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Vision-based Autonomous Landing of Unmanned Aerial Vehicle on a Motional Unmanned Surface Vessel

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Abstract: This paper has developed a vision-based control approach for autonomous tracking and landing on a motional Unmanned surface vessel (USV) with an unmanned aerial vehicle (UAV). First, a novel three-stage visual detection method is proposed to estimate the relative 3D position between UAV and USV, where the USV stays in a suitable view of the camera of the UAV. Then a PID controller is designed to regulate the attitude of the quadrotor and the movement of the vessel, which enables the successful landing procedure of the UAV on a motional USV. Finally, lake experiments are conducted to verify the effectiveness of the proposed algorithm.

Key Words: Autonomous landing, Unmanned aerial vehicle, Unmanned surface vessel, Computer vision

1 Introduction

Recently, a large volume of unmanned systems have been widely developed due to the lower cost, higher flexibility and easier portability, which has huge potential in detection, territorial, rescue and surveillance, etc. As a representative unmanned system, unmanned aerial vehicle(UAV) has been playing an increasing important role in the disaster rescue, naval attacks and area logistics, etc. Most Moreover, the

However, due to the theoretical challenge in the moving target tracking problem, most of the works focused on the stationary target. For instance, Hu & Lu [1] initially proposed an adaptive robust controller to Land a UAV on a stationary platform. Lin [2] designed an H-shaped target and used a drone to identify the target with a monocular camera.

With the increasing sophisticated environment and complex tasks, many scholars have devoted to the tracking problem with a moving target. Panagiotis & Panos [3] developed a model-based predictive controller to track a vision-based mobile tilting platform. Miguel A & Somasundar [4] tracked and landed on moving platforms with different sizes tracking, which completes the ROS simulations and outdoor experiments. Bruno & Tarek [5] presented a nonlinear controller for vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV) on a moving platform. Davide [6] designed an X-shaped target to drive the drone automatically land on a mobile platform using airborne sensing and computing functions. Daewon & Tyler [7] afterward introduced an image-based visual servoing (IBVS) and sliding mode controller to track the moving platform. JeongWoon & Yeondeuk [8] has used as a camera to capture and process images to estimate the position and speed of the moving platform, where the drone landed on the moving platform. Tru & Enkhmurun [9] has designed different sizes targets to land a UAV on a moving platform to complete the drone landing on the moving platform. Hao & Jerome [10]

Fig. 1: Our experiment in the lake

extended different sizes targets to land a UAV on a moving platform. Pedro & Rita [11] used image-based visual servo control to solve the vertical take-off and landing of a quadrotor on a mobile platform. Then, Engelbert & Andreas [12] presented a system consisting of a miniature unmanned aerial vehicle (UAV) and a small carrier vehicle, in which the UAV is capable of autonomously starting from the moving ground vehicle. It is worth mentioning that the tracking problem is investigated with challenge competition. Tomas & Petr [13] proposed the perception, control, and trajectory planning for an aerial platform to identify and land on a moving car at $15km/h$, where the hexacopter unmanned aerial vehicle (UAV) is equipped with onboard sensors and detects the car using a monocular camera. Marius & Matthias [14] developed a strategy to estimate the motion trajectory of the car based on vision and selects the optimal route to land on a moving car at $15km/h$ with a drone.

However, the mentioned works only focused on the ground moving target and have not touched the tracking problem with the USV in the sea, which is more difficult than the moving ground target due to the shaking environment and the reflection of the sea. Moreover, the motional USV poses another challenge in the tracking problem, which is an urgent task to be solved in practice. Unfortunately, to the best of our knowledge, there are no kinds of literature concerning UAV tracking and landing on a motional USV.

