

# INTEGRATION OF ANALYTICAL METHODS AND COMPUTER SIMULATION IN KINEMATIC MECHANISM ANALYSIS

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**Abstract:** This paper deals with the kinematic analysis of multi-member mechanisms and robotic manipulators using MSC ADAMS simulation software. Attention is focused primarily on the analysis of trajectories, positions, velocities and accelerations of selected points of mechanisms, as well as the determination of the working space of manipulators. Analytical relationships and numerical calculations performed in the MATLAB environment were used to solve direct and inverse kinematics tasks, and the resulting trajectories were subsequently verified using simulations in MSC ADAMS. The results obtained confirm the suitability of integrating analytical methods and computer simulation for accurate analysis of the motion of mechanical systems, effective trajectory planning and visualisation of the behaviour of mechanisms in real operating conditions.

## KEYWORDS

kinematics, multi-link mechanisms, robotic manipulator, motion trajectory, workspace, inverse kinematics

## 1 INTRODUCTION

The development and application of modern mechanical and robotic systems place increasingly high demands on precision, efficiency, safety and movement adaptation. With the growing development of mechanisms — whether industrial manipulators, parallel manipulators or specialised mechanisms — the ability to analytically evaluate kinematics, define the workspace, plan trajectories and predict movement possibilities and potential collisions is becoming crucial [Vagas 2025].

Modern production lines today depend on the use of industrial robots [Demcak 2024]. Robotic arms on fixed or mobile platforms are used for various types of object handling. Initially, robotic arms were mounted on fixed platforms. Gradually, development progressed to robots with two or even more arms. They progressed from arms on fixed platforms to arms on mobile chassis, which brought greater flexibility of movement. Mobile robots can be used for remote handling in the production process [Baskar 2022, Brada 2023, Carbone 2026].

Recently, there have been a number of new research studies and publications introducing advanced methods for kinematic analysis and motion planning. These methods not only take into account basic kinematic equations, but also integrate trajectory planning, parameter optimisation, workspace feature detection, and adaptation to real-world conditions (collisions, dynamics, redundancy).

When designing and using robotic manipulators or multi-member mechanisms, it is essential to know their workspace,

i.e., the set of positions and orientations that the effector or mechanism members can occupy. Workspace analysis helps to reveal [Ceccarelli 2024]:

- geometric limits of movement,
- areas where singularities or loss of controllability occur,
- possible collisions or self-collision arrangements,
- the effectiveness and usability of the mechanism in planned tasks.

The authors [Pacheco Quinones 2025] analysed not only classical direct and inverse kinematics, but also the working space, various working modes, and the impact of self-collisions.

In addition to static kinematics, it is necessary to solve the trajectory of movement. Simulations can be used to determine how the mechanism moves, taking into account smoothness, safety, efficiency, and possible obstacles in the environment in which it operates.

The authors of [Zhao 2025] use polynomial-interpolated trajectories to define the movements of the manipulator arms, using the classic method of kinematics (forward/inverse kinematics) and testing the planned movements using simulation tools.

The software designed for computer analysis and simulation of multi-body systems (MBS) contains a set of predefined basic bodies of various shapes. These are used to build a complex model of a system of bodies. Compared to the analytical approach, this process leads to significant time savings. After starting the model simulation, the software then compiles the equations of motion and calculates the necessary data. Examples of software in this category are Matlab/SimMechanics, Matlab/Simulink, Dynast and MSC Adams [Delyova 2014].

MSC ADAMS software, a globally recognised tool for multibody dynamics, enables engineers and researchers to model mechanisms, analyse their movements, evaluate speeds, accelerations and positions, and predict behaviour under real operating conditions.

In recent years, there has been a growing number of studies that use ADAMS not only for static kinematic analysis, but also for dynamic simulation, verification of trajectories designed in external tools (e.g., MATLAB), and integration with strength analysis or trajectory planning software. The authors in [Hroncova 2023, Hroncova 2024, Fetso 2024, Xu 2025] focused on a 6-degree-of-freedom (6-DOF) industrial robot, on a model of which they implemented forward and inverse kinematics, then simulated the movement of the manipulator in ADAMS and exported the resulting data to ANSYS for structural strength analysis. This approach showed that the integration of kinematics, motion simulation and dynamic analysis provides realistic and reliable results.

