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CONTRIBUTIONS TO POSITIONING ACCURACY DURING LINEAR MOTION OF CNC MACHINE TOOL TABLE

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Abstract: *New evolution of machine tools involves various elements of artificial intelligence for workpiece in the best conditions of precision and quality. High geometrical precision is the main factor in achieving performance criteria. This requires certain objectives: establishing a methodology for measuring positioning errors and ways to decrease them; establishing a methodology regarding the causes and prevention of errors; utilisation of a software error compensation and modifying CNC program using a CAM application; verification of the software efficiency by machining a workpiece without errors compensation, and machining a second one with processing paths improved. After performing these virtual operations, the workpiece was machined in order to verify the dimensional and form accuracy. Thus, it was used a software application, which we called it "Optimization of the numerical control", which based on measurements of precision positioning, was used to optimize the coordinates of path processing, so that to increase the geometrical and dimensional accuracy of the workpiece. This program was checked by machining a test workpiece resulting an important reduction of the finished piece dimensional errors. Thus, the main contribution, of this paper is that using the proposed approach the precision of CNC machine tools can be improved without the intervention upon the structural elements of the machine tool.*

Key words: *machine tool, geometric precision, error map, CNC program, error compensation software.*

1. INTRODUCTION

In the last recent years, a great progress has been made in precision machining. Nowadays, it is possible to make precision parts with submicron or even nanometre accuracy, which paves the way for many applications in biomedical, electronic or aerospace engineering. However, for the rest of problems into aeronautics and automotive industry a number of problems remain unsolved. For instance, the hardness of the cutting tools and workpiece pose a major limitation on the accuracy of the machined parts and tool life. To achieve high accuracy, ultra-precision machine tools are needed, which are very expensive. To improve the machining accuracy further without significant capital investment, real-time error compensation based on sensing and control techniques is needed. It is known that a machining process consists of four parts: (1) the machine tool structure including the motor and spindle; (2) tables of the machine tool and the driving systems; (3) workpiece; and (4) cutting process. During the machining operations, various errors may occur.

The majority of numerical commands systems offer possibility of introducing numerical values for each axis, in order to improve the performance of positioning machine tool table [1, 2]. We can use the following correction: step correction, thermal correction, mutual position of two axes [3, 4]. Older Computer Numerical Control (CNC) until the 1990 used 4−5 values of step correction along one axis. Actual Numerical Control, like Siemens, Fanuc or Heidenhain, use a correction systems with an automatic increment 1 000 point in both side of movement of machine tool table (+ and − for X, Y and Z directions).

2. RESEARCH GOAL

Position accuracy depends on thermal and dynamic effects, wear of the moving parts of the structure. To control precision of machined parts advance solutions must be found to compensate positioning errors. This paper aims to achieve an algorithm to improve the positioning accuracy of the tool / workpiece during cutting process.

3. COMPENSATION THEORY AND ALGORITM

We used in our research a software application developed in the Machines and Manufacturing Systems Department, written in Visual C ++ programming language.

In the approach used for the software application, a matrix of errors on the three directions corresponding to axis X, Y and Z was used. Then make the overlay coordinate of machining program over 3D matrix of errors, changing their values, based on the coordinates to be achieved by the cutting.

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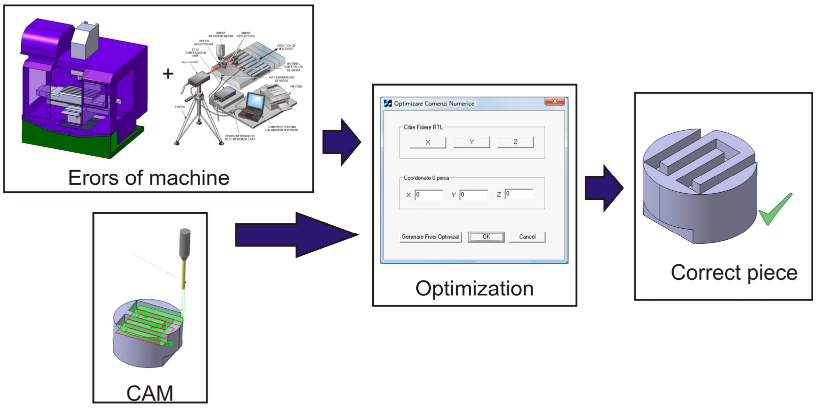


Fig. 1. Implementation of errors into developed application and export new optimization program.

