Fe^3 – A Monte Carlo Simulation Capability for Evaluation of New Air Traffic Management Concepts

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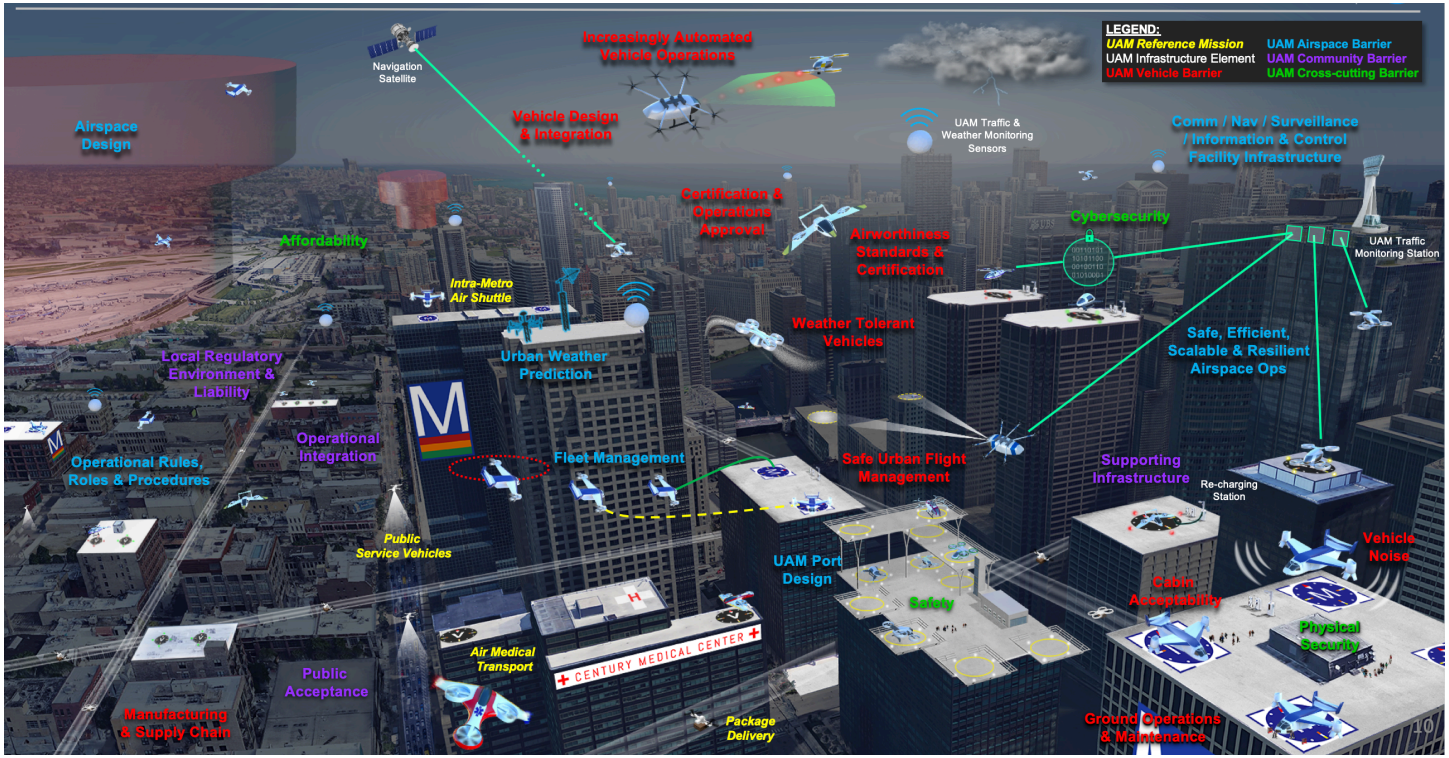
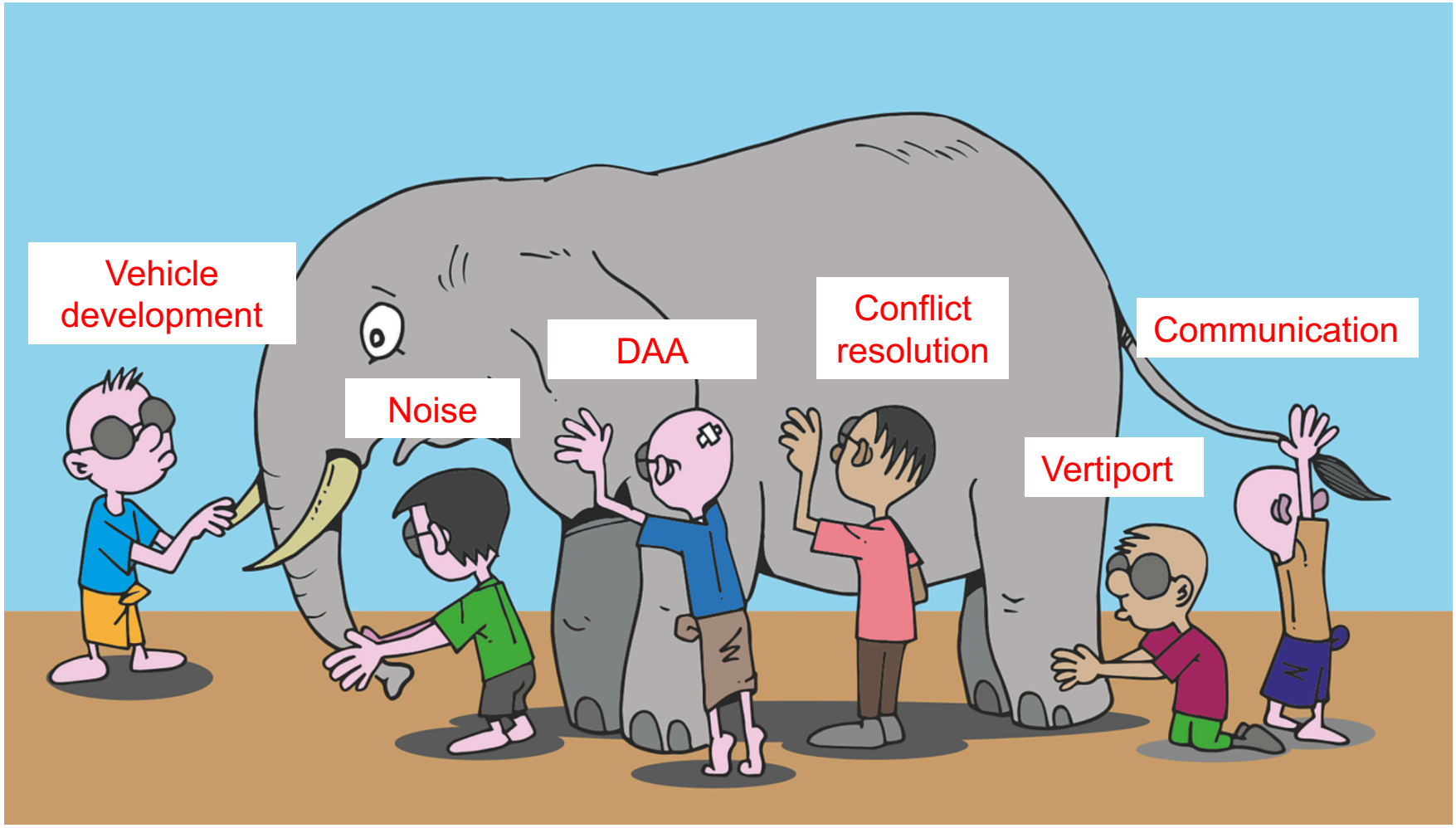
Challenges in evaluating new concepts



- **Density:**
  ATM: ~0.004/nmi^2; UAM: >50/nmi^2
- Autonomous airspace system
- **Urban environment**
- Low Altitude Wind

