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Robust feedforward-feedback control of a hysteretic piezocantilever under thermal disturbance

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Abstract: In micromanipulation, piezoelectric cantilevers are commonly used in grippers performing pick-and-place of micro-objects. Indeed, these materials offer high accuracy and high speed. On the one hand, when working with large electric field, the behavior of the piezocantilevers provides hysteresis nonlinearity reducing their performances. On the other hand, the temperature variation of the workspace influences the accuracy. In this paper, a feedforward control is used to linearize the hysteresis and a robust feedback controller is implemented to reject the thermal disturbance. The former is based on the inverse Prandtl model while the second on the H_∞ robust control.

Keywords: Piezoelectric cantilever, hysteresis, Prandtl inverse model, temperature effect, H_∞ control.

1. INTRODUCTION

Piezoelectric materials are very used in micromanipulation due to their high resolution and rapidity. One of their applications is the piezoelectric microgripper which is made up of two piezoelectric cantilevers (piezocantilevers) [1]. They are used to pick, transport and place micro-object very accurately (Fig. 1).

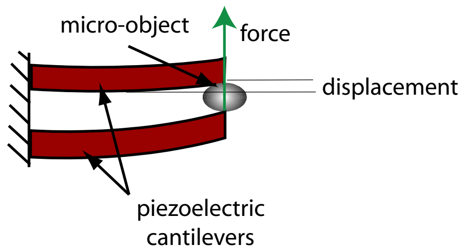

Fig. 1. A piezoelectric microgripper which manipulates a micro-object.

When large electric fields are applied to the piezocantilevers, the hysteresis nonlinearity becomes non-negligible. This indeniably reduces the accuracy of the micromanipulation task. To reject the effect of the hysteresis, open loop and closed-loop techniques have been proposed.

In the open loop technique (feedforward), the hysteresis is first modeled. Then, the calculated model is inverted and put in cascade with the piezocantilever in order to have a linear system. Such technique necessitates a precise model. The Preisach model is the most accurate [2][3] but due to its complexity, this model and its inverse need high computing memory and power. Another used model is the Prandtl model [4]. Not only it gives an enough accuracy but the implementation is also easy. However, when subjected to a disturbance, the feedforward technique is not suitable and closed-loop methods should be used.

In the closed-loop techniques [5][6][7], feedforward-feedback and feedback methods are applied. The feedforward-feedback method is based on a feedforward technique for cancelling the hysteresis and a feedback linear controller. In the feedback method, a linear approximate model is used to model the nonlinearity and to design a linear controller.

Besides the hysteresis, the accuracy of a micromanipulation task is also strongly influenced by the environment conditions, notably by the temperature. In our previous works [8], it has been demonstrated that a temperature variation of 10° could generate a displacement error more than $10\mu m$ in a micromanipulation system. A linear robust controller has been proposed to reject the thermal effect. However, when the applied electric field (and then the deflection) becomes large, the hysteresis of the actuator must be taken into account as well as the thermal disturbance.

In this paper, a feedforward-feedback controller is proposed in order to cancel the hysteresis and to reject the thermal disturbance. While a Prandtl inverse model is used for the feedforward compensator, a H_∞ control is implemented for the feedback controller. The paper is organized as follow. The influence of the temperature on the

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piezocantilever is presented in the second section. Then, the third section presents the modelling of the hysteresis and the implementation of the feedforward compensator. Finally, the H_∞ robust controller is detailed in the last section.

2. OPEN-LOOP ANALYSIS

In this section, the influence of the temperature variation in a piezocantilever is analyzed. The experiments (Fig. 2) were performed with a bimorph piezocantilever made up of a piezolayer and a Cupper layer. The sizes are: total thickness of $0.3mm$ (where $0.2mm$ is for the piezolayer), width of $2mm$ and length of $15mm$. A DSpace board and a computer material were used to supply the signal while a keyence sensor laser ($10nm$ resolution and $0.5\mu m$ accuracy) for the measurement. Finally, while a spotlight is used to vary the working temperature, a thermocouple measures it.

