

Bimodal MorphoCopter for Wildfire Suppression: Transforming Quadcopters to All-Terrain-Vehicles (ATV)

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Abstract

Wildfire suppression technologies have become increasingly critical in the face of escalating climate challenges and growing threats to ecosystems and human settlements. While early detection remains essential for effective wildfire management, the speed and efficiency of suppression technologies are equally vital to containing the spread. Unmanned aerial vehicles (UAVs), particularly quadcopters, have been widely explored for tasks such as monitoring fire propagation and deploying fire-extinguishing balls. Despite their limitations in direct suppression due to harsh environmental conditions, quadcopters can be effective when deployed as part of an intelligent swarm system. However, aerial-only drones face serious constraints in hostile fire zones, prompting the need for innovative, ground-compatible drone designs. The main aim of this study is to introduce a novel hybrid uncrewed system to the scientists in the field. The design is termed the Bimodal MorphoCopter (BMC), which incorporates a planar inverted slider-crank mechanism to enable seamless transformation between aerial (drone) and terrestrial (all-terrain vehicle, ATV) modes. The proposed mechanism offers morphable, bimodal functionality, allowing drones to switch modes and directly engage wildfires from the ground, particularly in areas surrounding settlements such as Los Angeles. To achieve this functionality, the retraction motion of the coupler through the output link must be transformed into a solely extension — a key mechanical challenge addressed in this research. The kinematic design problem is formulated and solved using the Bee Algorithm, an optimization technique inspired by the foraging behavior of honeybees. The results aim to enhance swarm-based wildfire intervention systems by providing robust, adaptive ground-air mobility in dynamic fire-prone environments.

1. Introduction

The 21st century ushered in robotics, expanding the capabilities of firefighting vehicles (Kitano and Satoshi, 2001) highlighting the importance of robotic systems for firefighting operation. The first significant use of UAVs in firefighting occurred in the 2006 Esperanza Fire in Southern California (Coen, and Philip, 2014) demonstrating UAV feasibility for firefighting. By the 2010s, drones were widely adopted for fire assessment, mapping, and fire-retardant delivery (Lattimer et. al., 2023) which serve as foundational studies in firefighting UAVs. In 2017, Shark Robotics introduced Colossus, the first commercially available robotic firefighter, paving the way for autonomous fire suppression (Wang, M., Chen, X. and Huang, X., 2024). Since 2020, quadruped robots have been deployed for indoor fire suppression (Lattimer et. al., 2023). The continuous evolution of firefighting technology highlights the growing integration of automation and aerial-ground hybrid systems, shaping the future of wildfire response (Toan et. al., 2019).

Jin, Kim, and Moon (2024) introduced an innovative drone-based method for constructing firebreaks to suppress low-intensity wildfires. Their system uses UAVs equipped with continuous fire-extinguishing ball deployment modules, enabling rapid response and high targeting accuracy. The study involved expert input, prototype development, and field tests under varied conditions. Real-time kinematic positioning and ground control systems ensured automated flight paths and precise payload delivery. Tests showed 100% operational success and stable hovering, with effective firebreak creation confirmed in live trials. Although conducted in controlled

settings, the results demonstrate strong potential for early-stage wildfire suppression in inaccessible or high-risk areas. However, further testing under windy conditions is needed, and the system is currently limited to ground-level grass fires.

Aydin et al. (2019) explored the use of drones carrying lightweight 0.5 kg fire-extinguishing balls for early wildfire suppression in grasslands and wildland-urban interfaces. Field tests showed effective suppression of small grass fires within a one-meter radius, highlighting potential for rapid response in hard-to-reach areas. While promising for spot fire control and firebreak creation, the system's stability under windy conditions remains untested and requires theoretical improvement.

The Multi-Modal Mobility Morphobot (M4)—a novel vehicle that can autonomously switch between eight different locomotion modes (e.g., flying, rolling, walking, crouching, tumbling) by repurposing its appendages. Inspired by animals like birds and sea lions, M4 mimics nature's strategy of using the same limbs for different purposes, achieving unprecedented locomotion plasticity (Sihite et.al., 2023). M4's key innovation is using the same components (legs with shrouded propellers) as wheels, thrusters, legs, and manipulators, enabling seamless transitions between ground and aerial modes. Although it can provide several types of motion, it needs a stable frame with the least actuators especially for the wheels which can be transformed to propellers in case of fire suppression.