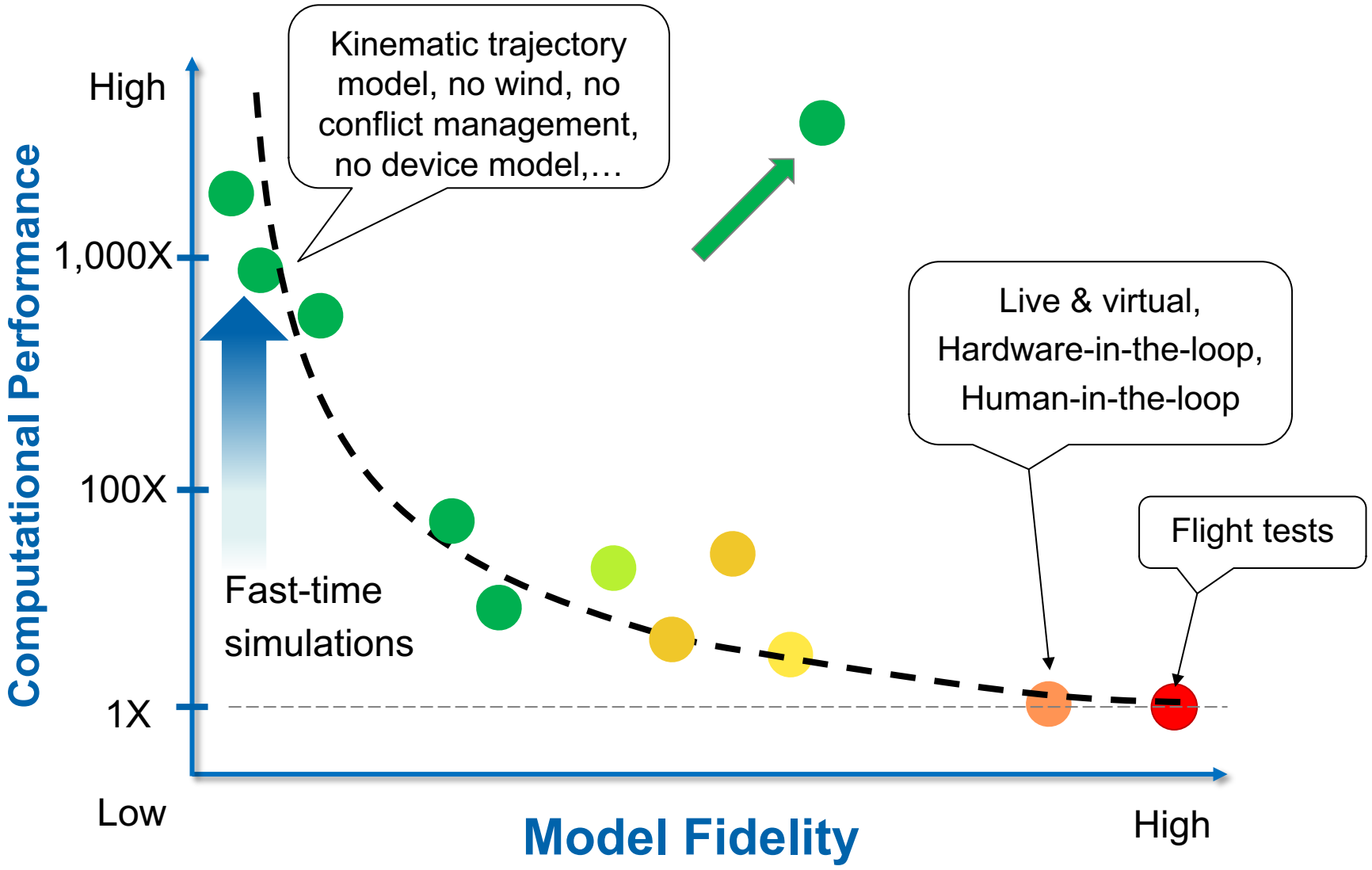
- Communication, navigation, surveillance
- Energy/battery
- Noise
- Interaction with ATM
- …

System integration



Parable of the “**blind men and an elephant**”

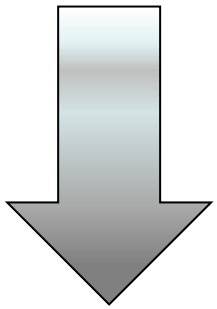
Levels of simulations for air traffic system



Simulations for UAM traffic system research

Monte Carlo Simulations (1,000x)

- Fidelity: high (e.g. error <1-3%)
- Speed: >100x
- Uncertainty study using statistics
- Comprehensive trade space studies
- Explore even more scenarios and help select scenarios for further investigation



Live & Virtual Simulations (1x)

- Fidelity: super high, HITL
- Speed: 1x
- Expensive: only for a few scenarios
- Good for validation

Outline

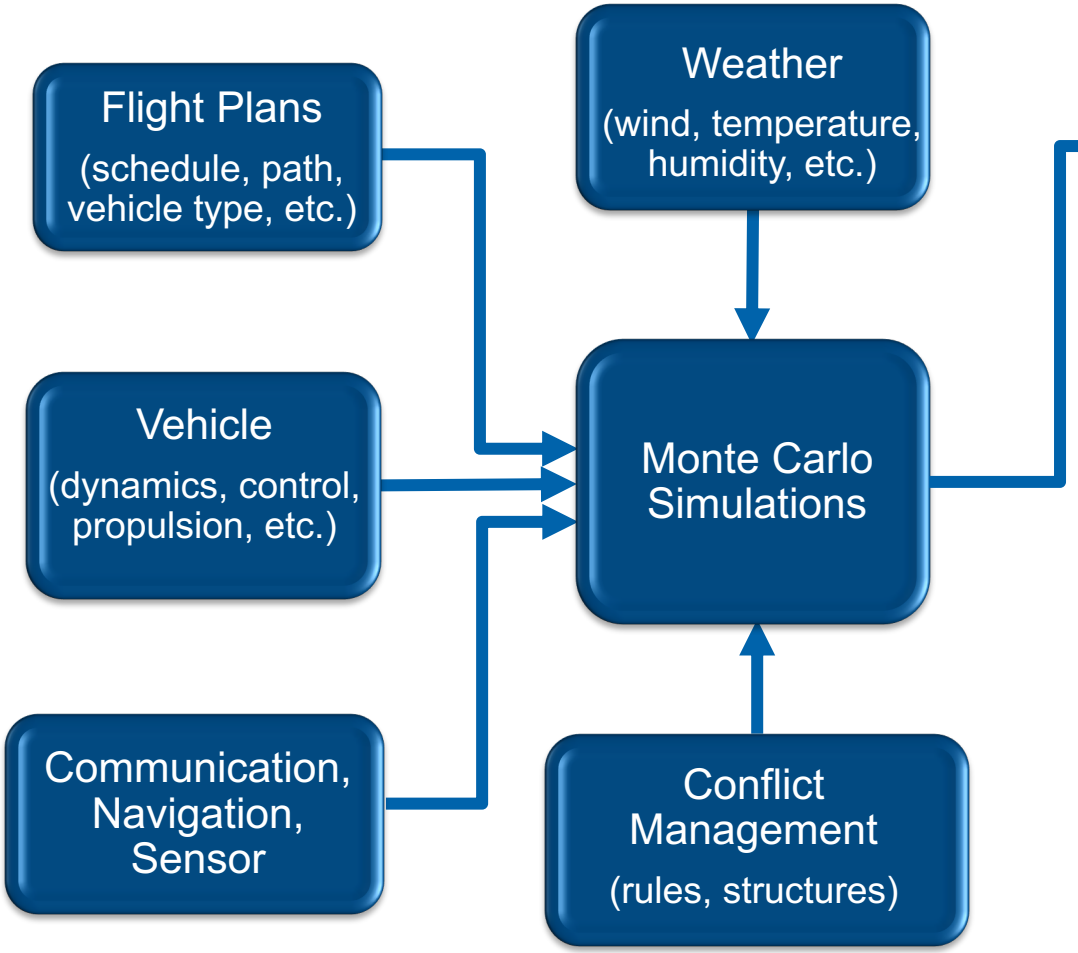
- Fe^3 Simulator
- Cloud Implementation
- Applications
- Summary

***Fe^3 - Flexible engine for Fast-time evaluation of Flight environments**

Outline

- Fe^3 Simulator
  - System diagram
  - Vehicle model
  - Conflict management model
  - Communication & sensor models
  - Wind model
  - Core architecture
- Cloud Implementation
  - Cloud architecture
  - Web interface
  - Computational performance
- Applications
  - Trade space studies
  - Future research and applications
- Summary

Fe^3 system diagram



Key characteristics:

- High-fidelity: 6DOF, navigation, communication, wind, etc.
- Multi-vehicle operations
- Time step: 500ms
- Uncertainties
- Monte Carlo – statistics
- Capability of running thousands of simulations parallelly

***Fe^3 - Flexible engine for Fast-time evaluation of Flight environments**

Vehicle model: trajectory

6DOF trajectory model (dynamics + PD controller):