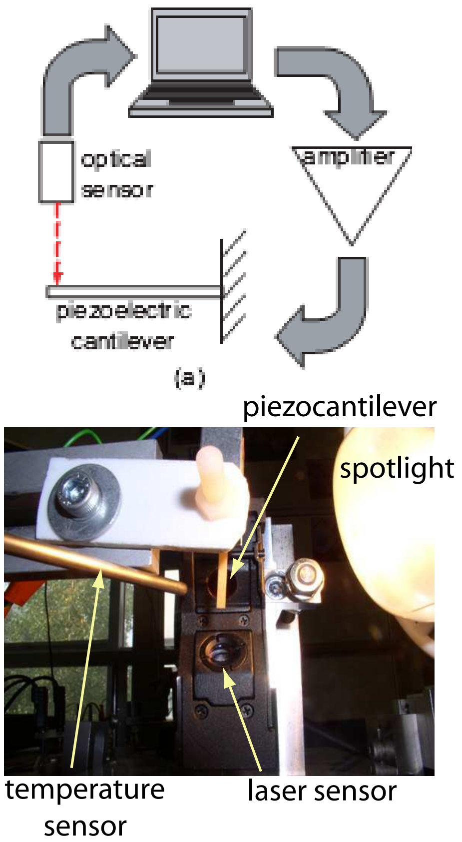

Fig. 2. The experimental setup.

First, the thermal effect on the transient part is analyzed. For that, a step voltage with $40V$ of amplitude is applied to the piezocantilever. It appears that for two environmental temperatures ($T = 22°$ and $T = 32°$), the transient part of the cantilever is unchanged (Fig. 3).

The second experiment consists in regarding the effect of the temperature when we apply the step voltage and observe the deflection more than $3min$. It appears that the creep phenomenon is highly amplified (Fig. 4). While with $T = 22°$ the creep is negligible, its amplitude is important with $T = 32°$. Such drift largely decreases the accuracy of a micromanipulation system and should be rejected.

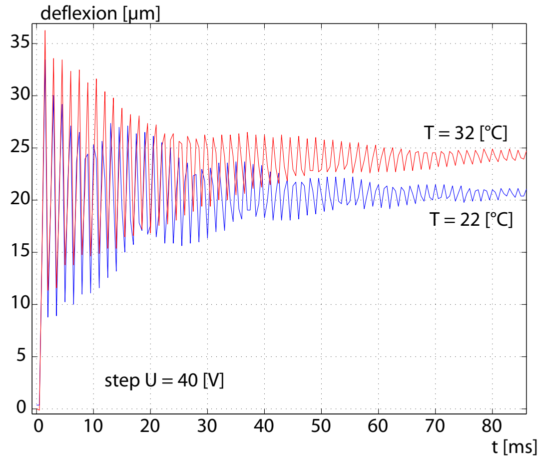

Fig. 3. The temperature does not affect the transient part.

The fact that the creep is amplified when the temperature increases is well known in mechanical engineering.

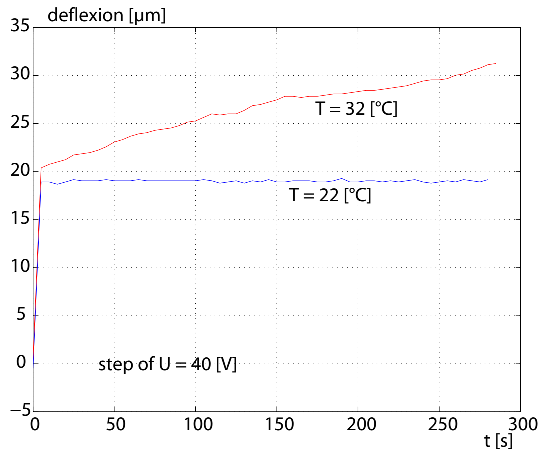

Fig. 4. The amplitude of the creep is amplified by the temperature.

Finally, the influence of temperature on the hysteresis is observed. To perform that, a sine voltage of $1Hz$ of frequency and $40V$ of amplitude is applied to the piezocantilever. After measuring the delfection, the static graph relating the deflection and the voltage is plotted. According to the results (Fig. 5), the hysteresis is weakly affected by the temperature variation.

