Exploring Batteryless UAVs by Mimicking Bird Flight

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ABSTRACT

We demonstrate the first flight of battery-free, energy harvesting, and small-sized Unmanned Aerial Vehicle (UAV). UAVs' flight times are severely constrained due to being forced to navigate the trade-off between battery energy storage and weight. Even for UAVs that recharge their batteries mid-flight, eventually, the batteries must be replaced. We explore a new paradigm of UAVs that can survive entirely off energy harvested from the sun. These UAVs store energy momentarily in small super-capacitors before using that energy to create lift. By removing the requirement for battery recharging and replacement, these UAVs can provide extended flight times and open up new applications. Unfortunately, the design space for these UAVs is complex and interdependent. Materials, wing structure, UAV type, motor and harvester efficiency, environmental effects, and many other things significantly affect the aircraft's performance. We engage in a principled design space exploration of various UAV designs to reach battery-free mechanical flight. We explore and test multiple prototypes before landing on an ornithopter-like UAV with a solar rack on top and a single BLDC motor. We then perform the first flight of a battery-free ornithopter. This is the first work to explore zero maintenance long-term flight for small craft and could enable numerous new applications that require large-scale, sustained aircraft flight, such as wildfire monitoring, smart agriculture, and urban air quality assessment.

CCS CONCEPTS

• **Computer systems organization** → **Robotics**.

KEYWORDS

Battery Free UAV, Energy harvesting, Ornithopter

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1 INTRODUCTION

Drones have been promoted to be a transformative technology that will support various applications over the next decade, including military training, search and rescue, logistics, precision agriculture, and aerial photography. While drone concepts are exciting, most are still out of reach due to short flight times, maintenance, and cost [11]. Although DJI is known as a leading industry in building reliable and widely used drones [5], their best-selling drones such as DJI Phantom 4, Mavic 2, Inspire two support only 30 minutes flying time maximum [7]. Their industrial drone, Matrics 300 ($13k), supports 55 minutes of flying time. Flight time can be improved a bit if fixed-wing drones are used. Fixed-wing drones such as Black Swift S2 TM [6] and NM& F300 [8] support up to a few hours of flight time. However, these drones must require dedicated take-off and landing spaces and not support hovering. Vertical take-off and landing (VTOL) drones, e.g., Censys Sentaero VLOS [10] and UKRSPEC PD-2 [9], have been recently considered as they can support long-endurance (a few hours) with the ability to vertical take-off, land, and hover. Unfortunately, they are expensive (>$20k), difficult to control, and require special pilot training [23, 35]. Lastly, LiPo batteries often reduce significantly after a few weeks due to the high current discharges required during take-off and flight.

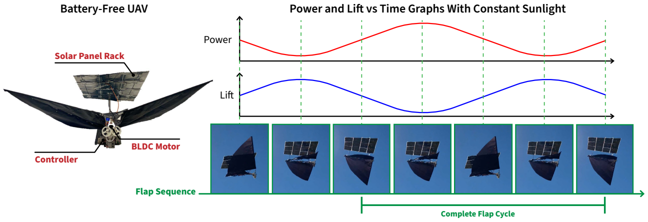

Figure 1: Battery-free and energy harvesting small UAV. All energy for flight is harvested from the solar panel rack mounted on the top of the ornithopter. Energy is opportunistically used to create lift from flapping.

Solar-based multi-rotor UAVs were successfully fabricated [15, 16] and could fly approximately 3 minutes above the ground. Indeed, the limited flying efficiency of multi-rotor UAVs makes them relatively large (2m × 2m). Additionally, a battery is needed to saturate the output voltage to a max power point. Another solution widely used to endure the flight time of UAVs is using solar panels to harvest energy and charge the battery while discharging the battery to operate the propellers [26–28]. In this case, the battery is degraded significantly due to the simultaneous charging/discharging cycles, especially Li-Po batteries suffer this problem the most and get degraded quickly [24, 25, 31]. Robo Raven IIIv2 [29, 30] is another solar-powered UAV, but it requires a battery to operate. To fill this gap, we design and implement *the first* working battery-free flapping UAV prototype.

