Autonomous Alignment of Free-Space-Optical Links Between UAVs

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ABSTRACT

Free-Space-Optical (FSO) communication has the potential to make high data rate point-to-point transfers possible. Despite its capacity advantages, FSO communication (FSOC) requires establishment and maintenance of line-of-sight (LOS) alignment. We consider two Unmanned Aerial Vehicles (UAVs), each with one FSO transceiver mounted on a hemispherical structure/head capable of rotating 360° in the horizontal plane and 180° in the vertical plane. We propose a novel scheme that deals with the problem of automatic establishment and maintenance of LOS alignment between the UAVs with mechanical steering of the FSO transceivers. The proposed method shows that using such mechanically steerable transceivers and a simple auto-alignment mechanism, it is possible to maintain an optical wireless link between two UAVs with nominal disruption.

1. INTRODUCTION

Free-space-optical (FSO), a.k.a. optical wireless communication has recently attracted significant interest from telecommunication research and industry, mainly due to the increasing capacity crunch faced by the RF wireless technologies. It uses the same baseline technology as the fiber optic communications over the unlicensed optical spectrum. FSO communication (FSOC) allows high spatial reuse and can easily reach modulation speeds of 10 Gbps and even exceed 1 Tbps [10]. It can also provide connectivity in conditions that are unfavorable for RF communication [13] and has low probability of interception and detection [11]. Equipping UAVs with such high-speed FSO transceivers can enable a large set of applications involving transfers of very large wireless data. There are many different applications of UAVs, like surveillance for a military mission (e.g., observation behind the enemy lines) or a civil mission (e.g., monitoring of a traffic jam or a disaster area, or to broadcast critical data at some sport events) which require many sensors. UAVs with several sensors generate a lot of data which has to be delivered to either another UAV or a ground station [8]. Currently UAVs communicate through RF which offers a maximum capacity of around 274Mbps. The higher data rate required for communication links to transmit more information between UAVs triggered the idea of employing FSOC to meet the increasing demand [12]. Also, FSOC is immune to detection, interference, interception or jamming. These properties make the FSOC more advantageous than a legacy RF link for UAV missions [8]. However, the FSO systems are vulnerable to adverse weather conditions such as (atmospheric) turbulence, fog, smoke, rain and dust [4].

FSOC requires effective maintenance of LOS due to its vulnerability against mobility [6]. The optical transmitter and the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. When the link to be maintained is highly directional, the link maintenance becomes a significant challenge as it requires very sensitive mechanical steering of rotational heads and very accurate calculation of each mobiles' position with respect to each other. The most relevant to our work was recently proposed in [6] that deals with the problem of automatic detection, establishment and maintenance of LOS alignment between two autonomous mobile nodes moving on 2D plane with mechanical steering of FSO transceivers, our work solves the problem in 3D for UAVs.

UAV-based FSOC is a challenging but emerging technology [9]. It is becoming more practical to handle the FSO links' extreme sensitivity to movement with the recent advances in nano-mechanical positioning and steering. Methods for establishing and maintaining an FSO link among nearby balloons with the aid of GPS, RF, camera, and communication with a ground station have recently been shown in [2] and [3]. In [5], maintaining an FSO link between UAVs hovering in a given location and orientation was considered.

When extremely directional transceivers like lasers are used, the FSO link becomes even further challenging to maintain. More support from hardware, e.g., micro-mirrors or gimbals, is needed in such cases. In [7], the authors presented a simulation-based study to analyze the performance of a laser beam steering control system consisting of gimbals, a fast steering mirror, GPS, and attitude sensors.

In this paper, we propose a novel scheme showing the feasibility of maintaining an FSOC link among two nodes/UAVs moving in 3D. We assume that the UAVs have mechanically steered transceivers and a simple auto-alignment protocol by exchanging beacon messages. We consider two autonomous aerial nodes/UAVs flying in random directions, each initially unaware of the location of the other. We focus on the case where the mobiles have an FSO transceiver

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each, mounted on a mechanically steerable hemispherical structure/head capable of rotating 360° in the horizontal plane and 180° in the vertical plane. We show that using such mechanical steering capability to control the rotation of the transceivers, the problem of LOS detection, establishment and maintenance can be dealt with effectively. The key novelty of our work is that we assume *no GPS support and use the FSOC link itself to exchange the orientation information among the two UAVs*, which then autonomously decide where and how much to turn their heads.