From the precedent observations, it can be assumed that the temperature T behaves like a fictive force applied to the piezocantilever and can be considered as an external disturbance. If the nonlinear relation between the applied voltage U, the external force F and the resulting deflection δ is:

$$\delta = \Gamma(U) + s_p \cdot F \tag{1}$$

Introducing the thermal disturbance, we have:

$$\delta = \Gamma(U) + s_p \cdot F \cdot D(s) + g(T) \tag{2}$$

where $\Gamma(U)$ represents an operator including the hysteresis and the creep, s_p is the elastic constant, $D(s)$ (such as

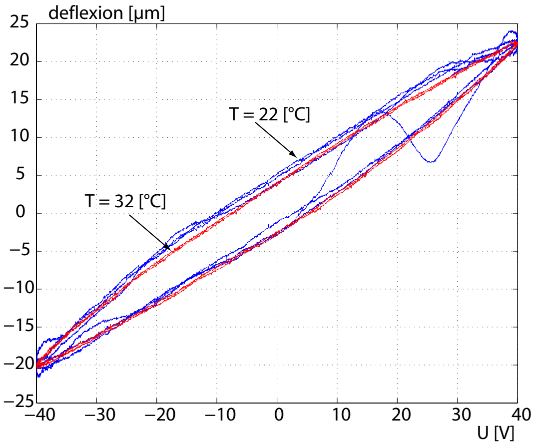

Fig. 5. The temperature weakly affects the hysteresis.

$D(0) = 1$) is a dynamic part and $g(T)$ an operator relating the temperature and the deflecion. We have $g(22°) = 0$

However, in previous works, the following remarks have been raised:

- the creep can be considered as a fictive force and then an external disturbance [9],
- the hysteresis inside a piezoecantilever is static (rate-independent) [10],
- the dynamic parts of the electromechanical transfer and the elastic transfer are similar and noted $D(s)$ [10].

From these remarks and the (Equa. 2), we have:

$$\delta = H_s(U) \cdot D(s) + b \tag{3}$$

where H_s is the static hysteresis and b an external disturbance defined:

$$b = s_p \cdot F \cdot D(s) + g(T) + C_{reep}(U, T) \tag{4}$$

with $C_{reep}(U, T)$ the operator relating the temperature, the voltage and the creep.

The Fig. 6 gives the corresponding scheme.

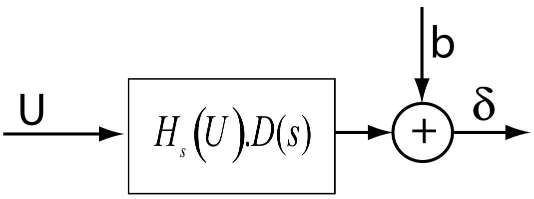

Fig. 6. The scheme of the open-loop system.

The dynamic part $D(s)$ has been identified from the Fig. 3:

$$D(s) = \frac{1}{5.7 \times 10^{-8} \cdot s^2 + 8.1 \times 10^{-6} \cdot s + 1} \tag{5}$$

3. FEEDFORWARD CONTROL

In this section, the hysteresis is cancelled in order to obtain a linear system. For that, a feedforward compensator is used: after modeling the static hysteresis, the inverse model is computed and implemented in cascade with the piezocantilever (Fig. 7). The new obtained system is then a linear one with a static gain $g = 1$. In the figure, $H_s^{-1}(\delta)$ represents the inverse hysteresis operator and δ^{ref} is the reference input.

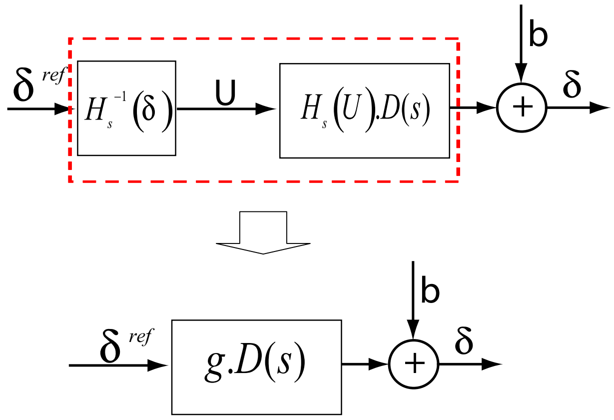

Fig. 7. The scheme of the feedforward control.

