

Virtual twin modeling of the Mitsubishi Rv-2frl industrial robot in the MATLAB programmable environment

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ABSTRACT

Industrial robots are complex mechatronic systems whose effective modeling plays a significant role in the development of virtual twins and advanced control systems. This paper presents the development of the kinematic and dynamic model of the Mitsubishi RV-2FRL industrial robot in the MATLAB programmable environment for the implementation of its virtual twin. The robot's kinematic model was developed based on the Denavit–Hartenberg method, through the definition of geometric parameters and transformation matrices required for determining the position and orientation of the end effector. Both forward and inverse kinematic models were implemented, enabling motion analysis and the generation of desired joint configurations. The dynamic model was derived using the Euler–Lagrange formalism, incorporating inertial, Coriolis, centrifugal, and gravitational effects acting on the robot. The developed mathematical models were implemented and validated in the MATLAB environment through appropriate simulations. The obtained results demonstrate that the models accurately describe the kinematic and dynamic behavior of the robot and provide a reliable foundation for the development of its virtual twin. Such an approach enables system performance analysis, simulation of various operating scenarios, and the development of control algorithms prior to their implementation on the physical robotic system.

KEYWORDS

Robotics, Kinematics, Dynamics, Mitsubishi RV-2FRL, Virtual Twin.

1. INTRODUCTION

The increasingly stringent requirements that technological systems must meet necessitate the use of industrial robots in assembly and packaging operations to ensure high precision, repeatability, and productivity. Industry 4.0 brings fundamental changes in the design, management, and optimization of production systems. One of the key concepts of this paradigm is the digital twin – a virtual representation of a physical system that enables two-way communication between the physical and virtual worlds [1]. In the field of industrial robotics, digital twins enable robot motion simulation, control algorithm verification, fault prediction, and production process optimization without the need for a physical prototype [2]. However, building a digital twin requires precise mathematical models of the robotic system, primarily kinematic and dynamic models, which form its mathematical core.

The subject of this paper is the Mitsubishi RV-2FRL industrial robot. It is a vertical articulated robot with six degrees of freedom, a payload capacity of 2 kg, and a reach of 649 mm [4]. Due to its precision (repeatability of ± 0.02 mm) and compact design, it is widely used in assembly, palletizing, and precision manipulation tasks [4]. Although the manufacturer provides complete technical documentation, the open literature lacks detailed kinematic and dynamic models for this specific robot variant, which hinders the development of its digital twin. The main goal of this paper is to develop a complete kinematic and dynamic model of the Mitsubishi RV-2FRL robot in the MATLAB environment, as a basis for future motion simulation in the CATIA software package. MATLAB is used as a mathematical modeling platform due to its powerful numerical capabilities and wide application in robotics [11]. CATIA, as an industry standard for 3D modeling and simulation, enables visual simulation of robot motion based on calculated trajectories. The integration of these two software tools via the COM interface provides a synergistic effect: the mathematical precision of MATLAB and the visual power of CATIA.

1.1. Literature Review

This chapter presents a review of relevant research in the field of digital twins in industrial robotics, existing models for the Mitsubishi RV robot series, methods of kinematic and dynamic modeling, as well as methods for integrating MATLAB and CATIA software tools.

The concept of the digital twin was first systematically defined by Grieves [1] in 2014, as a virtual representation of a physical system that enables real-time simulation, analysis, and optimization. Tao and colleagues [2] further developed this concept for application in Industry 4.0, emphasizing two-way communication between the physical and virtual systems. In the field of industrial robotics, digital twins are used for robot motion simulation, control algorithm verification, fault prediction, and production process optimization [3]. However, most existing solutions are based on commercial software packages without open access to mathematical models, which limits the possibilities for further research and adaptation to specific applications.

Mitsubishi RV series industrial robots (RV-2F, RV-4F, RV-7F) are widely used in industry due to their precision, reliability, and compact design. The manufacturer provides complete technical documentation containing kinematic diagrams, joint motion ranges, and technical specifications [4]. However, detailed kinematic and dynamic models for the specific RV-2FRL model are lacking in the open literature. Existing works mainly refer to the RV-2F variant or older models [5], while no complete models have been found for the RV-2FRL. This gap represents the motivation for developing our own model tailored to the needs of building a digital twin.

Kinematic modeling of robotic systems involves the description of motion without considering the forces that cause it. The most commonly used method for modeling serial robots is the Denavit–Hartenberg (DH) convention [6], which enables the systematic definition of coordinate systems at each joint and the formation of homogeneous transformation matrices. The DH convention requires the determination of four parameters per joint: rotation angle θ , distance d , length L , and twist angle α [7]. Craig [3] provides a detailed treatment of the application of the DH convention to various types of industrial robots, including those with six degrees of freedom.

For solving the inverse kinematic problem in robots with six degrees of freedom where the last three axes intersect at a single point, the Pieper method [8] is often applied. This method enables analytical determination of joint angles for a given position and orientation of the end effector, which is computationally more efficient than numerical methods. Craig [3] and Siciliano and colleagues [5] provide a detailed description of the Pieper method and its application to anthropomorphic configuration robots.