The rest of the paper is organized as follows: In Sections 2 and 3, we describe our proposed method for maintaining communication link between two autonomous UAVs using FSOC. Section 4 presents an initial simulation-based evaluation of our approach. Finally, we conclude in Section 5.

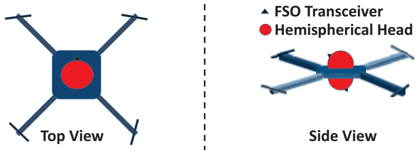


Figure 1: A quadcopter/UAV with hemispherical heads mounted with optical transceivers

2. TECHNICAL APPROACH

2.1 Problem Statement and Assumptions

For the problem of maintaining an FSO link between two aerial nodes, we make the assumptions that the two nodes:

- are mobile and autonomous with no GPS support;
- cannot use an out-of-band RF link to exchange control information (e.g., their orientation and velocity), but can only use the FSO link itself;
- move on straight lines only but in any direction;
- are equipped with Inertial Measurement Units (IMU) giving them the sense of velocity and orientation;
- are equipped with two mechanically steerable hemispherical heads each, one on top and one at the bottom of the UAV, mounted with FSO transceivers (Fig. 1);
- can scan complete 360° in the horizontal plane and 180° in the vertical plane with each head.

We further assume that the UAVs initially use GPS and RF communication to discover each other, and then exchange information about their positions and point the FSO transceivers towards each other to initiate the FSO link. Once the FSO link is established, we, in this paper, focus on maintaining the LOS link between the two UAVs.

2.2 Maintaining The Link

While establishing the link, a node conveys the information about its velocity, the direction in which it is moving, its position, and the orientation of its head to the other node. This information is used by the other node to set the angular velocity and the direction of rotation (clockwise/counterclockwise and up/down) of its head to maintain the link. The nodes periodically exchange this orientation and velocity information to keep the link up. A key difference from the prior work is that the nodes exchange the information *in-band* using the FSO link itself.

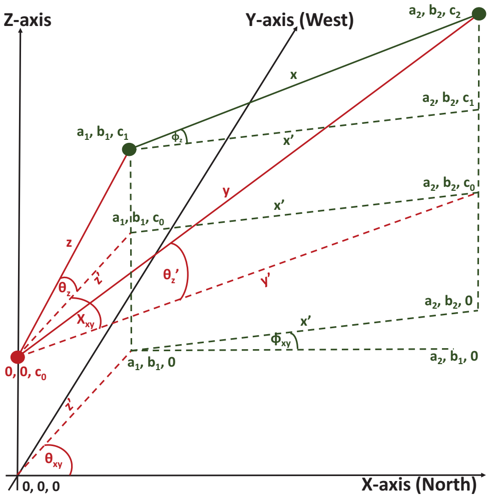


Figure 2: Case I: A stationary and B moving

2.2.1 Setting Up The Angular Velocity

Assuming that two aerial nodes A and B have established an FSO link, there can be two cases depending on the relative velocities and positions of the nodes. We detail these cases for autonomously calculating the angular velocity of the nodes' heads so that the link can be maintained.

Case I: One Mobile, One Stationary. As depicted in Fig. 2, let's consider the case when A is stationary and B is mobile, with initial positions of A and B being $(0, 0, c_0)$ and (a_1, b_1, c_1), respectively. Further assume that B moves a distance of x in during time t (in the order of tens of milliseconds) to a new position (a_2, b_2, c_2). To sustain the link, both A and B will need to rotate their heads in both horizontal and vertical planes. For A, let the rotation angles be $[\angle X_{xy}, \angle X_z]$, where $\angle X_z = |\angle\theta_z' - \angle\theta_z|$. $\angle X_{xy}$ and $\angle\theta_z'$ can be determined by:

$$X_{xy} = \arccos\frac{y'^2 + z'^2 - x'^2}{2y'z'} \tag{1}$$

$$\theta_z' = \arccos\frac{y'}{y} \tag{2}$$

where $x' = x\cos\phi_z$, $y' = \sqrt{a_2^2 + b_2^2}$, and $z' = z\cos\theta_z$.