Skygauge Robotics has developed a unique industrial inspection drone featuring a thrust-vectoring propulsion system (Skygauge, 2021). Unlike conventional drones, Skygauge can apply controlled force to surfaces, enabling contact-based tasks like

ultrasonic thickness measurements. Its rotors are mounted on articulating arms that dynamically adjust thrust direction, allowing stable surface contact from various angles. The stability gained by the help of articulated arm which changes the rotation axis of propellers would not be permanent under the windy condition of the weather in case of usage in fire incident. Even though, the stability would be gained, the battery of the quadcopter would be consumed rapidly.

An integrated design combining an autopilot control system with an active arm-morphing mechanism was proposed to enhance quadrotor performance (Kose, and Oktay, 2020). The morphing arms improve maneuverability in turbulence, and simultaneous perturbation stochastic approximation-based optimization reduces rise time, settling time, and overshoot, yielding a 44% better cost index. The study demonstrates the benefits of merging morphing design with control optimization for UAVs. But there is no test for spraying a suppressant or some similar liquid which can break the stability under turbulent conditions along with the load on the platform.

A novel quadrotor design that combines aerial agility with adaptive morphology to tackle complex navigation challenges was introduced (Falanga et al., 2018). The drone is equipped with four independently folding arms, allowing it to dynamically change shape during flight without compromising stability. This morphing capability enables the drone to pass through gaps smaller than its unfolded size, closely inspect vertical surfaces, and even grasp and transport objects without external sensors or motion capture systems, relying solely on onboard visual-inertial perception and real-time adaptive control. The prototype is so small that can not be used for fire suppression. The morphing capability can be a proof for the feasibility of this paper.

Despite the increasing body of research dedicated to drone-based wildfire suppression, there remains a significant gap in the literature regarding the integration of a fully autonomous, AI-driven firefighting ecosystem. To date, no study has proposed a fully integrated system that utilizes a strategically positioned mobile base station connected via satellite to coordinate and manage three specialized drone swarms: (1) monitoring drones for real-time surveillance and fire localization, (2) fire-extinguishing drones that deploy retardant-filled payloads to create firebreaks and prevent the spread of flames, and (3) direct intervention drones engineered to autonomously engage active fire fronts with precision suppression techniques. While the first two drone categories have been partially explored in previous works, these efforts often overlook the critical influence of environmental variables such as dynamic wind conditions, fluctuating temperatures, and complex terrain. More importantly, current literature lacks any substantial investigation into the design, control, and deployment of autonomous drones capable of direct, stable, and effective engagement with active wildfire fronts.

A critical gap identified in the literature is the lack of quadcopter stability during active fire suppression. To address this, we propose a novel quadcopter design, referred to as the BMC, capable of both aerial and terrestrial transport of fire suppressant from a mobile station to the fire site. The core innovation enabling this bimodal functionality is the inverted slider-crank mechanism (ISCM), which allows the BMC's wheel axes to rotate vertically for ground locomotion. ISCM represents the key contribution of this study to develop an optimal kinematic design for the ISCM. Therefore, the future work will be possible. Section 2 presents the core problem

context. Section 3 formulates the corresponding optimization model, and present and evaluate potential solutions. Section 4 includes results and discussions. Section 5 presents conclusions.

2. Proposed Design of The System

BMC is a novel drone concept designed to integrate both aerial and ground-based mobility, enabling the system to function as both an aerial vehicle and a terrestrial transporter. One of the primary challenges in wildfire suppression lies in the extreme environmental conditions present within active fire zones. High ambient temperatures, coupled with unpredictable and often intense wind speeds, significantly reduce the operational efficiency and endurance of aerial fire-suppression systems. These harsh conditions limit the feasibility of sustainability of drone-based suppression efforts conducted solely from the air. This section gives a brief explanation for the clarity of the reason of the problem.

To overcome these limitations, the BMC introduces an innovative dual-mode operational capability: rapid airborne deployment to the vicinity of a wildfire, followed by transformation into a ground vehicle for close-range suppression. This versatility enables the BMC to transport suppressant efficiently through vertical takeoff and landing (VTOL) and then approach the fire directly from the ground, where suppressant can be applied with improved precision and reduced environmental interference. This hybrid design aims to enhance both the flexibility and resilience of wildfire response operations within a swarm of BMC, particularly in rugged or high-risk terrains where conventional aerial firefighting methods are severely constrained.

