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Synthesis of Optimal Trajectories with Functions Control at the Level of the Kinematic Drive Couplings

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Abstract: The development and diversification of machines and mechanisms with applications in all fields require new scientific researches for the systematization and improvement of existing mechanical systems by creating new mechanisms adapted to modern requirements, which involve increasingly complex topological structures. The modern industry, the practice of designing and building machinery is increasingly based on the results of scientific and applied research. Each industrial achievement has backed theoretical and experimental computer-assisted research, which solves increasingly complex problems with advanced computing programs using an increasingly specialized software. The robotization of technological processes determines and influences the emergence of new industries, applications under special environmental conditions, the approach of new types of technological operations, manipulation of objects in the alien space, teleoperators in the top disciplines like medicine, robots covering a whole field greater service provision in our modern, computerized society. Movable, robotic, mechatronic mechanical systems have entered nearly all industrial spheres. Today, we can no longer conceive of industrial production without these extremely useful systems. They are still said to steal from people's jobs. Even so, it should be made clear that these systems create value, work in difficult, repetitive, non-pausing, high-quality work, without getting tired, without getting sick, without salary, and producing value who are paid and people left without jobs, so that they can work elsewhere in more pleasant, more advantageous conditions, with the necessary breaks. Before studying the trajectory of a tracer point, through the command laws in the active kinematic clutch space of the robot, the MPz configuration must be set in which the characteristic point occupies the initial and final positions. In the general case, the trajectory of the characteristic point of MPz is materialized by a curve in 3D geometric space, a curve that can be obtained by interpolation on specific portions, depending on the set points of precision. For the manipulation of an object between the initial and the final positions, the following work operations are required: grip (in the initial position), lifting-detachment (by the laying surface), displacement (to the final position, descent) and release (in the final position).

Keywords: Mechanism, Robots, Mechatronics, Mechanical Systems, Optimal Trajectories

Introduction

The development and diversification of machines and mechanisms with applications in all fields require new scientific researches for the systematization and improvement of existing mechanical systems by creating new mechanisms adapted to modern requirements, which involve increasingly complex topological structures.

The modern industry, the practice of designing and building machinery is increasingly based on the results of scientific and applied research.

Each industrial achievement has backed theoretical and experimental computer-assisted research, which solves increasingly complex problems with advanced computing programs using an increasingly specialized software.

The robotization of technological processes determines and influences the emergence of new industries, applications under special environmental conditions, the approach of new types of technological operations, manipulation of objects in the alien space, teleoperators in the top disciplines like medicine, robots covering a whole field greater service provision in our modern, computerized society.

Movable, robotic, mechatronic mechanical systems have entered nearly all industrial spheres.

Today, we can no longer conceive of industrial production without these extremely useful systems. They are still said to steal from people's jobs.

Even so, it should be made clear that these systems create value, work in difficult, repetitive, non-pausing, high-quality work, without getting tired, without getting sick, without salary, and producing value who are paid and people left without jobs, so that they can work elsewhere in more pleasant, more advantageous conditions, with the necessary breaks. In other words, robots do not destroy people but help them in the process of work.

Let us not remember the fact that in some environments people could not even work. In fact, the robot's profitability for work without stopping, repetitive, and qualitative, is no longer in question. In addition, there are many heavy operations that are absolutely necessary for the presence of robots.

You can’t create microchips with people directly without interposing the robot. Man can not directly work with objects of such small size. Neither difficult medical operations can be designed without robotic mechatronic systems.

The most used robotic mechanical mechanical systems are the anthropomorphic ones in the class of serial systems. To this we have studied the direct kinematics in previous castings, and in this paper we are going to study the inverse kinematics.

As examples of such combined mechanisms, several kinematic schemes of gears and gears can be observed, presented by Kojevnikov (1969), AUTORENKOLLEKTIV (1968); Şaskin (1963; 1971); Maros (1958); Rehwald *et al.* (200; 2001); Antonescu (1993; 2003; Antonescu and Mitrache, 1989).