Because of the accuracy and the non-complexity of the Prandtl-Ishlinskii (PI) model, we choose this model for the static hysteresis of the piezocantilever. The PI model is based on the superposition of many elementary backlash operators characterized by the threshold r and with weighting coefficient w (Fig. 8) [11].

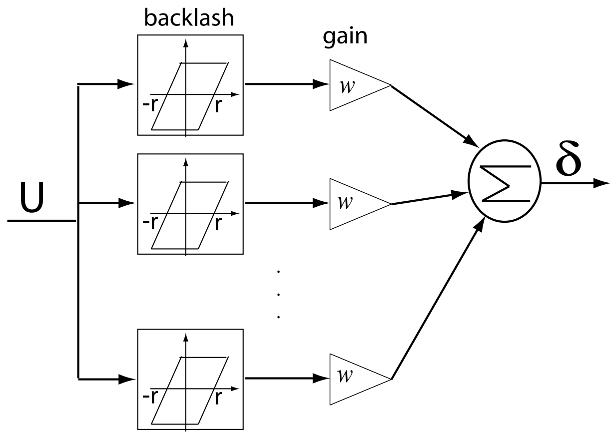

Fig. 8. The PI static hysteresis model.

Let $H_{ri}[U, \delta_{Oi}](t)$ be the i-th backlash operator characterized by its threshold ri and the initial state δ_{Oi}. The complex hysteresis is given by the following equation:

$$\delta = H_s(U) = [w]^T \cdot [H_r[U, \delta_O](t)] \tag{6}$$

where:

- $[H_r[U, \delta_O](t)] = [\, H_{r0}[U, \delta_{O0}](t) \; ... \; H_{rn}[U, \delta_{On}](t)\,]^T$ is the vector of backlash operators,
- $[w] = [\, w_0 \; ... \; w_n \,]^T$ is the weight vector,
- and $n + 1$ is the number of backlash operators.

To compute the inverse PI model, another static hysteresis is considered. In this, while the deflection δ is the input, the voltage U is the output. The same principle than the direct PI model can be applied. The new thresholds r'_i and weighting elements w'_i are given as follow [12]:

$$r'_i = \sum_{j=0}^{i} w_j \cdot (r_i - r_j) \ ; \ i = 0...n \tag{7}$$

and

$$\begin{aligned} w'_0 &= \frac{1}{w_0} \\ w'_i &= \frac{w_i}{\left(w_0 + \sum\limits_{j=1}^{i} w_j\right)\left(w_0 + \sum\limits_{j=1}^{i-1} w_j\right)} \ ; \ i = 1...n \end{aligned} \tag{8}$$

The inverse model has been implemented in the computer-DSpace board. As reference, we use a sine signal with $20\mu m$ of amplitude and $1Hz$ of frequency. According to the results (Fig. 9), when the relative temperature is null, the controller ensures the accuracy. However, when the relative temperature varies, the slope (static gain) of the linear system changes and the error between the reference and the output increases. We remark that the weak dependency of the hysteresis on the temperature (Fig. 5) becomes important when the hysteresis is linearized. That may be due to the fact that the compensator is independent on the temperature so that the final results (compensator and hysteresis) will have a larger temperature dependency.

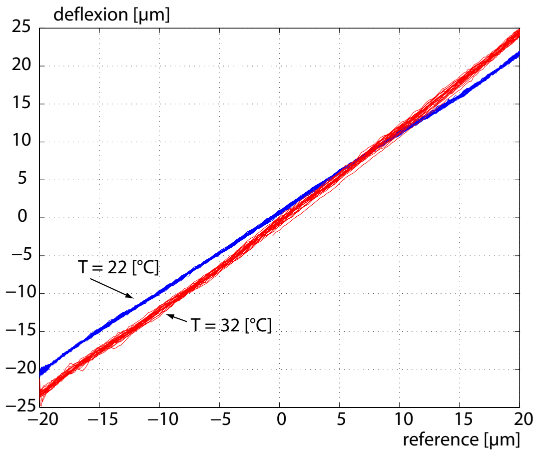

Fig. 9. Experimental results of the feedforward control.

Despite the linearity of the new system, it is necessary to use a closed-loop control in order to reject the thermal disturbance (Fig. 10) and to ameliorate the transient part of the piezocantilever, notably to reduce the vibration and to improve the rapidity.

