# Quadrotor Collision Avoidance/Recovery
# Part 2 - Papers and Analysis

# Reflections from Last Meeting

- We needed to research more to further distinguish between quadcopters with obstacle avoidance features, morphing capabilities, or collision recovery methods would be best suitable to build.
    - We need to quantify our results regarding the parameters we are investigating.
    - Three main types of quadrotors: **morphing**, **collision recovery**, and **obstacle avoidance**.
    - Read papers covering those types of quadrotors while also looking at information regarding materials, logic control and algorithms, sensors, etc…
- Stick with our main research goal
    - The current goal of our research project is to get high speed quadrotors to avoid obstacles through the means of morphing.

# Parameters need to Consider

- Quantify time
  - Time of flight to destination when obstacles are present for each type of quadrotor
  - Time for quadrotor to adjust to obstacle circumstance.
    - Morphing: Time it takes for quadrotor to change into a different shape
    - Obstacle Avoidance: Time it takes quadrotor to avoid obstacle and continue its course
    - Collision Recovery: Time it takes for quadrotor to recover after colliding with an obstacle.
- Materials
  - Rigid Robotics vs Soft Materials when Morphing? Less actuators but implementing springs into the process. Onboard sensors, IMUs.
  - Materials used to construct the arms and propellers; could affect how we quantify time.
- Obstacles Used/Environment
  - Was it just walls? Collision avoidance might be best. Irregular surfaces; morphing? Poles or cylindrical obstacles; collision recovery?
  - Squeezed environment, spaced out with just walls, urban like environment
- Simulations
  - Most papers did simulations but we need to understand the complexity of each one. Were there ones just with walls, various types of obstacles, squeezed environments.
  - Some papers also did experiments.
- Algorithms
  - The complexity of the algorithm used, does it deal with contact geometry, easy use of sensors, easy to follow?

# Papers Read

## Collision Recovery Papers

- Fly Crash Recover a Sensor Based Reactive Framework for Online Collision Recovery of UAVs
- Dynamics of a Quadrotor Undergoing Impact with a Wall
- Toward Impact-Resilient Quadrotor Design, Collision Characterization and Recovery Control to Sustain Flight after Collisions
- **Recovery Control for Quadrotor UAV Colliding with a Pole**
- **Quadrotor Collision Characterization and Recovery Control**
- Insect Inspired Mechanical Resilience for Multicopters

## Morphing Quadrotor Papers

- **A Quadrotor with an Origami Inspired Protective Mechanism**
- **The Foldable Drone A Morphing Quadrotor that can Squeeze and Fly**
- Soft Pneumatic Actuated Morphing Quadrotor: Design and Development
- **Geometry Aware NMPC Scheme for Morphing Quadrotor Navigation in Restricted Entrances**
- Design and Control of a Passively Morphing Quadcopter
- Design, Planning, and Control of an Origami-Inspired Foldable Quadrotor
- Foldable and Self-Deployable Pocket Sized Quadrotor
- Design, Modeling, and Control of a Novel Morphing Quadrotor
- Design and Dynamic Modeling of a Rotary Wing Aircraft with Morphing Capabilities
- Design and Control of a Midair-Reconfigurable Quadcopter using Unactuated Hinges

## Obstacle Avoidance Papers

- Modeling and Adaptive Control of Flexible Quadrotor UAVS
- Autonomous Quadrotor Collision Avoidance and Destination Seeking in a GPS-denied environment.
- **Fast Obstacle Avoidance Motion in Small Quadcopter Operation in a Cluttered Environment**
- **Collision Avoidance for Quadrotor Using Stereo Vision Depth Maps**
- A High Fidelity Simulator for a Quadrotor UAV using ROS and Gazebo

# Main Idea from each paper (Recovery & Obs. Avd.)

Fly-Crash-Recover **(Simulation and Experiment)**

- A Sensor-based Reactive Framework for Online Collision Recovery of UAVs - Collision recovery is achieved by running the inertial sensors on the quadrotor at high frequencies to quickly detect and recover the quadrotor from a collision.