The main problems with plane and spatial gears and gears refer to kinematic analysis and geometric-kinematic synthesis under certain conditions imposed by technological processes, Bruja and Dima (2011); Buda and Mateucă (1989); Luck and Modler (2013); Niemeyer (2000); Tutunaru (1969); Popescu (1977); Braune (2000); Dudita (1989); Lichtenheldt (1995); Lederer (1993); Lin (1999); Modler and Wadewitz (1998; 2001; Modler, 1979); Neumann (1979; 2001); Stoica (1977); (Petrescu and Petrescu, 2011c-d; Petrescu, 2012d-e); (Petrescu, 2016, 2017a-q; Aversa *et al.*, 2017a-e; 2016a-o; Mirsayar *et al.*, 2017; Petrescu and Petrescu, 2016a-c; 2013a-d; 2012a-d; 2011a-b; Petrescu, 2012a-c; 2009; Petrescu and Calautit, 2016a-b; Petrescu *et al.*, 2016a-b; Maros, 1958; Modler and Wadewitz, 2001; Manolescu *et al.*, 1968; Margine, 1999).

Materials and Methods

Before studying the trajectory of a tracer point, through the command laws in the active kinematic clutch space of the robot, the MPz configuration must be set in which the characteristic point occupies the initial and final positions.

In the general case, the trajectory of the characteristic point of MPz is materialized by a curve in 3D geometric space, a curve that can be obtained by interpolation on specific portions, depending on the set points of precision.

For the manipulation of an object between the initial and the final positions, the following work operations are required: grip (in the initial position), lifting-detachment (by the laying surface), displacement (to the final position, descent) and release (in the final position).

According to these operations, four distinct positions (Fig. 1) are identified at the level of each kinematic coupler (actuators): initial, lifting, displacement, approach and final.

The extremes of the "motion trajectory" of the motion law at the level of a motor kinematic couple must be within the physical and geometric limits of MPz.

The time intervals t_1 - t_0, t_3 - t_2 (Fig. 1), of the initial (0–1) and final (2–3) segments, correspond to the speed of advancement of the griper (gripping device) to and from the surface of the manipulated object. These times are a constant parameter and are a function of the electric drive motor characteristic of each active kinematic coupler.

In intermediate time $t_2 - t_1$, corresponding to the middle segment 1–2, the maximum velocity and angular acceleration values occur in the relative movement of an arm j relative to the adjacent one j–1.

To optimize motion (from motor kinematic couplers) the maximum of this time $(t_2–t_1)_{max}$ is used which corresponds to the maximum time of the active kinematic coupler at the lowest speed.

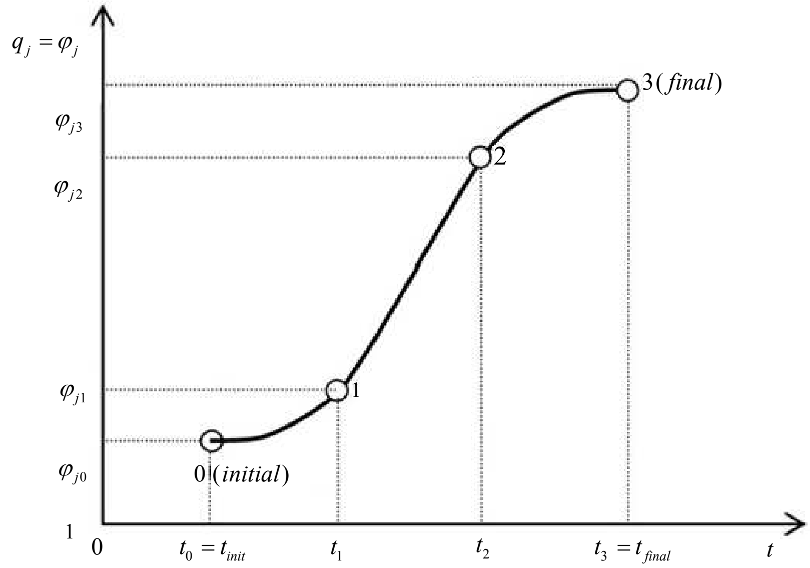

Fig. 1: At the level of each kinematic coupler motors (actuators), four distinct positions are identified: Initial, lifting, displacement, approach and final

At both intermediate points 1 and 2 the control function curve, the position (as instantaneous displacement), the speed and the acceleration must meet the continuity conditions with respect to the anterior 0-1 respective posterior 2-3 segment.

To satisfy these continuity requirements at all four known points (0,1,2,3), polynomial functions whose first two derivatives are continuous over time will be used (t_0, t_3).