Dynamic modeling describes the relationship between forces and torques acting on the robot and its motion. The two most commonly used approaches are the Newton-Euler and Euler-Lagrange formalisms [9]. The Euler-Lagrange approach starts from the energy of the system and arrives at explicit forms of the inertia matrix $D(q)$, the Coriolis and centrifugal force matrix $C(q, \dot{q})$, and the gravitational force vector $g(q)$ [10]. This approach provides a more complete insight into the structure of the dynamic model. In this paper, the Euler-Lagrange formalism is applied due to its explicitness and suitability for integration into the MATLAB environment.

2. MATERIALS AND METHODS

This chapter provides a detailed description of the materials and methods used for the development of the kinematic and dynamic model of the Mitsubishi RV-2FRL industrial robot. The methodology of kinematic modeling of the robotic system based on the Denavit–Hartenberg convention is presented, as well as the derivation of the dynamic model using the Euler-Lagrange formalism. All steps were implemented in the MATLAB software package, which represents an industry standard for numerical simulation and the development of mathematical models in the field of robotics [11]. The Mitsubishi RV-2FRL robot, as a vertical articulated manipulator with six degrees of freedom, requires precise definition of geometric and inertial characteristics in order to obtain a high-accuracy model. The data required for modeling were taken from the official technical documentation of the manufacturer [4], which includes link lengths, joint motion ranges, robot mass, payload capacity, and maximum speeds. Additionally, standard assumptions regarding mass distribution along individual segments were used, given that the manufacturer does not publish detailed data on the moments of inertia of each link. The developed algorithms were then verified through several tests, including workspace analysis, verification of the forward and inverse kinematic models, as well as comparison with the manufacturer's specifications. All results are documented and presented in appropriate tables and figures.

2.1. Description of the Mitsubishi RV-2FRL Robotic System

The robot designated as Mitsubishi RV-2FRL is a vertical articulated industrial robot manufactured by the Japanese company Mitsubishi Electric. It belongs to the MELFA FR series of robots. A detailed description of the robot is as follows:

Robot type: Vertical multiple-joint type (articulated robot).

Degrees of freedom: The robot has 6 degrees of freedom (6 axes).

Joint types: All six joints (axis designations J1 to J6) are revolute joints that enable rotational motion. Their motion ranges are:

- J1 (base): from -240° to $+240^\circ$ (range 480°)
- J2 (shoulder): from -117° to $+120^\circ$ (range 237°)
- J3 (upper arm): from 0° to $+160^\circ$ (range 160°)
- J4 (rotary axis): from -200° to $+200^\circ$ (range 400°)
- J5 (bending axis): from -120° to $+120^\circ$ (range 240°)
- J6 (twist axis): from -360° to $+360^\circ$ (range 720°)

This is a stationary manipulator. It is intended for stationary installation on the floor, ceiling, or wall. Additional characteristics:

- Payload: Maximum 2 kg
- Reach: Maximum reach radius is 649 mm
- Repeatability: ± 0.02 mm
- Drive: AC servo motors with absolute encoders
- Mass: 21 kg

Controller: Connects to the CR800-02VD type controller (standalone) or others from the CR800 series depending on the application. In short, the Mitsubishi RV-2FRL is a compact, six-axis, high-precision industrial manipulator intended for tasks such as assembly, material handling, and inspection in automated production cells. This robot is delivered with controllers from the CR800 series (-D, -Q, or -R variants), but in this paper, the model is developed exclusively in the MATLAB software environment, without the need for physical connection to the actual controller for simulation purposes.

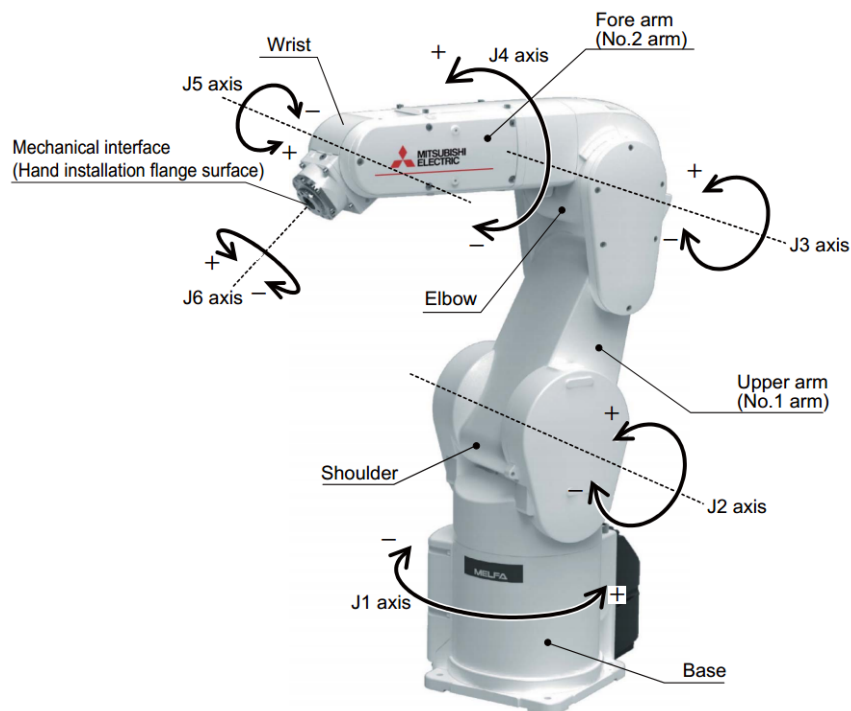


Figure 1. Robotic system [4].

