Toward Impact-resilient Quadrotor Design, Collision Characterization and Recovery Control to Sustain Flight after Collisions

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Motivations

Quadrotor applications:

- Deployed in complex, cluttered and partially-known environments
- Aggressive maneuvers
- Interactions with environments
- Swarms

Survive collisions

Image credit: FAST Lab, ZJU

Post-collision freefalls

- Risk of damaging sensitive onboard devices
- Unable to land on certain surfaces, e.g., fluidic, high-temperature

Sustain flight after collisions

Challenges & Objectives

Challenges:

- Impact-resilient mechanical design
- Rigidity for model-based control in free flight
- Sensors for rapid and accurate collision detections
- Sustain post-collision flight

Objectives:

- A novel collision-resilient quadrotor with a compliant arm design to enable model-based control while allowing for 1 DOF to absorb shocks
- A novel collision detection method based on Hall sensors and a recovery control to sustain flight after collisions

Related Work

Existing work on collision-resilient UAVs includes:

- **Incorporating protective structures to reduce impact**

  - Cages or protective frames
    e.g., A. Klaptocz et al. 2013, R. Naldi et al. 2014, Y. Mulgaonkar et al. 2017

  - Rotation or added angular momentum to reject disturbance
    e.g., A. Borid et al. 2014, N. Bucki et al. 2018

  - Bio-inspired approaches and soft materials to survive crashes
    e.g., S. Mintchev et al. 2017, P. Sareh et al. 2018, J. Shu et al. 2019

- Utilizing sensors to detect collisions and recover

Related Work

Existing work on collision-resilient UAVs includes:

- Incorporating protective structures to reduce impact

- **Utilizing sensors to detect collisions and recover**

  - Inertial measurement unit (IMU)
    e.g., T. Tomić et al. 2017, G. Dicker et al. 2017, A. Battiston et al. 2019, Y. Mulgaonkar et al. 2020

  - Motion capture system (MoCap)
    e.g., Y. Mulgaonkar et al. 2017

  - Hall sensor
    e.g., A. Briod et al. 2013

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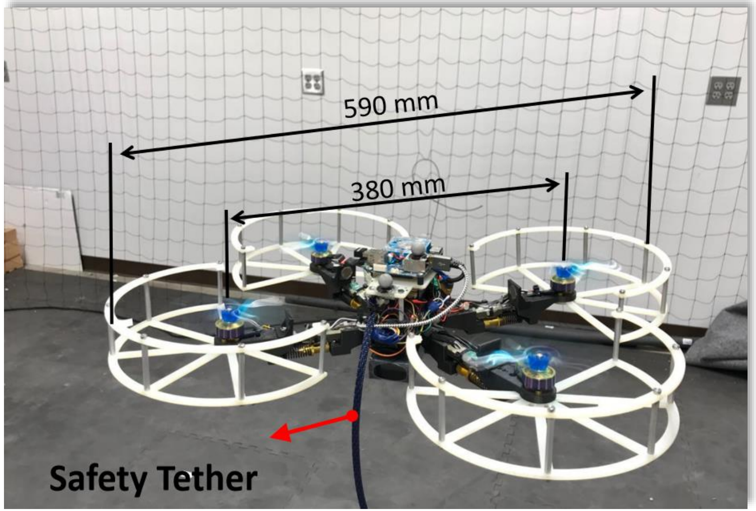
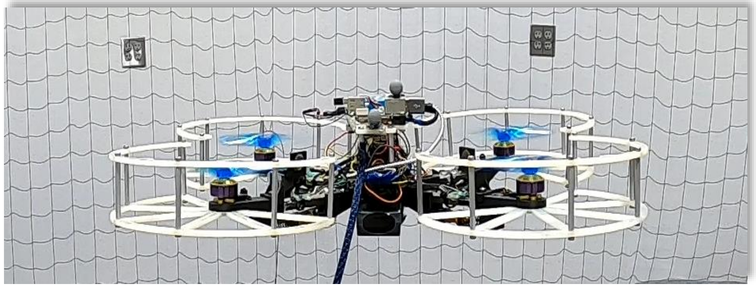
Summary

In this work, we develop or propose:

- ❖ A novel Actively Resilient Quadrotor (ARQ) that incorporates compliance and collision resilience
- ❖ A collision detection and characterization method based on Hall sensors
- ❖ A recovery control method to generate and track smooth trajectories after collisions





