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Crazyflie 2.1 Quadcopter Nonlinear System Identification

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Project Background

Quadcopters (quad) are used widely in many industry with crucial applications such as infrastructure inspection or package delivery. The Crazyflie 2.1 quad from Bitcraze provides an excellent platform for research and development. In this project, our goal is to perform system identification on the Crazyflie to propose a complete model. A gray box method is explored, which includes leveraging the parameters that are already known, to develop a set of equations. Through theory, simulations, and measurements, a complete quadcopter model is developed.

Problem Statement

- Develop system models to accurately predict flight dynamics (linear time invariant, and non-linear)
- Develop an improved battery supply model to account for voltage drop under full propellor load.
- Characterize the non-linear motor/propellor thrust coefficient (C_T), including sensitivity analysis

Project Scope

- To linearize the quad over hover from nonlinear equations, Mason's gain rule is explored to find the transfer function of the closed loop system and implemented with Python.

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix}_e = \begin{bmatrix} c\theta c\psi u_b + (s\phi s\theta c\psi - c\phi s\psi)v_b + (c\phi s\theta c\psi + s\phi s\psi)w_b \\ c\theta s\psi u_b + (s\phi s\theta s\psi + c\phi c\psi)v_b + (c\phi s\theta s\psi - s\phi c\psi)w_b \\ -s\theta u_b + s\phi c\theta v_b + c\phi c\theta w_b \end{bmatrix}$$

$$\frac{d}{dt}\begin{bmatrix}\delta z\\ \delta w\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta z\\ \delta w\end{bmatrix} + \begin{bmatrix}0\\ 1/m\end{bmatrix}\delta F_z$$

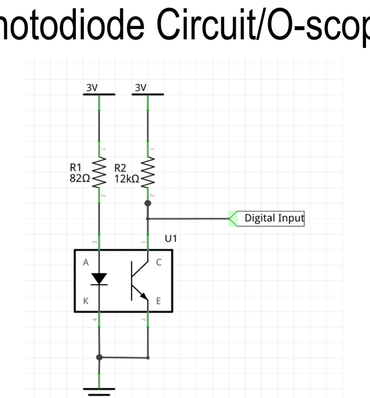
$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix}_b = \begin{bmatrix} g\sin\theta + rv - qw \\ -g\sin\phi\cos\theta - ru + pw \\ \frac{C_T}{m}\sum_{i=1}^{4}\omega_i^2 - g\cos\phi\cos\theta + qu - pv \end{bmatrix}_b$$

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix} p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ q\cos\phi - r\sin\phi \\ q\sin\phi/\cos\theta + r\cos\phi/\cos\theta \end{bmatrix}$$

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = \begin{bmatrix} \frac{1}{J_{xx}}(\tau_x + qr(J_{yy} - J_{zz})) \\ \frac{1}{J_{yy}}(\tau_y + pr(-J_{xx} + J_{zz})) \\ \frac{1}{J_{zz}}(\tau_z + pq(J_{xx} - J_{yy})) \end{bmatrix}$$

- To model a step response, only the position and velocity in the z direction matter. Hence the state variables z and w are analyzed.

- Motor Characterization:
  1. Set up the photodiode/resistor circuit and connect it up to an o-scope, voltage generator, and scale. Increase voltage and record appropriate values.
  2. To specifically find resistive and inductive vales, directly hook up the motor to the RLC meter and record the various values at a desired frequency.
  3. Sensitivity of a certain parameter is found by increasing the current value by a percentage.
- Photodiode Circuit/O-scope Set Up:



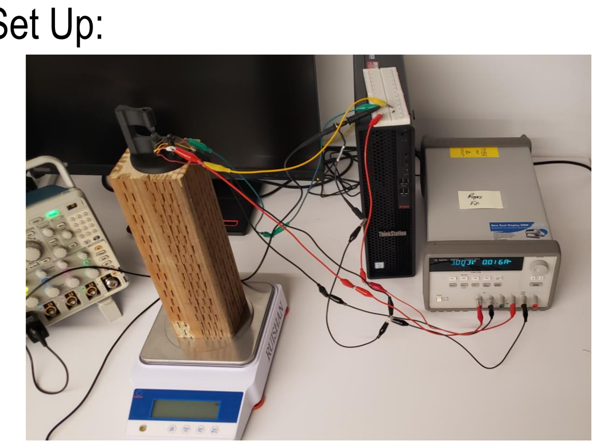
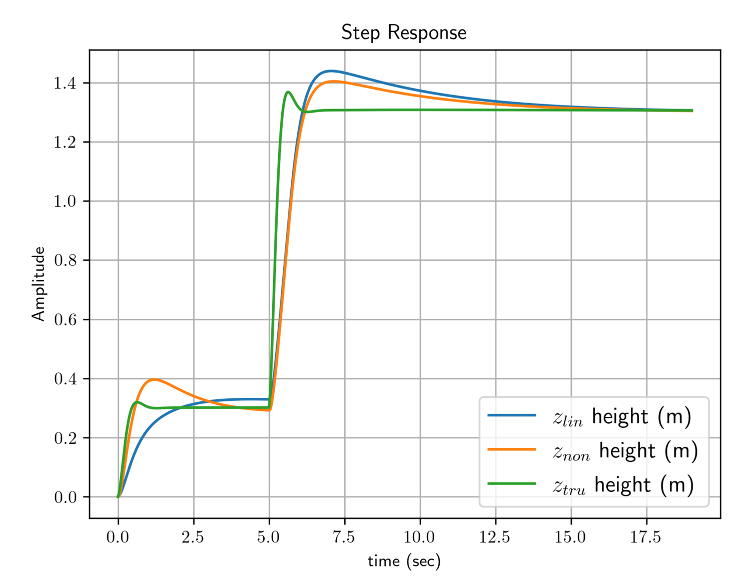


Image courtesy of Bitcraze[1]

- To find a good model for the nonlinear time variant 250 mAh, 3.7V, Li-Po battery cell, an extensive literature review is performed with an acceptable implementation to the Crazyflie quad system.

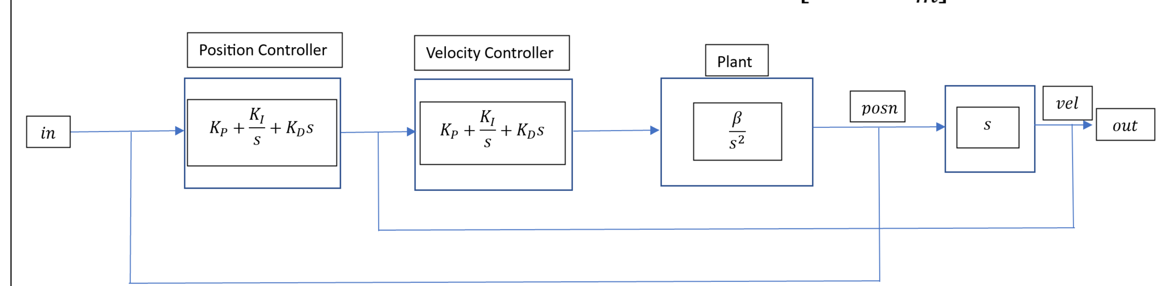
Image courtesy of Bitcraze[1]