This paper asks the question: *Can a small-size UAV fly without a battery?* While lithium-ion batteries are commonly used for UAV design, they are not suitable for hazardous environments such as wildfire monitoring since the electrolyte consists of lithium salt and

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organic solvents, which can lead to fire hazards or explosion [18]. More importantly, batteries add weight costs and require charging or replacement, shortening aerial time. A battery-free UAV will provide the opportunity for ultra-long multi-day missions, low maintenance, and a lower ecological impact. A solar-powered UAV with low power consumption (i.e., a few Watts) could leave the battery behind and operate perpetually, entirely from the energy harvested from sunlight. By removing the battery recharging and replacement requirement, these UAVs can provide extended flight times. New applications emerge with this extended flight time, including data ferrying, aerial imaging, air quality monitoring, and others. The battery-free UAV is potentially a critical device for future large-scale monitoring applications that must be sustainable and low maintenance.

Challenges.

- *Unexplored Design Space.* While significant bodies of literature discuss the design of UAVs and energy efficiency, none consider a model where a UAV must function only on harvested energy, with no backup storage in a battery. This shifts the design space into unexplored territory around optimizing size, materials, motor, speed control, energy management, UAV type, wind design, wing angle, and other factors. These unknowns extend further into the aircraft type and size.
- *Tight Constraints.* Energy budgets are tight, materials and components imperfect. Small supercapacitors momentarily hold harvested energy but are orders of magnitude less energy-dense than a battery (however, they are virtually infinitely rechargeable). This energy constraint means that the inconsistency and imperfection of standard commercial off-the-shelf materials, electronic components, and fabrication tools make for complex engineering for a robust prototype.
- *Impacts of Dynamic and Intermittent Power.* Most existing battery-free devices like the Battery-free Game Boy [13] and Cell phone [33] have focused on computing tasks that consume μW-mW level, while UAV's power consumption goes up to a few W or more, and then back down to zero. Designing circuits, systems, and mechanicals to survive through these dynamics is challenging.

This paper details the design and development of a small-size, battery-free, energy-harvesting, Unmanned Aerial Vehicle. The flying prototype is shown in Figure 1, built after an extensive and principled design space exploration. Our UAV is an ornithopter, as it flaps to generate lift and uses a solar rack to gather energy to power all operations. Our in-lab experiments confirmed that the UAV is able to harvest sufficient energy to power its entire operation, including wireless communication, computing, and flapping. When launched from eye height, our drone is able to stay aloft under its power for a few seconds. This represents a foundational starting point for the further development of battery-free UAVs. To our knowledge, this is the first demonstration of a small-scale battery-free drone flying.

Contributions

- We uncovered and defined the problems for future battery-free UAV research, including the unknown relationship between harvested energy, generated force, weights, material properties, machine imperfection, and others.
- To the best of our knowledge, this is the first work to explore battery-free design for small aircraft and could enable numerous new applications that require large-scale, sustained monitoring.
- Through a principled and iterative process, we build a 99.89g battery-free UAV with an 84cm wingspan. The developed UAV provides sufficient energy to flap at 4Hz frequency with a maximum power of 3W in daily sunlight conditions. We demonstrate that the UAV can fly for a couple of seconds under its own power.
- We present the behaviors of the developed UAV through in-lab and outdoor experiments. The experimental results and real-world demonstration presents the feasibility of the current design.

2 RELATED WORK

Researchers have been improving the flying time of fixed-wing UAVs using the solar-powered engine as a hybrid solution. NASA Pathfinder is the pioneer in solar-powered UAVs with an average flight time of 12 hours [14]. Pseudo-Satellite makes use of long flying time fixed-wing hybrid-powered UAVs to operate satellites in providing the wireless connection for specific areas, and aerial vehicles in weather sensing and forecasting [3]. AtlantikSolar utilizes a hybrid approach that can prolong the fixed-wing UAV's flight time up to 81 hours [26–28]. Other works also exploit similar approaches to improve flight time of fixed-wing UAVs varies ranging from small ones to big ones in sizes [24, 25, 31]. However, fixed-wing UAVs do not have the ability to hover, making sensing applications complicated in real-world deployment.

Robo Raven IIIv2 with solar panels on its wings can enhance its flight time duration by approximately 29% [29, 30]. One of the key concerns for Robo Raven IIIv2 is that it is not sufficient for long flying-time applications due to its battery dependence and high power consumption.