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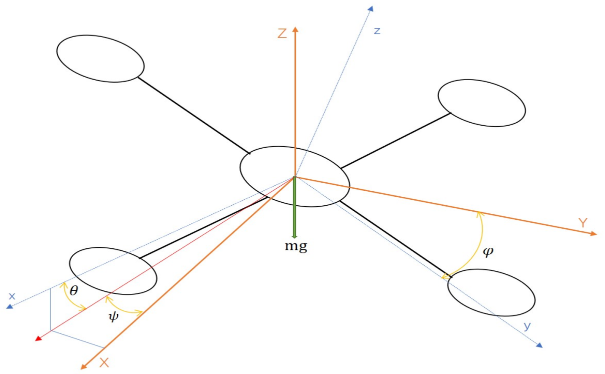


Fig. 2: The coordinate frames and the Euler angles of a quadrotor

To this end, this paper proposes a vision-based multi-stage recognition method that enables UAV to land smoothly on a motional USV, and takes experiments with our UAV and HUSTER-68 USV to verify the feasibility of the proposed methods.

As shown in Fig. 1, our UAV and USV are experimenting in the lake. It is a snapshot of our drone during landing, and the detailed procedures will be introduced afterward.

This paper is organized as follows: Section II presents the system and mathematical model; Section III gives the control strategy and vision approach, Section IV carries out the outdoor experiment with the proposed method discusses the experiment results; the conclusions are drawn in Section V.

2 System And Mathematical Model

This section describes the camera systems and the mathematical model of the UAV and USV.

2.1 Quadrotor Drone

The UAV consists four motors, each of which can independently control its own speed to create thrusts. And the thrust generated by each motor is defined as f_i. The different speeds of the four motors can produce different degrees of thrust, which can make the drone change roll, and yaw angle and then change the speed of the drone.

We use a common quadrotor model in [15] for controller design. Denote

$$P_q = [X_q, \dot{X}_q, Y_q, \dot{Y}_q, Z_q, \dot{Z}_q, \phi_q, \dot{\phi_q}, \theta_q, \dot{\theta_q}, \psi_q, \dot{\psi_q}]^T$$

where **x**=$[X_q, Y_q, Z_q]$ is the position of the drone in the inertial frame, ϕ_q, θ_q and ψ_q are the Euler angles of the quadrotor. and g $= 9.81 m/s^2$ is the constant, as illutrated by Fig. 2. We also denote

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -l & 0 & l & 0 \\ 0 & l & 0 & -l \\ d & -d & d & -d \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{1}$$

where U_1 is the sum of thrusts of four motors, l is the distance from the center of mass of the drone to a motor, U_2, U_3 and U_4 are the angular torque caused by the rotor around x, y and z body frame axes. Denote $\omega = [p, q, r]^T$ the body angular velocity. $I \in \mathbb{R}^{3\times 3}$ is the body inertia matrix of the drone

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{2}$$

and $I_x, I_y, I_z \in \mathbb{R}$ are the inertia about x,y and z body axes. Denote $R \in \mathbb{SO}_3$. We consider an inertial reference frame denoted by $[e_1, e_2, e_3]$. The dynamic model of the drone are given by

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{v} \\ m\dot{\mathbf{v}} &= U_1 R e_3 - m g e_3 \\ I\dot{\omega} + \omega \times I\omega &= \mathbf{M} \end{aligned} \tag{3}$$

where **M**= $[U_2, U_3, U_4]^T$,along all axes of the body-fixed frame.

The altitude of the drone is as follows

$$\ddot{Z}_q = \frac{1}{m}\cos\phi_q \cos\theta_q U_1 - \mathrm{g} \tag{4}$$

Let

$$U_1 = \frac{m}{\cos\phi_q \cos\theta_q}(\alpha_z + \mathrm{g}) \tag{5}$$

then we feedback linearize the plant into the following form

$$\ddot{Z}_q = \alpha_z, \quad \forall \phi_q, \theta_q \in (-\frac{\pi}{2}, \frac{\pi}{2}) \tag{6}$$

In order to control the altitude, we need to calculate U_1, then we can use U_1 to calculate the angles ϕ_q and θ_q needed to regulate X and Y positions.