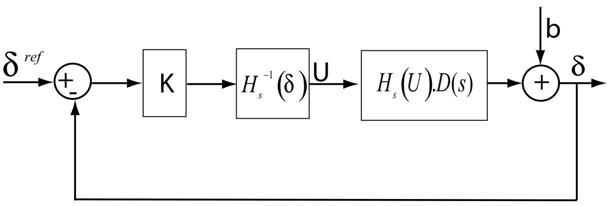

Fig. 10. Scheme of the closed-loop control.

4. ROBUST FEEDBACK-FEEDFORWARD CONTROL

In this section, a H_∞ controller K is designed. The objective is to reach the specified performances and to reject the effect of the temperature. For that, we introduce two weghting functions W_1 and W_2 (Fig. 11).

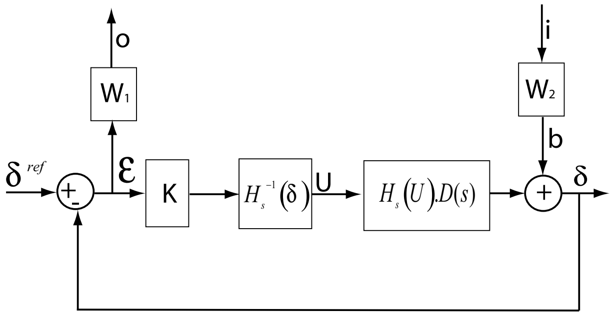

Fig. 11. Scheme of the closed-loop control with the weighting functions.

4.1 The standard H_∞ problem

Let $P(s)$ be the augmented system including the nominal system $G(s) = D(s)$ (because $g = H_s^{-1}(\delta) \cdot Hs(U) = 1$) and the weighting functions. The Fig. 12 shows the corresponding standard form.

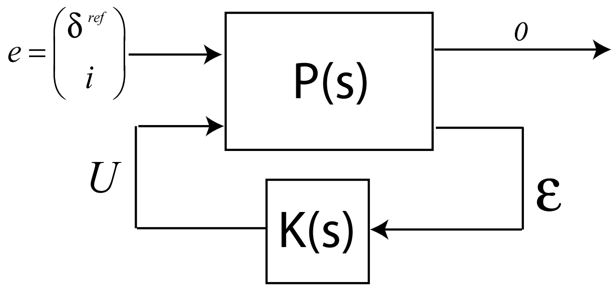

Fig. 12. The standard form.

The standard H_∞ problem consists in finding an optimal value $\gamma > 0$ and a controller $K(s)$ stabilizing the closed-loop scheme of the Fig. 12 and guaranteeing the following inequality [13]:

$$\left\| F_{low}\left(P(s), K(s)\right) \right\|_\infty < \gamma \tag{9}$$

where $F_{low}(.,.)$ is the lower Linear Fractionar Transformation and is defined here by $F_{low}\left(P(s), K(s)\right) = \frac{o(s)}{e(s)}$.

From the Fig. 11, we have:

$$o = W_1 \cdot S \cdot \delta^{ref} - W_1 \cdot S \cdot W_2 \cdot i \tag{10}$$

where $S = (1 + K \cdot G)^{-1}$ is the sensitivity function.

Using the condition (Inequa. 9) and the (Equa. 10), we infer:

$$\begin{matrix} \|W_1 \cdot S\|_\infty < \gamma \\ \|W_1 \cdot S \cdot W_2\|_\infty < \gamma \end{matrix} \Leftrightarrow \begin{matrix} |S| < \dfrac{\gamma}{|W_1|} \\ |S| < \dfrac{\gamma}{|W_1 \cdot W_2|} \end{matrix} \tag{11}$$

To solve the problem (Inequa. 11), we use the Glover-Doyle algorithm which is based on the Riccati equations [14][15].

4.2 Weighting functions

The transfer functions $\frac{1}{W_1}$ and $\frac{1}{W_1 \cdot W_2}$ are chosen from the specifications respectively on the tracking performances and on the disturbance rejection. The weighting functions W_1 and W_2 are automatically deduced. According to the performances needed in our micromanipulation, we use the following specifications:

- maximal response time: $10ms$
- overshoot: null
- maximal static error: 0.05%
- and disturbance rejection: $\frac{0.5\mu m}{10°C}$. Where $10°C$ is the difference between the normal temperature ($22°C$) and the considered maximal temperature ($32°C$).