Dynamics:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{h}\end{bmatrix} \models \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ s\theta & -s\phi c\theta & -c\phi c\theta \end{bmatrix} \begin{bmatrix} u\\ v\\ w\end{bmatrix}$$

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \begin{bmatrix} rv - qw\\ pw - ru\\ qu - pv\end{bmatrix} + \begin{bmatrix} -g\sin\theta\\ g\cos\theta\sin\phi\\ g\cos\theta\cos\phi\end{bmatrix} + \frac{1}{m}\begin{bmatrix} F_x\\ F_y\\ F_z\end{bmatrix}$$

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta}\end{bmatrix}\begin{bmatrix} p\\ q\\ r\end{bmatrix}$$

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = \begin{bmatrix} \frac{J_y - J_z}{J_x}qr\\ \frac{J_z - J_x}{J_y}pr\\ \frac{J_x - J_y}{J_z}pq\end{bmatrix} + \begin{bmatrix} \frac{1}{J_x}M_\phi\\ \frac{1}{J_y}M_\theta\\ \frac{1}{J_z}M_\psi\end{bmatrix}$$

Controller:

$$\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix} = \begin{bmatrix} k_p(x_d - x) + k_d(\dot{x}_d - \dot{x})\\ k_p(y_d - y) + k_d(\dot{y}_d - \dot{y})\end{bmatrix}$$

$$\begin{bmatrix}\phi_d\\ \theta_d\end{bmatrix} = \frac{m}{F_z}\begin{bmatrix} -\sin\psi & -\cos\psi\\ \cos\psi & -\sin\psi\end{bmatrix}^{-1}\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix}$$

$$\begin{bmatrix}M_\phi\\ M_\theta\end{bmatrix} = \begin{bmatrix} k_{p,\phi}(\phi_d - \phi) + k_{d,\phi}(\dot{\phi}_d - \dot{\phi})\\ k_{p,\theta}(\theta_d - \theta) + k_{d,\theta}(\dot{\theta}_d - \dot{\theta})\end{bmatrix} l$$

Vehicle model: power consumption

- Power: $p = \tau \cdot \omega = V_{in} \cdot I$

Low-fidelity model

$$p = \tau \cdot \omega$$
$$= k_m \cdot \omega^3$$

High-fidelity model

$$p = V_{in} \cdot I$$
$$I = x_x + \sqrt{x_x^2 + \frac{u\,\alpha_M}{R_A}}$$
$$x_x = \frac{u\,V_{in}\beta_M - k_t\,\omega_{M_i}}{2\,R_A}$$

- Motor thrust:

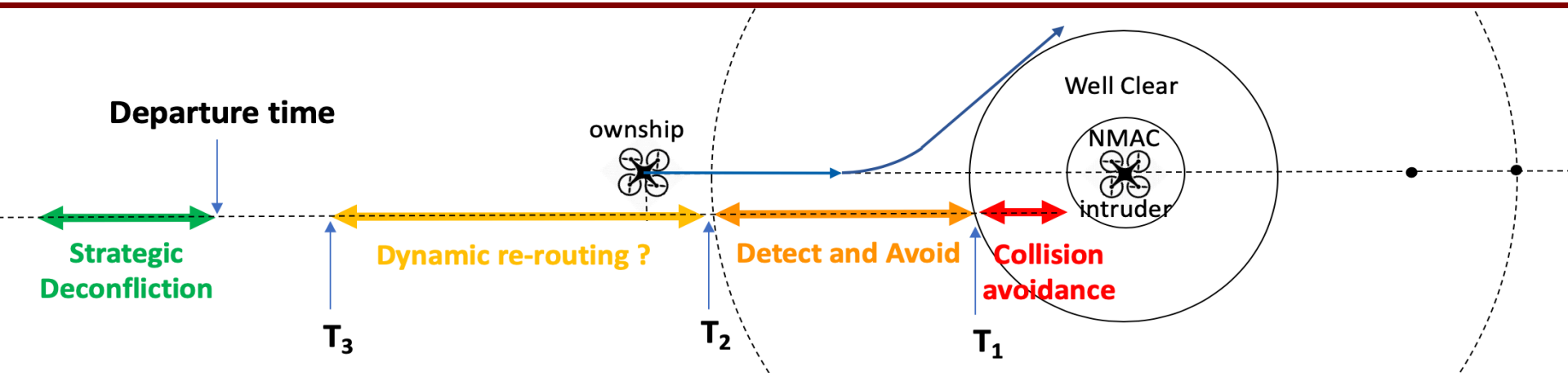
Low-fidelity model

$$F = K_f \cdot \omega^2$$

High-fidelity model

$$F = C_{T,0}\omega_M^2 + C_{T,1}v_1\omega_M \pm C_{T,2}v_1^2$$

Generalized conflict management model



Inputs:

- Position
- Speed
- Intent
- Health
- Terrains
- Airspace constraints

Decision making:

- Parameters
- Objective
- Trajectory prediction
- Rules or Logics

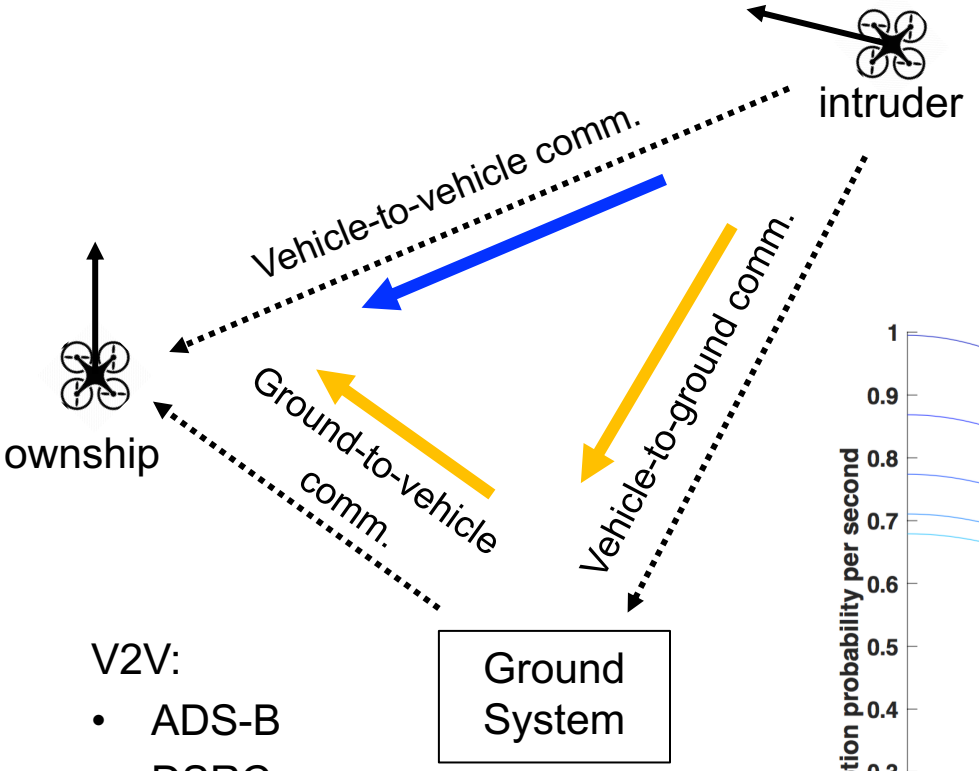
Action:

(Maneuver or updated flight plans)

Decision logics (When? Who? What?)

