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# MULTI-LEVEL FINE POINTING TEST-BED for SPACE APPLICATIONS

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## ABSTRACT

For space applications that need high accuracy pointing of the payload, fine pointing system is an indispensable tool. To reach high level of high accuracy pointing and tracking, proper synchronization between the attitude of the satellite and each stage of the pointing module should be considered. This study focuses on developing and demonstrating staging control for fine pointing system. Currently, an experimental model for multi-stage control has been built in the laboratory to be used as a testbed and a teaching tool to validate the control strategies. This paper gives a brief introduction of the study, experimental model design criteria and staging control strategy. An example of a controller synthesis for multi-stage actuators based on  $H_\infty$  is also presented.

## INTRODUCTION

Fine pointing mechanism (FPM) is a sub-system in spacecraft which contains group of actuators, sensors working together in order to achieve high precision pointing attitude control for various types of payloads. The capability to point and track with high precision is an essential requirement for many types of space missions. For example, in case of laser optical telecommunication terminal between ground-space or space-space [9], formation flying interferometer [7], remote sensing satellites or exoplanet observation [10].

Despite there are various types of high precision actuators currently available in the industry, it is still not possible to achieve fine pointing and tracking performance requirements by using only single actuator. This is due to the fact that each actuator resolution, saturation level and operation bandwidth are limited. From this reason, multiple actuators are needed to be combined and synchronized in an appropriate way in order to satisfy high precision goals. From literature reviews, most of the researches on multi actuator precision pointing control are dedicated to the control of hard disk drive read-write head servo mechanism. For hard disk drives, in order to have higher data density, the read-write head must be able to search and follow very narrow data tracks ( $\approx 1\mu\text{m}$  [3]). Dual-stage control with voice coil motor (larger travel range, slower response, lower accuracy) as a primary actuator and a complement piezo actuator (shorter range, faster response, higher accuracy) connected in series is widely used for this type application. Moreover, applications of multi-stage actuators are also found in those ultra high precision alignment machine in the semiconductor industry [6], camera stabilization system [11], positioning - feeding manipulators [5], [14] and opto-mechatronic system [13].

For the framework of this study, we present an experimental testbed that is built in the laboratory in order to demonstrate staging control strategies. Assume a space mission for small satellite that

fine pointing and orientation of the payload is one of the requirement ; ex. exoplanet observer camera, laser communication terminal, etc. ; where attitude of the satellite can be adjusted to maintain pointing orientation. In this case, it is possible to use the attitude control of the satellite itself as a coarse actuator where another finer, faster actuator works in complement to suppress disturbances or vibrations caused by environment or other payloads.

To demonstrate this proposed system, a friction-free rotary platform with a reaction wheel is used to represent a satellite and its attitude control system. A voice coil motor (VCM) is mounted on top of the platform to be the fine pointing actuator. More details are given in the following section.

## TESTBED MODEL

The experiment model is designed as a testbed to demonstrate multiple types of fine-pointing strategy for space applications (the model is shown in figure 1). In the first phase of this study, staging control will be demonstrated by using a reaction wheel as a coarse actuator and a VCM is used as a fine pointing actuator. Laser module is then fixed on the fine pointing actuator to represent the payload. Linear array sensor is used to detect the laser position to get the system feedback. Design consideration for each components are as followings;

