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Adam GASKA[1*]
Wiktor HARMATYS[1]
Maciej GRUZA[1]
Piotr GASKA[1]
Jerzy SLADEK[1]

DETERMINATION OF INFLUENCE OF THE PARAMETERS CONNECTED WITH THE STABILIZATION OF THE POSITION ON THE 5-AXIS MANIPULATORS' OPERATION ACCURACY

The 5-axis systems, especially those that use in their kinematic chain both prismatic joints and revolute kinematic pairs are gaining popularity in many scientific disciplines with manufacturing, metrology and robotics at the forefront. This is therefore important to undertake research aiming in identification of sources of inaccuracies in their functioning and investigation on possibility of eliminating or compensating them. A significant impact on 5-axis kinematic structures accuracy may be assigned to parameters associated with the stabilization of the machine position and angular position, such as position stabilization time, position overshoot and drift of positioning accuracy. These parameters are well described in ISO 9283 standard related to performance criteria and test methods for industrial robots. The methodology presented in this standard is adapted for testing the impact of mentioned parameters for functioning of 5-axis kinematic structures other than industrial robots, which mainly include five-axis coordinate measuring systems and machine tools. A series of experiments performed on five-axis coordinate measuring system is presented in this paper, their results are assessed in a quantitative manner and basing on them a general algorithm for assessing the significance of impact of position stabilization parameters on functioning of the manipulator is proposed.

1. INTRODUCTION

The 5-axis kinematic systems that use in their kinematic chain both prismatic joints and revolute pairs are gaining a lot of popularity in different fields of engineering [1-3]. It happens because they combine the advantages of commonly known kinematic systems that use only translational (e.g. Coordinate Measuring Machines or transporting manipulators) or rotary pairs (e.g. industrial robots) and what is the most important for modern industry they allow to significantly speed up the production or measurement process with almost no loses for its accuracy [4, 5].

[1] Cracow University of Technology, Faculty of Mechanical Engineering, Laboratory of Coordinate Metrology, Cracow, Poland
[*] E-mail: agaska@mech.pk.edu.pl
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Increasing popularity of these systems creates a need for undertaking the research on finding the sources of inaccuracies in their functioning and investigation on possibility of eliminating or compensating them in order to improve their accuracy.

As the authors of this paper deal mainly with coordinate metrology and use 5-axis systems for coordinate measurements, considerations presented here will be related especially with 5-axis coordinate measuring systems but the methodology presented in this paper may be successfully used also for checking the errors connected with stabilization of the position for 5-axis systems used in other fields of engineering like manufacturing or robotics.

During previous experiments performed by the authors, it was noticed that the errors related to probing of the point performed using 5-axis coordinate measuring system are usually the biggest for the first point measured in a sequence. The example of such situation is presented in Fig. 1 for measurement of standard ring with diameter equal to around 30 mm. This made the authors start searching for the possible cause. The most probable reasons are the dynamics of the system and its principle of working.

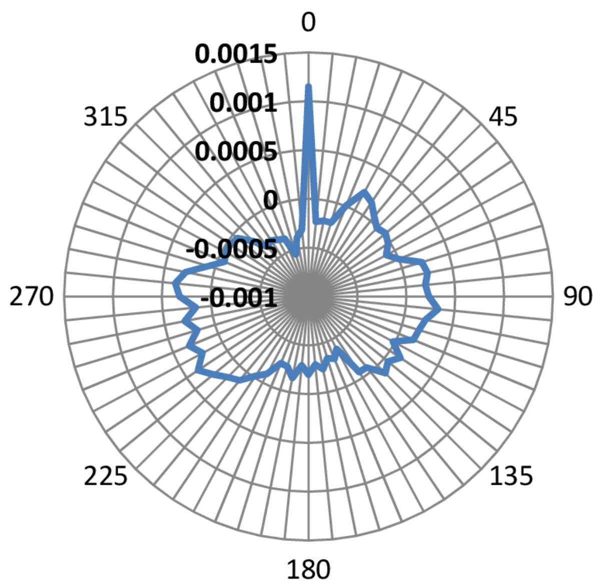


Fig. 1. Probing errors during measurement of standard ring performed on five-axis coordinate measuring system, values on the circumference of a graph given in degrees, numbers in vertical axis in mm