The method of improving the positioning displacement of machine tool table is presented in Fig. 1, being emphasized four main steps. For the first step we measured the errors for each axis, the machine used for tests has three numerical controlled axes. After that we utilized a program for a probe workpiece. We inserted both into our application for optimization of trajectory and the program returned the new optimization program for the probe part.

4. EXPERIMENTAL SETUP

4.1. Data acquisition

The measurements were made using a Renishaw interferometer equipment [6]. The device is mounted to performing measurements on all 3 axes, *X*, *Y* and *Z*, each at a time. Mounting of the laser was done by placing the tripod on the ground, using the level contained in the tripod in order to obtain a perfect alignment parallel to the ground. The measurement setup was completed with the mobile mirror mounted on the machine table, which is able to perform measurements on all three axes, *X*, *Y* and *Z*.

In order to achieve the measurement accuracy of the *X* axis, the arrangement in the Fig. 3 there was achieved, in which the laser beam which leaves the laser unit has a linear trajectory passing through the interferometer, then on the reflector, returning into the laser after passing once through the interferometer. By changing the distance between the interferometer and the reflector, the device detects the difference in wavelength, causing the detection of the distance the table of the machine tools travels.

To determine the error on the *Y* axis, the Renishaw system was mounted in front of the machine tool, as shown in Fig. 4.

For the *Z* axis, the interferometer could not be mounted to take measurements directly, so that it was chosen a variant in which the laser beam is reflected at an angle of 90° as shown in Fig. 5.

The machine tool, on which the system presented above was installed, is a milling machining centre with vertical spindle and three numerically controlled axes (FIRST MCV300).

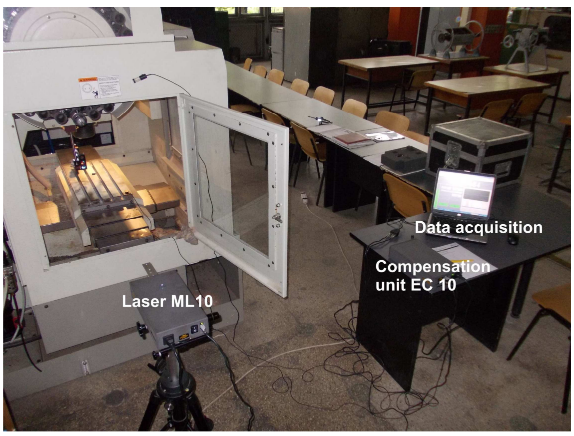


Fig. 3. Installing the *X* axis measurement setup.

Fig. 4. Installing the *Y* axis laser.

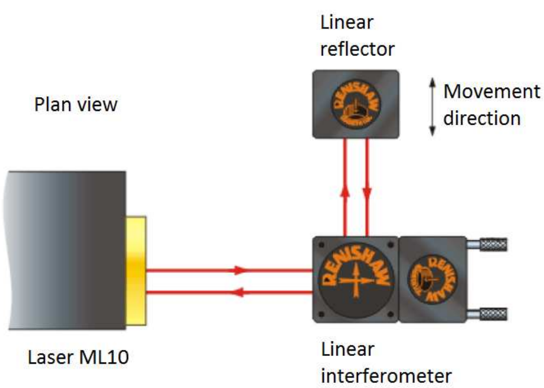


Fig. 5. Mirrors aligned for measurement at 90°.

EC10 compensation unit compensates the wavelength of the laser beam for the changes in air temperature, pressure and relative humidity. It may also accept inputs from up to three sensors, which measure the temperature of the machine, as long as that the expansion of the material to be defined in the software of ML10 laser. This will allow the normalization of the measurements of the machine tool (in terms of material). This expansion refers both to the expansion of the machine table (not so important), and to the expansion of the ball screw (important for long lengths of 3−4 m.

Also, this unit allows the compensation for thermal expansion of the material in linear measurements [7]. If it is not used the compensation unit EC10, the variation in the refractive index of air can lead to significant measurement errors.

