

A Robotic Platform for Testing Moth-Inspired Plume Tracking Strategies

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Abstract—A mobile autonomous robot capable of tracking an odor plume to its source could be used to locate hazardous material spills or leaks. To test plume tracking strategies in a laboratory environment, a robotic platform consisting of a linear Cartesian robotic gantry mounted inside a wind tunnel with a mobile floor has been designed. A plume of ionized air is created by an ion detector installed in the wind tunnel. A two-dimensional plume tracking strategy based on the behavior of the tobacco hornworm moth *Manduca sexta* was implemented and tested. It was discovered that a plume tracking algorithm can be implemented with the robotic platform almost as easily as in simulation.

Keywords- *Biologically Inspired Systems, moth, plume tracking, Robot Sensing and Sensor Fusion, wind tunnel*

I. INTRODUCTION

A mobile autonomous robot capable of tracking an odor plume to its source could be used to locate hazardous material spills or leaks. In theory, such a robot could locate anything emitting an odor provided the robot has an appropriate sensor to detect the odor. The idea of using robots for these tasks has been suggested by other authors [1]. Robots are well suited to these tasks since they are inherently dangerous for humans. There are three types of odor tracking robots: terrestrial, air-borne, and water-borne. This paper focuses on the development of a robotic platform for testing air-borne plume tracking strategies

Several challenges arise when trying to develop a flying odor tracking robot. A flying robot must be capable of tracking a plume to its source in three-dimensions. Such a plume tracking algorithm is not expected to be a simple extension of a two-dimensional plume tracking algorithm for a terrestrial robot. Also, flying robots are generally more difficult to control than wheeled robots. Flying robots cannot be stabilized by ground contact and can be disturbed by air currents. In addition, flying robots cannot approximate position and velocity from motor encoder readings. Instead, inertial measurements such as from optical flow sensors or GPS receivers are necessary.

Although there are several challenges that must be overcome in developing a flying odor tracking robot, there are also some advantages to this approach. One advantage of being air based is that the orientation of the robot will not be disturbed by obstacles on the ground. Also, a flying robot can track a plume that does not remain close to the ground.

One can imagine many possible strategies for tracking an odor plume to its source. These strategies could be based on some simple rules and further developed through trial and error. However, the problem is complex because the concentration of an odor plume does not uniformly decrease with increasing distance from the source. If this were the case, a plume tracking robot would only need to follow the plume concentration gradient. In reality, an odor creates a time-averaged gradient, but at any instant in time, the odor is concentrated in packets that move downwind and diffuse primarily by the effects of turbulence generated by the source itself [2-5].

Another approach for developing a plume tracking strategy is to study a biological system which has already solved the plume tracking problem. Most of our current knowledge of odor tracking in flying animals is based on the observed behavior of male moths tracking wind-borne plumes of female sex attractant pheromone. Several algorithms have already been developed based on this knowledge and tested in simulation [5-6].

The plume tracking behavior of the tobacco hornworm moth *Manduca sexta* (Fig. 1) has been extensively studied in a laboratory wind tunnel [7]. A piece of filter paper containing pheromone is placed at the upwind end of the test section of the wind tunnel and a male moth is released at the downwind end. The behavior is recorded from above and from downwind. The position of the moth is then digitized from the video recordings to obtain a three-dimensional reconstruction of the flight path.



Figure 1. *Manduca sexta*, the tobacco hornworm moth

The overhead view of a male *M. sexta* tracking a pheromone plume is shown in Fig. 2. The position of the moth was sampled at 30 Hz and is shown relative to the source at (0,0). The source was not in view of the overhead camera in

this experiment. When initially introduced to a plume the moth immediately turns into the wind. With a stationary source, the odor plume can only travel downwind. The moth then tacks rhythmically back and forth across the wind. On average, the inter-turn duration of these tacks is about 500 ms [8]. If the position of the moth had been recorded all the way to the source, one would see that the upwind progress becomes slower as the moth approaches the source [9-11]. Far from the source these tacks make upwind progress, while close to the source the tacks become perpendicular to the wind direction. This is due to the decrease in forward speed as the moth approaches the source. Another aspect of the moth odor tracking is the searching or “casting” behavior. If the moth loses the plume, it will fly perpendicular to the wind in order to reacquire the plume [8]. This casting behavior can be seen in Fig. 2 at about 0.8 meters from the source.