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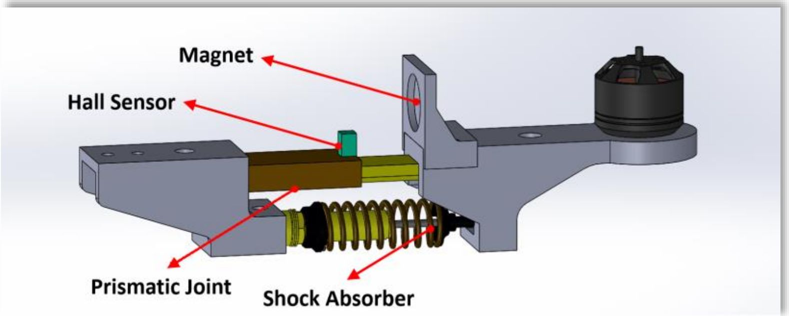
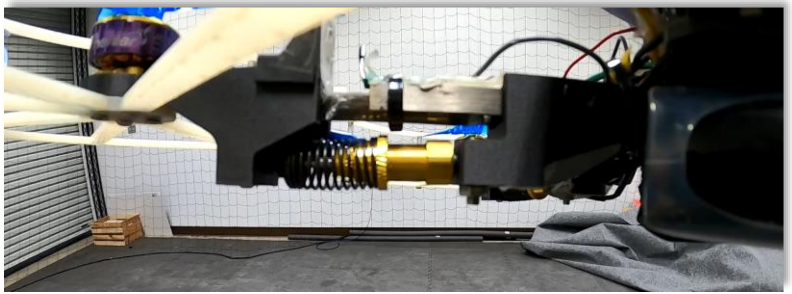
Novel Arm Design

❖ Novel arm design consists of:

- Prismatic joint
- Shock absorber
- Hall sensor
- Magnet

❖ Retain rigidity when in free flight while allowing for 1 passive DOF





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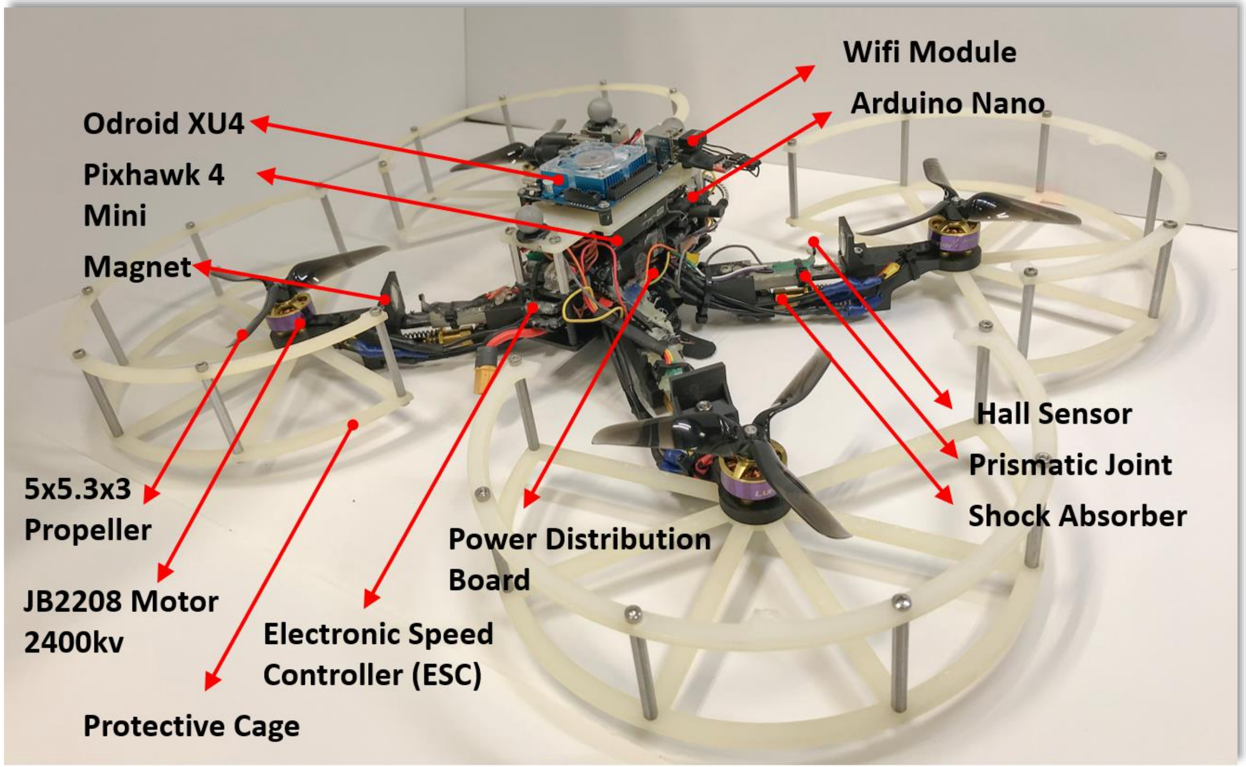
Hardware Overview

- ❖ Design is based on of-the-shelf components and custom 3D-printed parts.

