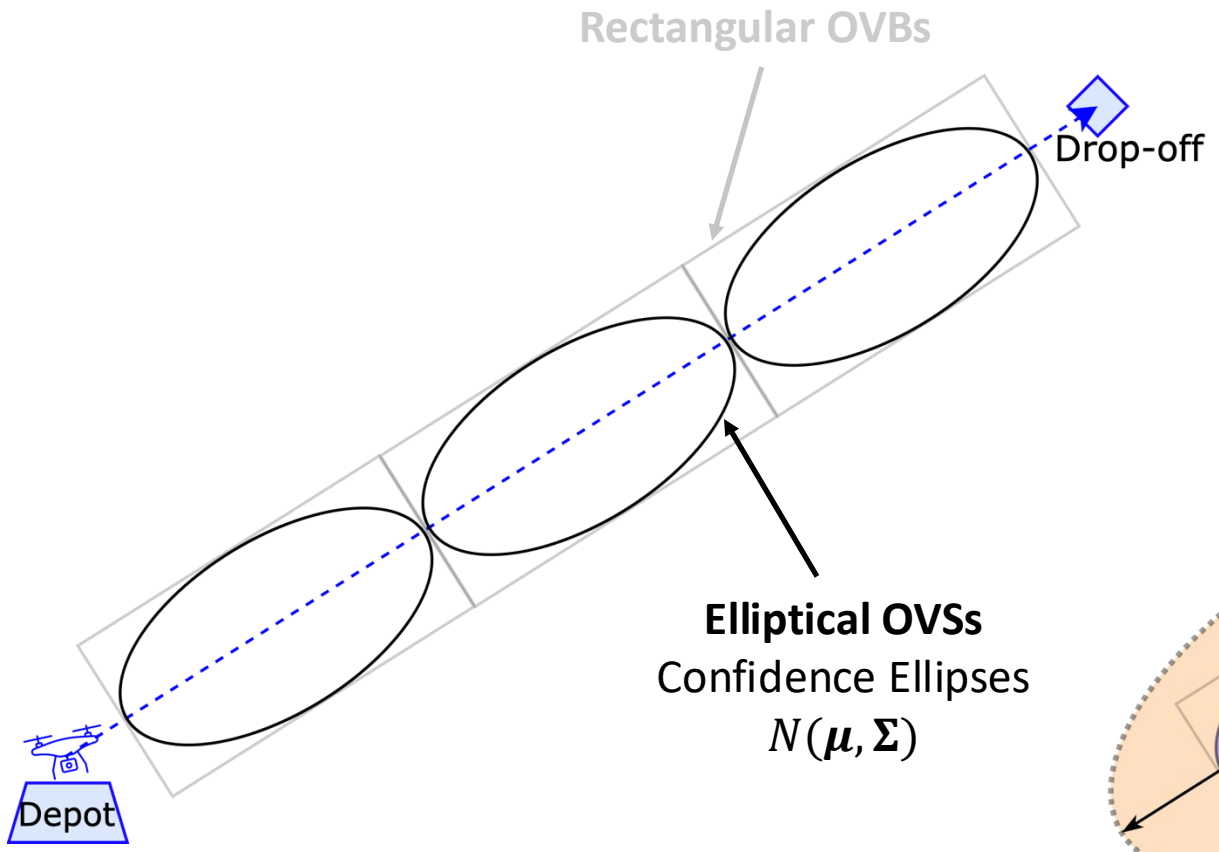
Paper research contributions – Adaptive buffer

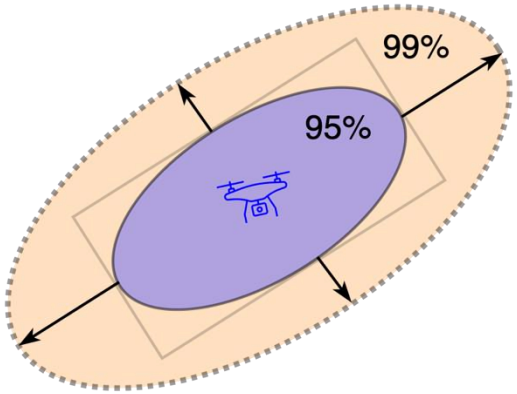


Paper research contributions – Adaptive buffer



Paper research contributions – Adaptive buffer



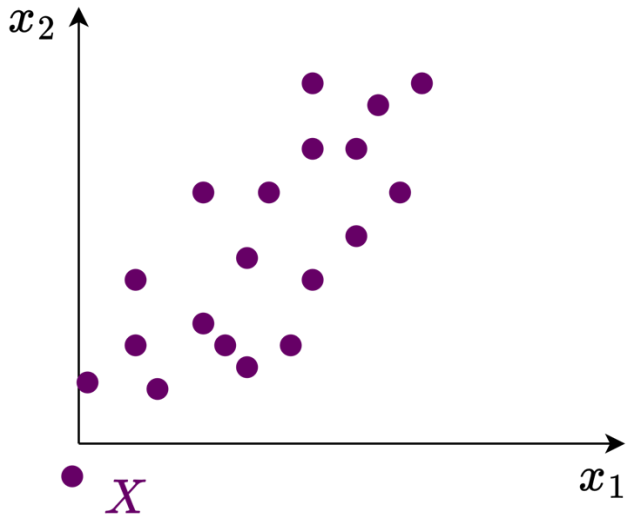


Paper research contributions – Adaptive buffer

Mahalanobis distance

Vehicle position samples

$$\boldsymbol{X} \sim N(\boldsymbol{\mu}, \boldsymbol{\Sigma})$$



Paper research contributions – Adaptive buffer

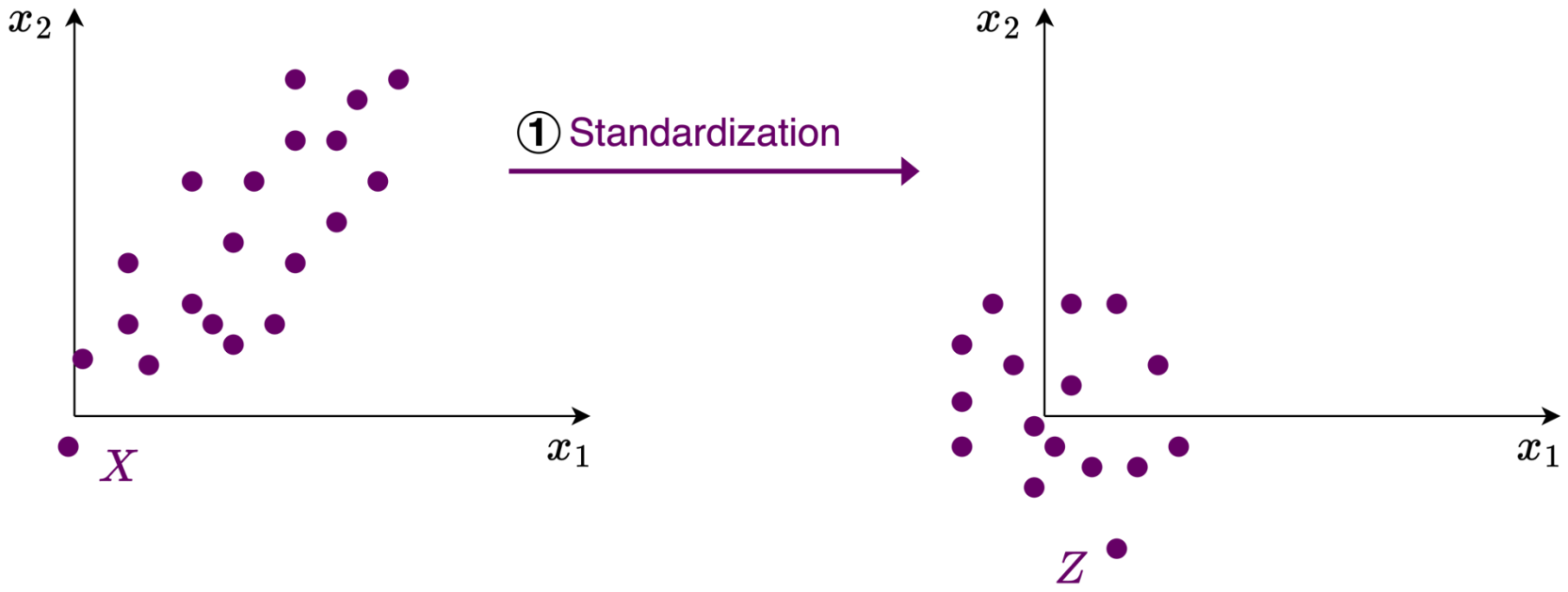
Mahalanobis distance

Vehicle position samples

$$\boldsymbol{X} \sim N(\boldsymbol{\mu}, \boldsymbol{\Sigma})$$

Standardized samples

$$\boldsymbol{Z} = \boldsymbol{\Sigma}^{-0.5}\,(\boldsymbol{X} - \boldsymbol{\mu})$$



