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# Morphological Synthesis and Kinematic Analysis of a Foldable Arm Drone

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**Abstract** :This project presents the morphological synthesis and kinematic analysis of a foldable arm quadcopter drone aimed at improving portability and deployment efficiency. Conventional drones use rigid arms, which increase storage space and reduce transport convenience. To overcome this limitation, a foldable arm mechanism is proposed that allows compact storage and rapid deployment before flight. Different conceptual mechanisms were studied using morphological synthesis, and an optimal folding arrangement was selected based on simplicity, reliability, and structural balance. Kinematic analysis of the foldable arm was carried out to determine position, velocity, acceleration, synchronization, deployment time, and collision clearance during motion. The study shows that smooth synchronized deployment enhances structural stability and minimizes actuator load. A controlled motion profile reduces vibration, impact loading, and hinge wear. The proposed design offers improved portability without affecting flight configuration, making it suitable for surveillance, inspection, delivery, and emergency applications.

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## 1. Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have become important tools in industries such as agriculture, surveying, surveillance, delivery, photography, and disaster management. Their ability to reach difficult locations, capture real-time data, and operate efficiently has increased their demand in both commercial and industrial sectors.However, one major limitation of conventional drones is portability. Most quadcopters use rigid arms fixed to the main frame, which increases storage space and makes transportation less convenient. This becomes a challenge for users who need compact systems for travel, field operations, or rapid deployment.Foldable drones provide an effective solution by allowing the arms to fold inward during storage and unfold during operation. This reduces overall size while maintaining normal flight configuration. Popular systems from DJI have shown the growing market interest in compact UAV platforms.Designing a foldable drone is a challenging engineering task because the mechanism must be lightweight, strong, reliable, and capable of smooth synchronized deployment. It should also avoid interference between arms and maintain structural stability during flight.

This research focuses on the morphological synthesis and kinematic analysis of a foldable arm quadcopter drone. Morphological synthesis is used to generate and compare different design concepts, while kinematic analysis is used to study arm motion, deployment time, velocity, and positional accuracy. The aim of this study is to develop a compact, practical, and efficient foldable drone design for future UAV applications.

### ❖ Literature review

- Falanga et al. (2018) – The Foldable Drone: A Morphing Quadrotor that can Squeeze and Fly
This paper presents a morphing quadrotor with four independently rotating arms that can adapt into X, H, O, and T configurations for navigating confined spaces. It introduces an adaptive control framework that updates the inertia matrix in real time to maintain stability in asymmetric shapes. The drone operates fully autonomously using onboard vision and computation. Experiments demonstrate successful navigation through cluttered environments and narrow gaps. The work significantly advances adaptive aerial robotics and morphing UAV design.

- Wu et al. (2024) – Peregrine Falcon: Folding and Launchable Quadcopter
This study introduces a compact quadcopter capable of being launched from confined barrels and deploying mid-air using a servo-based folding mechanism. It integrates launch dynamics analysis and control compensation to stabilize the drone after deployment. The system ensures smooth transition from ballistic launch to autonomous flight. Experiments confirm reliable arm deployment and stable control in both static and moving launch scenarios. The design is suitable for emergency and surveillance applications.

- Shiferaw et al. (2021) – Morphed Multi-Rotor with Obstacle Detection
This paper presents a morphing UAV that changes from X to H configuration using synchronized rotary actuation. It integrates ultrasonic sensors for real-time obstacle detection and triggers automatic arm folding during flight. The system combines kinematic modeling with real-time sensing for adaptive navigation. Experiments show effective obstacle avoidance and smooth arm synchronization. The work enhances real-time morphing and autonomous navigation capabilities.

- Xing et al. (2024) – Review on Morphing Quadrotors

This review paper analyzes various morphing quadrotor technologies, including folding arms, variable geometry, and smart actuators. It systematically covers actuation mechanisms, control strategies, and motion planning methods. The study highlights applications such as inspection, grasping, and search-and-rescue missions. It emphasizes how morphing UAVs outperform rigid drones in adaptability. The paper provides a comprehensive foundation for future morphing UAV research.

- Tuna et al. (2020) – FOLLY: Self-Foldable and Self-Deployable Quadcopter

This study presents a quadcopter with a four-bar crank-rocker mechanism enabling automatic arm folding and deployment using a single servo. The system achieves full deployment within 0.6 seconds. It includes kinematic and dynamic analysis for efficient mechanism design. Dual flight modes enhance operational flexibility and collision avoidance. Experimental results confirm stable flight and reliable deployment performance.