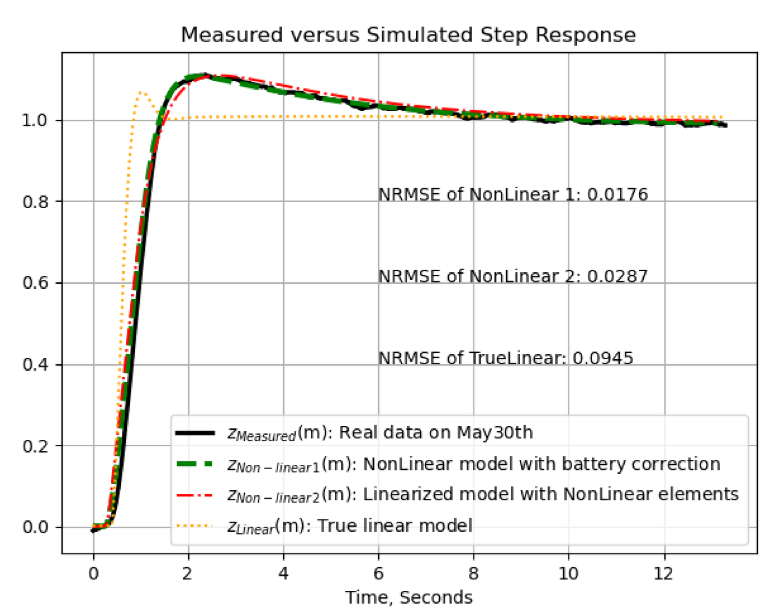
Designing a truly linear model



- There are significant discrepancies in the 3 simulated models.
- The same cascaded PID controllers are used for non-linear, partially linear, and true linear control.

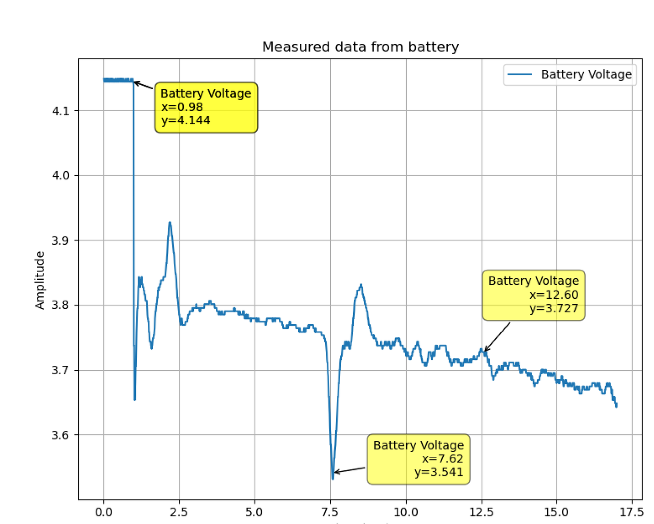
$$\beta = 4\left[(2C_T\omega_h)\frac{1}{m}\right] \times 0.04077 \times 1000$$



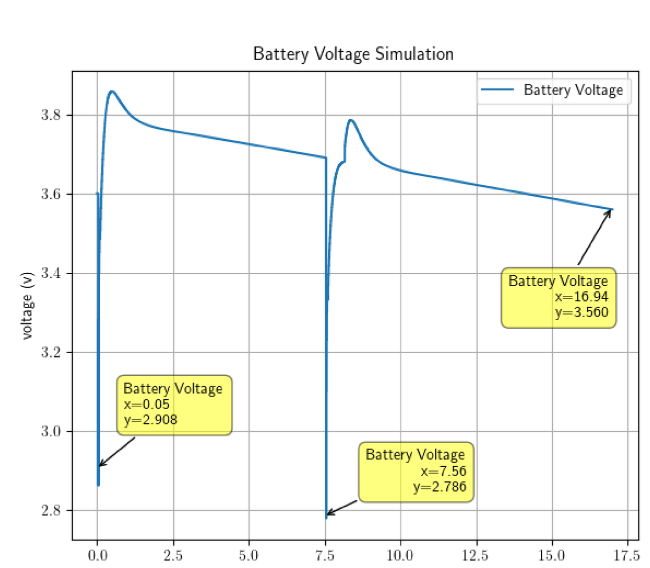


- Models are compared using a normalized root mean square error (NRMSE) method.
- Notice improvement in fit as model complexity increased.

Battery behavior modeling

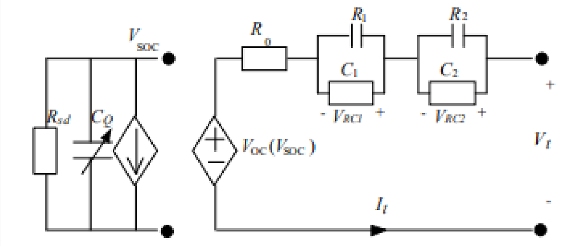


- The measurement shows 3 interesting points:
  - The battery open circuit voltage (OCV) of 4.1 [V] dropped to the Nominal Voltage of 3.7 [V] under load.
  - Notice the sharp voltage drop when the quad accelerates at 7.5 seconds.
  - Voltage decay as quad remains in hover.