- *Scheduling/strategic deconfliction*
- *Tactical deconfliction*
- *Separation assurance*
- *Route structures*
- *Contingency*

Communication model



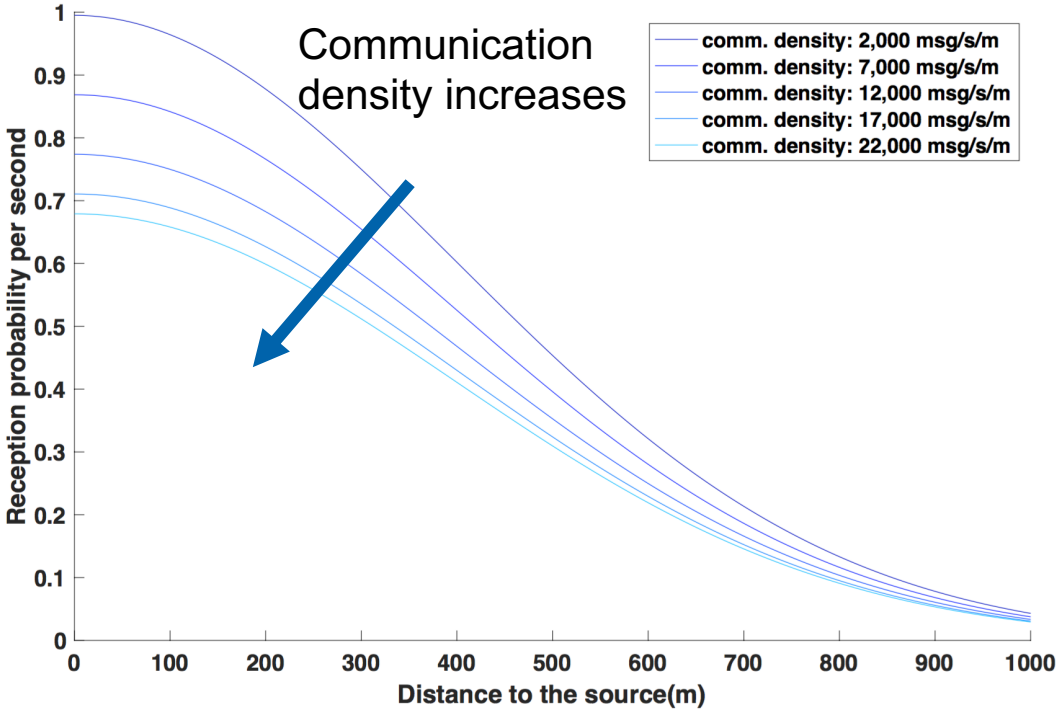
V2V:

- ADS-B
- DSRC
- Cellular V2X
- …

V2G:

- Vehicle-USS-USS-Vehicle
- …

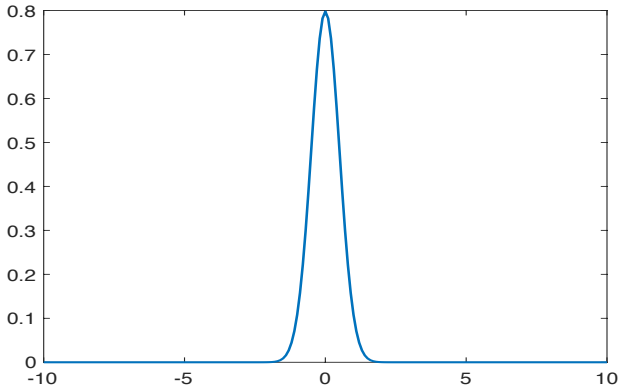
DSRC: $\mathrm{p}(d) = Pe^{-(2M-3)\rho}e^{-\pi\left(\frac{d}{d_r}\right)^2}$



