IROS 2025 Workshop: Advancements in Aerial Physical Interaction

Safety-Critical Aerial Physical Interaction

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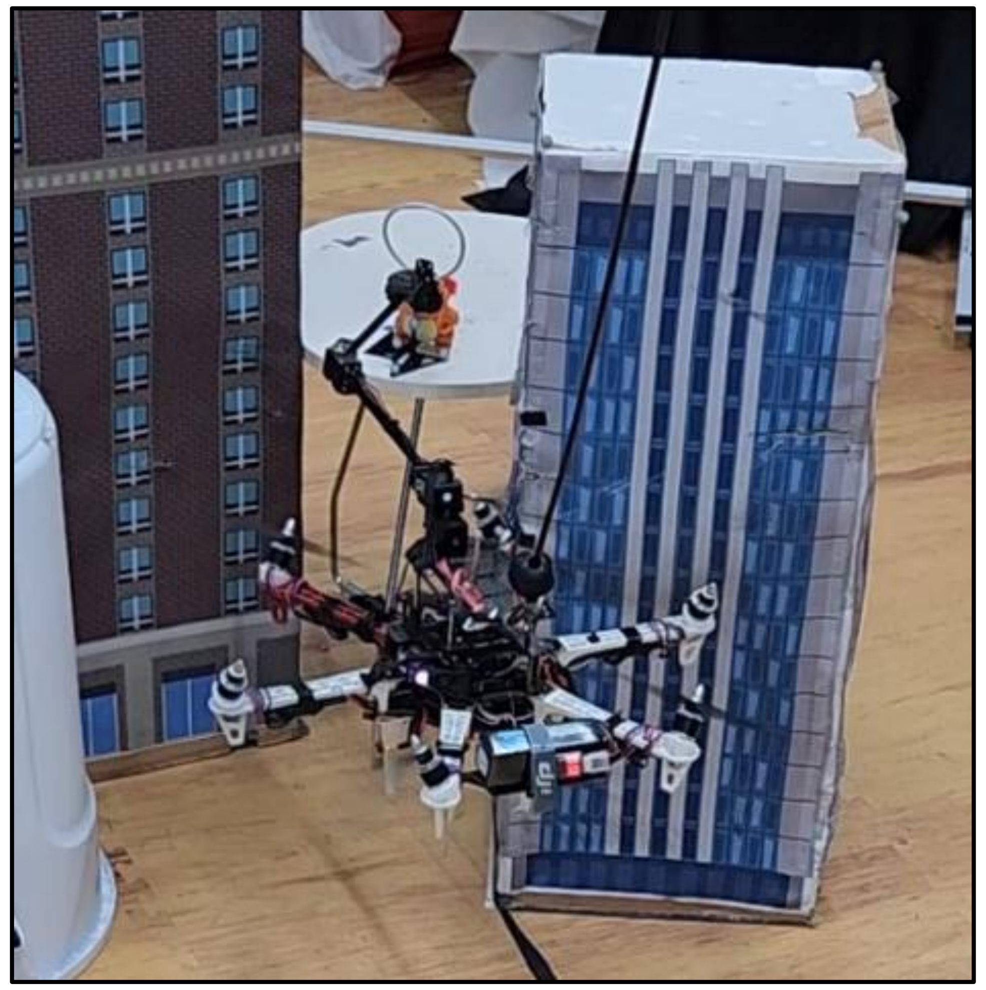
Motivation

Safety in Aerial Physical Interaction

- Well-known robot safety: Collision avoidance



[Video] Failure case due to the collision [1]

- Specific safety for Aerial Physical Interaction: Motor saturation avoidance

[Video] Failure case due to motor saturation [2]

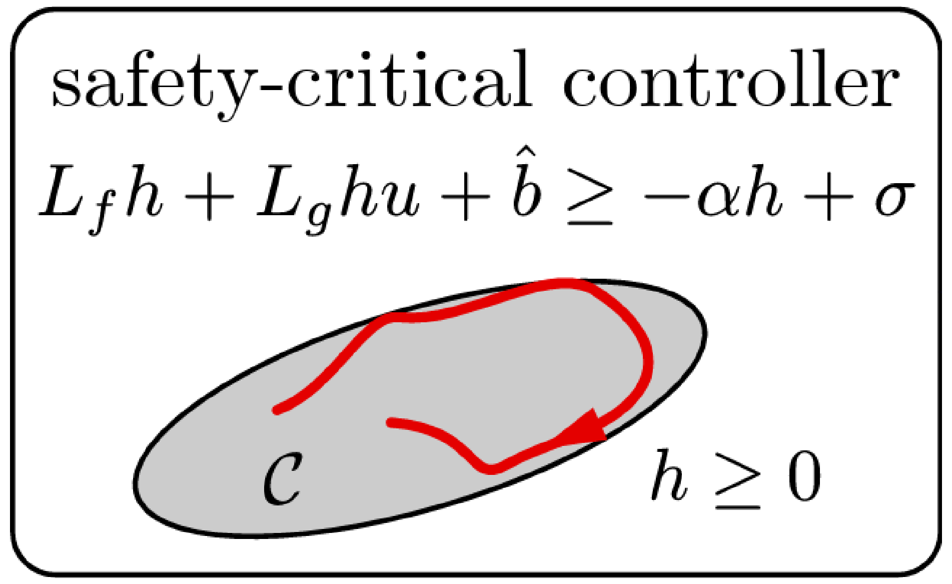
- Other safety constraints: Power flow limit [3], speed limit, compliance, etc.

[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.
[2] D. Lee, H. Seo, I. Jang, S. J. Lee and H. J. Kim, "Aerial Manipulator Pushing a Movable Structure Using a DOB-Based Robust Controller," in *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 723-730, April 2021
[3] E. Cuniato, N. Lawrance, M. Tognon and R. Siegwart, "Power-Based Safety Layer for Aerial Vehicles in Physical Interaction Using Lyapunov Exponents," in *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 6774-6781, July 2022

Motivation

Safety-“Critical” Aerial Physical Interaction

- Safety-critical control
  - ✓ Controller with mathematical proven safety constraints.
  - ✓ Examples: Reachable Forward Set (RFS) [4], Control Barrier Function (CBF) [5], Model Predictive Controller (MPC) [6], etc ⋯
  - ✓ Our choice: Control Barrier Function
    - ➢ Fast computation with quadratic programming (QP)-based optimization with linear inequalities
    - ➢ No need for explicit physical interaction model
    - ➢ Rigorous guarantee on system safety and dynamic feasibility

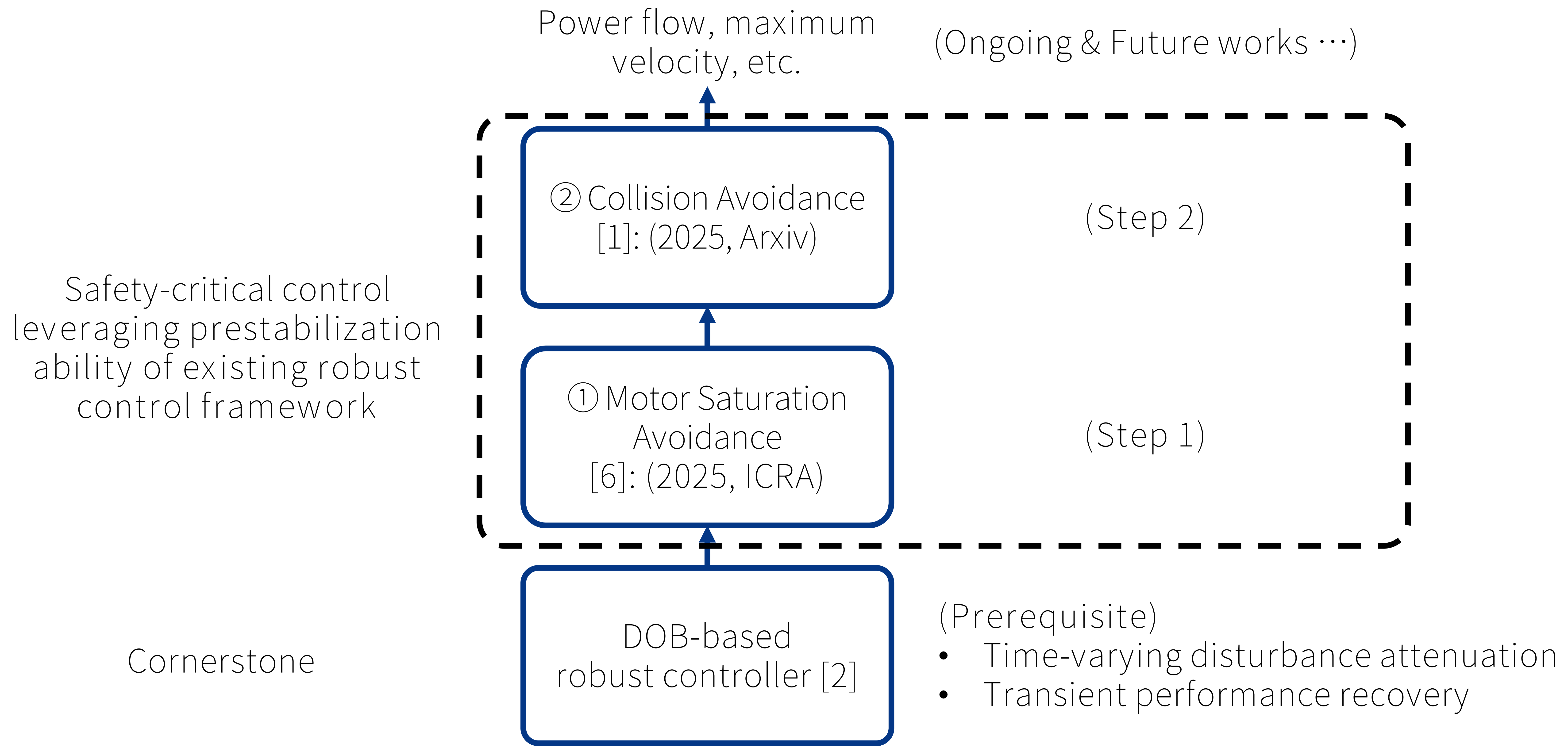


[Fig] Illustration of the formal behavior of a system under safety-critical control framework. [5]

[4] Lee, D., Seo, H., Kim, D., & Kim, H. J. (2020, May). Aerial manipulation using model predictive control for opening a hinged door. In *2020 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 1237-1242). IEEE.
[5] A. Alan, T. G. Molnar, E. Das, A. D. Ames, and G. Orosz, “Disturbance observers for robust safety-critical control with control barrier functions,” IEEE Control Systems Letters, vol. 7, pp. 1123–1128, 2022.
[6] Jang, Inkyu, et al. "Robust and recursively feasible real-time trajectory planning in unknown environments." *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021.