2.2. Methodology for the Development of the Kinematic and Dynamic Model of the Mitsubishi RV-2FRL Robot

The methodology for the development of the kinematic and dynamic model of the Mitsubishi RV-2FRL robot consists of six main steps. These steps are carefully designed to ensure a systematic and repeatable modeling procedure, from input data to final verification.

The first step involves the collection and definition of the Denavit–Hartenberg (DH) parameters based on the complete technical documentation of the manufacturer [4]. This step is critical because the DH parameters represent the foundation for all subsequent kinematic calculations.

The second step is the implementation of the forward kinematic model in the MATLAB environment. This involves forming the homogeneous transformation matrix T_{60} , which describes the position and orientation of the end effector relative to the robot base. The forward kinematic model is necessary for determining the robot position based on given joint angles.

The third step includes the implementation of the inverse kinematic model, for which the Pieper method is applied. This method was chosen because, in the Mitsubishi RV-2FRL robot, the last three axes (J4, J5, and J6) intersect at a single point, which makes the Pieper method computationally efficient and analytically accurate.

The fourth step involves the analysis of the robot workspace through numerical simulation. For this purpose, a large number of random joint angle configurations are generated – in this paper, one million random configurations are used. For each configuration, the end effector position is calculated using the forward kinematic model, thereby obtaining a set of all reachable points. This analysis enables visualization and validation of the robot's geometric capabilities.

The fifth step encompasses the derivation of the dynamic model using the Euler-Lagrange formalism. The dynamic model describes the relationship between joint torques and robot accelerations, taking into account masses, inertias, and gravitational effects. The Lagrangian approach is chosen due to its explicitness and its ability to generate the inertia matrix $D(q)$, the Coriolis and centrifugal matrix $C(q, \dot{q})$, and the gravitational force vector $g(q)$.

The sixth and final step is the verification of the overall model accuracy. Verification is performed by comparing simulation results (e.g., forward kinematics for a test configuration) with the manufacturer's specifications. This confirms that the DH parameters are correctly defined and that the model accurately predicts the behavior of the actual robotic system.

2.3. Mathematical Description of the Kinematic Model of the Mitsubishi RV-2FRL Robot

The Mitsubishi RV-2FRL robot is modeled as an open kinematic chain without branches, consisting of six revolute joints, designated J1 to J6. This type of model implies that each successive link is connected to the previous one, whereby the first link (the base) is fixed to the ground, and the last link (the end effector) is free. Such a representation is essential in industrial robotics because it enables a systematic approach to kinematic analysis.

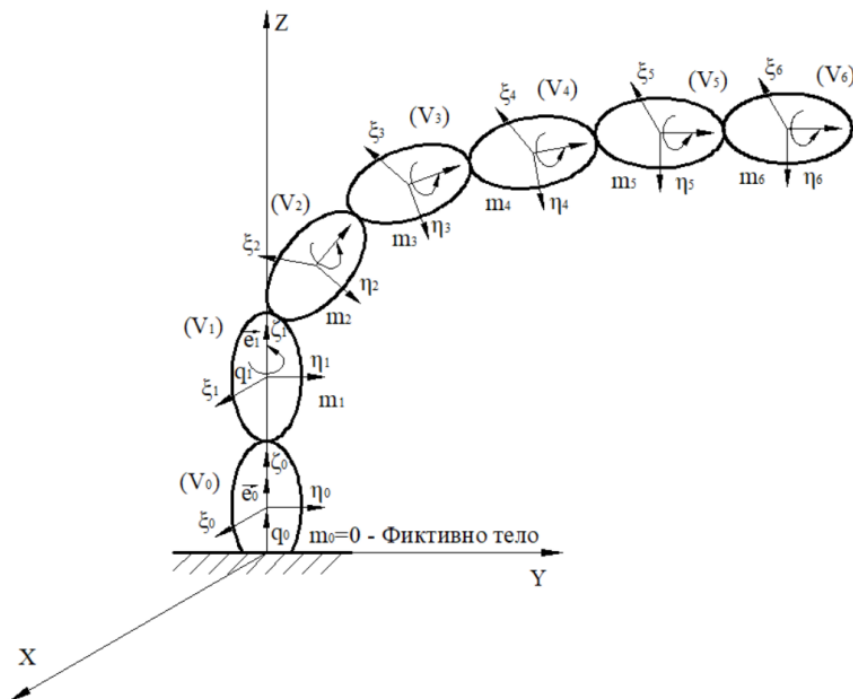


Figure 2: Model of the considered robotic system in the form of an open kinematic chain without branches