Battery-free devices that harvest energy from sunlight, thermal gradients, and RF sources have risen as a popular alternative in the research realms to mitigate the consequences of a trillion battery-powered devices that need constant charging or replacement. Battery-free mobile computing has sparked new ideas, like a battery-free cell phone [33], a battery-free Game Boy [13], toolkits and frameworks to facilitate building battery-free sensing systems [36], and novel programming, runtime, and architecture level techniques to provide reliable computation and sensing despite the volatility of energy harvesting and in many cases frequent power failures [12, 17, 19–22, 34]. This project is in the same spirit as these devices; however, it tackles new challenges in mechanical design and energy harvesting to realize battery-free flight.

3 ORNITHOPTER DESIGN AND IMPLEMENTATION

3.1 System Overview

The Battery-free UAV includes five main components: (1) Energy harvesting and management, (2) Actuation control, (3) Computing, (4) Sensing, and (5) Communication. The entire UAV is powered by energy harvested from the 12 solar cells placed on the body UAV above the wings. The harvested energy is stored in the super-capacitor. A lightweight, efficient and durable flapping system, including an actuator and power transmission mechanism, are developed to provide sufficient lift and thrust forces to fly the UAV.

The UAV's main computing unit includes flight control and data management to collect data from sensors to flap and maneuvers. Last, the UAV supports Bluetooth communication, allowing it to communicate to remote control in real-time.

The electrical and mechanical flapping subsystems are the main components of the developed UAV. We utilize Brushless DC (BLDC) as the main actuator due to its efficiency, torque, and weight. The gear and power transmission then convert the rotation of the motor to the flapping motion of the wings as long as the torque relationship of the system is satisfied. Four bar linkage mechanism is the typical mechanical design that can convert the rotational to flapping motion. The UAV also has the tails to balance the momentum and maneuver the flying direction. Two RC servo motors are used to direct the system in Azimuth and Elevator angles. The main motor is controlled by an Apollo3 Blue MCU from Ambiq, which connects to the UAV controller through Bluetooth.

3.2 System Implementation

We design and fabricate the bird as shown in Figure 2.This version of the prototype overcomes most issues related to durability, reliability, and lightweight. As discussed below since the prototype works reliably, we integrate the energy harvesting component onto the UAV. We will describe these details in the following discussion.

■ **Flapping Mechanism and Main Frame**. All mechanical connections are on the same plan (2-D mechanism); therefore, the mechanical positioning and fabrication are much more manageable Figure 2. Building multiple prototypes helps us understand the limitations of existing DIY materials and fabrication machines. The critical problem that we solved, including (1) Frame, (2) materials, and (3) solar panel placement. Regarding the frame, we use rigid 10k resin from Formlabs to have the best stiffness. The body bar is CNC machined by a 3mm carbon fiber plate with multiple mounts for the house, tail, circuits, and solar panels.

■ **Motor and Transmission Gears.** Due to the durability, we increased the size and added more joints to fix the connection. Our motor is rated at 5Kv and weighing 5.9 grams. It is rated up to 3s (11.7V). Our Solar panel is now working at 4.6V; therefore, the rated speed is $4.5 \times 5000 = 23,000$ rpm, equal to 383.3 Hz of flapping frequency. We then designed the gear ratio to reduce the flapping to 4Hz, which needs a 96:1 reduction ratio. However, we develop a 70:1 reduction ratio with two reduction gears due to the spatial constraint. Durable Resin from Formlabs is chosen due to the wear resistance. The motor and gearbox, weighted 26.54 grams, is tested to work reliably for five hours without load. We used a 3D printing technique called stereolithography (SLA), to get better resolution and properties than the Extruding technique.

■ **Flapping Wings: Structure and Materials.** Observing from our initial prototype, we found that (1) The lift coefficient depends on the flexibility of the wings, the materials, and also the straightness; (2) The more weight on the wings, the more torque is needed to run the motor. Then, we perform a thorough analysis to decide the Wings parameters. We CNC machined carbon fiber wings frame with a wingspan of 1m abd wing spar from 1.5 millimeters to 3 millimeters. We observe that the more substantial the wing spar, the better the flapping motion performed and better lift force, but the higher power consumed due to the load increase. Due to our limited energy budget, we finally fabricated the wing with three spars as a triangular wingspan of 820 millimeters. 40D Ripstop Nylon makes the wing sewed on the carbon fiber spars with Durable 3D Printed connections. Lastly, as can be seen in Figure 2 (right), the tail includes two main direction controllers that allow the UAV to change its elevation and direction while flying. Inspired by nature, we simply the tails of our battery-free UAV by leverage two low-power, light-weight micro-servo motors.