- The simulation also shows compelling information:
  - Average PWM values with a decaying slope can capture the steep voltage changes and self-discharge trend.
  - Lack OCV and hover point voltage dynamics.
  - Lack complexity.

Battery Equivalent Circuit Model (ECM)



$$\begin{cases} \dot{V}_{SOC} = \frac{-V_{SOC}}{R_{sd}C_Q} + \frac{1}{C_Q}I_t \\ \dot{V}_{RC1} = \frac{-V_{RC1}}{R_1C_1} + \frac{1}{C_1}I_t \\ \dot{V}_{RC2} = \frac{-V_{RC2}}{R_2C_2} + \frac{1}{C_2}I_t \\ V_t = V_{OC} + R_0I_t + V_{RC1} + V_{RC2} \end{cases}$$

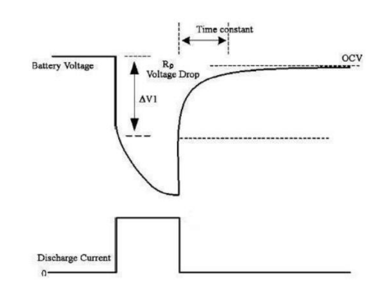
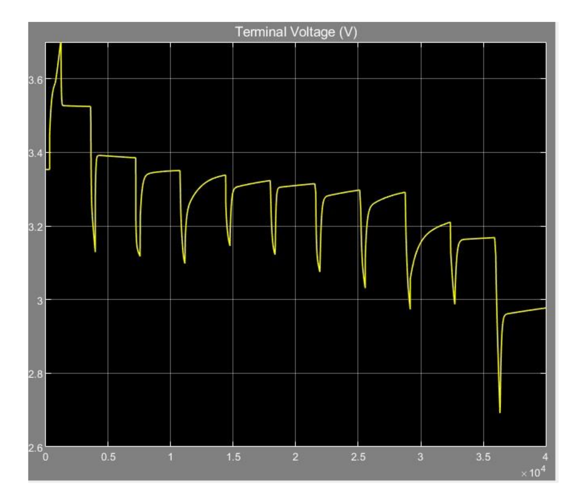


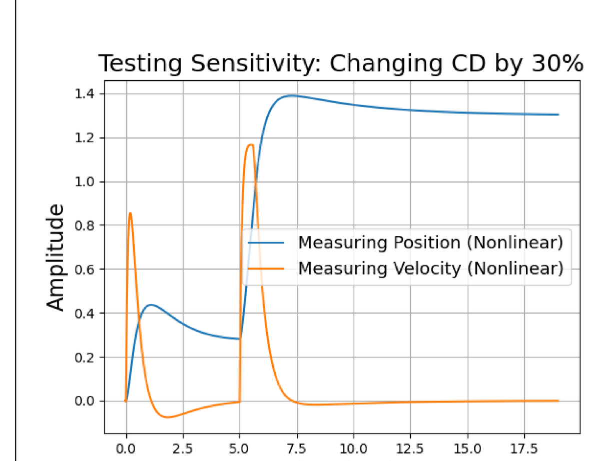
Image courtesy of Mathworks[2]

