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Kinematics of Self-Reconfigurable Robotic System

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BIOGRAPHICAL NOTES

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KEY WORDS

Self-Reconfigurable Robot, Kinematic, Modular System

ABSTRACT

Theory of mechanisms with variable structure in robotic applications self-reconfigurable structures is one of the directions of development of robotics. On our faculty is developed self-reconfigurable modular robotic system capable of rebuilding a structure according to the requirements of the current task. To perform kinematic changes of its structure we needs to have information on where to find the modules and their submodules. Therefore it is necessary to know the mathematical relationship between the positions of its individual parts. Spatial kinematic chains is investigated based on the theory of simultaneous movements, where the position of each member is specified in the global coordinate system using local coordinate systems associated with individual members. To identify the position of the individual local coordinate systems were used transformation matrix, the accuracy of which is verified in mathematical programs and results from these programs are then compared with results of movement analysis notified by simulation procedures.

INTRODUCTION

Number of modules and module properties fundamentally affect the properties of the modular system and also feature a modular metamorphic robot (MMR) assembled from this system. In the design of MMR is therefore necessary to know how many degrees of freedom (DOF) should have proposed module MMR and the extent to which extend the MMR in maintaining the reliability of its functions. To design these module features a modular system can use this knowledge:

- *with the number of modules, number of possible configurations grows exponentially and the number of degrees of freedom linear, this makes an extremely versatile modular robots [1];*
- *possible changes in shape and size of the robot increases its versatility. At the same time, however, this increase in added restrictions on the design and construction management software, [2];*
- *added DOF makes modular robot more versatile in its potential capabilities, but also will increase the mechanical and computational complexity [3].*

Advantages of modular robotics are apparent only where, owing to the required tasks should be applied to several special-purpose robots, or where the environment and the tasks cannot be fully defined in advance [3]. It is therefore appropriate to propose a module, respectively modules, which would be able to cover the maximum amount of the required tasks. In a complex module is therefore easier to modify its control, respectively the individual algorithms and achieve the maximum amount of usable applications. Like design a module and MMR with minimal changes and identify opportunities that projected construction module substantially restrict the wide range of application of MMR and adjust its structure with the entire control.

The results in solution of MMR shows that it is possible to design a module that has a high degree of adjustability, working in 3D space and can support a chain and a lattice structure of MMR. A comparison of present modules and their possible variations, which could be, a link 3D geometric shapes, it is concluded that for use in MMR is most advantageous cube modul into which it is possible to apply the four axes of rotation, which are his body diagonals. On Fig. 1. shows the robotic system composed of three modules MG [4].

In self-reconfigurable MMR systems working movement of end member composition, there is an active movement of individual modules. In industrial robots move of end member is defined composition active movements of individual cells. On the basis that it is possible to apply the knowledge of the theory of industrial robots as a method of modeling of kinematics and dynamics as well as the description self-reconfigurable MMR. To meet the possibility of modifying the connection of individual modules self-reconfigurable MMR system is necessary to extend the skills and knowledge for the automatic compilation of equations for kinematic chains. This need is linked to the formation of new kinematic structures in the conversion system and the formation of new kinematic structures of modules in the proposed module MG.

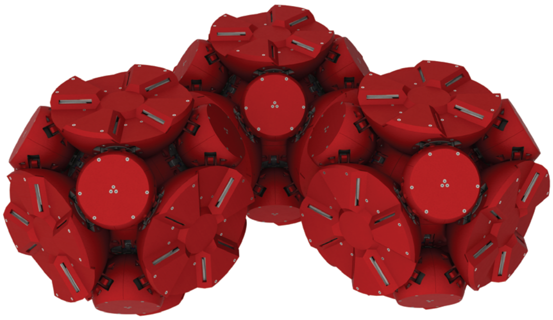


Fig. 1 *Three connected modules of self-reconfigurable robotic system Multi-Group*

An important part of the analysis is complete robot kinematic model of a mechanical system that provides all the necessary kinematic quantities for a dynamic model of a mechanical system such as action forces, load modules, sizing, as well as for control purposes, the synthesis of speed and position regulators. This is particularly the process of the position and orientation of end-member in the time course and the corresponding position of system modules. Position is described by the so-called modules generalized coordinates, which indicate the rotation axes of motion [5].

Movement of spatial kinematic chains is investigated based on the theory of simultaneous movements. Where is the location of each member specified in the global coordinate system (GCS) using local coordinate systems (LCS) associated with individual members. For use in these systems is preferable to use Denavit - Hartenberg deployment principle coordinate system, which allows to compile the mutual transformation matrix automatically.