Structurally, the BMC is equipped with four wheels, two of which are shown in the front view of the BMC in Figure 1 specifically designed to enable ground mobility and air transportation. These wheels are integrated into a transformation mechanism that allows the foldable propellers to extend outward during the transition to flight mode, and to retract when the motor stops for system transitions to ground mode. Each wheel should be engineered as a sun gear within a planetary gear system, allowing a single brushless motor to drive both the wheels and the foldable propellers based on the selected operational mode. In addition to that, the wheel's sun gear configuration also serves as a protective housing, concealing the propellers during ground transportation.

The folding and unfolding mechanism of the propellers relies on the inertia and centrifugal force generated by the rotational motion of the brushless motor. During flight, the propellers extend automatically when the motor rotates; once the motor is stopped, the propellers fold back due to the inertia acting on the blades, which are mechanically linked via joints at the tips of the inner blades as shown in [this video](#). This configuration eliminates the need for additional folding mechanisms, simplifying the overall design. Specifically, the inner blades are fixed to the rotor without requiring a rotational joint, whereas the outer blades must be connected to the inner blade tips via a rotational joint to allow the folding motion upon motor shutdown. While a detailed analysis of the blade structure and planetary gear system lies beyond the scope of this paper, the working principle of the foldable propellers is briefly presented here to clarify the design rationale behind the mechanism selection.

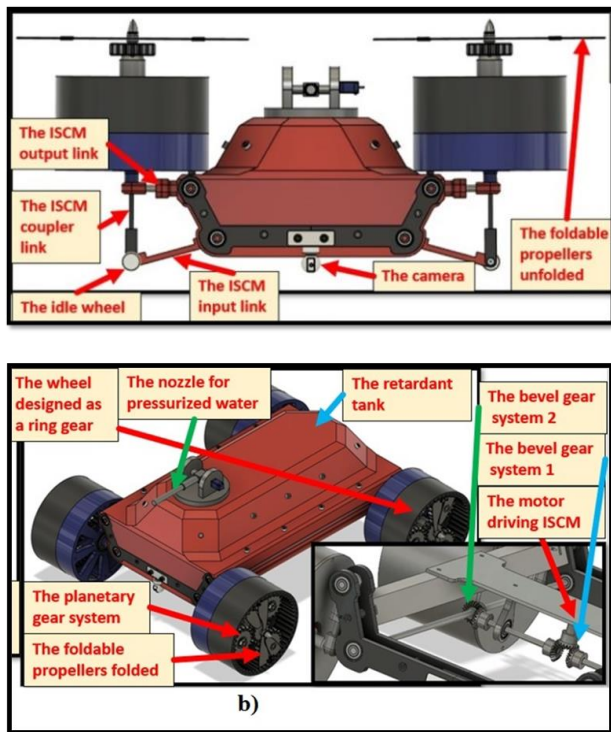


Figure 1. The two modes of conceptual design of BMC; a) Flight mode, b) terrestrial mode.

3. The Transformation Mechanism

In forest environments, exposed propellers are prone to damage from terrain or other environmental impacts. To prevent this, the BMC uses an inverted slider-crank mechanism (ISCM) to rotate the wheel axes upward, enclosing the propellers within the wheel structure for protection during terrestrial mode.

The ISCM consists of three main components: an input link, a coupler link, and an output link, with the output link directly attached to the wheel. When the input link is actuated, the coupler slides through a central opening in the wheel, applying torque to both the output link and the wheel. A critical design requirement is the controlled change in distance between points B and C (Figure 1) to prevent mechanical interference between the propellers and the planetary gear system housed within the wheel. To avoid damage, the absolute velocity of point B must remain lower than that of point C throughout the transformation path. This condition is achieved by solving an optimization problem based on the mechanism's link lengths and the angular parameter θ_1 .