■ **Electrical Subsystem.** The main components of the electrical subsystem includes the ESC, main computing unit, solar panels, IMU(Inertial Measurement Unit), and pressure sensors.

Electronic Speed controller (ESC). We are using an off the shelf mini ESC suitable can work from 3V to 8V and supply up to 7A peak and 4A continuous and has a weight of 0.96 grams. In our lab testing we found that the average parasitic power draw of the ESC is 32.86 mW.

Main Computing Unit. The Battery-free UAV is controlled by a Sparkfun redboard artemis nano development board. This incorporates an Ambiq Apollo3 Blue microcontroller which is one of the lowest power mcu available with BLE built in. The micro controller has 1MB flash and 384k RAM and runs at runs at 48MHz with a 96MHz turbo mode and requires 6 μA/Hz. The microcontroller also interfaces with a low power 6DoF IMU (LSM6DSL) and a pressure sensor. The microcontroller board along with the required voltage regulation circuits have a parasitic power draw of 10.77 mW.

Solar Panels. The solar panels dominate the weight of our Battery-free UAV so we wanted to maximize our power-to-mass ratio. We compared some of the best solar panels available on the market in Table 1. While multi-juntion GaInP/GaAs/Ge have the highest power-to-area ratios they are extremely fragile and expensive. Due to their fragile nature they would require a thick encapsulation to improve their durability which would further decrease its power-to-mass ratio. On the other hand Silicon cells have a significantly worse power-to-mass ratio compared with the Ascent Solar cell. The CIGS solar cells have one of the best power-to-mass ratios on the market and they are also extremely durable and flexible. We connected these solar panels in a 1s12p configuration to give a peak voltage of 4.8V and current of 1.7A at $1000W/m^2$

There were two main options for mounting the solar panels; we could mount them on the wings or we could mount them separate to the main UAV structure. Initially we wanted to mount the solar panels on the wings but adding the extra weight of the solar panels to the wings greatly increases the torque force required by the motor to flap. This leads to more power being consumed and a lower maximum flapping frequency. This problem was worsened by the increase in cosine losses from the solar panels due to a change in the wing angle while flapping, reducing system efficiency. To combat these issues we decided to suspend the solar panels on top of the body of the UAV using carbon fiber rods. This design improves our solar panel efficiency and also improves the lift force generated by the system.

■ **Testing and Lesson Learned**. We perform multiple indoor and outdoor experiment to verify the feasibility of making a battery-free UAV fly. We observe that with $4m/s$ wind speed, the lift force generated while the UAV gliding is 116 grams, which indicates that when the relative velocity of the UAV over the air is high

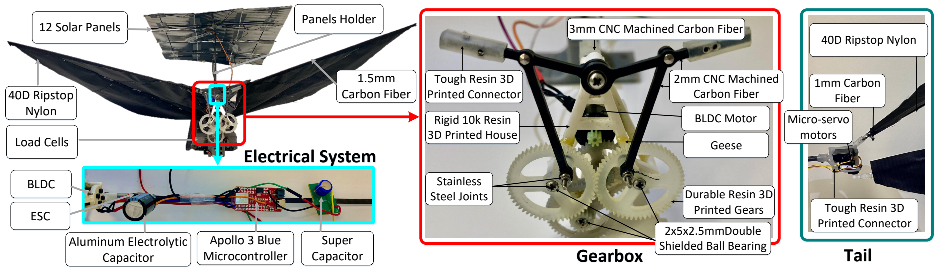

Figure 2: Prototype #3 - 1-DoF 2D four-bar-linkage flapping mechanism (Prototype).