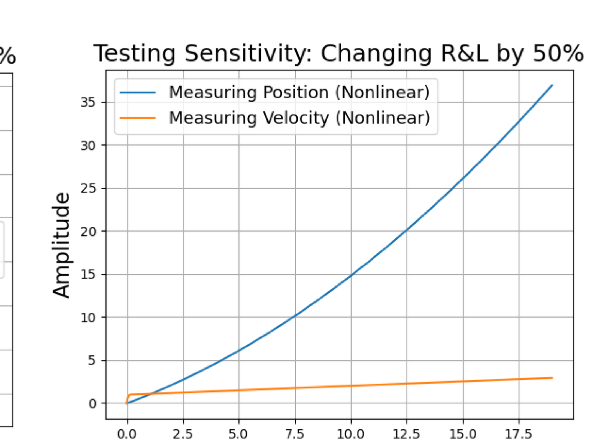


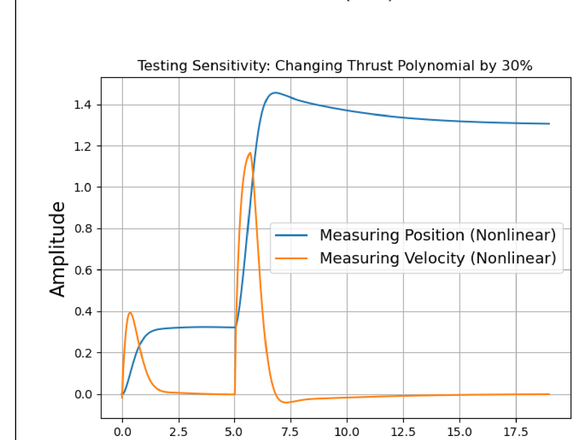
- The ECM proposed in [2] [3] serves as a good generalization for lithium cell battery modeling.
- Simulation results from MATLAB & Simulink show the key battery dynamics.
- Future work:
  - Identify accurate circuit parameters (resistors and capacitors) to apply to the model with fast time constant responses.
  - Identify the dependent current source relationship with the State-of-charge voltage (Vsoc) on our system.
  - Investigate different circuit topologies to model the overshoot dynamic in the charge cycle during a step.

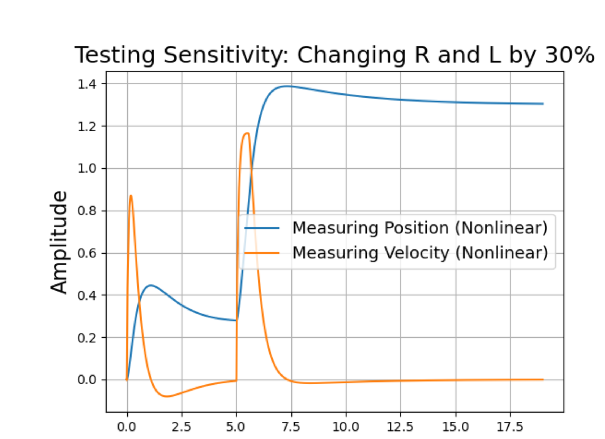
Sensitivity of different characterization constants

- From the sensitivity findings, it can be concluded that the parameter that exhibits the highest sensitivity is thrust.
- After a certain point, all parameters will affect the model.
- Adjusting the constants will adjust the poles on the s-plane. So, past a certain value, the constants will drive the model to instability.
- What's Next:
  - A major next step is to include all dynamics into the mix, for true 3D motion.