Given the initial conditions imposed on the trajectory of the tracer point, the following balance of unknown results for the control function (of a motor kinematic coupler):

- An unknown position φ_0 is represented at the starting point 0
- In the points 1 and 2 there are 2×3 = 6 unknown (position, speed, acceleration): $\phi_1, \dot{\phi}_1, \ddot{\phi}_1; \phi_2, \dot{\phi}_2, \ddot{\phi}_2$
- There is only one unknown ϕ_3 at the ending point 3: The angular position ϕ_3
- The 8 unknowns can be the coefficients of a 7th degree polynomial function interpolating the entire trajectory within the specified time interval $t_3 - t_0$

Such a polynomial function is written for the leading kinematic couple j as:

$$q_j(t) = \sum_{k=0}^{7} a_k t^k = a_7 t^7 + a_6 t^6 + a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0 \quad (1)$$

The extremes of such a grade 7 polynomial function tend to be placed outside the range of movement of the kinematic coupler and the robot arms.

A practical and efficient approach as a whole consists in dividing the entire trajectory of the tracer point and the command line curve into multiple segments, so that polynomials of less than 7 degree can be used to interpolate each trajectory segment.

There are several possibilities of dividing the trajectory at the motor kinematic couple, these variants having 3, 4 or 5 distinct portions.

The most convenient variants are those with 3 portions, with 3 polynomials of 4-3-4 or 3-5-3.

The 5-part variant uses 5 polynomials of the same grade 3, ie 3-3-3-3-3.

For a trajectory where the control law is modeled with polynomial 4-3-4, a Mp with n kinematic motor couplings (c.c.m.) will obtain 3n segments of curve and 8n coefficients.

Results

Synthesis of Interpolation Polymorphs Type 4-3-4

For each trajectory segment, a variable (non-dimensional) of standard time $t \in [0,1]$ is introduced for the c.c.m. level, which allows for the similar solving of each curve portion for the motion law of each c.c.m. (as the relative rotation angle of the arm).

The normed time varies from $t = 0$ (the initial time of each trajectory segment to the c.c.m.) to $t = 1$ (the final time for each of the segments of the control law curve of c.c.m.).

Real time τ is defined in seconds, whose variation is between the τ_{i-1} (minimum) and τ_i (maximum) limits, ie $\tau \in [\tau_{i-1}, \tau_i]$.

The normalized time is calculated using the formula:

$$t = \frac{\tau - \tau_{i-1}}{\tau_i - \tau_{i-1}} \in [0, 1] \quad (2)$$

The curve of the motion law of a cc.c. consists of polynomial segments $p_i(t)$ which together form the variation curve of the control law of c.c.m. *j*.

The three polynomial functions for each c.c.m. are:

$$p_1(t) = a_{14}t^4 + a_{13}t^3 + a_{12}t^2 + a_{11}t + a_{10} \quad (3)$$

$$p_2(t) = a_{23}t^3 + a_{22}t^2 + a_{21}t + a_{20} \quad (4)$$

$$p_3(t) = a_{34}t^4 + a_{33}t^3 + a_{32}t^2 + a_{31}t + a_{30} \quad (5)$$

The boundary conditions to be satisfied by the functions (13.3, 4, 5) at a c.c.m. of rotation are:

Point 0: $\phi_0 = \phi(t_0);\ \omega_0 = 0;\ \varepsilon_0 = 0;$

Point 1: $\phi_1 = \phi(t_1);\ \phi(t_1^-) = \phi(t_1^+);\ \omega(t_1^-) = \omega(t_1^+);\ \varepsilon(t_1^-) = \varepsilon(t_1^+);$

Point 2: $\phi_2 = \phi(t_2);\ \phi(t_2^-) = \phi(t_2^+);\ \omega(t_2^-) = \omega(t_2^+);\ \varepsilon(t_2^-) = \varepsilon(t_2^+);$