Since we know B's velocity, $\vec{v_b}$, from the last time they discovered each other, we calculate x by measuring the time difference between the two positions of B and applying: $x = v_b \times t$. We use: $y = \sqrt{a_2^2 + b_2^2 + (c_2 - c_0)^2}$. We represent the distance between the two nodes at the moment of discovery as $z = \sqrt{a_1^2 + b_1^2 + (c_1 - c_0)^2)}$, where $a_1 = z'\cos\theta_{xy}$, $b_1 = z'\sin\theta_{xy}$, $a_2 = a_1 + x'\cos\phi_{xy}$, $b_2 = b_1 + x'\sin\phi_{xy}$, and $c_2 = c_1 + x\sin\phi_z$. Here, $[\theta_{xy}, \theta_z]$ represents the orientation of A's head and $[\phi_{xy}, \phi_z]$ the direction of B's motion at the last discovery time, where θ_{xy} and ϕ_{xy} are azimuthal angles, and $90° - \theta_z$ and $90° - \phi_z$ are zenith angles.

Case II: Both Nodes Mobile. Assume that A and B are moving with velocities $\vec{v_a}$ and $\vec{v_b}$. Further assume that

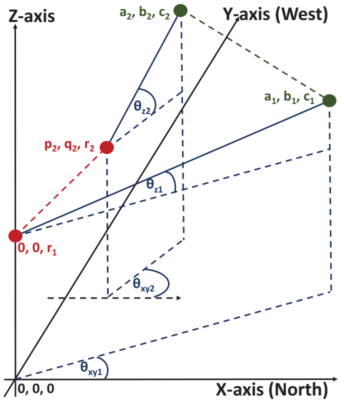


Figure 3: Neighbor in Northeast Quadrant

Table 1: Rotation Direction

Western Quadrants		Eastern Quadrants	
Condition	*Rotation*	*Condition*	*Rotation*
$\theta_{xy1} < \theta_{xy2}$	CCW	$\theta_{xy1} < \theta_{xy2}$	CW
$\theta_{xy1} > \theta_{xy2}$	CW	$\theta_{xy1} > \theta_{xy2}$	CCW
$\theta_{xy1} = \theta_{xy2}$	None	$\theta_{xy1} = \theta_{xy2}$	None
$\theta_{z1} < \theta_{z2}$	Up	$\theta_{z1} < \theta_{z2}$	Up
$\theta_{z1} > \theta_{z2}$	Down	$\theta_{z1} > \theta_{z2}$	Down
$\theta_{z1} = \theta_{z2}$	None	$\theta_{z1} = \theta_{z2}$	None

A moves a distance of x_2 from $(0, 0, r_1)$ to (p_2, q_2, r_2) and B moves a distance of x_1 from (a_1, b_1, c_1) to (a_2, b_2, c_2) in time interval t. Again, to sustain the link, both A and B will need to rotate their heads. From A's perspective, the problem becomes the same as Case I if we assume A as stationary and B as moving with relative velocity $\vec{v_a} + \vec{v_b}$. This means B's relative displacement, x, can be found by $\vec{x} = \vec{x_1} - \vec{x_2}$. This gives us B's apparent (as perceived by A) position (a_2', b_2', c_2'). We, then, perform the calculations in Case I for solving A's problem. Then B's rotation angles can be calculated by performing the same procedure from B's perspective.

2.2.2 *Rotation Direction*

Another important decision to make for the nodes is which way to rotate: clockwise (CW) or counterclockwise (CCW) on the horizontal plane, and up or down on the vertical plane. As depicted in Fig. 3, assume that A is at $(0, 0, r_1)$ and B at (a_1, b_1, c_1), and the orientation of A's head is given by azimuthal angle θ_{xy1} and zenith angle θ_{z1}. After a time interval, A and B move to (p_2, q_2, r_2) and (a_2, b_2, c_2), respectively. At its new location, the orientation of A's head is given by azimuthal angle θ_{xy2} and zenith angle θ_{z2}. For the horizontal plane, if $\theta_{xy1} < \theta_{xy2}$, then rotation should be CCW. If $\theta_{xy1} > \theta_{xy2}$, then rotation should be CW and if $\theta_{xy1} = \theta_{xy2}$, then there is no need for A to rotate its head on the horizontal plane. The rotation direction is determined similarly by comparing θ_{z1} and θ_{z2}. Table 1 shows all the possible cases for rotation directions of a node.

