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SIMULATION OF THE MODULAR WALKING ROBOT MOVEMENT

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Abstract: *Modern methods of drawing up machines and tools necessarily include a simulation stage of their functioning, which means to use a mathematical pattern of the real, original system. These activate the functioning simulation that encompasses several rules and specifications whose enactment generates behavior data and the instructions operating on the pattern's description variables. The veracity and validity of a real system depend on the compliance degree. The real system and the model are different by the fact that whereas for the former the manner to generate conduct data can be completely unknown, for the latter they mean a group of rules or specifications, whose enactment puts out the conduct data, namely instructions operating of the model's description variables. In the paper, a robust model of the direct and inverse analysis of the open kinematic chains of the walking robot legs is constructed.*

Key words: *modelling, simulation, walking robot, modular walking robot, robot legs.*

1. INTRODUCTION

Since long ago, many research teams worldwide have been focused on goals such as creating an autonomous walking robot equipped with functions like handling objects, locomotion, perceiving, navigation, learning, judgment, information storage and intelligent control, and that can carry out tasks like altering the multitude of the parts belonging to a dynamic universe.

Scientists of all times have been permanently mesmerized and have studied the simplest but the most important movement, namely the mechanical movement of humans and animals. Humankind is so much anthropomorphism addicted that it is almost impossible for it to conceive or imagine automatic systems, even having artificial intelligence, and that are not anthropomorphic.

The access of man to dangerous areas where his safety is jeopardized made the scientific research approach topics of various purposes and conceive devices that through their performances aim at covering different fields. The architecture of these systems is quite different and depends on their purpose and destination.

For example, walking robots protect the environment better because their contact to the ground is discrete, which substantially diminishes the surface to be crushed, the robot's weight can be optimally distributed on the contact surface through controlling the forces. The variation of the distance from the ground allowed the robot to step over young trees or other vegetation growing in the area it moves on.

The walk is defined by the manner the waking robot moves between two points, under specific circumstances. To achieve and guide a walking robot requires thorough knowledge about all walking possibilities because choosing the number of legs and their structure depends very much on the selected walk. The selection of the walk type depends on several elements such as:

- shape and consistency of the ground the robot walks on,
- walk stability driving and controlling the movements of the elements of the walking systems,
- speed and mobility movement requires.

It is very difficult to select the type of walk, mainly during real walking. Therefore, it is necessary that the ground surface to be defined before selecting the walk.

The walking robot steps are a sequel of movements of the legs, coordinated with a succession of movements of the body for the purpose of moving the robot from one place to another

2. THE ESTABLISHING THE MATHEMATICAL PATTERN OF THE MOVEMENT SYSTEM

Theoretical research of robot movement assumes nine important stages:

1. the establishing of the mathematical model of the movement of the kinematic and dynamic system;
2. process and construe the results obtained through simulation with a view to determining the system's conduct;
3. structural and geometrical optimization of the movement systems compounds;
4. movement of compounds system;
5. establish the functional block scheme to calculate the compounds;
6. establishing of the test methodology to perform the system's functions that is need and the identity of the functions generators walking requires;
7. design of the guidance system's software;
8. determination of the initial parameters and data characteristics of the system structure and state;
9. conduct of the simulation program.

