Conflict Resolution Strategies for Balloon-Airship Encounters in Upper Class E Traffic Management (ETM)

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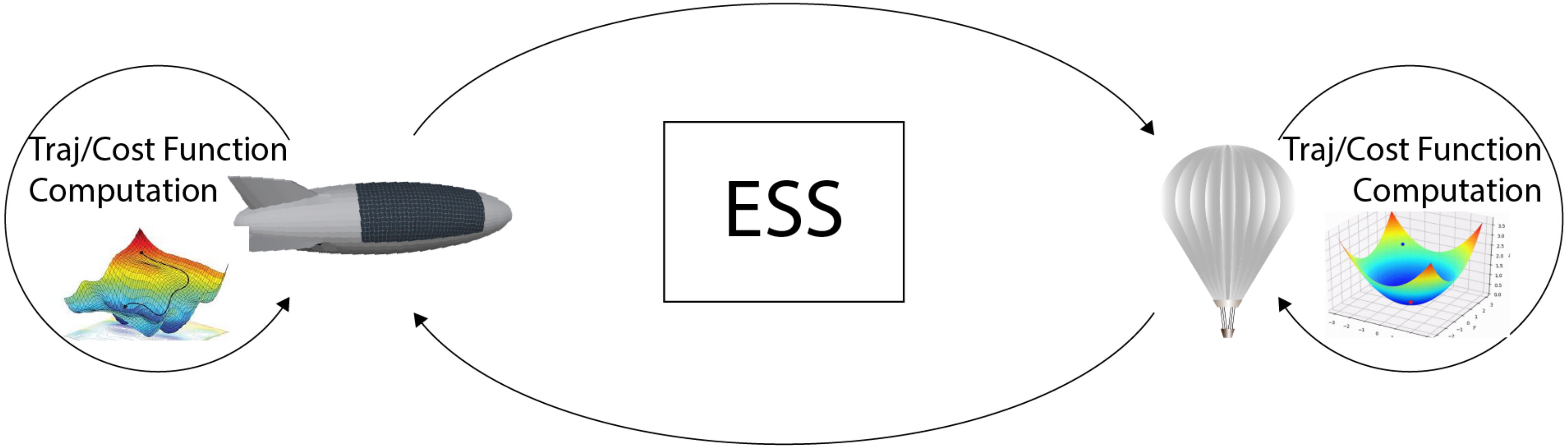
Introduction and Motivation

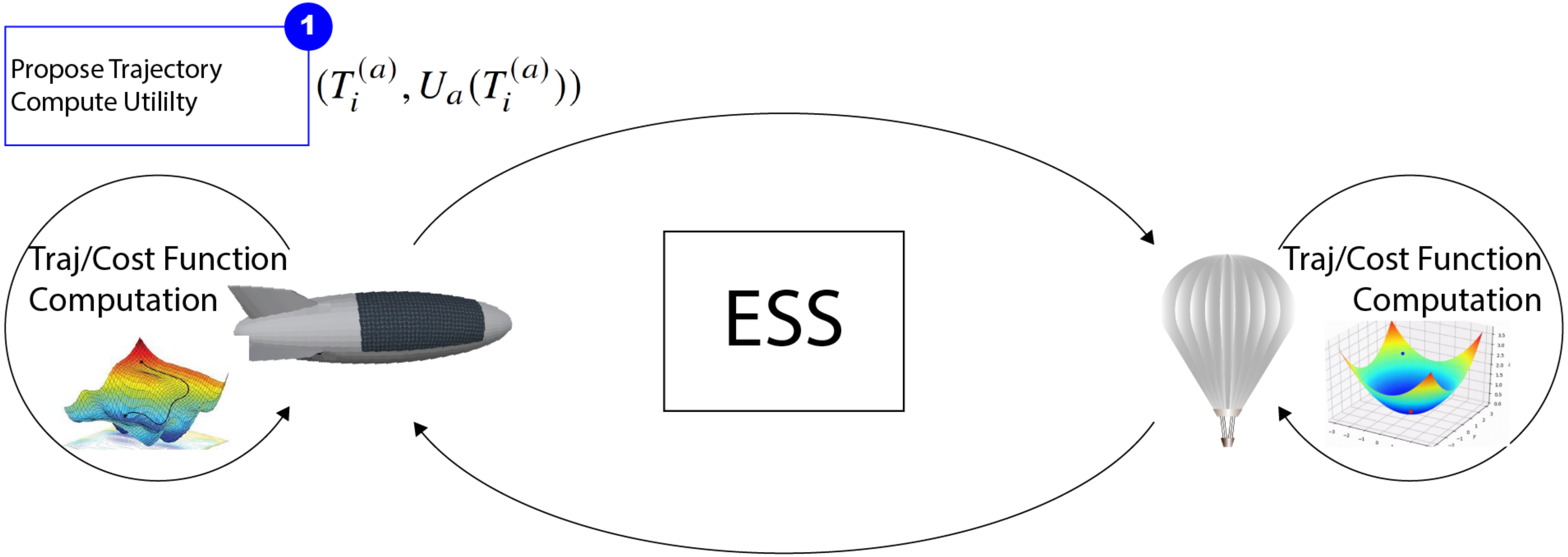
- HAPS market revenue of $4 billion by 2029
- No specific provisions for air traffic management systems above 60,000 ft.
- NASA and FAA are investigating air-traffic management strategies for this emerging market. This is termed **ETM** or Upper Class **E T**raffic **M**anagement
- This presentation focuses on conflict resolution strategies for airship-balloon interaction leveraging optimal control and negotiation.