3. IN-BAND LOS ALIGNMENT

A crucial part of our approach is to let the nodes decide how fast to turn their heads autonomously. We assume that the nodes exchange their position, direction, velocity and signal quality values periodically over the FSO link. These periodic exchanges allow the nodes to recalculate how fast they should turn their heads so that the FSO link stays up. Another key part of the simulation is to model transmission and field-of-view areas of an FSO transceiver, which follow the Lambertian law. Following the 2D approximation of an FSO transceiver's Lambertian coverage area in [10], we approximated the volume covered by an FSO transceiver as the combination of a cone and a hemisphere. We considered two different simplistic protocols.

3.1 Protocol A: Maximum Angle of Deviation

Every time the nodes exchange their information with each other, the receiver node sees if it has deviated greater than a preset threshold. If so, the receiver node recalculates the angular speed of its head. Let t_x be the time period of information exchange between the two nodes. Further let α be the ratio between the angle of deviation (θ_d) of the receiver from the height of the transmitter's cone and the divergence angle (θ), and α_{max} be the maximum allowed value of α or θ_d/θ before rotational speed is recalculated. At every t_x, α is checked, and if $\alpha > \alpha_{max}$ then the angle of rotation for the mobile FSO nodes are recalculated using one of the methods described in 2.2.1. And every 1ms it is checked if $\alpha > 1$. Here, $\alpha > 1$ means that the link is down.

3.2 Protocol B: Minimum SNR

In this protocol, every time the nodes exchange their information, the receiver node sees if its received Signal-to-Noise Ratio (SNR) is less than a preset threshold. If so, the receiver node recalculates the angular speed of its head. This design is particularly useful if quality of the FSO link is important. Let γ be the difference (in dB) between the received SNR of the receiver and the receiver's minimum required SNR (30dB) [1], and γ_{min} be the minimum allowed γ before recalculation of rotational speed is performed. At every t_x, γ is checked, and if $\gamma < \gamma_{min}$ then the angle of rotation for the mobile FSO nodes are recalculated. And every 1ms it is checked if $\gamma < 0$. A value of $\gamma < 0$ means that the link is down.

4. PERFORMANCE EVALUATION

To gain insight into effectiveness of our approach, we performed simulations using MATLAB. We randomly picked the initial positions and velocities of the nodes for each simulation run. We considered both laser and LED transmitters. For lasers, we used maximum range of R_{max}=2.5km and node speed between $0 - 25$m/s. Similarly, for LEDs, we used R_{max}=100m and node speed between $0 - 5$m/s. We observed the percentage of time the link was down for different values of the divergence angle θ (2-2.5 mRad for lasers, $3 - 7.5°$ for LEDs), α_{max} (0.25, 0.5 and 0.75) and γ_{min} ($2dB$, $4dB$ and $6dB$). For each t_x, we calculated average percentage of link down time over 100 simulation runs.

4.1 Finding Maximum t_x

We observed from most simulation scenarios that a small increase in t_x decreases the computation and communication overhead exponentially, which is because the number of times our protocol checks the status of the link is $1/t_x$. So, setting t_x correctly can save a lot of protocols' messaging overhead. We performed simulations to find out the maximum value of t_x for a minimum link up time, i.e., the percent of the time the link was up. For example, to find out the maximum t_x that can maintain the link up for 90% of the time (for a given α_{max} and θ), we first ran the simulation for $t_x = 1$ms. If the link was up for at least 90% of the link duration (time during which the nodes were within each others range), t_x was doubled and the simulations were rerun. This was repeated until the link up time was less than 90%. After this step, the average of the last two t_x values was tried. This binary search step was repeated until the link up time was within a predefined error of the target 90%, e.g., $(1 \pm .025) * 90\%$. The algorithm for finding the maximum t_x is shown in Algorithm 1.