Works [Malik 2025, Marcinko 2024, Chengjun 2025, Sarga 2025] were aimed at the trajectory of a robotic arm planned in MATLAB and subsequently verified in ADAMS. The simulation demonstrated smooth arm movement without sudden changes, confirming the correctness of the designed trajectory and enabling realistic drive dimensioning.

The combination of kinematic analysis, dynamic simulation, trajectory planning and subsequent verification of movement in real or simulated conditions represents the current trend in the development of mechanisms and robotic systems.

The rapid development of technology and the mechanisation of production processes places high demands on the development and theory of planar and spatial mechanisms. The transition to production machines and production lines requires precise and simple mechanisms to perform complex spatial movements. However, their implementation in technical practice is usually hindered by the difficulty of kinematic methods for solving mechanisms and thus also the synthesis of these mechanisms.

The task of the kinematic analysis of mechanisms is to determine the movement of other members, especially the kinematic quantities of the relevant mechanism, for a given movement of the driving member. The initial requirements for the mechanism, which result from the production technology, are kinematic and geometric. The mechanism is usually designed for the type and quality of movement. Computers with the appropriate software for kinematic analysis allow for the most accurate determination of the parameters of mechanical systems, as can be seen in the works of the authors [Hroncova 2012, Delyova 2014, Sapietova 2018, Kelemen 2021, Kelemenova 2021, Krenicky 2022, Duhancik 2024].

The aim of this paper is therefore to examine and successfully apply MSC ADAMS in the field of kinematics and trajectory planning.

## 2 USE OF SOFTWARE PRODUCTS FOR KINEMATIC ANALYSIS

From a kinematic point of view, industrial robot mechanisms represent a system of bodies. The individual members (bodies) of the system are interconnected by links (kinematic pairs). The robot arms perform simultaneous movements during their work. From a kinematic point of view, they represent open or mixed kinematic chains.

The lambda mechanism in Fig. 1 is a four-bar mechanism, i.e., it consists of four members, one of which is a fixed member (frame). Let  $O_2O_4 = 60$  mm. Member 2 with length  $O_2A = 20$  mm rotates around axis  $O_2=z_2$  at an angle  $\varphi_2$ , and member 4 with length  $O_4B = 80$  mm rotates around axis  $O_4=z_4$  at an angle  $\varphi_4$  in Fig. 1. The length of member 3 is 160 mm, where  $AB = 80$  mm and  $BC = 80$  mm. Member 3 performs a general plane motion consisting of translational motion and rotational motion. The motion of point B is described by the vector equation:

$$\vec{v}_B = \vec{v}_A + \vec{v}_{BA} \quad (1)$$

The trajectories of the points of member 3 of the lambda mechanism in MSC Adams View are shown in Fig. 2. The trajectories of the individual points A, B, C of member 3 are shown in Fig. 3 a-c.

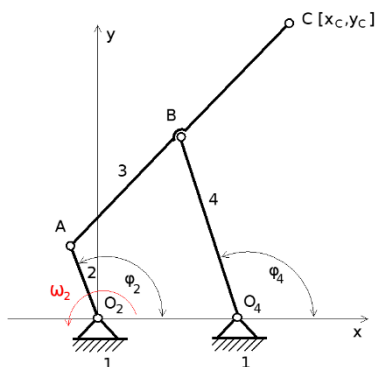


Figure 1. The kinematic scheme of the lambda mechanism

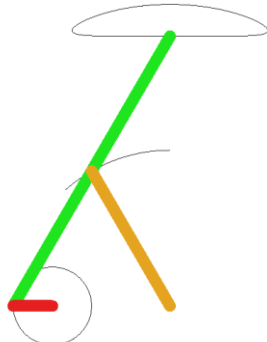
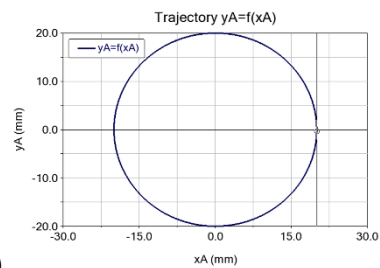
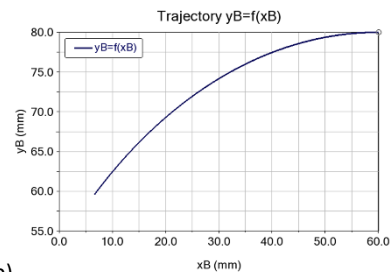