3.1 The Inverted Slider Crank Mechanism

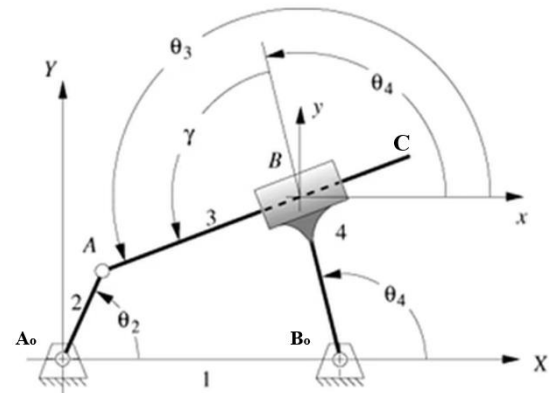


Figure 2. The general schematical illustration of ISCM with parameters.

ISCM is an inversion of a slider-crank mechanism. The difference is simply the rotational motion of the slider. The velocity difference between C and B must be positive to always increase the distance between point C and point B along the trajectory;

$$V_C - V_B \geq 0 \quad (1)$$

This means the objective function;

$$f_{obj(min)} = V_C - V_B \geq 0 \quad (2)$$

The objective can be converged to zero between the velocity of point C and point B along the trajectory. So that, the extension of the point C with respect to the point B is guaranteed without a damage on the foldable propeller. Therefore, an optimization of parameters; a, b, d, c shown in Figure 3 and θ_1 shown in Figure 1 are necessary. The constraints must be able to find the parameters that can provide a proper transmission angle in the range of 90° and 40° along the trajectory.

$$90^\circ \geq \mu \geq 40^\circ \quad (3)$$

3.2 The Velocity of Point B and Point C

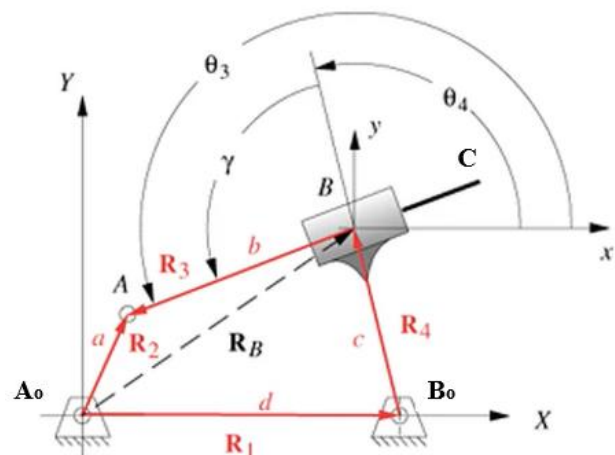


Figure 3. Closed-loop vector diagram of ISCM.

Kinematic analysis of a mechanism for the velocities starts with closed-loop vectors for the positions of joints.

$$\mathbf{R}_2 - \mathbf{R}_3 - \mathbf{R}_4 - \mathbf{R}_1 = 0 \quad (4)$$

Where, $\mathbf{R}_2 = ae^{j\theta_2}$, $\mathbf{R}_3 = be^{j\theta_3}$, $\mathbf{R}_4 = ce^{j\theta_4}$, $\mathbf{R}_1 = de^{j\theta_1}$.

$$a(\cos\theta_2 + j\sin\theta_2) - b(\cos\theta_3 + j\sin\theta_3) - c(\cos\theta_4 + j\sin\theta_4) - d(\cos\theta_1 + j\sin\theta_1) = 0 \quad (5)$$

Where, θ_1 is between $\pi/2$ and π due to the wheel, $\theta_3 = \theta_4 \pm \gamma$.

If the Eq. 5 is reorganized by separating the sinus and cosines functions as;

$$a(\cos\theta_2) - b(\cos\theta_3) - c(\cos\theta_4) - d(\cos\theta_1) = 0 \quad (6)$$

$$a(\sin\theta_2) - b(\sin\theta_3) - c(\sin\theta_4) - d(\sin\theta_1) = 0 \quad (7)$$

Knowing that $\gamma = 90^\circ$ and substituting $\theta_3 = \theta_4 \pm \gamma$ in the Eq. 6 and Eq. 7;

$$\cos\theta_4(acos\theta_2 - dcos\theta_1) + \sin\theta_4(asin\theta_2 - dsin\theta_1) - c = 0 \quad (8)$$