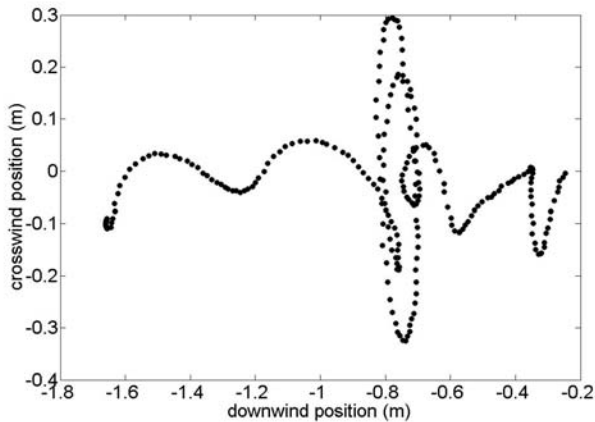


Figure 2. Overhead view of a male *M. sexta* tracking a pheromone plume

The goal of this project is to develop a robot for testing airborne plume tracking strategies in a laboratory environment. To do this, a robotic platform has been designed consisting of a 2-axis linear Cartesian robotic gantry mounted inside a wind tunnel with a mobile floor. Since the primary goal of this project is to develop a platform for testing plume tracking strategies and not to replicate the physiology of a moth, the robot has little resemblance to a moth. However, because the robot can translate in three dimensions in an air flow and the behavior of the robot is based on the plume tracking behavior of a moth, the robot has been named Robo-moth.

II. DESIGN OF ROBO-MOTH

Robo-moth is a wind tunnel with a linear Cartesian robotic gantry located at the downwind end of the test section (Fig. 3). The wind created in the wind tunnel carries a plume from a plume generator to the robot. The floor of the treadmill is the surface of a conveyor belt. In Robo-moth, the plume source rests on the conveyor belt and moves downwind over time instead of the robot moving upwind toward the source. Robo-moth’s control system coordinates vertical and lateral motions of the gantry with forward motion of the conveyor belt for a total of three translational degrees of freedom.

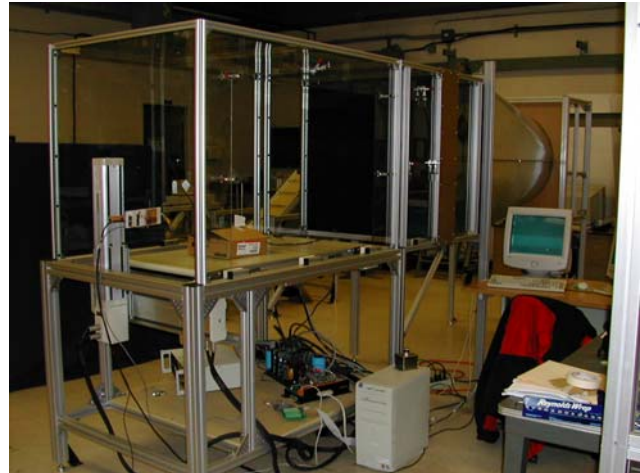


Figure 3. Robo-moth

Robo-moth is designed as an open pushing wind tunnel similar to the wind tunnel used to study the behavior of *M. sexta*. Air is pushed through the wind tunnel by a fan at the upwind end and exits through an opening downwind of the test section. Wind is generated by a 31.5” diameter fan housed in a 32” diameter circular duct and driven by a ¼ hp Dayton 2Z846D permanent magnet DC motor and speed controller unit. The wind generated by the fan passes through a 5 ft. long diffusion section to expand to the one meter square cross section of the test section. One vertical plate and one horizontal plate that intersect along the centerline of the tunnel in the diffusion section reduce the vorticity of the flow. The motor housing and diffusion section are vibration isolated from the test section by a 6” long neoprene boot. After passing through the boot, airflow is then directed into a 6” long aluminum flow straightener. The flow straightener has a “honeycomb” design with a cell size of 0.5”. Once air passes through the flow straightener, it enters the 2 meter long test section of the tunnel. The test section of the wind tunnel has the same cross section as the one used to study the behavior of *M. sexta* tracking pheromone plumes. The support structure of the wind tunnel is constructed of Bosch aluminum structural framing. This allows for easy reconfiguration of the wind tunnel if needed in the future. The tunnel is enclosed on the top and sides by 7/32” thick clear polycarbonate sheet. Doors were built into one side of the test section to allow easy access to the robot and plume generator. A conveyor belt was installed into the floor of the test section. The area on the floor of the test section around the conveyor belt is enclosed with ¼” thick hardboard. The fan housing and diffusion section are shown in Fig. 4. The interior of the test section is shown in Fig. 5