Point 3: $\phi_3 = \phi(t_3); \omega_3 = 0; \varepsilon_3 = 0.$

Polynomial equations (3, 4, 5) are derived from real time τ:

$$\begin{aligned} \omega_i(t) &= \frac{dp_i(t)}{d\tau} = \frac{dt}{d\tau} \cdot \frac{dp_i(t)}{dt} = \\ &= \frac{1}{\tau_i - \tau_{i-1}} \cdot \frac{dp_i(t)}{dt} = \frac{1}{\Delta\tau_i} \cdot \dot{p}_i(t); \quad i = 1,2,3,4 \end{aligned} \quad (6)$$

$$\begin{aligned} \varepsilon_i(t) &= \frac{d^2 p_i(t)}{d\tau^2} = \left(\frac{dt}{d\tau}\right)^2 \cdot \frac{d^2 p_i(t)}{dt^2} = \\ &= \frac{1}{(\tau_i - \tau_{i-1})^2} \cdot \frac{d^2 p_i(t)}{dt^2} = \frac{1}{(\Delta\tau_i)^2} \cdot \ddot{p}_i(t); \\ i &= 1,2,3,4 \end{aligned} \quad (7)$$

On the interval (0-1), from the polynomial (3), the velocity and the angular acceleration are deduced using formulas (6, 7):

$$\omega_1(t) = \frac{1}{\Delta\tau_1}(4a_{14}t^3 + 3a_{13}t^2 + 2a_{12}t + a_{11}) \quad (8)$$

$$\varepsilon_1(t) = \frac{1}{\Delta\tau_1^2}(12a_{14}t^2 + 6a_{13}t + 2a_{12}) \quad (9)$$

For $t = 0$ Equations (3, 8, 9) become:

$$\begin{aligned} &\phi_1(0) = a_{10}; \Rightarrow a_{10} = \phi_0; \\ &\omega_1(0) = \frac{1}{\Delta\tau_1}a_{11}; \Rightarrow a_{11} = \omega_0 \Delta\tau_1 = 0 \\ &\varepsilon_1(0) = \frac{2}{\Delta\tau_1^2}a_{12}; \Rightarrow a_{12} = \frac{1}{2}\varepsilon_0 \Delta\tau_1^2 = 0 \end{aligned} \quad (10)$$

Under these conditions Equation (3) is written:

$$p_1(t) = a_{14}t^4 + a_{13}t^3 + \phi_0 \quad (11)$$

For $t = 1$ Equations (3, 8, 9) become:

$$\phi_1(1) = a_{14} + a_{13} + \phi_0 \quad (12)$$

$$\omega_1(1) = \frac{1}{\Delta\tau_1}(4a_{14} + 3a_{13}) \quad (13)$$

$$\varepsilon_1(1) = \frac{6}{\Delta\tau_1^2}(2a_{14} + a_{13}) \quad (14)$$

On the interval (1-2), from the polynomial Equation (4), the following formulas are obtained by derivation:

$$\omega_2(t) = \frac{1}{\Delta\tau_2}(3a_{23}t^2 + 2a_{22}t + a_{21}) \quad (15)$$

$$\varepsilon_2(t) = \frac{1}{\Delta\tau_1^2}(6a_{23}t + 2a_{22}) \quad (16)$$

For $t = 0$, the Equations (4, 15, 16) become:

$$\phi_2(0) = a_{20}; \omega_2(0) = \frac{1}{\Delta\tau_2}a_{21};\ \varepsilon_2(0) = \frac{2}{\Delta\tau_2^2}a_{22} \quad (17)$$

From the continuity conditions in point 1 the equivalences result:

$$\phi_2(0) = \phi_1(1); \omega_2(0) = \omega_1(1); \varepsilon_2(0) = \varepsilon_1(1) \quad (18)$$

Or explicitly, observing the relationships (12, 13, 14, 17):

$$\begin{aligned} &a_{20} = a_{14} + a_{13} + \phi_0 \\ &\frac{1}{\Delta\tau_2}a_{21} = \frac{1}{\Delta\tau_1}(4a_{14} + 3a_{13}) \\ &\frac{2}{\Delta\tau_2^2}a_{22} = \frac{6}{\Delta\tau_1^2}(2a_{14} + a_{13}) \end{aligned} \quad (19)$$

For $t = 1$ Equations (4, 15, 16) become:

$$\phi_2(1) = a_{23} + a_{22} + a_{21} + a_{20} \quad (20)$$

$$\omega_2(1) = \frac{1}{\Delta\tau_2}(3a_{23} + 2a_{22} + a_{21}) \tag{21}$$

$$\varepsilon_2(1) = \frac{2}{\Delta\tau_1^2}(3a_{23} + a_{22}) \tag{22}$$

On the interval (2-3), the polynomial Equation (5) is written (if replaced $\overline{t} = t - 1$):

$$\phi_3(\overline{t}) = a_{34}\overline{t}^4 + a_{33}\overline{t}^3 + a_{32}\overline{t}^2 + a_{31}\overline{t} + a_{30} \tag{23}$$

In which for $t \in [0, 1]$ to deduce $\overline{t} \in [-1, 0]$.