		Electrical			Mechanical		Efficiency	
Solar cell	Chemistry	V	I	P	Area	Mass	P/Area	P/Mass
Ascent Bare cell [1]	CIGS	4.8	0.17	0.816	84	1	0.155	0.816
Azure multi-junction [2]	GaInP/GaAs/Ge	3.025	0.433	1.31	30.18	2	0.347	0.655
Maxeon Gen II [32]	Monocrystalline Si	0.58	6	3.48	153	6.5	0.227	0.535

Table 1: Solar cell comparison and characterization across various chemistries.

enough (there is a strong wind or the UAV has enough velocity), the aerodynamic force generated would be sufficient for gliding. During outdoor experiments, the prototype #3 flaps continuously under the sunlight condition as shown in Figure 1.

4 EVALUATION AND FLIGHT

In this section, we evaluate the performance of Battery-free UAVprototype by measuring the generated lift force, thrust force, and power consumption under different conditions. These experiments are designed to answer the following questions

- Can the Battery-free UAV generate enough lift force to fly?
- Can the Battery-free UAV sustain flight without a battery?
- How do different environmental conditions affect the Battery-free UAV?

4.1 In-lab Experiment Setup

Our in-lab experiment setup consists of an artificial illumination source and solar irradiance meter used to simulate 1000 W/m^2. A fan is used to simulate different wind speeds and an anemometer to measure the incident wind speed. The UAV is mounted on an RCBenchmark Series 1585 [4] stand, which can be used to measure the thrust and lift force generated via three embedded load cells. The power consumed by the electronics is recorded via Joulescope.

4.2 System Evaluation and Lesson Learned

Our developed UAV successfully harvests energy from outdoor sunlight stores energy momentarily in small super-capacitors before using that energy to create lift. We perform the first flight of a battery-free ornithopter. Figure 1 illustrates an example flight sequence. We engage in a principled design space exploration of various UAV designs to reach battery-free mechanical flight. We will discuss our design space exploration in detail in the following discussion.

To validate the response of the system, we conducted the following experiments and measure the lift force, thrust force, and power consumed by our system: (1) illumination blocking test, (2) constant flapping frequency with no wind, (3) no flapping with wind, (4) alternating flapping frequency with no wind.

■ *Illumination blocking test:* We use the artificial illumination source to stimulate the solar power with the intensity of $1000W/m^2$. The testing procedure is as below:

- Step 1: shine the light directly on the solar rack without blockage
- Step 2: start operating the UAV with the full speed
- Step 3: block the light from source to the solar rack
- Step 4: remove the blockage
- Step 5: repeat the step 3 and 4

From our observation, when the illumination is blocked, the UAV can only perform two flapping cycles due to the energy stored in the capacitor, then completely stop. Due to the limited discharge current provided by the capacitor, the voltage drops below $3.3V$. At these voltages, the motor is unable to produce enough torque to flap the wings. Therefore, the capacitor can only provide the limited energy to smooth the flapping motion for small interruptions in harvested solar energy and is not acting as a battery.

■ *Constant flapping without wind:* This experiment was done to validate the relationship between thrust force and lift force generated during downstroke and upstroke cycles of the wings. As can be seen in Figure 3 (a), most of the positive lift force is generated during downstroke cycles. When the wing starts an upstroke, it begins to produce a negative lift, which begins to cancel out on our overall lift. The maximum lift force we generated was 2.1311 N, while we have an average lift force of 0.1209 N. The significant difference between these values indicates how much lift force we lose due to upstrokes.