During work with 5-axis system it is important to use its ability to measure the most of workpiece's parts using only the probe head rotary movements. These kind of measurements are much faster than typical 3-axis measurements because there is no need to move the whole body of the machine during measurement of all considered points. Instead of it, the movements are done by light and quick probe attached to probe head while the rest of machine holds still. During measurement of the first point in a sequence, the measurement is the combination of three-axis measurement and measurement performed using only the probe head movements. The machine approaches the point from which the measurements may be done using only the probe head movements and then the measurement begins. The mass and inertia of the machine however causes that during the measurement of the first point, mentioned position may not be stable and this should be regarded as a main reason of error related to measurement of this point.

In order to identify this impact quantitatively the authors decided to adapt the methodology presented in ISO 9283 [6] that is related to testing the accuracy of industrial robots. One of tests presented in it shows the procedure for determination of parameters associated with the stabilization of the machine position and angular position, such as position stabilization time, position overshoot and drift of positioning accuracy (these parameters will be described in the next section).

Similar problem, which is the influence of position stabilization parameters on accuracy of functioning of manipulators, was noticed by researchers dealing with other areas of science and presented in [7] where Barnfather et al. examined this influence during manufacturing of large volume parts using robotic machine tools, in [8,9] where authors pointed out the importance of parameters related to position stabilization in case of robots used for medical treatments or in [10] where Mei et al. developed an in-process method for position stabilization and accuracy improvement during multi-station aircraft assembly.

2. PARAMETERS ASSOCIATED TO STABILIZATION OF THE MACHINE POSITION, PROCEDURE OF THEIR DETERMINATION AND ITS ADAPTATION FOR USAGE IN 5-AXIS COORDINATE MEASURING SYSTEM

2.1. MACHINE POSITION STABILIZATION PARAMETERS

According to ISO 9283 the parameters associated with the stabilization of the machine position and angular position include [6]:

- position stabilization time (t), it quantifies how quickly a machine can stop at the attained pose. It is measured as the elapsed time from the instance of the initial crossing into the limit band (the limit band is understood as the pose repeatability *RP* defined according to [6] or a value stated by the manufacturer) until the instance when the machine remains within the limit band,

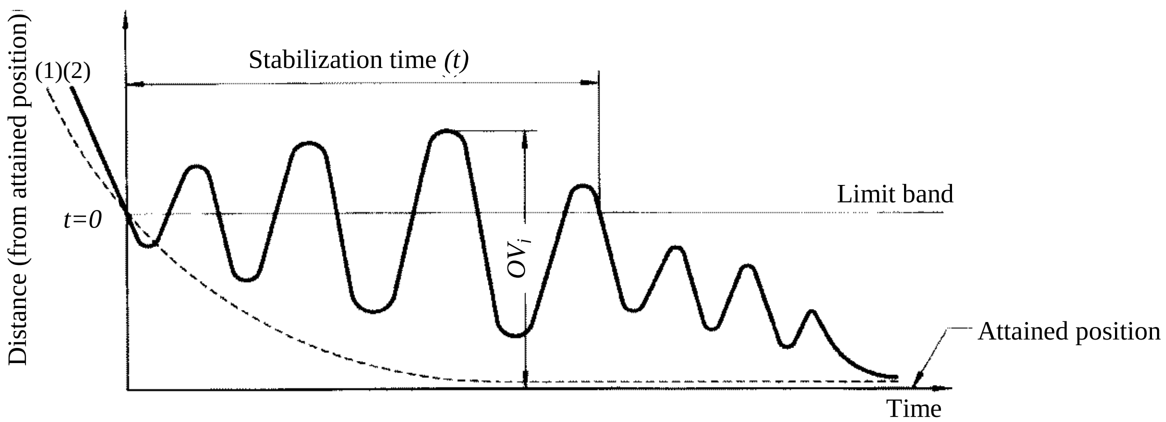


Fig. 2. Position stabilization time (t) and position overshot (OV_j) [6]

- position overshoot (OV_j), it quantify the machine capability to make smooth and accurate stops at attained poses. The overshoot is measured as the maximum distance from the attained position after the instance of the initial crossing into the limit band and when the machine goes outside the limit band again,
- drift of positioning accuracy, it is the variation of pose accuracy over a specified time (T).