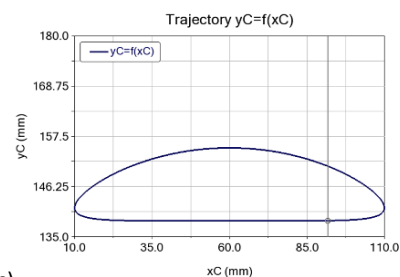
Figure 2. The kinematic scheme of the lambda mechanism in MSC Adams/View



a)



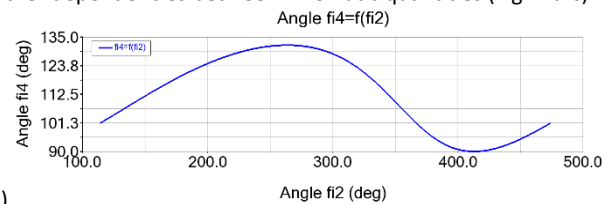
b)



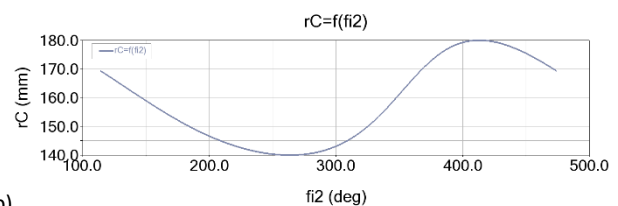
c)

Figure 3. Trajectories of the points of link 3 of the lambda mechanism a)  $y_A=f(x_A)$ , b)  $y_B=f(x_B)$ , c)  $y_C=f(x_C)$

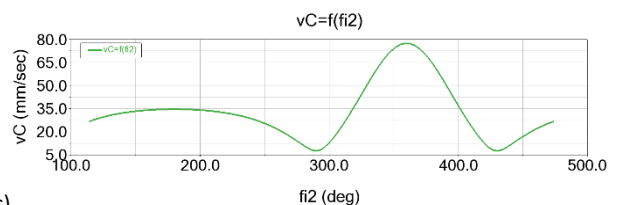
Other dependencies between kinematic quantities (Fig. 4 a-c):



a)



b)



c)

Figure 4. Kinematic quantities a) angle  $\varphi_4=f(\varphi_2)$ , b) position vector  $r_C=f(\varphi_2)$ , c) velocity vector  $v_C=f(\varphi_2)$  of the lambda mechanism

### 2.1 Use of inverse kinematics

When examining the trajectory, a two-member manipulator was considered, a robot model on a fixed base (Fig. 5a) and on a mobile chassis (Fig. 5b). The first member, arm  $O_1O_2$  has a length  $L_1 = 0.51$  [m] and a mass  $m_1 = 0.5$  [kg], and the second arm  $O_2M$  has a length  $L_2 = 0.67$  [m] and a mass  $m_2 = 0.6$  [kg] according to

Fig. 5c. The end point of the arm is marked M. The generalised coordinates of the kinematic pairs are  $q_1 = \theta_1$  and  $q_2 = \theta_2$  (Fig. 5c).

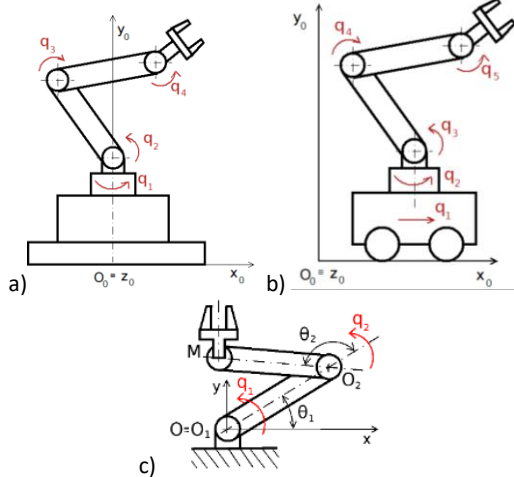


Figure 5. Two-link robotic arm a) on a fixed base, b) on a mobile chassis, c) generalised coordinates  $q_1 = \theta_1$  and  $q_2 = \theta_2$  of the arm

An MSC Adams model was created to simulate the trajectory of the manipulator's end effector on a fixed base. The figure 6 shows the trajectories of the manipulator's end effector when moving an object from defined positions (Fig. 7).