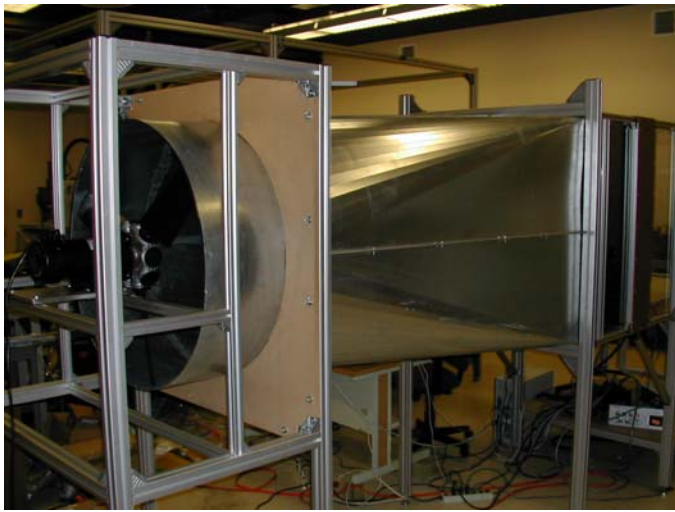


Figure 4. Fan housing and diffusion section of the Robo-moth wind tunnel

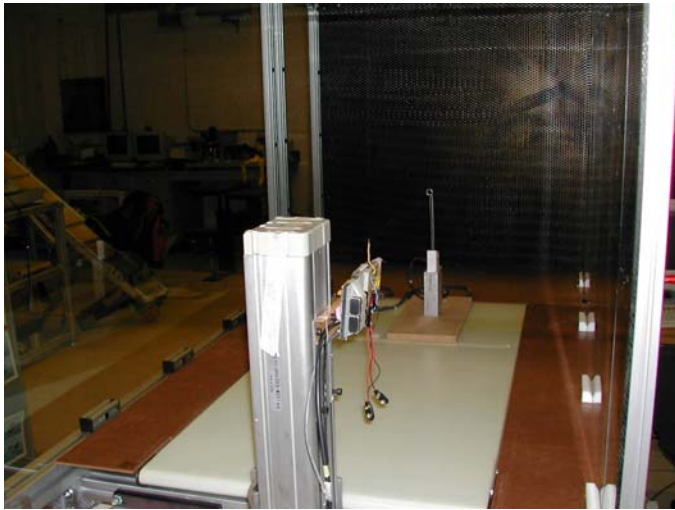


Figure 5. Test section of the Robo-moth wind tunnel as viewed from the exhaust end

A robotic gantry is installed near the open (exhaust) end of the test section of the wind tunnel. The gantry is an Adept 97N1-005 series 2-axis Cartesian linear actuator. It is configured such that one axis moves horizontally and one moves vertically through the cross section of the wind tunnel. This system provides a range of travel of 42 cm (16.25 inches) in the crosswind and vertical directions. Instead of adding a third linear actuator to the robotic gantry, a Dorner 2100 series conveyor belt was built into the floor of the wind tunnel to move the plume source toward the robot. This conveyor belt is 61 cm (2 feet) wide and 122 cm (4 feet) long. The conveyor belt is driven by a Baldor ME-3353-DLBCN DC servomotor. The output shaft of the conveyor belt motor goes through a 1.455:1 gear reduction. The motors are controlled by a Galil motion control system. The motors are connected to an ICM/AMP-1900 interconnect module, which is controlled by a

DMC-1802 motion control card installed in a 450 MHz Pentium 2 PC.