Motivation

Steps Towards Safer Aerial Physical Interaction

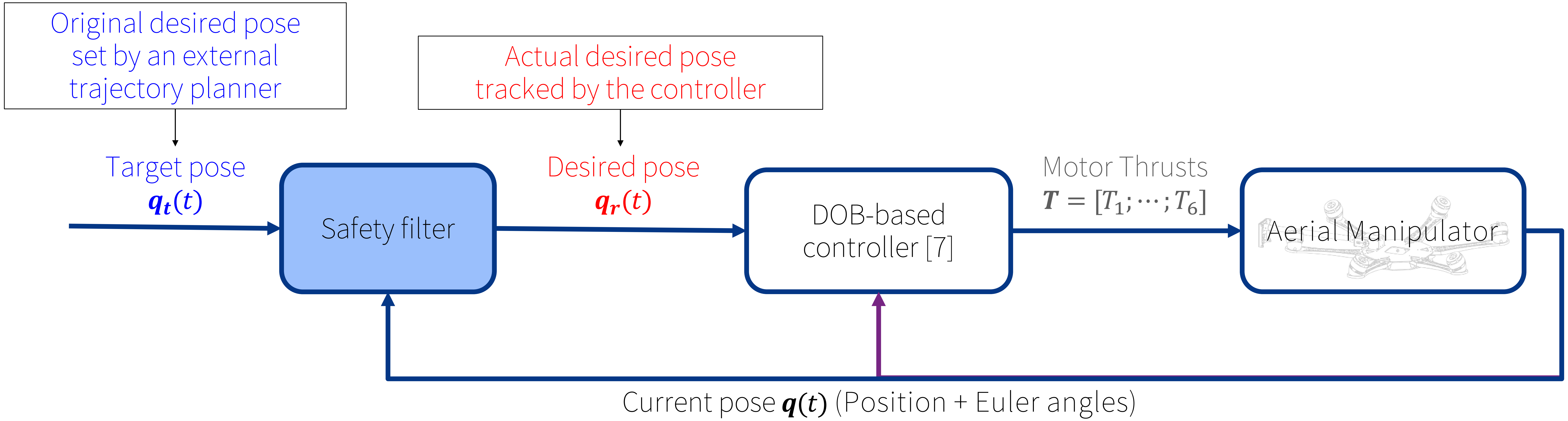


[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.
[2] D. Lee, H. Seo, I. Jang, S. J. Lee and H. J. Kim, "Aerial Manipulator Pushing a Movable Structure Using a DOB-Based Robust Controller," in *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 723-730, April 2021
[6] J. Byun, Y. Kim, D. Lee and H. J. Kim, "Safety-Critical Control for Aerial Physical Interaction in Uncertain Environment," *2025 IEEE International Conference on Robotics and Automation (ICRA)*, Atlanta, GA, USA, 2025, pp. 7526-7532

1st Step: Motor Saturation Avoidance

Motor Saturation-Aware Safety-Critical Controller

- Safety filter (Proposed) + DOB-based controller [7]
  - Divide the entire control law into the outer-loop (safety filter) and inner-loop (DOB-based controller) to leverage high performance of the DOB-based controller



[7] W. Ha and J. Back, "A disturbance observer-based robust tracking controller for uncertain robot manipulators," International Journal of Control, Automation and Systems, vol. 16, pp. 417–425, 2018.

1st Step: Motor Saturation Avoidance

Motor Saturation-Aware Safety-Critical Controller

- Safety filter (Proposed)

① Integrated system of control framework & nominal dynamics

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}\ddot{\boldsymbol{q}}_r + \boldsymbol{w}(\tilde{\boldsymbol{d}})$$

- $\boldsymbol{x} \in \mathbb{R}^{36}$: Current pose & twist / desired pose & twist / DOB variables
- $\boldsymbol{w}(\tilde{\boldsymbol{d}})$: Model uncertainty arisen by imperfect disturbance attenuation

② Motor saturation CBFs: "$\boldsymbol{T} = \boldsymbol{T}(\boldsymbol{x})$"

$$h_{T,i}(\boldsymbol{x}) = \left(\frac{T_{\max} - T_{\min}}{2}\right)^2 - \left(T_i(\boldsymbol{x}) - \frac{T_{\max} + T_{\min}}{2}\right)^2, i = 1, \cdots, 6$$

- **Formal formulation of robust CBF-QP** [5]

$$\min_{\ddot{\boldsymbol{q}}_r} \|\ddot{\boldsymbol{q}}_r - \ddot{\boldsymbol{q}}_t\|^2$$

$$\begin{aligned} s.t.\ & \sigma_{T,1} - \hat{\beta}_{T,1}(\boldsymbol{x}) \le \mathcal{L}_f h_{T,1}(\boldsymbol{x}) + \mathcal{L}_g h_{T,1}(\boldsymbol{x})\ddot{\boldsymbol{q}}_r + \gamma_{T,1} h_{T,1}(\boldsymbol{x}) \\ & \vdots \\ & \sigma_{T,6} - \hat{\beta}_{T,6}(\boldsymbol{x}) \le \mathcal{L}_f h_{T,6}(\boldsymbol{x}) + \mathcal{L}_g h_{T,6}(\boldsymbol{x})\ddot{\boldsymbol{q}}_r + \gamma_{T,1} h_{T,6}(\boldsymbol{x}) \end{aligned}$$

Estimations of $\boldsymbol{w}(\tilde{\boldsymbol{d}})$-related terms

Nominal CBF constraint:
$0 \le \dot{h}_{T,i}(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \gamma_{T,i}(\boldsymbol{x}) h_{T,i}(\boldsymbol{x})$

Positive parameters for robustness

[5] A. Alan, T. G. Molnar, E. Das, A. D. Ames, and G. Orosz, "Disturbance observers for robust safety-critical control with control barrier functions," IEEE Control Systems Letters, vol. 7, pp. 1123–1128, 2022.

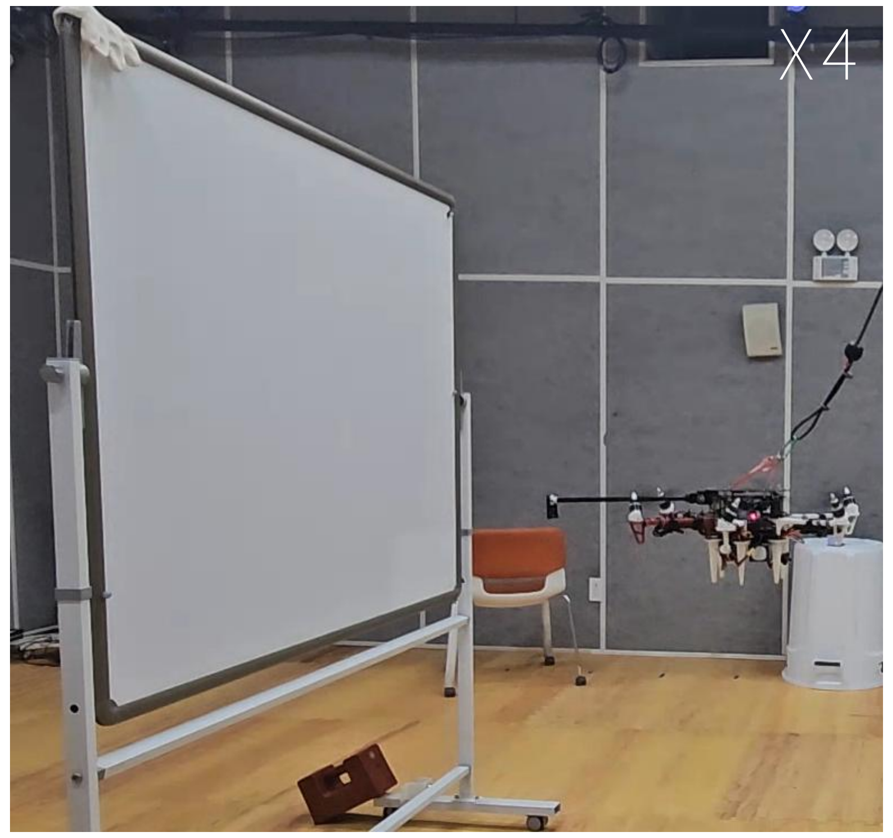
1st Step: Motor Saturation Avoidance

Comparative Experiments

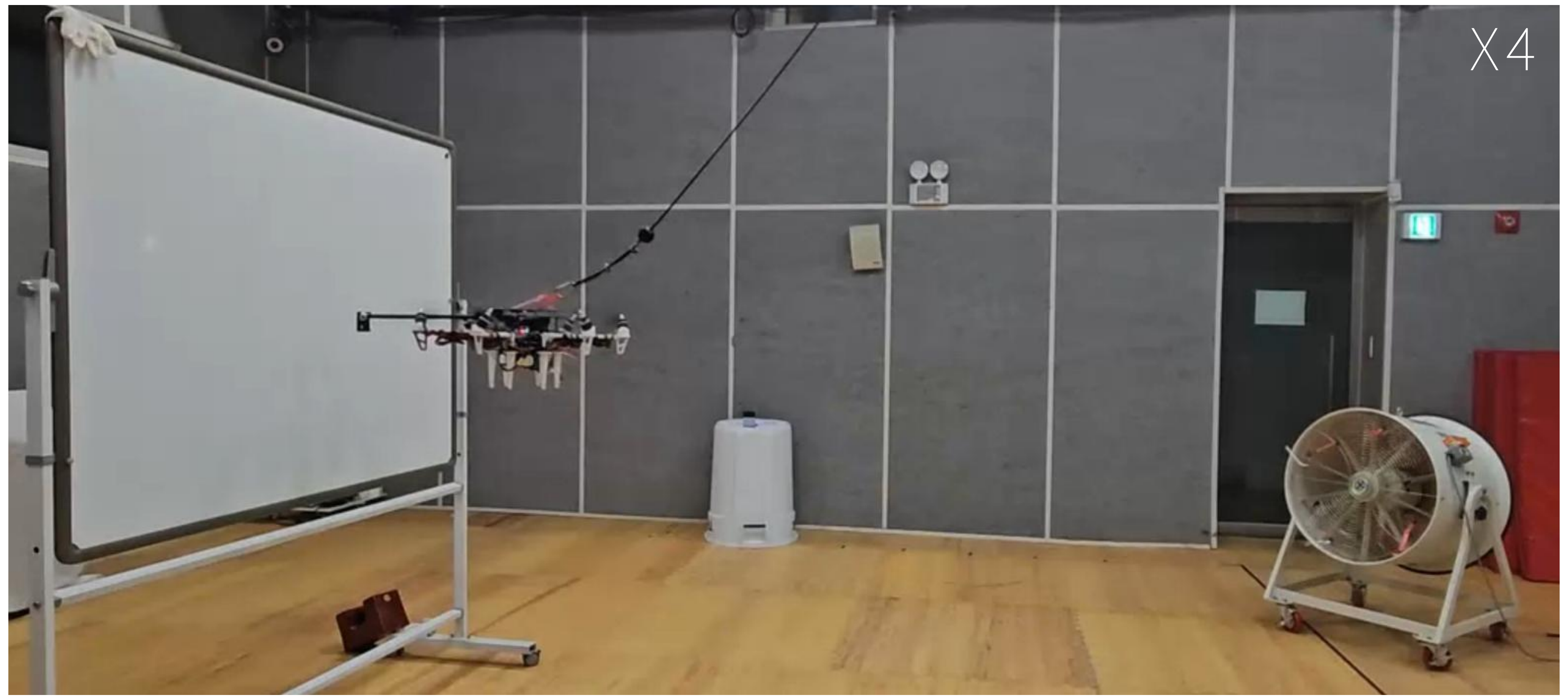
- What if the target pose is located in unreachable regions?
  1) Pushing a static wall: Target pose beyond the wall