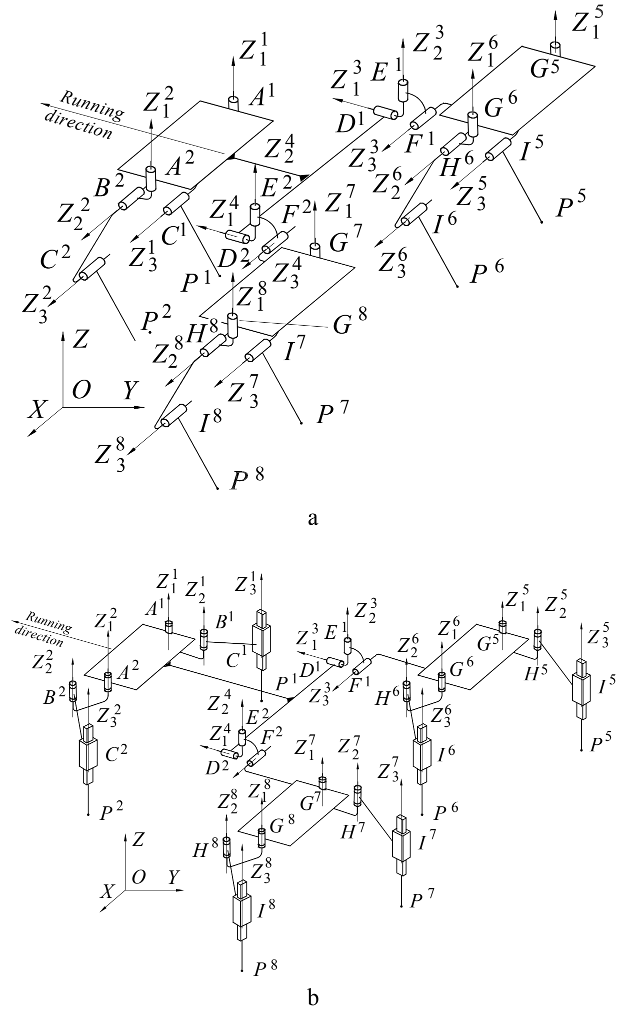

Fig.1. The Denavit –Hartenberg axis system attached of modular walking robot it is suggested support of technological equipments, for a leg mechanism RRR a), and RRT b).

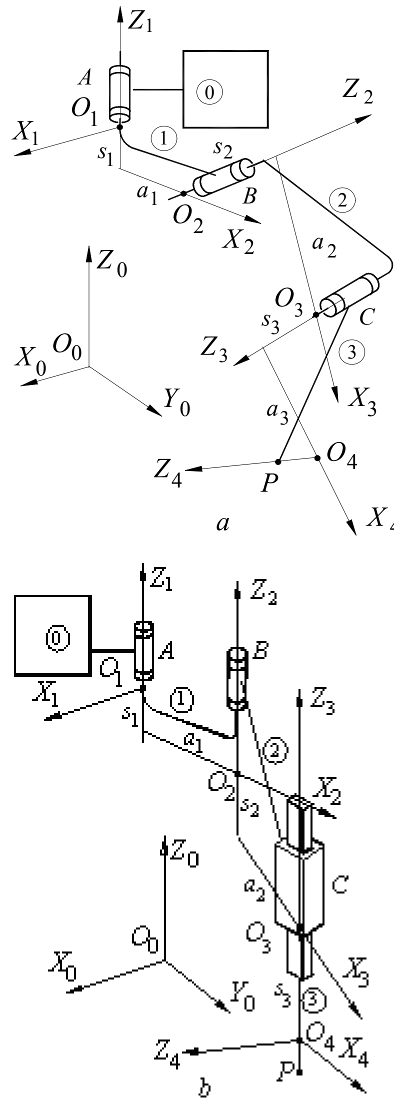

Fig. 2. The Denavit – Hartenberg coordinate axes systems for a leg mechanism RRR a), RRT b).

2.1 Movement simulation by Denavit – Hartenberg formalism

Let us a modular walking robot consist of three modules [3]. Each module has two 3-DOF legs, symmetrically arranged on the platform axis (Fig. 1).

The legs on the right – onto the movement direction are superscript marked with $2i,\ i=\overline{1,6}$ whereas the legs on the left with $2i-1$. Each platform of the rear modules is connected to the platform of first module by a 3-DOF kinematic chain with two links and three rotational pairs. The axes if these pairs are concurrent and perpendicular two by two.

In order to carried out the movement simulation of a leg, a coordinate axes system is attached to each link, with the Denavit – Hartenberg rule [2]. This formalism may not only simplify the problem formulation, but can also yield considerable advantage in the solution of simulation problem. The pairs of each leg are numbered consecutively from A which is pair number 1 to C which is pair number 3.