The position stabilization time and the position overshot are schematically presented in Fig. 2.

2.2. ADAPTATION OF TEST PROCEDURE FOR ROBOTS TO USAGE FOR TESTING 5-AXIS COORDINATE MEASURING SYSTEMS

Test procedure for checking the stabilization time and position overshot for robots presented in [6] includes two main steps. In the first one, the position repeatability RP_l should be determined for all points included in measurement sequence, which consists of 5 points distributed in corners of rectangle chosen in robot's volume and one point being the intersection of rectangle's diagonals. The robot moves at least 30 times to all of these points and positions at which it stops are recorder by measuring device capable of tracking its movements, usually Laser Tracker system.

In second step, the sequence of movements is repeated three times and position stabilization time is determined as a mean stabilization time obtained for each point from three repetitions and position overshot as maximum overshot recorded for each point (OV_j). OV_j is calculated using equation (1).

$$\begin{aligned} &OV = \max OV_j \\ &OV_j = \max D_{ij} \quad \text{if } \max D_{ij} > \text{limit band} \\ &OV_j = 0 \quad \text{if } \max D_{ij} \leq \text{limit band} \end{aligned} \tag{1}$$

where:

$$\max D_{ij} = \max\sqrt{(x_{ij}-x_j)^2+(y_{ij}-y_j)^2+(z_{ij}-z_j)^2} \qquad i=1, 2, \ldots m$$

x, y, z – positioning characteristics along the x, y, z axis,
i – i-th abscissa,
j – j-th cycle.

Drift of pose characteristics is determined using sequence of movements between 2 points, which is repeated 10 times. Each time after the sequence is completed the robot performs so called warm up cycle that is described in detail in [6]. The measuring sequence followed by warm up cycle are repeated for 8 hours. For each sequence the positioning accuracy AP_P and positioning repeatability RP_l are recorded and the drift of pose characteristics is determined as (2):

$$\begin{aligned} &dAP_P = \max(\,|AP_{t=1} - AP_{t=T}|) \\ &dRP_P = \max(\,|RP_{t=1} - RP_{t=T}|) \end{aligned} \tag{2}$$

where $t = 1, 2, ..., n$ is the number of measuring sequence.

As mentioned above, the Laser Tracker system is usually used for measuring the actual position of robot. These kind of systems are accurate enough for supervision of robots but its accuracy is not sufficient for checking the Coordinate Measuring Machines (CMM). This is why other, more accurate laser tracking system was used in experiments presented in this paper. It was LaserTracer (LT) system made by ETALON AG. This system is capable of measurements of distances with very high accuracy, it is however impossible to use it directly for determination of point coordinates (determination of point coordinates is possible using measurements from different positions of LT and multilateration technique) [11, 12]. It is why the amendments to procedure presented in [6] had to be made.

Measurement procedure used for determination of drift of pose characteristics was almost the same as in [6] with this difference, that the AP_P and RP_l parameters were measured using only one coordinate (in this case it was length measured along axis crossing through the reference point of LT and two points required in the sequence) instead of three. Also a predefined number of cycles (ten cycles) was used instead of 8-hour-measurement recommended in [6]. Changes to procedure used for determination of position overshot and stabilisation time included changes to distribution and number of points used in a sequence. Instead of five points distributed over a plane, two points distributed along a line were used. In this case, the distance from attained position presented in Figure 2 was calculated as an absolute value from distance between actual position of reflector to distance programmed for considered point.

3. EXPERIMENTS AND RESULTS

Measurements were performed on Zeiss WMM850S machine that is a base of five-axis coordinate measuring system. The temperature during measurements changed from 19.9 to 20.3 °C. Experiment set up is presented in Fig. 3.

Fig. 3. Measurements of position stabilization parameters on coordinate measuring system

As presented in Fig. 3, the retroreflector was mounted instead of CMM's probe head. At the beginning of test procedure the position of LaserTracer was measured, using measurement of distances from LT reference point to reflector in six different points arranged in a star pattern. Using multilateration technique the LT position in CMM's working volume was determined. Next, four measuring lines were generated: along *x*, *y* and *z* axes of coordinate measuring system working volume and along one chosen spatial diagonal of it. During execution of measuring sequence the actual distance from reflector to LT was recorded with frequency equal to 16 Hz. For all axes two steps of measurements described in section 2.2 were done.