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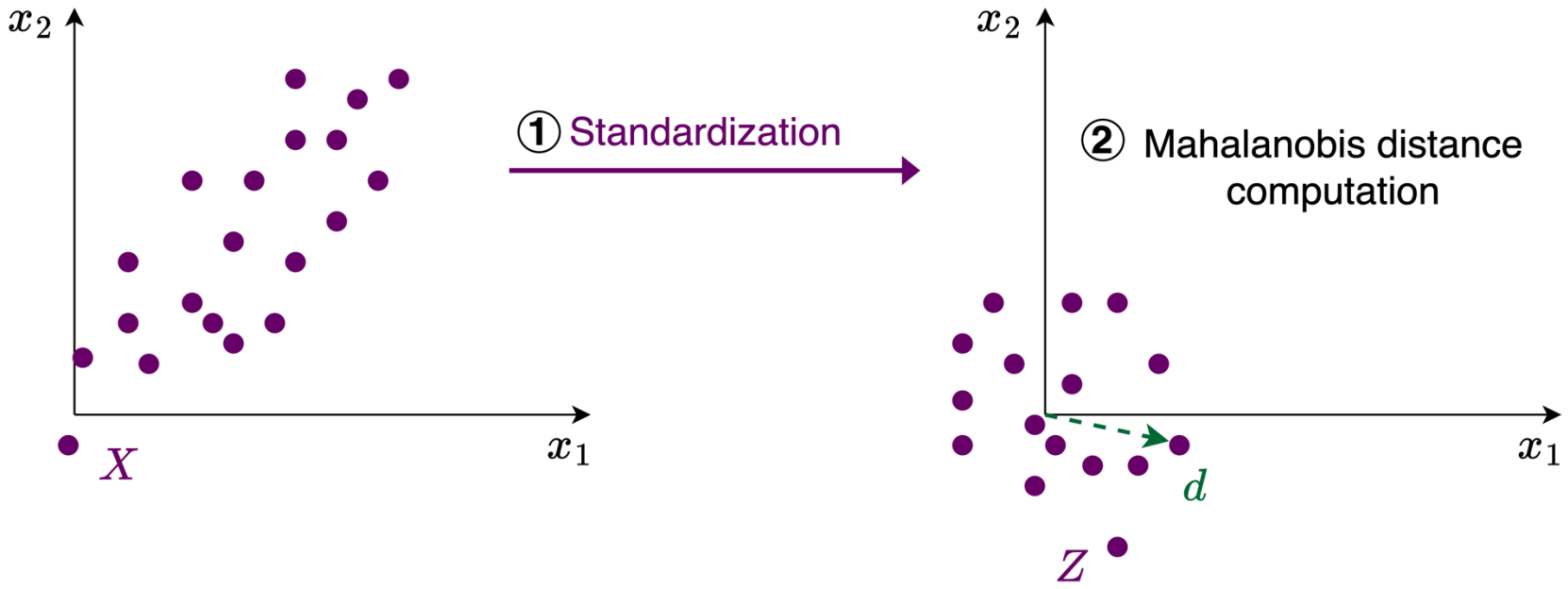
Chi-square distribution

$$\boldsymbol{Z}^T\boldsymbol{Z} = \sum_{i}^{2} Z_i^2 = d^2 \sim \chi_2^2$$



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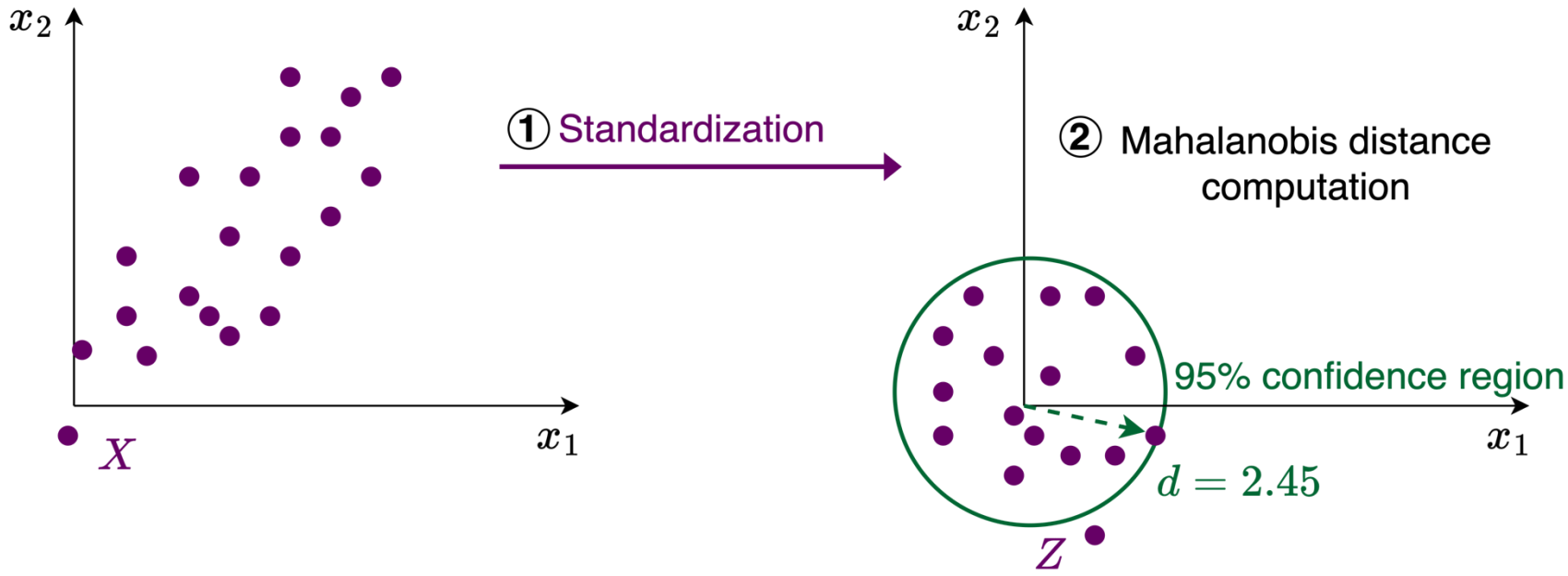
Mahalanobis distance

$$d = \sqrt{(\chi_2^2)^{-1}(0.95)}$$



Paper research contributions – Adaptive buffer

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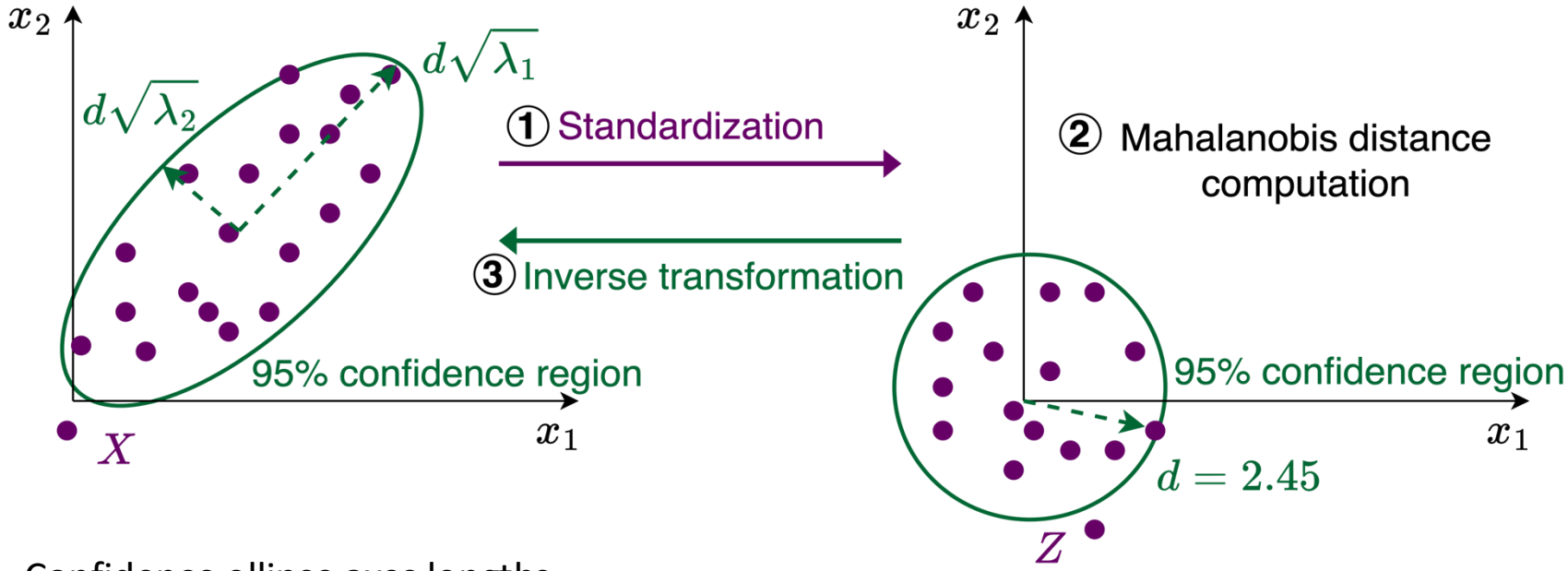