- ❖ Size:
  - ▪ 380mm from propeller tip to tip
  - ▪ 590mm from protective cage tip to tip

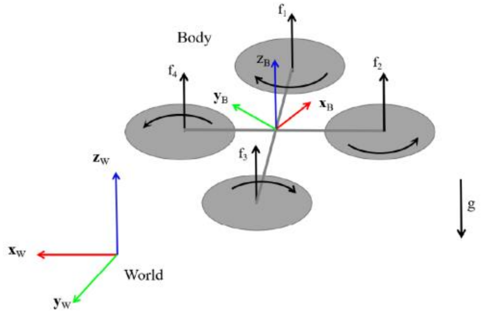
- ❖ Weight: 1.42kg with the battery



Modeling & Control

- Quadrotor equations of motion

$$\dot{\mathbf{x}} = \mathbf{v}$$
$$m\dot{\mathbf{v}} = -mg\mathbf{e}_3 + f\mathbf{R}\mathbf{e}_3$$
$$\dot{\mathbf{R}} = \mathbf{R}\hat{\Omega}$$
$$J\dot{\Omega} + \Omega \times J\Omega = \mathbf{M}$$



- Calculate forces for each motor*

$$\begin{bmatrix} f \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & -l & 0 & l \\ l & 0 & -l & 0 \\ -c_f & c_f & -c_f & c_f \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}$$

- Geometric controller (*T. Lee et al. 2010*)

$$f = -(-k_x\mathbf{e}_x - k_v\mathbf{e}_v - mg\mathbf{e}_3 + m\ddot{\mathbf{x}}_d) \cdot \mathbf{R}\mathbf{e}_3$$
$$\mathbf{M} = -k_R\mathbf{e}_R - k_\Omega\mathbf{e}_\Omega + \Omega \times J\Omega - J(\hat{\Omega}\mathbf{R}^T\mathbf{R}_d\Omega_d - \mathbf{R}^T\mathbf{R}_d\dot{\Omega}_d)$$

*When a collision happens, the arm length shortens, therefore changing the parameters in the equation. However, ARQ can wait until a collision ends, and the arm length is recovered. In this way, the model can be used before and after collision.

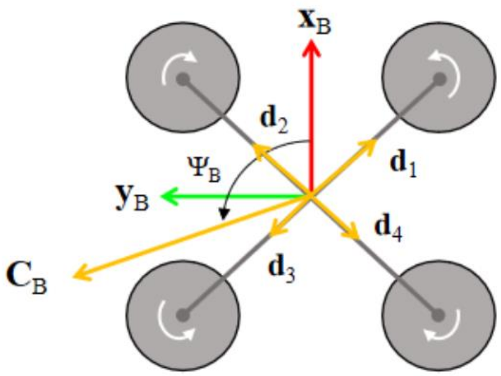
Collision Detection & Characterization

- **Objective**: to detect and characterize collision based on Hall sensor readings, e.g., maximum collision intensity, position and start time

- Calculate projections of Hall sensor readings*

- Estimate the intensity and position (in the body frame) of the collision

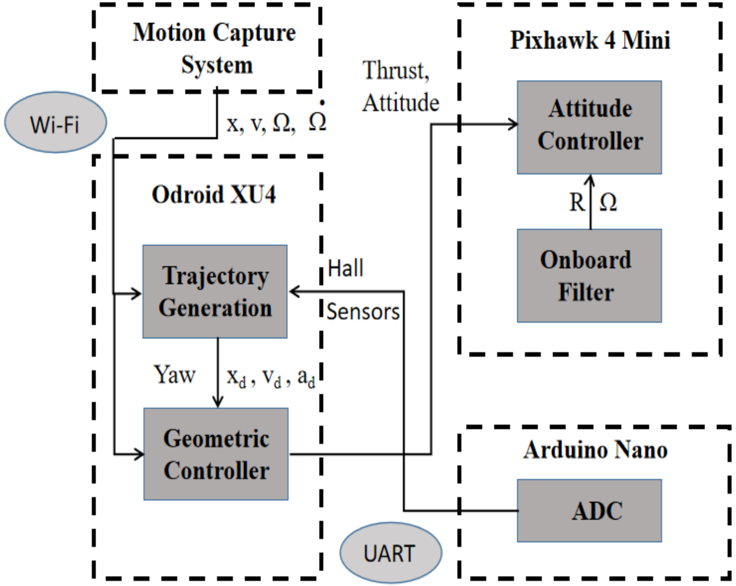
- Follow an algorithm to find the maximum collision intensity and its position, as well as a time to trigger recovery control (arm length recovered)



