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KINEMATICS OF POSITIONING DEVICE FOR MATERIAL HANDLING IN MANUFACTURING

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Abstract: Different types of robots are used in many areas of industry. Industrial manipulators are used to ensure productivity and flexibility in automated production lines. Most of them is used for tasks that automatically repeat the same operation in a familiar environment. The key element in the development and analysis of industrial robots is their kinematic analysis. The article deals with the kinematic analysis of this positioning equipment. Individual relations of kinematic quantities are plotted graphically. Matrix methods were used for the analysis.

1 Introduction

People have thousands of sensations, movement and intelligence that coordinates them and adapts them to their current environment. Industrial robot has only a few sensors and the ability to perform certain movements, but without a human assistance it lacks the intelligence to adapt to its new task. In manufacturing, individual robots are programmed to perform one group of tasks and need to be reprogrammed for another group of tasks. The main difference between a human and a robot is flexible decision making. Up until now, robotics technology has not made a large impact in the world of logistics. This is change as advanced robots enter our warehouses, sorting centres, and even help with final delivery. Logistics workers has benefit from collaborating with robots, while customers are seeing faster service and higher quality. The main reason for the lack of logistics robots is techno logical. Until recently, robots have been stationary, blind, and relatively unintelligent. They perform the same movements over and over again thousands of times a day with a high degree of accuracy and precision. For many simple manufacturing processes, such as welding or transferring parts, these skills are all that are needed. The world of logistics, however, is much more complex than manufacturing and requires a robot with more ability.

The automated assembly line connects industrial robotic manipulators and various robotic equipment for material transporting, positioning and moving. The main elements of robots are common to many industrial systems. Individual handling equipment is designed to pick up the material and precisely transport it from one position to another. These devices handle the material in cooperation with a human. This makes it easy for people to manipulate even heavy objects [1-7].

The handling or positioning device can be considered as an open kinematic chain. The basic precondition for the operability of the device is a reliable calculation. The actual construction of the device depends on the calculation of the relevant mechanical quantities, which determine the dimensioning of individual components or nodes of the device [8-15]. The actual calculation is performed after a simplification of the investigated device on a mechanical model, which includes all main parameters of the actual device affecting the behaviour of the device according to its design. For the purpose of a mechanical model, all devices can be in general understood as a bound system of bodies [16-25].

The movement of the mobile robot in the work environment is shown in Figure 1 [3]. Sensors monitor the working environment of the robot with control system and navigating his movement in the production environment. The mobile robot enables communication between the operator and the robots. Depending on the mobile platform, different degrees of automation are added to the control system.

Industrial production currently requires new logistics concepts in the production premises, which are intelligent, versatile, networked, modular and also mobile. Mobile devices should have the ability to work between people and the production line. As well as people deployed in the production of mobile robots, they can monitor the working cycles of the machines, move freely around them and connect the individual production sites and thus create new, highly flexible production units. For example, the mobile and intelligent KMR iiwa is also shown in Figure 1

[3]. An example of a mobile robot model in the workflow environment of a production process made in the MSC Adams program is shown in Figure 2 [[4-8,21]. Each robot contains a gripping device.

Figure 1 Mobile robot KUKA KMR iiwa [3]

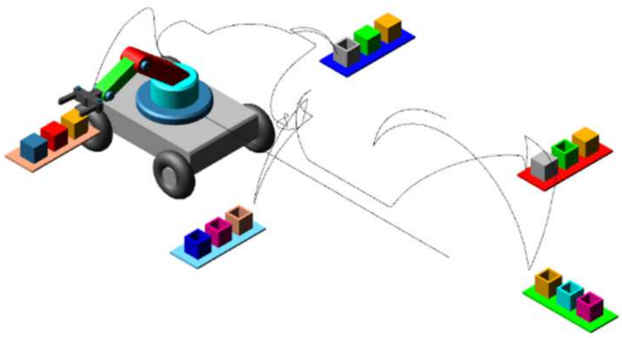

Figure 2 Model of mobile robot in MSC Adams View and trajectory of end-effector [4]

The end effector is a separate part of the robot, which is used to hold the manipulation object - the gripper. In industrial robots, a technological head such as a welding torch, a painting nozzle and the like is often used as an effector. In this paper, we further focus on the gripper representing a mechanism with three degrees of freedom of movement. The kinematic analysis of individual members is given in the following sections.