Dynamics of a Quadrotor Undergoing Impact with a Wall **(Simulation and Experiment)**

- The goal of this paper was to develop control methods for the quadrotor that would allow automatic recovery for the drone. In the paper, they formulated the dynamics of a quadrotor and ran it through a series of tests in simulations which was directly matched with excellence in real life experiments.

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

- A compliant arm design implemented surrounding the propellers provide the ability for free flight and prevents crashes. They also proposed a collision detection and characterization methods.Types of collisions tested: Wall, Pole, Unstructured Surface, Free Fall, and Passive Collision (robot hitting someone’s hand).

Recovery Control for Quadrotor UAV Colliding with a Pole **(Simulation and Experiment)**

- Investigating collision dynamics between quadrotor with bumpers and vertical pole using a 3 step recovery logic algorithm. Importance of looking at other obstacles.

Collision Characterization and Recovery Control **(Simulation and Experiment)**

- Collision recovery using dynamics, fuzzy logic, aggressive quadrotor attitude control. Priority it protect propellers and implementing safety feature to flight controller.

Insect Inspired Mechanical Resilience for Multicopters

- Use energy from collision to have quadcopter morph instead of having actuators use additional energy to morph itself. (Morphing & Collision Recovery Combination)

Modeling and Adaptive Control of Flexible Quadrotor UAVs

- Use of flexible dynamics to identify rigid body motions and elastic deformations during morphing. Use of adaptive control implementation and identification of time delays.

Autonomous Quadrotor Collision Avoidance and Destination Seeking in a GPS-denied environment **(Simulation and Experimental Results)**

- Quadrotor uses collision avoidance and destination seeking algorithm to go through GPS denied environments. Feedback measurements use onboard sensors.

Fast Obstacle Avoidance Motion in Small Quadcopter Operation in a Cluttered Environment **(Simulation and Experimental Results)**

- Fast Obstacle Avoidance Motion (FOAM) : algorithm to perform sense and avoid obstacles using low levels of power, low latency, and low cost. Had outdoor experimentation.

Collision Avoidance for Quadrotor Using Stereo Vision Depth Maps **(Simulation and Experiment)**

- In this paper, they used stereo vision to detect the obstacles’ depths and based on that information, executed an obstacle avoidance maneuver with promising results.

A High Fidelity Simulator for a Quadrotor UAV using ROS and Gazebo **(Simulation Results Only)**

- Navigation algorithm allowing quadrotor to create an optimal trajectory while simultaneously avoiding obstacle. Has sensors to detect and react to surroundings.

# Main Idea from each paper(Morphing)

A Quadrotor with an Origami Inspired Protective Mechanism **(Simulation & Experiment Results)**

- Incorporate flexible materials and create foldable arms to protect the control board in quadrotor when colliding wall. Idea was successful for head-on collisions, not collisions from top or bottom.

The Foldable Drone A Morphing Quadrotor that Can Squeeze and Fly **(Simulation & Experiment Results)**

- 4 different morphing configurations for quadrotor to fly through narrow gaps, close proximity surface inspection (mainly our objective), and object grasping/transportation.

Soft Pneumatic Actuated Morphing Quadrotor **(No Simulation & Experiment Results)**

- The use of soft robotics to implement morphing mechanism to alter shape of quadrotor during flight. Use soft actuators for aerial robotic platform.
- Only discussed about mechanics and designed. No simulation results were proposed. Idea has not been too explored yet and the paper was published in July 2022.

Geometry Aware NMPC Scheme for Morphing Quadrotor Navigation in Restricted Entrances **(Simulation Results Only)**

- Incorporate a Nonlinear Model Predictive Control algorithm to help quadrotor morph. This paper suggested the idea that morphing increases versatility and requires low level control for maintaining stability after changing shape. Squeezable entrances include cubic, cylindrical holes, or impassable entrances.

Design and Control of a Passively Morphing Quadrotor **(Simulation & Experimental Results)**

- Use of less actuators by incorporating spring hinges to massively decrease the size of drone. Stems from origami-style arms. Really only useful for deploying items or racing, but not beneficial for our research.