Humidity sensors are mounted inside the environmental compensation unit EC10. In general, it is not necessary to measure air pressure and humidity in the vicinity of the laser beam path. This is because large variations of pressure and humidity are required to give a significant error in the measurement and there should not be a significant change in the work area. However, EC10 unit should be located away from heat sources [5].

For exact determination of the machine tool table, an axis movement was performed at the end of the machine table movement, noting the value displayed by the control, and a movement in the opposite direction was made, achieving the difference between the two values displayed by the control.

Then, the movement of the three axes was shared in an incremental manner.

To validate the measurements, it was chosen to make attempts in several stages, as follows: 100 mm, 50 mm, 20 mm, 18 mm, and 10 mm. It was stopped at a pitch of 10 mm because in this step, the machine could not physically accelerate on the motor axis to reach the required feed speed. However, to precisely determine the positioning error, the smallest increment was set at 1 mm, and the feed rate at 1 000 mm/min.

4.2. Writing the program for displacement of machine tool table.

For the acquisition of data, it is necessary for the machine tool table to move with good accuracy. To respect the standard ISO 230-2, data acquisition was made by displacing the machine tool table in both positive and negative directions five times, with a large number of points, where measurements were performed on the three numerically controlled axes [6].

The representation of movement in a linear fashion was decided for easy indicating the points by moving with an increment. There is a time delay in displacement (indicated by arrow tips), of five seconds for the software to have enough the time to make data acquisition. The trajectory scheme in Fig. 6 is followed by the machine table during running the programmed movement of machine tool table, where data acquisition is done. In addition, movements occurring under the scheme are justified by highlighting the ball screw, if any, [3].

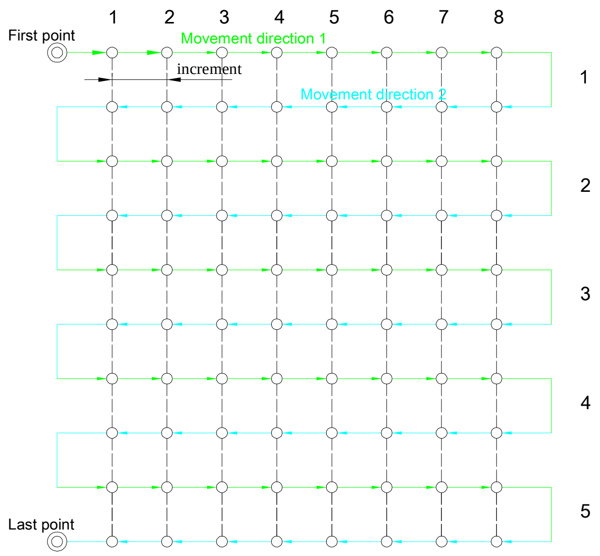


Fig. 6. Representation of movement for machine tool table.

Data acquisition is done automatically. We just have to launch the numerical program and expect to reach the M00 line (which means that the program waits an operator to intervene). At this time, it reaches the line of the program, the movable element of the machine tool (machine table or the spindle depending on the type of machine tool) is in the origin of the program. Then, we initialize Renishaw software on zero position. This is necessary for the error curve to start from the origin [8]. After the acquisition of data is automatically started, the operator starts the program for displacement of the machine tool table.

Thus, as the machine tables moves, data is acquired automatically step by step, with a break between acquisitios. The role of this break is to stabilize the measured value (as in a small range devices it takes more singular values, which then mediates a value that is displayed on the screen). It should be noted that according to ISO 230, the measurements were made without processing the material.

5. RESULTS AND DISCUSSION

5.1. Error map on *X*, Y and Z axes

In this paper measurements on the accuracy of the positioning of all the machine axes *X*, *Y* and *Z* were made, twice time two-ways working, positive and negative, in this way measured values are accompanied by an extremely small error. To view the effects of incremental speed determined values, two factors described above were varied.

The determination of the *X* axis positioning errors was done during five double strokes performed by the machine tool table. The accuracy of the machine according to this travel axis is presented in Fig. 7, obtaining the maximum accuracy of 44.2 µm.