In first step two points along measuring line were measured 30 times and RP_l parameters were determined. In second step two points were measured 3 times. Drift of pose characteristics was determined only for spatial diagonal. Results of performed experiments are presented in Tables 1 and 2.

Table 1. Results of determination of position overshot and stabilization time for WMM850S machine, P1 denotes point closer to LT and P2 the farther one

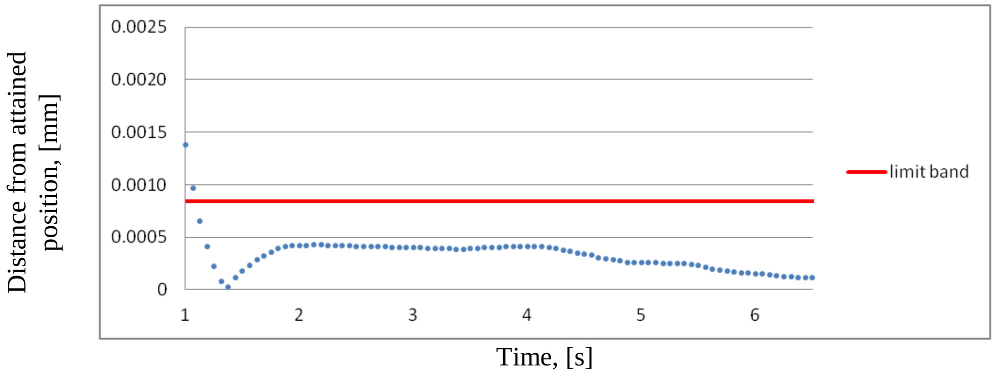
Measurement axis	Point	Parameter	Value
x	P1	*OV*, mm	0
		t, s	0
	P2	*OV*, mm	0
		t, s	0
y	P1	*OV*, mm	0.0004
		t, s	0.917
	P2	*OV*, mm	0.0006
		t, s	5.125
z	P1	*OV*, mm	0
		t, s	0
	P2	*OV*, mm	0
		t, s	0
spatial diagonal	P1	*OV*, mm	0.0012
		t, s	1.042
	P2	*OV*, mm	0.0015
		t, s	2.062

Table 2. Results of drift of pose determination for spatial diagonal, P1 denotes point closer to LT and P2 the farther one

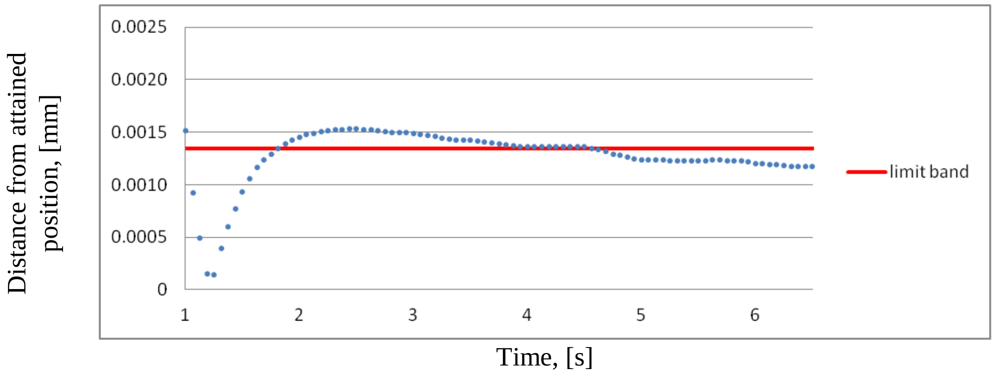
Point	Parameter	No of cycle								
		1	2	3	4	5	6	7	8	dAP_P/ dRP_P
		Value, mm								
P1	AP_t	0.0002	0.0001	0.0001	0.0006	0.0006	0.0002	0.0004	0.0003	0.0004
	RP_t	0.0005	0.0009	0.0009	0.0009	0.0008	0.0005	0.0006	0.0006	0.0004
P2	AP_t	0.0004	0.0002	0.0004	0.0013	0.0007	0.0006	0.0009	0.0007	0.0009
	RP_t	0.0009	0.0005	0.0004	0.0010	0.0006	0.0008	0.0007	0.0009	0.0005

Figure 4 presents the relation between distance from attained position and measurement time for measurements along diagonal of CMM's volume.