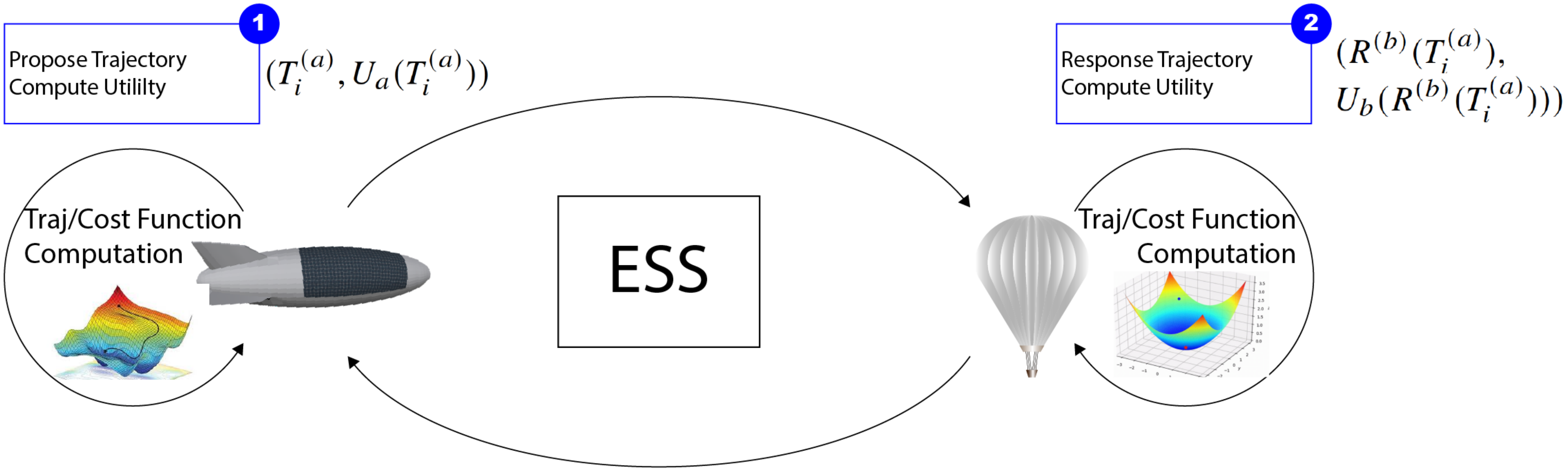
2021 Upper Class E Traffic Management Workshop 2021

Organization

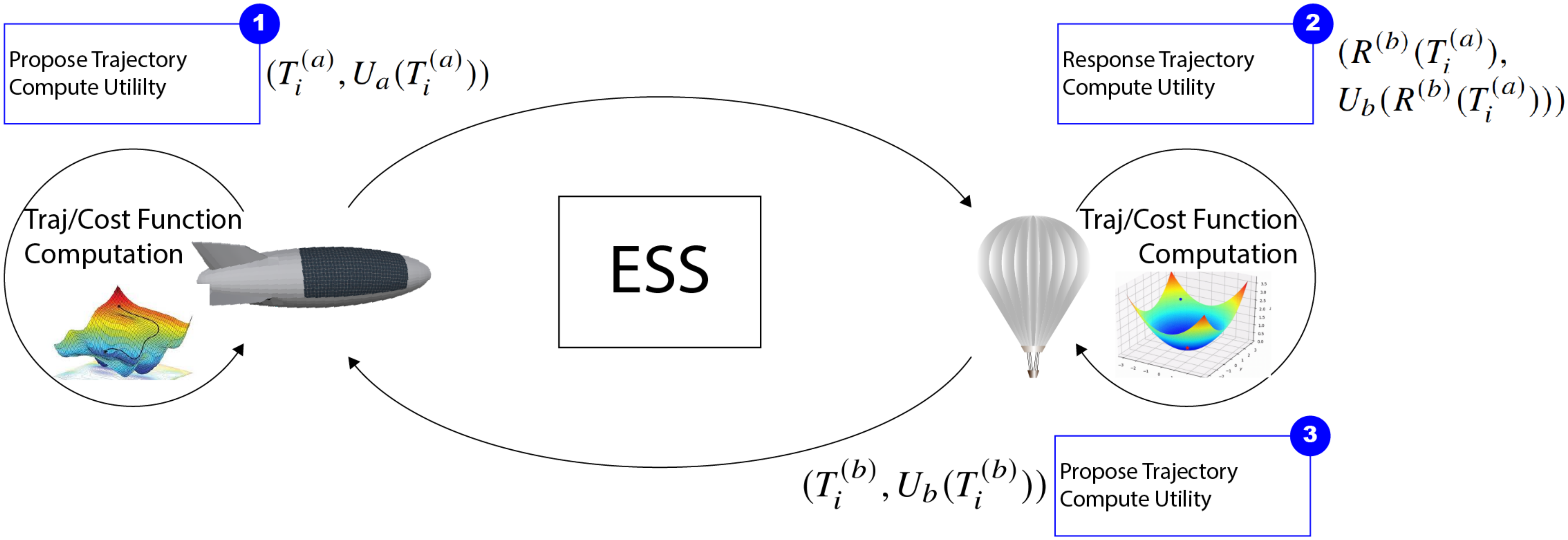
- Big Picture
- Balloon and Airship Dynamics
- Optimal Control Problem Formulation and Numerical Solutions
- Main Results
- Conclude