The Denavit - Hartenberg systems attached to each link are subscript numbered as the pairs respectively. The platform is designed as link number (**0**) and the remaining links are numbered consecutively. All pairs of the leg mechanism are rotational and actuated ones.

2.1.1 Denavit - Hartenberg systems attached to the leg links of the walking robot. The characteristic axis Z_i of each pair should be defined. The positive sense of each of these axes is defined arbitrarily. If the axes Z_i and Z_{i-1} are skew with respect to each other, then there is one common perpendicular between them. The perpendicular is designed as the X_i axis. If the Z_i and Z_{i-1} axes are parallel, the X_i axis may chosen as any common perpendicular. The positive direction of the X_i axis is designed as proceeding from Z_{i-1} to Z_i. If the Z_{i-1} and Z_{i-1} intersect, the positive sense of X_i axis is arbitrarily.

When the X_i axes are all defined, then are define both the Y_i axes and the origin of each right hand coordinate system. So, a coordinate system defined is attached to each link. The parameter a_i is defined as the distance from O_iZ_i to $O_{i+1}Z_{i+1}$ axes, measured along $O_{i+1}X_{i+1}$. Because of the orientation of the $O_{i+1}X_{i+1}$.axis, a_i is always positive.

The parameter α_i is defined as the angle between the positive O_iZ_i and the positive $O_{i+1}Z_{i+1}$ axes, as seen from positive $O_{i+1}X_{i+1}$.

The parameter θ_i is the angle between positive O_iX_i and the positive $O_{i+1}X_{i+1}$ axes, as seen from positive O_iZ_i.

The parameter s_i is defined as the distance from O_iX_i to $O_{i+1}X_{i+1}$ axes, measured along the O_iZ_i axis.

Under this definition, the Denavit – Hartenberg transformation matrix $\mathbf{A}_i^j$ has the well-known form:

$$\mathbf{A}_i^j = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ a_i^j \cos\theta_i^j & \cos\theta_i^j & -\cos\alpha_i^j \sin\theta_i^j & \sin\alpha_i^j \sin\theta_i^j \\ a_i^j \sin\theta_i^j & \sin\theta_i^j & \cos\alpha_i^j \cos\theta_i^j & -\sin\alpha_i^j \cos\theta_i^j \\ s_i^j & 0 & \sin\alpha_i^j & \cos\alpha_i^j \end{Vmatrix} \quad (1)$$

To mould the walking robot's moves is assumed that:

1. The kinematical length of the binary link (**1**) is null and it is connected to the platform (**0**), by pair A and to the link (**2**) by pair B; the axis of pairs A and B are perpendicular.
2. the binary link (**2**) is connected to the link (**1**) by the pair B and to link (**3**) by the pair C; the axis of pairs B and C are parallel.

The $\mathbf{A}_3^j$ matrix performed the coordinate transformation of a point belonging to link (**3**) from $O_4^jX_4^jY_4^jZ_4^j$ system to $O_3^jX_3^jY_3^jZ_3^j$ system attached to link (**2**). In a similar manner, the coordinates of lower end point P belonging to link (**3**) from $O_4^jX_4^jY_4^jZ_4^j$ system to $O_1^jX_1^jY_1^jZ_1^j$ system attached to the platform (**0**) is performed by the equation

$$\begin{Vmatrix} 1 \\ X_{1P}^j \\ Y_{1P}^j \\ Z_{1P}^j \end{Vmatrix} = \prod_{k=1}^{3} \mathbf{A}_k^j \begin{Vmatrix} 1 \\ X_{4P}^j \\ Y_{4P}^j \\ Z_{4P}^j \end{Vmatrix}, j = 1, 2. \quad (2)$$

This matrix equation described the geometrical model of the leg 1 and 2 of the walking robot. The goal of the direct kinematic analysis is to calculate the position, velocity and acceleration of the end point P, in terms of the pair variables θ_i^j, $i = \overline{1,3}$. In inverse kinematic analysis, matrix equation (2) is solved with respect to the pair variables θ_i^j, $i = \overline{1,3}$.