Denavit - Hartenberger method describes the overall transformation matrix between the base coordinate system and the last n-th coordinate system as the multiplication of transformation matrices for adjacent systems in the order they are numbered locally coordinate systems. The matrix is a function of all the generalized coordinates and symbolic form leads to very complicated trigonometric expression for the matrix elements of each site.

$$T_b^n(q_1,q_2,...,q_n) = A_b^0 . A_0^1 . A_1^2 ... A_{n-1}^n(q_n) \quad (1)$$

In self-reconfigurating robotic systems, the overall transformation matrix between the base coordinate system and n-coordinate system given by multiplying the individual transformation matrices for adjacent systems in the order they are locally coordinate systems through linked modules and is a function of generalized co-ordinates all.
Direct kinematics i.e. conversion of coordinates from the last n-th local system of grid in the base system is known to feed rate and rotation kinematic pair q_1, q_2, ... $q_n$given by:

$$\begin{bmatrix} x_b \\ y_b \\ z_b \\ 1 \end{bmatrix} = T_b^n(q_1,q_2,...,q_n).\begin{bmatrix} x_n \\ y_n \\ z_n \\ 1 \end{bmatrix} \quad (2)$$

Module MG builds from motional options module Molecube allowing rotation one half module around axis laying one from body diagonals. Since this module has one axis rotation his description covers description of rotation q around his axis and description position of connection mechanism that module given to base coordinate system. Where moving half module will transformational matrix shape $T_b^{nsi}(q_n)$, where si is place connections with neighboring modulus on variable component, q is turning angle given to solid section. Transformational matrix is multiplying individual transformation matrices describing locally coordinate systems in positive direction. In solid section module it description bonding cities to focus and transformational matrix has shape T_b^{nsj}, where sj is place connections with neighboring modulus on solid section module. Transform matrix is multiplying the individual transformation matrix of local coordinate system in the positive direction. Thus obtained location information and connecting cities use the swivel axis formation transformational matrix T_b^n, which refers to the position n-th modules in the system relative to base module resp. position of the connecting point's modules.

On definition of transformation matrices used the following transformation matrix:

- *transformation matrix of rotation around the x-axis:*

$$T_n^{n+1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(d*p_{n+1}) & -\sin(d*p_{n+1}) & 0 \\ 0 & \sin(d*p_{n+1}) & \cos(d*p_{n+1}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

- *transformation matrix of rotation around the z-axis:*

$$T_n^{n+1} = \begin{bmatrix} \cos(d*p_{n+1}) & -\sin(d*p_{n+1}) & 0 & 0 \\ \sin(d*p_{n+1}) & \cos(d*p_{n+1}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

- *transformation matrix of displacement along the z-axis:*

$$T_n^{n+1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d*p_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Where d is a coefficient determined by calculating the direction of transformation matrices:

- **d** = 1, *if there is calculation from the basic local coordinate system to one of joining sides,*
- **d** = -1, *if there is calculation from one of joining sides to the basic local coordinate system.*

Description of transformation matrices must be performed separately for each submodule. The advantage is the identity of sub-module of core and sub-module of rotation. When is created an optimal transformation matrix in the positive and negative direction for each module, then is created six transformation matrices in one module. Combining of these transformation matrices can determine the position of local coordinate system modules and submodules. Subsequently, the transformation matrix can be multiplied in the order in which there is a link and thus we determine the location of grid system required local and state in a combination of several modules into one unit.
When submodule of control must describe transfor-

mation matrix so that when we requested substituting variables reached the desired local coordinate system on the coupling with the adjacent submodules. Fig. 2 are shown the main local coordinate systems of modules. Basic LCS_b, which lies at the intersection of the axes of rotation in the middle of the submodule, four LCS with the possibility of rotation around the axis of rotation and four LCS without rotation.

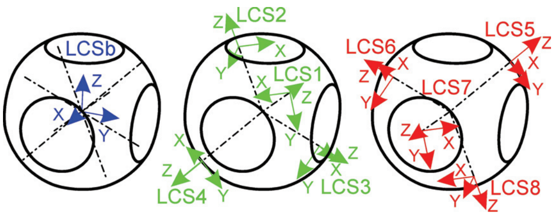


Fig. 2 *Local coordinate systems in submodule of core*

The sequence of steps for defining $LCS_{i,j}$ with matrix (3), (4) and (5):