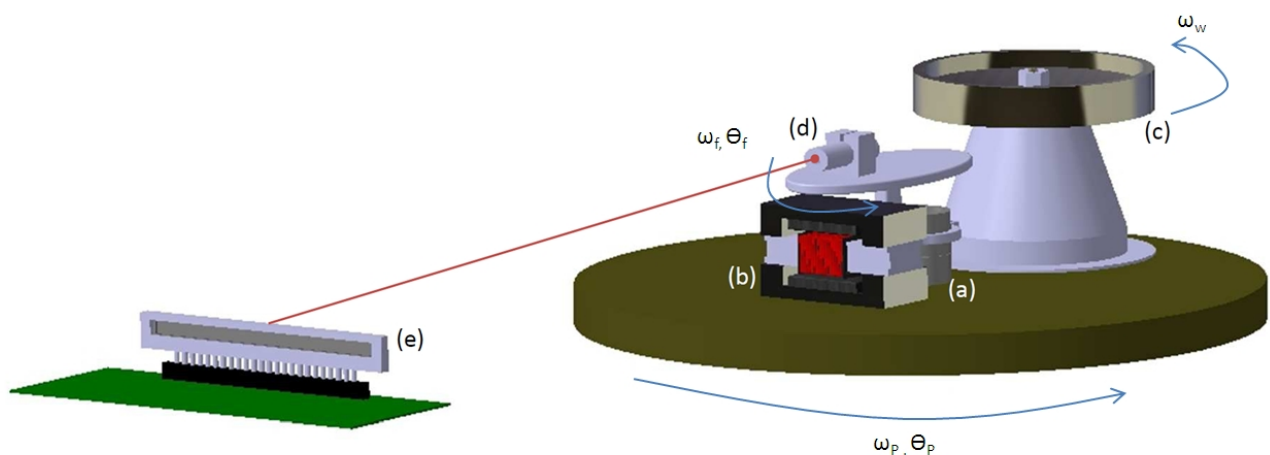


Figure 1: Experimental model (a) Pivot bearing; (b) VCM; (c) Inertia wheel; (d) Laser module; (e) Linear array sensor

- *Reaction wheel* : The coarse pointing state is done by using the transfer of momentum from a reaction wheel. This wheel will be driven by 24V brushless DC motor.
- *Pivot bearing* : Preloaded pivot bearing is used in the system as an axis of the fine pointing state in order to overcome the friction force. When idle, the fine pointing actuator has to counteract the spring torsion load from this bearing. The size of the pivot bearing has to be chosen according to available actuator torque since too large counteracting torque will result in poor control response. In this model, the preloaded bearing has a torsional spring rate of 0.37 Nm.
- *Voice Coil Motor (VCM)* : VCM is a kind of DC motor that consists of the coil (attached to the movable load) that moves in magnetic field. VCM is chosen as a fine pointing actuator for this testbed because its high resolution of micro-radian scale (the resolution also depends mainly on quantization of the actuator input from the controller). VCM has an advantages of its ease of controlling as its torque is directly proportional to the current in the coil. In comparison with piezoelectric actuator or magnetic actuator, VCM also gives longer stroke. In this experiment,

the voice coil actuator must be capable of generating sufficient torque to counteract the pivot bearing. The VCM that is selected has the peak torque at 1.85 Nm with 0.798 Nm continuous torque with no backlash and low hysteresis effect. Its travel angle is  $\pm 3.75^\circ$ .

- *Laser module* : Laser diode is used to indicate the pointing direction. Red light laser with 700 nm wavelength was chosen for this experiment since it is the visible wavelength that is closest to the peak of photodiode spectral responsivity.
- *Linear Array Sensor* : The optical sensor array is used to acquire the feedback of the fine pointing. The sensor array selected to use in this experiment is a 1280 x 1 pixel optical sensor array with 400 dpi resolution (63.5  $\mu$ m pixel center-to-center spacing). According to the output voltage of the sensor given in equation 1.

$$V_{out} = V_{dark} + (R_e)(E_e)(t_{int}) \quad (1)$$

where  $V_{dark}$  is an output voltage when there is no light on the sensor,  $R_e$  is the device sensitivity for a given light wavelength,  $E_e$  is the incident irradiance and  $t_{int}$  is integration time for the sensor to collect light on each pixel. According to this relation, with our current laser power and model setup which the position detection is done through an analogue threshold detection circuit, the sensor sampling time (function of  $t_{int}$ ) could be reduced to 0.2ms. With respect to the pixel size, the angular resolution of the sensor can be calculated. The sensor is located at 5m from the model, the angular resolution that can be detected will be  $\approx 3$  arcseconds.

