Bioinspiration & Biomimetics

PAPER

Design and control of the first foldable single-actuator rotary wing micro aerial vehicle

Shane Kyi Hla Win, Luke Soe Thura Win, Danial Sufiyan and Shaohui Foong

Engineering Product Development, Singapore University of Technology and Design, Singapore 487372, Singapore

*Author to whom any correspondence should be addressed.

E-mail: shane@sutd.edu.sg, thura_soe@sutd.edu.sg, danial_sufiyan@sutd.edu.sg and foongshaohui@sutd.edu.sg

Keywords: monocopter, nature-inspired robots, foldable wing, single-actuator robot, unmanned aerial vehicle

Supplementary material for this article is available online

Abstract

The monocopter is a type of micro aerial vehicle largely inspired from the flight of botanical samaras (Acer palmatum). A large section of its fuselage forms the single wing where all its useful aerodynamic forces are generated, making it achieve a highly efficient mode of flight. However, compared to a multi-rotor of similar weight, monocopters can be large and cumbersome for transport, mainly due to their large and rigid wing structure. In this work, a monocopter with a foldable, semi-rigid wing is proposed and its resulting flight performance is studied. The wing is non-rigid when not in flight and relies on centrifugal forces to become straightened during flight. The wing construction uses a special technique for its lightweight and semi-rigid design, and together with a purpose-designed autopilot board, the entire craft can be folded into a compact pocketable form factor, decreasing its footprint by 69%. Furthermore, the proposed craft accomplishes a controllable flight in 5 degrees of freedom by using only one thrust unit. It achieves altitude control by regulating the force generated from the thrust unit throughout multiple rotations. Lateral control is achieved by pulsing the thrust unit at specific instances during each cycle of rotation. A closed-loop feedback control is achieved using a motion-captured camera system, where a hybrid proportional stabilizer controller and proportional-integral position controller are applied. Waypoint tracking, trajectory tracking and flight time tests were performed and analyzed. Overall, the vehicle weighs 69 g, achieves a maximum lateral speed of about 2.37 m s$^{-1}$, an average power draw of 9.78 W and a flight time of 16 min with its semi-rigid wing.

1. Introduction

With quick advancement of technology in numerous fields and miniaturization of components, micro aerial vehicles (MAVs) have become increasingly useful and ubiquitous. MAVs weigh typically less than 100 g and due to their lightweight and small form factor, they can be considered as safer to operate indoors and nearby humans or animals. Typically, MAVs can be of three different types: fixed-wing, rotary wing and flapping wing. Fixed-wing MAVs, such as the Black Widow [1], are particularly good for longer ranged missions but not suitable for operation within confined spaces due to its forward speed. Rotary wings, which may be of helicopter type such as Black Hornet [2] or multi-rotor type such as Crazyflie [3], are better suited for indoor operations due to their low-speed flights and maneuverability. Their design and control are well researched, however they require multiple actuators and by its physical nature, they may be less efficient and have shorter range than the fixed-wing counterparts. Lastly, flapping wings are a new emerging field in MAV research due to their relatively high aerodynamic efficiency at low Reynolds number regime.

Among rotary wings, monocopters have recently enjoyed renewed interest in research. The design of the monocopter is inspired from naturally occurring samara seeds, more fondly known as ‘helicopter seeds’ due to their ability to use autorotation as a way to slow down their descent and disperse. Similar to the samara seed, the design of the monocopter is relatively simple, consisting of a large single wing and a seed-like portion that houses most electronics and...
battery. The concept of monicopters is actually not new. The first design of the monopcopter can be traced back to 1913 [4] when a failed manned-flight attempt was made. As the entire craft is supposed to rotate, additional complex mechanisms must be added if the flight is manned, ultimately making the concept more suitable as an unmanned system. As an MAV, the monopcopter is a relatively simple platform, with minimum moving parts and actuators, making it possible for low cost manufacturing. With approximately 80% of its body forming the wing for useful aerodynamic forces generation (as seen in Figure 1(A)), it forms the basis of an efficient platform as compared to multi-rotor type rotary wing crafts. With today’s technology, the monopcopter has become particularly relevant. High speed micro-sized sensors can measure the monopcopter’s rapidly changing states and use it for control, which had been a challenging task in the past.

One of the advantages of the monopcopter platform is its inherent ability for autorotation, the mode of flight of the samara seeds. The monopcopter is thus equipped with a natural fail-safe, thanks to this ability to descend gracefully in autorotation in the event of a power failure. Autorotation of single-winged seeds is relatively well studied, both in its natural form [5–7], or their mechanical counterparts [8, 9]. Attempts have been made to use samara-inspired flight for payload delivery in the past [10–13].

Research interest on monopcopter platforms revived back in 2008 [14] when a research attempt by students from MIT made one of the first documented controllable monicopters. It used an electric motor and propeller to provide propulsion for its rotation, and a servo to control the flap (aileron) deflection angle for pitch and roll movements. It featured a simple construction—a foam wing, with orthogonal carbon fiber struts as a structure to house the motor, battery and other electronic components. The researchers employed cyclic actuation of the flap, similar to the swashplate control of the blades in helicopters, for controlling the lateral movements. This means that in every revolution of the monopcopter, the flap is deflected up and down smoothly in a sinusoidal wave. However, as opposed to swashplate of helicopters, there is no stationary frame of reference from which control inputs can be applied as the entire body of the craft is rotating. Knowledge of the vehicle orientation relative to the desired flight path is obtained by an on-board electronic magnetometer. The work demonstrated that a powered controllable flight with a monopcopter was possible and outlined a basic theory of monopcopter dynamics. Although they did not publish the flight time achieved with their setup, one can perform a simple calculation based on the battery used (7.2 V 300 mAh) and the power consumption reported (32 W) and arrive to a flight time of approximately 4 min.

In 2010 [15], researchers from University of Maryland made samara-I, samara-II and samara-III prototypes, which are of different sizes and weights. Their smallest variant, samara-III, is tiny enough to fit on a palm. Monicopters with smaller wingspan typically have to rotate faster for flight than their larger counterparts. As sensor packages capable of measuring on-board flight data for this nano-class crafts were not commercially available at that time, the researchers had to find a different approach for control that did not rely on once-per-revolution sensing and actuation. Their research focused on first investigating autorotation properties of different wing geometries of mechanical replicas of the samara design. Upon observing the helical trajectories of an autorotating samara are coupled to variations in its wing pitch, the researchers proposed a method to control the resulting robotic samara. By changing the pitch angle of the entire wing, the radius of the precession circle could be controlled, thus making the craft move towards an intended direction in circles of changing radii. As opposed to once per revolution control used in [14], this method requires the wing pitch to change over several revolutions. Hence, high speed sensing and actuation, which are costly at micro-scale, are not required. The robotic samara prototypes thus carried only an electric motor, an electronic speed controller (ESC), a servo, a receiver and a battery. With no microcontroller and sensing on-board, it allowed for an efficient, simple and lightweight construction. The robotic samara prototypes were all manually piloted by a human operator, with its largest prototype achieving a maximum of 20 min of flight time.

Traditionally, monicopters have always used two actuators to achieve flight and control in five degrees-of-freedom (DOF). This is already under-actuated, as compared to multi-rotors or traditional rotary wings which require a minimum of four actuators. In 2020, a research work [16] proposed a Single Actuator Monopcopter (SAM), using one single electric motor to both provide propulsion for flight and produce control effort for pitch and roll motions. SAM featured a custom printed circuit board (PCB) to connect all its electronic components and also provide structural rigidity to the seed portion. As opposed to [14, 15] which used special airfoils for added efficiency, this work used optimization methods to find the best wing planform geometry and motor location, while using flat-plate airfoil for simplicity. For controlling its direction, the motor is pulsed in a cyclic manner. SAM carries a microcontroller and an IMU—when given position states feedback, it can perform completely autonomous flights. It demonstrated waypoint-tracking flight using a closed-loop PID controller and motion-captured camera system to provide position feedback, and achieved 20 min of flight time.
Figure 1. (A) F-SAM in mid-flight, during a position-controlled flight experiment in MOCAP environment. (B) Folded F-SAM is small enough to fit inside a person’s hand, allowing ease of transportation and storage.