2 Kinematic analysis of bound systems of bodies

The main principle of analytical kinematic analysis of bound systems is in determination of the relations of geometric quantities describing the position of significant points of the driven members on the position of the driving members [5-10]. Based on the position, the speed and the acceleration of the individual members can be determined.

The kinematic and dynamic analysis of a system of bodies uses software, which are often based on the matrix methods. Individual physical vector quantities are entered in matrix notation. In matrix method the coordinates are transformed. Orthogonal transformation is used for this transformation [4,20].

It is necessary to properly select the coordinate systems of the individual members of the system to simplify the calculation. In the case of a revolute kinematic pair, it is advantageous to select one coordinate axis as the axis of rotation. The remaining axes are selected to suit the shape of the body or the location of the next kinematic pair. With a prismatic kinematic pair, we place one axis in the direction of the linear motion [10-16]. Transformation matrices expressing the respective rotations around the individual axes are used to define the spherical motion. Transformation matrices of relative motions and vectors of the relative positions of the origins of the coordinate systems can be compiled for the selected coordinate systems. This gives the necessary relationships for the numerical calculation of the position vector for the given relative positions of the members of the mechanism [20].

The disadvantage of the derived matrix relations for the position, velocity and acceleration of the kinematic chain is the fact that it is necessary to make products of matrices and vectors but also a number of sums. This makes the expressions rather unclear and the calculations are time consuming. It is convenient to use so-called homogeneous coordinates and work with extended matrices and vectors to eliminate this disadvantage. Matrix relationships for the position, velocity and acceleration of the mechanism can be used for analysis but also for some tasks of mechanism synthesis. The matrix method enables the kinematic analysis of any complex planar and spatial mechanism [4,20].

The movement of a member of the bound system or one of its points is achieved by several simultaneous movements of the system. The movement of the *n*-th member of the system can be expressed by means of a position vector or the parametric equation (1) of the trajectory of the point M

$$r_{1M} = T_{12} \cdot T_{23} \dots T_{n-1,n} r_{n,\mathrm{M}} \tag{1}$$

where T_{1n} is the transformation matrix of the motion n:1 and the following expression (2) applies

$$T_{1n} = \prod_{i=1}^{n-1} T_{i,i+1} \,. \tag{2}$$

The velocity of the point M can be expressed by the relation (3), (4)

$$v_{1M} = T_{14} V_{14} r_{4M}, \tag{3}$$

$$\text{where } V_{14} = V_{12} + V_{23} + V_{34} = T_{34}^{-1} T_{23}^{-1} V_{12}^{(2)} T_{23} T_{34} + T_{34}^{-1} V_{23}^{(3)} T_{34} + V_{34}^{(4)} \tag{4}$$

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Acceleration of any point M (5) of member 4

$$a_{1M} = T_{14} A_{14} r_{4M} \tag{5}$$

where A_{14} (6) is the complete acceleration of member 4 relative to member 1 and is expressed by the relation

$$A_{14} = a_{14} + V_{14}^2 \tag{6}$$

The partial acceleration matrix a_{14} is expressed (7) by the Resal acceleration.

$$a_{14} = \dot{V}_{14} = A_{12} + A_{23} + A_{34} + A_R \tag{7}$$

where A_R (8) is Resal acceleration and is expressed by the relation.

$$A_R = (V_{12}V_{23} - V_{23}V_{12}) + (V_{12}V_{34} - V_{34}V_{12}) + (V_{23}V_{34} - V_{34}V_{23}) \tag{8}$$

3 Movement of members of the positioning device

Diagram of the positioning device in the Figure 3, represents an open kinematic chain with three degrees of freedom of movement. For the positioning device, the equations of motion of the point M of the member 4 with respect to the other members were derived. The configuration in Figure 3 corresponds to the position of the device in time $t = 0\,s$.

