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A Review of Origami-Inspired Reconfigurable Structures for Micro Air Vehicles

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Abstract. Micro air vehicles (MAVs) are used for inspection, environmental monitoring, and exploration in confined or hazardous environments. Most MAVs have a fixed structure, but reconfiguration may be useful when a mission requires compact transport, passage through narrow openings, collision tolerance, or operation under different flight conditions. This review examines rigid-folding and thick-panel origami principles and considers their use in foldable wings, airframes, and protective structures. It first explains how coordinated folding can reduce stored size and how panel thickness creates interference in physical mechanisms. It then compares deployable airframes, collision-protection systems, and shape-changing wings. Existing studies provide physical evidence for compact deployment and impact protection, while repeated morphing during flight has received less experimental validation. Reconfiguration also introduces additional hinges, actuators, and locking parts, which may increase mass and reduce stiffness. Other concerns include hinge fatigue, actuator response, and aerodynamic stability. Origami-inspired reconfiguration should therefore be treated as a mission-dependent design option rather than a general replacement for fixed aircraft structures.

Keywords: micro air vehicles, engineering origami, reconfigurable structures, morphing wings

1. Introduction

MAVs research gained momentum during 1990s. The early work included aircraft with wingspans between 7.4 and 15 cm for optical surveillance, followed by the US Defense Advanced Research Projects Agency (DARPA) launched a program to develop flying devices smaller than 15 centimeters [1]. Since then, small aerial vehicles have been studied for inspection, environmental sensing, search and rescue, and operation in places that are difficult or unsafe for people to enter [2]. The term MAV now covers several configurations, including fixed-wing, rotary-wing, and hybrid vehicles. These configurations serve different purposes: multirotor drones can hover and perform maneuvers at low speed, while fixed-wing vehicles are generally better suited to sustained forward flight.

A fixed geometry is not necessarily a weakness. For a vehicle operating under one predictable condition, it is usually lighter and easier to control than a reconfigurable design. Difficulties arise when one mission combines conflicting requirements. A large wing may support low-speed flight

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and efficient gliding, but it also occupies more storage space and makes narrow openings harder to cross. A compact vehicle is easier to transport yet may provide less lifting area once airborne. Morphing-aircraft research has attempted to reduce such compromises by changing wingspan, sweep, twist, or camber during operation. However, the aerodynamic gain must be considered together with the mass, power demand, and complexity of the mechanism [3].

To find a possible solution, researchers started looking at origami geometry around the 2010s. While origami is an old paper-folding art, the mathematical model offered a different way of reconfiguration. Panels and fold lines can be arranged so that a compact structure unfolds through coordinated motion. Instead of using heavy joints, origami mechanisms rely on folding a flat, 2D sheet along specific crease lines to create a 3D shape. In recent years, patterns like the Miura-ori have been successfully applied to MAVs. A rotary protective structure designed to reduce collision damage, and an earwig-inspired wing that folds into a smaller area before gliding [4, 5]. These systems should not be treated as equivalent. A frame that folds for storage, a guard that deforms during impact, and a wing that changes aerodynamic geometry solve different problems and require different evidence. Successful deployment does not by itself demonstrate improved flight efficiency.

This review aims to examine origami-inspired reconfiguration at the level of MAV. It considers three questions, which origami principle has been applied to MAV, what functions have been verified in real machines and under what conditions the benefits can cover the additional mass and mechanical risk. The review covers rigid and thick-panel mechanisms, deployable airframes, protective structures, and foldable or morphing wings. Conventional control surfaces and folding devices without a clear origami-based geometric principle are used only as comparisons.

2. Origami principles for reconfigurable aerial structures

Before applying origami to flight structures requires translating geometric rules into load-bearing mechanisms. Traditional paper folding allows the material to bend and twist. However, this is unacceptable in aerospace structures like drone wings, which are made of stiff materials like carbon fiber. Therefore, engineers focus entirely on "rigid origami", where the main panels can retain their shape [6].

2.1. Rigid foldability and degrees of freedom

In the ideal rigid-origami model, panels are treated as rigid bodies that rotate exclusively along crease lines, which function as rotational joints. Assuming a sheet with zero thickness, a single crease intersection (vertex) behaves mathematically as a spherical linkage, where all hinge axes converge at a central point. The Miura-ori is a typical example of a coordinated rigid-folding pattern. Figure 1 shows its repeating parallelogram panels and coordinated folding motion. In the ideal zero-thickness model, the pattern follows geometric conditions such as Kawasaki's theorem and Maekawa's theorem, allowing it to fold flat [7].