	Method	Remarks
Baseline 1	DOB + Thrust clipping	$T_i = \min(\max(T_{d,i}, T_m), T_M)$
Baseline 2	DOB + Thrust adjustment by CBF	Control affine system with $\dot{\boldsymbol{T}}$ as an input
Proposed	DOB + Reference adjustment by CBF	Control affine system with $\ddot{\boldsymbol{q}}_{\boldsymbol{r}}$ as an input

[Video] Baseline 1



[Video] Baseline 2



[Video] Proposed

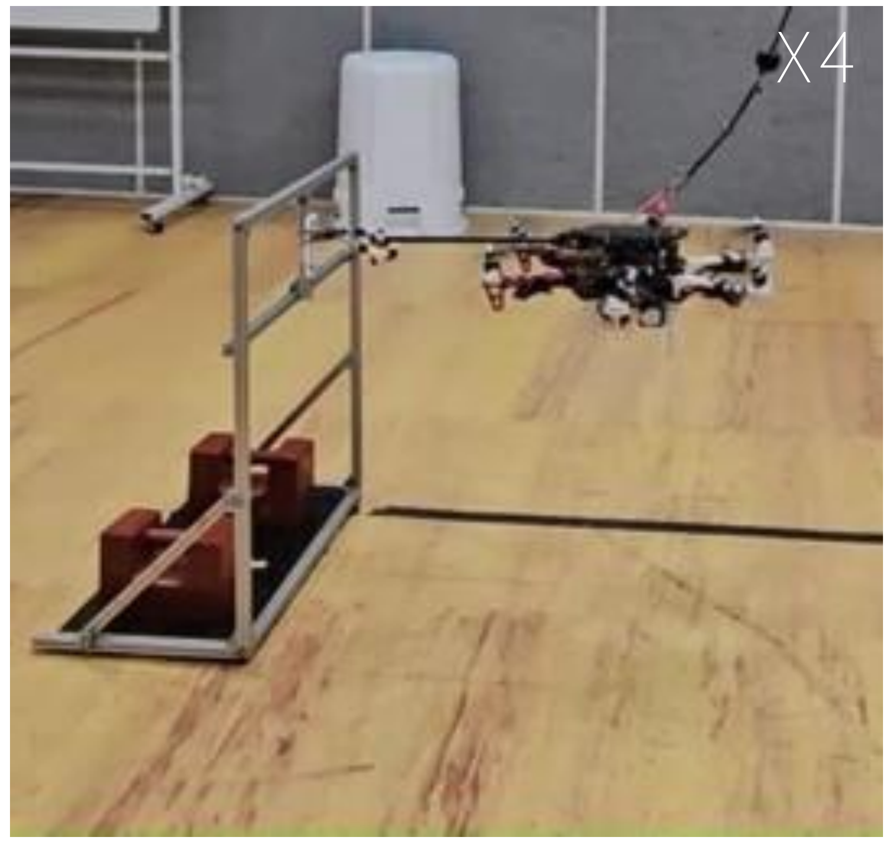
[6] J. Byun, Y. Kim, D. Lee and H. J. Kim, "Safety-Critical Control for Aerial Physical Interaction in Uncertain Environment," *2025 IEEE International Conference on Robotics and Automation (ICRA)*, Atlanta, GA, USA, 2025, pp. 7526-7532

1st Step: Motor Saturation Avoidance

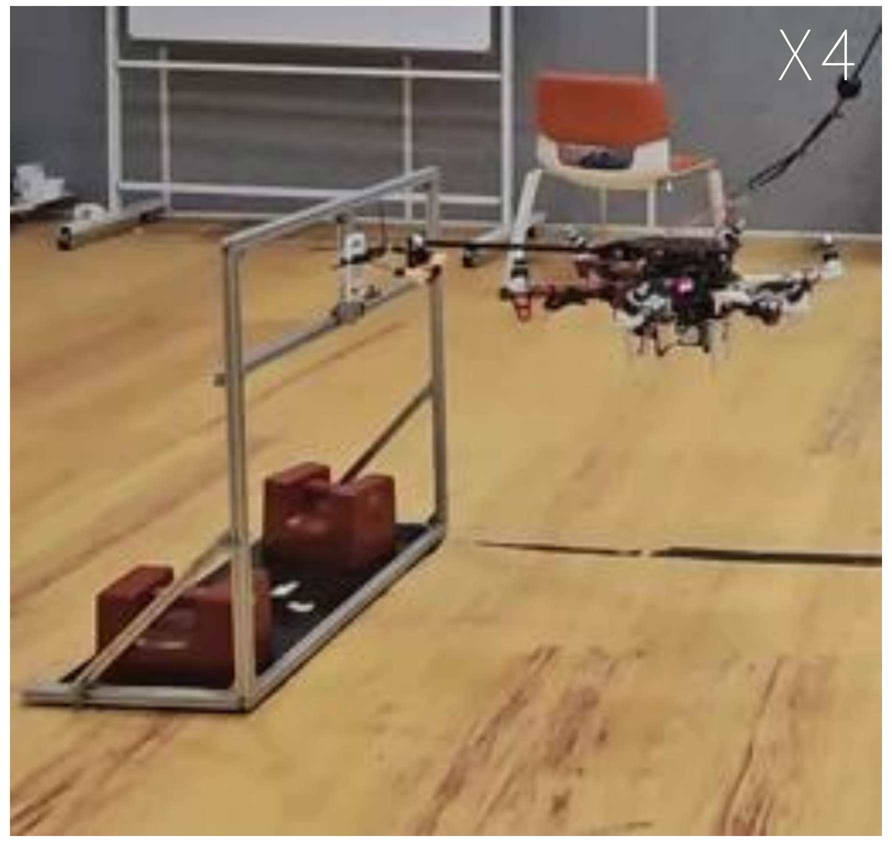
Comparative Experiments

- What if the target pose is not reachable?
  2) Pulling a firmly attached plug: Target pose is located away from the socket in the pulling direction.

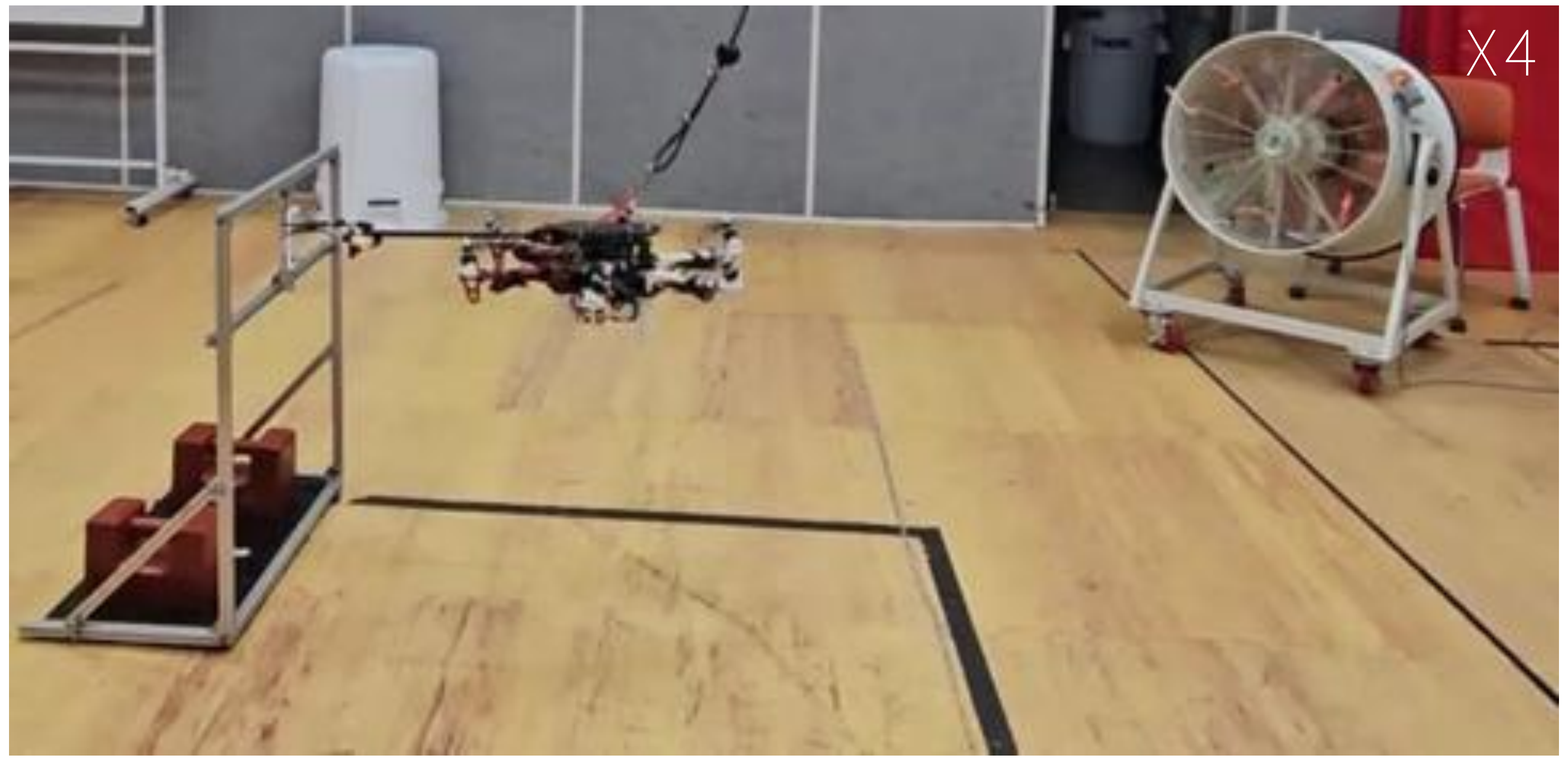
	Method	Remarks
Baseline 1	DOB + Thrust clipping	$T_i = \min(\max(T_{d,i}, T_m), T_M)$
Baseline 2	DOB + Thrust adjustment by CBF	Control affine system with $\dot{\boldsymbol{T}}$ as an input
Proposed	DOB + Reference adjustment by CBF	Control affine system with $\ddot{\boldsymbol{q}}_{\boldsymbol{r}}$ as an input



[Video] Baseline 1



[Video] Baseline 2



[Video] Proposed

[6] J. Byun, Y. Kim, D. Lee and H. J. Kim, "Safety-Critical Control for Aerial Physical Interaction in Uncertain Environment," *2025 IEEE International Conference on Robotics and Automation (ICRA)*, Atlanta, GA, USA, 2025, pp. 7526-7532