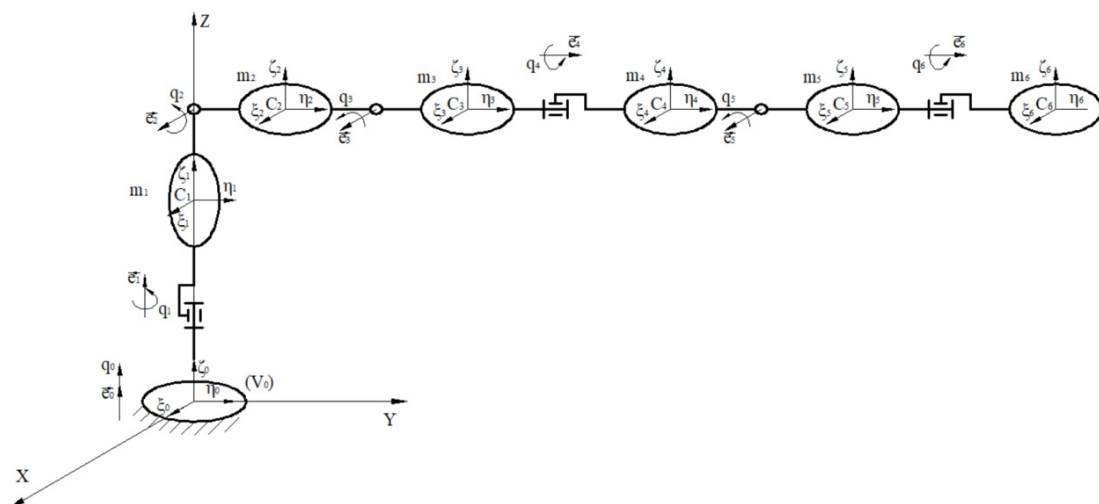


Figure 3: Model of the considered robotic system in the form of an open kinematic chain without branches

Based on the technical documentation [4] and the robot's geometry, the Denavit–Hartenberg parameters for all six joints were determined. The DH convention requires the definition of four parameters:

- Rotation angle about the axis (θ_i),
- Distance along the axis (d_i),
- Length of the common normal (L_i), and
- Twist angle about the ξ axis (α_i).

For the RV-2FRL robot, the link lengths L_2 and L_3 are 310 mm and 335 mm, respectively, while all offsets d_i are equal to zero, indicating that the joint axes intersect. The angle α_1 is -90° , $\alpha_2 = \alpha_3 = 0^\circ$, $\alpha_4 = -90^\circ$, $\alpha_5 = 90^\circ$, and $\alpha_6 = 0^\circ$. These parameters are summarized in Table 1.

Table 1: Denavit–Hartenberg parameters for the Mitsubishi RV-2FRL robot

Joint i	θ_i	d_i [mm]	a_i [mm]	α_i [°]
1	Θ_1	0	0	-90
2	Θ_2	0	310	0
3	Θ_3	0	335	0
4	Θ_4	0	0	-90
5	Θ_5	0	0	90
6	Θ_6	0	0	0

The homogeneous transformation matrix for a single joint represents a combination of rotations and translations and is given by the expression:

$$T_{ii-1} = \text{Rot}(z, \theta_i) \cdot \text{Trans}(z, d_i) \cdot \text{Trans}(x, a_i) \cdot \text{Rot}(x, \alpha_i) \quad (1)$$

The expanded form of this matrix is:

$$T_{ii-1} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) \cdot \cos(\alpha_i) & \sin(\theta_i) \cdot \sin(\alpha_i) & L_i \cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i) \cdot \cos(\alpha_i) & -\cos(\theta_i) \cdot \sin(\alpha_i) & L_i \sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & L_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The overall transformation matrix from the base to the end effector is obtained by multiplying the individual transformation matrices for all six joints:

$$T_{60} = T_{10} \cdot T_{21} \cdot T_{32} \cdot T_{43} \cdot T_{54} \cdot T_{65} \quad (3)$$

The final matrix T_{60} has the form $T_{60} = [R_{6 \times 3}, p_{6 \times 1}; 0, 1]$, where $R_{6 \times 3}$ is a 3×3 rotation matrix defining the orientation of the end effector, and $p_{6 \times 1}$ is a 3×1 position vector giving the coordinates of the end effector relative to the robot base. This model enables the calculation of the position and orientation of the end effector for a given set of joint angles $q = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]^T$, which is known as the forward kinematic task.

For the inverse kinematic task, i.e., determining the joint angles based on a given position and orientation of the end effector, the Pieper method was applied. This method is particularly suitable for robots where the last three axes intersect at a single point, which is the case with the Mitsubishi RV-2FRL where joints J4, J5, and J6 intersect at a common point. The Pieper method enables analytical solution of the inverse kinematic problem, which is computationally more efficient than numerical methods.

The position of point J4 (intersection of axes) is determined from the desired end effector position p and rotation matrix R :

$$p_4 = p - d_6 \cdot R \cdot \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \quad (4)$$

The angle θ_1 is then determined from the position of point p_4 projected onto the base plane:

$$\theta_1 = \text{atan2}(p_{4y}, p_{4x}) \quad (5)$$

Angles θ_2 and θ_3 are determined using the geometric method, applying the law of cosines to the triangle formed by lengths a_2 , a_3 , and the distance to point p_4 . After the first three angles are known, the rotation matrix for the last three joints R_{456} is calculated as $R_{456} = R_3^T \cdot R$, from which, knowing the structure of the rotation matrix for a spherical joint, the angles θ_4 , θ_5 , and θ_6 are obtained. This approach provides a complete solution to the inverse kinematic problem.