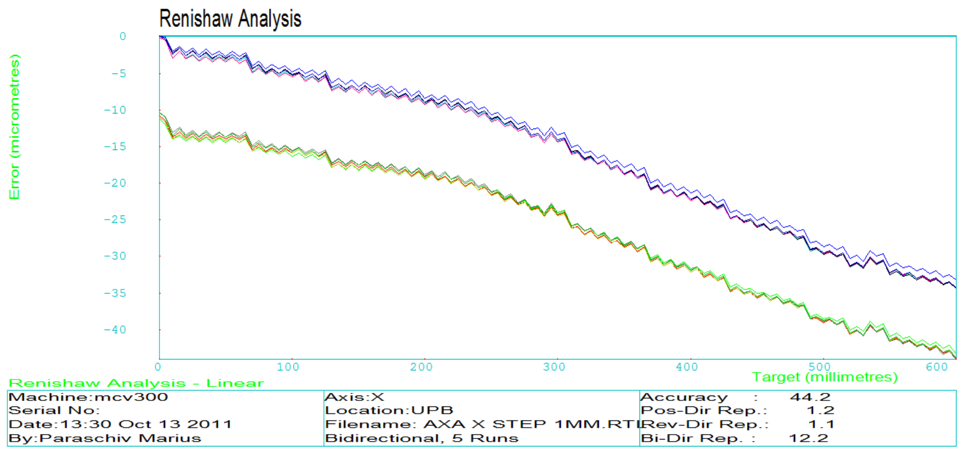


Fig. 7. Representation of errors on *X* axis.

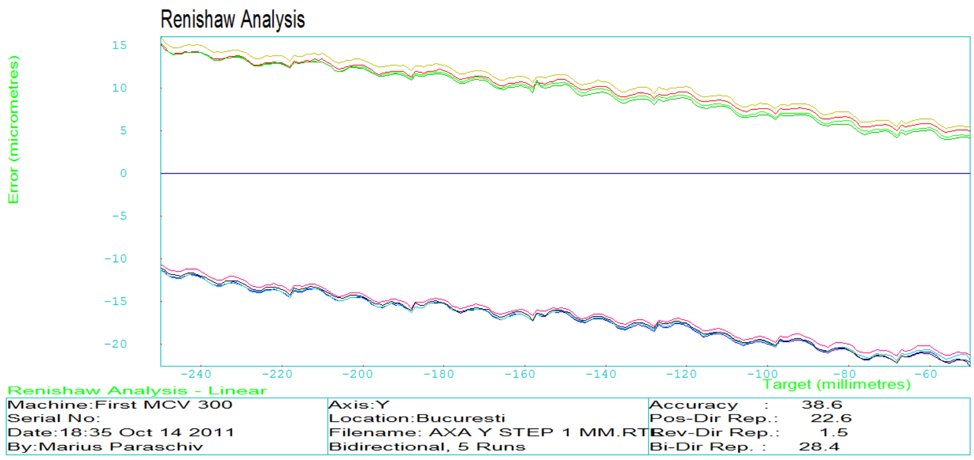


Fig. 8. Representation of errors on *Y* axis.

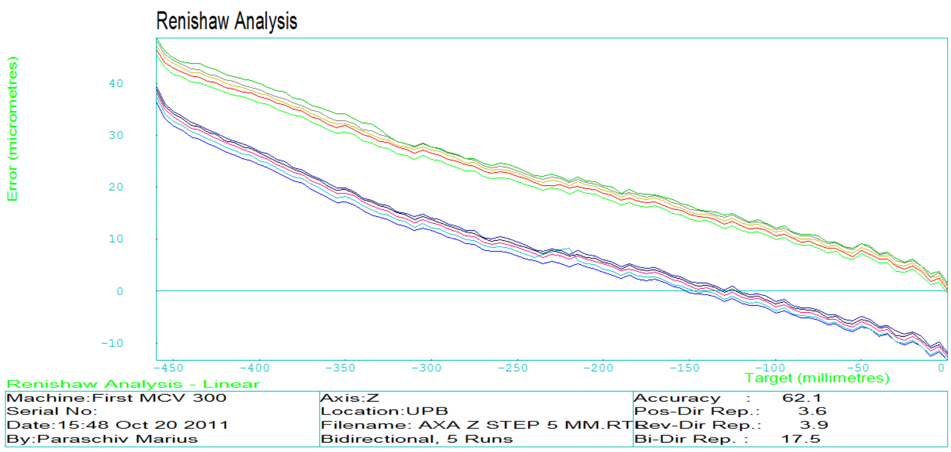


Fig. 9. Representation of errors on *Z* axis.