Traj/Cost Function Computation
ESS
Traj/Cost Function Computation

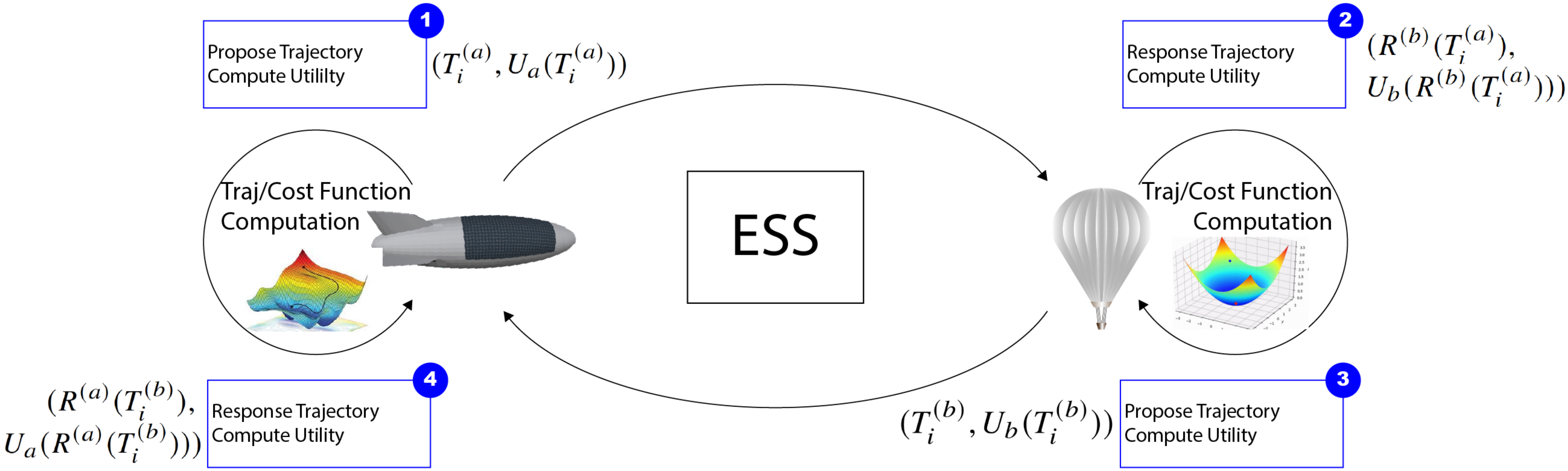

Propose Trajectory
Compute Utililty
1
$(T_i^{(a)}, U_a(T_i^{(a)}))$
Traj/Cost Function Computation
ESS
Traj/Cost Function Computation



1
Propose Trajectory
Compute Utililty
$(T_i^{(a)}, U_a(T_i^{(a)}))$
2
Response Trajectory
Compute Utility
$(R^{(b)}(T_i^{(a)}),$
$U_b(R^{(b)}(T_i^{(a)})))$
Traj/Cost Function
Computation
ESS
Traj/Cost Function
Computation