From (23) we obtain, by derivation, the formulas of velocity and angular acceleration in the form:

$$\omega_3(\overline{t}) = \frac{1}{\Delta\tau_3}(4a_{34}\overline{t}^3 + 3a_{33}\overline{t}^2 + 2a_{32}\overline{t} + a_{31}) \tag{24}$$

$$\varepsilon_3(\overline{t}) = \frac{1}{\Delta\tau_3^2}(12a_{34}\overline{t}^2 + 6a_{33}\overline{t} + 2a_{32}) \tag{25}$$

For t = 0 and $\overline{t} = -1$ the Equations (23, 24, 25) are written:

$$\phi_3(-1) = a_{34} - a_{33} + a_{32} - a_{31} + a_{30} \tag{26}$$

$$\omega_3(-1) = \frac{1}{\Delta\tau_3}(-4a_{34} + 3a_{33} - 2a_{32} + a_{31}) \tag{27}$$

$$\varepsilon_3(-1) = \frac{1}{\Delta\tau_3^2}(12a_{34} - 6a_{33} + 2a_{32}) \tag{28}$$

The continuity conditions of point 2 are written:

$$\phi_3(-1) = \phi_2(1);\ \omega_3(-1) = \omega_2(1);\ \varepsilon_3(-1) = \varepsilon_2(1) \tag{29}$$

Or explicitly, observing relations (20, 21, 22) and (26, 27, 28):

$$a_{34} - a_{33} + a_{32} - a_{31} + a_{30} = a_{23} + a_{22} + a_{21} + a_{20} \tag{30}$$

$$\frac{1}{\Delta\tau_3}(-4a_{34} + 3a_{33} - 2a_{32} + a_{31}) = \frac{1}{\Delta\tau_2}(3a_{23} + 2a_{22} + a_{21}) \tag{31}$$

$$\frac{1}{\Delta\tau_3^2}(12a_{34} - 6a_{33} + 2a_{32}) = \frac{1}{\Delta\tau_2^2}(6a_{23} + 2a_{22}) \tag{32}$$

For $t = 1\,(\overline{t} = 0)$, Equations (26, 27, 28) derive the free terms:

$$\phi_3(0) = a_{30}$$
$$\omega_3(0) = \frac{1}{\Delta\tau_3}a_{31}; \Rightarrow a_{31} = 0 \tag{33}$$
$$\varepsilon_3(0) = \frac{2}{\Delta\tau_3^2}a_{32}; \Rightarrow a_{32} = 0$$

Finally, the following equations are retained: (10, 10', 10''), (12, 19, 19', 19''), (20, 30, 31, 32), 33, 33', 33''), whose expressions are:

$$a_{10} = \varphi_0; a_{11} = 0; a_{12} = 0; a_{13} + a_{14} = \varphi_1 - \varphi_0; a_{20} = a_{13} + a_{14} + \varphi_0;$$
$$3a_{13} + 4a_{14} = (\Delta\tau_1 / \Delta\tau_2).a_{21};\ 3(a_{13} + 2a_{14}) = (\Delta\tau_1 / \Delta\tau_2)^2.a_{22};$$
$$a_{20} + a_{21} + a_{22} + a_{23} = \varphi_2; a_{20} + a_{21} + a_{22} + a_{23} = a_{30} - a_{31} + a_{32} - a_{33} + a_{34};$$
$$a_{21} + 2a_{22} + 3a_{23} = (\Delta\tau_2 / \Delta\tau_3).(a_{31} - 2a_{32} + 3a_{33} - 4a_{34});$$
$$2a_{22} + 3a_{23} = (\Delta\tau_2 / \Delta\tau_3)^2.(a_{32} - 3a_{33} + 6a_{34}$$
$$a_{30} = \varphi_3; a_{31} = 0; a_{32} = 0.$$