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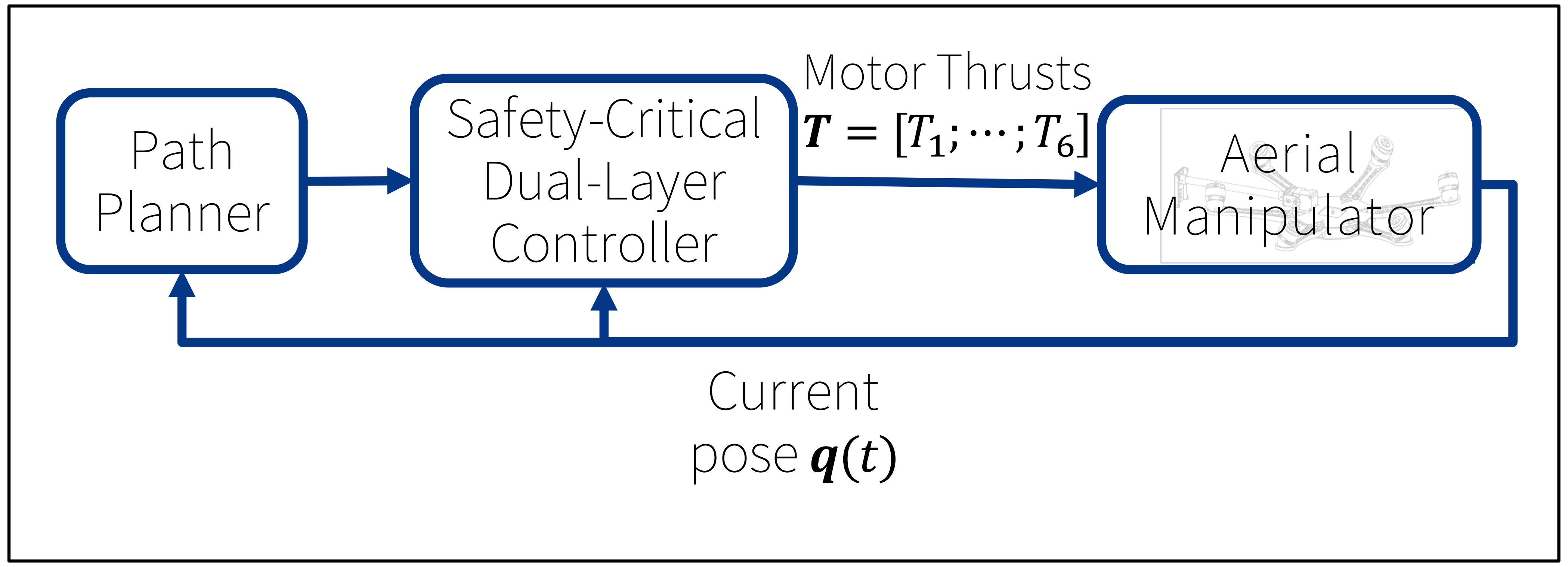
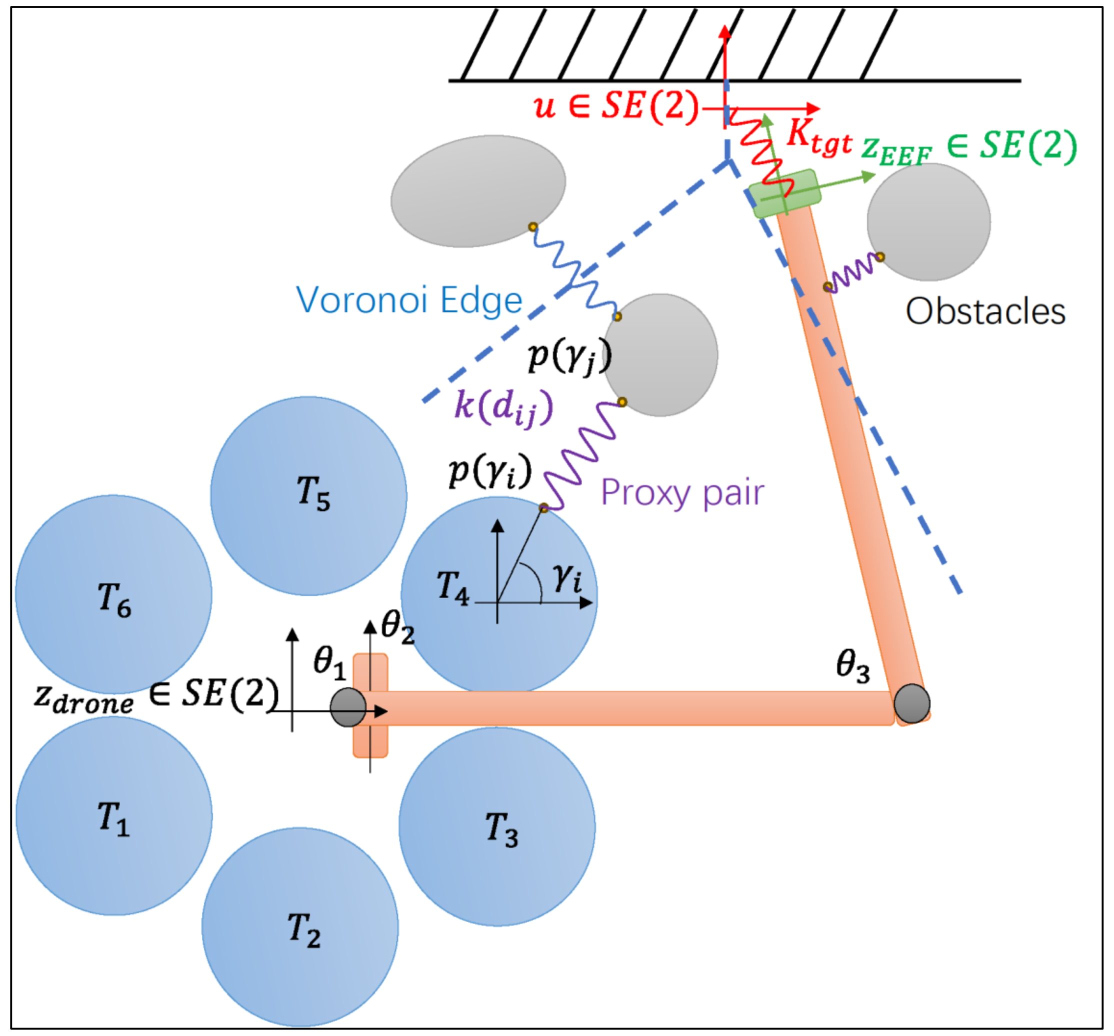
2nd Step: Collision Avoidance

Planning and Control for Collision Avoidance

- Objective
  - ✓ Passing through a narrow gap that can only be traversed by the thin linkages of the robot arm
  - ✓ Still, avoiding motor saturation



[Fig] Controller Diagram



[Fig] Illustration of the aerial manipulator's end-effector reaching its goal position [2]

[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.

2nd Step: Collision Avoidance

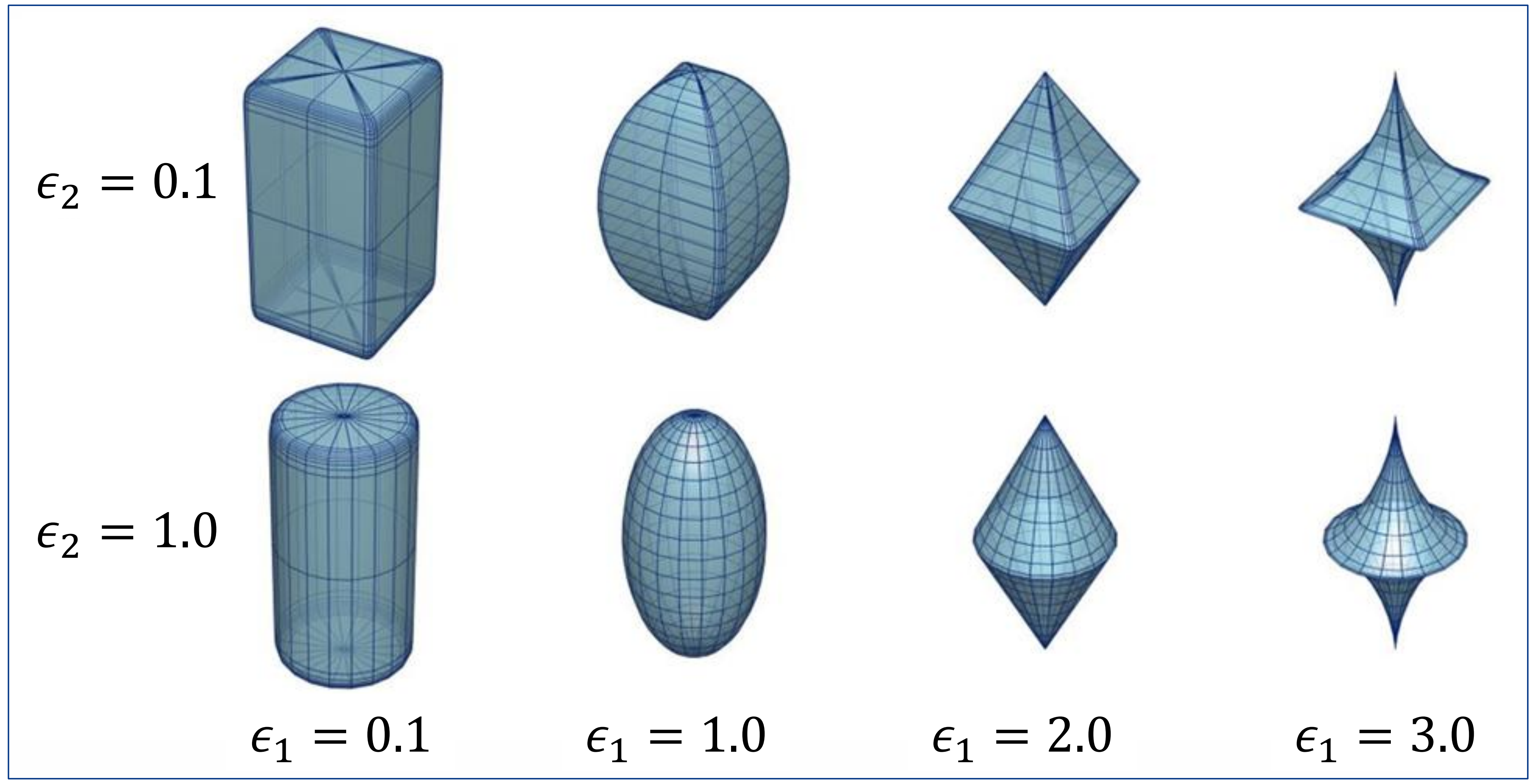
Geometric Representation of Vehicle & Obstacles

- Superquadrics (SQs): Reduced conservativeness
  - ✓ Implicit equation [8]

$$F(x,y,z) = \left(\left(\frac{x}{a_1}\right)^{2/\epsilon_2} + \left(\frac{y}{a_2}\right)^{2/\epsilon_2} \right)^{\epsilon_2/\epsilon_1} + \left(\frac{z}{a_3}\right)^{2/\epsilon_1}$$

If F $>$ 1 (outside), F=1 (on), F $<$ 1 (inside)