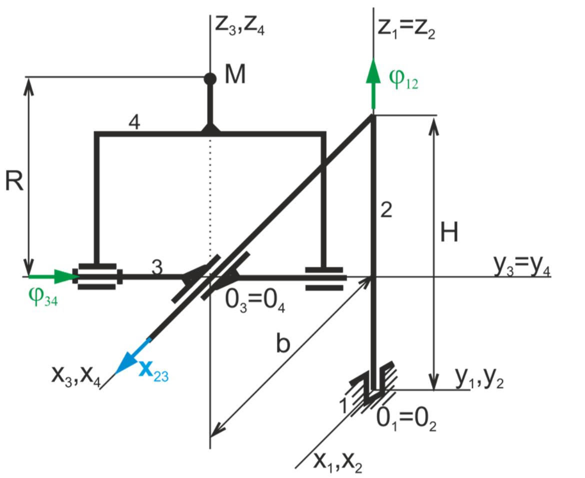

Figure 3 Positioning device in the initial position in time t = 0 s

Local coordinate systems are introduced in individual members of the system, Figure 3. During the relative motion of member 2 to member 1, the z-axis remains identical in each position ($z_1 = z_2$). The coordinate axes x_2, y_2 are identical to the axes x_1, y_1 only in the initial position for time $t = 0\,s$. The member 2 performs a rotational movement with respect to the base 1 and the rotation angle φ_{12} of the member 2 relative to base 1 is function of time. The origin of the coordinate system of member 3 is shifted by the value H in the direction of the z-axis and by a value b in the direction of the axis x_3 of member 2. Member 3 performs a sliding movement with respect to member 2, where $x_{23} = x_{23}(t)$. The member 4 rotates about the axis $y_3 = y_4$ of the member 3 by an angle $\varphi_{34} = \varphi_{34}(t)$. The position of the end point M of the member 4 is at a distance R.

The matrix equation of the trajectory of point M of the positioning device is (9)

$$r_{1M} = T_{12} \cdot T_{23} \cdot T_{34} r_{4M} \tag{9}$$

The respective transformation matrices (10), (11), (12) of basic movements of the positioning device are

$$T_{12} = T_{\varphi_z}(\varphi_{12}) = \begin{bmatrix} c\varphi_{12} & -s\varphi_{12} & 0 & 0 \\ s\varphi_{12} & c\varphi_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$T_{23} = T_{p_x}(x_{23}) = \begin{bmatrix} 1 & 0 & 0 & (b + x_{23}) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & H \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$T_{34} = T_{\varphi_y}(\varphi_{34}) = \begin{bmatrix} c\varphi_{34} & 0 & s\varphi_{34} & 0 \\ 0 & 1 & 0 & 0 \\ -s\varphi_{34} & 0 & c\varphi_{34} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

The transformation matrix (13) of member 4 with respect to member 1 is

$$T_{14} = T_{12} \cdot T_{23} \cdot T_{34} = \begin{bmatrix} c\varphi_{12}c\varphi_{34} & -s\varphi_{12} & c\varphi_{12}s\varphi_{34} & (b + x_{23})c\varphi_{12} \\ s\varphi_{12}c\varphi_{34} & c\varphi_{12} & s\varphi_{12}s\varphi_{34} & (b + x_{23})s\varphi_{12} \\ -s\varphi_{34} & 0 & c\phi_{34} & H \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

substituting equations (3) to (5) into (1) and (2) we get the equation of the trajectory of point M of member 4 in the coordinate system of base 1 using the basic matrices (14):

$$r_{1M} = T_{12}.T_{23}.T_{34}.r_{4M} \tag{14}$$

The extended position vector (15) of the point M in the space of the member 4 is

$$r_{4M} = [0 \quad 0 \quad R \quad 1]^T \tag{15}$$

Position vector (16) of point M with respect to the coordinate system O_1, x_1, y_1, z_1.

$$r_{1M} = T_{14}.r_{4M} = \begin{bmatrix} c\varphi_{12}(b + x_{23}) + Rc\varphi_{12}s\varphi_{34} \\ s\varphi_{12}(b + x_{23}) + Rs\varphi_{12}s\varphi_{34} \\ H + Rc\varphi_{34} \\ 1 \end{bmatrix} \quad (16)$$

Three variants of the input parameters were selected to calculate the movement of the positioning device. They are listed in Table 1.

Table 1 Input parameters

	$\dot{\varphi}_{12}$ (rad/s)	$\dot{\varphi}_{34}$ (rad/s)	$\dot{x}_{23}$ (m/s)
P1	1	1	1
P2	0.5	0.5	1
P3	0.35	0.35	1

Figure 4 shows the trajectory of the point M for respective input data according to Table 1. The relations of the individual components of the position vector are for variants P1 to P3 in Figure 4 to Figure 6.