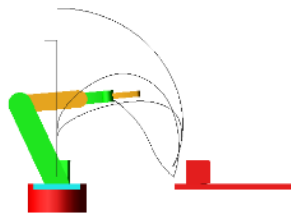


Figure 6. Plotting the trajectories of the manipulator's movement

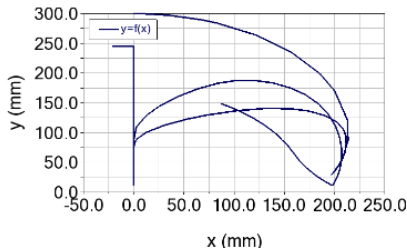


Figure 7. Trajectory function of the end effector

Figure 8 shows the position vector, velocity and acceleration of the manipulator's end effector when moving an object from individual positions.

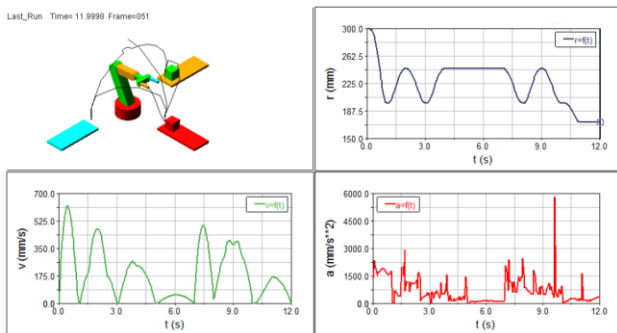


Figure 8. Magnitude of the position vector, velocity and acceleration of the effector as a function of time

When considering a mobile manipulator, the movement of the end effector was monitored in the working process of arm movement in positions A, B, C, D, E, F, G and H according to Fig. 9. The coordinates of point M in individual positions when moving the object are listed in Table 1.

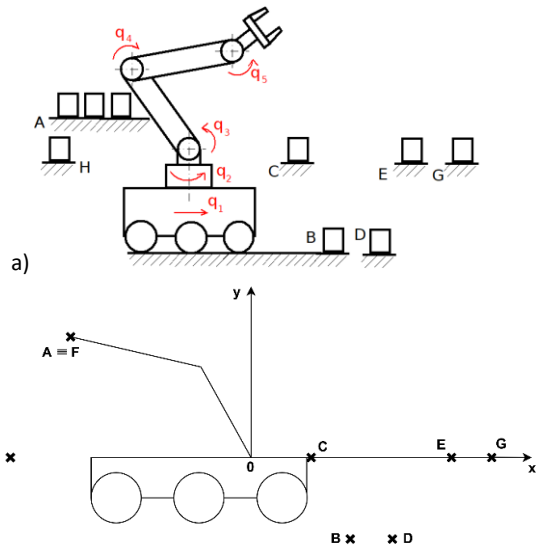


Figure 9. a)-b) Manipulator movement positions when moving objects

Table 1. Coordinates  $x_i, y_i$  of points A, B, C, D, E, F, G, H

	A	B	C	D	E	F	G	H
$x_i$ [m]	-0.89	0.5	0.3	0.7	1.0	-0.89	1.26	-1.26
$y_i$ [m]	0.44	-0.4	0.0	-0.4	0.0	0.44	0.0	0.0

One way to create a smooth trajectory of the given end point coordinates is to use a 5th order polynomial. The polynomial can be used if the initial and final velocities and accelerations are known. Using Matlab, the individual angles of arm 1 and arm 2 were determined at known end point positions using the following relationships

$$x = L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) \quad (2)$$

$$y = L_1 \sin \theta_1 + L_2 \sin(\theta_1 + \theta_2) \quad (3)$$

An example of solving an inverse kinematics problem is described by the motion of end point M, which passes through points A, B, C, D, E, F, G, H listed in Table 1. We solve two equations (2) and (3) with two unknowns  $\theta_1$  and  $\theta_2$  and obtain the results of the angles by solving inverse kinematics. The angles are shown in Table 2.