Confidence ellipse axes lengths

$$\begin{bmatrix} a \\ b \end{bmatrix} = d\sqrt{\boldsymbol{\lambda}}$$

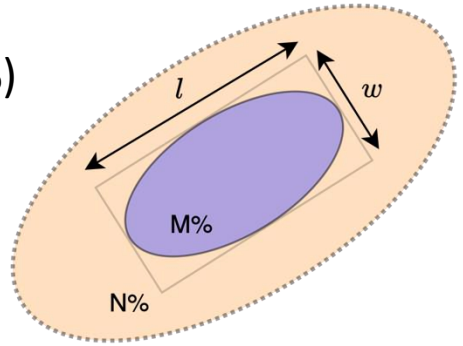
Paper research contributions – Adaptive buffer

Recipe for adaptive buffer (confidence ellipse expansion)

M%: initial confidence level from operator (e.g. 95%)

N%: target confidence level (e.g. 99%)

l, w: rectangular OVB dimensions



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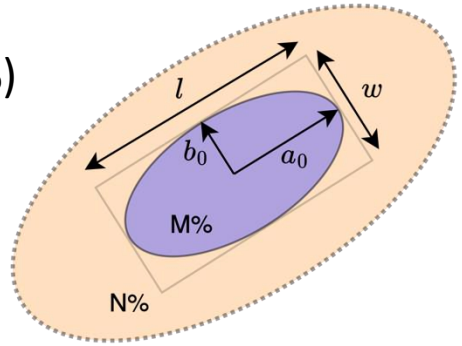

1. Compute axes lengths of OVB inscribed ellipse

1. $\begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} l \\ w \end{bmatrix}$

Paper research contributions – Adaptive buffer

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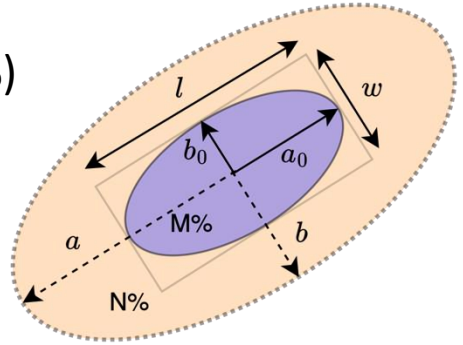


1. Compute axes lengths of OVB inscribed ellipse
2. Compute Mahalanobis distance of the ellipse
3. Compute the Mahalanobis distance of the desired ellipse
4. Compute the axes lengths of expanded ellipse

1. $\begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} l \\ w \end{bmatrix}$

2. $d = \sqrt{(\chi_2^2)^{-1}\left(\frac{N}{100}\right)}$

3. $d_0 = \sqrt{(\chi_2^2)^{-1}\left(\frac{M}{100}\right)}$

4. $\begin{bmatrix} a \\ b \end{bmatrix} = \frac{\boldsymbol{d}}{\boldsymbol{d_0}} \begin{bmatrix} a_0 \\ b_0 \end{bmatrix}$

Paper research contributions – SD approach

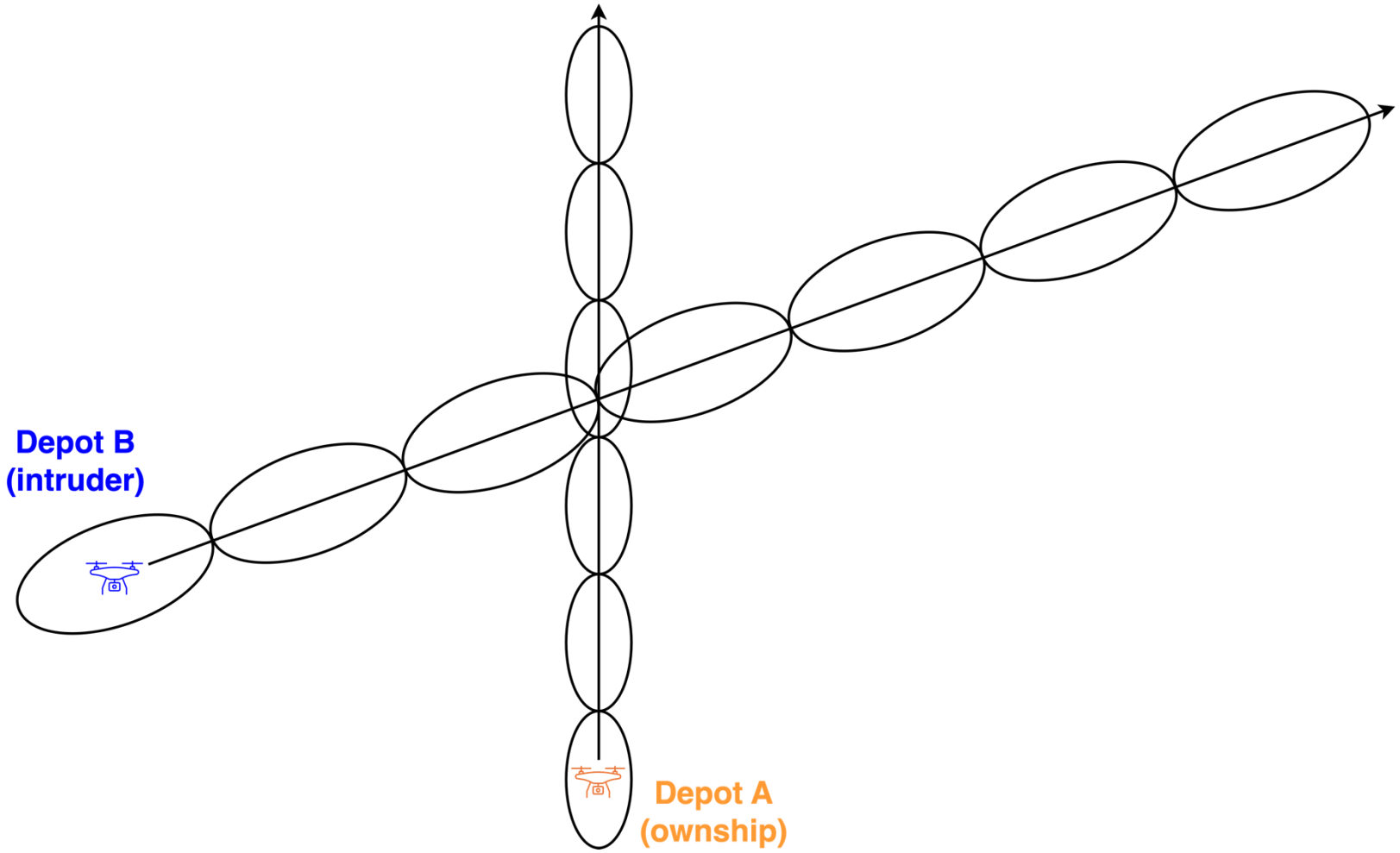
Rolling Horizon with K-Position Search

- Mixed Integer Linear Programming formulation
- Objective function: minimize total ground delay
- Constraints:
  - Departure temporal separation
  - Crossing waypoints temporal separation