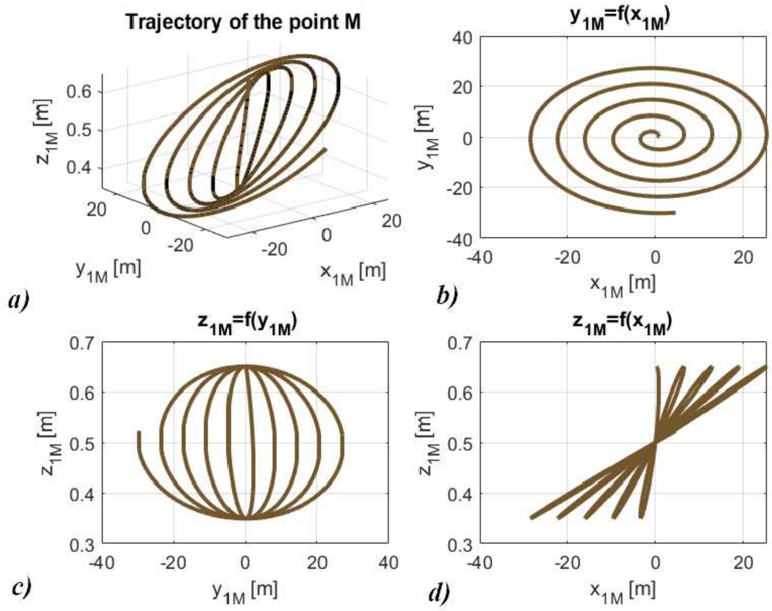

Figure 4 Trajectory of the movement of the point M for the input data P1: a) input data P1, b) y = y (x), c) z = z (y), d) z = z (x)

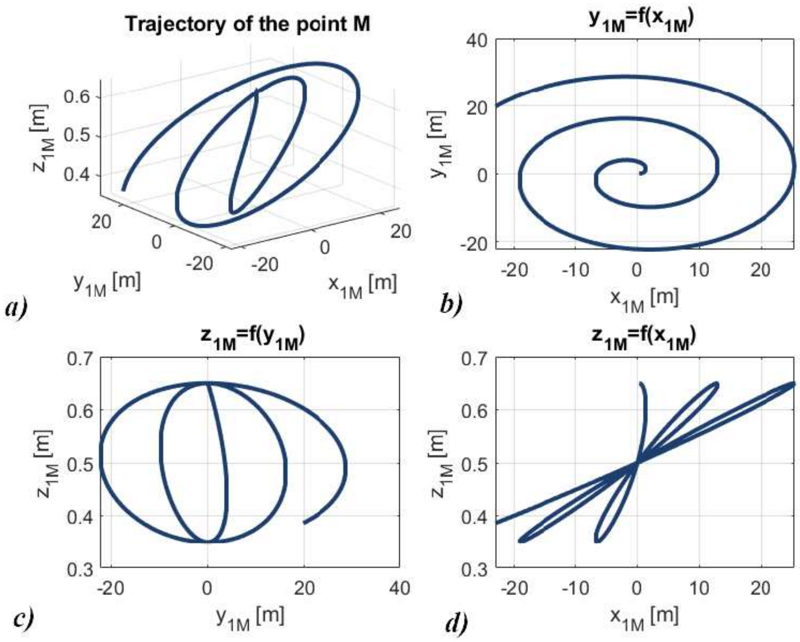

Figure 5 Trajectory of the movement of the point M for the input data P2: a) input data P2, b) y = y (x), c) z = z (y), d) z = z (x)

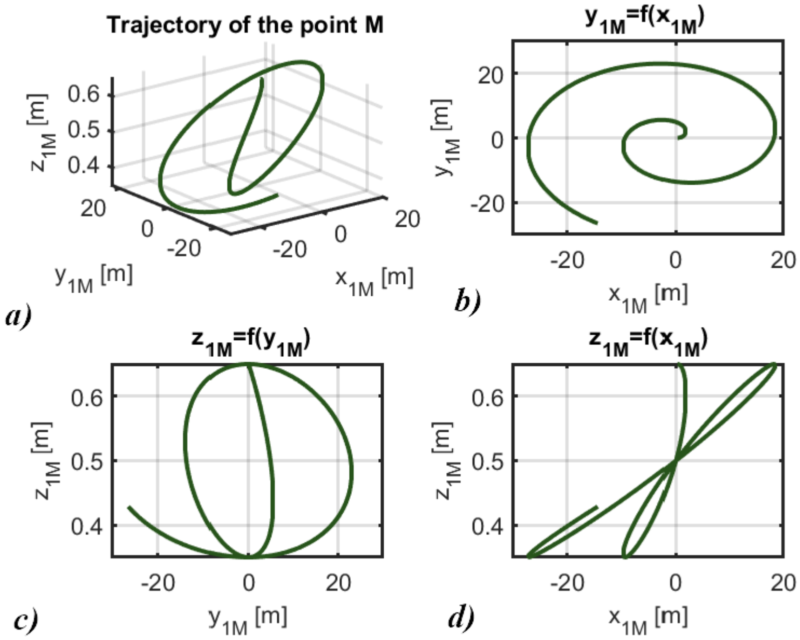

Figure 6 Trajectory of the point M for the input data P3: a) input data P3, a) y = y (x), b) z = z (y), c) z = z (x)

Figure 7 shows the time graph of the position vector of the point M for respective input parameters.