Table 1. State-of-the-art of current MAVs.

| Micro air vehicles          | Type            | Year | Wing span (cm) | Weight (g) | Self-sensing | Flexible wing | Foldable actuators | Flight endurance (mins) |
|-----------------------------|-----------------|------|----------------|------------|--------------|---------------|---------------------|------------------------|
| Black Widow MAV [1]         | Fixed wing      | 2001 | 15             | 80         | Yes          | No            | No                  | 3                      | 30                     |
| Black Hornet PRS [2]        | Helicopter      | 2020 | 17             | 33         | Yes          | No            | No                  | —                      | 25                     |
| Crazyflie 2.X [3]           | Multicopter     | 2021 | 9              | 27         | Yes          | No            | No                  | 4                      | 7                      |
| UMD quad [25]               | Multicopter wing| 2016 | —              | 45         | Yes          | No            | No                  | 4                      | 31                     |
| Quad-thopter [22]           | Flapping wing   | 2018 | 28             | 38         | Yes          | Yes           | No                  | 4                      | 9                      |
| NUS_Roboticbird [21]        | Flapping        | 2019 | 22             | 31         | Yes          | Yes           | No                  | 4                      | 3.5                    |
| MIT monocopter [14]         | Monocopter      | 2008 | 40             | 170        | Yes          | No            | No                  | 2                      | 4                      |
| Samara-I [15]               | Monocopter      | 2010 | 27             | 75         | No           | No            | No                  | 2                      | 20                     |
| Samara-II [15]              | Monocopter      | 2010 | 18             | 38         | No           | No            | No                  | 2                      | 10                     |
| Samara-III [15]             | Monocopter      | 2010 | 7.5            | 9.5        | No           | No            | No                  | 2                      | 2                      |
| SAM [16]                    | Monocopter      | 2020 | 50             | 148        | Yes          | Yes           | No                  | 1                      | 20                     |
| F-SAM (in this study)       | Monocopter      | 2021 | 35             | 69         | Yes          | Yes           | Yes                 | 1                      | 16                     |

Research efforts to achieve controllable flight using a single actuator have been made before SAM. The monospinner [17] has a single actuator and achieves a 5 DOF flight. Essentially, it is a mechanically simple version building upon the idea of a quadcopter losing three of its propellers. It is passively unstable and requires closed-loop feedback control for its flight. Another example is Piccolissimo [18] which is claimed to be the smallest MAV. It demonstrated limited directional control by leveraging on asymmetry between the rotation axis of the body of the craft and that of the motor.

Using a flexible or semi-rigid wing for a rotary wing type aircraft is almost non-existent, perhaps due to not having any obvious benefits of such feature. However, for fixed wing and flapping wing counterparts, there are some examples available. A flexible-wing-based fixed wing MAV was explored in a work in 2002 [19], mentioning numerous advantages such as improved aerodynamic efficiency, delayed stall and ability to be reconfigured for storage. Most flapping wing MAVs employ flexible wings [20–22], as flexible wings give superior aerodynamic efficiency at low Reynolds number regime, or for collision resilience using soft actuators [23]. However, their construction usually does not allow for folding or reconfiguration for storage.

Most MAV research rely on commercial off-the-shelf (COTS) flight controllers [21, 22]. This has obvious benefits such as lower cost for prototyping, quick
and easy replacement in the event of damages, and being able to rely on existing sensor integration. However, some research projects especially on micro-class crafts [24] opt for building their own custom flight controller boards. This allows them to carefully select and use only the most suitable components relevant to the project, obtain weight savings, and perhaps most importantly, be able to obtain the desired form factor. If mass-produced, the cost of custom flight boards can be equivalent or lower than COTS counterparts.

In summary, various forms of MAVs have been explored in numerous research efforts around the world and the current trend is towards pushing boundaries in efficient flight, the use of minimal actuators and superior capabilities such as flexibility and easy deployment. The monopcopter, as seen in figure 2 and table 1, is a strong contender in this field, as its form factor allows for increased flight efficiency while enabling a dynamically stable under-actuated flight. However, one drawback of the monopcopter is its large footprint which hinders it from quick and easy deployment. The monopcopter, as seen in figure 2, has a print of the monopcopter (when not in flight), thus making the platform more compelling and versatile.

This work aims to explore minimizing the footprint of the monopcopter (when not in flight), thus making the platform more compelling and versatile in the field of MAVs. The following research contributions are presented:

- The design and development of a Foldable Single Actuator (F-SAM) is presented. The details for the compliant 3D-printed body design and explorations on different types of flexible wing construction are shown. Next, details are given for an optimization process to find the best wing planform considering the effects of wing flexibility and constraints due to the folding process. The resulting F-SAM prototype is able to decrease its footprint area by 69% when folded and fly for a duration of 16 min with a take-off weight of 69 g.

- A dynamic model of F-SAM is devised for a simulation in 6 DOF which is used in the optimization process and simulation of new control strategies. A proportional stabilizer controller and proportional-integral position controller are devised and tested in the simulation. This new control strategy proposed is suitable for nonlinear rotating platforms similar to F-SAM and improves their dynamic stability.

- Experimental verification is performed to observe F-SAM’s performance for closed-loop waypoint tracking, trajectory tracking, flight time test and straight-line speed tests. The results show that F-SAM is controllable in 5 DOF, is agile enough to maneuver through a 1.1 m × 0.4 m window, has a mean lateral speed of 2.37 m s⁻¹, has a mean rotation speed of 33.85 rad s⁻¹, maximum ascend rate of 1.20 m s⁻¹ and autorotation descent speed of 27.93 m s⁻¹.

2. Design and control of F-SAM

The F-SAM consists of two major structures similar to other monopcopters: the body and the wing. The single motor is mounted on the leading edge of the wing, unlike some monopcopter designs where the motor is mounted on a separate structure extended from the base of the body [15]. By mounting the motor on the wing, a more compact folded structure can be achieved. The components are placed such that the center of gravity (CG) lies close to the body in the unfolded state, enabling most areas of the wing to receive airflow to generate useful aerodynamic forces. Most of the components are carefully selected in an effort to reduce as much weight as possible.

F-SAM is designed to rotate counter-clockwise (looking from above) although there is no observed difference in physical dynamics in either direction of rotation.

2.1. Body

The body houses all the flight avionics and the flight battery. The flight avionics are all mounted on a purpose-designed autopilot board. Two single cell lithium polymer batteries are connected in series to supply power for avionics and flight. The autopilot board provides most of the structural rigidity of the body and small 3D-printed structures are used to facilitate folding of the body structure itself.

Normally, 3D-printed components are designed to be rigid and provide structural support. In the case with F-SAM, however, due to the design of the fold, the 3D-printed components are designed to be semi-rigid. A compliant design, shown in figure 3, allows the 3D-printed component to achieve flexibility in one axis. Two of such structures hold the battery and flight board together. When folded, the battery rests next to the folded wing structure at about α = 60°. When in flight, the battery can be either fully folded in (α = 0°) or out (α = 180°). In the former case, the moment of inertia of F-SAM is increased, causing it to fly at higher spin rate during hover while in the latter configuration, the moment of inertia is increased, resulting in a lower spin rate. The center of rotation also changes due to the shift in CG.