Modification: deconfliction of ellipses instead of rectangles

Paper research contributions – SD approach

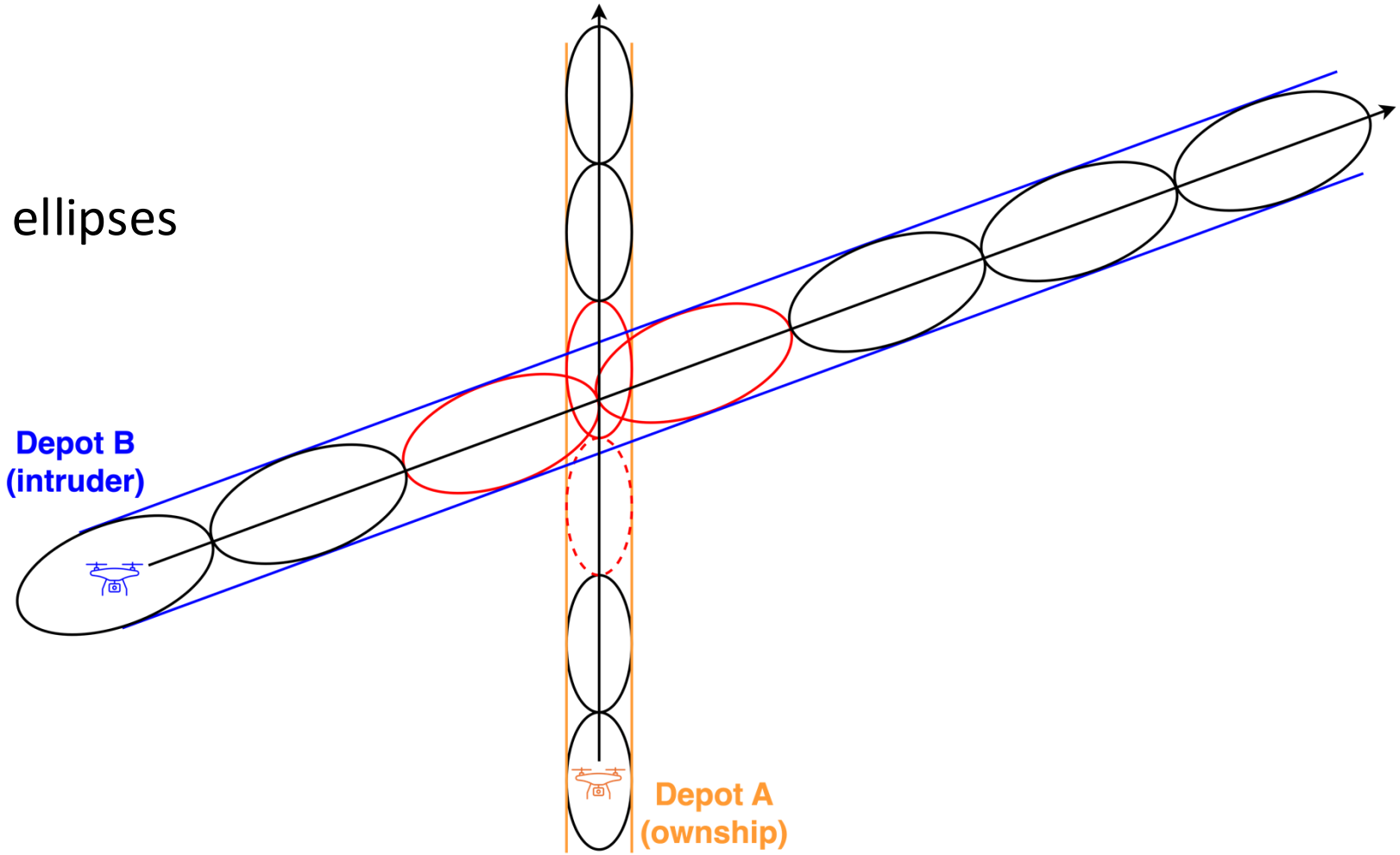
SD modification



Paper research contributions – SD approach

SD modification

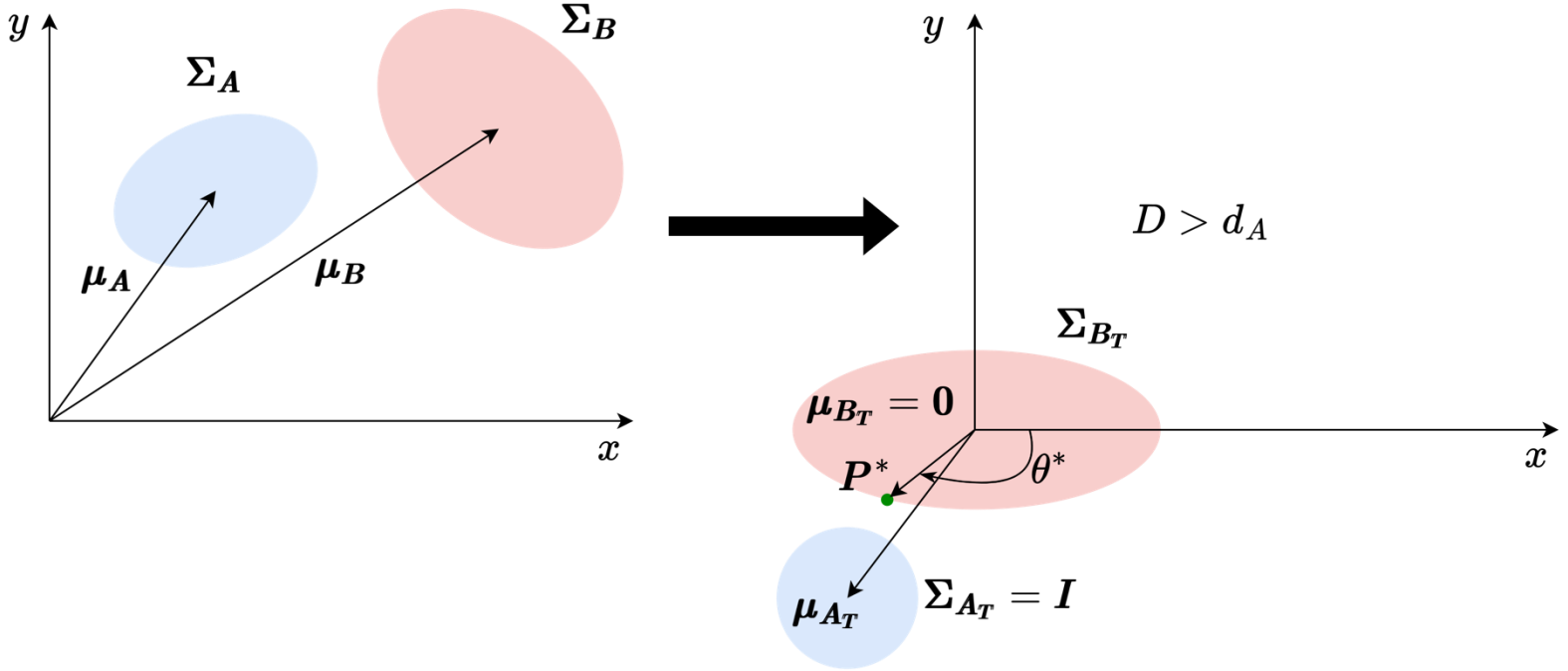
- Heuristic to discard ellipses



Paper research contributions – SD approach

SD modification

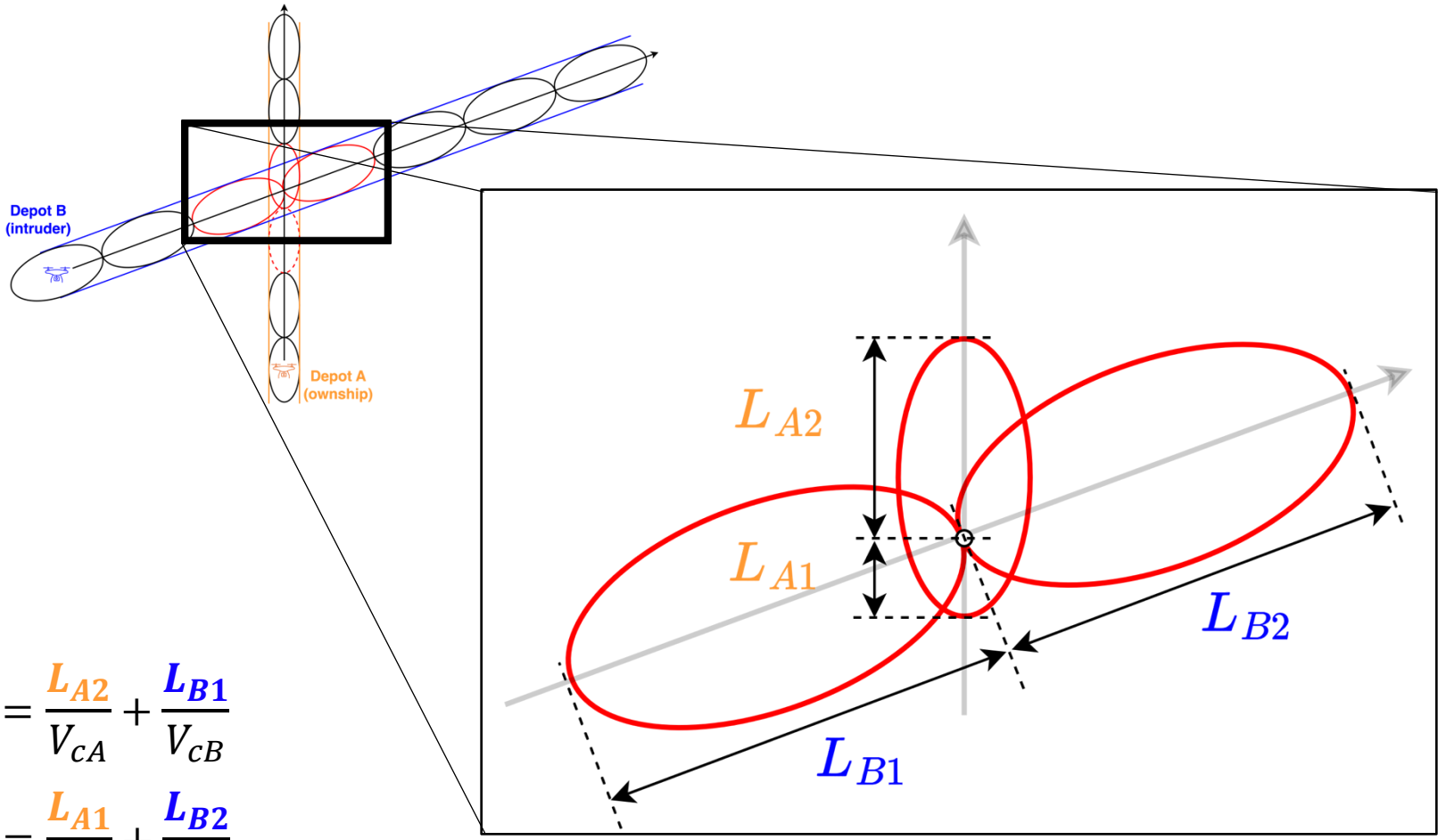
- Heuristic to discard ellipses
- Check intersection for candidate ellipses