Inertia wheel	Wg : 315g, diameter : 99 mm, $J_w = 0.00012 \text{ kgm}^2$
Platform	$J_p = 0.0124 \text{ kgm}^2$
Inertia wheel motor	ESCAP 23HV48-216 ( $K_w = 23.5 \text{ mNm/A}$ , $R_w = 9.7 \Omega$ )
VCM	BEI RA54-18-000A, Continuous torque = 798 Nmm ( $K_v = 0.741 \text{ Nm/A}$ , $R = 12.5 \Omega$ , $L = 0.011 \text{ H}$ , $K_{emf} = 0.74 \text{ V}/(\frac{\text{rad}}{\text{s}})$ , $J_f = 8 \times 10^{-5}$ )
Pivot bearing	Torsional spring rate = 368.5 Nmm/deg.
Laser module	700nm, 2mW (Class I)
Line array sensor	TAOS TSL 1410R

Table 1: Components list

## SYSTEM MODELING

The model is integrated according to the diagram in figure 1. A DC motor rotor is connected to the reaction wheel and spins it with an angular velocity  $\omega_w$ . An angular momentum  $L_w$  created by the reaction wheel is then transferred to the platform and makes angular displacement  $\theta_p$  with angular velocity  $\omega_p$ . This platform angular displacement is measured by a potentiometer mounted on the axis.

Next, a voice coil motor with laser pointer on top is fixed on top of the platform. It moves the pointer module with an angular velocity  $\omega_f$  and an angular displacement  $\theta_f$ . The laser pointer is pointing toward the array sensor which measures angular displacement output of the system. The measurement by the array sensor is  $\theta = \theta_p + \theta_f$ .

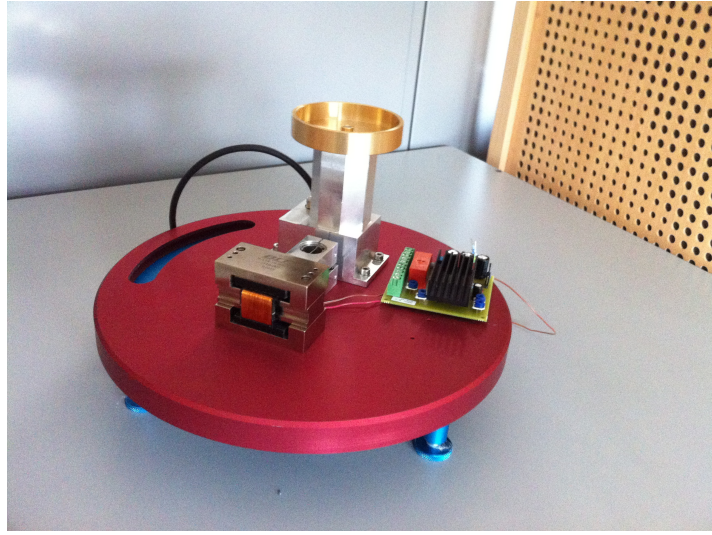


Figure 2: Model built in the laboratory

Hence, the system can be separated into two parts, the coarse pointing which is done through the movement of the platform due to the reaction wheel and the fine pointing by the VCM. The diagram of the coarse pointing can be shown as in 3.  $R_w, L_w, K_w$  are the motor parameters for resistance, inductance and torque constant respectively.  $V$  is the motor voltage input,  $J_w$  is the inertia of rotor axis with inertia wheel and  $J_p$  is the inertia of the platform.

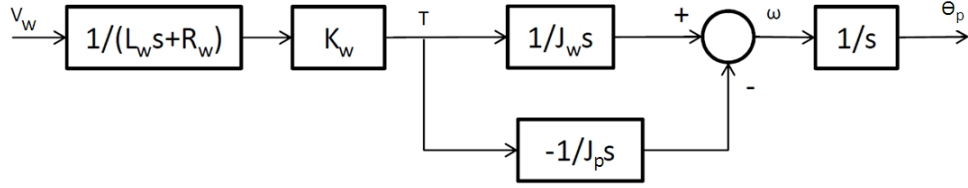


Figure 3: Coarse pointing actuator

Fine pointing is done by VCM actuator. The dynamic equation for fine pointing can be expressed in equation 2.

$$J_f \ddot{\theta}_f = T_f - T_p \quad (2)$$

where  $J_f$  is the inertia of the moving part of the VCM attached with laser pointing module;  $T_f$  is the torque from VCM actuator and  $T_p$  is the counteract torque from preloaded pivot bearing. In this case, as the model consist of preloaded bearing, the torque friction could be neglected. The electrical model of the VCM can be expressed in equation 3.

$$V_{VCM} = RI_f + L_f \dot{I}_f + e_m \quad (3)$$

where  $V_{VCM}$  is the voltage input to the coil,  $I_f$  is the coil current,  $L_f$  is the coil inductance and  $e_m$  is the back electromotive force which is proportional to the angular rate with constant. The torque produced by VCM can be written as  $T_f = K_f I$ .

with the relations above, the block diagram of the VCM can be shown in 4.