The positions of the point P and the positions of the platform with respect to the reference coordinate axes system $OXYZ$ fastened to the ground are considered as known. Therefore, the position of the point P with respect to the platform coordinate axes system are known.

The movement of the legs of the rear modules are controlled by the following equations:

$$\begin{Vmatrix} 1 \\ X_{1P}^5 \\ Y_{1P}^5 \\ Z_{1P}^5 \end{Vmatrix} = \mathbf{A}_1^3\mathbf{A}_2^3\mathbf{A}_3^3\mathbf{A}_1^5\mathbf{A}_2^5\mathbf{A}_3^5 \begin{Vmatrix} 1 \\ X_{4P}^5 \\ Y_{4P}^5 \\ Z_{4P}^5 \end{Vmatrix},$$

$$\begin{Vmatrix} 1 \\ X_{1P}^6 \\ Y_{1P}^6 \\ Z_{1P}^6 \end{Vmatrix} = \mathbf{A}_1^3\mathbf{A}_2^3\mathbf{A}_3^3\mathbf{A}_1^6\mathbf{A}_2^6\mathbf{A}_3^6 \begin{Vmatrix} 1 \\ X_{4P}^6 \\ Y_{4P}^6 \\ Z_{4P}^6 \end{Vmatrix},$$

$$\begin{Vmatrix} 1 \\ X_{1P}^7 \\ Y_{1P}^7 \\ Z_{1P}^7 \end{Vmatrix} = \mathbf{A}_1^4\mathbf{A}_2^4\mathbf{A}_3^4\mathbf{A}_1^7\mathbf{A}_2^7\mathbf{A}_3^7 \begin{Vmatrix} 1 \\ X_{4P}^7 \\ Y_{4P}^7 \\ Z_{4P}^7 \end{Vmatrix},$$

$$\begin{Vmatrix} 1 \\ X_{1P}^8 \\ Y_{1P}^8 \\ Z_{1P}^8 \end{Vmatrix} = \mathbf{A}_1^4\mathbf{A}_2^4\mathbf{A}_3^4\mathbf{A}_1^8\mathbf{A}_2^8\mathbf{A}_3^8 \begin{Vmatrix} 1 \\ X_{4P}^8 \\ Y_{4P}^8 \\ Z_{4P}^8 \end{Vmatrix} \quad (3)$$

Each of these matrix equations is equivalent with three nonlinear equations and has six unknowns, namely variables of the pairs. In the inverse kinematic analysis three out of six unknowns must be imposed from independent conditions.

Table 1

Parameters of the Denavit – Hartenberg transformation (left leg)

Pairs	***A*²**	***B*²**	***C*²**
Coordinate systems	$O_1^2X_1^2Y_1^2Z_1^2$	$O_2^2X_2^2Y_2^2Z_2^2$	$O_3^2X_3^2Y_3^2Z_3^2$
Transformation matrix	$\mathbf{A}_1^2$	$\mathbf{A}_2^2$	$\mathbf{A}_3^2$
a [mm]	0	350	350
α	-π/2	0	-π/2
θ	θ_1^2	θ_2^2	θ_3^2
s [mm]	150	0	0

Table 2

Parameters of the Denavit – Hartenberg transformation (right leg)

Pairs	***D*⁴**	***E*⁴**	***F*⁴**	***G*⁸**	***H*⁸**	***I*⁸**
Coordinate systems	$O_1^4X_1^4Y_1^4Z$	$O_2^4X_2^4Y_2^4Z$	$O_3^4X_3^4Y_3^4Z$	$O_1^8X_1^8Y_1^8Z$	$O_2^8X_2^8Y$	$O_3^8X_3^8Y$
Trans. matrix	$\mathbf{A}_1^4$	$\mathbf{A}_2^4$	$\mathbf{A}_3^4$	$\mathbf{A}_1^8$	$\mathbf{A}_2^8$	$\mathbf{A}_3^8$
a [mm]	0	0	670	0	350	350
α	π/2	π/2	π/2	π/2	0	0
θ	θ_1^4	θ_2^4	θ_3^4	θ_1^8	θ_3^8	θ_3^8
s [mm]	200	0	0	380	0	0