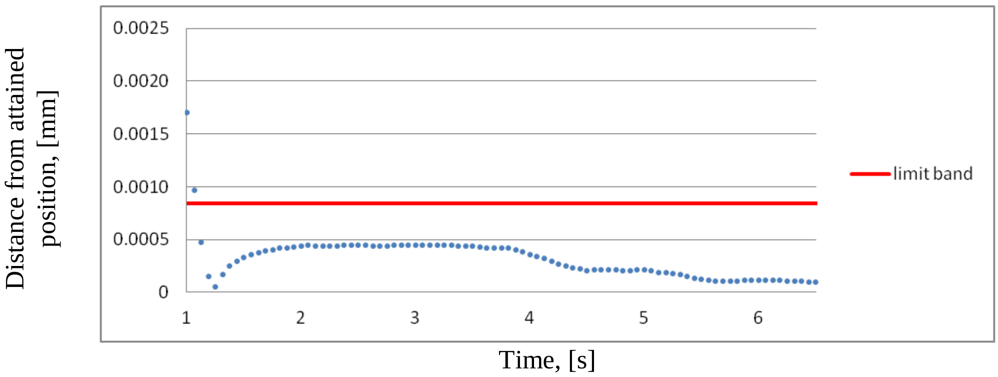
a)


Distance from attained position, [mm]
0.0025
0.0020
0.0015
0.0010
0.0005
0
1
2
3
4
5
6
Time, [s]
limit band

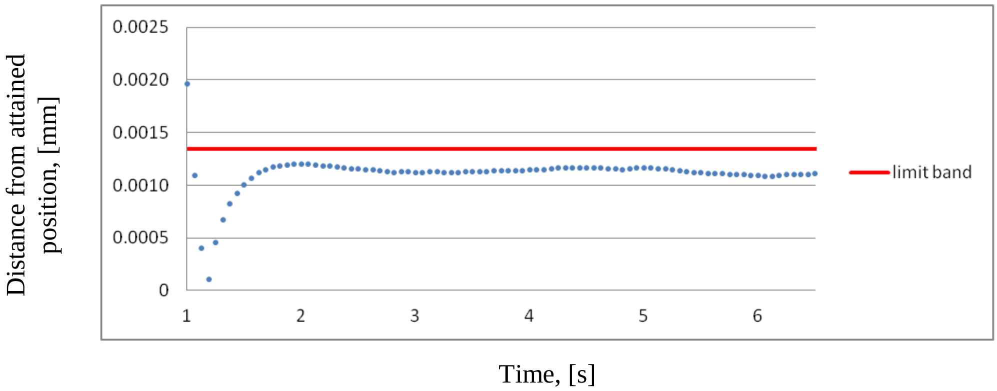
b)


Distance from attained position, [mm]
0.0025
0.0020
0.0015
0.0010
0.0005
0
1
2
3
4
5
6
Time, [s]
limit band

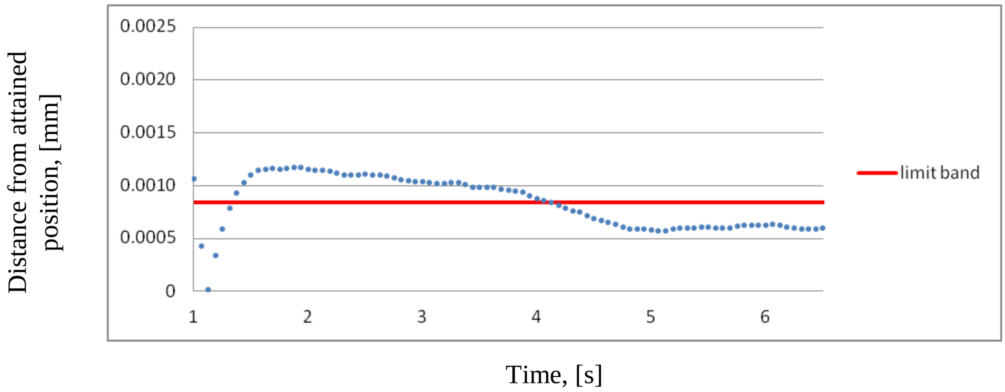
c)