Where, $q = acos\theta_2 - dcos\theta_1$ and $p = asin\theta_2 - dsin\theta_1$ and substituting in Eq. 8 and reorganizing for θ_4 ;

$$\theta_4 = \text{atan}\left(\frac{c-q}{p}\right) \quad (9)$$

$$\omega_3 = \omega_2 \left(\frac{asin(\theta_2 - \theta_4)}{bsin(\theta_4 - \theta_3)} \right) \quad (10)$$

$$\omega_4 = \omega_2 \left(\frac{asin(\theta_2 - \theta_3)}{csin(\theta_4 - \theta_3)} \right) \quad (11)$$

Consequently, knowing θ_4 can help to calculate θ_3 which means both the velocity of point C and point B can be calculated for each value of θ_2 and the other parameters; a, b, c, d, θ_1 . By differentiating those angles with the method of limit function, a numerical solution can be obtained. This problem can be solved by using an algorithm embedded in excel or MatLab.

3.3 The Bees Algorithm

Population	n	20
Number of selected sites	m	10
Number of top selected sites out of m selected sites	e	4
Number of bees recruited for best e sites	n_{ep}	20
Number of bees recruited for the other (m-e) selected sites	n_{sp}	10
Initial patch size	n_{gh}	0.001
Number of iterations	i_{max}	100

Table 1. Bees Algorithm Parameters

The BA (Bee Algorithm) was developed by Prof. Duc Truong Pham. It is an intelligent optimization method inspired by swarm behavior. The Bees Algorithm is a nature-inspired optimization technique modeled after the foraging behavior of honeybees (Pham, et. al, 2006.). It is used to solve complex optimization problems, particularly those involving high-dimensional, nonlinear, and multimodal search spaces. It can balance global exploration with local refinement effectively. It is relatively straightforward to implement. However, its parameters must be adjusted sensitively. Moreover, its iterative nature can be computationally expensive due to its iterative nature and multiple evaluations of fitness. In this paper, we used the parameters that were used in the study conducted by Acar et al. (2019).

4. Results and Discussion

The Bees Algorithm was run in a PC specifications Intel® Core™ i7 @ 2.6 GHz, RAM: 16GB, Windows 10 64-bit. The results are given in the Table 2. The obtained mechanism can provide a motion without any mechanical interference between propellers and the planet gears. The trajectory and the initial and final positions of the mechanism for the task were shown in the Figure 5 and Figure 6. The change of distance between point B and point C along the trajectory of the mechanism and the moment at point B were illustrated in Figure 7.

a (cm)	b (cm)	c (cm)	d (cm)	$\theta_1 = \Phi$ (Degree)
11.231	19.342	4.021	6.512	118

Table 2. The design variables

According to Figure 7, the distance between points C and B decreases as the input link angle increases, due to the clockwise rotation of the input link during the transition from terrestrial to aerial mode. This transformation begins from the initial position shown in Figure 5 and progresses to the final position illustrated in Figure 6. In other words, the end of the graph is initial position of the mechanism. As expected, the moment at point B decreases as the input link rotates clockwise, which is consistent with typical mechanical behavior. The initial moment is higher due to the frictional resistance between the wheel and the ground.