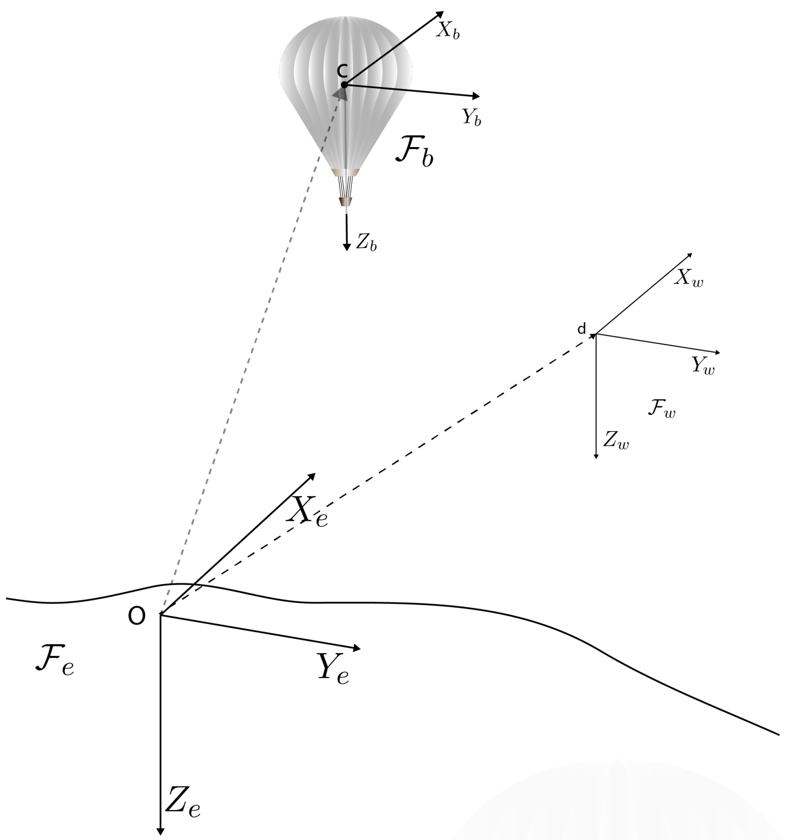


1
Propose Trajectory
Compute Utility
$(T_i^{(a)}, U_a(T_i^{(a)}))$
2
Response Trajectory
Compute Utility
$(R^{(b)}(T_i^{(a)}), U_b(R^{(b)}(T_i^{(a)})))$
Traj/Cost Function Computation
ESS
Traj/Cost Function Computation
$(T_i^{(b)}, U_b(T_i^{(b)}))$
3
Propose Trajectory
Compute Utility



Pritchett, A. R., & Genton, A. (2017). Negotiated decentralized aircraft conflict resolution.
Wollkind, S., Valasek, J., & Ioerger, T. (2004, August).
Zlotkin, G., & Rosenschein, J. S. (1989, August)

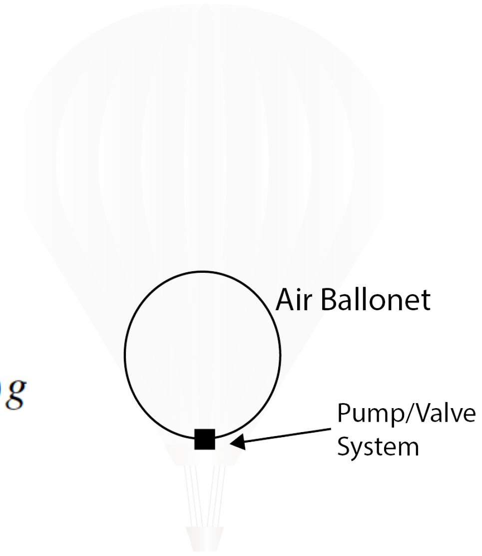
Balloon Dynamics



Forces acting on the balloon

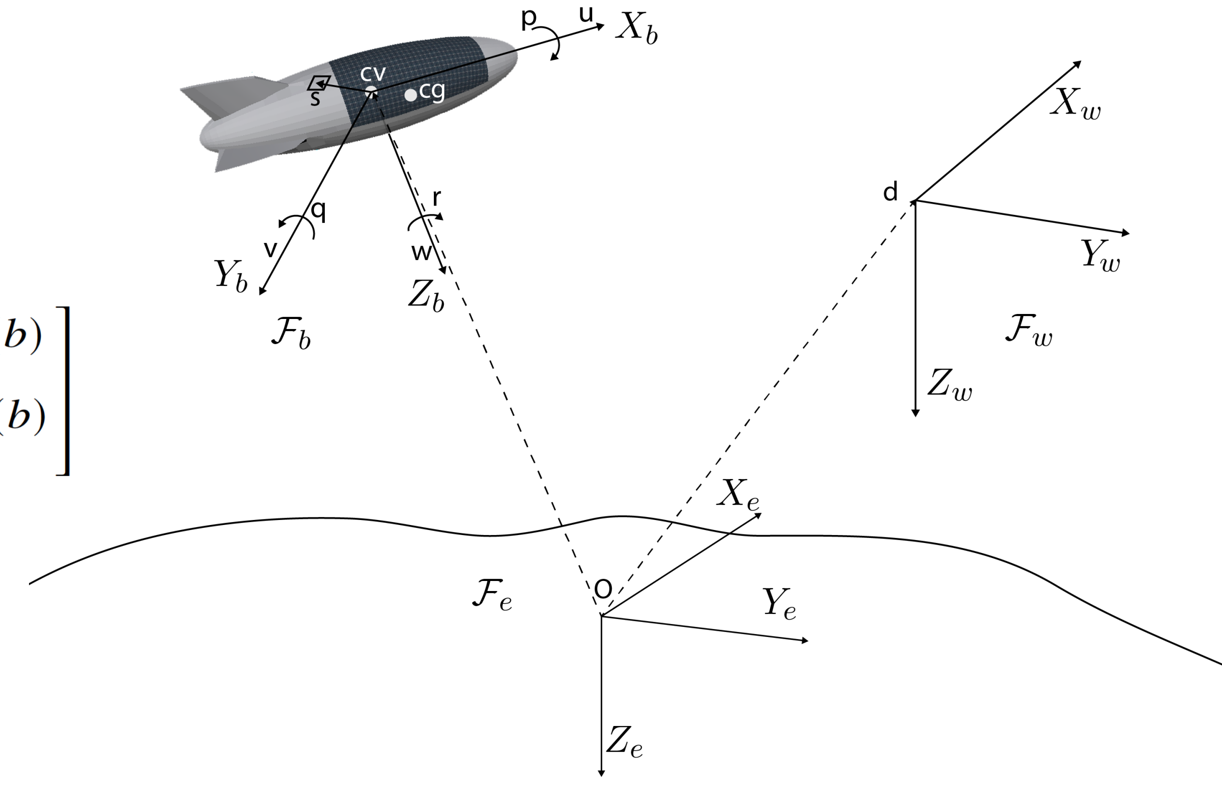
$$\vec{F}^{(e)} = \vec{F}^{(e)}_{aero} + \vec{F}^{(e)}_{buoy} + \vec{F}^{(e)}_{g}$$