$$\begin{bmatrix} \ddot{X}_q \\ \ddot{Y}_q \end{bmatrix} = \begin{bmatrix} \cos\phi_q \sin\theta_q \cos\psi_q + \sin\phi_q \sin\psi_q \\ \cos\phi_q \sin\theta_q \sin\psi_q - \sin\phi_q \cos\psi_q \end{bmatrix} \frac{U_1}{m} \tag{7}$$

for a small angle θ,we can get that

$$\cos\theta \approx 1, \qquad \sin\theta \approx \theta. \tag{8}$$

Then we can convert (7) as

$$\begin{aligned} \begin{bmatrix} \ddot{X}_q \\ \ddot{Y}_q \end{bmatrix} &= \begin{bmatrix} \theta_q \cos\psi_q + \phi_q \sin\psi_q \\ \theta_q \sin\psi_q - \phi_q \cos\psi_q \end{bmatrix} \frac{U_1}{m} \\ &= \begin{bmatrix} \cos\psi_q & \sin\psi_q \\ \sin\psi_q & -\cos\psi_q \end{bmatrix} \begin{bmatrix} \theta_q \\ \phi_q \end{bmatrix} \frac{U_1}{m} \end{aligned} \tag{9}$$

which means that we can using θ_q and ϕ_q to control the position of quadrotor when the value of ψ_q does not change.

2.2 Surface vessel

We consider the model of the vessel which neglects the roll, heave and pitch motion, and we do not consider the environmental forces caused by wind, currents and waves in the model. Furthermore, we assume that the added mass, inertia and damping matrices are diagonal. As is shown in Fig. 3 then we can describe the vessel dynamics see e.g.[16] as:

$$\begin{aligned} \dot{u} &= \frac{m_{22}}{m_{11}} v r - \frac{d_{11}}{m_{11}} u + \frac{1}{m_{11}} u_1 \\ \dot{v} &= -\frac{m_{11}}{m_{22}} u r - \frac{d_{22}}{m_{22}} v \\ \dot{r} &= \frac{m_{11} - m_{22}}{m_{33}} u v - \frac{d_{33}}{m_{33}} r + \frac{1}{m_{33}} u_2 \\ \dot{x} &= u\cos\psi - v\sin\psi \\ \dot{y} &= u\sin\psi + v\cos\psi \\ \dot{\psi} &= r, \end{aligned} \tag{10}$$

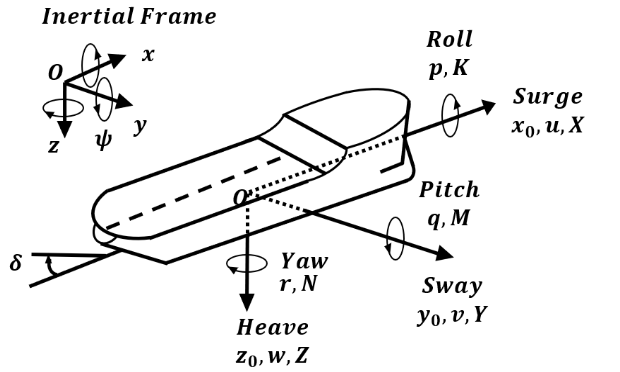


Fig. 3: The inertial frame and body-fixed frame of the vessel

where v, r and u denote velocities in sway, yaw and surge, and x, y, ψ denote the position and direction of the vessel in the earth-fixed frame. The parameters $m_{ii} > 0$ are given by the vessel inertia and added mass effects. The parameters $d_{ii} > 0$ are given by the hydrodynamic damping. The available controls are the surge force u_1, and the yaw moment u_2.

3 Control Strategy And Vision Approach

This section describes a vision-based recognition method of targets and the control strategy of the UAV.

3.1 Vision-based detection of targets

In order to identify the exact position of the unmanned vessel, we put a target on the vessel, which is called April-Tag. We identify the target via [17], which includes adaptive threshold, continuous boundary segmentation, fitting quads, quick decoding, edge refinement. UAV can use this method to identify the target on USV.