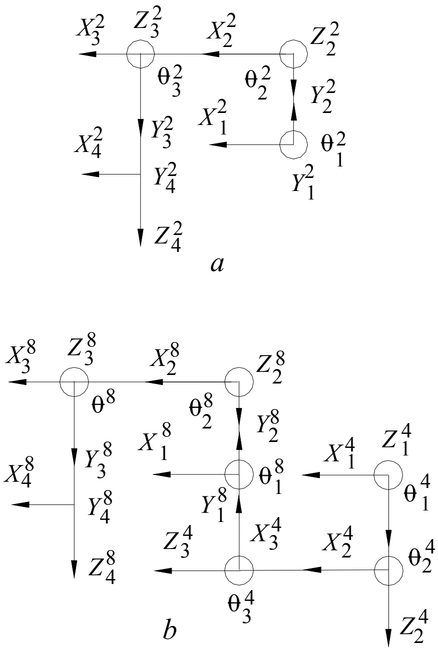

Fig 3. The Denavit – Hartenberg axes systems attached to the links of the left leg of the first module (*a*) and of the rear module (*b*).

Figure 3 shows the schemes of the sequence of the Denavit-Hartenberg coordinate systems attached to the links of the left leg of the first module (*a*) and to the links of the leg of the left rear module (*b*).

In the movement simulation program, the parameters of the Denavit-Hartenberg transformation matrices have the values in Tables 1 and 2.

2.1.2 First and second – time derivative of the pair variables. Through the repeated differentiated of the equation (2) with respect to the time, yields:

$$\begin{Vmatrix} 0 \\ \dot{X}_{1P}^{i} \\ \dot{Y}_{1P}^{i} \\ \dot{Z}_{1P}^{i} \end{Vmatrix} = \left(\frac{\partial \mathbf{A}_1^i}{\partial \theta_1^i} \mathbf{A}_2^i \mathbf{A}_3^i \dot{\theta}_1^i + \mathbf{A}_1^i \frac{\partial \mathbf{A}_2^i}{\partial \theta_2^i} \mathbf{A}_3^i \dot{\theta}_2^i + \mathbf{A}_1^i \mathbf{A}_2^i \frac{\partial \mathbf{A}_3^i}{\partial \theta_3^i} \dot{\theta}_3^i \right) \begin{Vmatrix} 1 \\ X_{4P}^{i} \\ Y_{4P}^{i} \\ Z_{4P}^{i} \end{Vmatrix}, i = 1, 2; \tag{4}$$

In the inverse analysis, these equations are solved with respect to the first and second – time derivative respectively of the pair variables.

The velocity and the acceleration components of the point *P* on the axes of the coordinate system attached to the platform (**0**) are considered as known. In a similar manner are differentiated the equations (3).

In these matrix equations, the variables θ_k^{2i} $\dot{\theta}_k^{2i}$ and $\ddot{\theta}_k^{2i}$, $k = \overline{1,6}$ of the pairs and their derivatives with respect to the time are imposed by the walking simulation program.

Keeping stable is a special problem that occurs while the robot walks, when one or more legs are in the transfer phase. When all the legs are in the support phase, it is obvious that the protection of the center of gravity is within the support polygon.