$$\begin{cases} \dot{x}_b = v_{bx} \\ \dot{y}_b = v_{by} \\ \dot{z}_b = v_{bz} \\ \dfrac{d}{dt}\left((m_0 + m_{air}(t) + \eta m_a)\left(v_{bx} - \zeta_x\right)\right) = -\bar{q}_b S_b C_d \left(v_{bx} - \zeta_x\right) / \|\vec{V}_{rel}\| \\ \dfrac{d}{dt}\left((m_0 + m_{air}(t) + \eta m_a)\left(v_{by} - \zeta_y\right)\right) = -\bar{q}_b S_b C_d \left(v_{by} - \zeta_y\right) / \|\vec{V}_{rel}\| \\ \dfrac{d}{dt}\left((m_0 + m_{air}(t) + \eta m_a)\left(v_{bz} - \zeta_z\right)\right) = -\bar{q}_b S_b C_d \left(v_{bz} - \zeta_z\right) / \|\vec{V}_{rel}\| + (m_a - m_0 - m_{air}(t))g \\ \dot{m}_{air}(t) = u(t) \end{cases}$$



Airship Dynamics

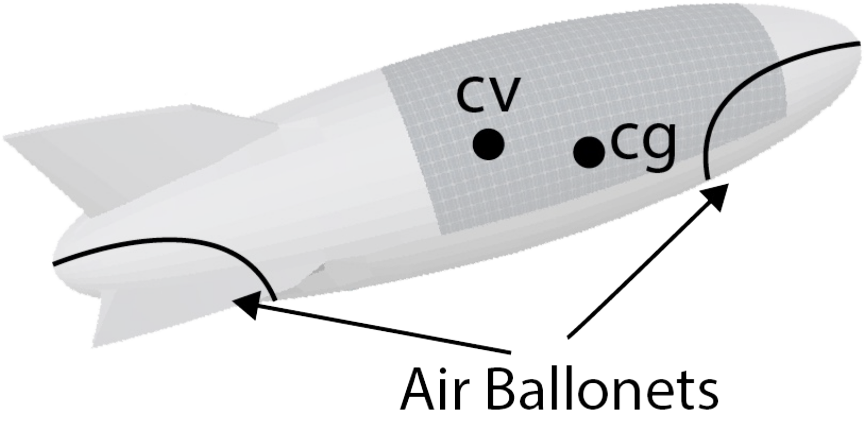
$$\begin{bmatrix} mI_{3\times 3} & mD_{cg} \\ -mD_{cg} & I \end{bmatrix} \begin{bmatrix} \dot{\vec{v}}_{\zeta}^{(b)} \\ \dot{\vec{\omega}}^{(b)} \end{bmatrix} + \begin{bmatrix} \vec{H}^{(F)} \\ \vec{H}^{(M)} \end{bmatrix} + m \begin{bmatrix} \vec{A}_{cg} \\ \vec{B}_{cg} \end{bmatrix} = \begin{bmatrix} \vec{F}^{(b)} \\ \vec{M}^{(b)} \end{bmatrix}$$



$\vec{\omega}^{(b)} = [p\ q\ r]^T$ angular rates

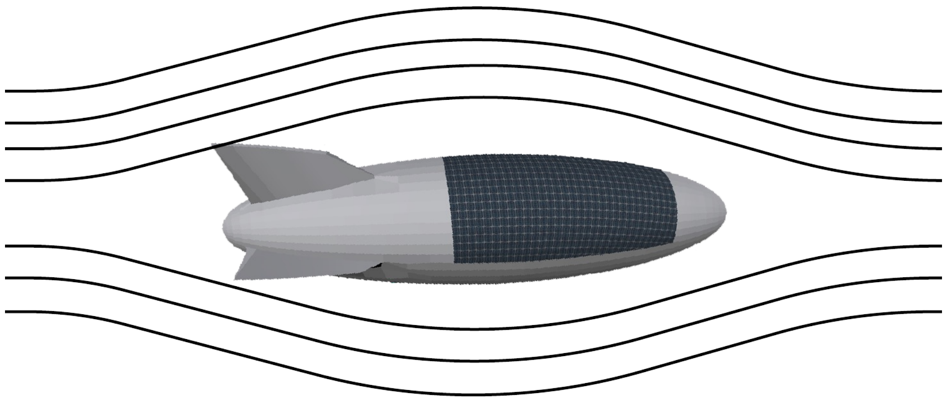
$\vec{v}_{\zeta}^{(b)} := [u + \zeta_x^{(b)}\ \ v + \zeta_y^{(b)}\ \ w + \zeta_z^{(b)}]^T$ body velocities with wind

$$D_{cg} = \begin{bmatrix} 0 & d_z & -d_y \\ -d_z & 0 & d_x \\ d_y & -d_x & 0 \end{bmatrix} \qquad \vec{H}_F = m\vec{\omega}^{(b)} \times \vec{v}_{\zeta}^{(b)} \qquad \vec{H}_M = \vec{\omega}^{(b)} \times I\vec{\omega}^{(b)}$$