Distance from attained position, [mm]
0.0025
0.0020
0.0015
0.0010
0.0005
0
1
2
3
4
5
6
Time, [s]
limit band

d)


Distance from attained position, [mm]
0.0025
0.0020
0.0015
0.0010
0.0005
0
1
2
3
4
5
6
Time, [s]
limit band

e)



f)

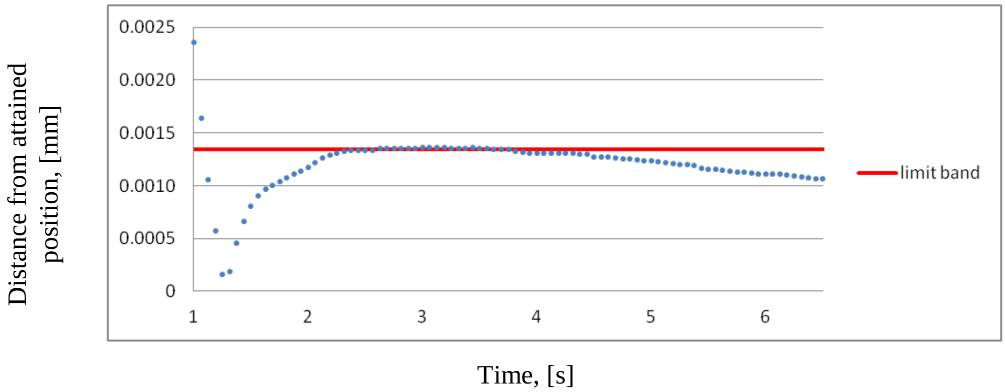


Fig. 4. Relation between distance from attained position and measurement time for: a) measurement of P1 point in first cycle of second step, b) measurement of P2 point in first cycle of second step, c) measurement of P1 point in second cycle of second step, d) measurement of P2 point in second cycle of second step, e) measurement of P1 point in third cycle of second step, f) measurement of P2 point in third cycle of second step

4. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

Results of performed experiments clearly show that the worst parameters values were obtained for spatial diagonal of measuring system's volume and *y* axis. For movements along *x* and *z* axes the parameters related to position stabilization have no impact on accuracy of their functioning. Generally, values of accuracy parameters related to kinematics of the machine are usually the worst for spatial diagonals as the movement along it is a combination of movements along all machine axes, and their errors are superposing. In case of machine that was used in presented experiments the errors of *y* axis are the main contributor to values of errors for the diagonal.

The most probable cause for this situation is that the *y* axis is the one in which movement of whole machine's bridge is required and the errors connected to machine dynamics has the strongest influence. It was also noted that the errors are bigger for movements in the positive direction of the *y* axis (the results are worse for the P2 point which was measured in positive direction). Similar conclusion may be drawn when analyzing results for diagonal, the results are worse when the *y* axis is moving in its positive direction. This information may be useful during preparation of five-axis coordinate system errors model that is now under development in Laboratory of Coordinate Metrology at Cracow University of Technology.

It is also probable that identified situation is the cause for bigger errors of probing during measurement of the first point measured in a circular sequence on standard ring with diameter around 30 mm. The machine that is moving fast before reaching the first point in a measurement sequence is unable to stop at required position and is oscillating around it for some time. It is not the case during measurement of next points in a sequence as machine moves slower because the distance it has to pass is much smaller.

Further research related to determination of position stabilization parameters are planned. They will aim in giving the answer if the position stabilization parameters are dependent on position of the machine’s end effector in its volume. Measurements should then be performed using many points distributed over a multiple lines with different orientations. Also the scale of differences in position stabilization parameters values for the same point but measured in different directions (positive/negative) would be investigated.

Development of method for correction or compensation of identified errors is also very important direction for further research. As changes to mechanical construction of machines that are already used don’t seem to be the best and cheapest solution to identified problem the compensation method should be based on determination of relation between position stabilization parameters values and values of probing errors resulting from them. In cases, where measurement time is not crucial, a simple compensation method may be developed basing on utilization of delay times equal to experimentally determined position stabilization time before starting the measurement of considered geometrical feature.

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