- Advantages
  - Compact parameterization: Low Storage requirements & Low computational overhead
  - Wide shape variability: Broad range of shapes - Near-spherical to box-like.
  - Smooth surfaces: Continuously differentiable (C^1) surfaces
    → Ideal for gradient-based computations and optimization



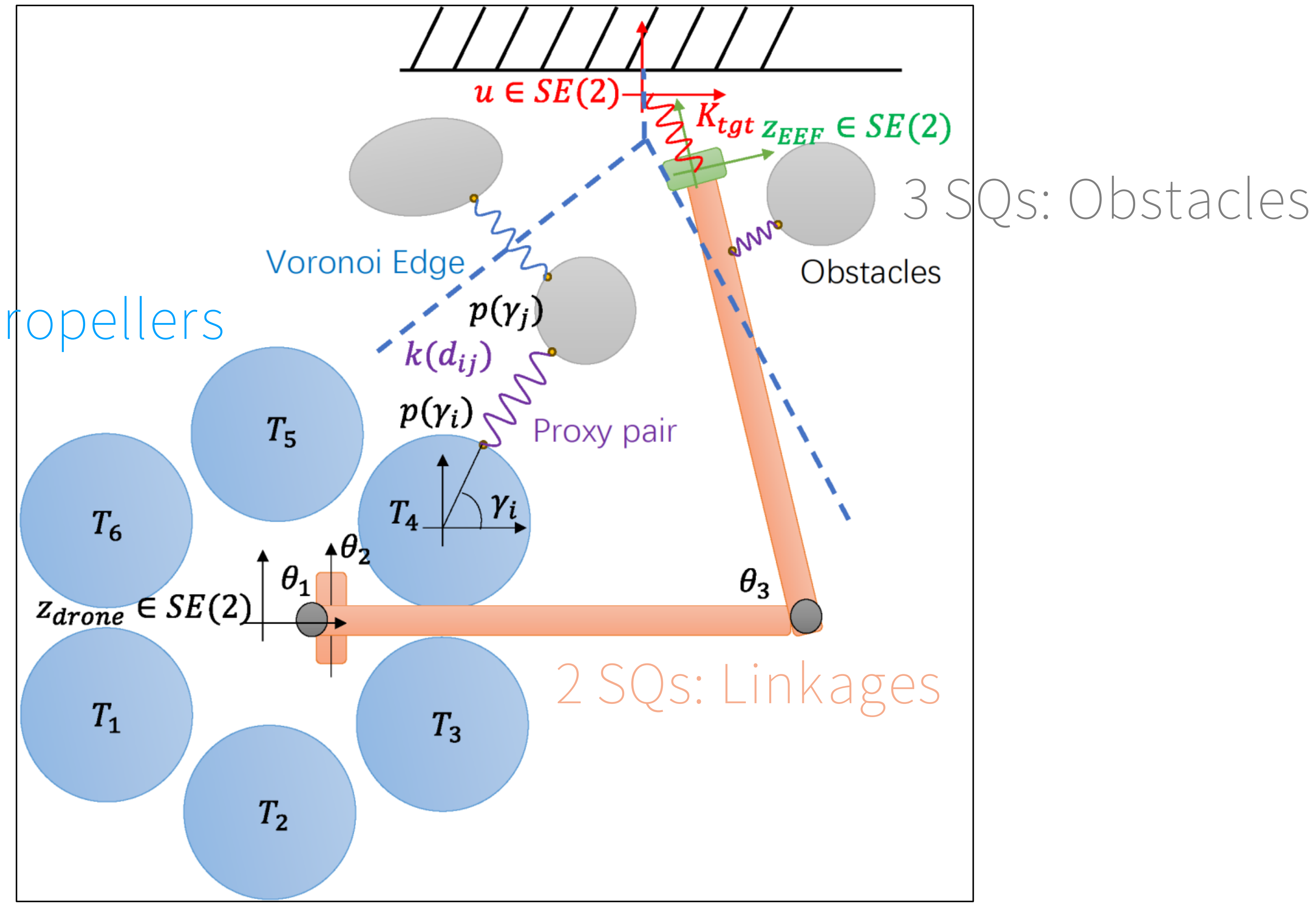
[Fig] Illustration of wide shape variability of superquadrics [8].

[8] A. Jaklic, A. Leonardis, and F. Solina, Segmentation and recovery of superquadrics, vol. 20. Springer Science & Business Media, 2000.

2nd Step: Collision Avoidance

Whole-Body Path Planner

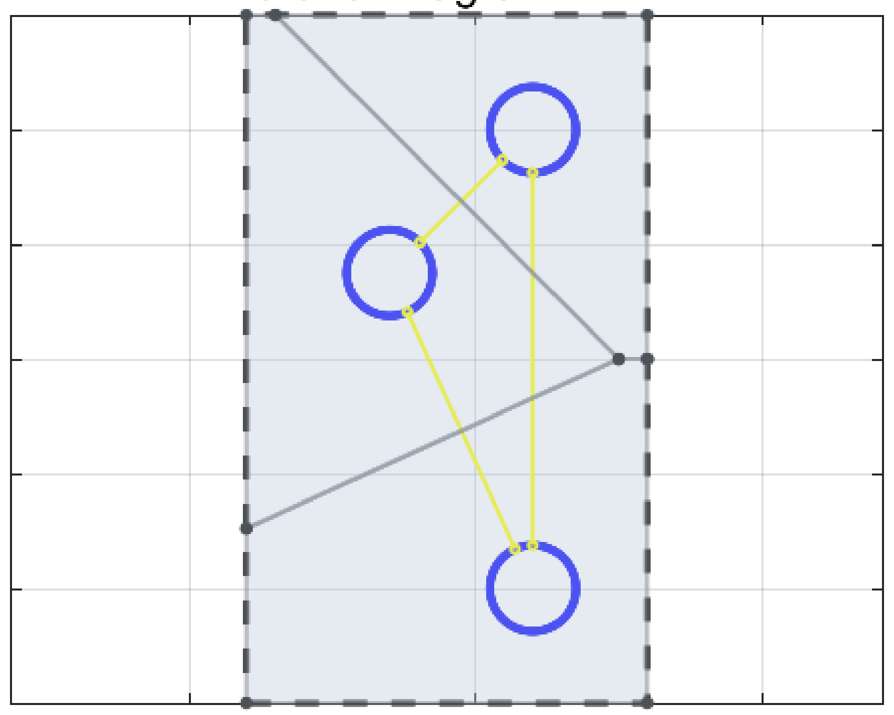
- SQs representation [1]



[Fig] SQ representations for our hexarotor-based aerial manipulator with 2-link robot arm and obstacles

- Maximum Clearance Whole-Body Path Planner [2]

1) Voronoi Diagram based on obstacle SQs



2) Generate path on equilibrium manifold [9]

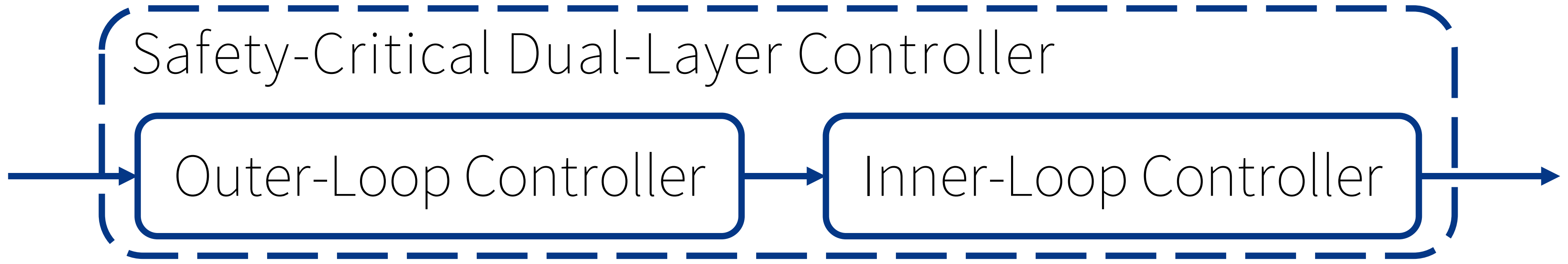
→ Potential function-based method attracting pose of the end-effector

Collision avoidance potential
+
Goal-attracting potential

[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.
[9] Campolo, D., & Cardin, F. (2025). A geometric framework for quasi-static manipulation of a network of elastically connected rigid bodies. *Applied Mathematical Modelling*, *143*, 116003.

2nd Step: Collision Avoidance

Safety-Critical Dual-Layer Control Architecture



1) Outer-Loop Controller (Robust CBF-QP)
   - Constraint 1: Motor saturation-aware CBF [6]

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[2] D. Lee, H. Seo, I. Jang, S. J. Lee and H. J. Kim, "Aerial Manipulator Pushing a Movable Structure Using a DOB-Based Robust Controller," in *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 723-730, April 2021
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[10] Yang, L., Turlapati, S. H., Lv, C., & Campolo, D. (2025). Planning for quasi-static manipulation tasks via an intrinsic haptic metric: a book insertion case study. *IEEE Robotics and Automation Letters*

2nd Step: Collision Avoidance

Safety-Critical Dual-Layer Control Architecture

Safety-Critical Dual-Layer Controller

→ Outer-Loop Controller → Inner-Loop Controller →

1) Outer-Loop Controller (Robust CBF-QP)

- Constraint 1: Motor saturation-aware CBF [6]
- Constraint 2: SQ Distance-based CBF [1]