$$\begin{Vmatrix} 0 \\ \ddot{X}_{1P}^{i} \\ \ddot{Y}_{1P}^{i} \\ \ddot{Z}_{1P}^{i} \end{Vmatrix} = \left(\frac{\partial^2 \mathrm{A}_1^i}{\partial (\theta_1^i)^2} \mathrm{A}_2^i \mathrm{A}_3^i (\dot{\theta}_1^i)^2 + \mathrm{A}_1^i \frac{\partial^2 \mathrm{A}_2^i}{\partial (\theta_2^i)^2} \mathrm{A}_3^i (\dot{\theta}_2^i)^2 + \mathrm{A}_1^i \mathrm{A}_2^i \frac{\partial^2 \mathrm{A}_3^i}{\partial (\theta_3^i)^2} (\dot{\theta}_3^i)^2 + \right.$$

$$+ 2 \frac{\partial \mathrm{A}_1^i}{\partial \theta_1^i} \frac{\partial \mathrm{A}_2^i}{\partial \theta_2^i} \mathrm{A}_3^i \dot{\theta}_1^i \dot{\theta}_2^i + 2 \frac{\partial \mathrm{A}_1^i}{\partial \theta_1^i} \mathrm{A}_2^i \frac{\partial \mathrm{A}_3^i}{\partial \theta_3^i} \dot{\theta}_1^i \dot{\theta}_3^i + 2 \mathrm{A}_1^i \frac{\partial \mathrm{A}_2^i}{\partial \theta_2^i} \frac{\partial \mathrm{A}_3^i}{\partial \theta_3^i} \dot{\theta}_2^i \dot{\theta}_3^i +$$

$$\left. + \frac{\partial \mathrm{A}_1^i}{\partial \theta_1^i} \mathrm{A}_2^i \mathrm{A}_3^i \ddot{\theta}_1^i + \mathrm{A}_1^i \frac{\partial \mathrm{A}_2^i}{\partial \theta_2^i} \mathrm{A}_3^i \ddot{\theta}_2^i + \mathrm{A}_1^i \mathrm{A}_2^i \frac{\partial \mathrm{A}_3^i}{\partial \theta_3^i} \ddot{\theta}_3^i \right) \begin{Vmatrix} 1 \\ X_{4P}^{i} \\ Y_{4P}^{i} \\ Z_{4P}^{i} \end{Vmatrix}, i = 1, 2.$$

Because of these variables' particular values, the Denavit-Hartenberg transformation matrices have the following simpler particular forms:

$$\mathbf{A}_1^{2i} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_1^{2i} & -\sin\theta_1^{2i} & 0 \\ 0 & \sin\theta_1^{2i} & \cos\theta_1^{2i} & 0 \\ s_1^1 & 0 & 0 & 1 \end{Vmatrix},$$

$$\mathbf{A}_2^{2i} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ a_2^{2i}\cos\theta_2^{2i} & \cos\theta_2^{2i} & -\sin\theta_2^{2i} & 0 \\ a_2^{2i}\sin\theta_2^{2i} & \sin\theta_2^{2i} & \cos\theta_2^{2i} & 0 \\ s_2^1 & 0 & 0 & 1 \end{Vmatrix}$$

$$\mathbf{A}_3^{2i} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ a_3^{2i}\cos\theta_3^{2i} & \cos\theta_3^{2i} & -\sin\theta_3^{2i} & 0 \\ a_3^{2i}\sin\theta_3^{2i} & \sin\theta_3^{2i} & \cos\theta_3^{2i} & 0 \\ s_3^{2i} & 0 & 0 & 1 \end{Vmatrix} \tag{5}$$

If one or more legs are in the transfer phase, the geometry of the support polygon changes and it occurs the risk that the protection of the center of gravity moves outside the support polygon.

Solutions to such situations depend on how the modular walking robot is configured. In Fig. 4 are shown some sequence of the computer simulation of the gait of the modular walking robot.