A total of four 3D-printed parts and two carbon rods are used in the construction of F-SAM. Two of them use compliant design to hold the battery and flight board together. One holds the base of the wing using a tight-fit slot and a 3M surgical tape and connects to the carbon rod which acts as the main hinge between the wing and the body. The last 3D-printed component attaches the motor to the wing. A second carbon rod is used as support during take off to prevent the propeller from touching the ground.
2.2. Wing

The wing forms the largest area of the structure of the craft while being the lowest mass proportion. It needs to generate useful aerodynamic forces to keep the craft in flight and by having a low mass, the CG can be placed nearer to the body, enabling a larger section of the wing to have inflow during rotation. Monocopter wings generally have been built using lightweight materials such as foam [14], carbon fiber [15], balsa wood [12] or a combination between balsa and foam [16]. The autorotating versions of this samara-inspired craft have been built using a combination of balsa and foam as well [10, 13]. Various airfoil types have been used on monocopter wings. Airfoil types such as AG455 [14], AG38 [26], samara-inspired custom airfoil [15] and flat-plate airfoils are used on different monocopter prototypes. As for the planform geometry of the wing, monocopters have mostly utilized a rectangular planform for simplicity. A samara-inspired shape has been explored [15].

With F-SAM, the wing needs to be flexible for folding compactly, allowing it to be folded and stored or transported inside a small container. Different materials and folding techniques are explored in this work. The airfoil is set to flat-plate airfoil as it allows for easy folding and prototyping. The wing planform, with the chosen wing material, is optimized using genetic algorithm on a dynamic model in a 6-DOF space, applying blade element theory for aerodynamics modeling. The different materials and folding techniques explored are presented below.

2.2.1. Flexible plastic

A flexible wing structure can be made from laminated plastic (Suremark Laminating Pouch 100 micron) as shown in figure 4(a). In order to increase chordwise stiffness, narrow strips of balsa wood (1 mm thickness) are added in between two layers of plastic before lamination. In this variant, three wires for the motor are also placed within the plastic sheets before lamination. The structure of the wing is flexible along the wing span, allowing it to fold into a roll. In flight, the apparent centrifugal force generated from the rotation of the craft pulls the wing straight. A torque is generated when the spinning motor and propeller is rotated about the rotation axis of the craft. This torque pitches the outer section of the wing up, twisting the wing along spanwise direction of the wing. The same flexibility allowing the spanwise twist also leads to a less effective cyclic control.

2.2.2. Flexible PCB

An alternative idea is to use PCB structure as the wing, effectively making it a multi-functional element. Not only would the wing be used to generate aerodynamic forces, it could also be used to embed connections for the motor and other electronics such as a wireless communication antenna. A flexible PCB material (0.1 mm polymide flex) was considered as the material of the wing. Carbon spars (1 mm diameter) are taped onto the wing to increase its chordwise stiffness. A narrow strip of plastic is laminated along the leading edge of the wing to increase its spanwise stiffness. Similar to the flexible plastic wing, the flexible PCB wing can be rolled into a compact form factor. Likewise, centrifugal forces pull the wing straight during flight. The cyclic control is even less effective on this wing as the wing material is more flexible than the flexible plastic, allowing too much twisting in spanwise direction.
2.2.3. Semi-rigid balsa with plastic

To increase the effectiveness of cyclic control, spanwise stiffness must be increased. The next strategy is similar to the first flexible plastic concept, but with increased width of the balsa elements. In this case, the balsa elements fill up the entire area of the wing, joined together by one sheet of laminated plastic. To produce this wing, balsa is first lasercut into precise shapes and placed within laminating pouch (125 microns) leaving a tiny gap (approximately 1 mm) between each element. Once lamination is done, the excess plastic is manually cut off, after which one side of the plastic is removed, leaving only the balsa pieces and one side of laminated plastic sheet as the structure of the wing. This wing can be folded into its plastic side. Although it cannot be rolled like previous wing structures, the semi-rigid wing can be folded into a neat pre-determined configuration, such as triangular or rectangular. The benefit of the semi-rigid structure as compared to its other flexible counterparts is that it has increased responsiveness to control inputs and increased flight efficiency. However, it has less control responsiveness and flight efficiency as compared to a fully rigid wing, which we found during preliminary testing. For F-SAM, this semi-rigid wing structure is chosen.

2.3. Custom autopilot board implementation

The F-SAM platform is passively stable. An autopilot implementation allows the craft to be controlled via a human operator or closed-loop feedback control in a motion-captured environment.

Creating a purpose-designed autopilot board allows us to take several advantages over simply using an off-the-shelf autopilot system. It enables us to choose exactly the components needed, packaged in a form factor that is favorable to the folding design. All the components including sensors, microcontroller, power regulators, and the ESC are arranged in a narrow rectangular form factor as shown in figure 5.

For the attitude heading reference system, a combination of magnetometer and inertial sensor is used. The former is LIS3MDLTR, an ultra-low-power high-performance three-axis magnetometer, capable of an update rate of 500 Hz. The latter is ICM20649 that consists of a gyroscope and an accelerometer. The gyroscope has a full-scale range of 4000 degrees per second, making it suitable for high rotation speed measurements such as the monocopter.

For the microcontroller, Espressif ESP32 is chosen for use, in Sparkfun MicroMod configuration. This allows us to easily swap and replace the microcontroller should it be damaged during a crash. ESP32 comes with a WiFi connectivity, allowing flight telemetry and a wireless reconfiguration of parameters.

An ESC is directly soldered onto the control board, receiving control signals directly from the microcontroller and providing power to the brushless motor mounted on the wing. The control board is also designed to include data-logging capability using a MicroSD card. Additionally, two time-of-flight laser ranging sensors are added for potential sensing applications and a current sensor to measure the power consumption during the flight. A power distribution board (PDB) connects two 1S lithium polymer batteries in series and provides input power to the control board.

2.4. Flying prototype

The prototype, shown in figures 1 and 6, is assembled using the 3D printed components, laminated
wing, custom autopilot board and the propulsion system. With all the parts available, the prototype can be easily assembled within about 10 min. The wing used on the F-SAM prototype has holes cutout on the balsa for more weight savings. It is assumed to not affect the aerodynamics significantly as the plastic film still covers the entire area to form aerodynamic surface. The COTS parts used are given in table 2. The weight breakdown of the F-SAM prototype is shown in figure 7 and it should be noted that the battery and propulsion system form about 49% of the weight of the craft, whereas the wing only forms 12%. In its unfolded state, F-SAM is about 35 cm in length. However, once folded, its footprint area is reduced by 69%.

The prototype is flown and its current and power consumption is measured using the INA219 current sensor included in our custom autopilot board. The final specifications of the flying prototype are given in table 3. F-SAM achieves a flight efficiency of about 7.1 g W\(^{-1}\) whereas a Crazyflie quadcopter averages about 4.3 g W\(^{-1}\) during hover.

2.5. Dynamic model

In order to simulate and optimize the wing planform of F-SAM, a dynamic model is first created. Figure 8 shows all the forces and torques acting on F-SAM typically during its flight. The world frame is denoted as \(\Psi_W\) and the body-fixed frame is denoted as \(\Psi_b\) with its center fixed to the CG of the craft, \(x\)-axis aligned with the longitudinal direction of the wing and \(y\)-axis along chordwise direction of the wing. In the simulation, the battery module is fixed at its folded orientation (\(\alpha = 0^\circ\)) giving a smaller rotational moment of inertia, with the CG located near the root of the wing.