***Y* axis measurement.**

The determination of the *Y* axis positioning errors was done during five double strokes performed by the machine tool table. The accuracy of the machine according to this travel axis is presented in Fig. 8, obtaining the maximum accuracy of 38.6 µm.

Z axis measurement.

The determination of the *Z* axis positioning errors was done during five double strokes performed by the machine tool table. The accuracy of the machine according to this travel axis is presented in Fig. 8, obtaining the maximum accuracy of 62.1 µm.

The measurements were done with the following conditions:

- for *X* axis: feed of 8 000 mm/min and displacement increments of 1 mm, for a length of 600 mm;
- for Y axis: feed of 5 000 mm/min, and displacement increment of 1 mm for a length of 300 mm;
- for Z axis: feed of 1 200 mm/min, ad displacement increment of 5 mm for a length of 460 mm.

Table 1

Maximum errors for *X*, *Y* and *Z* axes

Axis	*X*	*Y*	*Z*
Accuracy [µm]	44.2	38.6	62.1

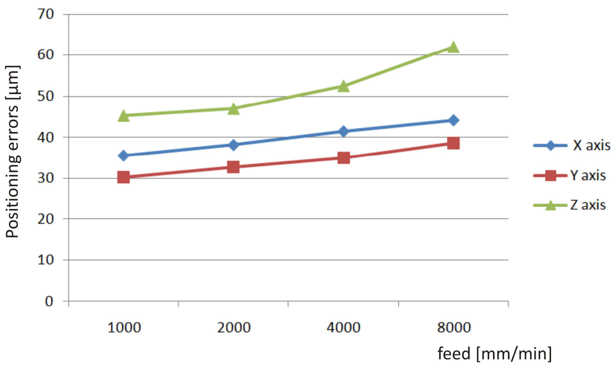


Fig. 9. Error evolutions for *X*, *Y* and *Z* axes.

To determine the precision levels for each axis separately, more accurate linear measurements were made, modifying the feed rate for each test and displacement increment (determining distance required to accelerate to maximum speed specified in the initial set-up). The biggest errors on each axis are presented in Table 1.

As we mentioned above, the feed rate was varied to determine the precision. This is the factor that most influences positioning errors without taking into account the cutting forces. For these measurements the feed rate was varied from 1 000 mm/min up to 7 000 mm/min on each axis, because this is the range of the feed rates used in the usual working on this machine. Further we present the variation results for all three axes.

5.2. Testing the "Optimization of the numerical control" software in order to improve the tolerance of a machined test piece.

After measuring each axis separately, in the next stage, it was machined and measured a test part on the CNC machine tool. This part was machined without using the trajectory optimization program *Optimization of the numerical control*. The dimensions followed to be achieving for test part are shown in Fig. 10 and detailed in Table 2.

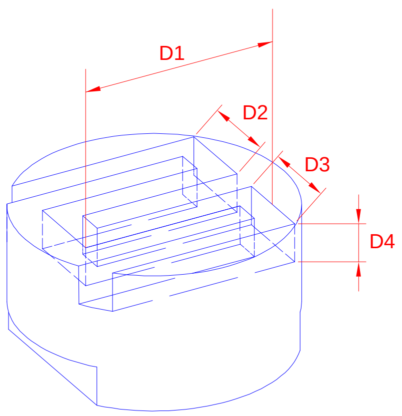


Fig. 10. The dimensions followed during the tests.