Design, Planning, and Control of an Origami-Inspired Foldable Quadrotor **(Simulation Results Only)**

- Origami Quadrotor made from cardboard that had arms extending and folding: change moment of inertia and ambient air flow. Stable when changing arm lengths. Aggressive turning maneuvers in cluttered environments.

Foldable and Self-Deployable Pocket Sized Quadrotor **(No Simulation & Experiment Results)**

- Folding arms of quadrotor using origami technique with no actuator. Folding process works by utilizing torque generated by the motors of the propellers. Downside was morphing was before flight not during flight.

Design, Modeling, and Control of a Novel Morphing Quadrotor (**Simulation & Experimental Results)**

- Quadrotor transform configuration during flight; fly stably & accurately in air while undergoing shape transformation (even asymmetrically): Reinforcement Learning Algorithm

Design and Dynamic Modeling of a Rotary Wing Aircraft with Morphing Capabilities **(Simulation Results Only)**

- Proposes idea where platform of quadrotor can rotate itself to a vertical flying mode configuration. Fit through narrow gaps and save battery. Also flies with 4 engines in case of rotor failure.

Design and Control of a Midair-Reconfigurable Quadcopter using Unactuated Hinges **(Simulation & Experimental Results) - Recently just looked at so not very thorough looking**

- Folds 2 of the four arms when morphing to traverse through narrow gaps, tunnels, or grasping. Flies normally with four arms are deployed again and perches on wires when four arms are folded. Issue is when flying with just two propellers, might be challenging to control weight of drone.

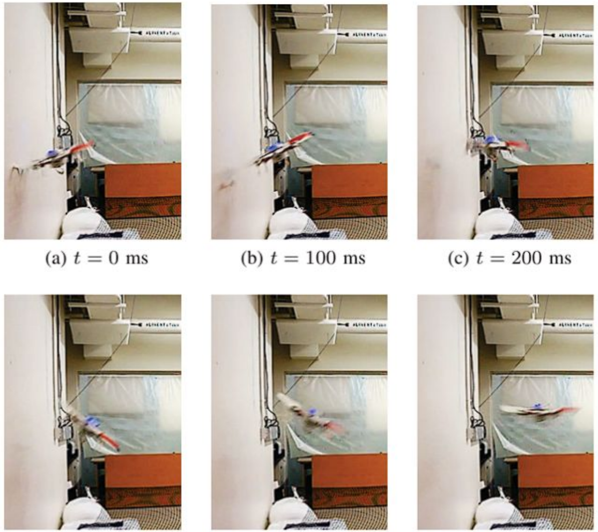
# Paper - 'Quadrotor Collision Characterization and Recovery Control'

Problem - Typical morphing drones increase the complexity of the drone or decrease its controllability.

Solution - This paper presents a novel and simpler quadrotor with four independently rotating arms that fold around the mainframe.

Brief Recovery Overview -

1. Collision is detected using accelerometer
2. Direction of impact is estimated
3. Collision intensity is characterized using Fuzzy Logic
4. Intensity is used to generate a desired acceleration pointed away from the obstacle (wall)
5. The desired acceleration is tracked
6. The quadrotor reorients to a level attitude and stabilizes its altitude

(a) $t = 0$ ms (b) $t = 100$ ms (c) $t = 200$ ms

(d) $t = 300$ ms (e) $t = 400$ ms (f) $t = 500$ ms

Fig. 1. Quadrotor recovering from a collision with a wall. In (a), collision characterization is performed and recovery begins. The quadrotor re-orients (b-d) away from the wall, and then (e-f) returns to hover and stabilizes altitude.

# Paper - 'Recovery Control for Quadrotor UAV Colliding with a Pole'

Problem - Collisions between quadrotors and the urban environment like walls and poles due to wind gusts, operator errors, etc. can lead to crashes making it a safety hazard to surrounding people and can cause irreversible damages to the quadrotor.

Solution - This paper investigates the collision dynamics of the quadrotor with a pole and also produces a collision recovery method upon collision with a pole.