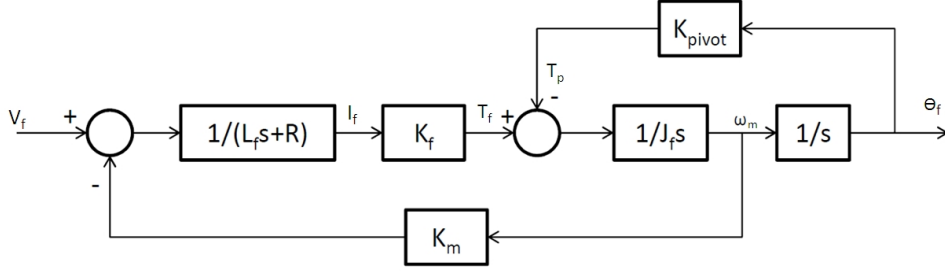


Figure 4: Fine pointing actuator (VCM)

In this model, two measurements,  $\theta$  and  $\theta_p$  are available for the feedback. Therefore, feedback loop can be provided on each actuator. Since the VCM is mounted on top of the platform, the movement introduced by VCM will have some coupling effect on the platform which is needed to be identified. The block diagram with controllers  $C_c$ ,  $C_f$  can be shown as in figure 5.

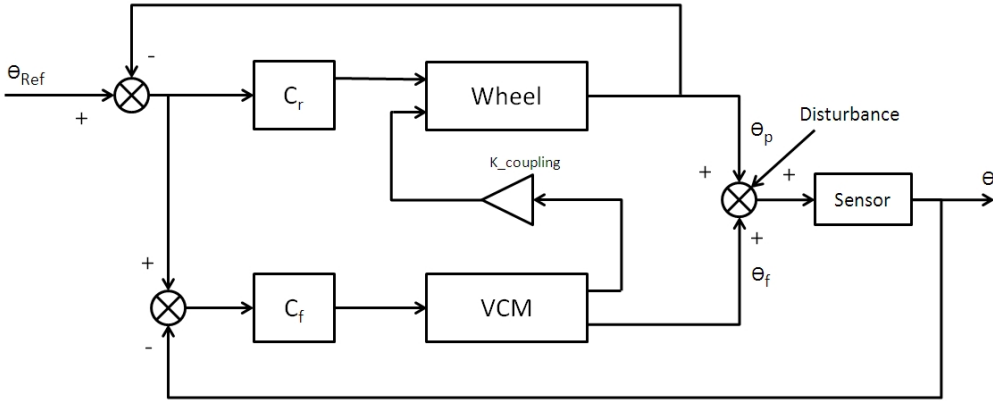


Figure 5: Closed loop control with two feedbacks

## CONTROL CONFIGURATION

The objective of this study is to implement staging control in order to minimize tracking error. The baseline strategy is to use coarse pointing state to primarily track the angular reference while the fine pointing helps to compensate the perturbation and error in the high resolution and high frequency bandwidth zone.

Researches on controlling of multi-stage actuators have been conducted continuously in this decade. Numbers of control strategies had been reported. [12], [8] had reviewed conventional approaches to design cascade controllers based on diverse configurations where each controller is defined based on the the shape of their frequency characteristics. Observer based LQR/LQG controller for dual-stage servo control had been introduced in [4]. Another approach which has been recently developed is the composite nonlinear feedback control which can be seen in [14].

For this paper, the  $H_\infty$  loop shaping controller design technique is chosen, since its ease to ensure the close-loop robustness. An example of  $H_\infty$  loop shaping for dual-stage actuator can be found in [1]. In addition to classical  $H_\infty$  approach, the newly developed fixed structure  $H_\infty$  synthesis [2] is used in this study with helps of the toolbox `hinfstruct()` in MATLAB. By this approach, the structure of the controller resulting from  $H_\infty$  synthesis can be defined which makes implementation in the real system to be more practical.