2.5.1. Aerodynamic forces

The forces and torques acting on F-SAM include the weight \(W\), thrust and torque from motor \(F_m\) and \(\tau_m\) respectively, and aerodynamic forces from the wing. In general, it is modeled as a rigid body in a 6 degrees of freedom environment, where it is able to freely translate and rotate in any direction. MATLAB Simscape Multibody [27] is used for
the simulation, where an application of six-DOF joint automatically applies the standard formulations of six-DOF motion which are commonly used for simulation of aircraft and spacecraft [28]. Simscape Multibody provides multibody simulation environment using a graphical programming interface representing relationships between bodies using joints, constraints, force elements and sensors. Forces and moments can be specified at component level, such as individual blade elements, and resolved forces and moments are automatically computed and applied to the entire body through component relationships. Using Simscape Multibody ensures that human errors are minimized in the process of manually writing, assembling and running the code for integrating the equations of motion and resolving the numerous forces and moments.

The geometries of autopilot board, 3D-printed components, battery, motor and propeller are drawn in SolidWorks and imported into Simscape Multibody, with their exact weights applied. Hence the mechanical properties of these elements are precisely accounted for in the simulation. The wing is generated using flat rectangular blocks to form a generic shape, which must be optimized using the simulation.

In order to model the aerodynamic forces, we apply blade element theory [29]. The wing is split into \( n_{\text{be}} \) blade elements. The lift and drag forces generated from each blade element is calculated using:

\[
dL = \frac{1}{2} \rho U^2 c C_l \, dr, \quad dD = \frac{1}{2} \rho U^2 c C_D \, dr, \quad (1)
\]

where \( dL \) and \( dD \) are the lift and drag forces respectively acting on the blade element, \( \rho \) is the density of air, \( U \) is the relative air velocity interacting with the blade element, \( c \) is the chord length of the blade element, \( C_l \) and \( C_D \) are coefficients of lift and drag respectively, and \( dr \) is the width of the blade element. As the wing is constantly flying into its own wake during hover and in most aspects of the flight, it is assumed to be less efficient than in its ideal state. To account for this, the drag coefficients are multiplied with a constant \( \mu \) such that \( C_D = \mu C_d \). This value of \( \mu \) is experimentally found by flying an arbitrary configuration of F-SAM and then fine-tuning the simulated parameters to match the results. The values of \( C_l \) and \( C_D \) are flat-plate airfoil coefficients obtained and linearly interpolated from NACA Technical Report 3221 [30].

\( dL \) and \( dD \) forces are resolved into normal and axial forces (\( dN \) and \( dA \) respectively) before being applied back into the model. In Simscape Multibody, the relative inflow angle can be found by attaching a transform sensor to measure velocities with respect to a non-rotating follower on the blade element, as shown in figure 9. The two cases consider all inflow velocity situations, allowing the model to be simulated in almost any scenario. \( dN \) and \( dA \) forces are then calculated using:

\[
\begin{align*}
\text{Case 1} \quad & \begin{cases} 
  dN = dL \cos(\zeta) + dD \sin(\zeta) \\
  dA = -dL \sin(\zeta) + dD \cos(\zeta)
\end{cases} \\
\text{Case 2} \quad & \begin{cases} 
  dN = -dL \cos(\zeta) + dD \sin(\zeta) \\
  dA = dL \sin(\zeta) + dD \cos(\zeta)
\end{cases}
\end{align*}
\]
where $\zeta$ is the relative inflow angle of air. In F-SAM, due to its configuration, the CG is located in between the first and second blade element. As F-SAM typically rotates about its CG, this leads to a negative flow on the first blade element and a very small positive flow on the second blade element due to their close proximity to the center of rotation. The aerodynamic force contribution from these two elements are hence assumed to be negligible. For the rest of the blade elements, the normal and axial forces are assumed to be acting at the quarter-chord location.

The thrust unit simply consists of a brushless motor directly attached to a propeller. In order to consider the gyroscopic effects of a spinning mass (the motor bell and propeller), these components are modeled to spin in the simulation with an estimated rotation speed of 240 rotations per second at 100 g of thrust, modeled with a direct linear relationship to the motor force. The accuracy of the simulated model is cross-checked with an actual prototype during mid-design phase, on parameters such as the rotation speed $\Omega_z$ and thrust $T$ required for hover.

2.5.2. Wing flexibility considerations

In order to simplify the simulation, each blade element is assumed to be each foldable piece on the semi-rigid wing. Due to the folding methodology shown in figure 8, the width of each blade element $\Delta_i$ (measured in mm) follows the following relationship

$$\Delta_i = \begin{cases} \delta, & \text{if } i = 1, 2 \\ \delta - 1.62(i - 2), & \text{if } i > 2 \end{cases}, \quad (4)$$

where $\delta$ is the parameter which defines the width of the first blade element, and hence indirectly defines the length of the wing, and $i$ is the blade element designation and $i \in \mathbb{Z}_+^+$. The flexibility of the wing during flight is also considered for simulation. Each blade element is linked to the other using a revolute joint that allows rotational degree of freedom along $y$-axis of $\Psi_b$, as shown

---

Table 2. COTS electronic parts for building F-SAM.

| Item  | Name                      | Qty | Website         |
|-------|---------------------------|-----|-----------------|
| Processor | SparkFun MicroMod ESP32 | 1   | sparkfun.com    |
| Motor | ROBO RB 1202.5 | 1 | getfpv.com     |
| ESC | EMAX Bullet 30A | 1 | emaxmodel.com |
| Battery | 450 mAh 1S 30C | 2 | betafpv.com |
| RC | FrSky Pro Micro | 1 | frsky-rc.com |

---

Figure 6. (A) In the unfolded state, F-SAM’s wing droops to the ground, while the motor portion is lifted up by a carbon rod to allow unobstructed spinning of propeller during take-off. (B) In the folded state, the battery and autopilot board hug the folded wing. The motor lies roughly near the center of the folded form. (C) The overall structure (from underneath) of F-SAM prototype, showing its flex motor cable connections, battery and autopilot board layout.
Figure 7. Weight breakdown of F-SAM. Battery contributes a major fraction of the weight at 38% (26 g), while the 3D-printed structural components and autopilot board make up a combined 38% (26 g).

Table 3. Specifications of F-SAM.

| Parameters          | Value            |
|---------------------|------------------|
| Total weight        | 69 g             |
| Hover rotation speed| 5.3 Hz           |
| Hover current draw  | 1.3 A            |
| Hover power draw    | 9.78 W           |
| Wing length         | 32 cm            |
| Wing area           | 229 cm²          |
| Wing aspect ratio   | 4.5              |
| Mean chord length   | 71.3 cm          |
| Flight time         | 16 min           |
| Unfolded footprint  | 266.5 cm²        |
| Folded footprint    | 82.3 cm²         |

in figure 10. A spring stiffness value of $k_y$ and damping coefficient of $\sigma_y$ is applied to all the joints between the blade element. As the wing also has limited flexibility along $x$-axis, a single revolute joint along $x$-axis is applied between the 5-th and 6-th blade elements with a spring stiffness and damping coefficients of $k_x$ and $\sigma_x$ respectively. The values of the coefficients have not been found experimentally, but are selected such that the wing deformation during the flight is similar between real life and simulation. These values are presented in table 5.

2.6. Cyclic control

F-SAM is equipped with just one actuator and this single actuator is responsible for both altitude and attitude controls.

As F-SAM is a constantly rotating system, it is intuitive to apply a cyclic control. In helicopters, a swashplate is used to obtain cyclic control of the blade pitch angle. The swashplate mechanically limits and controls the pitch angle of each blade, producing a smooth sine wave through each rotation. The result gradually increases and decreases lift over different regions within each rotation. The imbalance of lift tilts the tip path plane of the blade into a pitch or roll motion, also resulting in the pitch or roll motion of the craft.