* $0 \leq d_i \leq 1$denotes values from the analog to digital conversions, where 0 means no contact force is detected and 1 indicates that the minimum length of the shock absorber reached.

Recovery Control & Software

- **Objective**: to generate and track a smooth and safe trajectory to stabilize the robot after a collision
- Calculate a safe desired position* (in world frame) based on the collision characterization
- Generate a minimum-snap trajectory to reach the goal position and stop by solving an optimization with constraints
- Track the desired trajectory with geometric controller to stabilize the robot



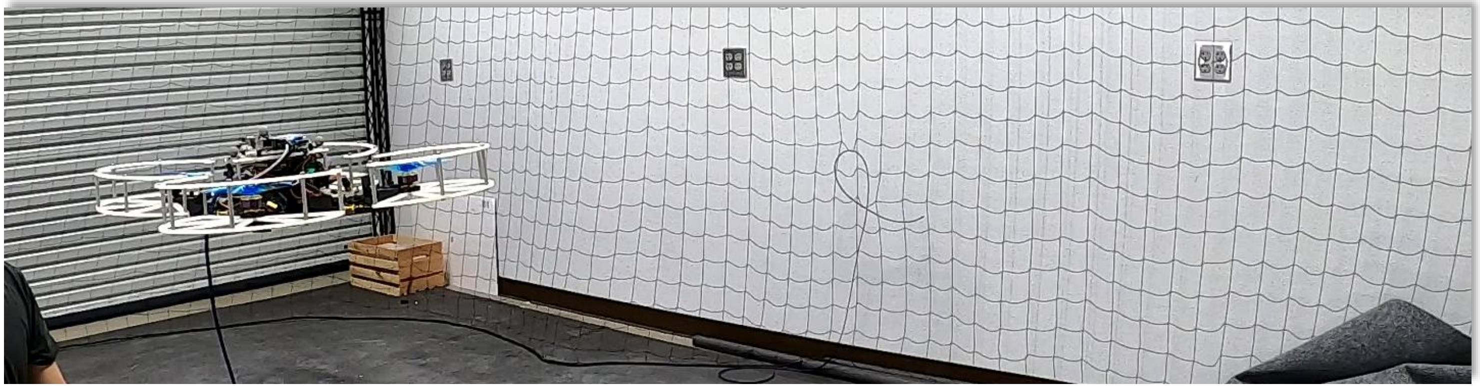
Software Architecture

* In the opposite direction of the collision at a distance proportional to the collision intensity.

Experiment

1. Passive collision

❖ ARQ can sustain flight after being passively hit at a collision speed* of 1.3 m/s



* The norm of the vehicle’s linear velocity after the collision.

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Experiment

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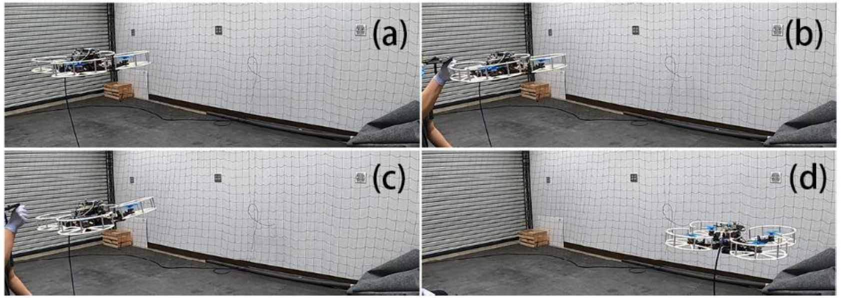
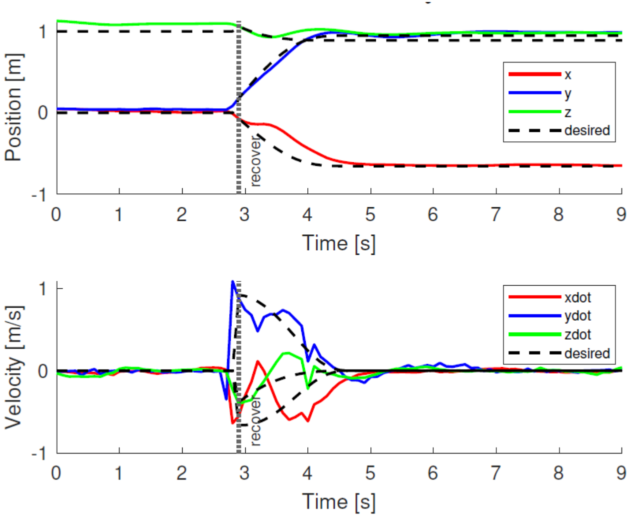
❖ ARQ can sustain flight after being passively hit at a collision speed* of 1.3 m/s