For the guideline of controller design, the model for  $H_\infty$  analysis is shown in figure 6. Two exogenous input  $\theta_r$  and  $\theta_c$  with four exogenous outputs  $z_{er}$ ,  $z_{ef}$ ,  $z_{ur}$  and  $z_{uf}$  are augmented into the system. Reference models for coarse and fine actuators are used to help in angular position tracking for each actuator loop where  $z_{er}$ ,  $z_{ef}$  outputs are weighted in order to penalize the errors between the reference and actual outputs.

Weighing filter  $W_c$  is shaped as a high pass filter and placed on the disturbance input to attenuate the low frequency disturbances.  $z_{ur}$ ,  $z_{uf}$  outputs are used to weight the control input for the coarse stage actuator (reaction wheel) and the fine stage actuator (VCM) respectively.  $W_{ur}$  and  $W_{uf}$  are placed to define frequency separation between each actuator. In this case,  $W_{uf}$  is a high pass filter since the attenuation at low frequency should be set according to the objective that the VCM should response in the high frequency. For the coarse actuator, as its dynamic is already slow, the shape of  $W_{ur}$  is set as a constant.

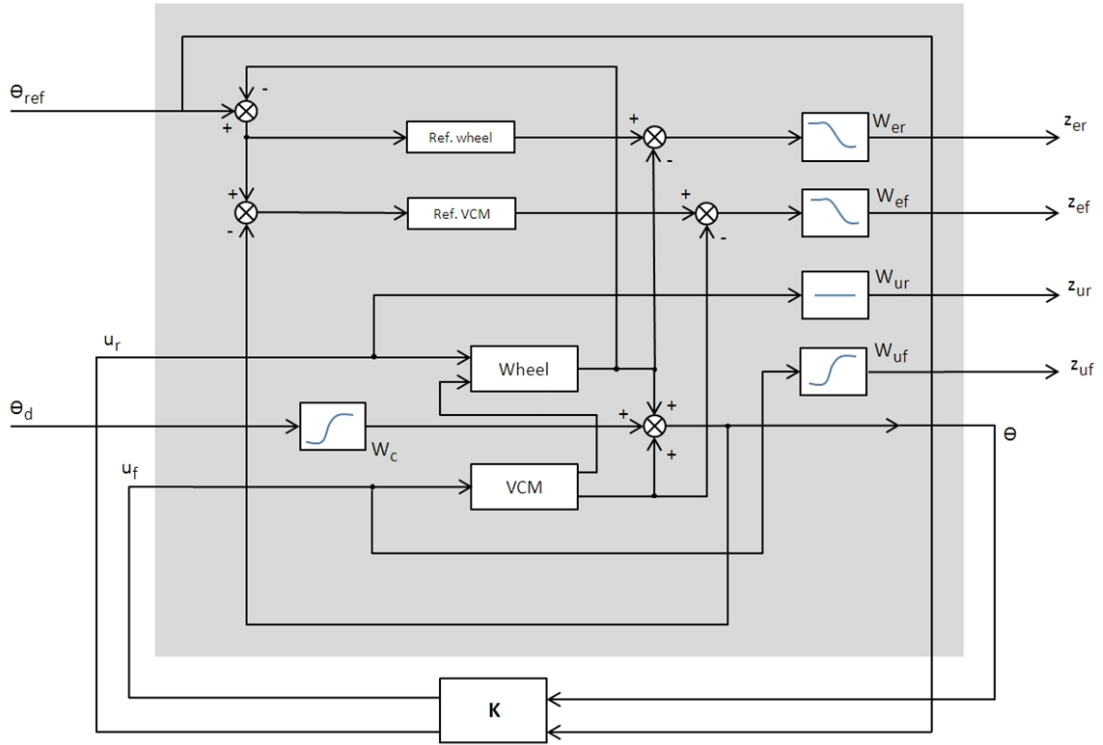


Figure 6: Augmented system with weighing functions for  $H_\infty$  analysis.

## SIMULATION

In this first stage, as the testbed is still not fully integrated, the reaction wheel and VCM model for simulation was set based on the available parameters (see table 1). The weighing filters were set as,  $W_c = \frac{0.5s+1}{0.3s+1}$ ,  $W_{uf} = \frac{s+0.1}{0.5s+125}$ . Figure 7 shows the response of the system to step input. In term of disturbance rejection, a sinusoidal disturbance signal  $\sin(2\pi t)$  is fed into the system, started at  $t = 2.5$ . The response shows that the fast response of the fine actuator helps the system in reducing the rise time (as fast as the speed of VCM) and helps the system to reject disturbance. However, there still rest some effects of overshoot. From this simulation case, when effected by disturbance, the system could keep the bound of the error as low as 0.002 deg.