A defining feature of the Miura-ori is its single degree of freedom (1-DOF), meaning its kinematic path is strictly coupled during expansion and contraction. In principle, a low-degree-of-freedom pattern can reduce the number of independently controlled joints and simplify deployment sequences. However, kinematic coupling in an ideal model does not guarantee that a real aerial structure requires only a single actuator, nor does it automatically yield a lighter or more energy-efficient system once joint friction, structural stiffness, and aerodynamic forces are accounted for.

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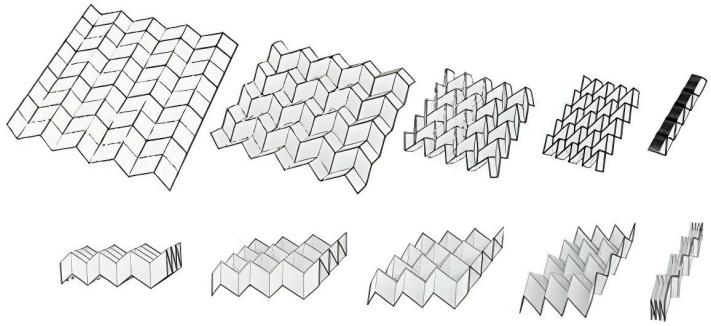


Figure 1. Kinematic model and folding process of the Miura-ori pattern, adapted from [8]

2.2. Kinematic solutions for thick-panel origami

While traditional mathematical origami assumes the material has zero thickness, real-world MAV wings are manufactured from thick, rigid materials like carbon fiber. When engineers try to fold panels with physical thickness, a critical geometric problem occurs: physical interference. The axes of the hinges no longer meet at a single central point, which prevents the panels from folding flat. To overcome this, researchers have applied spatial mechanism theory to model thick-panel origami. Early solutions involved modifying the rigid Miura-ori into spatial 4R (four-revolute) closed-loop linkages, such as Bennett linkages. However, to make these 4R models fold compactly, the panels had to be designed with non-uniform (varying) thickness. This approach is highly impractical for mass manufacturing and reduces the structural strength of the MAV wing [9].

A breakthrough in this field was achieved by introducing "kirigami" (the art of paper cutting) into thick-panel folding. As demonstrated by leading researchers in deployable structures, introducing a diagonal physical cut (a slit) along the crease transforms the restrictive 4R closed chain into a 6R closed kinematic chain (such as the 6R Waldron hybrid linkage or Bricard linkage) [10]. This kinematic transformation is revolutionary for aerospace design. It allows panels of identical, uniform thickness to fold perfectly flat into compact stacks without any physical collision. Most importantly, even with the added complexity of the 6R linkage and the physical cut, the entire mechanism still maintains a single degree of freedom (1-DOF). This means MAV wings made of standard thick panels can achieve highly compact packaging inside a launch tube and deploy flawlessly using minimal actuation power.

3. Engineering applications for MAVs

The mechanisms discussed in Section 2 offer systematic ways to achieve structural reconfiguration in small aerial platforms. Existing physical examples can be grouped based on their diverse goals: reducing packed volume for storage, providing compliance for collision tolerance, and modifying lifting surfaces for flight adjustment. These functions place different demands on the structure and call for different kinds of experimental evidence.

3.1. Deployable airframes and protective structures

A practical engineering application of origami in MAVs is solving the problem of portability. In military or planetary exploration scenarios, MAVs often must be transported in compact containers, such as cylindrical launch tubes. A smaller package can simplify transport and may help a vehicle to slip through narrow space, although the reduction in volume usually comes with extra hinges,

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flexible joints, or locking parts. Engineers built an origami-inspired foldable quadrotor in which the folding frame also helped shield the vehicle during contact [11]. Their work gives a physical example of combining deploy ability with a protective airframe, but it should not be taken as proof that any foldable quadrotor can be launched from a tube or deploy reliably in mid-air.

Another application concerns collision protection. Small aerial robots working near obstacles can bump into walls, branches, or other objects. In these situations, a compliant or foldable outer structure can deform during impact and cut down the load passed to the central body. A study showed this idea with Rotorigami, a rotary origami protective system for robotic rotorcraft. The design's main value is its ability to bend and spring back during contact, rather than any direct gain in aerodynamic performance. Figure 2 shows how the Rotorigami structure deforms during contact with an obstacle. Its creases bend and absorb part of the impact energy, reducing the load transferred to the main body of the aircraft. After contact, the structure can return towards its original shape. In the reported experiments, the protective system remained functional after repeated impacts.