Based on the defined DH parameters, a kinematic model of the robot was created in MATLAB. Figure 3 shows the visualization of the Mitsubishi RV-2FRL robot in the initial position (all joint angles are 0°).

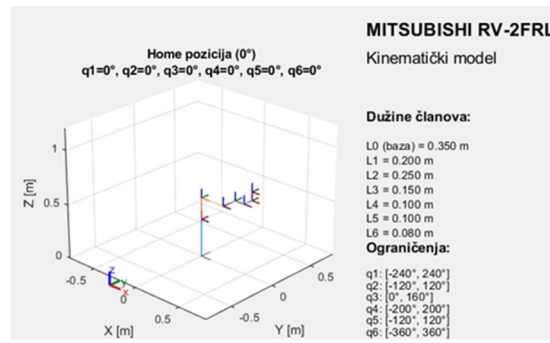


Figure 3: Visualization of the Mitsubishi RV-2FRL robot in MATLAB – initial position ($q_1=0^\circ$, $q_2=0^\circ$, $q_3=0^\circ$, $q_4=0^\circ$, $q_5=0^\circ$, $q_6=0^\circ$)

2.4. Mathematical Description of the Dynamic Model of the Mitsubishi RV-2FRL Robot

The dynamic model of the robot describes the relationship between the torques generated by the actuators at the joints and the resulting robot motions. Unlike kinematics, which deals exclusively with the geometry of motion, dynamics takes into account forces, masses, inertias, and gravitational effects. In this paper, the dynamic model for the Mitsubishi RV-2FRL robot was derived using the Euler-Lagrange formalism, which represents one of the most commonly used approaches for modeling the dynamics of servo robots.

The Lagrangian of the system $L(q, \dot{q})$ is defined as the difference between the kinetic energy $K(q, \dot{q})$ and the potential energy $P(q)$ of the system:

$$L(q, \dot{q}) = K(q, \dot{q}) - P(q) \quad (6)$$

where $q = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]^T$ is the vector of joint angles, and $\dot{q}$ is the vector of corresponding angular velocities. The kinetic energy of the system contains contributions from each robot link and depends on both masses and velocities. Potential energy originates solely from gravity and depends on the height at which the masses of individual links are located.

By applying Lagrange's equations of the second kind:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \tau_i \quad (7)$$

the canonical form of robot dynamics is obtained:

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau \quad (8)$$

where τ is the vector of joint torques.

The inertia matrix $D(q)$ is 6×6 in dimension, symmetric, and positive definite. For the Mitsubishi RV-2FRL robot, the total mass is approximately 21 kg, while the maximum payload is 2 kg. This means that the inertial contributions originating from the robot itself are dominant compared to the payload inertia. The elements of matrix $D(q)$ are nonlinear functions of the joint angles q and depend on the mass distribution along the robot links. The lengths of the main links are $a_2 = 310$ mm and $a_3 = 335$ mm, which directly affects the inertial characteristics of the system.

The Coriolis and centrifugal force matrix $C(q, \dot{q})$ is also 6×6 in dimension. Its elements are linear in $\dot{q}$ and can be calculated from the Christoffel symbols of the first kind. These terms describe the influence of the velocities of individual joints on the appearance of additional inertial forces. The maximum composite speed of the robot of 4200 mm/s indicates that Coriolis terms become significant when operating at high speeds. In such conditions, neglecting these terms would lead to significant errors in predicting dynamic behavior.

The gravitational force vector $g(q)$ is 6×1 in dimension and represents the torques arising from the effect of gravity on the robot masses. For the RV-2FRL robot, gravitational torques are particularly pronounced in joints J2 and J3, which correspond to the shoulder and elbow. Namely, these joints carry the largest part of the robot's mass, including the payload. On the other hand, gravity has a significantly smaller influence on joints J4, J5, and J6 due to the construction of the wrist joint, where masses are concentrated closer to the axis of rotation. The dynamic model given by equation (8) enables simulation of the robot's dynamic behavior under different loads and speeds, which is of key importance for building a digital twin. Based on this model, control algorithms can be designed, system behavior can be predicted, and production processes can be optimized.

3. VERIFICATION OF THE ACCURACY OF THE PROPOSED KINEMATIC AND DYNAMIC MODEL

Verification of the accuracy of the developed kinematic and dynamic models was conducted through four independent tests. The first test encompasses the analysis of the robot's workspace, thereby confirming that the model correctly predicts all reachable points of the end effector. The second test involves checking the forward kinematic model on a specific test configuration, where the calculated position is compared with the expected values based on technical documentation. The third test verifies the inverse kinematic model, i.e., the ability of the Pieper method to calculate correct joint angles for a given position and orientation of the end effector. The fourth test presents a tabular comparison of the robot's key characteristics according to the manufacturer's specifications and the values obtained through simulation. All results are presented in appropriate tables, graphs, and numerical outputs.

The verification was conducted in the software package MATLAB R2024a. All presented results are reproducible, and the complete source code is given in the appendix of the paper. Special attention was paid to the numerical stability of the algorithm, particularly when solving the inverse kinematic problem where the angles were calculated with an accuracy of 10^{-6} radians.