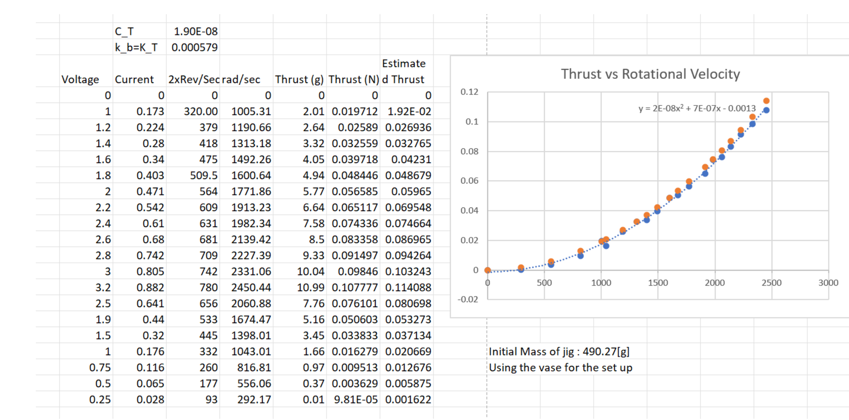




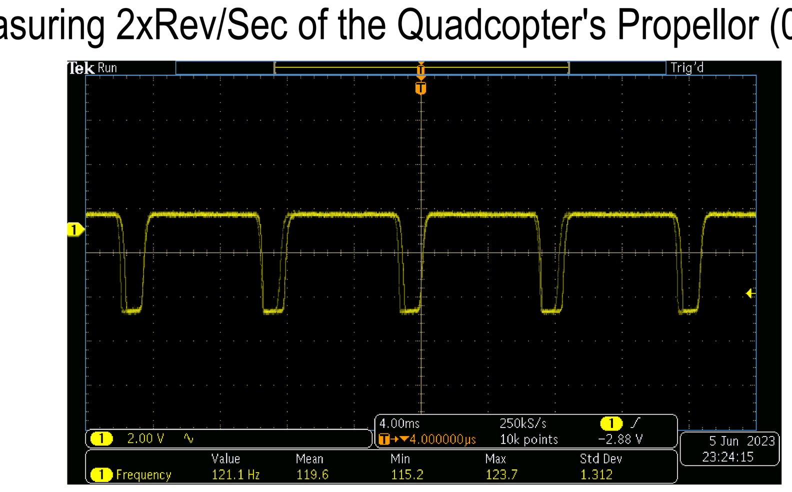


Datasheet Measurements

- Measuring Thrust Polynomial:



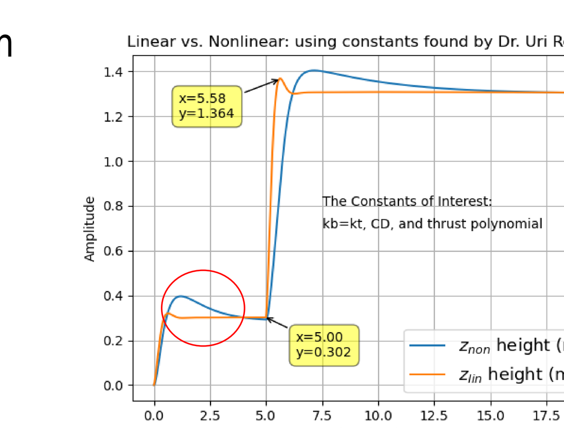
- Measuring 2xRev/Sec of the Quadcopter's Propellor (0.35[V]):

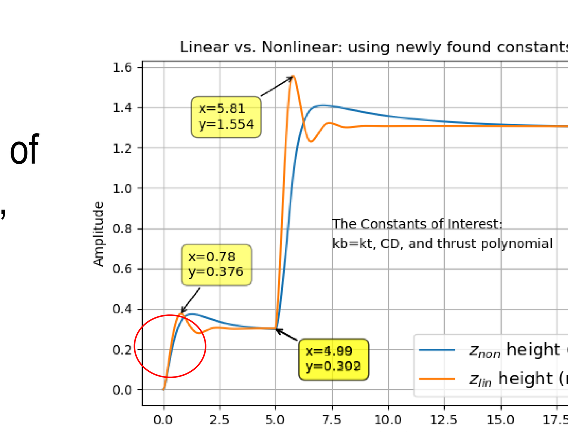


- One of the biggest challenges to overcome was obtaining a signal that has the least amount of noise.
- Wire connections must be separated from the scale to prevent EM noise and access good instrumentation is necessary.

Simulated linear model from newly found constants

- Notice the discrepancy in using the previously defined constants when the quadcopter is at 0.3[m].
- The tradeoff with using the constants developed by us is the overshoot when attempting to go up to 1[m].
- The constants that were of focus to us were: kb (kt), CD, R, L, and the thrust polynomial.





What we learned

- While simple in theory, the transfer functions was arduous to obtain and implement correctly to our system. The true linear model can capture the essential yet not accurate dynamics of the quad.
- The Non-Linear model is 2x better than the Partial Linear and 4x better than the True Linear model.
- The Non-Linear Time Variant battery is challenging to model, but the current model can show the essential changes during the flight.
- The Linear model's accuracy increased at 0.3[m]. However, a drop of accuracy at 1[m] is observed with updated constants.

Citations

1. Tobias, "Measuring propeller RPM: Part 1", *Bitcraze*, 2015.
2. Tarun H. et al., "Simplified Extended Kalman Filter Observer for SOC Estimation of Commercial Power-Oriented LFP Lithium Battery Cells", *MathWorks, Inc*, 2013.
3. Carlo T., Simona O., "State of Charge Estimation Using Extended Kalman Filters for Battery Management System", *Stanford*.

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