Paper research contributions – SD approach

SD modification

- Heuristic to discard ellipses
- Check intersection for candidate ellipses
- Compute temporal separation between ellipses at intersections

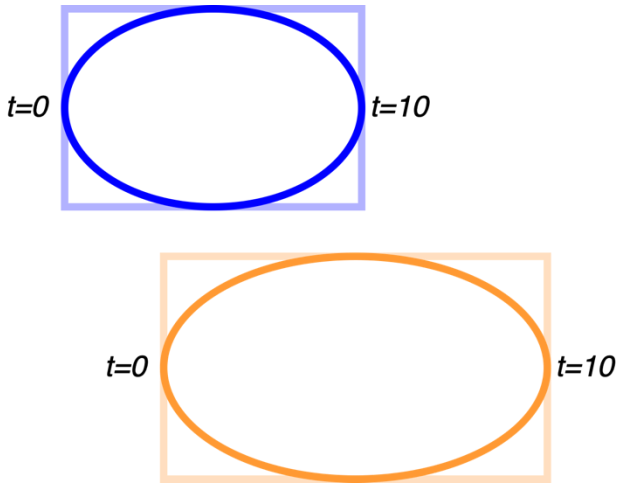


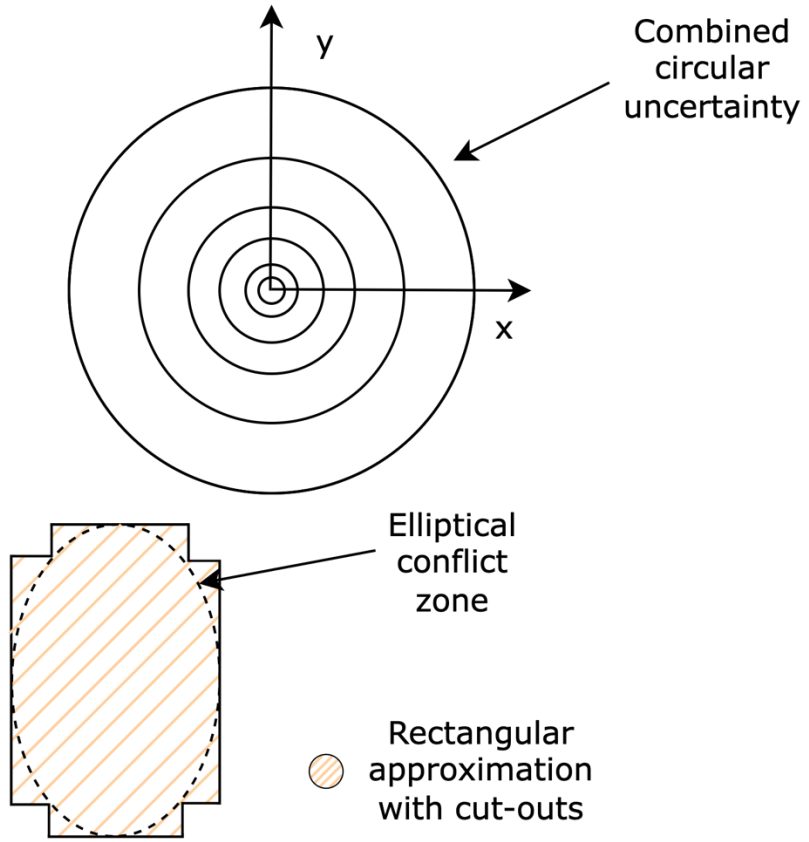
$$\begin{cases} \Delta t_A = \dfrac{L_{A2}}{V_{cA}} + \dfrac{L_{B1}}{V_{cB}} \\ \Delta t_B = \dfrac{L_{A1}}{V_{cA}} + \dfrac{L_{B2}}{V_{cB}} \end{cases}$$

Paper research contributions – Safety metric

- **Hwang's method**: 1-to-1 ellipse perfect temporal overlap

Probability of NMAC between ellipses
$P_{\alpha i,\beta j}$



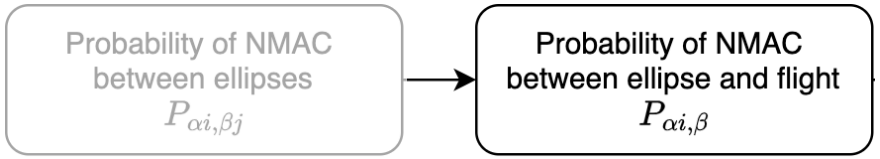


[2]

NMAC: Near Mid-Air Collision

Paper research contributions – Safety metric

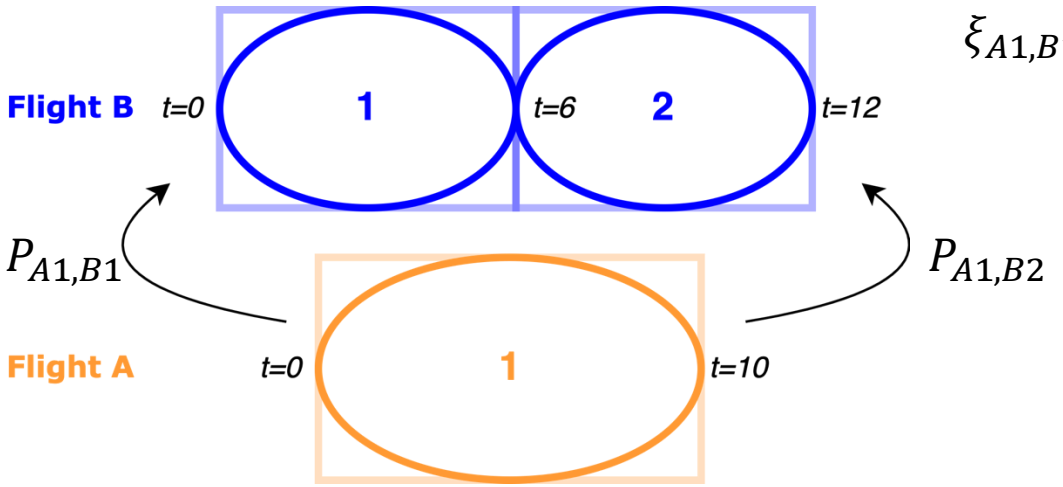
- **Hwang's method**: 1-to-1 ellipse perfect temporal overlap



- **Time weighted average:** 1-to-many overlap

$$P_{A1,B} = \xi_{A1,B1} \cdot P_{A1,B1} + \xi_{A1,B2} \cdot P_{A1,B2} = \sum_{j=1}^{n_B} \xi_{A1,Bj} \cdot P_{A1,Bj}$$