Brief Dynamics Simulation Results and Recovery Overview -

1. Post collision yaw rates for non head on collisions were very high
2. For pitch angles less than 15° there were no crashes and higher than 37° had all crashes
3. In the recovery process, the first step is to get the quadrotor to orient itself such that it is pointing away from the pole at an angle of 30° vertically
4. The second step is to get the quadrotor to get an upright position before exiting the recovery stage
5. Same parameters were used for simulation with the recovery control and majority of the collisions which would have resulted in a crash did not crash with recovery control engaged

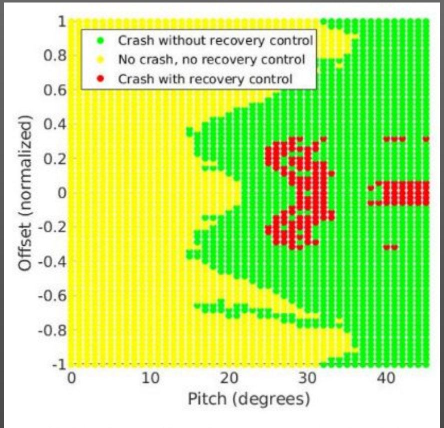
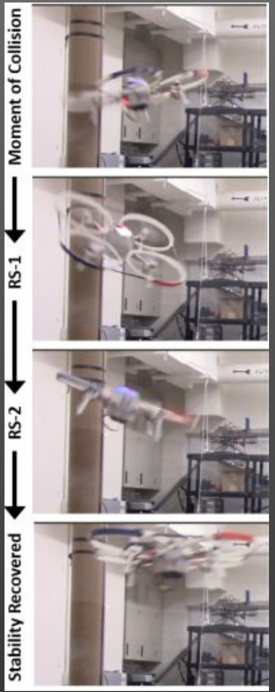
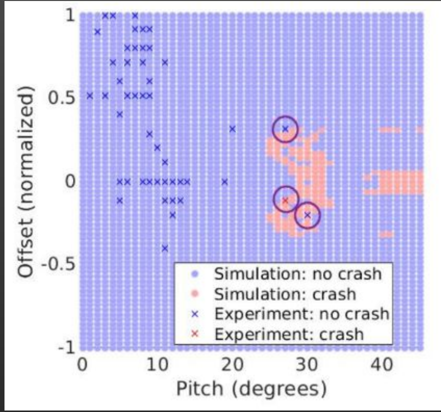
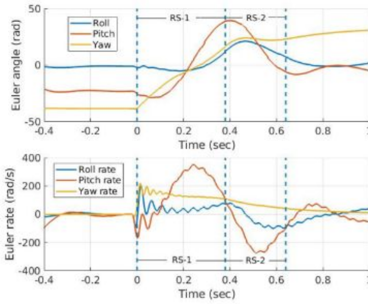
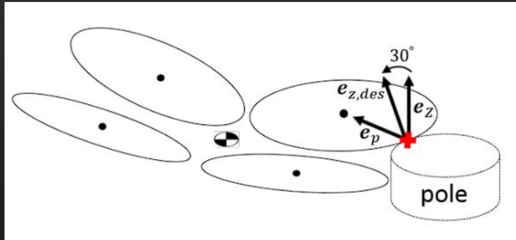


Fig. 9. Crash conditions with recovery control implemented



# Paper - 'A Quadrotor With an Origami-Inspired Protective Mechanism'

Problem - Collisions between quadrotors and the environment are inevitable which can lead to crashes making it a safety hazard to surrounding people and can cause irreversible damages to the quadrotor.

Solution - They present an idea to incorporate a **passive** foldable airframe as a protective mechanism made with flexible material with unique properties to protect the mainframe upon impact with an obstacle.