We use a pinhole camera model to be our camera model. The entire camera structure is abstracted into an infinitesimal hole which is called a pinhole and an image plane projection. Simply put, the pinhole camera model is to simplify the camera into small hole imaging. The 2D coordinates imaged in the camera are mapped from points in the 3D world. In the case, where the target size is known, the spatial position of the target can be calculated from the position of the pixel point of the target in the image, and it is necessary to know three or more feature point information of the object. We use the rectangular target so there are four corner points, which is Enough to solve the position of the target with the above model. Following from [18], the specific method is described as follows:

The 3D coordinate of this point (X,Y,Z) is related to its 2D coordinates (x,y) in the image by the following equation:

$$sm' = A[R|t]M' \tag{11}$$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{12}$$

where u,v is the pixel coordinates of the object in the image, X,Y,Z are the 3D coordinates in the world space, s is the z coordinate of the object in the camera coordinate system, matrix A is the intrinsic parameters of the camera, [R—t] is the extrinsic parameters of the camera. These parameters are generated during the formula derivation process. The intrinsic parameters are determined only by the camera itself, which is fixed for a camera. The extrinsic parameters are related to the world coordinate system and camera position. Then for a target, we can use the above method to get the position of the camera in the target coordinate system. Furthermore, the position error of the drone and the unmanned vessel is obtained.

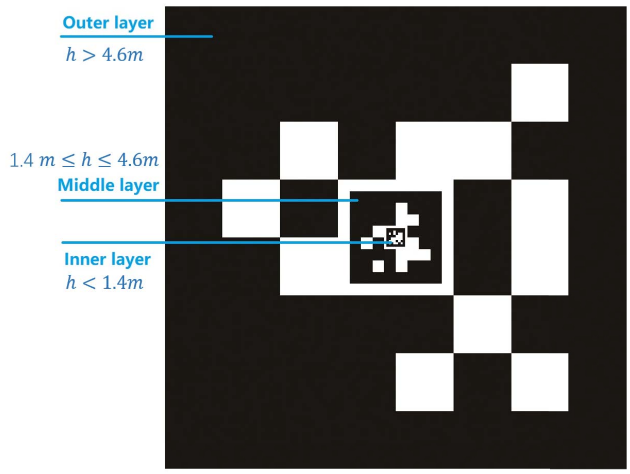


Fig. 4: Our nested target consisting of three differently sized targets

But only one tag is not feasible, since the target will be larger and larger in the field of view during the landing of the drone, which will cause the target to occupy too many pixels in the image and make the detection slower or even unable to detect the target. For example, if the target is visible at 10 meters high and the displayed size is normal, then at 1 meter high, the target will be very large. So it can not satisfy the landing requirements. In this paper, we propose a new target design scheme as shown in Fig. 4., which is made up of a set of targets of different sizes and the drone identify different sizes of targets in different situations. We define two heights $h_1 = 4.6\ m$ and $h_2 = 1.4\ m$, which divide the space into three layers, and we detect different sizes of targets at different height levels. And our targets are nested together so that they are smoother when switching the detecting targets.

We can change the target of identification according to the height of the UAV or the target's field of view in the camera. So that the target is always in a suitable size in the camera's field of view. Due to our three small targets have the same center point, the calculated position information is smooth when switching targets, which is very efficitive for us to control the drone land.

3.2 Control Strategy

We design a control law for the unmanned surface vehicle. After analyzing the kinetic equation, we denote $\sigma_1 = \dot{u}$ and $\sigma_1 = \dot{r}$, which can influence the surge velocity u and the heading angle ψ. Since our vessel has only two inputs σ_1

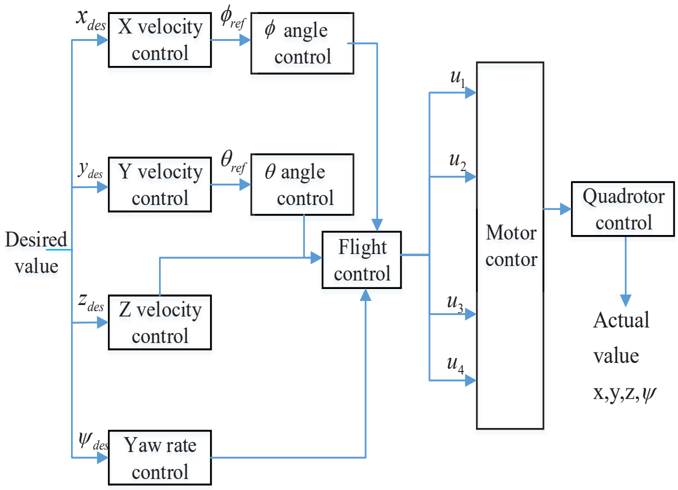


Fig. 5: A control framework of the UAV.