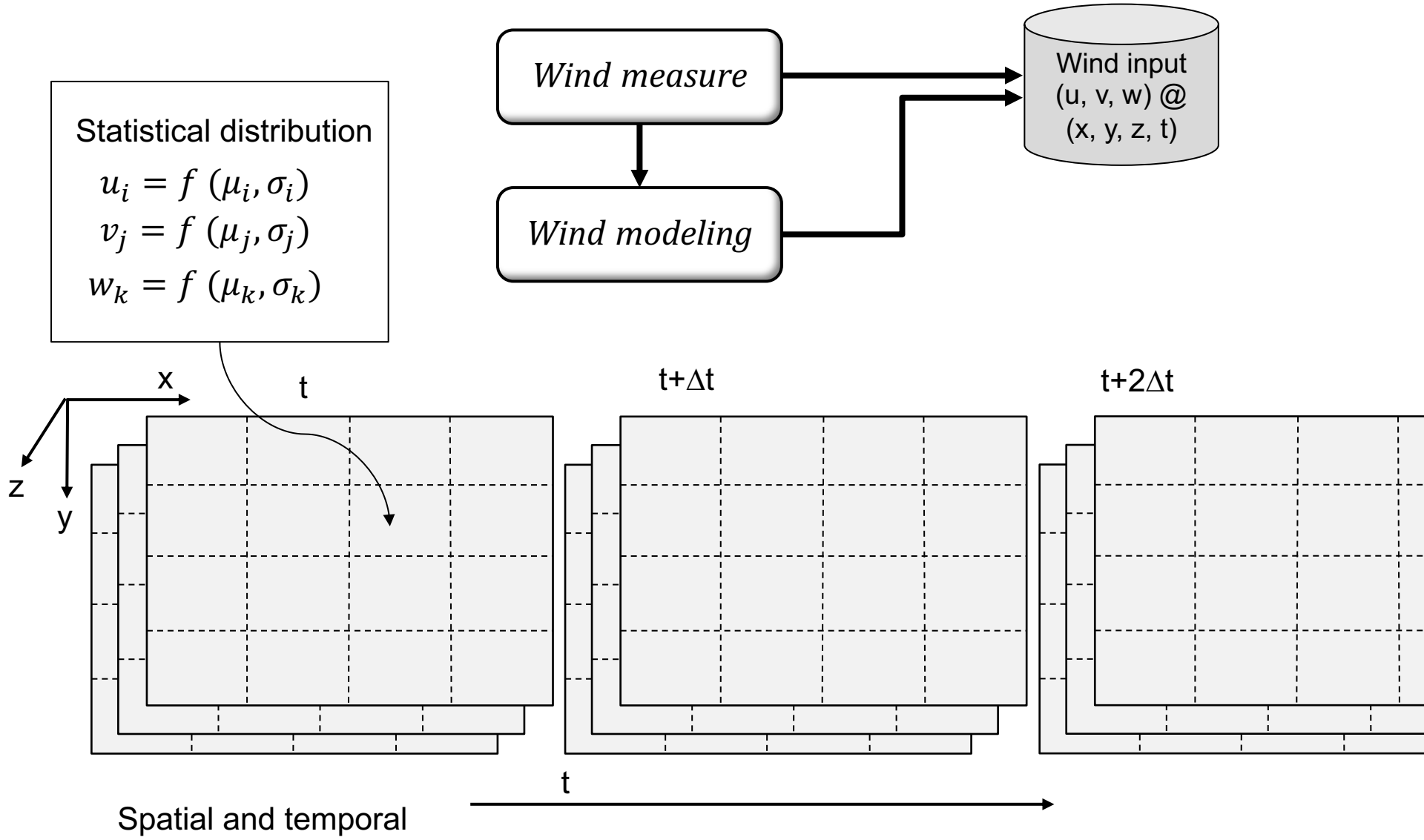
Sensor model

- Types:
  - Radar
  - LiDAR
  - Vision
  - …

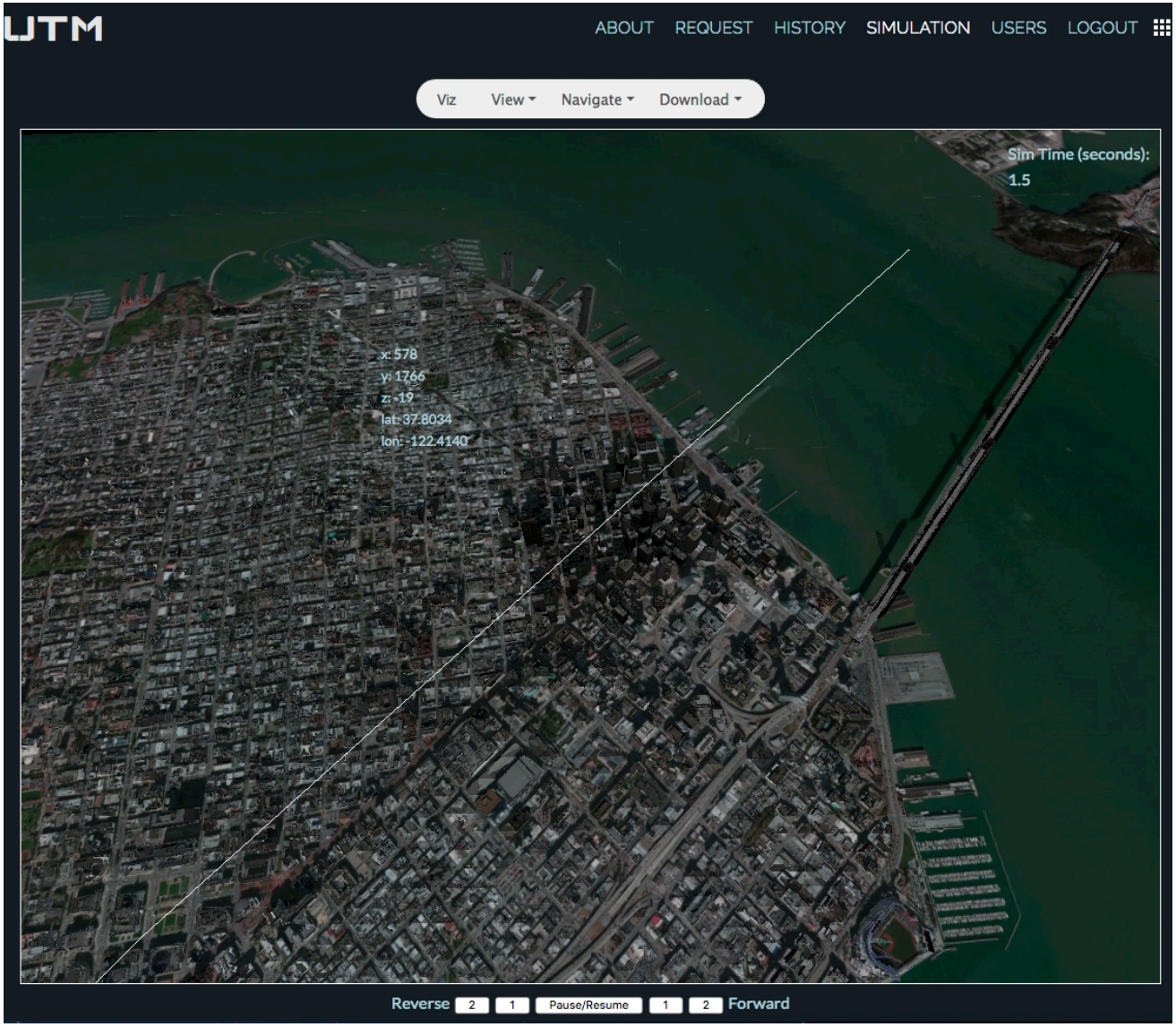
- General model:
  - Detection range (constant)
  - Azimuth range (constant)
  - Elevation range (constant)
  - Range (Gaussian) $f(\mu_1, \sigma_1)$
  - Azimuth (Gaussian) $f(\mu_2, \sigma_2)$
  - Elevation (Gaussian) $f(\mu_3, \sigma_3)$
  - Velocity (Gaussian) $f(\mu_4, \sigma_4)$



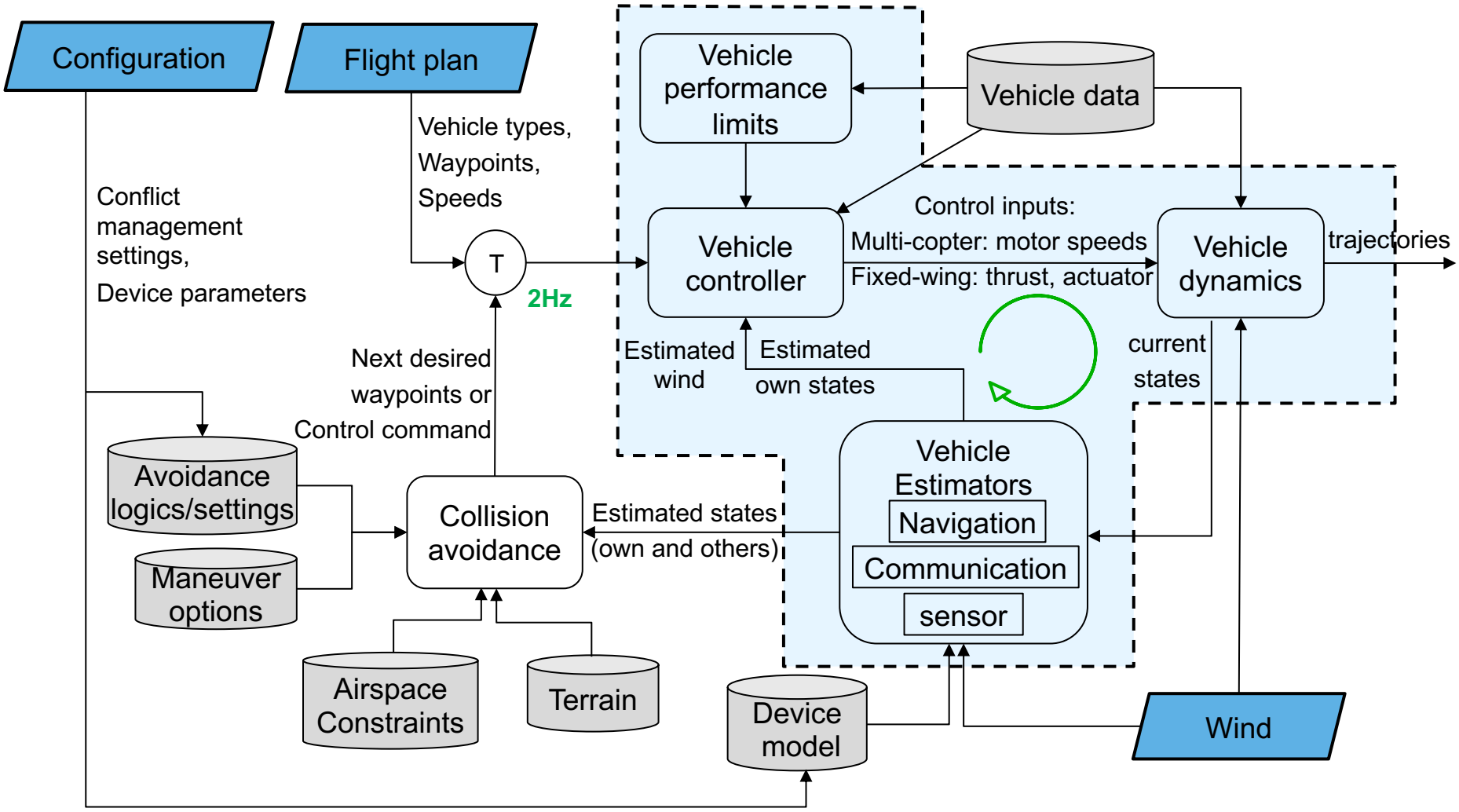
Wind model


Statistical distribution
$u_i = f\ (\mu_i, \sigma_i)$
$v_j = f\ (\mu_j, \sigma_j)$
$w_k = f\ (\mu_k, \sigma_k)$
Wind measure
Wind modeling
Wind input
(u, v, w) @
(x, y, z, t)
x
t
z
y
t+Δt
t+2Δt
t
Spatial and temporal