* The norm of the vehicle's linear velocity after the collision.

Experiment

2. Wall collision

❖ ARQ can recover from wall collision with a single arm in contact at a collision speed of 2.58m/s

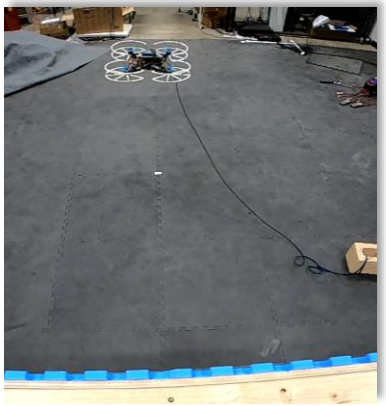
Experiment

2. Wall collision

- ARQ can estimate the intensity and orientation of the collision based on hour Hall sensors, to recover from wall collision with two arms at a speed of 1.92m/s

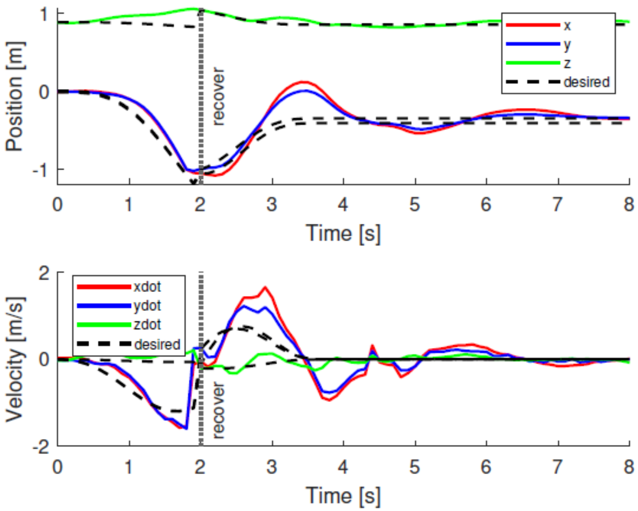
- One Arm

- Two Arms

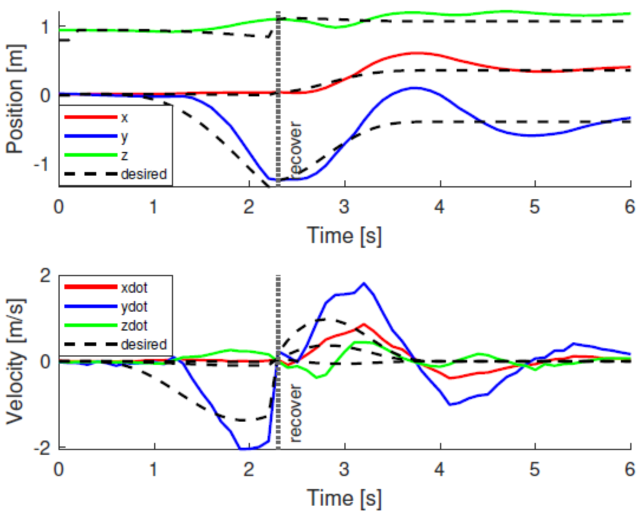


Experiment
2. Wall collision

❖ One Arm



❖ Two Arms

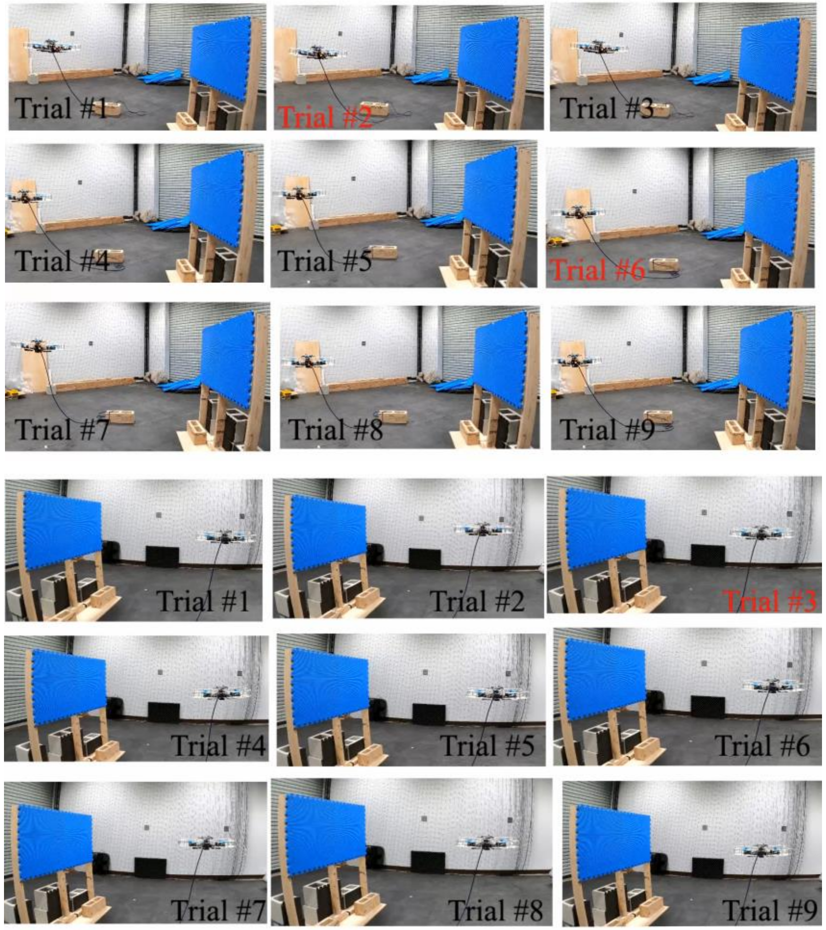


❖ State Tracking

Experiment
2. Wall collision

❖ **More experiments**:

- Success rate tests in both single-arm and two-arm types at the highest speeds
- Results: 9/10 and 8/10 successful recoveries* for the two types



* Survive collisions and sustain flight.

Experiment

2. Wall collision

❖ **More experiments**:

- Compliant arm without recovery controller & Rigid arm without recovery controller tests