and σ_2, we set $\dot{v}$ to zero, then we can control the movement of the vessel by selecting σ_1 and σ_2.

Define the heading angle error and the surge velocity error as:

$$\begin{aligned} e_u &= u_s - u_t \\ e_\psi &= \psi_s - \psi_t, \end{aligned} \tag{13}$$

where u_s and ψ_s is the set value, u_t and ψ_t is the feedback value. After getting the error value, we can design the PID controller to get the output σ_1 and σ_2:

$$\begin{aligned} \sigma_1(t) &= K_{pu} e_u(t) + K_{iu} \int_0^t e_u(\tau) d\tau + K_{du} \frac{d}{dt} e_u(t) \\ \sigma_2(t) &= K_{p\psi} e_\psi(t) + K_{i\psi} \int_0^t e_\psi(\tau) d\tau + K_{d\psi} \frac{d}{dt} e_\psi(t) \end{aligned} \tag{14}$$

where (K_{pu}, K_{iu}, K_{du}) and $(K_{p\psi}, K_{i\psi}, K_{d\psi})$ are positive constant. Then we can control our vessel. In this paper, the main task of our USV is to go straight, which means that the vessel can keep the course and speed as smooth as possible. So our set value u_s and ψ_s is constant throughout the landing. After the unmanned vessel's running status remains stable, we can control the drone to complete the landing.

Based on the position-solving method above, we can get the 3D position(X, Y, Z) and yaw(ψ) between the drone and the unmanned vessel. Our control scheme for quadrotor is shown as Fig. 5. Enter the information(X, Y, Z, ψ) into our controller, whose output is the attitude of the quadrotor. In Fig.2 we denote the attitude angle ϕ, θ, ψ. Then the flight controller will convert attitude angle to motor control, with which we can control the quadrotor flight to complete the landing mission. And we design the attitude angle controller.

We can get the information(X, Y, Z, ψ) from the target solution, where ψ is the angle error between the camera of the drone and the target on the vessel (we set the target and the vessel in the same direction), and there is also a diagonal error between the nose of the drone and the camera ψ_1. We denote e_ψ to be the diagonal error between the nose of the drone and the vessel, where $e_\psi = \psi + \psi_1$.

Input this to the PD controller:

$$\dot{\psi}(t) = K_p e_\psi(t) + K_d \frac{d}{dt} e_\psi(t) \tag{15}$$

due to the X,Y are the coordinates of the camera of the drone in the target coordinate system, we convert it to the coordinates of the target in the UAV coordinate system e_x, e_y:

$$\begin{aligned} e_x &= X \cos(e_\psi) + Y \sin(e_\psi) \\ e_y &= X \sin(e_\psi) + Y \cos(e_\psi) \end{aligned} \tag{16}$$

with these we can get the attitude of quadrotor from the controller:

$$\begin{aligned} \theta(t) &= K_{p\theta} e_y(t) + K_{i\theta} \int_0^t e_y(\tau) d\tau + K_{d\theta} \frac{d}{dt} e_y(t) \\ \phi(t) &= K_{p\phi} e_x(t) + K_{d\phi} \frac{d}{dt} e_x(t) \end{aligned} \tag{17}$$

where θ is the pitch angle of the quadrotor ,ϕ is the roll angle of the quadrotor. We use the PID and PD controller to compute the attitude angle of the drone θ and ϕ, which is entered to the flight controller to control the quadrotor. For the height control of the unmanned vessel, we control the drone to drop at a constant speed while tracking the unmanned vessel in the landing area. So that we can achieve landing of a UAV on a moving USV.