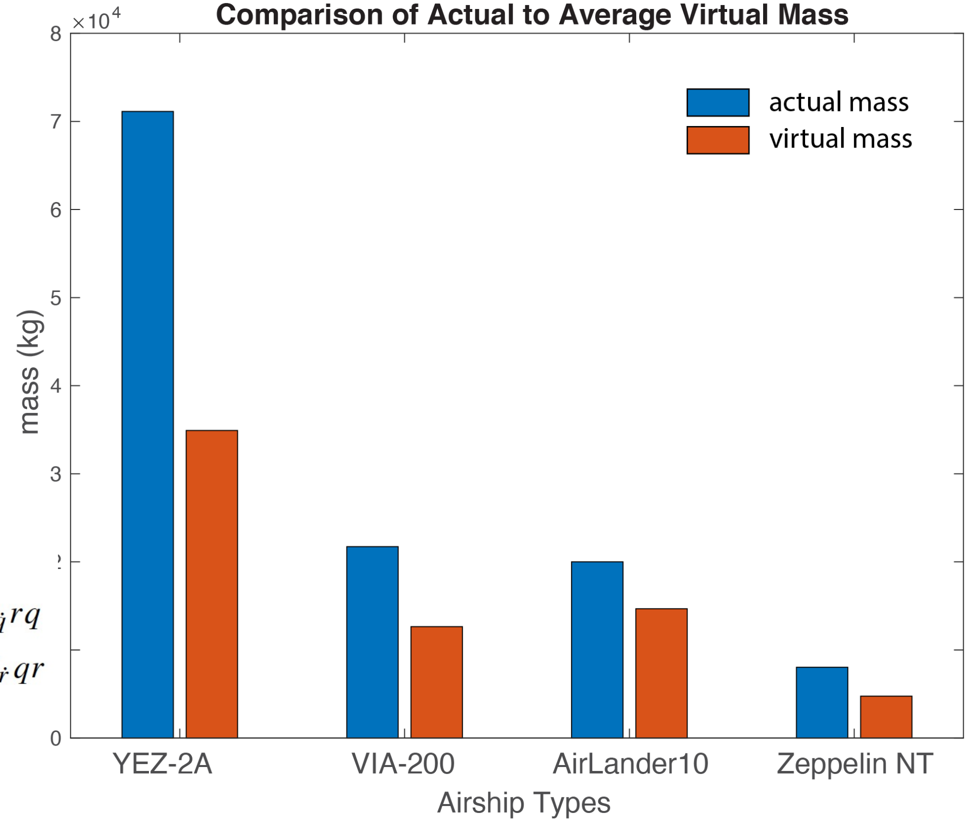
$$\vec{A}_{cg} = \begin{bmatrix} -d_x(q^2+r^2) + d_y pq + d_z pr \\ -d_y(p^2+r^2) + d_z r q d_x p q \\ -d_z(p^2+q^2) + d_x pr + d_y qr \end{bmatrix} \qquad \vec{B}_{cg} = \begin{bmatrix} d_y\left(pv_\zeta - qu_\zeta\right) - d_z\left(ru_\zeta - pw_\zeta\right) \\ d_z\left(qw_\zeta - rv_\zeta\right) - d_x\left(pv_\zeta - qu_\zeta\right) \\ d_x\left(ru_\zeta - pw_\zeta\right) - d_y\left(qw_\zeta - rv_\zeta\right) \end{bmatrix}$$

Virtual Mass/Inertia



$$\vec{F}_v^{(b)} = \Gamma_1 \dot{\vec{v}} + \Gamma_2 \dot{\vec{\omega}} + E_F$$

$$\vec{M}_v^{(b)} = \Gamma_3 \dot{\vec{v}} + \Gamma_4 \dot{\vec{\omega}} + E_M$$



$$\Gamma_1 = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} \\ X_{\dot{v}} & Y_{\dot{v}} & Y_{\dot{w}} \\ X_{\dot{w}} & Y_{\dot{w}} & Z_{\dot{w}} \end{bmatrix} \Gamma_2 = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} \\ X_{\dot{v}} & Y_{\dot{v}} & Y_{\dot{w}} \\ X_{\dot{w}} & Y_{\dot{w}} & Z_{\dot{w}} \end{bmatrix} E_F = \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

$$E_x = Z_{\dot{w}} qw + Z_{\dot{q}} q^2 + X_{\dot{w}} qu - Y_{\dot{v}} rv - Y_{\dot{p}} rp - Y_{\dot{r}} r^2 - X_{\dot{v}} ru - Y_{\dot{w}} rw - (Y_{\dot{q}} - Z_{\dot{r}}) rq$$
$$E_y = X_{\dot{v}} rv - Y_{\dot{w}} pv - Z_{\dot{p}} p^2 + X_{\dot{r}} r^2 + (X_{\dot{p}} - Z_{\dot{r}}) pr - X_{\dot{w}} pu + X_{\dot{w}} rw - Z_{\dot{w}} pw + X_{\dot{u}} ru - Z_{\dot{q}} pq + X_{\dot{q}} rq$$
$$E_z = -X_{\dot{w}} qw - X_{\dot{u}} qu - X_{\dot{q}} q^2 + Y_{\dot{v}} pv + Y_{\dot{r}} rp + Y_{\dot{p}} p^2 + Y_{\dot{w}} pw + X_{\dot{v}} pu - X_{\dot{v}} qv - (X_{\dot{p}} - Y_{\dot{q}}) pq - X_{\dot{r}} qr$$