- Suthar and Jung (2021) – Foldable Robot Arm Using Twisted String Actuator (FRAD-TSA)

This paper introduces a lightweight foldable robotic arm for drones using a twisted string actuator for compact and efficient actuation. It combines kinematic modeling and force analysis to validate performance. The arm can fold/unfold while maintaining sufficient payload handling capability. Experiments confirm reliable operation for aerial manipulation tasks. The design improves UAV-based grasping and interaction capabilities.

- Tian et al. (2025) – Self-Foldable and Deployable Drone Arm Mechanism

This study proposes a drone arm using a crank-slider and gear-rack mechanism driven by a single servo for synchronized folding. It employs particle swarm optimization to improve structural parameters. The system achieves rapid deployment within 0.42 seconds and significant size reduction. Experimental validation confirms stable hovering performance. The design enhances portability and compact UAV architecture.

- Ma (2025) – Portable Foldable UAV Structure

This paper presents a lightweight foldable UAV with a detachable frame for improved portability and maintenance. The design features horizontally foldable arms to reduce storage space. Structural optimization and simulations validate performance under flight conditions. The UAV achieves a weight under 500 g with over 20 minutes of endurance. The study highlights practical design improvements for portable drone systems.

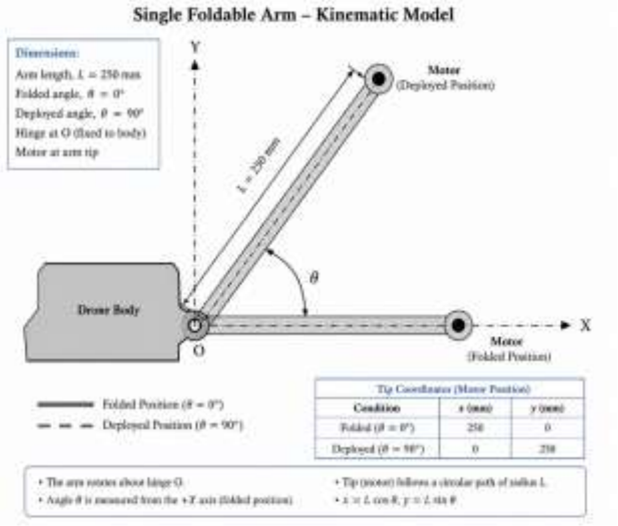
- Acar et al. (2025) – Review of Morphing Structures and Control in Quadrotors

This review explores various morphing mechanisms such as linkages, sliding arms, and compliant structures in UAVs. It integrates control strategies including MPC, adaptive control, and reinforcement learning. The paper explains how stability is maintained during dynamic structural changes. It also discusses advanced applications like aerial-terrestrial systems and wildfire response. The work provides a unified framework for morphing UAV design and control.

➢ Research Gap

Current morphing drone research mainly focuses on prototype designs and controlled environment testing, with limited real-world validation in dynamic outdoor conditions. Key challenges include poor understanding of long-term durability of folding mechanisms, high energy consumption during morphing, and limited payload scalability. Additionally, there is a lack of AI-driven autonomous morphology decision-making and minimal development in swarm-based morphing systems. Integration of advanced sensing, real-time adaptive control, and large-scale practical deployment remains underexplored.

## Kinematic Analysis of Foldable Drone Arm (Considering OneArm)



### 1. Assumed Single Arm Geometry

A drone arm is treated as a rigid rotating link connected to the center body by a hinge.

**Given Dimensions**

- Arm Length = **L = 250 mm = 0.25 m**
- Motor mount at free end
- Folded angle = **θ = 0°**
- Deployed angle = **θ = 90°**
- Constant angular velocity during opening

- Where:
- **O** = hinge joint fixed to drone body
- **θ** = arm rotation angle
- **L** = arm length

- **3. Position Analysis**
- Coordinates of motor tip:
- $x = L\cos\,\theta$
- $y = L\sin\,\theta$
- **Equation (1)**
- $x = L\cos\,\theta$

- **Equation (2)**
- $y = L\sin\,\theta$

- **At Folded Position (θ = 0°)**
- $x = 0.25, y = 0$

- **At Open Position (θ = 90°)**
- $x = 0, y = 0.25$

- So tip follows circular arc.