4 experiments

In Section 3, we conduct the experiment of landing the drone on the unmanned boat on the outdoor lake. First, let us introduce our experiment platform.

4.1 Experiment Platform

The UAV is the DJI Matrice 100 Developer Platform. Which has its own flight controller. And it supports secondary development. And the camera is the DJI Zenmuse Z3, which can provide an image resolution of 1920 × 1080-pixel, and it is enough for us to detect the target. We use the onboard computer manifold to run our algorithms. All of these are shown in Fig. 6(a).

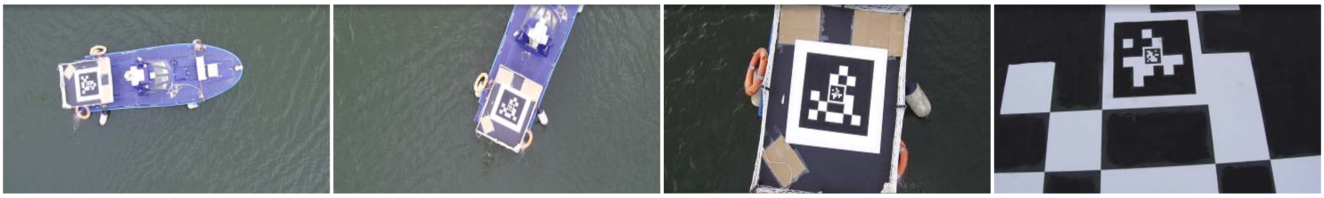
As shown in Fig. 6(b), the USV in the experiments is HUSTER-68 USV, which is a high performance, integrated unmanned vessel with differential GPS, lidar, binocular vision and other equipment. And it can achieve target detection, track planning, autonomous navigation and so on. In the experiments, we built a landing platform on the vessel, then put the target that we designed in the middle of the platform.

4.2 Outdoor experiments

Fig. 7 shows the camera view of the quadrotor during the tracking and landing, and we can clearly see that the UAV detect different layers' target at different heights, which changes from the outer layer to the middle layer to the inner layer, and then land on the moving USV.

(a) The UAV (b) The USV

Fig. 6: The UAV and USV in our experiments



(a) (b) (c) (d)

Fig. 7: Camera views of the quadrotor during the tracking and landing. (a) The camera of the UAV captures the moving USV, (b) the UAV detect the outer target at height $> h_1$, (c) the UAV detect the Middle target at $h_2 <$ height $< h_1$, (d) the UAV detect the inner target at height $< h_2$.

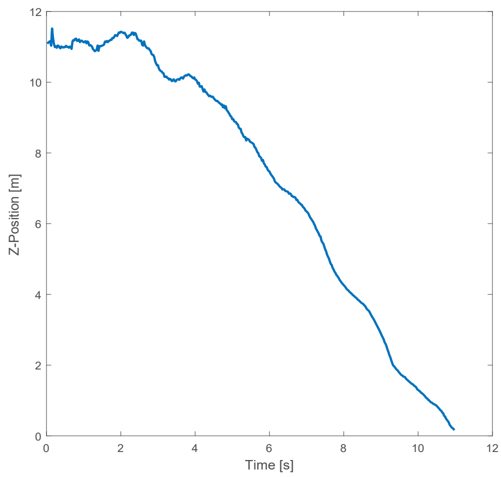


Fig. 8: The transition of the relative h during the landing process.

The results of the real experiments is shown in Fig. 8. This picture shows transitions of the heigh of the UAV, which shows our UAV lands on a vessel from a height of 12 meter. After 11 seconds, our UAV successfully landed on the moving vessel.

5 CONCLUSION

In this paper, we propose a novel method of UAV tracking and landing on the moving USV and take lake experiments. With the assistance of the designed target on the USV, the UAV detects the relation position between itself and the USV. Then, a PID controller is utilized for the UAV to track and land on the USV. In the experiments, after detecting the target in three stages, the UAV automatically tracks the USV and lands on the USV using only onboard computer and sensors, which verifies the proposed approach.

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