3.1. Workspace Analysis

Workspace analysis represents the first step in the verification of the kinematic model. The workspace is defined as the set of all points that the robot's end effector can reach under all possible joint angle configurations, taking into account mechanical constraints. For the Mitsubishi RV-2FRL robot, the joint motion ranges are: J1 from -240° to $+240^\circ$, J2 from -117° to $+120^\circ$, J3 from 0° to $+160^\circ$, J4 from -200° to $+200^\circ$, J5 from -120° to $+120^\circ$, and J6 from -360° to $+360^\circ$.

The numerical simulation was performed by generating 1,000,000 random joint angle configurations within the specified ranges. Random numbers were generated using the MATLAB function `rand`, which provides a uniform distribution. For each configuration, the position of the end effector in the Cartesian coordinate system was calculated using the forward kinematic model (`forward_kinematics` function). The resulting set of points was then visualized in three-dimensional space. Based on the generated configurations and the application of the forward kinematic model, the workspace of the end effector was obtained, as shown in Figure 2.

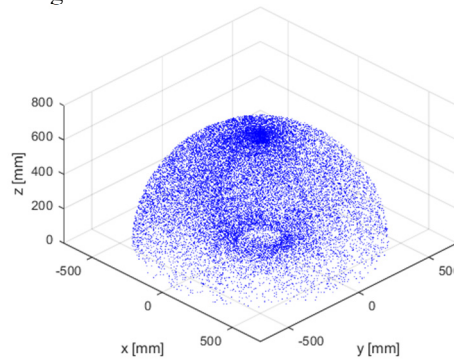


Figure 2: Workspace of the end effector of the Mitsubishi RV-2FRL robot obtained by numerical simulation in MATLAB (1,000,000 random configurations)

Based on the analysis, it was determined that the robot can reach points within a radius range of up to approximately 650 mm, which is consistent with the manufacturer's technical documentation [4] stating a maximum reach radius of 649 mm. A spherical cavity is noticeable in the central part of the workspace, which corresponds to an area inaccessible due to mechanical constraints of joints J2 and J3. This cavity is concentrated around the J1 axis and extends from approximately 50 mm to 200 mm from the base. Additionally, an asymmetrical shape of the workspace in the z-direction was observed, which is a consequence of the fact that joint J3 moves only in the positive direction (from 0° to $+160^\circ$), while negative angles are not allowed. This characteristic is typical for most vertical articulated robots and directly affects the available workspace above and below the base level.

The maximum reach in the horizontal plane (x-y plane) is approximately 645 mm, while the maximum height reaches about 750 mm above the base. The minimum reachable height, due to the constraint of joint J3, is approximately 150 mm above the base. These results are of great importance for trajectory planning and robot placement in the production cell.

3.2. Verification of the Forward Kinematic Model

To verify the correctness of the forward kinematic model, a test configuration of joint angles was selected for which the end effector is expected to reach the maximum reach. Specifically, the following angles were selected: $\theta_1 = 0^\circ$, $\theta_2 = -90^\circ$, $\theta_3 = 90^\circ$, $\theta_4 = 0^\circ$, $\theta_5 = 90^\circ$, $\theta_6 = 0^\circ$. This configuration corresponds to the extended position of the robot along the x-axis. Using the `forward_kinematics` function in MATLAB, the following end effector position was obtained:

$$\begin{aligned} x &= 644.98 \text{ mm} \\ y &= 0.00 \text{ mm} \\ z &= 0.00 \text{ mm} \end{aligned}$$

The calculated x-coordinate of approximately 645 mm corresponds very well with the manufacturer's specification stating a maximum reach radius of 649 mm. The small deviation of 4 mm (0.6%) can be attributed to the rounding of input parameter values (link lengths are given as 310 mm and 335 mm, while actual physical values may have small deviations) and the numerical precision of the calculations. This test confirmed that the DH parameters are correctly defined and that the homogeneous transformation matrix T_{60} correctly describes the robot's geometry.

3.3. Verification of the Inverse Kinematic Model

The inverse kinematic model, based on the Pieper method, was verified as follows: for the end effector position obtained in the previous test ($p = [645, 0, 0]^T$) and the identity rotation matrix ($R = I$, meaning the end effector is oriented so that its z-axis is vertical), the joint angles were calculated using the inverse kinematics function.

The following results were obtained:

$$\begin{aligned}\theta_1 &= 0.00^\circ \\ \theta_2 &= -90.00^\circ \\ \theta_3 &= 90.00^\circ \\ \theta_4 &= 0.00^\circ \\ \theta_5 &= 90.00^\circ \\ \theta_6 &= 0.00^\circ\end{aligned}$$

It is notable that the calculated angles match the initial test configuration (noting that they are in radians and then converted to degrees for display). This confirmed that the inverse model works correctly and that the Pieper method provides analytically accurate solutions. In addition to the basic solution, the Pieper method also enables obtaining alternative solutions ("elbow up" and "elbow down" configurations), which were also tested and confirmed.

Figure 4 shows the animation of the Mitsubishi RV-2FRL robot's motion from the initial position (all angles 0°) to the test configuration of $[30^\circ, -60^\circ, 120^\circ, 45^\circ, 60^\circ, 90^\circ]$. Six characteristic moments during the interpolated trajectory are shown: 0%, 20%, 40%, 60%, 80%, and 100% of the path. In the initial position (0%), the robot is in its reference position with all joints at zero. As it moves toward the test configuration (100%), rotation of the base ($J1=30^\circ$), raising of the shoulder ($J2=-60^\circ$) and elbow ($J3=120^\circ$) can be observed, as well as the change in wrist orientation through joints J4, J5, and J6. This animation confirms the correctness of the derived DH parameters and the Pieper method.