Optimal Control

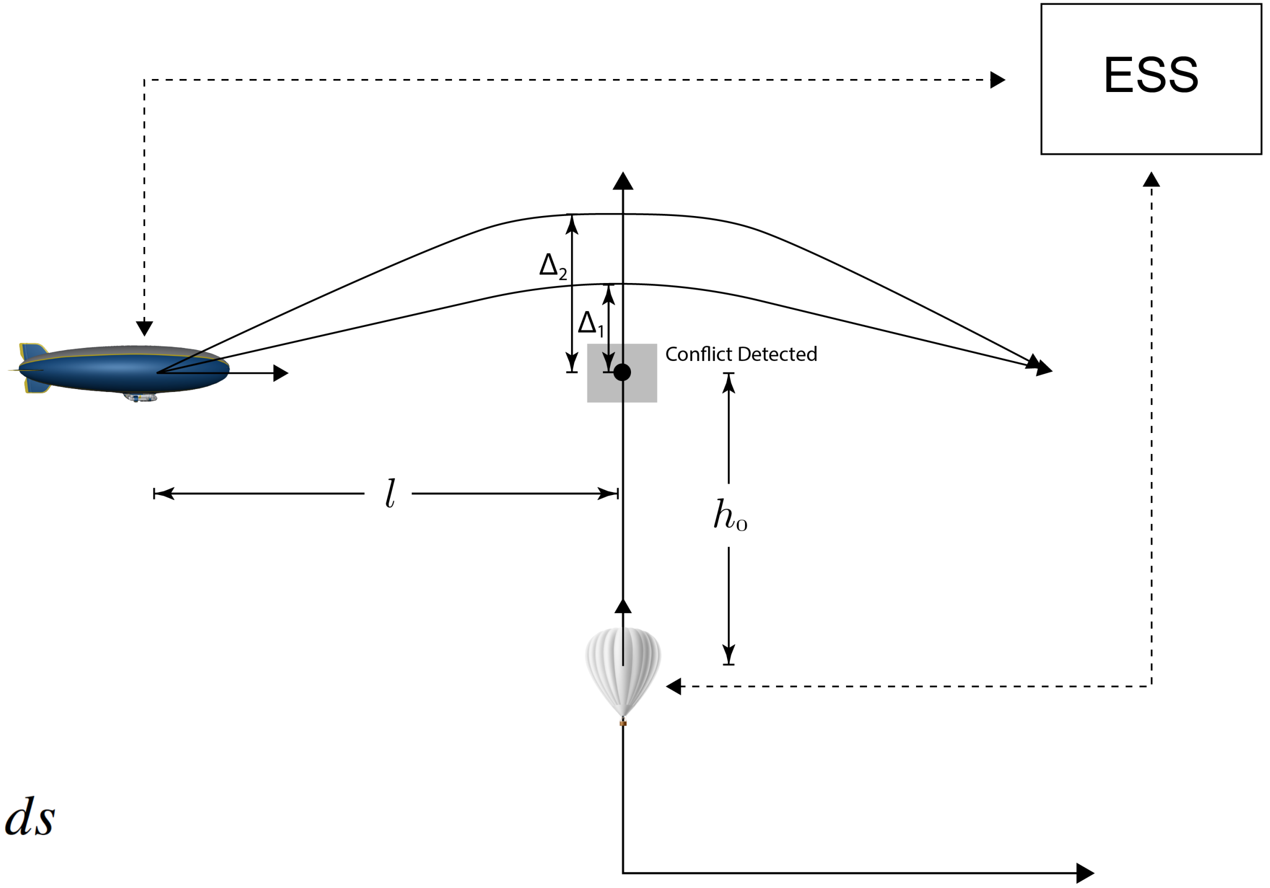
- Non-Dimensionalization

$$\begin{cases} \dot{x} = f(t, x, u) \\ x(t_0) = x_0 \end{cases}$$

Plant Dynamics

$$\begin{cases} \dot{p} = -\dfrac{\partial H}{\partial x} \\ p(t_f) = -\dfrac{\partial \phi(x(t_f))}{\partial x} \end{cases}$$