Brief Functionality -

1. Upon impact, the force causes the fold trigger to push part of the arm
2. When the force is large enough, it overcomes the torque by the propellers' thrust and activates the arm causing the arms to fold inwards
3. It takes 0.52 N of force to activate the arms and folding process takes 0.2 s
4. Once it falls to the ground, the central parts along with the propellers are safe and without damage
5. After folding, the propellers were more than 1 cm from the control board

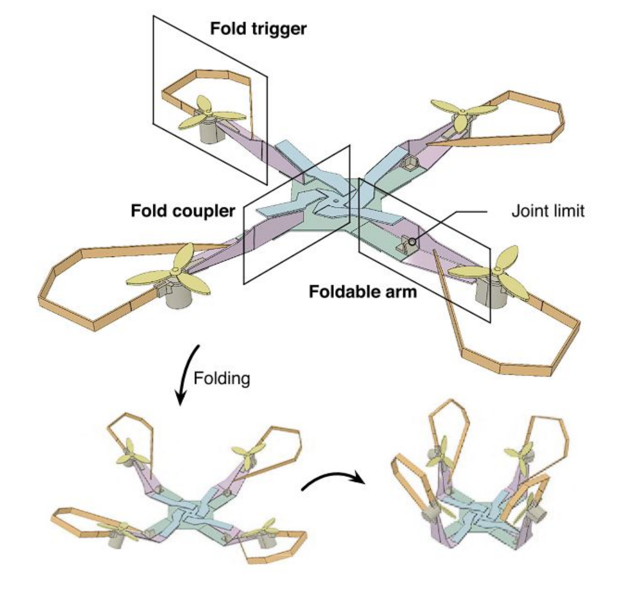


Fig. 2. An illustration of the three major components (foldable arm, fold coupler, and fold trigger), joint limits, and the folding sequence.

Fig. 14. Sequential images from a video footage showing the mid-flight collision when the robot had the translational speed of 1.5 $m.s^{-1}$. The images reveal that the impact triggered the folding of all arms in less than 0.15 s.

# Paper - 'Fast Obstacle Avoidance Motion in Small Quadcopter Operation in a Cluttered Environment'

Problem - Typical sense-and-avoid (SAA) operations require quadrotors to move in slow velocities or else there could arise latency issues and due to this problem, many researchers have to constrain their parameters to values in small magnitudes.

Solution - In this paper a novel algorithm called FOAM is proposed to perform SAA operations which is a low-latency perception-based algorithm that uses a monocular camera and 2D LIDAR.

Algorithm and Simulation -

1. How it works - camera captures image → image is processed to obtain a Probabilistic Occupancy Map (POM) → 2D LIDAR also generates POM in the horizontal plane → the two POMs are fused together, the resultant POM is used to determine free space by means of optimization
2. Then a local planner uses that information to set a desired yaw and linear velocity to reach an end goal
3. These desired values are sent to the velocity controller to control the orientation of the quadrotor
4. The IRL experiment validated the results from the simulation
5. Video Link

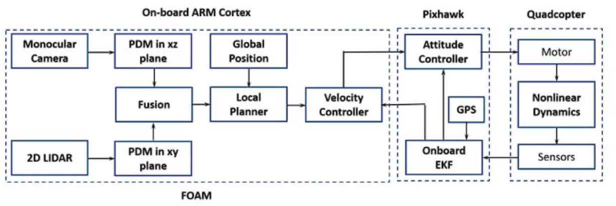



Fig. 4: A Schematic Diagram of FOAM System Architecture

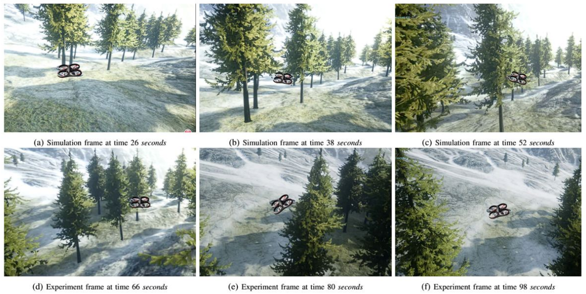



Fig. 6: Different instances of a AirSim Forest Simulation. The quadcopter flies towards Goal point while avoiding the obstacles.