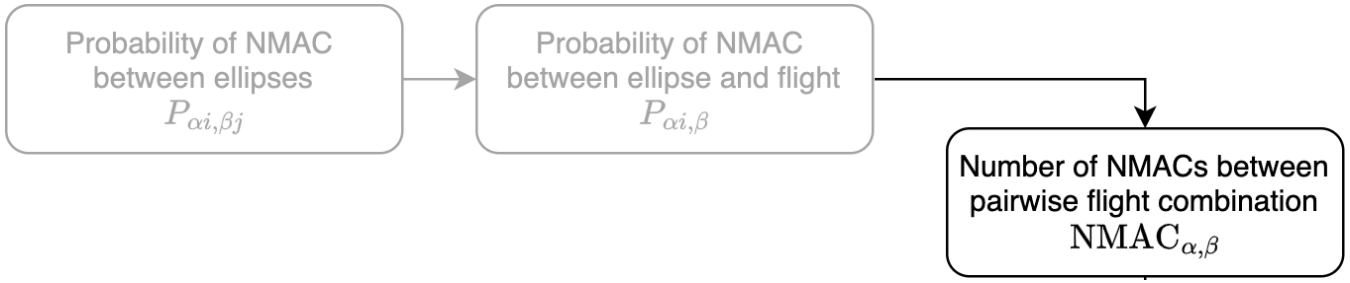
$$\xi_{A1,B1} = \frac{6}{10} \qquad \xi_{A1,B2} = \frac{4}{10}$$

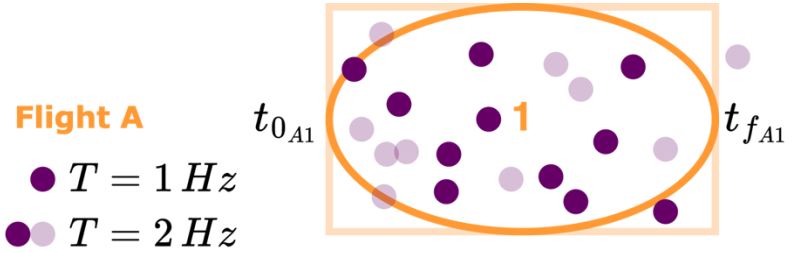


NMAC: Near Mid-Air Collision

Paper research contributions – Safety metric

- **Hwang's method**: 1-to-1 ellipse perfect temporal overlap
- **Time weighted average:** 1-to-many overlap
- **Sampling frequency**: conversion from probability to number of NMAC





$$NMAC_{AB} = \sum_{i=1}^{n_A} P_{A1,B} \cdot N_{Ai}$$

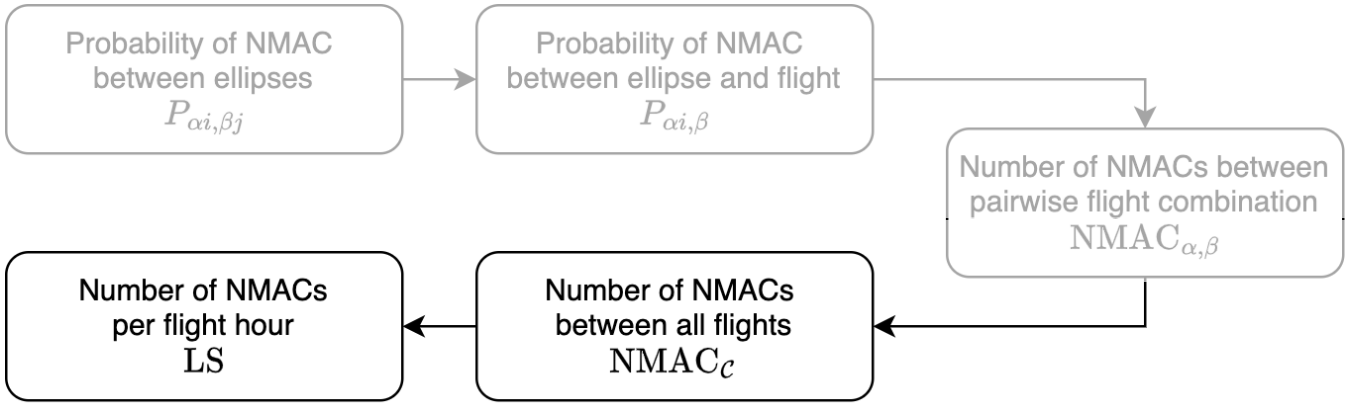
$$N_{Ai} = \frac{t_{f_{Ai}} - t_{0_{Ai}}}{T}$$

$$N_{A1} = \frac{10 - 0}{2} = 5$$

NMAC: Near Mid-Air Collision

Paper research contributions – Safety metric

- **Hwang's method**: 1-to-1 ellipse perfect temporal overlap
- **Time weighted average:** 1-to-many overlap
- **Sampling frequency**: conversion from probability to number of NMAC
- **# NMAC per flight hour**: Level of Safety (LS)
- **Average ground delay**



$$NMAC_{AB} = \sum_{i=1}^{n_A} P_{A1,B} \cdot N_{Ai}$$

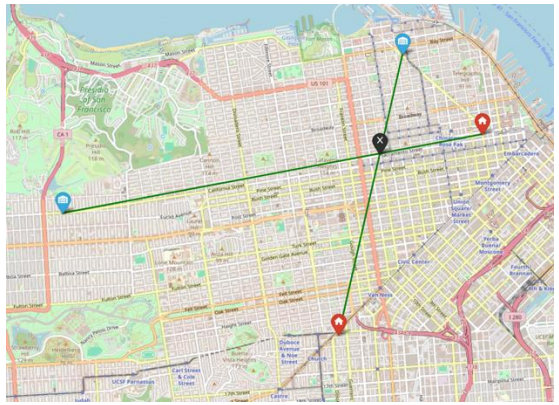
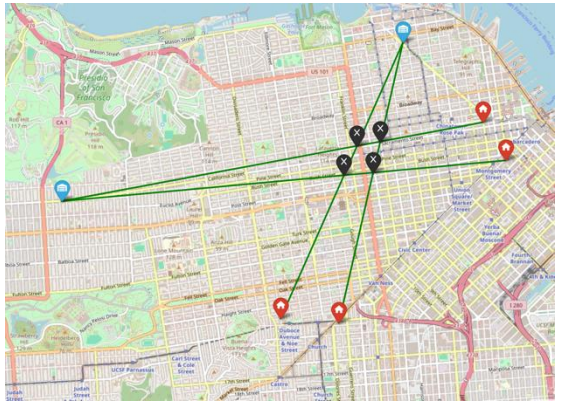
$$NMAC_C = \sum_{(f_A, f_B) \in C} NMAC_{A,B}$$

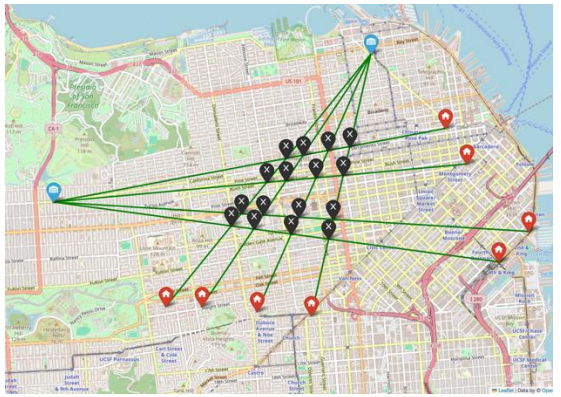
$$\boldsymbol{GD} = \frac{1}{n_f} \sum_{f \in \mathcal{F}} Dep(f) - Req(f)$$