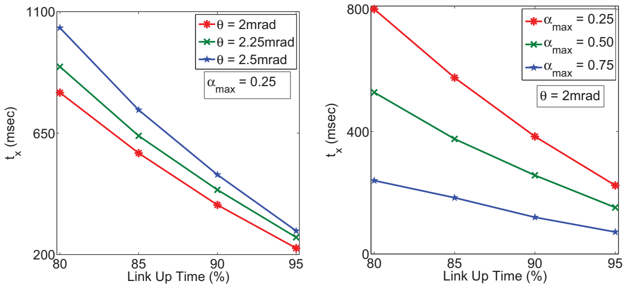
Algorithm 1 A binary search to find the maximum t_x required to maintain the FSO link at a target up time.

```
{Input Parameters}
mlink //percentage of link up time to be maintained
error //2.5% of mlink
{Return: Max $t_x$ to maintain the link at mlink uptime}
{Local Variables}
plink //average percentage of link up time
$t_x$ //period of information exchange
i //index of the values of $t_x$
Initialize $i = 1$, $t_x(i) = 1ms$, $t_{min} = 0$, and $t_{max} = 0$
Calculate plink of 100 simulation runs with $t_x(i)$
while plink > mlink do
    Set $i = i + 1$ and $t_x(i) = t_x(i-1) * 2$
    Calculate plink of 100 simulation runs with $t_x(i)$
end while
if plink <= mlink and i == 1 then
    return $t_x(i)$
end if
Set $i = i + 1$, $t_{min} = t_x(i-2)$, $t_{max} = t_x(i-1)$, and
    $t_x(i) = (t_{min} + t_{max})/2$
Calculate plink of 100 simulation runs for $t_x(i)$
while |plink - mlink|> error do
    if plink < mlink then
        $t_{max} = t_x(i)$
    else
        $t_{min} = t_x(i)$
    end if
    Set $i = i + 1$ and $t_x(i) = (t_{min} + t_{max})/2$
    Calculate plink of 100 simulation runs for $t_x(i)$
end while
return $t_x(i)$
```

4.2 UAVs with Lasers

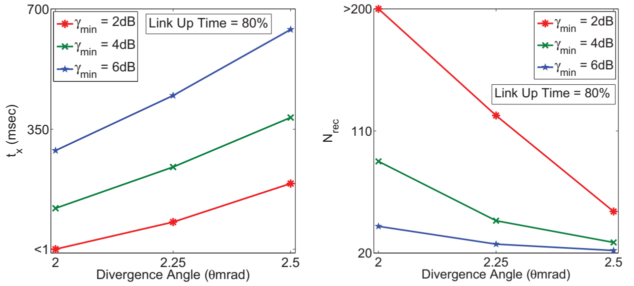
4.2.1 *Using Protocol A*

Fig. 4a shows how the maximum t_x behaves against the target link up time for various θ and a fixed α_{max}. We can observe that smaller t_x is required for attaining a higher link up time (or accuracy). Smaller t_x means more frequent information exchange between the nodes. For example, maintaining 80% link up time can be achieved with a t_x as high as 1.04s when $\theta = 2.5$ mRad. But for 95% link up time t_x has to be 3× lower at 288ms. Further, we can observe that t_x can be larger for larger divergence angles, e.g., for 90% link up time, t_x is 384ms when $\theta = 2$ mRad, but can be 496ms when $\theta = 2.5$ mRad. A larger θ with a fixed R_{max} (2.5km) provides a larger coverage area than a smaller θ. So, maintaining a target link up time with a larger θ is possible via smaller frequency of information exchange (or higher t_x) than that with a smaller θ. Fig. 4b shows how the maximum t_x behaves against the target link up time for various α_{max} and a fixed $\theta = 2$ mRad. We again observe that a smaller t_x is required for maintaining higher link accuracy. We can also observe that, required t_x is higher for smaller α_{max}. This is expected since a lower α_{max} value means that the recalculation of rotational speed is done for less deviation from the sender node's area of coverage. Thus, lower α_{max} yields more accurate calculation of angle of rotation and helps reducing frequency of information exchange.