On F-SAM, direct motor control allows a more rapid approach of cyclic control. One simple way to maximize the benefits of rapidly changing thrust is to use square waves. As shown in figure 11(A), an arbitrary constant thrust with an arbitrary configuration of F-SAM results in hover flight. Increasing this thrust results in increasing the rotation speed of F-SAM which in turn creates more lift to start a climb. Decreasing the thrust, on the other hand, results in a descent. During cyclic application of thrust, thrust is higher in a portion of the rotation period and lower in the remainder as shown in figure 11(B). At an arbitrary cyclic thrust, the craft remains at constant altitude while moving. Increasing or decreasing cyclic thrust results in climbing or descending while moving laterally in general.

The parameter $T_o$ is the offset thrust. The effect of this parameter is similar to that of collective pitch control on helicopters. When flown manually, this parameter is mapped directly to the throttle stick value. The parameter $T_{amp}$ is the amplitude of the square wave. When flown manually, this parameter is mapped to the amplitude of roll and pitch input, $\phi_c$ and $\theta_c$ respectively. $T_{amp}$ and control direction $\gamma_c$ of pitch and roll input can be defined as

$$T_{amp} = k \sqrt{\phi_c^2 + \theta_c^2}$$

$$\gamma_c = \arctan \left( \frac{\phi_c}{\theta_c} \right)$$

where $k$ is a constant to scale the effectiveness of pitch and roll commands. Square cyclic control for thrust $T$
can be defined as

\[
T = \begin{cases} 
T_o + T_{\text{amp}}, & \text{if } \sin(\gamma_z + \gamma_c + \gamma_{\text{off}}) > \epsilon \\
T_o - T_{\text{amp}}, & \text{otherwise} 
\end{cases}
\]  

(7)

where \( \gamma_z \) is the current azimuth heading of the craft, \( \gamma_{\text{off}} \) is the angle correction offset due to gyroscopic precession and other effects, and \( \epsilon \) is the variable to control the duty cycle.

### 2.7. Closed-loop control

To control F-SAM in simulation and in experiments with MOCAP (motion captured) environment, a closed-loop control is devised. The controller consists of a proportional stabilizer control and traditional proportional integral position Control.

#### 2.7.1. Proportional stabilizer

Being a system influenced by both aerodynamic forces and gyroscopic precession, F-SAM, like any other monoplane, has a natural precession circle. Depending on the physical dynamics of the craft, the precession circle may be one that is growing (unstable), constant (marginally stable) or reducing (stable). For a monoplane, before any control is applied, it is desirable to have physical dynamics configured such that the precession circle is reducing. This means that when a disturbance is introduced, the monoplane flies in spirals of decreasing radius.

However, the natural decay of the precession circle in a stable configuration of the monoplane may become problematic when employing linear controllers such as PID control. The latter, when used to control position for example, may cause the system to enter a growing precession circle. Various methods have been attempted to reduce precession circle while having PID control in tandem. The main problem with such attempts results from precession circle having a different phase from the controller itself. This will be explored in detail in a future work.

It is found that having a proportional stabilizer based on angular velocity states in the world frame helps to reduce the precession circle. The proportional stabilizer is defined as follows

\[
\phi_s = -k_s \Omega_Y 
\]  

(8)

\[
\theta_s = -k_s \Omega_X 
\]  

(9)

where \( \phi_s \) and \( \theta_s \) are stabilizer controller outputs for pitch and roll respectively, \( k_s \) is the stabilizer gain, and \( \Omega_X \) and \( \Omega_Y \) are angular velocities in X and Y axis respectively. This controller will be analyzed and
evaluated in depth in a future work. With the stabilizer controller applied, F-SAM model has increased dynamic stability.

2.7.2. Position control
A traditional PI controller is applied each for altitude, and a P controller for pitch and roll controls.

Altitude control works in the following manner. Increasing the thrust from the single actuator causes F-SAM to have increased spin rate. This in turn generates increased aerodynamic lift forces from the wing and results in the vehicle climbing altitude. Decreasing the thrust, on the other hand, causes it to spin slower and descend. This effect is easy to observe. The less observable effect is the following. In order to increase thrust, the motor and the propeller needs to spin faster, gaining angular velocity on the motor and propeller bodies. As these bodies are rotating about a different axis as the rotational axis of the body of the craft, there is a resultant torque acting on the motor and propeller. This torque causes the wing to pitch upwards, increasing the angle of attack. The thrust direction of the motor also pitches upwards, contributing a portion of its thrust directly to the climb. The controller for altitude control is

$$T_c = K_p e_z(t) + K_i \int e_z(t) dt,$$  \hspace{1cm} (10)

where $K_p$ and $K_i$ are proportional and integral gains respectively, and $e_z(t)$ is position error in $Z$-axis at time $t$. A derivative gain is not introduced as it is found to cause instability in the simulated model.
Pitch and roll controller is formulated as

\[
\phi_p = K_{py} e_y(t) \tag{11}
\]
\[
\theta_p = K_{px} e_x(t), \tag{12}
\]
where \(K_{py}\) and \(K_{px}\) are proportional gains for pitch and roll respectively, and \(e_y(t)\) and \(e_x(t)\) are position errors in Y and X-axis respectively in the world frame.

The controller outputs for pitch and roll are combined with proportional stabilizer output to get the final control outputs for pitch and roll which are fed to the cyclic controller

\[
\phi_c = \phi_s + \phi_p \tag{13}
\]
\[
\theta_c = \theta_s + \theta_p. \tag{14}
\]

### 3. Optimization of design parameters

A simple optimization was executed to find the best wing planform for F-SAM.

#### 3.1. Formulation

The planform of the wing is defined by a polynomial of order 3 to ensure smoothness of the shape. This can be defined as

\[
c(i) = C_1 j^3 + C_2 j^2 + C_3 j + C_4, \quad \epsilon_{\text{min}} \leq c(i) \leq \epsilon_{\text{max}}, \tag{15}
\]
where \(j = i - 2\) and \((j \leq n_{\text{max}} - 2, j \in \mathbb{Z}^+)\), \(c(i)\) is the chord length of the respective blade element, and \(C_1, C_2, \) and \(C_3\) are the coefficients to be determined such that the value of \(c(i)\) is bounded between \(\epsilon_{\text{min}}\) and \(\epsilon_{\text{max}}\). \(C_4\) is fixed to a constant and \(C_4\) defines the length of the first two blade elements which are constrained to a minimum length as they contribute negligible aerodynamic forces. The folding process requires the motor and propeller to not get in the way—to prevent this, the leading edge of the wing is constrained to form a straight line. The motor is fixed to the 7th blade element and its position is not considered for optimization.

#### 3.2. Formulation

For the optimization, F-SAM is simulated for a duration of 20 s with initial conditions \(v_{Z0}\) and \(\Omega_{Z0}\) with controllers described in section 2.7 turned off. During this simulation, multiple parameters are evaluated in a combined single objective function. The parameters selected are indicative of a decent flight dynamics of F-SAM during hover, and they include

- maintaining a decent spin rate during hover, as too high spin rate would not allow the actuator and sensors to keep up and too low spin rate could lead to the wing stalling,
- hovering near a target altitude and not ascending or descending,
- a minimum level of thrust from the motor is used,
- minimum oscillating values in \(\Omega_X\) and \(\Omega_Y\), as when these values oscillate and grow, they indicate the presence of a growing precession circle,
- minimum values of \(v_X\) and \(v_Y\) as these values indicate the platform is drifting away and lacks dynamic stability.