Table 2. Sizes of initial and final rotation angles when moving along trajectories between points A-B, B-C, C-D, D-E, E-F, G-H

	curve $k_1$ : A-B	curve $k_2$ : B-C	curve $k_3$ : C-D	curve $k_4$ : D-E	curve $k_5$ : E-F	curve $k_6$ : G-H
$\theta_{10}$	116.1	-108.9	-108.8	-85.6	-37.3	0
$\theta_{20}$	64.8	115.9	154.9	94.9	64.8	0
$\theta_{1tf}$	31.5	-108.8°	-85.6°	-37.3	116.1	180
$\theta_{2tf}$	-115.9°	154.9	94.9	64.8	64.8	0

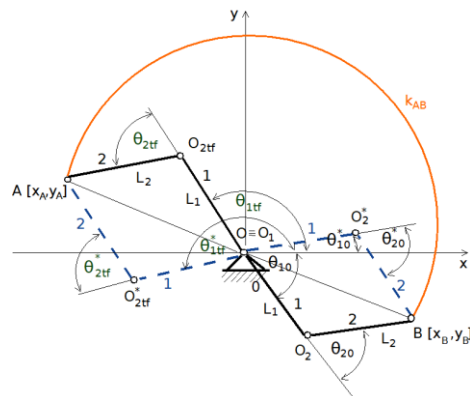


Figure 10. Position of the robot arms in point A and point B

Figure 10 shows the positions of the arms and the sizes of the arm angles in position A and position B.

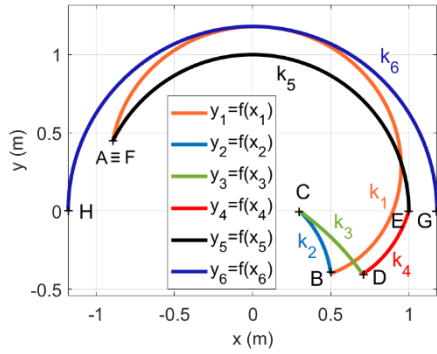


Figure 11. Trajectory during arm movement

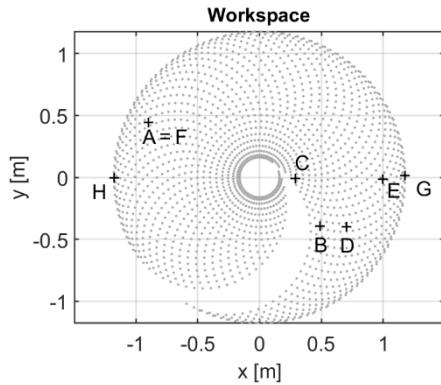


Figure 12. Points and Workspace

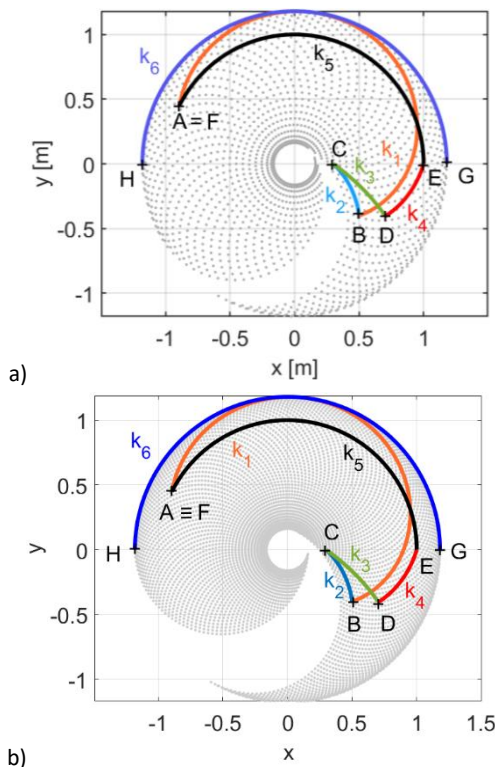


Figure 13. Trajectory and marking of the manipulator's working space for a)  $-120^\circ \leq \theta_1 \leq 210^\circ$  and  $0^\circ \leq \theta_2 \leq 180^\circ$ , b)  $-120^\circ \leq \theta_1 \leq 180^\circ$  and  $0^\circ \leq \theta_2 \leq 180^\circ$ , axis x [m], y [m]

The result was the acquisition of the trajectory of the end point of the manipulator as well as the angular rotations, angular velocities and angular accelerations of both arms (Fig. 11). The working spaces with selected angular limitations were plotted in Matlab (Fig. 12 and 13).