$$\boldsymbol{LS} = \frac{NMAC_C}{\sum_{f \in \mathcal{F}} Arr(f) - Dep(f)}$$

Simulation scenarios

Increasing Complexity

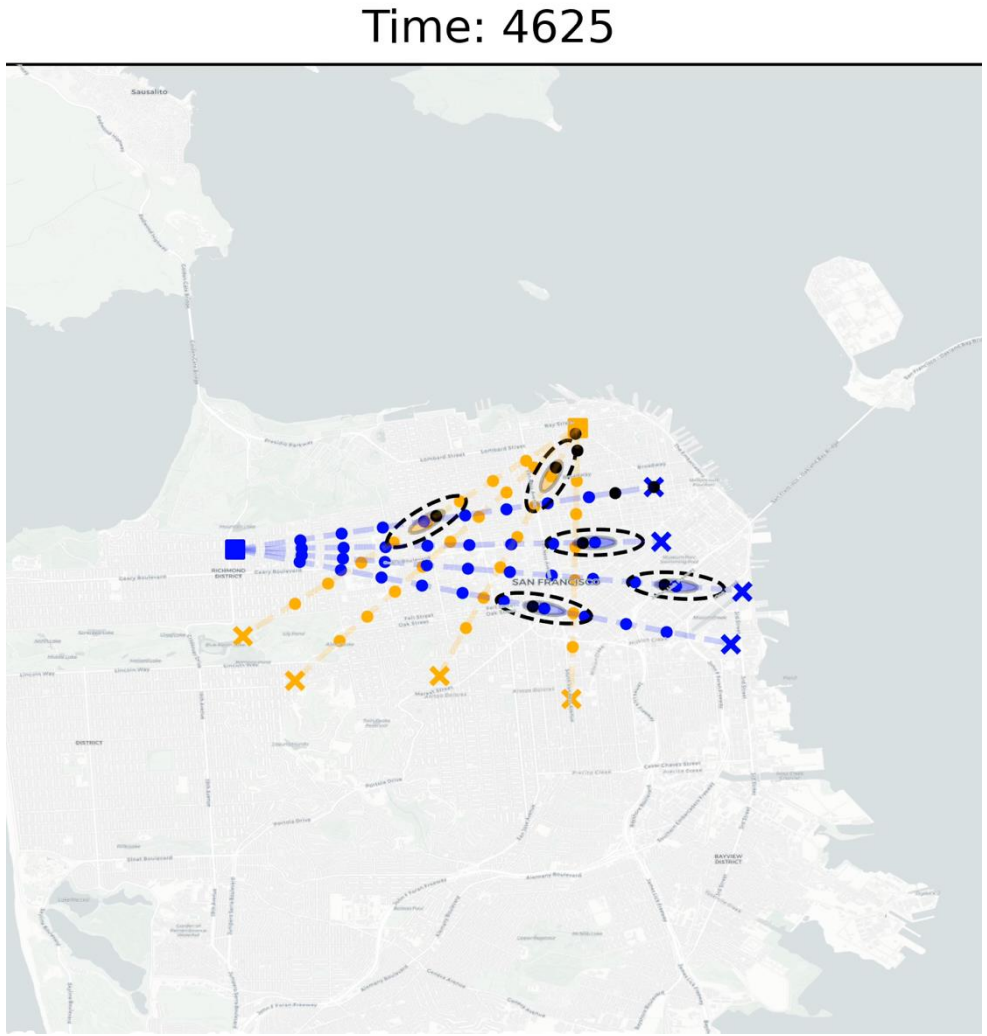





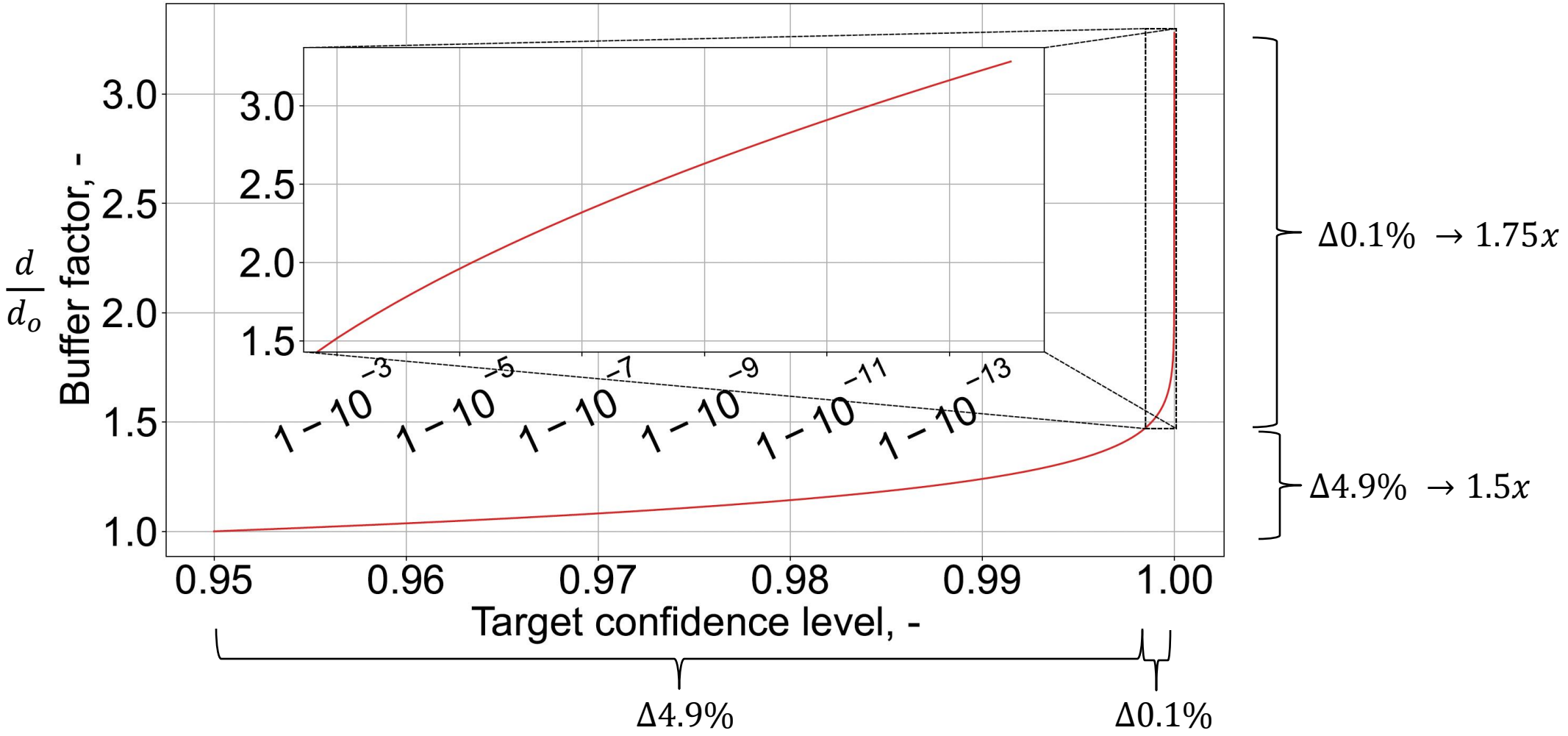
[3]

Parameter	Values	Parameter	Values
Number of flights per route	10 [-]	Loss of Separation radius (NMAC)	42.5 [m]
Poisson demand rate	60^{-1} [s^{-1}]	OVB length and width	600 [m] and 200 [m]