A plume is created with an ion generator placed on the conveyer belt. The ion generator is activated by a DC power supply capable of producing a maximum potential of 4.1 kV. When the ion detector is activated, ionized molecules are created as they pass through the ion generator. An ion detector is attached to an arm on the robotic gantry (Fig. 6). The ion detector is plugged into a National Instruments CB-68LP terminal block. The terminal block is connected to a National Instruments AT-MIO-16E-10 data acquisition card installed on the same computer as the motion control card. A camera is also mounted on the arm, but is currently not being used. In the future, the camera will be used to approximate the velocity of the robot. A wind sensor will also be added to measure airspeed.



Figure 6. Ion detector mounted to the Robo-moth gantry

Fig. 7 shows the time-averaged representation of the ionized plume created in the test section of Robo-moth with a wind speed of approximately 1 m/s. The plume concentration was measured in a horizontal plane intersecting the plume source. The plume concentration was measured at 21 equally spaced crosswind positions and 23 equally spaced upwind positions. The plume concentration at each location was sampled at 50 Hz and averaged for 4 seconds. The ionized air plume looks very similar to the time average of other odor plumes.

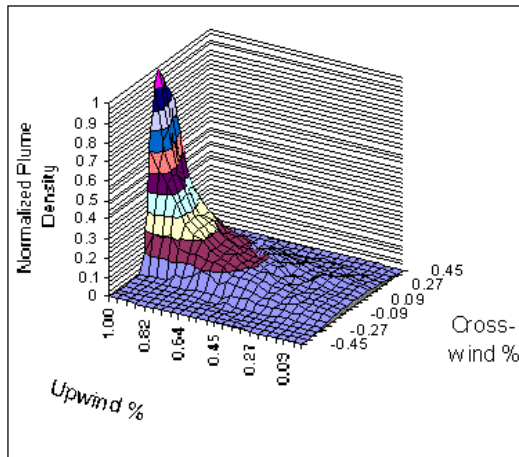


Figure 7. Time average plume density

III. ROBO-MOTH ODOR TRACKING ALGORITHM

A two-dimensional plume tracking algorithm based on the behavior of *M. sexta* has been implemented on Robo-moth. The algorithm incorporates the three primary behaviors of a moth tracking a pheromone plume: tacking, turning, and searching. Since not all is known about how *M. sexta* tracks a plume, some assumptions were made when designing the algorithm. The main assumption is that an inter-turn duration timer is started after each turn and then reset when the plume edge is reached. Resetting the timer after each turn prevents Robo-moth from flying too far from the plume. Resetting on the edge of the plume ensures that Robo-moth will be somewhat centered on the plume midline. The degree of centering depends on the width of the plume. A very thin plume would result in a centered flight track. In contrast, a very wide plume will result in one that is centered on the edge of the plume.

Experiments have shown that saturating the olfactory system of a moth causes premature near-source tracking behavior. This implies that the moth expects a certain pheromone concentration near the source. Plume concentration measurements in Robo-moth have been normalized with respect to the source concentration to trigger near-source tracking behavior at the appropriate time. A state diagram showing the details of Robo-moth's odor tracking algorithm is shown in Fig. 8.

IV. TESTING THE ROBO-MOTH ODOR TRACKING ALGORITHM

An example flight track using Robo-moth's odor tracking algorithm is shown in Fig. 9. Robo-moth centers about 20mm to the right of the plume source. This is because the plume is still relatively wide at the source and Robo-moth's speed is relatively slow. The plume width can be seen in the time averaged representation of the plume (Fig 7). Fig. 10 shows the plume concentration readings taken during the sample flight track. The plume concentration measurements show that the time-averaged representation of the plume is not a good indication of the instantaneous plume concentration.