- **4. Velocity Analysis**
- Differentiate position equations:
- **Equation (3)**
- $v_x = \frac{dx}{dt} = -L\omega\sin\,\theta$

- **Equation (4)**
- $v_y = \frac{dy}{dt} = L\omega\cos\,\theta$

- **Resultant Velocity**
- $v = L\omega$
- **Equation (5)**
- $v = L\omega$

- **5. Acceleration Analysis**
- Second derivative:
- **Equation (6)**
- $a_x = -L\alpha\sin\,\theta - L\omega^2\cos\,\theta$

- **Equation (7)**
- $a_y = L\alpha\cos\,\theta - L\omega^2\sin\,\theta$
- Tangential acceleration:
- **Equation (8)**
- $a_t = L\alpha$
- Normal acceleration:
- **Equation (9)**
- $a_n = L\omega^2$

- ### 6. Time Required for Deployment
- If arm rotates from 0° to 90° in 1.5 sec:
- **Equation (10)**
- $\omega = \frac{\theta}{t}$
- $\omega = \frac{\pi/2}{1.5} = 1.047\,rad/s$

- ### 7. Tip Velocity Calculation
- Using Eq. (5):
- $v = 0.25 \times 1.047$ $v = 0.262\,m/s$

- ### 8. Final Engineering Results

| **Parameter** | **Value** |
|---|---|
| Arm Length | 250 mm |
| Rotation Angle | 90° |
| Deployment Time | 1.5 s |
| Angular Speed | 1.047 rad/s |
| Tip Velocity | 0.262 m/s |

- ### 9. Conclusion

The arm rotates smoothly through a circular path.
Safe deployment is possible with low tip velocity. This model helps select:

- Servo motor torque
- Opening speed
- Hinge strength
- Folding timing
- Uneven geometry
- Thrust imbalance
- Controller calibration error
- Yaw instability during startup

Therefore synchronized actuation is critical.

### 9 Collision and Clearance Analysis

Let adjacent hinge spacing be **S** and arm thickness be **d**.

For safe folding:

$$S > d + 2c$$

Where:

- $c$= minimum clearance allowance

This prevents contact between neighboring arms during motion.

### 10 Center of Geometry Shift During Folding

As arms fold inward, rotor masses move toward body center. Equivalent radial distance:

$$r = L\cos\,\theta$$

Moment contribution of each motor mass:

$$M = mr$$

During deployment, radial moment increases progressively. This influences inertia and startup control response.

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### 11 Angular Momentum Consideration During Deployment

If arms are deployed while propellers are spinning (emergency transformable systems), changing moment of inertia affects yaw dynamics:

$$H = I\omega$$

Hence arm deployment should preferably occur before takeoff.

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### 12 Kinematic Optimization Criteria

The optimum mechanism should satisfy:

- Minimum deployment time
- Low peak acceleration
- Zero arm interference
- Exact final angular locking
- Equal motion in all four arms
- Low actuator energy requirement

Objective function may be expressed as:

$$J = w_1 t + w_2 a_{max} + w_3 e$$

Where:

- $t$= deployment time
- $a_{max}$= peak acceleration
- $e$= positioning error
- $w_i$= design weights

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### 13 Recommended Motion Profile

Instead of sudden constant speed, smooth S-curve deployment is preferred:

- Low initial acceleration
- Constant mid-speed motion
- Soft deceleration near lock position

This reduces shock and increases hinge life.

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### 14 Practical Example

Given:

- Arm length = 0.25 m
- Final angle = 90°
- Deployment time = 1.5 s

Angular velocity:

$$\omega = \frac{\pi/2}{1.5} = 1.047\ rad/s$$

Tip velocity:

$$v = L\omega = 0.25(1.047) = 0.262\ m/s$$

Thus deployment remains safe and mechanically practical.

### Conclusion

The present work successfully studied the design and motion characteristics of a foldable arm drone using morphological synthesis and kinematic analysis. Various foldable mechanisms were reviewed, and a practical compact arm-folding concept was selected. The kinematic study demonstrated that arm deployment follows predictable rotational motion, where velocity and acceleration depend on arm length and angular speed. Proper synchronization of all four arms is essential to maintain balance and flight stability. Collision clearance and inertia variation during folding were also considered for safe operation. The results indicate that smooth S-curve deployment profiles can reduce shock loads and improve hinge life. Overall, the foldable drone mechanism provides significant advantages in portability, storage efficiency, and rapid deployment. This concept has strong potential for future UAV systems used in commercial, industrial, and rescue operations.

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