Sample wind profile for San Francisco



Fe^3 core architecture



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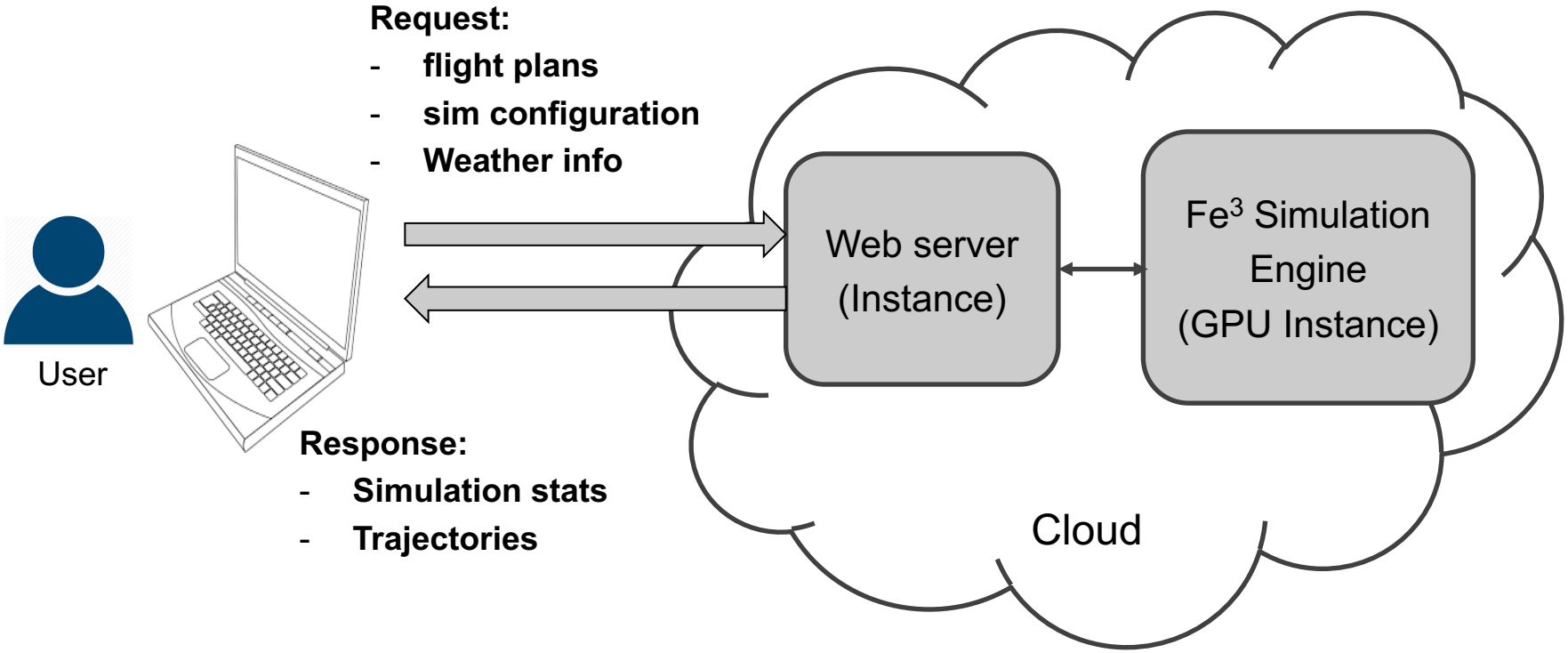
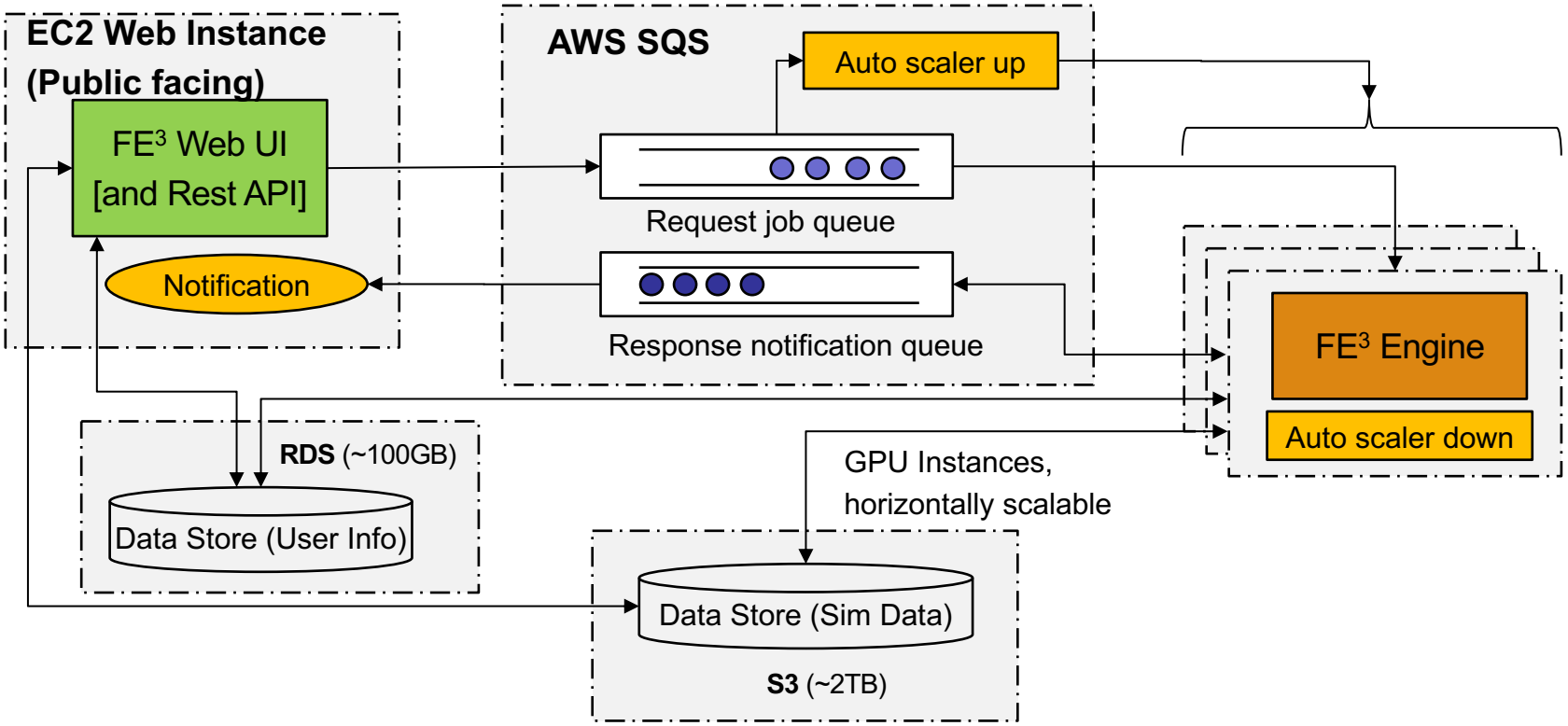
Cloud-based platform

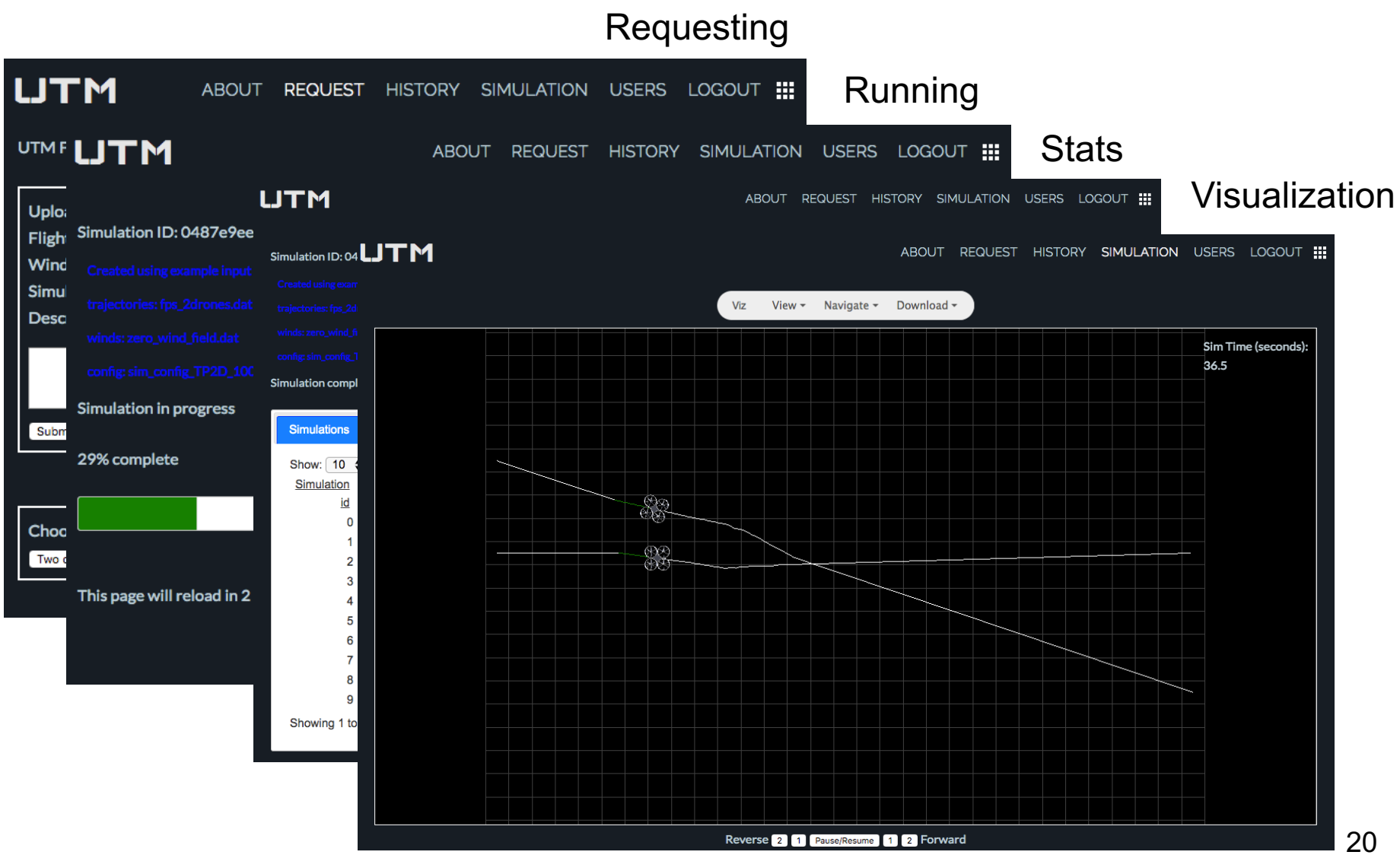


- **Graphic Process Units(GPU) – fast**
- **Cloud GPU instances –faster, convenient**
- **Web portal I/O – convenient**