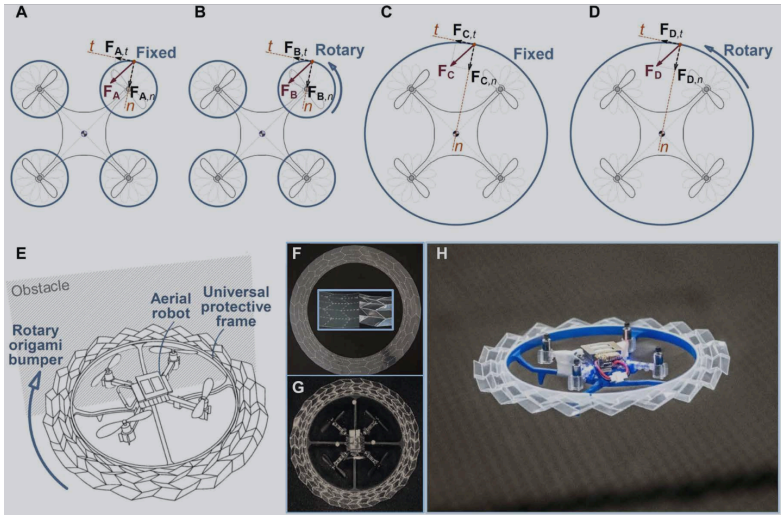


Figure 2. An origami-inspired protective structure for robotic rotorcraft deforming during contact with an obstacle, adapted from [12]

3.2. Foldable and morphing wings

Besides structural packaging, origami engineering offers a possible tool for optimizing MAV aerodynamics in real-time. In fluid dynamics, an aircraft's performance relies heavily on its wing geometry. A large wingspan provides high lift for energy-efficient gliding, much like an eagle. However, during high-speed dives or when flying through narrow gaps, a large wing creates excessive aerodynamic drag. These possible gains depend on the exact wing shape and flight condition and should be kept apart from sweeping claims of better aerodynamic efficiency. Figure 3 shows the earwig-inspired foldable origami wing developed and tested for MAV gliding. The wing occupies less space when folded and can be opened before gliding, providing a physical example of a foldable lifting surface on a small aerial vehicle. By embedding accordion-like crease patterns or sweeping Miura-ori structures into the wing skeleton, an MAV can retract its wings closer to the fuselage. This morphing action decreases the frontal area, instantly reducing parasitic drag for rapid acceleration. Conversely, when the MAV needs to loiter or conserve battery, the single-motor actuation can fully extend the origami wing. This extension significantly increases the lifting surface, thereby maximizing the lift-to-drag ratio (L/D) and extending flight endurance [4].

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However, the folding pattern must fit together with a load-bearing wing skeleton, hinges, and an actuation system, which is still a challenge.

The main difficulty is that a wing must be flexible enough to fold yet stiff enough to hold its aerodynamic shape after deployment. Folding joints can bring gaps, local soft spots, and small geometric errors, all of which may shift the aerodynamic loads and hurt the repeatability of the deployed shape. For this reason, a foldable wing should be judged not only by how small it can be packed, but also by how precise and stiff its deployed shape remains.

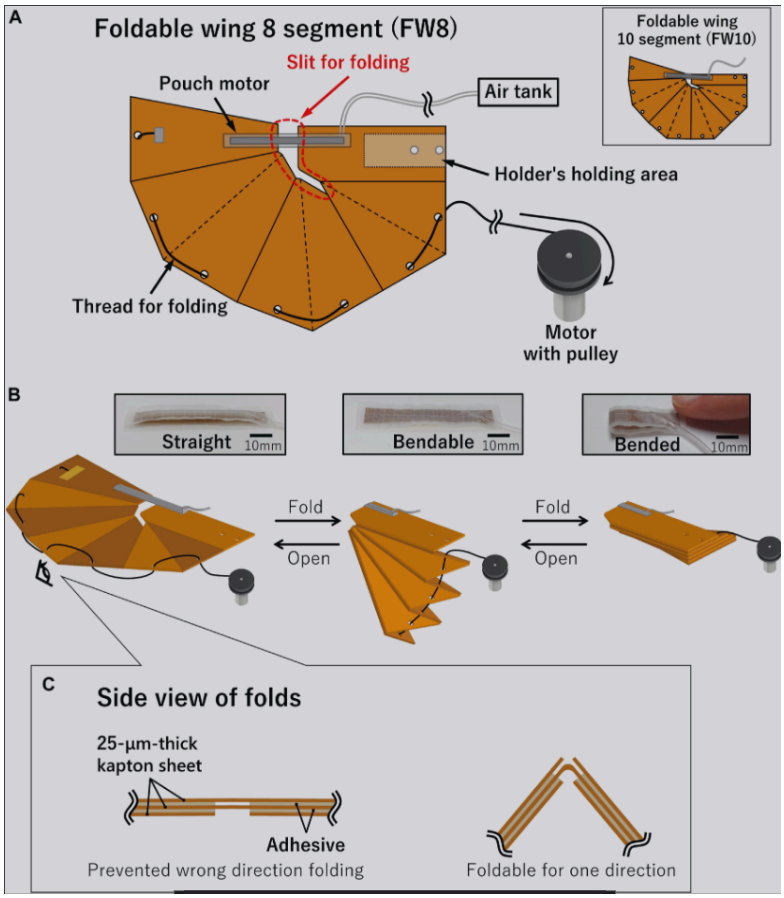


Figure 3. Earwig-inspired foldable origami wing for micro air vehicle gliding, adapted from [4]