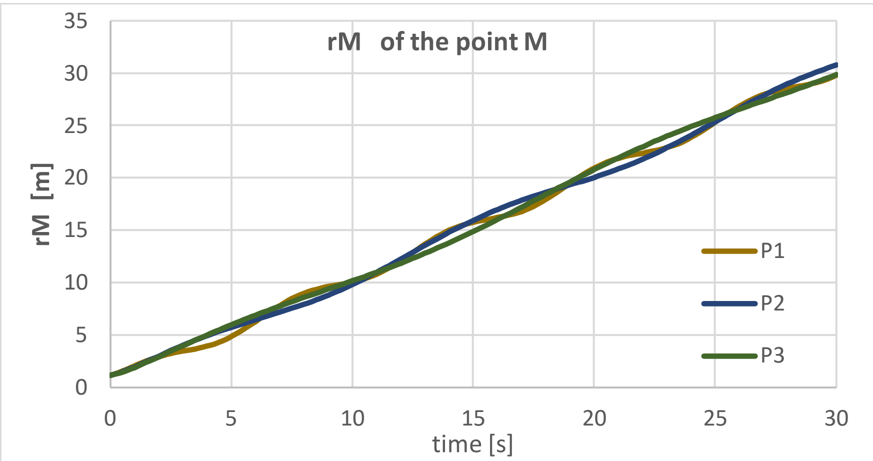

Figure 7 Time graph of the position vector

The mathematical expression of the components of the velocity vector (17) is

$$v_{1M} = T_{14}V_{14}r_{4M} = \begin{bmatrix} \left(R\dot{\varphi}_{34}c\varphi_{34} + \dot{x}_{23}\right)c\varphi_{12} - \left(b + x_{23} + Rs\varphi_{34}\right)\dot{\varphi}_{12}s\varphi_{12} \\ \left(R\dot{\varphi}_{34}c\varphi_{34} + \dot{x}_{23}\right)s\varphi_{12} + \left(b + x_{23} + Rs\varphi_{34}\right)\dot{\varphi}_{12}c\varphi_{12} \\ -R\dot{\varphi}_{34}s\varphi_{34} \\ 0 \end{bmatrix} \tag{17}$$

The relation of the velocity vector of the point M with respect to the basic coordinate system O_1, x_1,y_1, z_1 for the individual input parameters is shown in Figure 8.

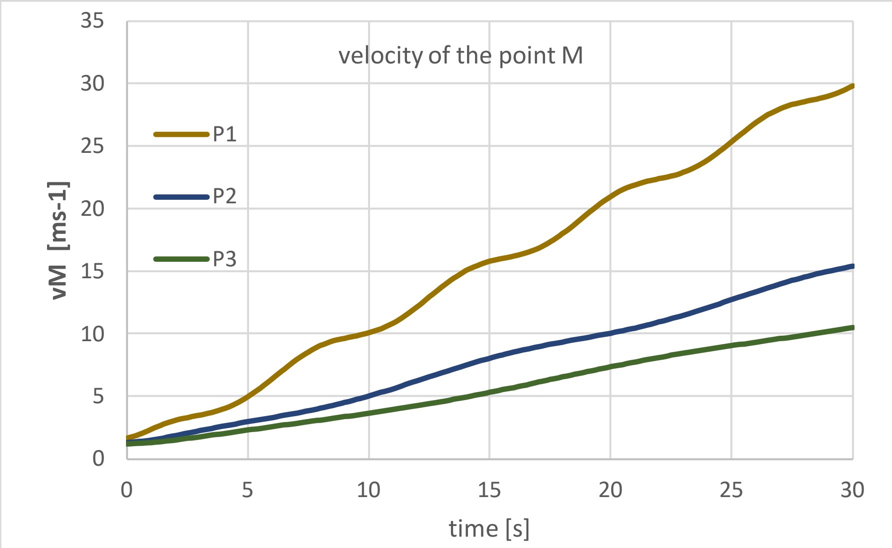

Figure 8 Time graph of the velocity vector

The acceleration components of point M with respect to base 1 are (18), (19), (20).