Table 2

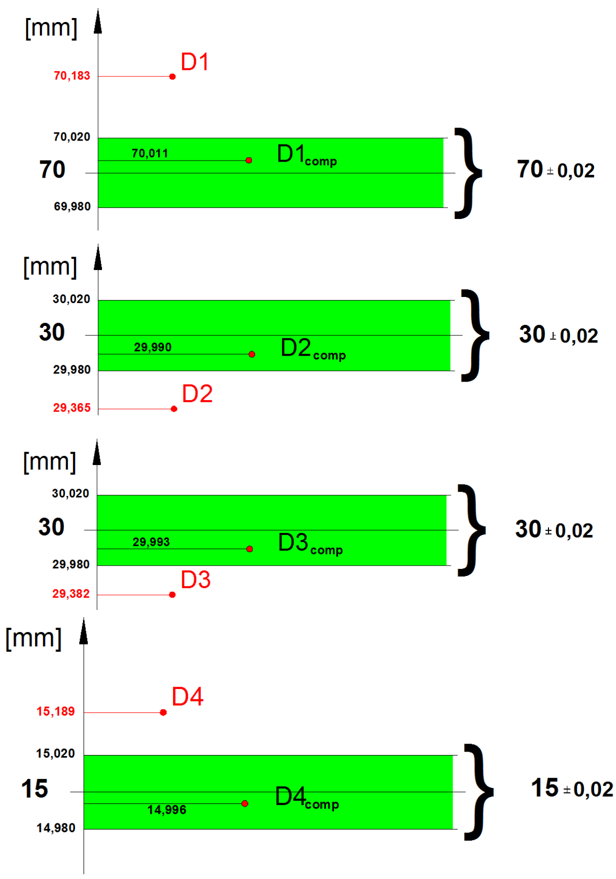
Dimension on drawing	Nominal dimension [mm]	Tolerance [µm]	Measured dimension [mm]	Difference between real surface and tolerance field [mm]
D1	70	±20	70.183	+0.163
D2	30	±20	29.365	−0.615
D3	30	±20	29.382	−0.598
D4	15	±20	15.189	+0.169

Table 3

Dimension on drawing	Real dimension [mm]	Tolerance [µm]	Measure dimension [mm]
$D1_{comp}$	70	±20	70.011
$D2_{comp}$	30	±20	29.990
$D3_{comp}$	30	±20	29.993
$D4_{comp}$	15	±20	14.996

After machining the first test part, we optimize the numerical program of part, with the help of *Optimization of the numerical control* software. A new part is machined with the same machining parameters as for the first part, using the same tools. The new values are presented in Table 3.

The differences in terms of achieving the value inside or outside tolerance field, for workpieces with and without optimization are shown very clearly in Fig. 11.



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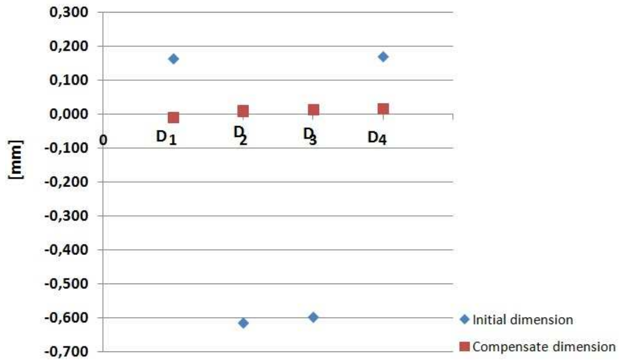

Fig. 12. Comparaison between initial dimensions and compensated ones.

Therefore, analyzing the differences between the two cases studies, we can make the following statement: by using this software, positioning error values decrease and a machine-tool that does not have a very high positioning accuracy can be software upgraded without modification of drives and kinematic structure.

The difference between the two tests is shown in the Fig. 12.

There is a high difference between the values obtained by applying the optimization algorithm of positioning errors with regard to values before compensation.

By using this solution of accuracy increasing, both qualitative and quantitative errors can be improved, yielding a maximum error value of 61.5μm.

6. CONCLUSIONS

Precision of the machine tools is the main feature of their processing quality. On the market conditions based on a higher quality at the lowest possible costs, the improvement of the geometric precision solutions is an indispensable solution in today industry.

This paper examines the geometric precision of a milling machining centre having three CNC axes. For highlighting the linear precision characteristic, an experimental protocol based on laser interferometry is used. Measurements were performed on the three directions, *X*, *Y* and *Z* getting the accurate information corresponding to each linear axis.

For increasing the quality of the machining process, an algorithm was developed, which aims to correlate the positioning errors with the position determined after CAM programming.

The measured positioning errors were analyzed in terms of feed rate and its linear behaviour was obtained.

Developing the compensating algorithms for the positioning precision, using neural networks is one of the future directions of this research.

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