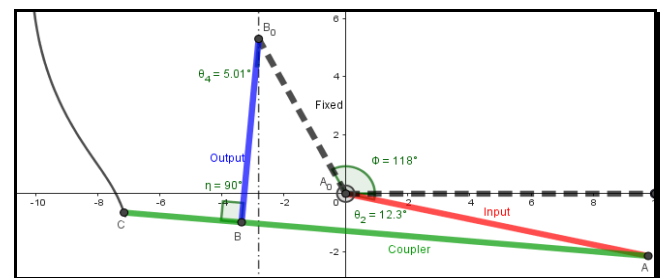


Figure 5. The initial position of the mechanism when BMC is on terrestrial mode

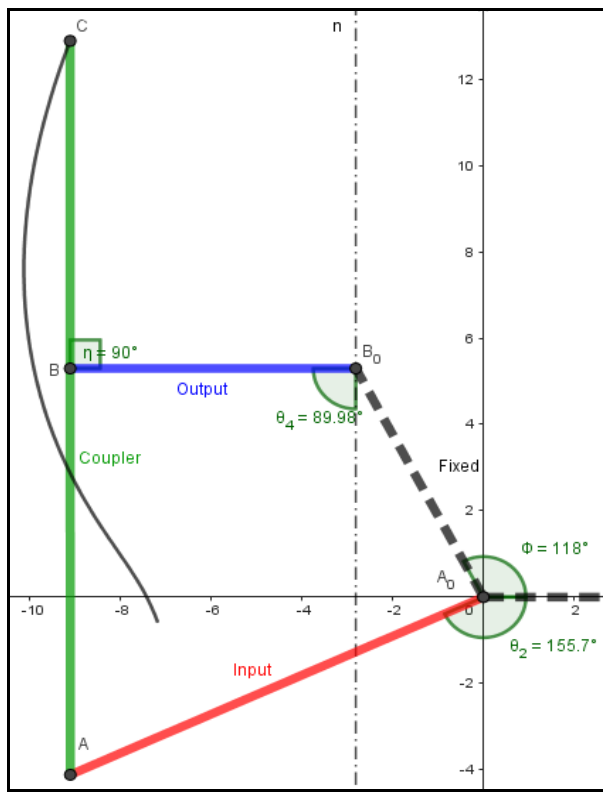


Figure 6. The final position of the mechanism when BMC is on flight mode

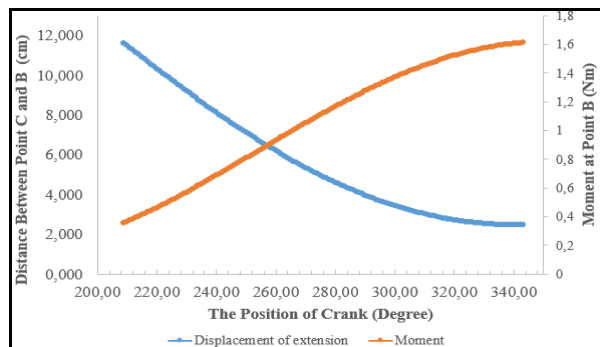


Figure 7. The change of distance between point C and B and moment at point B.

5. Conclusion

The primary focus of this study is the kinematic design of the ISCM. Therefore, details related to the foldable propeller design, the planetary mechanism driving both the wheel and propeller, and the ISCM drivetrain are beyond the scope.

As it is targeted, the problem of mechanical interference between propellers and components of planetary mechanism is prevented by the help of Bees Algorithm for optimization. The transmission angle is not as other planer mechanisms. It must be considered as force to torque or torque to torque transmission (Bagcı,1971). If one of these parameters in Table 1 or Table 2 would be slightly changed, the interference between propeller and the components of planetary mechanism could occur. Thus, this design is under patent investigation in Türkiye.

Future research will focus on enhancing the BMC system through both mechanical and operational improvements. One key objective will be the optimization of the conceptual design for reduced weight using advanced materials and topology optimization techniques. Light weighting is critical to improve flight endurance, maneuverability, and overall energy efficiency especially important in high-temperature, turbulent wildfire environments.

Additionally, a comprehensive multibody dynamic analysis of the inverted slider-crank mechanism (ISCM) and planetary gear system will be undertaken. This will help evaluate the dynamic loads, stresses, and vibrational behavior of the system during the transformation between aerial and terrestrial modes. Accurate modeling of these dynamics is essential to refine the mechanical design and ensure structural integrity during rapid mode transitions.

Another important area of investigation involves the aerodynamic and acoustic optimization of the foldable propellers. Experimental and computational studies will be conducted to identify optimal geometries that balance thrust generation, vibration minimization, and noise reduction. Comparative testing will be performed against conventional fixed-blade propellers under similar operational conditions to quantify performance benefits in terms of efficiency, stability, and durability.

On a systems level, future work will involve the development and field validation of a coordinated swarm of BMC units. This swarm will be tested in a controlled environment to suppress artificial fires, enabling assessment of swarm behavior, communication protocols, ground coordination algorithms, and autonomous task allocation. Integration with AI-based situational awareness systems will also be enhanced to improve decision-making in dynamic fire scenarios.

Furthermore, real-time localization and navigation capabilities will be expanded using SLAM (Simultaneous Localization and Mapping) techniques and terrain-adaptive path planning for both aerial and ground operations. Efforts will also be made to enhance the resilience of the system against environmental disruptions such as strong winds, signal jamming, or sensor failures.

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