3. CONCLUSIONS

The movement simulation of the walking robots may be idealized into a mathematical model for the purpose of kinematic analysis. The techniques of idealization can play the decisive role in easiness, precision and time of calculus for the problem solving. The Denavit – Hartenberg method is numerically robust, the solutions are either exact in the sense that is possible to refine them up to an arbitrary accuracy. A modular walking robot could have one or more modules. The motions of the legs must

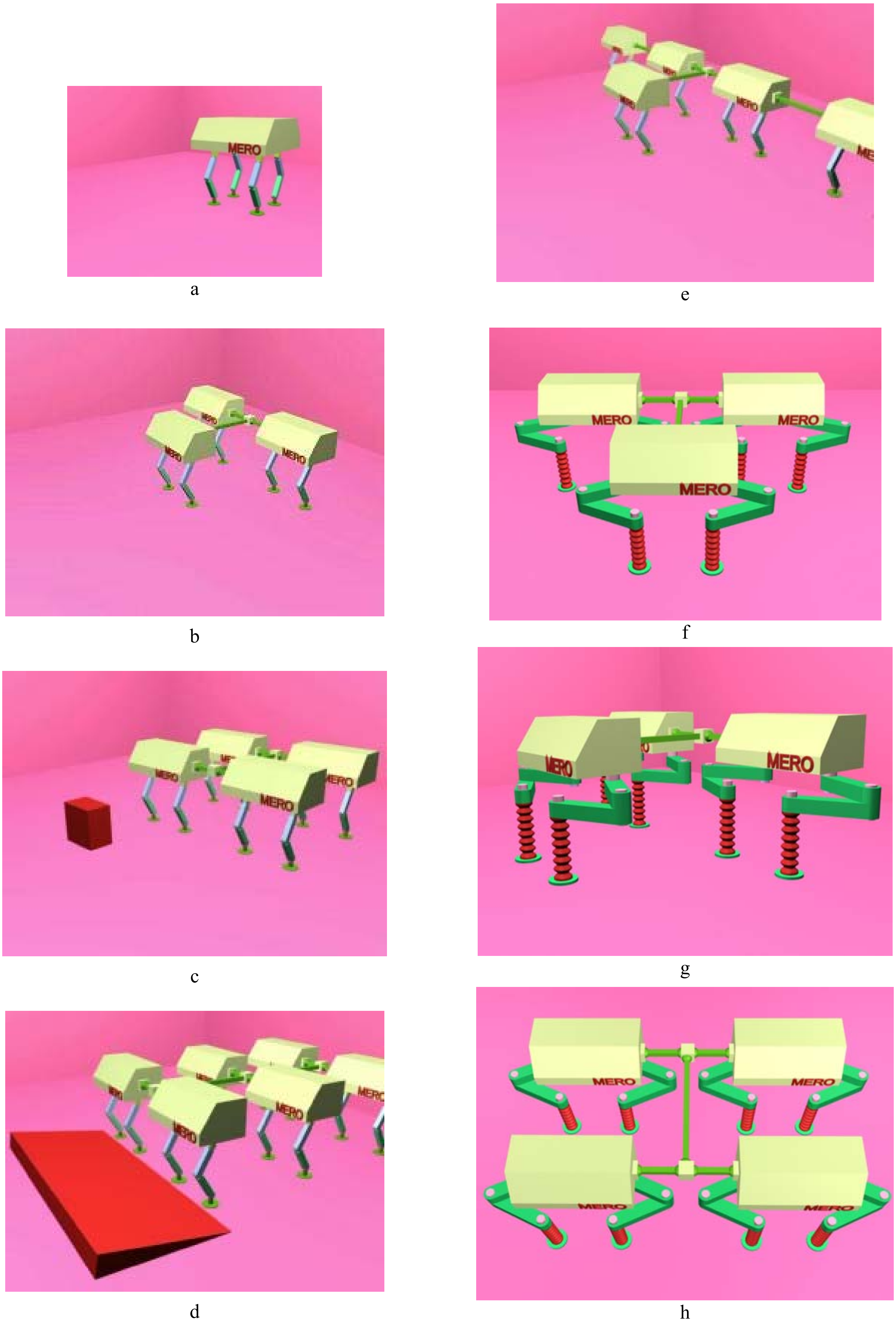

Fig. 4 Computer graphics simulation the gaits of the modular walking robot.

be coordinated so that the conditions of the gait stability of the system to be ensured.

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