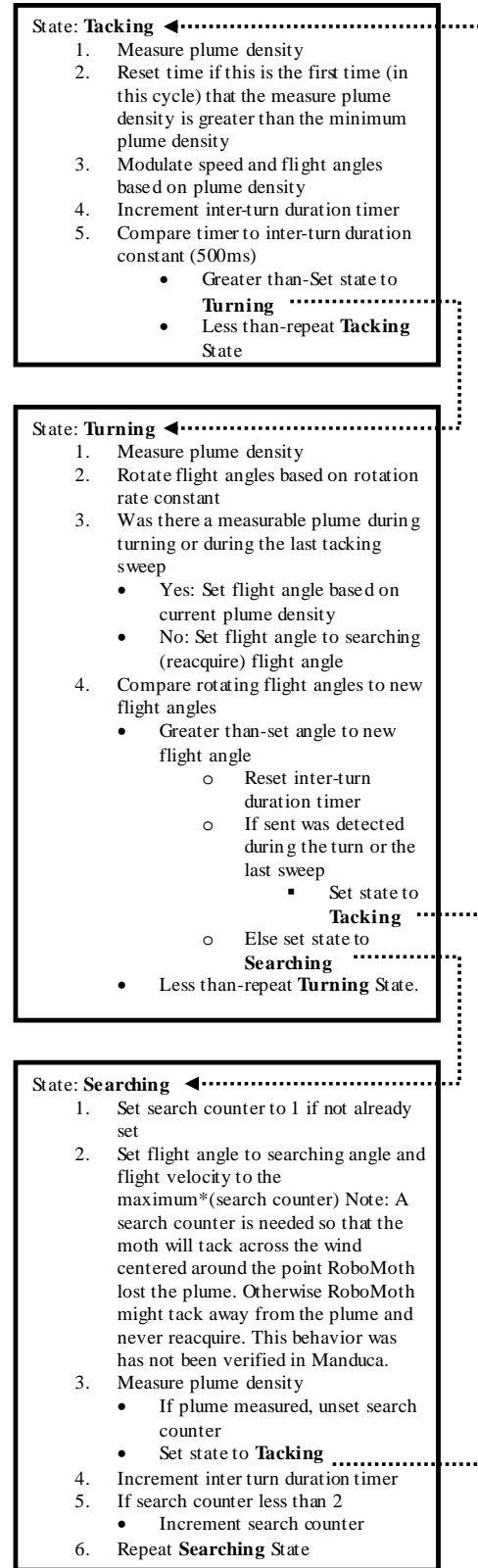


Figure 8. State diagram of the Robo-moth odor tracking algorithm

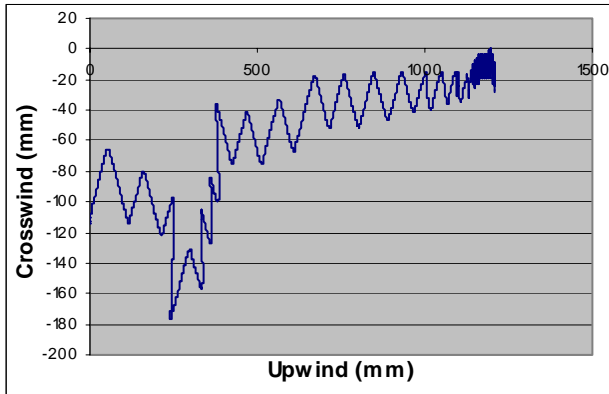


Figure 9. Sample trajectory of Robo-moth tracking an ionized plume

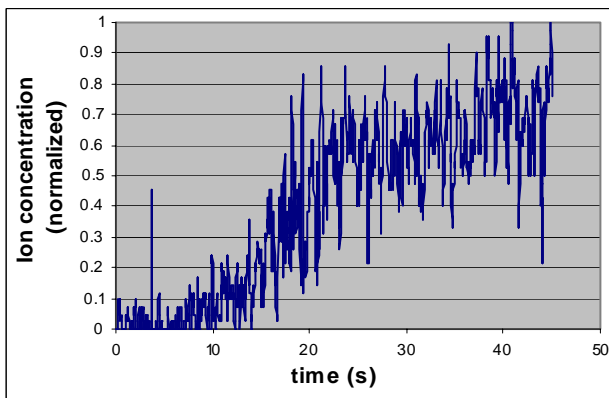


Figure 10. Normalized ion concentration readings taken during sample Robo-moth trajectory

Robo-moth modulates its trajectory speed and flight angle relative to the wind direction based on the plume concentration measurement. Robo-moth samples the plume concentration at 50 Hz and updates flight angle and speed at 10 Hz. The plume measurement is determined from the average of the last five plume measurements. These sampling rates are such that plume noise is reduced and large changes in flight parameters are avoided. Once the plume concentration has been determined, Robo-moth calculates the desired flight parameters. There isn't a direct relationship between flight parameters rather, the flight parameters remain relatively constant for much of the plume concentration range. At large concentrations there is a sudden shift in these flight parameters. Flight speeds are fast far from the source and slower close to the source. Flight angles are small far from the source and large close to the source. Below is shown the desired flight angles and speeds for the trajectory being discussed. Fig. 11 and Fig. 12 show that the Robo-moth algorithm uses only a few discrete values for flight angle and speed.