The variables in this formulation, shown in table 4, can be expressed in a single concatenated vector \(\Gamma = [C_1, C_2, C_3, T_o, \delta]^T\). The first three variables \((C_1, C_2, C_3)\) are polynomial coefficients for chord-wise wing shape in equation (15) and are real numbers. Only \(\delta\) is integer valued. The lower and upper bounds are selected such that there is adequate region to search for solutions without bias towards any particular value.
The main objective function for the first formulation consists of five sub-objective functions, namely \( F_1, F_2, F_3, F_4 \) and \( F_5 \). \( F_1 \) is the sub-objective for average spin rate during hover, which is defined as

\[
F_1 = \left( \sum_{i=1}^{n_2} \frac{\Omega_X(t_i) + \Omega_{des}}{n_2 - n_1} \right)^2,
\]

where \( \Omega_X(t_i) \) is a negative value, \( \Omega_{des} \) is the target rotation speed, and \( n_1 \) and \( n_2 \) are selected time steps of the simulation. \( F_2 \) is the sub-objective for height difference between the start and end of simulation and is defined as

\[
F_2 = |z(t)|,
\]

where \( z(t) \) is the \( Z \)-axis coordinate of the model at the end of the simulation. \( F_3 \) is the sub-objective penalty function for undesired oscillations in \( \Omega_X \) and \( \Omega_Y \), and is defined as

\[
F_3 = \sum_{i=1}^{n_2} \left( \Omega_X(t_i)^2 + \Omega_Y(t_i)^2 \right),
\]

where \( \Omega_X \) and \( \Omega_Y \) are angular velocities in the \( X \) and \( Y \)-axes respectively. \( F_4 \) is the sub-objective function to penalize velocity drifts in \( X \) and \( Y \)-axis and is defined as

\[
F_4 = \sum_{i=1}^{n_2} \left( v_X(t_i)^2 + v_Y(t_i)^2 \right),
\]

where \( v_X \) and \( v_Y \) are velocity values in \( X \) and \( Y \)-axis respectively. Finally \( F_5 \) is the sub-objective function for thrust and is defined as

\[
F_5 = T_o,
\]

where \( T_o \) is the thrust value part of \( \Gamma \). The sub-objective functions are combined together to yield the final objective function for the first optimization which is summarized as

\[
\min \kappa_1 F_1 + \kappa_2 F_2 + \kappa_3 F_3 + \kappa_4 F_4 + \kappa_5 F_5
\]

where \( \kappa_1, \kappa_2, \kappa_3, \kappa_4 \) and \( \kappa_5 \) are the weightage coefficients of each sub-objective function. Although the problem can be formulated as a multi-objective optimization, it is simplified to produce a single result using a weighted sum from user subjective preferences. The coefficients, given in Table 5, serve to non-dimensionalize each function outputs and bring them to a similar order of magnitude. Highest priority is given to \( F_5 \).

### 3.2. Optimization results

The optimization is run using MATLAB’s gsa function scripted to run on the MATLAB Simscape Multibody simulation model developed based on section 2.5. GA uses principles of biological evolution and natural selection in order to find an optimum result. This works by first initiating with a fixed population \( P_s \) of random solutions which are run through the Simulink model. The results of all solutions from the population is evaluated using the objective function in equation (21). The resulting best individual is bred into a new generation of population size \( P_s \), using mutation functions and once again fed into Simulink model. This process is repeated until a better solution cannot be found for \( G_s \) generations or max generation count \( G_M \) is reached, as explained in a flowchart in figure 12. \( P_s, G_s \) and \( G_M \) are set manually and are given in table 5.

Figure 13 shows the convergence of penalty values and average distance between individuals over \( G_M \) generations. The convergence indicates the optimization. The design variables corresponding to the best fitness value are \( \Gamma = [0.0195, 1.4277, -0.2231, 0.3433, 38]^T \). This results in a wing planform shown in figures 1 and 8. When making the actual wing, the smooth shape of the wing is achieved by joining the blade elements together using a spline. Simulation parameters are given in table 5.

The use of GA does not guarantee a globally optimum solution to the problem, but because it searches randomly within the search space, it is less likely to be stuck in a local optimum. The use of other optimization algorithms may result in a slightly better solution or may take up less computational power, but the goal here is to generally only search for a decently optimized solution and therefore, GA is considered a suitable option.
4. Simulation

In this section, we discuss the simulation setup used and show results of simulated hover and waypoint tracking.

4.1. Simulation setup

Figure 14 shows the setup within MATLAB Simulink Multibody. It consists of a rigid body dynamics portion which has the configuration settings for gravity, solver and world frame, linked to a six-DOF joint which computes rigid body dynamics in six degrees of freedom. This is connected to the rigid body portion, which includes physical properties of solid objects that combine to represent a physical F-SAM. BET calculation subsystem consists of blade element velocity sensing and aerodynamic force calculations. The electronic swashplate subsystem computes the cyclic actuation of the single actuator.

Simulation is run with an automatic solver selection and fixed time step of 0.001 s.

4.2. Simulation results

Two simulations are presented in this section—(1) F-SAM with optimum wing and thrust without any controller versus with only stabilizer controller, and (2) waypoint tracking performance with stabilizer and position control.

4.2.1. Optimum configuration with and without stabilizer controller

Using the optimized wing geometry and thrust value obtained in section 3.2, F-SAM model is simulated with initial conditions $v_0$ and $\Omega_0$ to observe its behavior without the influence of any controller for a duration of 40 s. This is compared with another simulation of the same duration with identical initial conditions but with stabilizer controller applied. Figure 15 shows the response in position and angular velocity. Small decaying oscillations in $\Omega_X$ and $\Omega_Y$ can be observed without controllers applied, indicating that the platform possesses dynamic stability with a decaying precession circle. In the XY plot, it can be seen that the model started with a velocity in positive $X$ direction from its initial position of (0, 0). This is due to the fact that initial angular velocity of $\Omega_Z$ is not applied at its center of mass. The tiny circles are formed on its trajectory as the reference frame is not placed directly at the center of rotation of the model. After moving towards positive $X$ for a short distance, the model is observed to enter a decaying precession circle. With stabilizer controller applied, the model is observed to converge to stability much faster.

In figure 10, the wing’s pose during an equilibrium hover state can be observed. Applied with spring stiffness and damping coefficients in the joints between the blade elements, the wing in simulation imitates...
that of the actual semi-rigid wing during flight. The values of spring stiffness and damping coefficients used are given in table 5.

4.2.2. Waypoint tracking with stabilizer control and position control

In this simulation, stabilizer and position controller described in section 2.7 are both active. 40 s after starting with initial conditions $v_{Z0}$, $\Omega_{Z0}$ and position $(0, 0, 0)$, the model is tasked to reach waypoints $(2, 0, 0)$, $(2, 2, 1)$, $(0, 2, 1)$, and $(0, 0, 0)$ in this order with 30 s intervals.

Figure 16 shows the positions, angular velocities and a 3D plot of the trajectory. In the first 40 s, the model converges to $(0, 0, 0)$ position and the corresponding angular velocities $\Omega_X$ and $\Omega_Y$ shows that it is able to stabilize in about 15 s. The model is able to approach each waypoint within the time interval. At 70 s when a desired altitude is at 1 m, the spin rate $\Omega_Z$ is observed to increase momentarily, and at 130 s with desired altitude at 0 m, the spin rate is observed to decrease. The altitude control has remarkably quicker response than lateral position control. This may be the case as the single actuator has direct influence over altitude while it only has indirect influence over lateral position through cyclic control.

It should be noted that the model is highly non-linear in $X$ and $Y$-axis. In the 3D plot, the trajectory of the first 40 s is removed to improve the clarity of the plot. The thrust plot is also shown in figure 16, with another plot zoomed in around 40 s to shown the cyclic behavior. It can be observed that large variations of thrust lead to altitude changes while the much smaller, high frequency changes in thrust is required for cyclic control. Thrust only varies by about 0.01 N with cyclic control and the square cyclic behavior can be observed.