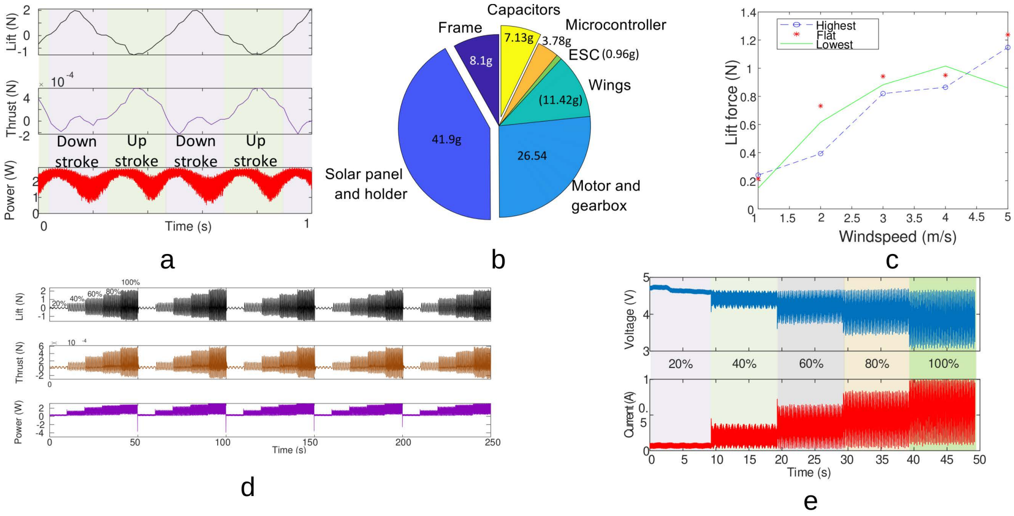

Figure 3: (a) Constant Speed Evaluation (b) Weight Distribution (c) Wind test (d) Varied Speed Evaluation (e) Voltage and current during varied speeds

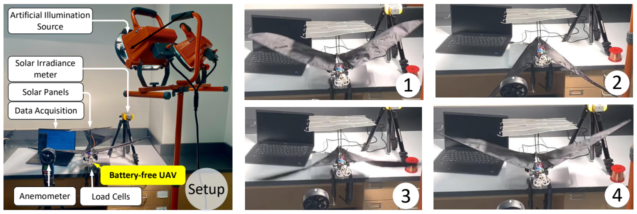

Figure 4: The designed test-bed for in-lab experiments.

■ *No flapping with wind:* This experiment was done to estimate the lift and thrust force generated due to the aerodynamics of the Battery-free UAV. In our evaluation, the artificial wind is created to measure the lift force and drag force with different wing positions. As can be seen in Figure 3 (c), the lift force rises as the wind speed increases. However, due to the inaccurate artificial wind source and the turbulent air, some samples did not follow the trend due to the imperfection of the measurement tools and wind generation. At 3 meters per second, we measured an average lift force of 0.942 N due to wind. This data indicates that aerodynamic lift currently makes up a large portion of our generated lift force and gives us enough total lift force to achieve flight.

■ *Alternative flapping speed evaluation:* We modulate the flapping frequency and measure the corresponding lift and thrust forces and the consuming power during the flapping motion. Figure 3(d) shows the resulting thrust and lift forces generated when we change the flapping frequency value from 20% to 100% with 20% interval. We found that the variations of the flapping frequency and lift force/thrust force are highly correlated. Analyzing the voltage and current during Alternative Speed Evaluation, we see that there is a significant voltage drop each time the PWM value increases, as seen in Figure3(e). We suspect the main factors contributing to this voltage drop are due to the high resistance of the current path. We need to investigate this further as a decrease in system voltage leads to a proportional decrease in the torque and speed of the motor. In addition, another area to improve is to eliminate the negative voltage spike produced when changing speed, as shown in Figure 3(e). This spike can be dangerous to our controlling circuits, so moving forward, we will need to incorporate a fly-back diode to limit the inductive spike.

5 FUTURE WORK

This paper has presented the first step in realizing battery-free UAVs, conducting an extensive design space exploration as a first foray into an emerging concept. We anticipate significant future work on the topic. Our current design space exploration and prototype can only stay aloft for a few seconds at the most, and must be launched. Additionally, the prototype is (as with most small craft) susceptible to wind and environmental factors due to the lack of a robust control algorithm. While this factors preclude the current prototype from useful applications (i.e., longer flight time, and the ability to land and takeoff to span multi day missions), this first step lays the ground work to figure out these issues.

6 CONCLUSION

We built the first working battery-free UAV that has a wingspan smaller than 1 meter. We describe the key challenges and solutions throughout a well-documented design space exploration. We provide details describing a working flapping UAV that can flap on the air leveraging sunlight energy without requiring any battery. We discuss the related models that were used to simulate and verify multiple versions of the developed prototype. We evaluate the system with in-lab experiments and confirm the feasibility of sufficient forces generated from harvested energy to lift the UAV. We also perform outdoor experiments to validate this feasibility. Lastly, we outline the current limitation and next research steps in building a robust battery-free UAV system.

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