- Results: demonstrate the individual contribution of compliance and recovery control

Compliant arm without recovery controller test

Rigid arm without recovery controller test

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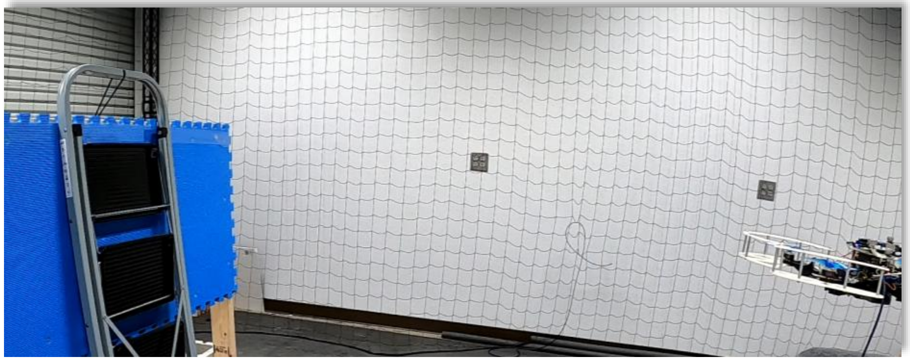
Experiment

3. Pole collision & 4. Unstructured surface collision

- ❖ Pole Collision, 2.04m/s

- ❖ Unstructured Surface Collision, 1.95m/s



- ❖ ARQ does not require prior knowledge of collision models

Experiment

5. Free Fall

- ARQ can survive free falls* from 1.8 m high, reaching a maximum velocity of 5.9 m/s

* The battery is removed. The robot weighs 1.12 kg without the battery.

Playback speed: 0.2x

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Discussion

Limitations:

- Collisions in vertical directions
- Cylinder obstacles with small diameters
- Impact of added weight to free flight performance

Future Work:

- Improve protective cage design
- Integration with map-based navigation methods
- Outdoor environments

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Thank you!
Any questions?