From the above specifications, we choose:

$$\begin{aligned} \frac{1}{W_1} &= \frac{s+1.5}{s+300} \\ \frac{1}{W_1 \cdot W_2} &= \frac{s+1.5}{s+300} \end{aligned} \tag{12}$$

4.3 Calculation of the controller

The computed controller K has an order of 5. However, the minimal form of K has an order of 3. We use the later for implementation.

$$\begin{cases} K = \dfrac{230 \cdot \left(s^2 + 142 \cdot s + 1.8 \times 10^7\right)}{(s+1.5) \cdot (s^2 + 2132 \cdot s + 1.9 \times 10^7)} \\ \gamma_{opt} = 4 \end{cases} \tag{13}$$

4.4 Experimental results

First, a temporal analysis is done. For that, a step reference of $20\mu m$ is applied. The Fig. 13 shows the corresponding results. It appears that the response time is about lower than $15ms$ whatever the temperature is. The reason why it is slightly different from the specification is that the optimal value of γ is not equal to unity. Despite that, the obtained performances are sufficient for our requirements in micromanipulation.

After that, a frequential analysis is done. The results (Fig. 14) show that whatever the temperature is, the frequential performances are similar. The cut-off frequency is about $200rad/s$.

5. CONCLUSION

Piezoelectric materials are very common in micromanipulation because of their good performances. On the one hand, when used in large deflection, piezocantilevers presents hysteresis. Such nonlinearity reduces the accuracy. On the other hand, the working temperature indeniably decreases the performances during the micromanipulation . This paper presents the control of a piezocantilever with hysteresis and working in a workspace with a temperature variation. An inverse hysteresis Prandtl-Ishlinskii model is used to cancel the hysteresis (feedforward control)

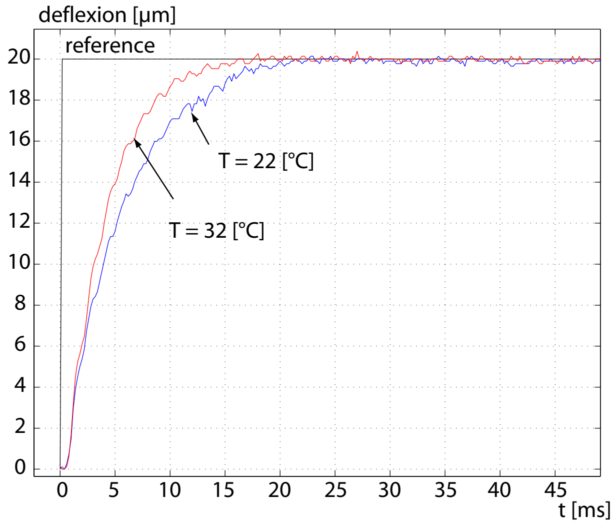

Fig. 13. Step response.

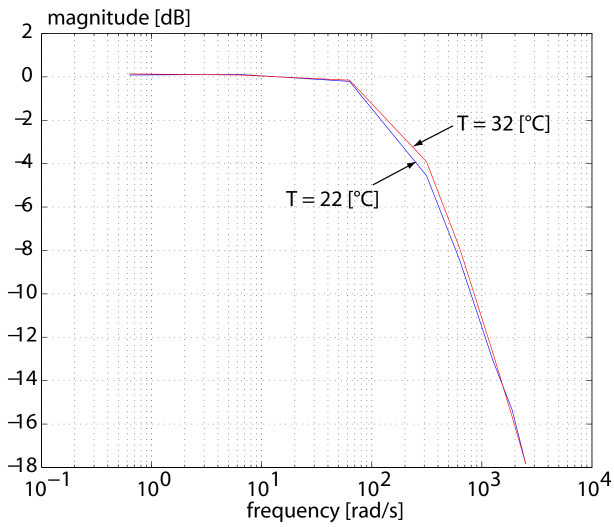

Fig. 14. Frequential response.

and a H_∞ robust controller is used to reject the thermal disturbance (feedback control). The implementation of the two controllers has made possible the rejection of the disturbance and the achievement of performances required in micromanipulation.

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