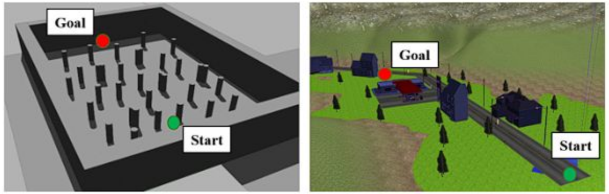



Fig. 5: Bugtrap (left) and Town (right) environments used in Gazebo simulator.

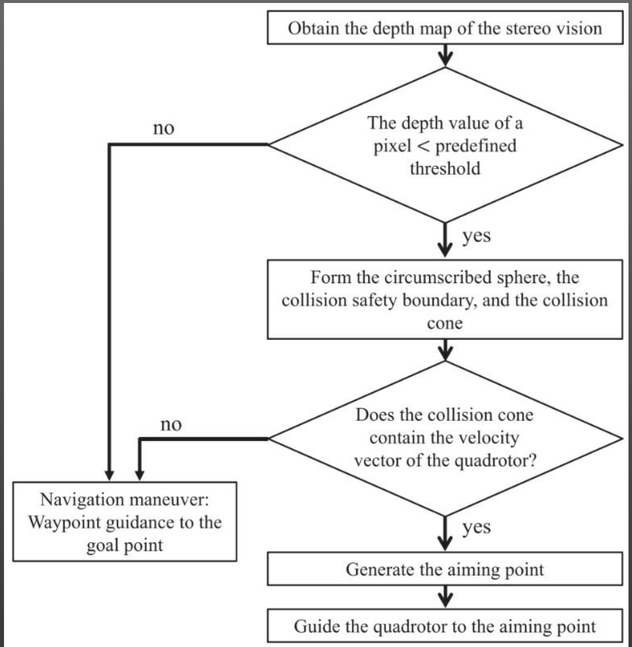
# Paper - 'Collision Avoidance for Quadrotor Using Stereo Vision Depth Maps'

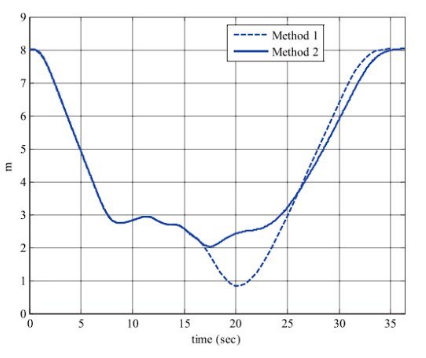
Problem - Obstacle detection is a major part of all collision avoidance algorithms. Without obstacle detection, a drone is prone to collision with an obstacle which could permanently damage the quadrotor and potentially damage the user and its surroundings.

Solution - The paper solves this problem by using stereo vision sensors which can capture depth map information which is used to detect an obstacle.

Functionality -

1. Procedure: stereo vision sensor detects obstacle → obstacle information is extracted → collision safety boundary and cone are constructed
2. Collision avoidance logic is: if the current velocity vector is inside the collision cone, execute obstacle avoidance
3. Once the velocity vector is inside the collision cone, the primary objective of the quadrotor is to direct itself to a new way point instead of the original goal point
4. 2nd method is when obstacles go out of the camera's FOV and still be able to avoid the obstacle - this is done by storing previous information about the obstacle when it was in the camera's FOV
5. Simulation results showed that the second method provided a safe distance from the obstacles compared to the first method



(a)