Cloud architecture

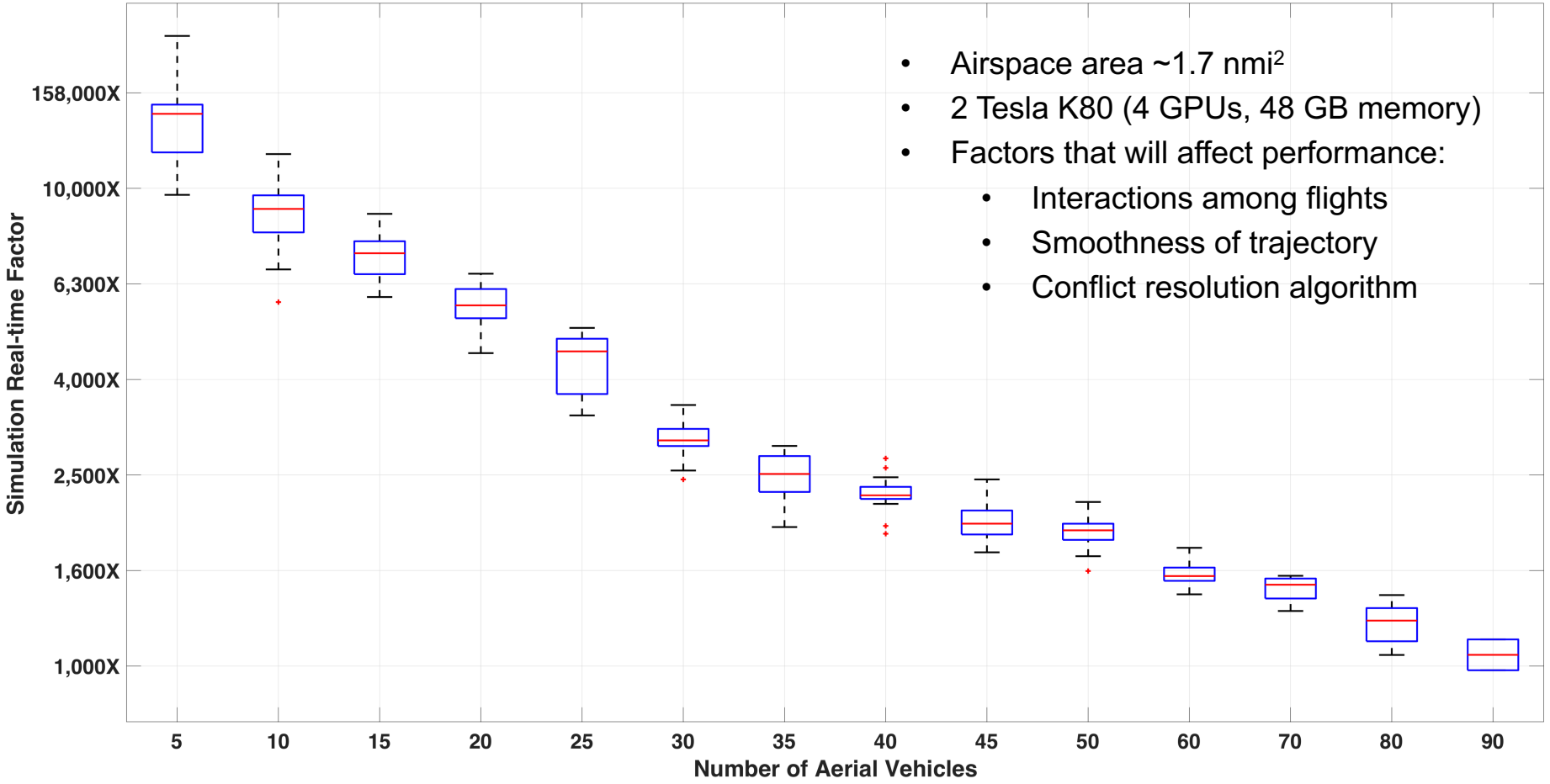


How to use Fe^3



Computational performance

$$Real\ Time\ Factor = \frac{Flight\ Time}{Simulation\ Run\ Time} \times Number\ of\ parallel\ simulations$$



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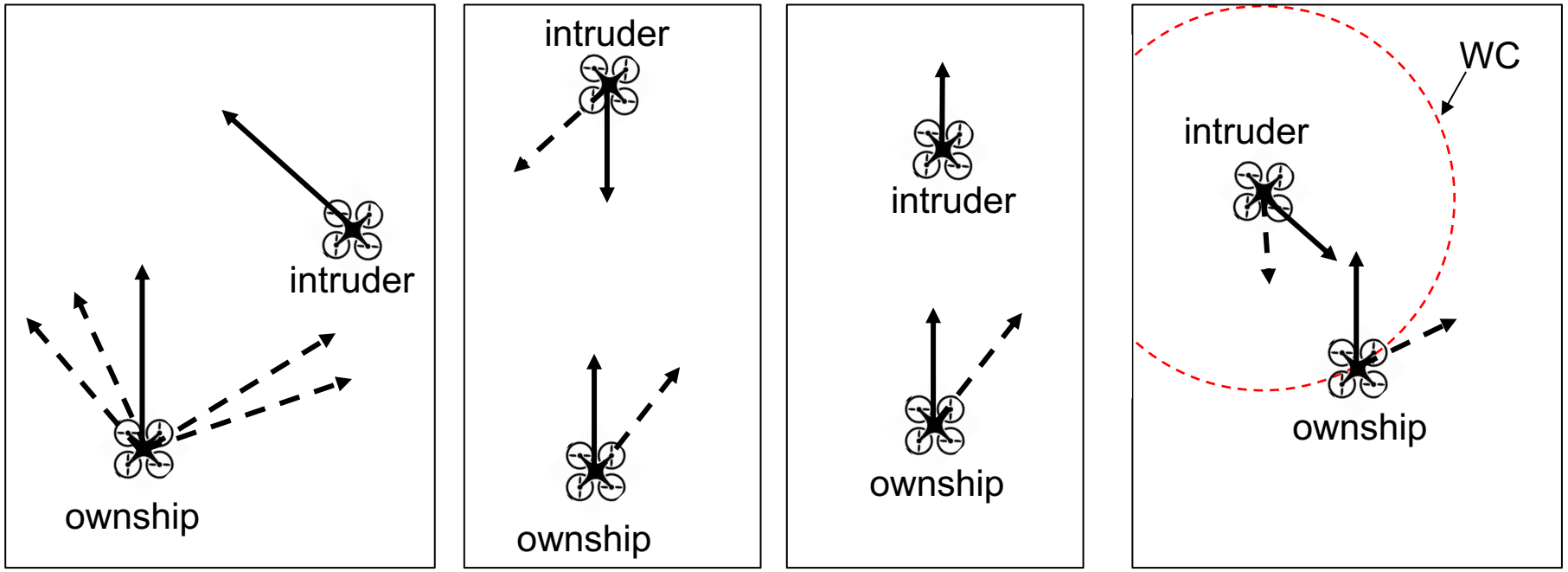
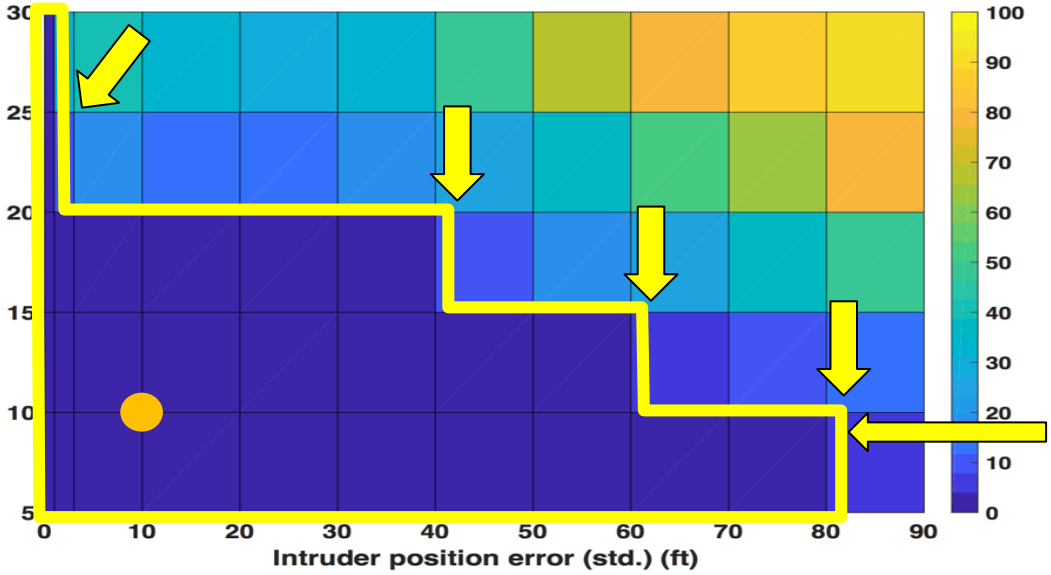
Sample conflict management model