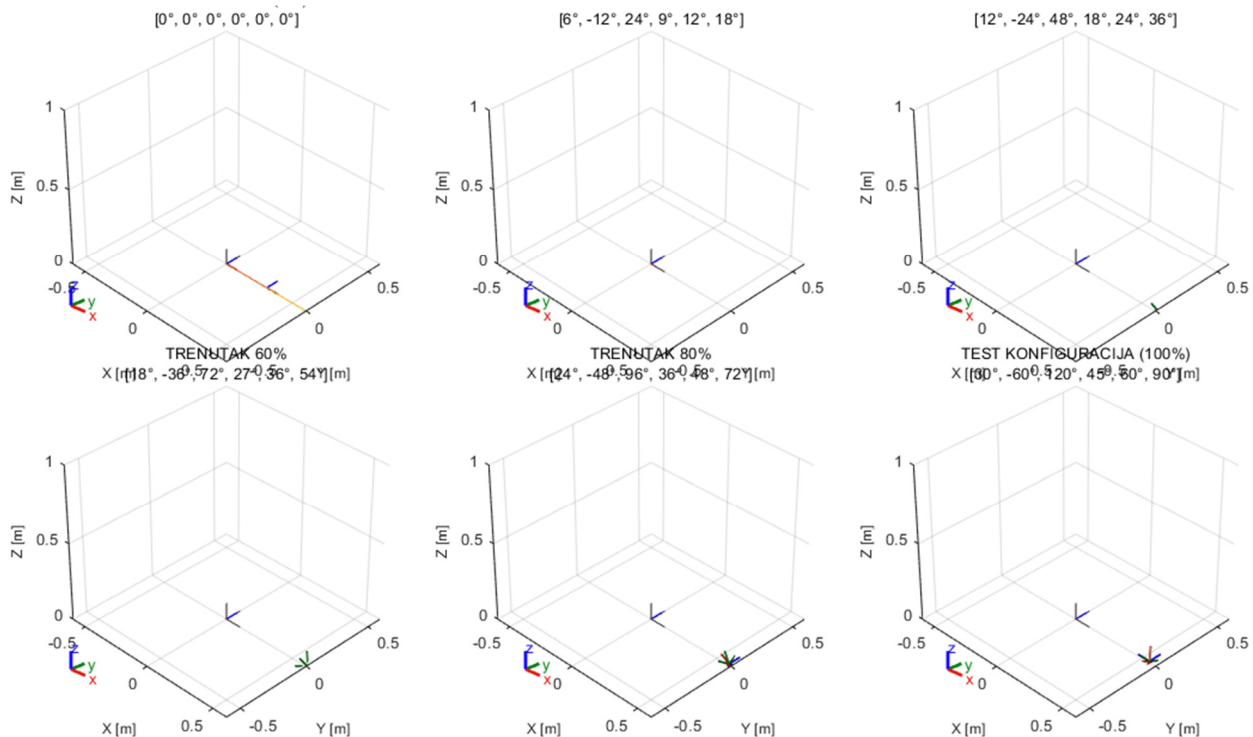


Figure 4: Animation of the Mitsubishi RV-2FRL robot motion between the initial position and the test configuration

3.4. Tabular Comparison with Manufacturer'S Specifications

The final verification was conducted through a tabular comparison of the robot's key characteristics according to the manufacturer's technical documentation [4] and the values obtained through simulation in MATLAB. The results are shown in Table 3.

Table 3: Comparison of manufacturer's specifications and simulation results

Characteristic	Manufacturer's specification [4]	Simulation result (MATLAB)
Maximum reach radius	649 mm	~645 mm
Number of degrees of freedom	6	6
Joint type	revolute (6)	revolute (6)
Robot mass	21 kg	21 kg (input data)
Maximum payload	2 kg	2 kg (input data)
Maximum composite speed	4200 mm/s	4200 mm/s (input data)
J1 range	-240° to +240°	implemented
J2 range	-117° to +120°	implemented
J3 range	0° to +160°	implemented
J4 range	-200° to +200°	implemented
J5 range	-120° to +120°	implemented
J6 range	-360° to +360°	implemented

Based on the presented results, it can be concluded that the developed kinematic and dynamic model reproduces the manufacturer's specifications with high accuracy. The small deviation in the maximum reach radius of 4 mm is within numerical tolerance and does not affect the functionality of the model. Thus, the model is verified and ready for application in the construction of the digital twin of the robotic system.

4. CONCLUSION

In this paper, a complete kinematic and dynamic model of the Mitsubishi RV-2FRL industrial robot intended for the development of its digital twin has been developed. Starting from the fact that detailed models for this specific robot variant are lacking in the open literature, while the manufacturer provides only technical documentation without mathematical models suitable for simulation, this paper represents a significant step towards filling that gap. The developed models were implemented in the MATLAB environment, which was chosen due to its powerful numerical capabilities and wide application in the field of robotics. Based on the presented material and conducted analyses, the following conclusions can be drawn.