(a) $\alpha_{max} = 0.25$ (b) $\theta = 2$ mRad

Figure 4: Effect of % Link Up Time Requirement on t_x



(a) t_x (b) Overhead

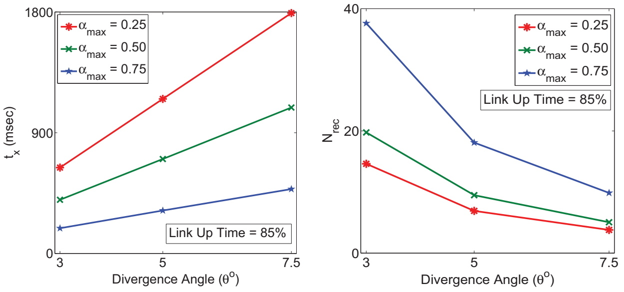
Figure 5: 80% link up time: Protocol B with Lasers

4.2.2 *Using Protocol B*

Fig. 5a shows the effect of θ and γ_{min} on t_x for maintaining the FSO link at least 80% of the time while the nodes are in each others coverage area. We can again observe that t_x is higher for larger divergence angles, and the required t_x is higher for higher γ_{min} similar to α_{max} of Protocol A. Fig. 5b shows the communication and computation overheads i.e., the number of recalculations (N_{rec}) of rotational angle for various θ and γ_{min} to maintain 80% link up time. We can observe that larger divergence angle not only helps reducing the frequency of information exchange, but also reduces the overhead. The same behavior can be observed for γ_{min}.

4.3 UAVs with LEDs

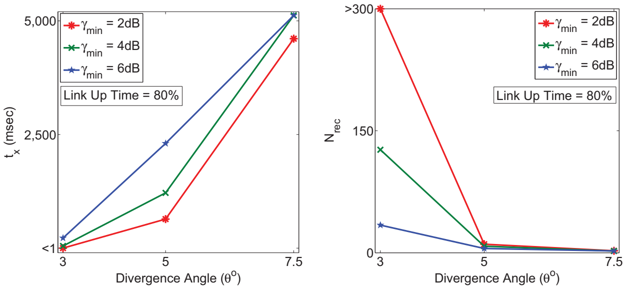
For LED transmitters, we observed behaviors similar to the lasers as well. Similar to lasers, Fig. 6 and Fig. 7 show that t_x is higher for larger divergence angle, for smaller α_{max} (for Protocol A) and larger γ_{min} (for Protocol B). Comparing Fig. 5 and Fig. 7, maintaining an FSO link with



(a) t_x (b) Overhead

Figure 6: 85% link up time: Protocol A with LEDs

a minimum SNR of 4dB requires about 30 recalculations of rotational angle, N_{rec} for lasers ($\theta = 2.5mrad$), while it requires about 10 recalculations for LEDs ($\theta = 7.5^o$) to maintain an 80% link up time. However, to maintain the same target SNR levels, the maximum period of information exchange, t_x, can be as large as 5 seconds for LEDs while about 300ms for lasers. This shows that Protocol B is clearly better suited for LEDs as they provide a higher quality transmission. However, when a similar comparison is made for Protocol A among LEDs and lasers, LEDs do not provide significant gains in terms of maintaining a target link up time (Fig. 4 and Fig. 6).



(a) t_x (b) Overhead

Figure 7: 80% link up time: Protocol B with LEDs

5. SUMMARY AND FUTURE WORK

We addressed the problem of maintaining an FSO link between two UAVs and proposed a novel scheme to overcome this problem. We considered two UAVs to be equipped with two mechanically steerable hemispherical heads, each of which are mounted with an FSO transceiver. Using the proposed algorithm to control the mechanically steered head mounted FSO transceivers, the nodes can maintain a communication link successfully. We outlined all possible cases for calculating the angular velocity and rotation direction of the nodes' heads so as to maintain the FSO link. We also presented two protocols for deciding when to recalculate the angular velocity based on the deviation of the receiver node from the transmitter's coverage region. We also proposed a method for selecting the time period of information exchange (t_x) between the nodes. In this work, we assumed the UAVs to be flying on straight lines only. We also assumed that the UAVs report perfect information (sensor readings from accelerometer, gyroscope, magnetometer) to each other regarding their orientation and velocity. But these readings may be erroneous due to atmospheric turbulence and vibrations. A promising line of future work is to extend the capabilities of the algorithm by considering UAVs/nodes flying on curved paths. We also plan to consider the effect of turbulence and vibration in the simulations. Furthermore, we plan to perform real testbed experiments to evaluate the effectiveness of the proposed method.

6. ACKNOWLEDGMENTS

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