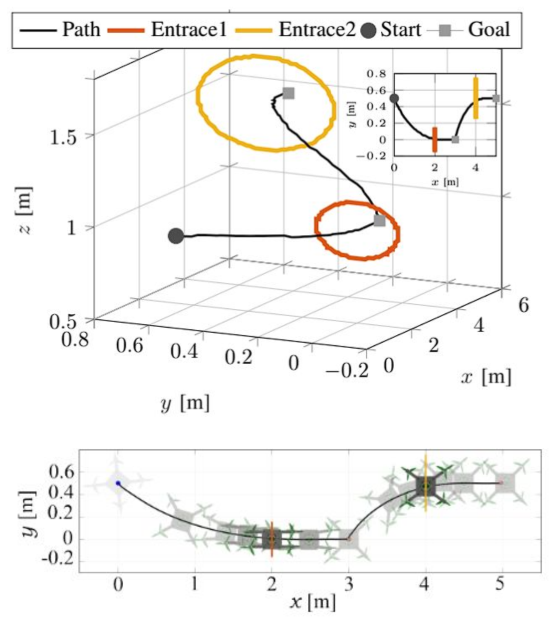
# Paper - ‘Geometry Aware NMPC Scheme for Morphing Quadrotor Navigation in Restricted Entrances’

Problem - In the field of Micro Aerial Vehicles (MAVs), most work is focused on maintaining stability after morphing. There isn’t enough focus on the actual morphing of the drone based on its environment.

Solution - This paper chose to developing a structure that modifies the morphology of a quadrotor based on its surroundings. It is called Nonlinear Model Predictive Control (NMPC) and it can morph the drone to fit through narrow entrances.

Functionality -

1. There are 4 arm configurations - X, Y, O, H
2. The quadrotor will morph into an appropriate configuration based on the entrance
3. Under simulation, the quadrotor changed its width by morphing into the H configuration to fit through a small sized circle and then morphed into the X configuration to fit through a bigger sized circle
4. When there is an impassable entrance, it will compute a safety distance from the entrance and then it will stop and land that distance away from the entrance
5. As soon as it reaches close to the entrance the quadrotor will morph and as soon as it exits the entrance, it will morph back to its original configuration which is the X



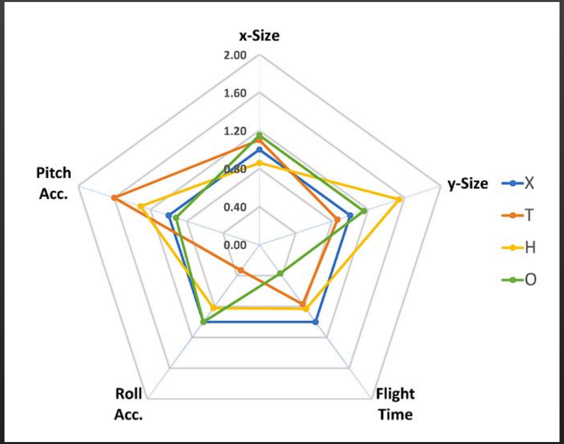
# Paper - 'The Foldable Drone: A Morphing Quadrotor That Can Squeeze and Fly'

Problem - Collisions occur when drones are expected to fit through narrow gaps and can fail in reconnaissance missions due to crashing causing many lives to be lost.

Solution - This paper chose to developing a structure that modifies the morphology of a quadrotor based on its surroundings. It is called Nonlinear Model Predictive Control (NMPC) and it can morph the drone to fit through narrow entrances.

Functionality -

1. The morphing is done through 4 actuators (servos) attached to each arm
2. To keep the quadrotor stable during and after morphing, it exploits an optimal control strategy
3. There are 4 different configurations - X, H, O, T
4. T - shape yielded best results for pitch acceleration and H - shape yielded best results for size
5. To test the control scheme, the 4 servos were set to random positions and tested and the control scheme "passed the test" by keeping the quadrotor stabilized



# Some Conclusions We Have Made

- **Pros to Morphing:** Go through cluttered environments while sustaining flight, can transport materials from one place to another, size of the drone can be much smaller.
- **Cons to Morphing:** When it comes to just wall obstacles, morphing into a different shape to circumnavigate the obstacle might take more time than just doing pure obstacle avoidance.
    - Also morphing has more risk into free fall since the center of gravity of a quadcopter will shift.
    - Multiple wall obstacles would not be so efficient.
    - No recovery if faced with a severe crash.
- **Pros to Collision Avoidance**: Quadrotors can go at very high speeds and recalculate trajectories.
- **Con to Collision Avoidance**: quadrotor sometimes large, no recovery if faced with severe crash, cannot easily go through tightly squeezed environments.
- **Pros to Collision Recovery**: Quadrotor can collide with obstacles at speeds like 4 to 5 m/s and recovery quickly. Propellers are not damaged since surrounded by bumpers.
- **Con to Collision Recovery**: With one wall obstacle, collision recovery is fine but with multiple wall obstacles, it would take longer for quadrotor to reach final destination. Quadrotors with collision recovery are larger compared to morphing quadrotors.