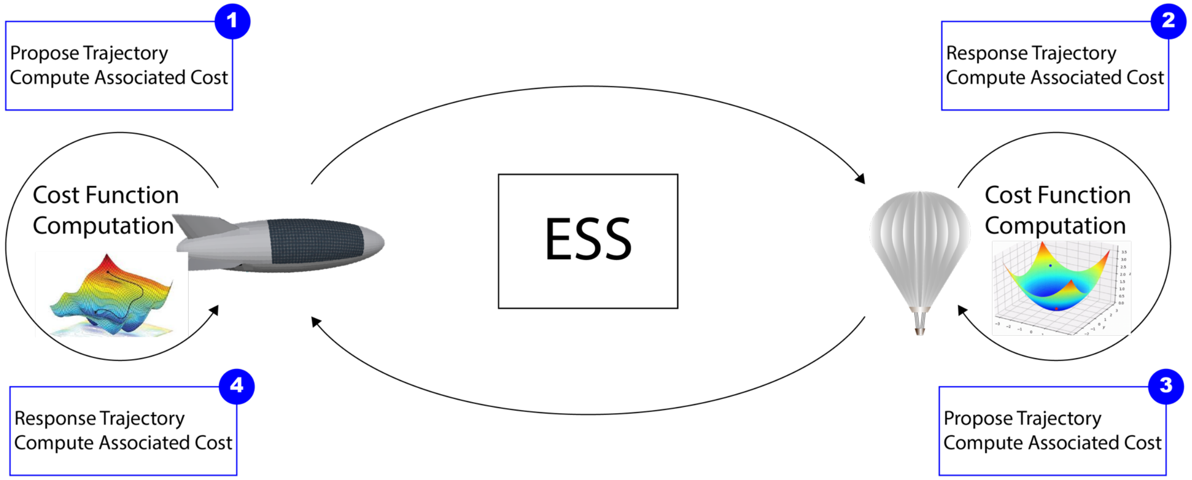
Co-State Dynamics

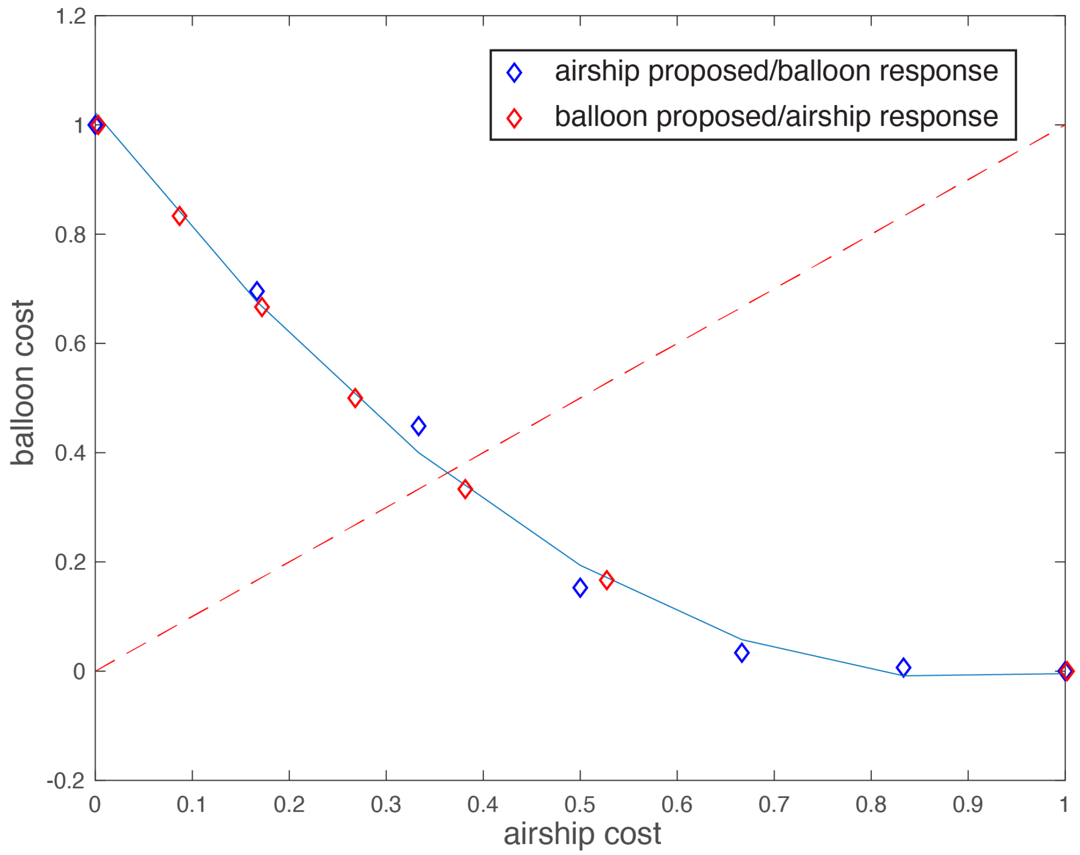


$$J[\bar{u}] := \int_0^{\tau_f} (1-\gamma)|\bar{u}| + \gamma \bar{u}^2 + \alpha \bar{R}(\tau, \bar{x}) ds$$

$$H(\tau, x(\tau; t_0, x_0, u^*), u^*(\tau), p(\tau)) \geq H(\tau, x(\tau; t_0, x_0, u^*), v, p(\tau))$$

Results





iteration	airship proposed cost	balloon response cost	balloon proposed cost	airship response cost
1	0.00	1.00	0.00	1.00
2	0.17	0.70	0.17	0.53
3	0.33	0.45	0.33	0.38
4	0.50	0.15	0.50	0.27

Conclusions

- There is a need for new approaches to traffic management in this emerging airspace
- A system modeled after UTM (UAS Traffic Management) terms ETM is currently being investigated.
- We presented an optimal control approach that could facilitate negotiation and conflict resolution between operators.
- Future work includes (1) analysis of convergence properties of the proposed framework, (2) exploration of different combinations of vehicles types, (3) real-time optimal control solutions.