$$a_{1Mx} = \left(R\ddot{\varphi}_{34}c\varphi_{34} + \ddot{x}_{23} - R\dot{\varphi}_{34}^2 s\varphi_{34}\right)c\varphi_{12} - \left(b + x_{23} + Rs\varphi_{34}\right)\ddot{\varphi}_{12}s\varphi_{12} - \\ -\left(b + x_{23} + Rs\varphi_{34}\right)\dot{\varphi}_{12}^2 c\varphi_{12} - 2\dot{\varphi}_{12}\left(R\dot{\varphi}_{34}c\varphi_{34} + \dot{x}_{23}\right)s\varphi_{12} \quad (18)$$

$$a_{1My} = \left(R\ddot{\varphi}_{34}c\varphi_{34} + \ddot{x}_{23} - R\dot{\varphi}_{34}^2 s\varphi_{34}\right)s\varphi_{12} + \left(b + x_{23} + Rs\varphi_{34}\right)\ddot{\varphi}_{12}c\varphi_{12} - \\ -\left(b + x_{23} + Rs\varphi_{34}\right)\dot{\varphi}_{12}^2 s\varphi_{12} + 2\dot{\varphi}_{12}\left(R\dot{\varphi}_{34}c\varphi_{34} + \dot{x}_{23}\right)c\varphi_{12} \quad (19)$$

$$a_{1Mz} = -R\ddot{\varphi}_{34}s\varphi_{34} - R\dot{\varphi}_{34}^2 c\varphi_{34} \quad (20)$$

The relation of the acceleration vector of the point M with respect to the basic coordinate system O_1, x_1,y_1, z_1 for individual input parameters is shown in Figure 9.

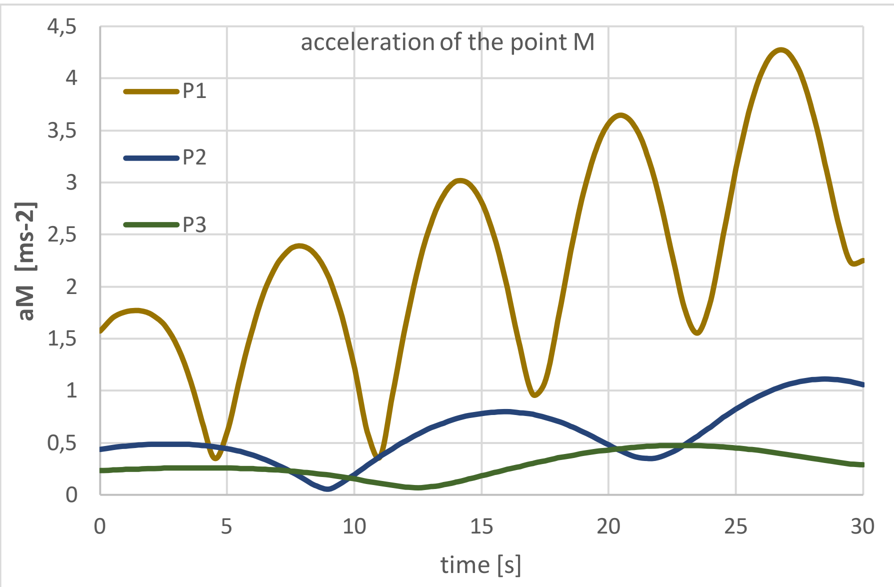

Figure 9 Time graph of the acceleration vector

4 Conclusions

The movement of individual members of the positioning device was addressed. Software was used to compile and evaluate matrices describing the movement of device members. The article presents the procedure for solving the problem of kinematic analysis of mechanisms by matrix notation, the principle of which are used by individual software for kinematic and dynamic analysis. The results are in the form of a time graph of the individual parameters determining the movement. At the same time, the trajectory of the movement of the positioning device endpoint is plotted depending on the individual coordinates. The contribution of the paper is mainly in the didactic area as a suitable tool for solving the problems of kinematics of the motion of a mechanism.

The results of the solution position, speed and acceleration of the robot endpoint for the selected member speeds are shown graphically. From the calculated kinematic quantities, we see that the movement of the end point of the robot is uniform at lower speeds. At higher speeds, the course of the dependence of the position vector on time acquires a sinusoidal character, which can be seen in the graphs.

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