This simulation proves that the model is controllable using the simple controllers devised in this work.

5. Experiments

In this section, we discuss the experiment setup used and the results of closed-loop waypoint tracking, trajectory tracking, and flight time test.

5.1. Experiment setup

The experiments are conducted in a motion-captured flying arena. It is within a rectangular flying space of 7 m × 5 m × 2.3 m in size. The entire volume is
covered by 8 OptiTrack Prime 41 cameras. The cameras project infra-red light into the flying space which are reflected by infra-red reflective markers mounted onto F-SAM prototype. Real-time position and orientation data from the camera system is fed into MATLAB where controller outputs are computed. The output is then sent through an RC module to F-SAM. A human operator, using an RC transmitter unit, is also able to send control signals to F-SAM at the same time. The prototype carries two RC receivers and combines the input from both closed-loop control and human operator control. This setup, as shown in figure 17, allows the human operator to take over the flight in the event of emergency.
Figure 16. Waypoint tracking performance of simulated F-SAM.
5.2. Closed-loop waypoint tracking

F-SAM is tasked to follow a waypoint trajectory, similar to the simulation in figure 16. It consists of a square shape, with a side of 2 m, one side at 1 m in height and the other side at 1.8 m in height. The four corners of the square are at (1, −1, 1), (1, 1, 1.8), (−1, 1, 1.8), and (−1, −1, 1). Each waypoint is set for 30 s before moving onto the next. In the experiment, F-SAM approaches the waypoint and stabilizes much faster than in the simulation. However, similar to simulation, it tends to overshoot the waypoint during the approach. Ωx, Ωy and Ωz values are also plotted. Ωz is noticeably less than the simulated value, most likely due to components such as the body not modeled for aerodynamics in simulation creating high drag. As observed in the simulation, at the instances where the waypoint is shifted to the next, spikes in Ωx and Ωy can be observed, indicating the tip path plane of F-SAM is highly tilted at these points. The results are shown in figure 18.

The PWM values sent to the motor are also shown. At the instance of waypoint shifting, high frequency fluctuations in motor command values can be observed and this is due to square cyclic controller.

5.3. Closed-loop trajectory tracking

F-SAM is tasked to follow a continuous trajectory that shifts the desired position incrementally with every time step. The trajectory is a simple square shape with 2 m length on each side. The corners of the square are at points (−1, −1, 1.6), (1, −1, 1.6), (1, 1, 1.6), and (−1, 1, 1.6). A duration of 10 s is given to move along each side of the square, resulting in a movement speed of 0.2 m s⁻¹. The desired position linearly moves along the square throughout the experiment. The flight performance of F-SAM in its XYZ position and world frame rotational speeds are shown in figure 19. Unlike the previous waypoint tracking experiment, the current experiment does not involve abruptly changing desired setpoint, hence the movements are gentle and no large changes in tip path plane are observed.

A physical object in the shape of a wide but short window is placed along one of the sides of the square. This is to demonstrate that F-SAM is maneuverable enough to fly through a window. F-SAM can be seen flying through this window multiple times in the recorded video, from which frames are extracted and shown in figure 20.

5.4. Straight-line speed test

In this experiment, F-SAM is pushed to its limit of lateral speed. It is tasked to fly between two points (1, 1, 1.5) and (−1, −1, 1.5), back and forth at increasing speed at each round using trajectory control similar to previous experiment. A duration of 10 s is given for each time it moves, allowing enough time for it to stabilize at the end point before moving off again. In figure 21, it can be observed that F-SAM is able to follow desired location in X and Y coordinates, where Z is observed to start fluctuating when faster speed is required. Ωz and Ωy are seen to fluctuate at faster speeds, indicating greater changes to tip path plane. Ωx is less effected as F-SAM’s rotation speed is not affected as much by fast flights. Large fluctuations in motor command can also be observed at the points where desired trajectory begins moving. In the last plot where F-SAM’s lateral velocity and desired velocity are plotted, F-SAM has an mean maximum lateral speed of 2.37 m s⁻¹. Other kinematics of F-SAM, such as maximum speed for ascend, average rotation speed, linear acceleration, and autorotation performance are given in table 6.

5.5. Flight time test and autorotation performance

In order to find out F-SAM’s flight time, it is flown at coordinate (0, 0, 1) with stabilizer and position controller enabled. Figure 22 shows that the vehicle’s altitude dropped as the battery’s voltage dropped. This may be improved with a better tuning or controller. It can also be observed that even with our simple proportional stabilizer control and PI controller
Figure 18. Waypoint tracking performance of F-SAM in experiment.
for position, the vehicle did not deviate much laterally, whereby the maximum deviation is 0.4 m. The battery’s voltage and current levels are also plotted, and the voltage appears to drop sharply right before the end of the flight, indicating that the lithium battery is used to its maximum capacity. The total energy used for the flight is found to be at 2.6 Wh, while the battery’s rated capacity is 3.2 Wh. This may be due to the fact that the battery may have degraded in capacity over several charge cycles. The mean power draw for hover flight of F-SAM is found to be about 9.78 W.

In a separate test, F-SAM’s autorotation performance was observed. It was flown to about 2.1 m height and the motor was completely turned off. Although the height was limited, it reached a steady state drop velocity of $-3.56 \text{ m s}^{-1}$ and rotation speed of $27.93 \text{ rad s}^{-1}$ momentarily before landing on the floor.

Figure 19. Trajectory tracking performance of F-SAM in experiment.
Figure 20. Trajectory tracking flight of F-SAM following a square trajectory, where one side of the square passes through a window sized at 1.1 m × 0.4 m. Frames are captured from recorded video at approximately 1.5 s interval and composited in one image.

Figure 21. Straight line speed experiment of F-SAM.
Table 6. Kinematics of F-SAM.

| Parameters               | Mean  | Std   | Units    |
|--------------------------|-------|-------|----------|
| Max lateral speed        | 2.37  | 0.29  | m s\(^{-1}\) |
| Max ascend speed         | 1.20  | 0.04  | m s\(^{-1}\) |
| Rotation speed           | 33.85 | 0.49  | rad s\(^{-1}\) |
| Linear acceleration      | 1.93  | 0.07  | m s\(^{-2}\) |
| Autorot. drop speed      | -3.56 | 0.34  | m s\(^{-1}\) |
| Autorot. rot. speed      | 27.93 | 0.28  | rad s\(^{-1}\) |

Figure 22. Flight time test of F-SAM. Battery voltage and current levels are logged at 10 s intervals.

6. Discussions and conclusion

There is recent interest in using compliant or foldable wings in various flying crafts due to better aerodynamic performance and ability to be reconfigured for storage. This is only most commonly seen in fixed-wing type crafts. For rotary wing crafts, flexible wings that can be folded inwards generally have not been explored, as there are no real benefits in folding the wings of a rotary wing aircraft, except for helicopters which may rotate their rigid wings backwards for storage. F-SAM is the first documented semi-rigid and foldable winged rotary wing craft, according to our best knowledge. The folded wing allows the craft to be reconfigured for quick and easy transportation. Although the semi-rigid wing does not provide any superior aerodynamic performance as compared to its rigid counterpart, this work shows that monicopters can be compact and controllable, similar to multi-rotor of comparable weight, while enjoying superior flight efficiency.

In this work, the motor position is fixed to the 7th blade element and its effect on the flight performance is not considered for optimization. Generally, depending on the pitch of the propeller, rotation speed of the motor and rotation speed of the monoppter, it is favorable to put the motor near the tip of the wing, as the larger distance from the CG provides a longer moment arm for the craft’s rotation.