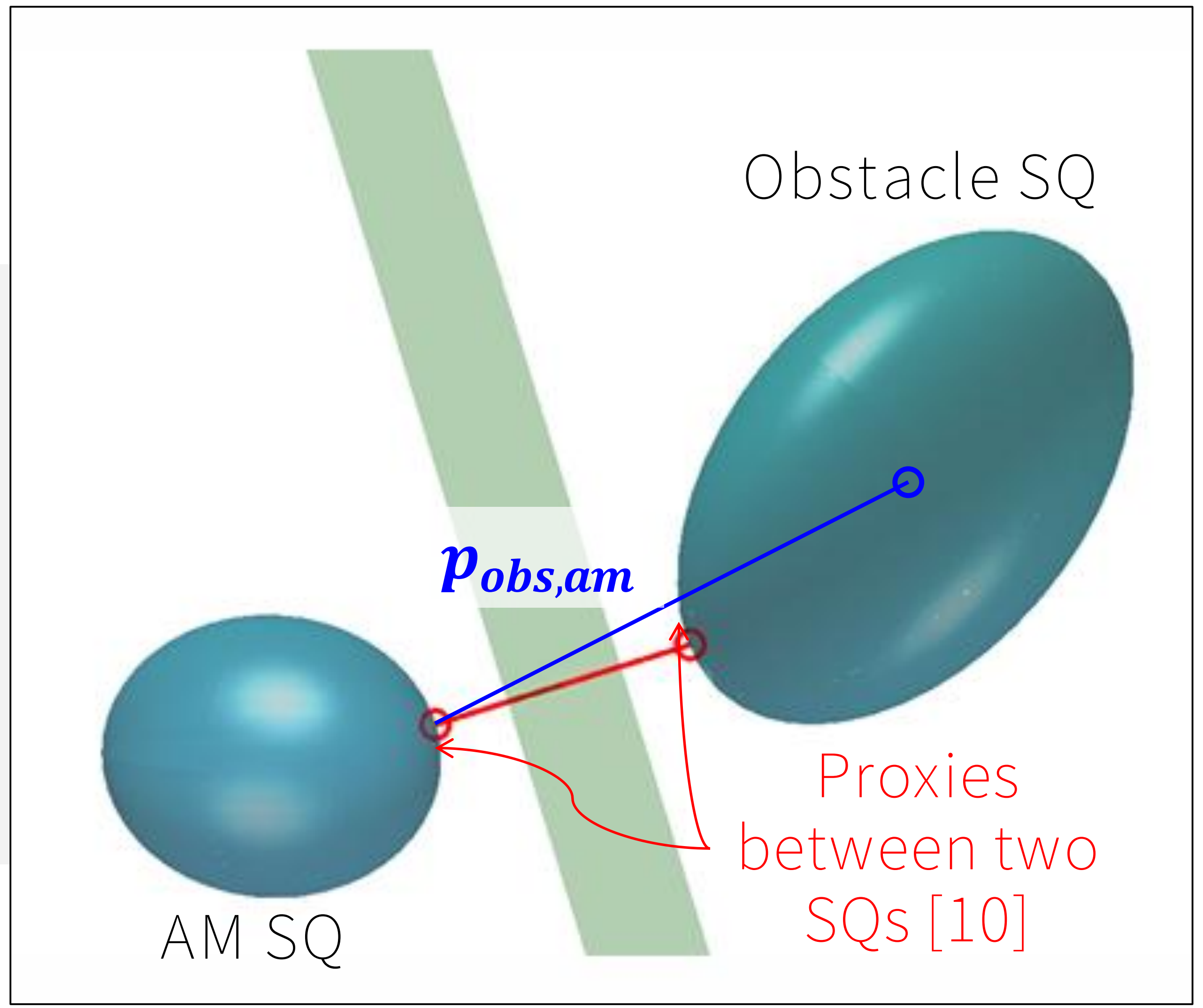
$$\rightarrow h_{co} = \boxed{\log}\left(F\left(\boldsymbol{p}_{obs,am}\right)\right)$$

$$F(x,y,z) = \left(\left(\frac{x}{a_1}\right)^{2/\epsilon_2} + \left(\frac{y}{a_2}\right)^{2/\epsilon_2}\right)^{\epsilon_2/\epsilon_1} + \left(\frac{z}{a_3}\right)^{2/\epsilon_1}$$

If F > 1 (outside), F=1 (on), F < 1 (inside)

Why? $F(\cdot)$ rapidly increases as the distance becomes larger.

$$\rightarrow \ddot{h}_{co} + \gamma_{co}\dot{h}_{co} + \gamma_{co}^2 h_{co} \geq -\hat{\beta}_{co} + \sigma_{co}$$ → Instantly avoid collision upon path following error.



[Fig] Illustration of the proxies and distance between them [10]

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[2] D. Lee, H. Seo, I. Jang, S. J. Lee and H. J. Kim, "Aerial Manipulator Pushing a Movable Structure Using a DOB-Based Robust Controller," in *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 723-730, April 2021
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2nd Step: Collision Avoidance

Safety-Critical Dual-Layer Control Architecture

Safety-Critical Dual-Layer Controller

Outer-Loop Controller → Inner-Loop Controller

1) Outer-Loop Controller (Robust CBF-QP)
   - Constraint 1: Motor saturation-aware CBF [6]
   - Constraint 2: SQ Distance-based CBF [1]

$$\rightarrow h_{co} = \boxed{\log}\left(F(\boldsymbol{p}_{obs,am})\right)$$

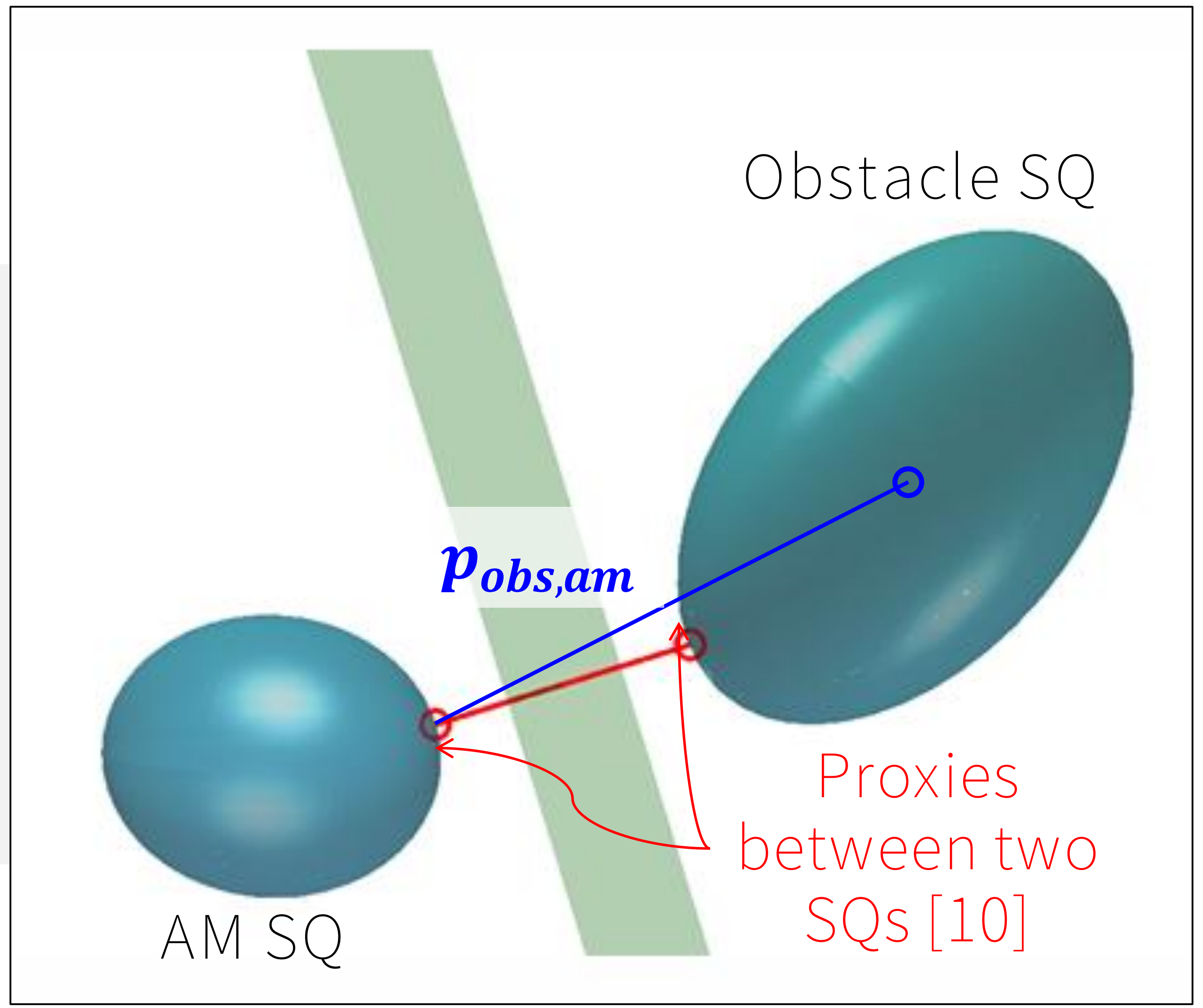
$$F(x,y,z) = \left(\left(\frac{x}{a_1}\right)^{2/\epsilon_2} + \left(\frac{y}{a_2}\right)^{2/\epsilon_2}\right)^{\epsilon_2/\epsilon_1} + \left(\frac{z}{a_3}\right)^{2/\epsilon_1}$$

If F $>$ 1 (outside), F=1 (on), F $<$ 1 (inside)

Why? $F(\cdot)$ rapidly increases after 1.

$$\rightarrow \ddot{h}_{co} + \gamma_{co}\dot{h}_{co} + \gamma_{co}^2 h_{co} \geq -\hat{\beta}_{co} + \sigma_{co}$$ → Instantly avoid collision upon path following error.

2) Inner-Loop Controller: DOB-based controller [2]