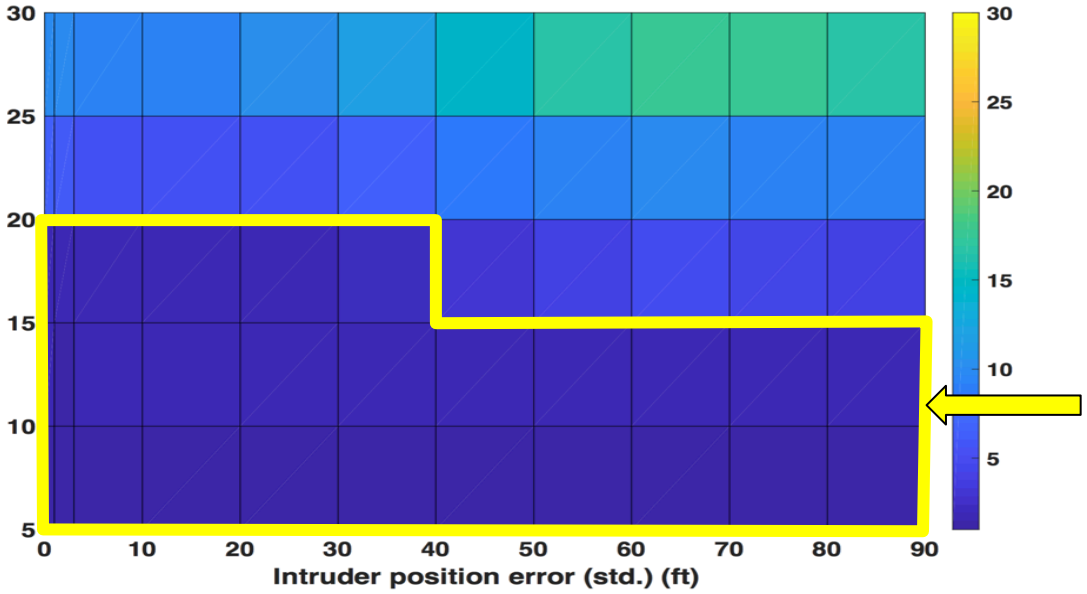
- If the intruder is on the right, then the ownship shall take an avoidance maneuver.
- If it's a head-on conflict, both the ownship and intruder shall turn right.
- If in-line, the trailing vehicle shall take an avoidance maneuver.
- If the well clear is violated, both the ownship and intruder shall take avoidance maneuvers.
- When there are multiple options, an avoidance maneuver with minimum deviation shall be chosen.

Trade space study: position error



Safety measurement: probability of loss of separation (%)

Safe operation zone

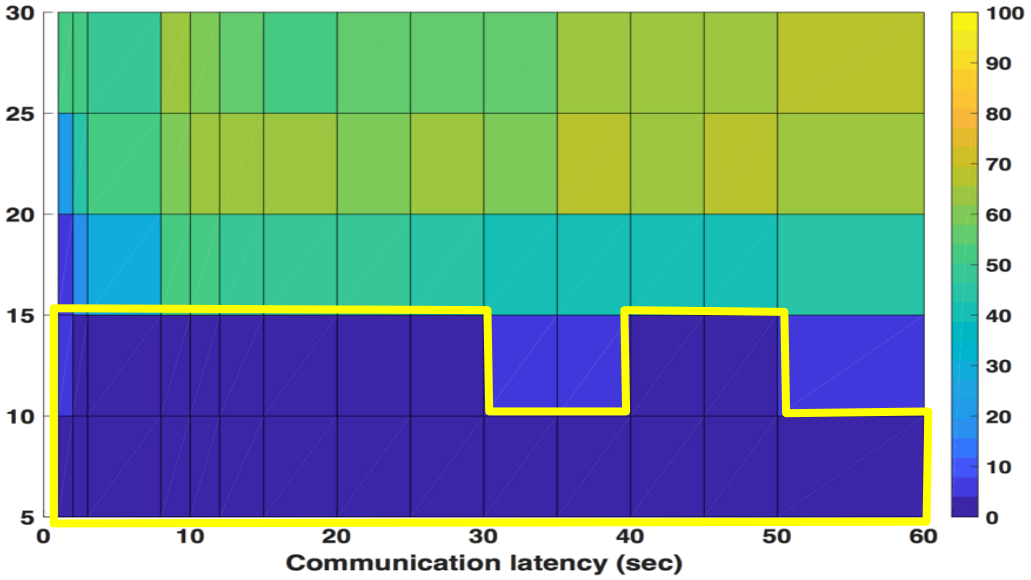


Efficiency measurement: extra flight distance (%)

5% extra distance

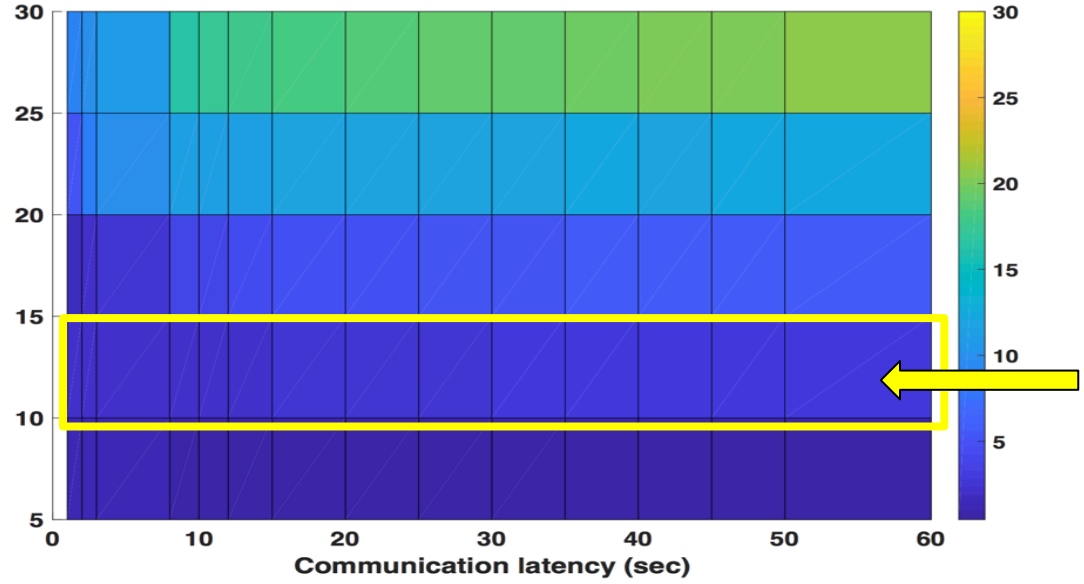
5% extra energy

Trade space study: communication latency



Safety measurement: probability of loss of separation (%)

More sensitive to aircraft count than communication latency



Efficiency measurement: extra flight distance (%)

~10% extra distance

~10% extra energy

Supporting future research and application

- System requirements
  - data, update rate, accuracy,
  - communication, navigation, surveillance,
  - centralized, decentralized, or coordinated?
  - interactions with ATM traffic (structure or not)?
  - others
- Traffic system safety/risk assessment
- …

[Note: Patent provisional application filed; software usage agreement (SUA) in progress]

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Summary

- A fast-time simulation that can address uncertainty is necessary for new ATM concepts
- The Fe^3 was carefully modeled, designed, and implemented to satisfy needs from both fidelity and computational performance.
- Preliminary traffic system trade study and potential in supporting research and application were discussed.

Questions?

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