4. Current challenges and future trajectories

Putting origami structures on a MAV is not simply about making things fold. Folding can help shrink the vehicle for storage or protect it during a crash, but it also adds hinges, actuators, and locking parts. Each of these extra parts brings weight, makes the structure less stiff, and adds something that could break. To turn a folding idea into a working aircraft, three problems need attention: how to drive the folding, how long the hinges last, and whether the wing stays stable in the air.

4.1. Actuation, locking, and mass constraints

The first major challenge is the actuation system. Traditional servo motors and mechanical gears are too heavy and bulky for micro-scale drones, which defeats the lightweight advantage of origami structures. To resolve this, engineers have attempted to use active smart materials, such as Shape

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Memory Alloys (SMAs), as solid-state actuators. SMA wires can contract like human muscles when heated by an electric current, allowing the origami wing to fold without complex motors. Still, an SMA needs power, a control circuit, and usually a spring or another SMA wire to pull it back the other way [13]. One recent morphing-wing design used SMA wires on both sides of the wing so they could pull in opposite directions, and the researchers actually tested it on a real aircraft [14].

However, SMAs suffer from a fatal thermal limitation: slow cooling rates. While heating an SMA wire to initiate morphing is relatively fast, cooling the material back to its original state relies on natural heat dissipation, which takes several seconds. For an MAV flying through turbulent winds, a morphing response delay of even one second can lead to an instant crash. Therefore, finding lightweight materials with high actuation frequencies remains a critical challenge [13].

4.2. Fatigue, deployed stiffness, and aeroelastic stability

The second severe limitation involves the mechanical durability and aerodynamic stability of the origami structure. By definition, origami wings must fold repeatedly along their crease lines. This continuous folding creates highly localized stress concentration at the hinges. Over hundreds of flight cycles, this stress leads to material fatigue, resulting in micro-cracks and eventual structural failure along the creases [15].

Stiffness matters just as much as foldability. After the wing opens, the hinges need to lock or at least resist twisting. If they stay loose, airflow can twist the wing out of its intended shape. In the worst case, the wing can start fluttering—the air pushes it one way, the structure springs back, the air pushes again, and the cycle feeds on itself. A 2024 study on a Z-shaped folding wing used simulation to show that both the folding angle and the hinge stiffness shift the speed at which flutter kicks [16]. Different wings, different folding patterns, so the numbers will not transfer directly to an origami design. But the point stands: if a hinge is soft enough to fold, it might also be soft enough to flutter, and that needs checking.

4.3. Verification focuses and mission-specific integration

So far, most studies have focused on showing that an origami structure can fold and unfold. The next step should be testing whether these designs work on a flying aircraft—not just on a lab bench. This means putting the folded wing in a wind tunnel, running it through hundreds of folding cycles to see how the hinges hold up, and measuring how much power the whole system uses compared to a normal fixed wing. Foldable wings are not a one-size-fits-all replacement for regular airframes. They make sense mainly for jobs where folding is really needed, such as fitting a drone into a launch tube, flying through tight spaces, or surviving crashes. In those cases, the extra weight, the added parts, and the risk of something breaking may still be worth it.

5. Conclusion

This paper examined how origami-based ideas have been used in the design of morphing wings and other reconfigurable structures for micro air vehicles. The studies discussed here show that folding patterns can change the wing area, sweep, or packed size without requiring many separate motors. However, the result depends strongly on the design of the hinges, the material, and the locking system. The review also showed that the gap between a paper model and a working aircraft is not small. Thick-panel origami and kirigami can help deal with the thickness of real materials and reduce unwanted interference during folding. At the same time, deployable structures can make an

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MAV easier to store and may help protect it when it hits an obstacle. These benefits are useful, but they do not automatically mean better flight performance. The added parts may increase the weight and make the structure harder to control. Several problems still need to be tested in more detail. These include the working life of the hinges, the speed and power requirements of the actuators, the stiffness of the wing after it opens, and its behavior in moving air. SMA actuators may be useful for compact designs, but their heating and cooling process can limit repeated movement. Foldable wings must also be checked for unwanted vibration and changes in shape during flight. In general, origami is not a universal replacement for a fixed aircraft structure. Its value is clearer when a mission requires a small, stored size, fast deployment, impact protection, or a wing that can change shape. Future work should therefore focus less on showing that a structure can fold and more on proving that it can fold repeatedly, fly safely, and provide a real advantage over a simpler design.

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