- Morphing would not be ideal if our goal is to just avoid an incoming wall when quadrotor is at high speed. Obstacle avoidance (drone going away wall) is much faster.

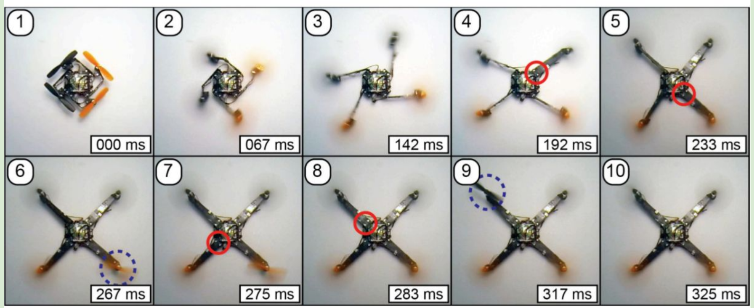
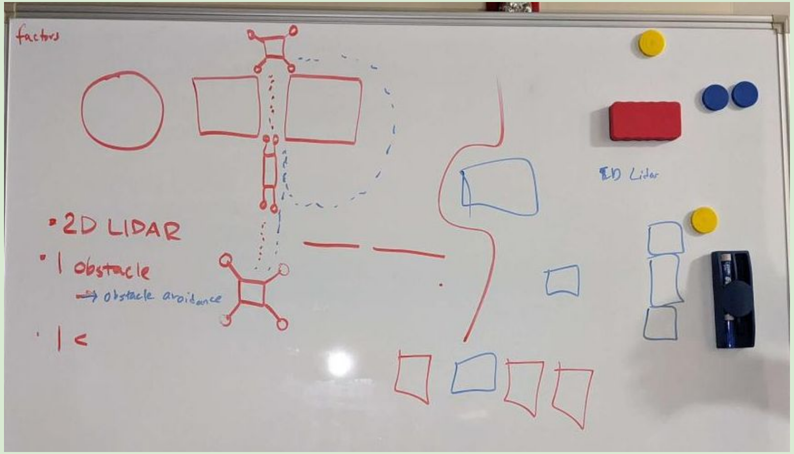


Figure 7. Snapshots of the deployment process, from the activation of the propeller to a fully deployed configuration. The main frame of the quadrotor is retrained.

Fast morphing in “Foldable and Self-Deployable Pocket Sized Quadrotor” but only on ground.

Based on “The Foldable Drone A Morphing Quadrotor That Can Squeeze and Fly”, the author states “However, this comes at a cost: the standard X morphology is the most efficient and therefore should be used as long as a different morphology is not strictly required by the task at hand.”

# Idea 1




- Pure obstacle avoidance seems to be the key when dealing with one or a mirage of wall obstacles. However, morphing quadrotors have so many more features than pure obstacle avoidance drones.
    - Why not combine the two ideas and create an algorithm for it?
- Quadrotor morphs when it is appropriate to morph (squeezed gap) but if encountering multiple walls or just one wall, quadrotor should just employ obstacle avoidance.
- Drawback: More time to develop it, need to thoroughly examine what materials to use and identify the dynamics of the quadrotor. A lot of coding would be needed to develop this complex algorithm.
- So we have to consider some factors
    - Star and end points
    - Configuration of obstacles
- Whether the quadrotor morphs or just avoids obstacles will be dependent on those two factors

# Idea 2

If the obstacle is made of metal, can we incorporate magnets in the design of the quadrotor to passively repulse away from the obstacle without the need of any sensor or actuators to fold or morph the drone saving energy and cost?