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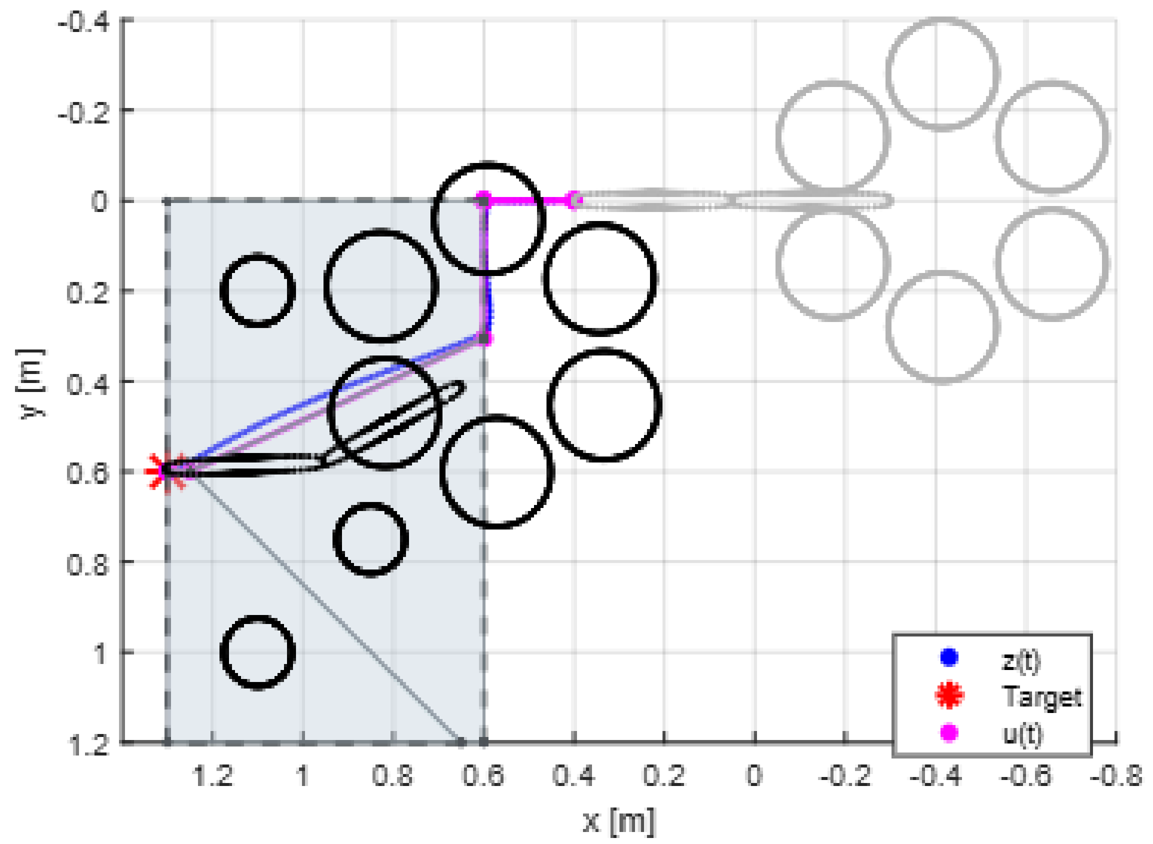
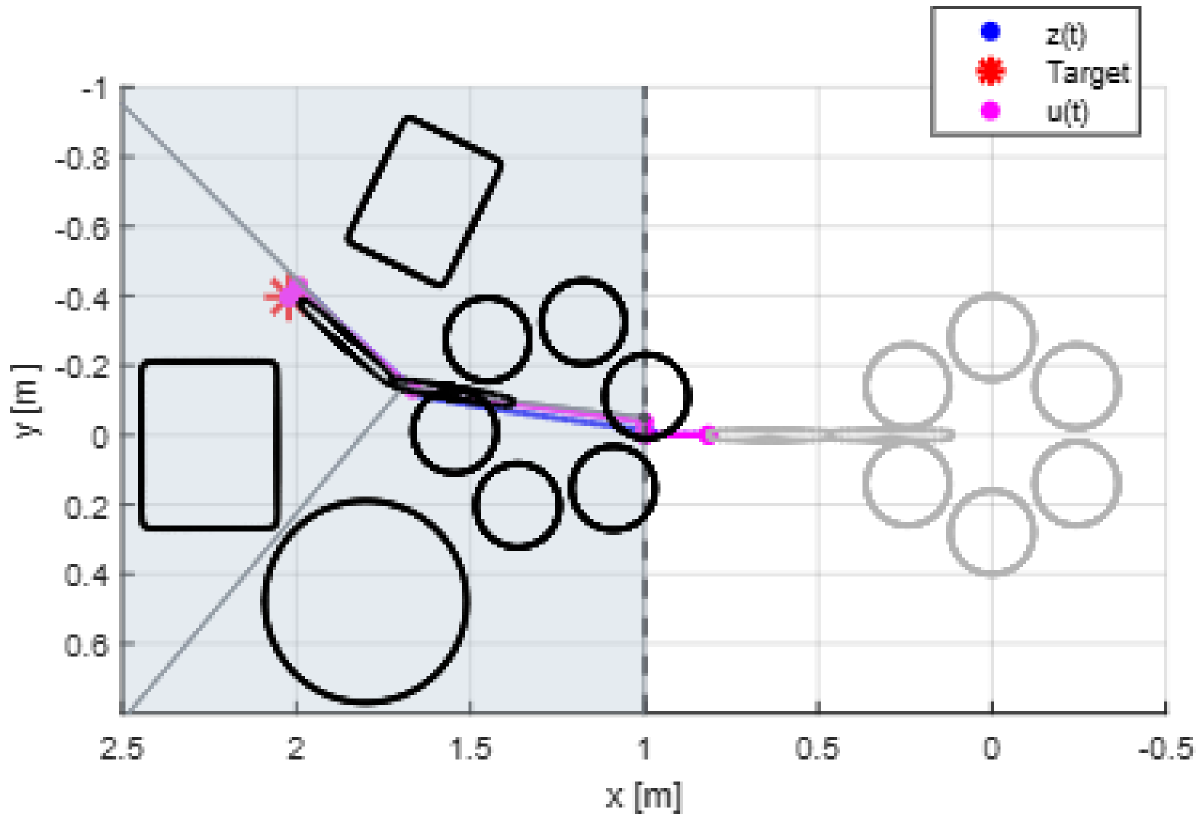
2nd Step: Collision Avoidance

Path Planning Results in Simulation

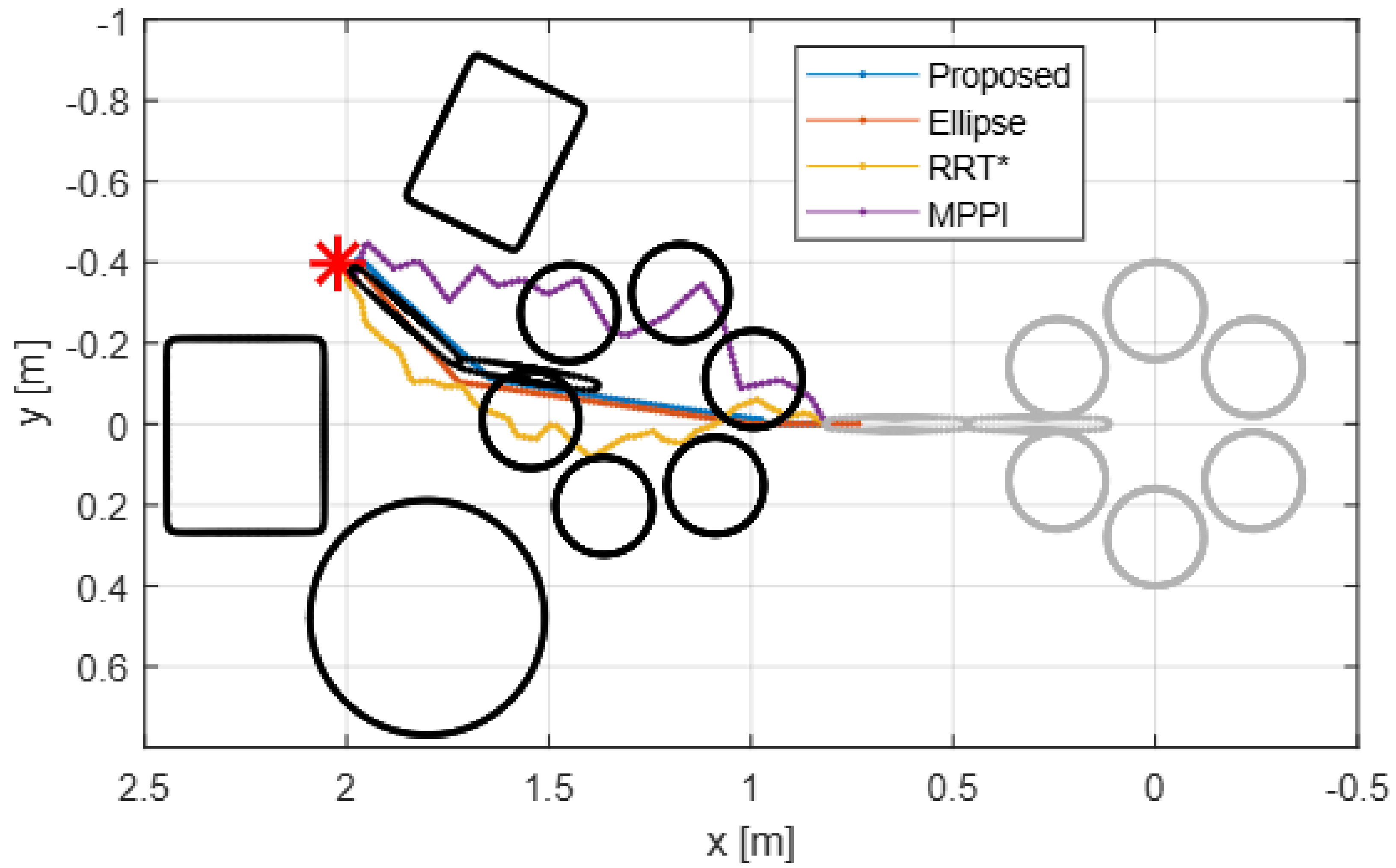
- Picking a target object [1]



[Fig] Environment with a narrow gap



[Fig] Environment with different obstacle shapes



Method	Time	Min-distance	Arc-length	Jerkiness
Proposed	0.128	0.0644	1.375	0.0016
Ellipse	0.113	-0.0049	1.383	0.0001
RRT*	105.8	0.0314	1.565	0.0032
MPPI	0.552	0.0039	1.721	0.0057

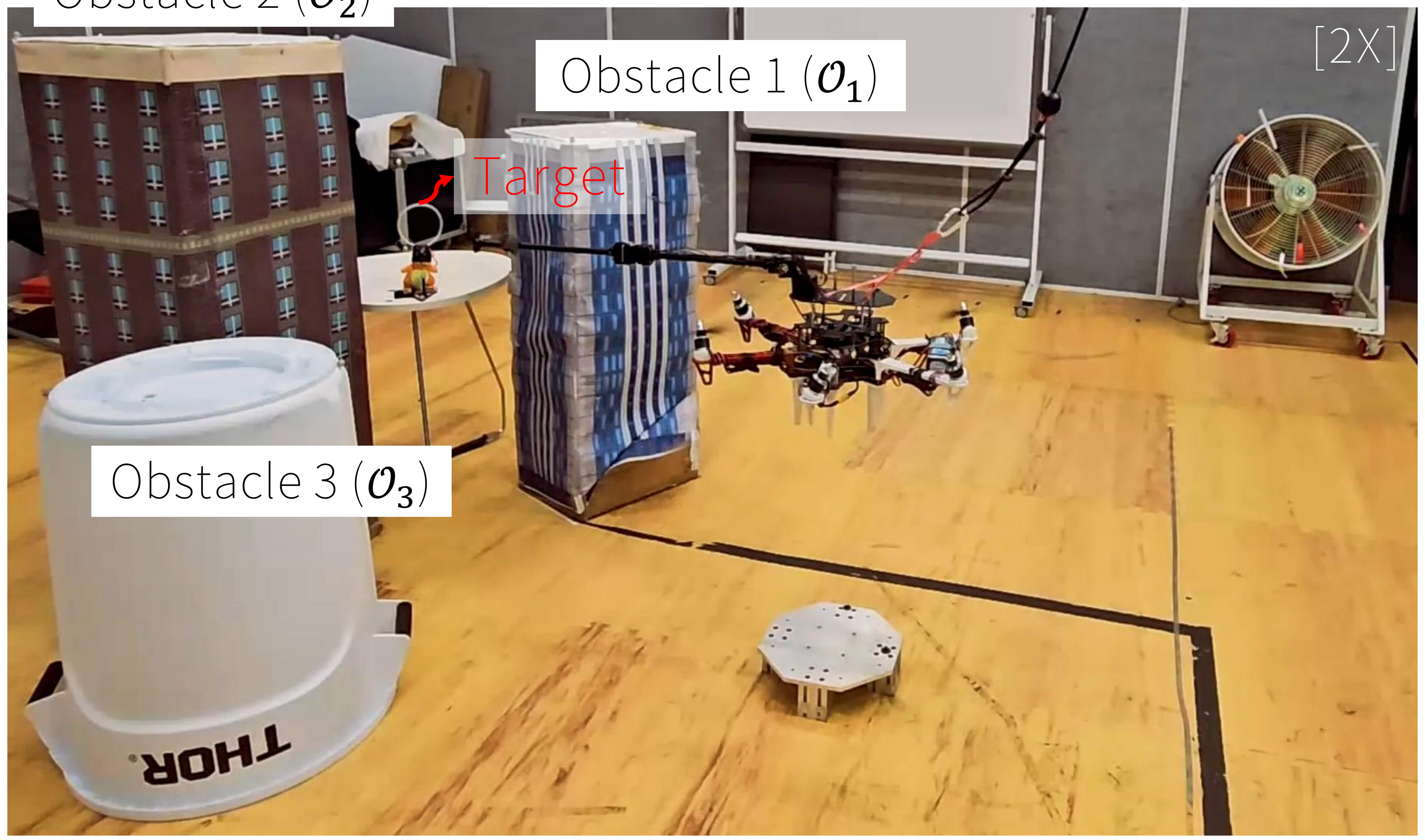
[Fig] Comparative simulations

[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.