Of the 14 Equations there are finally only 7 distinct equations:

$$a_{13} + a_{14} = \varphi_1 - \varphi_0; \tag{1*}$$

$$a_{13} + a_{14} + a_{21} + a_{22} + a_{23} = \varphi_2 - \varphi_0; \tag{2*}$$

$$a_{13} + a_{14} + a_{21} + a_{22} + a_{23} + a_{33} - a_{34} = \varphi_3 - \varphi_0; \tag{3*}$$

$$3a_{13} + 4a_{14} = (\Delta\tau_1 / \Delta\tau_2).a_{21}; \tag{4*}$$

$$3(a_{13} + 2a_{14}) = (\Delta\tau_1 / \Delta\tau_2)^2.a_{22}; \tag{5*}$$

$$a_{21} + 2a_{22} + 3a_{23} = (\Delta\tau_2 / \Delta\tau_3).(3a_{33} - 4a_{34}); \tag{6*}$$

$$2a_{22} + 3a_{23} = 3(\Delta\tau_2 / \Delta\tau_3)^2.(a_{33} + 2a_{34}. \tag{7*}$$

Discussion

In Equations (1^*) - (7^*) the real time ranges are known $\Delta\tau_1 = \tau_1 - \tau_0$; $\Delta\tau_2 = \tau_2 - \tau_1$; $\Delta\tau_3 = \tau_3 - \tau_2$; and the relative ($\varphi_1 - \varphi_0$), ($\varphi_2 - \varphi_0$), ($\varphi_3 - \varphi_0$).

Of the 7 Equations we obtain the 7 unknown ones, respectively the coefficients:

$$a_{13}, a_{14}, a_{21}, a_{22}, a_{23}, a_{33}, a_{34}$$

Practically, the relative angles are imposed:

$$\phi_{01} = \phi_1 - \phi_0 = \phi_1(1) - \phi_1(0) = a_{14} + a_{13} \tag{34}$$

$$\phi_{12} = \phi_2 - \phi_1 = \phi_2(1) - \phi_2(0) = a_{23} + a_{22} + a_{21} \tag{35}$$

$$\phi_{23} = \phi_3 - \phi_2 = \phi_3(-1) - \phi_3(0) = a_{34} - a_{33} \tag{36}$$

The coefficients $a_{14}, a_{13}, a_{23}, a_{22}, a_{21}, a_{34}, a_{33}$ are calculated as solutions of the linear system formed by Equations (34, 35, 36), plus two equations equivalent to the last two of (19) and two equations equivalent to relations (31, 32):

$$\frac{1}{\Delta\tau_2}a_{21} = \frac{1}{\Delta\tau_1}(4a_{14} + 3a_{13}) \quad (37)$$

$$\frac{1}{\Delta\tau_2^2}a_{22} = \frac{3}{\Delta\tau_1^2}(2a_{14} + a_{13}) \quad (38)$$

$$\frac{1}{\Delta\tau_3}(-4a_{34} + 3a_{33}) = \frac{1}{\Delta\tau_2}(3a_{23} + 2a_{22} + a_{21}) \quad (39)$$

$$\frac{3}{\Delta\tau_3^2}(2a_{34} - a_{33}) = \frac{1}{\Delta\tau_2^2}(3a_{23} + a_{22}) \quad (40)$$

In the last four equations, time intervals are required:

$$\Delta\tau_1 = \tau_1 - \tau_0;\ \Delta\tau_2 = \tau_2 - \tau_1;\ \Delta\tau_3 = \tau_3 - \tau_2$$

Corresponding to the three angular displacement intervals of the first three equations.

Conclusion

The kinematics of robots is the one that corresponds to the daily reality in which the robots are programmed to work in order to perform certain operations, to observe some imposed trajectories so that they move precisely to achieve and achieve the desired trajectory and all necessary kinematic parameters.

Before studying the trajectory of a tracer point, through the command laws in the active kinematic clutch space of the robot, the MPz configuration must be set in which the characteristic point occupies the initial and final positions. In the general case, the trajectory of the characteristic point of MPz is materialized by a curve in 3D geometric space, a curve that can be obtained by interpolation on specific portions, depending on the set points of precision. For the manipulation of an object between the initial and the final positions, the following work operations are required: Grip (in the initial position), lifting-detachment (by the laying surface), displacement (to the final position, descent) and release (in the final position).

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Author's Contributions

All the authors contributed equally to prepare, develop and carry out this manuscript.

Ethics

This article is original. Authors declare that are not ethical issues that may arise after the publication of this manuscript.

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Source of Figure:

Fig. 1: Petrescu and Petrescu, 2011b