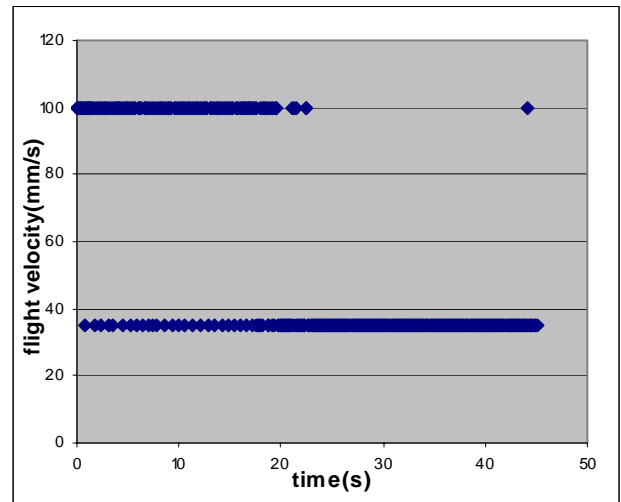


Figure 11. Flight velocity during sample Robo-moth trajectory

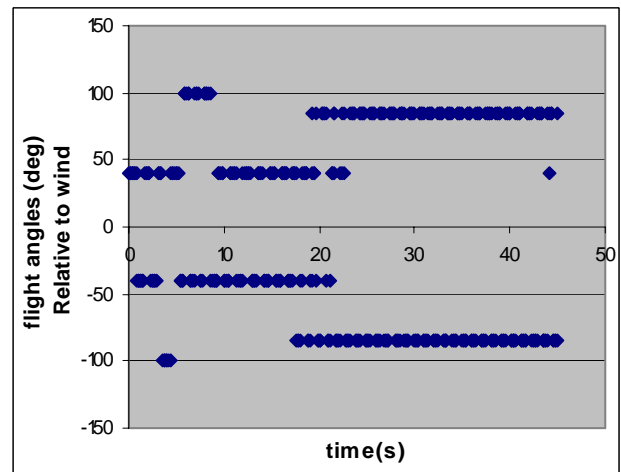


Figure 12. Flight angles during sample Robo-moth trajectory

V. DISCUSSION

Robo-moth provides an excellent platform for testing plume tracking algorithms in a laboratory environment. The plume tracking algorithm described in this paper served primarily as a test of the Robo-moth hardware. It was discovered that a plume tracking algorithm can be implemented with Robo-moth almost as easily as in simulation. Also, testing plume tracking algorithms with Robo-moth instead of in simulation eliminates the need to create a simulated plume. Results from Robo-moth will give a better indication of the performance of a plume tracking algorithm implemented on a flying robot in a natural environment.

Although Robo-moth has a high resolution plume concentration sensor, plume concentration mapped to only a few flight parameters. This implies that Robo-moth does not need the plume resolution available to it. A sensor that could only detect a few levels of plume concentration could be substituted for the current sensor. There are two flight

velocities and three flight angles used throughout the odor tracking flight, therefore, there only needs to be at most three levels of distinction of the odor plume.

The algorithm employed by Robo-moth is very simple. The sensors do not need to be very precise. The sampling rates are relatively slow. The algorithm consists of simple logic and slow feedback. The algorithm could be implemented with relatively simple circuits and would not require the use of a digital computer. The absence of a computer drastically reduces the cost of implementation of this algorithm, making it a desirable solution for odor tracking.

There are many possibilities for future work involving Robo-moth. It can be used to test other two-dimensional plume tracking strategies that have only been tested in simulation. However, the primary purpose of Robo-moth is to test plume tracking strategies in three-dimensions. Since there is currently little research describing the full three-dimensional motion of moths tracking a pheromone plume, a three-dimensional plume tracking algorithm has not yet been developed. Once a three-dimensional algorithm is available, it too will be tested on Robo-moth. In addition, further work will be performed to integrate visual and wind sensory information into plume tracking algorithms.

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