Simulation scenarios

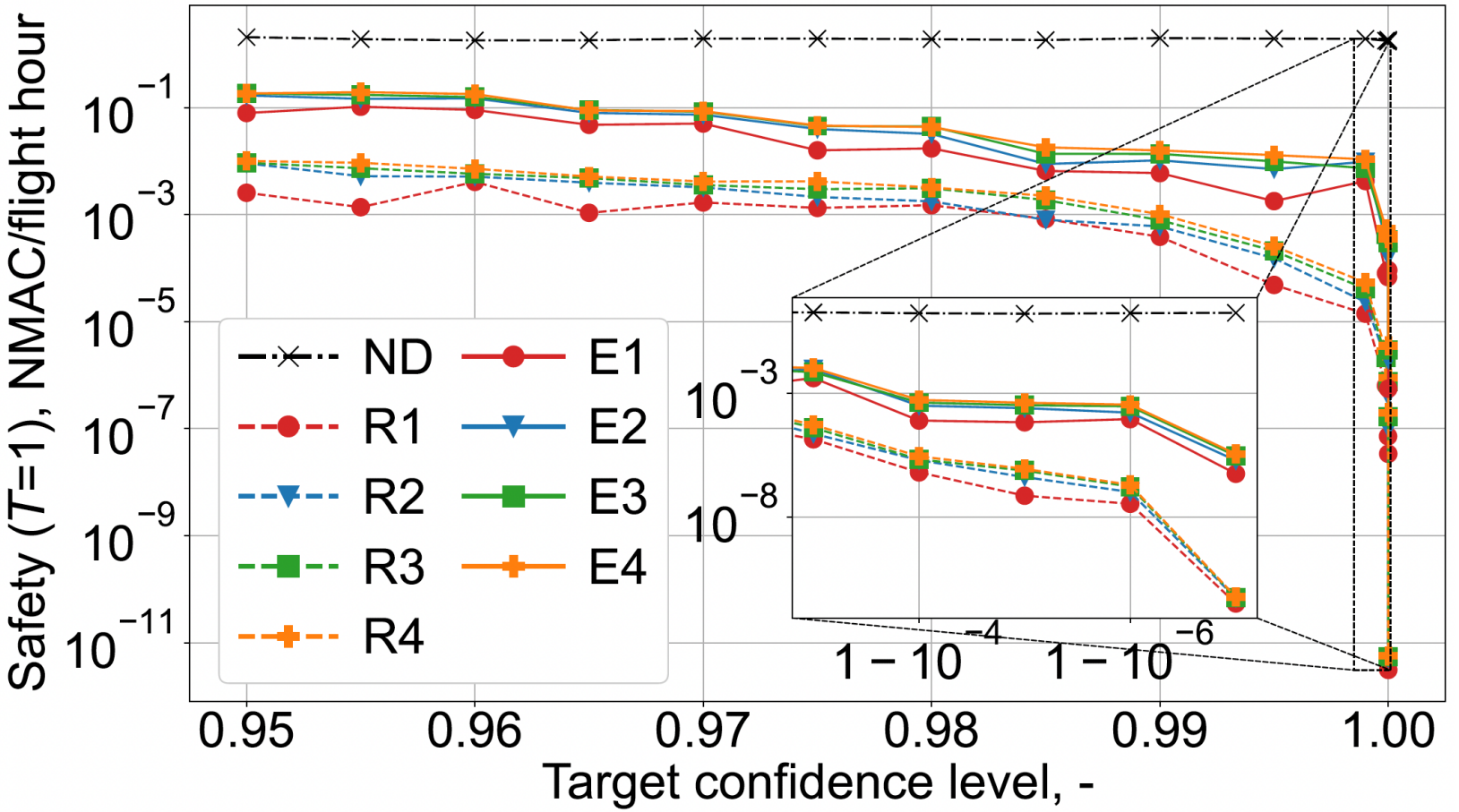


Results: buffer factor



Results: safety

1. **No deconfliction:** highest risk
2. **Complexity**
3. **Buffer**
4. **Geometry**

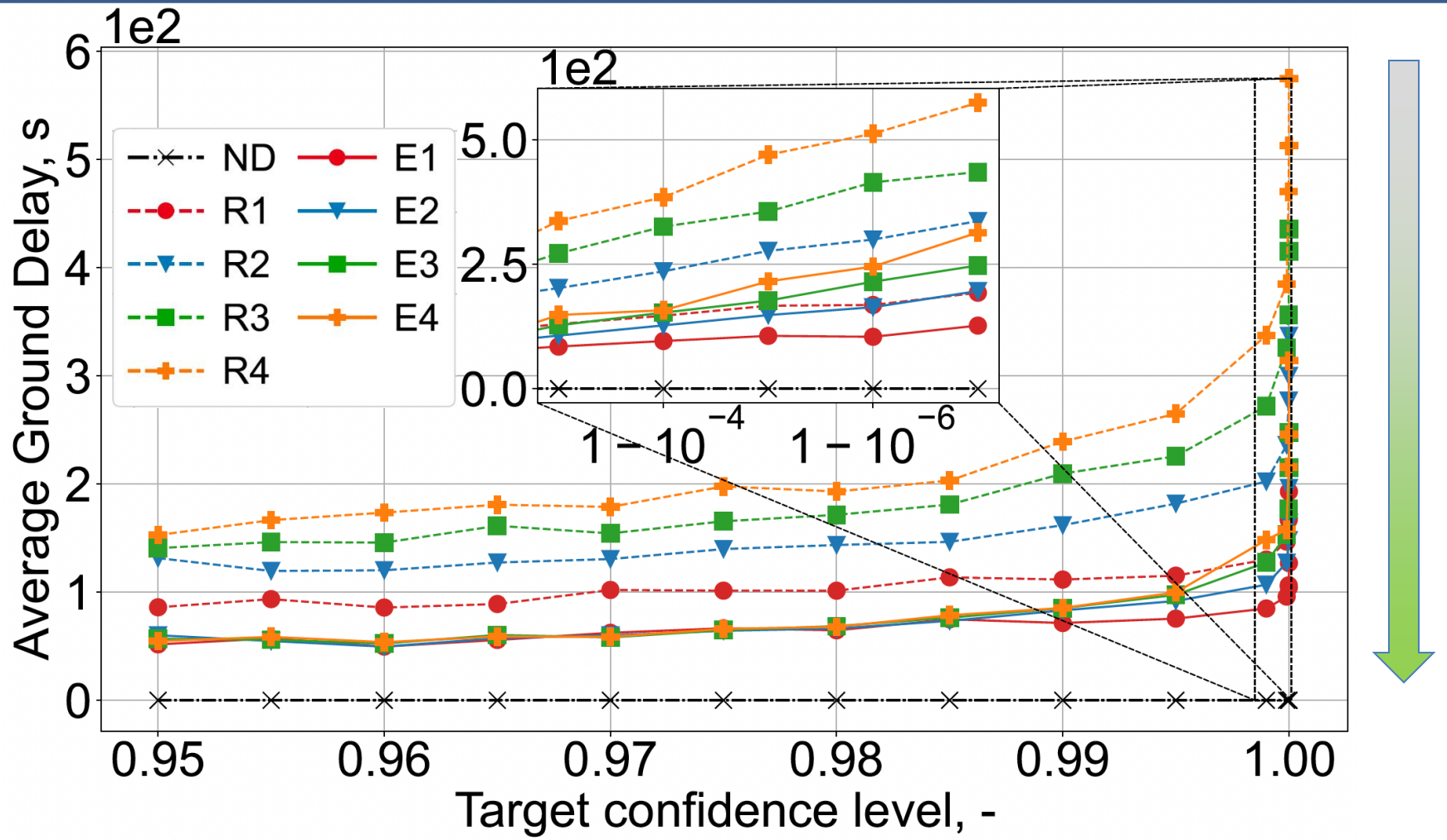


Increasing Safety

ND: No Deconfliction – **R**: Rectangle – **E**: Ellipse

Results: efficiency

1. **No deconfliction:** no delay
2. **Complexity**
3. **Buffer**
4. **Geometry**



Increasing efficiency

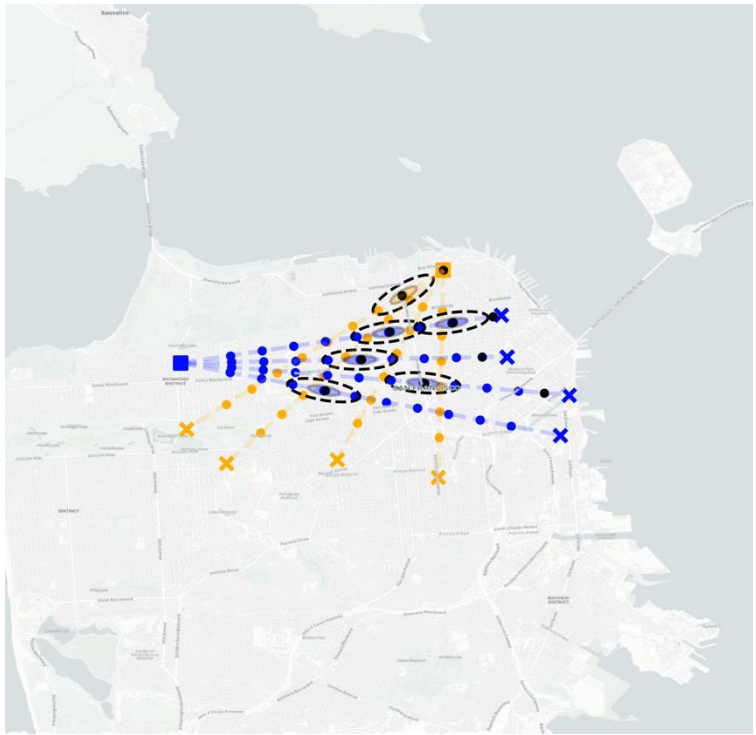
ND: No Deconfliction – **R**: Rectangle – **E**: Ellipse

Conclusions

- **Adaptive buffer** with **confidence level** as input
- New flavor of Rolling Horizon K-Position search strategic deconfliction approach with **accurate temporal separation** for **elliptical OVBs**
- **Safety metric** for risk estimation even without OVB overlap

- Outlook: safety metric + TLS ➞ confidence level requirement definition

Thanks for your attention!



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References

[1] NASA UTM technical interchange meeting 2021

[2] Hwang, I., and Seah, C. E., “Intent-Based Probabilistic Conflict Detection for the Next Generation Air Transportation System,” Proceedings of the IEEE, Vol. 96, No. 12, 2008, pp. 2040–2059. doi:10.1109/JPROC.2008.2006138.

[3] Pradeep, P., Yarramreddy, G. S., Amirsoleimani, N., Munishkin, A. A., Morris, R. A., Xue, M., Kalyanam, K. M., and Chour, K., “Rolling Horizon with K-Position Search Method for Strategic Deconfliction of Package Delivery UAS,” AIAA AVIATION Forum and ASCEND 2024, 2024. https://doi.org/10.2514/6.2024-4456.