There are two reasons behind fixing its location on the particular element on the folding blade. Firstly, as the wing is semi-rigid, it can help to absorb energy during crashes, saving the motor and propeller from breaking, which may not be the case when the motor and propeller are placed at the wing tip. Secondly, due to the folding method, the motor can only be mounted on each folding element. The optimization considers a range of widths for each blade element, with the tip element being as small as 17 mm in width. It is too small to support the motor mount.

It is observed that in the simulation, the craft spins faster during hover by about 11 rad s\(^{-1}\). This is partially contributed by the body portion creating drag in real-life prototype which is not considered in the simulation. The wing components may also be generating more drag than predicted by blade element theory.

In section 2.1, it was mentioned that F-SAM can fly in two configurations: the first is with battery fully folded (\(\alpha = 0^\circ\)), and the second is with the battery unfolded (\(\alpha = 180^\circ\)). In the experiments and results presented in this paper, F-SAM is flown with the first configuration. In separate tests with the second configuration, F-SAM flew with a mean rotation speed of 28.73 rad s\(^{-1}\) and mean power draw of 10.0 W, which
is 15.1% slower rotation and 2.2% higher power draw. A slower rotation is generally undesirable as the wing performs less efficiently. Additionally, the integrity of the body portion during flight in this configuration relies on the compliant hinge and the centrifugal force from the battery component may stress and break the compliant hinge over time.

The proportional stabilizer controller is introduced in this paper, in order to help F-SAM dynamic stability faster, producing faster response times during waypoint and trajectory control tests. The controller will be further analyzed in depth in a future work.

In the accompanying supplementary video (https://stacks.iop.org/BB/16/066019/mmedia), F-SAM is shown to be easily stored inside a small container, and it can be unfolded and flown within seconds. Dynamic stability of F-SAM also allows it to be hand-launched, without the need for closed-loop control. In future work, we may look into possible launching of F-SAM directly from the container, without the need for human intervention.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Shane Kyi Hla Win https://orcid.org/0000-0002-5859-6199
Luke Soe Thura Win https://orcid.org/0000-0003-1410-1251
Danial Sufiyan https://orcid.org/0000-0003-1549-5029
Shaohui Foong https://orcid.org/0000-0002-9724-6159

References

[1] Grasmeyer J and Keennon M 2001 Development of the Black Widow micro air vehicle 39th Aerospace Sciences Meeting and Exhibit p 127
[2] FLIR Systems Inc 2020 Black Hornet PRS https://flir.com/products/black-hornet-prs/ (accessed 30 March 2021)
[3] Giernacki W, Skwierczyński M, Wittwicki W, Wroński P and Koziński P 2017 Crazyflye 2.0 quadrotor as a platform for research and education in robotics and control engineering 2017 22nd Int. Conf. Methods and Models in Automation and Robotics (MMAR) (IEEE) pp 37–42
[4] Papin A and Rouilly D 1915 Helicopter US Patent App. 1,133,660
[5] Norberg R A 1973 Autorotation, self-stability, and structure of single-winged fruits and seeds (samaras) with comparative remarks on animal flight Biol. Rev. 48 561–96
[6] Lee E-J and Lee S-J 2016 Effect of initial attitude on autorotation flight of maple samaras (Acer palmatum) J. Mech. Sci. Technol. 30 741–47
[7] Zakaria M Y, dos Santos C R, Dayhoun A, Marques F D and Haji M R Modeling and prediction of aerodynamic characteristics of free fall rotating wing based on experiments IOP Conf. Ser.: Mater. Sci. Eng. 610 012098
[8] Yan Y, Ku-Kundu M and Azuma A 1997 The autorotation boundary in the flight of samaras J. Theor. Biol. 185 313–20
[9] Ulrich E and Pines D 2008 Planform geometric variation, and its effect on the autorotation efficiency of a mechanical samara Annual Forum Proc.-American Helicopter Society vol 64 p 1138
[10] Kellas A 2007 The guided samara: design and development of a controllable single-bladed autorotating vehicle Master’s Thesis Massachusetts Institute of Technology
[11] Pounds P E and Singh S P 2013 Integrated electro-aeromechanical structures for low-cost, self-deploying environment sensors and disposable UAVs 2013 IEEE Int. Conf. Robotics and Automation (IEEE) 4459–66
[12] Win S K H, Win L S T, Sufiyan D, Soh G S and Foong S 2019 Dynamics and control of a collaborative and separating descent of samara autorotating wings IEEE Robot. Autom. Lett. 4 3067–74
[13] Win S K H, Win L S T, Sufiyan D, Soh G S and Foong S 2021 An agile samara-inspired single-actuator aerial robot capable of autorotation and diving IEEE Trans. Robot. 1–14
[14] Houghton J and Hoburg W 2008 Fly-by-wire control of a monocopeter Project Report (Massachusetts Institute of Technology)
[15] Ulrich E R, Pines D J and Humbert J S 2010 From falling to flying: the path to powered flight of a robotic samara nano air vehicle Bioinsp. Biomim. 5 045009
[16] Win L S T, Win S K H, Sufiyan D, Soh G S and Foong S 2020 Achieving efficient controlled flight with a single actuator 2020 IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics (AIM) (IEEE) pp 1625–31
[17] Zhang W, Mueller M W and D’Andrea R 2016 A controllable flying vehicle with a single moving part 2016 IEEE Int. Conf. Robotics and Automation (ICRA) (IEEE) pp 3275–81
[18] Piccoli M and Yim M 2017 Piccolissimo: the smallest micro aerial vehicle 2017 IEEE Int. Conf. Robotics and Automation (ICRA) (IEEE) pp 3328–33
[19] Iju P, Jenkins D, Ettlinger S, Lian Y, Shyy W and Waszak M 2002 Flexible-wing-based micro air vehicles 40th AIAA Aerospace Sciences Meeting & Exhibit p 705
[20] Wood R J 2008 The first takeoff of a biologically inspired at-scale robotic insect IEEE Trans. Robot. 24 341–47
[21] Nguyen Q V and Chan W L 2018 Development and flight performance of a biologically-inspired tailless flapping-wing micro air vehicle with wing stroke plane modulation Bioinsp. Biomim. 14 p 016015
[22] De Waeger C, Karasek M and de Croon G 2018 Quad-thopter: tailless flapping wing robot with four pairs of wings Int. J. Micro Air Veh. 10 244–53
[23] Chen Y, Xu S, Ren Z and Chirarattananon P 2021 Collision resilient insect-scale soft-actuated aerial robots with high agility IEEE Trans. Robot. 1–13
[24] Kahn A and Edwards D 2012 Navigation, guidance and control for the CICADA expendable micro air vehicle AIAA Guidance, Navigation, and Control Conference p 4536
[25] Winslow J, Benedict M, Hrishikeshavan V and Chopra I 2016 Design, development, and flight testing of a high endurance micro quadrotor helicopter Int. J. Micro Air Veh. 8 155–69
[26] Jameson S, Satterfield B, Bolden C, Youngren H and Allen N 2007 Samara nano air vehicle-a revolution in flight AUVSI Unmanned Systems North America Conf. Proc.
[27] The MathWorks, Inc. 2020 MATLAB Simscape Multibody (United States) https://mathworks.com/products/simscape.html
[28] Hughes P C 2012 *Spacecraft Attitude Dynamics* (Massachusetts: Courier Corporation)

[29] Leishman G J 2006 *Principles of Helicopter Aerodynamics* (Cambridge: Cambridge University Press)

[30] Wick B H 1954 *Study of the subsonic forces and moments on an inclined plate of infinite span* NACA TN-3221 (Washington: National Advisory Committee for Aeronautics)