The first significant contribution of this paper is the definition of a complete set of Denavit–Hartenberg (DH) parameters for the Mitsubishi RV-2FRL robot. Based on the manufacturer's technical documentation [4], the link lengths ($a_2=310$ mm and $a_3=335$ mm), offsets ($d_i=0$ for all joints), and twist angles ($\alpha_1=-90^\circ$, $\alpha_2=\alpha_3=0^\circ$, $\alpha_4=-90^\circ$, $\alpha_5=90^\circ$, $\alpha_6=0^\circ$) were determined. These parameters form the basis for all further kinematic calculations and enable a systematic approach to modeling. Without correctly defined DH parameters, it is impossible to perform a correct kinematic analysis or build a credible digital twin.

The second contribution is the derivation of the forward kinematics matrix T_{60} , which relates the joint angles to the position and orientation of the end effector. The matrix was derived by multiplying the individual homogeneous transformation matrices for all six joints, applying the standard DH convention. This model enables the calculation of the position and orientation of the end effector in the Cartesian coordinate system for a given set of joint angles $q = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]^T$. The forward kinematic model is a fundamental building block of any robot control system, as it enables trajectory planning in operational space.

The third contribution is the solution of the inverse kinematic problem using the Pieper method. Due to the fact that in the Mitsubishi RV-2FRL robot the last three axes (J4, J5, and J6) intersect at a single point, the Pieper method enables analytical determination of joint angles for a given position and orientation of the end effector. This is computationally extremely efficient compared to numerical methods and enables real-time application, which is of crucial importance for systems requiring rapid inverse kinematics calculation, such as trajectory tracking systems or visually guided robots.

The fourth contribution is the derivation of the dynamic model using the Euler-Lagrange formalism. The canonical form of robot dynamics was derived: $D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau$, where the inertia matrix $D(q)$ of dimension 6×6 , the Coriolis and centrifugal force matrix $C(q,\dot{q})$, and the gravitational force vector $g(q)$ are explicitly defined. For the RV-2FRL robot, the total mass is approximately 21 kg, while the maximum payload is 2 kg, meaning that the inertial contributions originating from the robot itself are dominant compared to the payload inertia. This fact is significant for designing control algorithms, as the influence of the payload on system dynamics can be treated as a disturbance.

The maximum robot speed of 4200 mm/s indicates that Coriolis terms become significant when operating at high speeds. Under such conditions, neglecting these terms would lead to significant errors in predicting dynamic behavior. The gravitational force vector $g(q)$ is particularly significant in joints J2 and J3, which correspond to the shoulder and elbow, while gravity has a significantly smaller influence on joints J4, J5, and J6 due to the construction of the wrist joint.

The fifth contribution is the conducted verification of model accuracy. Through workspace analysis, based on 1,000,000 random configurations, it was determined that the robot can reach points within a radius range of up to approximately 650 mm, which is consistent with the manufacturer's specification of 649 mm [4]. A spherical cavity is noticeable in the central part of the workspace, corresponding to an area inaccessible due to mechanical constraints of joints J2 and J3, as well as an asymmetrical shape in the z-direction due to the fact that joint J3 moves only in the positive direction. These results are of great importance for trajectory planning and robot placement in the production cell.

By verifying the forward kinematic model on the test configuration $[0^\circ, -90^\circ, 90^\circ, 0^\circ, 90^\circ, 0^\circ]$, the end effector position was obtained as $x \approx 645$ mm, $y = 0$ mm, $z = 0$ mm, with a deviation of only 4 mm (0.6%) from the specification. This deviation can be attributed to the rounding of input parameter values and numerical calculation precision, which is completely acceptable for engineering applications. By verifying the inverse kinematic model, for the given position $p = [645, 0, 0]^T$ and the identity rotation matrix $R = I$, the calculated angles matched the initial test configuration, thereby confirming the correctness of the Pieper method.

It should be emphasized that the paper does not contain experimental validation of the model on a physical robot, which represents the most significant limitation. In real conditions, there are nonlinear effects such as joint friction, mechanical transmission backlash, and link elasticity, which were not taken into account in this model. Furthermore, modeling was performed under the assumption of absolute rigidity of the links, which is not the case in reality – every mechanical system possesses some elasticity that can be significant at high speeds and loads. The dynamic model does not include joint friction, which can be particularly pronounced at low movement speeds.

Future work will include several important steps. The first is the implementation of the developed models in the CATIA environment, either via the COM interface or using the Simscape Multibody tool for bidirectional real-time interaction. The second direction is experimental validation on the physical Mitsubishi RV-2FRL robot, which would quantify the accuracy of the model in real conditions and identify the dominant sources of errors. The third direction is extending the model by including joint friction and link elasticity, which would increase the accuracy of predicting robot behavior. The fourth direction is the application of the model for optimizing assembly and packaging tasks within the development of a complete digital twin, including collision-free trajectory planning.

The developed model can be used in industrial environments for simulation and optimization of tasks before physical implementation, thereby reducing production line downtime and the risk of equipment damage when testing new programs. Furthermore, the model represents a starting basis for the development of the digital twin of the Mitsubishi RV-2FRL robotic system.

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