Figure 8 shows the response of the system with the mixed sinusoidal reference input of  $2\sin(t) + 0.2\sin(10\pi t)$ . It can be seen that the reaction wheel mainly tracks the low frequency reference where VCM follows the higher frequency.



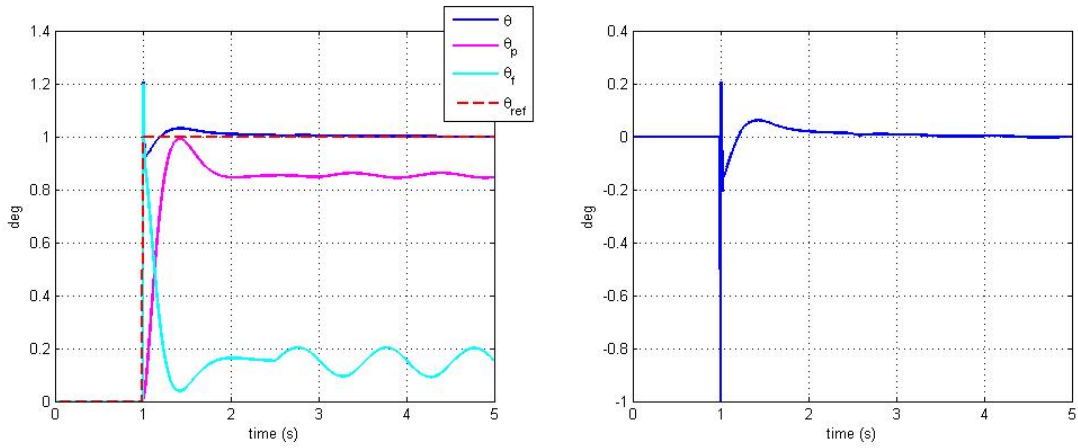


Figure 7: Left: System and actuators response to step input ( $t_r = 0.003$  s), Right: Error from step response

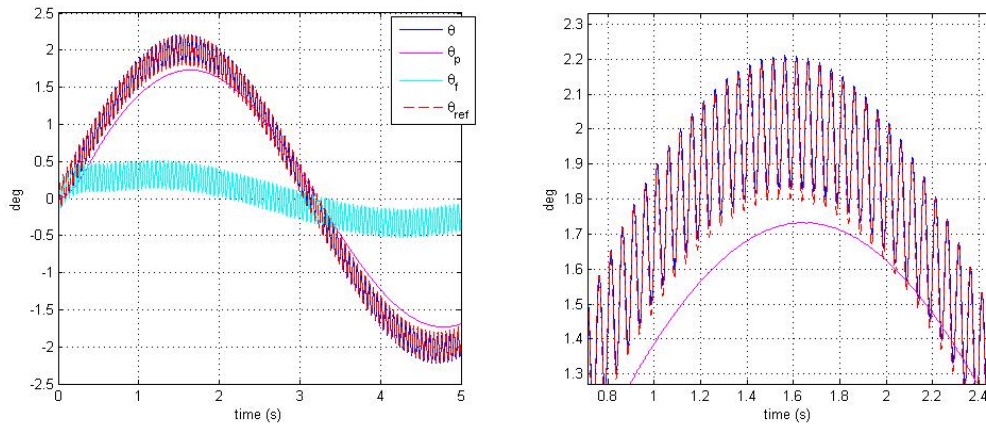


Figure 8: Response to sinusoidal input

## CONCLUSIONS AND FUTURE WORKS

This paper gives the details of the testbed for multi-stage control for space application. A guideline on controller synthesis based on  $H_\infty$  loop shaping is presented and simulation result is shown. Currently, the testbed model is being built in the laboratory. After the testbed model is completed, the simulation will be validated by experiment result. This model will be used as a teaching tool in the laboratory. In the future, multiple testbeds with the same type platform will be developed in order to illustrate further control designs (ex. centralized, decentralized) problem.

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