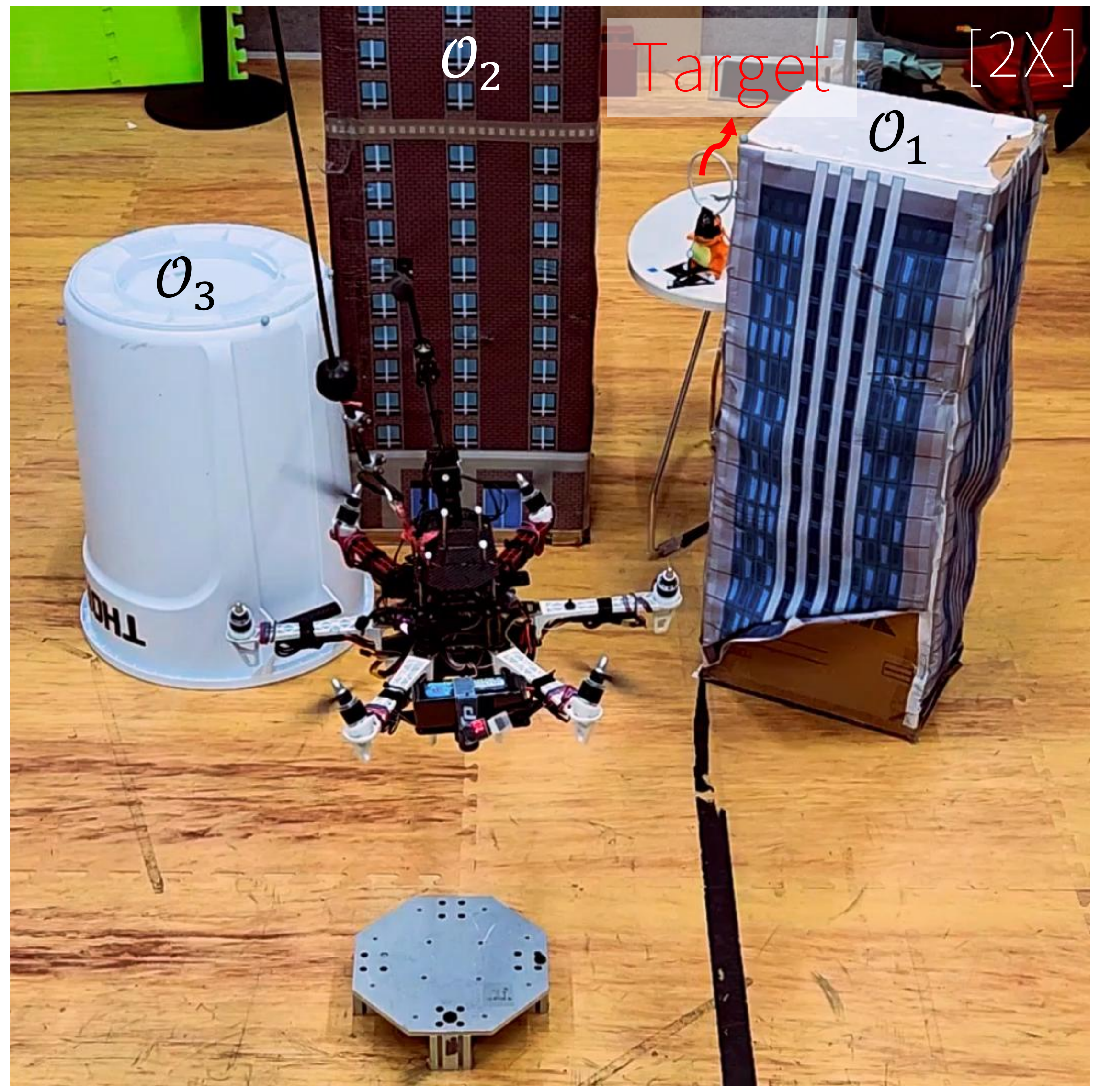
2nd Step: Collision Avoidance

Experimental Result

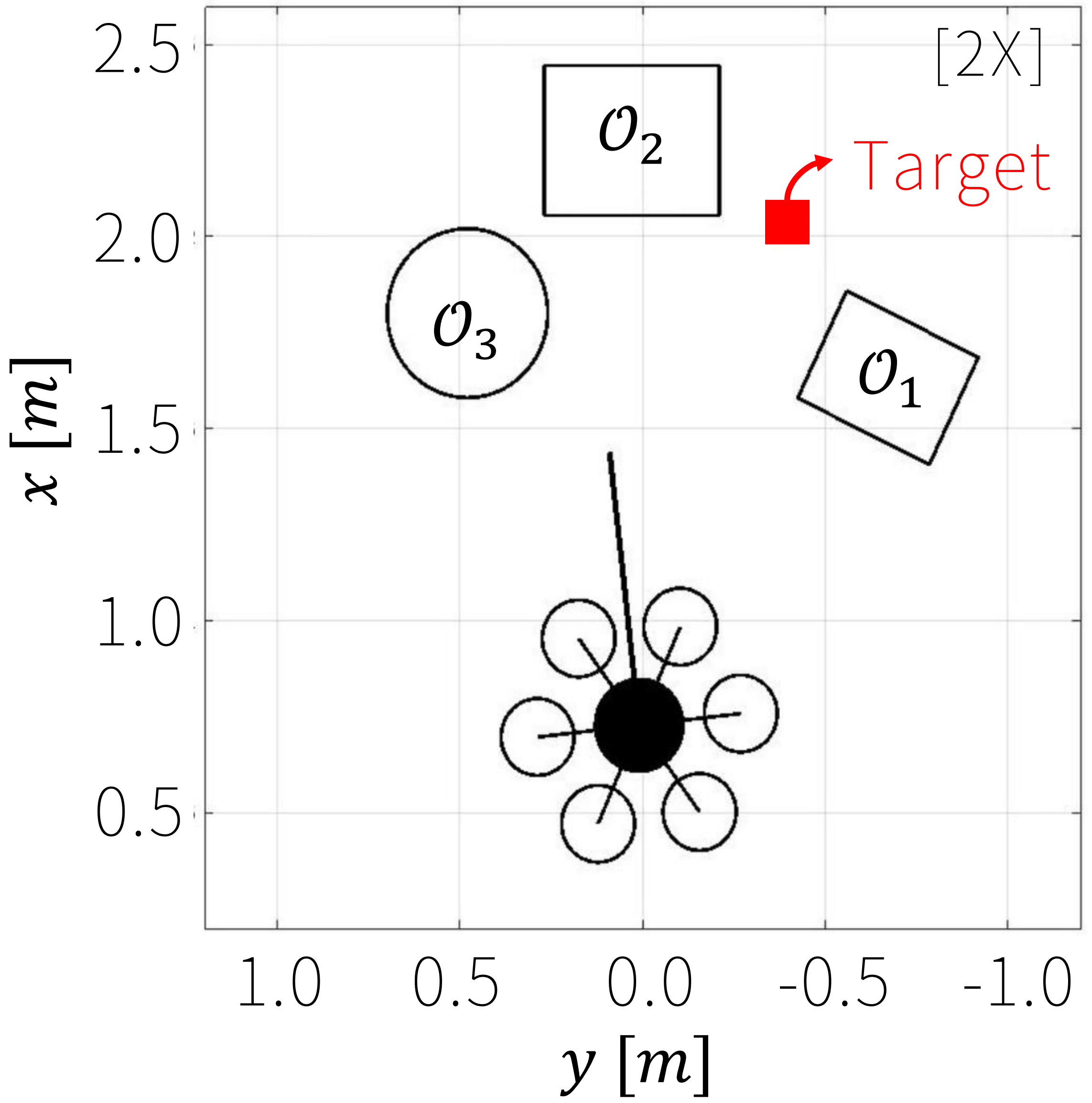
- Picking a target object [1]



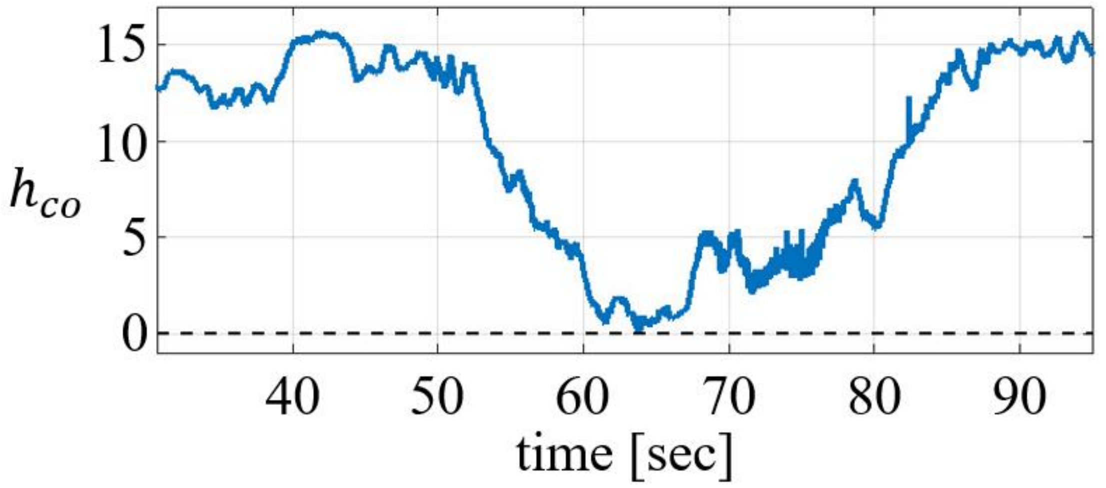
[Video] Side view video



[Video] Front view video



[Video] Top view animation



[Fig] History of collision-avoidance CBF with its minimum value of 0.115

[1] L. Yang, J. Lee, D. Campolo, H. J. Kim, and J. Byun, "Whole-body motion planning and safety-critical control for aerial manipulation," arXiv preprint arXiv:2511.02342, 2025.

Conclusion

Takeaways

- Can achieve strict enforcement of safety constraints through a CBF-based formulation built on the existing control law.
- Can realize effective collision avoidance in cluttered environments by combining superquadrics geometric representations.

Future Directions

- Further explore stronger mathematical guarantees on safety.
- Find sweet spot between stability and safety.
- Implement and compare existing safety-critical controllers to aerial physical interaction.

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Thank you

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Dr. Dongjae Lee (CMU, USA)

Mr. Lin Yang (NTU, Singapore)

Mr. Dohyun Eom (SNU, Korea)

Mr. Yeonjun Kim (SNU, Korea)

Mr. Jinwoo Lee (SNU, Korea)