### 3 DISCUSSION AND CONCLUSIONS

This paper presented the integration of analytical methods, MATLAB-based numerical calculations and MSC ADAMS simulation for the kinematic analysis of selected mechanical and robotic systems. The proposed approach was applied to a planar lambda mechanism and to a two-link robotic manipulator operating on both a fixed base and a mobile chassis.

For the lambda mechanism, a four-bar system with the dimensions  $O_2O_4 = 60$  mm,  $O_2A = 20$  mm,  $O_4B = 80$  mm and  $AB = BC = 80$  mm was analysed. The trajectories of points A, B and C of the moving member were obtained in MSC ADAMS, and the dependencies of the output angle  $\varphi_4$ , the position vector  $r_C$  and the velocity vector  $v_C$  on the input angle  $\varphi_2$  were evaluated. The results confirmed that the simulation model correctly describes the general plane motion of the connecting member and enables the determination of position and velocity characteristics of selected points of the mechanism.

The second part of the study focused on a two-link robotic manipulator with arm lengths  $L_1 = 0.51$  m and  $L_2 = 0.67$  m, and masses  $m_1 = 0.5$  kg and  $m_2 = 0.6$  kg. The motion of the end effector was analysed for prescribed points A, B, C, D, E, F, G and H with coordinates ranging from  $x = -1.26$  m to  $x = 1.26$  m and from  $y = -0.4$  m to  $y = 0.44$  m. Inverse kinematics was solved in MATLAB for the individual trajectory segments, and the calculated angular positions of both arms were subsequently used for trajectory verification in MSC ADAMS.

The obtained angular values confirmed the feasibility of the prescribed motion. For example, during the motion from point A to point B, the first arm changed its angular position from  $\theta_{10} = 116.1$  degrees to  $\theta_{1tf} = 31.5$  degrees, while the second arm changed from  $\theta_{20} = 64.8$  degrees to  $\theta_{2tf} = -115.9$  degrees. Other analysed trajectory segments included the transition from B to C, where  $\theta_1$  changed from  $-108.9$  degrees to  $-108.8$  degrees and  $\theta_2$  from  $115.9$  degrees to  $154.9$  degrees, as well as the segment G-H, where the angular position of the first arm changed from  $0$  degrees to  $180$  degrees and the second arm remained at  $0$  degrees. These results demonstrate that the selected end-effector positions can be reached by the proposed manipulator configuration.

A fifth-order polynomial was used to generate smooth trajectories between the defined points. This enabled continuous changes in position, velocity and acceleration of the end effector, which is essential for avoiding abrupt motion changes during robotic handling tasks. The simulation results confirmed that the generated trajectories are suitable for stable and controlled manipulator motion.

The workspace analysis showed the influence of joint angle limitations on the reachable area of the manipulator. Two angular configurations were evaluated:  $-120^\circ \leq \theta_1 \leq 210^\circ$ ,  $0^\circ \leq \theta_2 \leq 180^\circ$ , and  $-120^\circ \leq \theta_1 \leq 180^\circ$ ,  $0^\circ \leq \theta_2 \leq 180^\circ$ . The obtained workspace plots confirmed that the limitation of the first joint directly reduces the reachable operating area of the end effector. This information is important for assessing whether the manipulator can perform required handling operations within defined geometric constraints.

The achieved results confirm that the combination of analytical kinematic calculations, MATLAB trajectory generation and MSC ADAMS simulation represents an effective methodology for the analysis, verification and optimisation of mechanical and robotic systems. The presented procedure enables the determination of trajectories, joint angles, velocities, accelerations and workspace boundaries before practical implementation. Therefore, the proposed approach is suitable for the design and assessment of automated production systems, robotic manipulators and mechanisms requiring precise, smooth and safe motion.

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