- *rotation around the x-axis of value $p_0 = 0$ for the top half and $p_0 = \pi$ for the bottom half;*
- *rotation aroud the z-axis of value $p_1 = \pi/4$, $-3/4*\pi$, $-\pi/4$, $3*\pi/4$/ by rotation axis and the points of interconnection with neighboring sub-modules;*
- *rotation around the x-axis to the axis of rotation submodule of value $p_2 = -0{,}9553$ [rad];*
- *displacement along the z-axis of value $p_3 = r_{ro}$, where r_{co} is the radius of the submodule of core;*
- *rotation around the z-axis of the submodule degree of freedom and rotation of coordinate system to a local system of coordinate system of adjacent submodules of value $p_4 = q + s_i$, where s_i can be $s_1 = 0$, $s_2 = \pi/3$, $s_3 = -\pi/3$;*
- *rotation around the x-axis of value p_5, whereas for $d = 1$, $p_5 = 0$ and at $d = -1$, $p_5 = \pi$.*

The resulting transformation matrix from the LCS_b to $LCS_{i,j}$ where $d = 1$, has the form:

$$Tj_b^{i,j}(p_0, p_1, p_4, p_5, d) \tag{6}$$

And transformation matrix from the $LCS_{i,j}$ to LCS_b where $d = -1$, has the form:

$$Tj_{i,j}^{b}(p_5, p_4, p_1, p_0, d) \tag{7}$$

Submodule of rotation be described transformation matrix so that we are substituting the variables required achieve the desired local coordinate system on the connection with the adjacent submodules. Fig. 3 are shown the main local coordinate systems modules. Basic LCS_b, which lies at the intersection of the axes by the submodule, three LCS in the direction of active parts of connection mechanism and one LCS in the direction of passive connection mechanism.

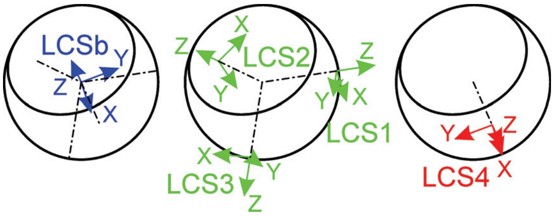


Fig. 3 *Local coordinate systems in submodule of rotation*

The sequence of steps for defining $LCS_{i,j}$ with matrix (3), (4) and (5):

- *rotation around the x-axis of value $p_0 = 0$ for the top half and $p_0 = \pi$ for the bottom half;*
- *rotation aroud the z-axis of value $p_1 = 0$, $2*\pi/3$, $-2*\pi/3$ by rotation axis and the points of interconnection with neighboring submodules;*
- *rotation around the x-axis to the axis of rotation submodule of value $p_2 = -0{,}6155$ [rad];*
- *displacement along the z-axis of value $p_3 = r_{ro}$, where r_{ro} is the radius of the submodule of rotation;*
- *rotation around the z-axis of the submodule degree of freedom and rotation of coordinate system to a local system of coordinate system of adjacent submodules of value $p_4 = s_i$, where s_i can be $s_1 = 0$, $s_2 = \pi/3$, $s_3 = -\pi/3$;*
- *rotation around the x-axis of value p_5, whereas for $d = 1$, $p_5 = 0$ and at $d = -1$, $p_5 = \pi$.*

The resulting transformation matrix from the LCS_b to $LCS_{i,j}$ where $d = 1$, has the form:

$$To_b^{i,j}(p_0, p_1, p_4, p_5, d) \tag{8}$$

And transformation matrix from the $LCS_{i,j}$ to LCS_b where $d = -1$, has the form:

$$To_{i,j}^{b}(p_5, p_4, p_1, p_0, d) \tag{9}$$

Submodule of connection should describe transformation matrix so that we required for substituting variables achieved the desired local coordinate system on the coupling with the adjacent submodules.

Fig. 4 are shown the main local coordinate systems modules. Basic LCS_b, which lies at the intersection of the axes by the submodule, four LCS in the direction of rotating parts connection mechanism and one LCS in the direction of the main connection mechanism.

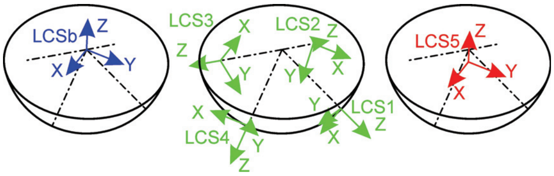


Fig. 4 *Local coordinate systems in submodule of connection*

The sequence of steps for defining $LCS_{i,j}$ with matrix (3), (4) and (5):

- ***displacement along z-axis of value $p_0 = -1$ for direction of rotation part of connection mechanism of submodule of value $p_0 = 0$ for the main connection mechanism;***
- ***rotation around the z-axis of value $p_1 = 0, \pi/2, \pi, -\pi/2$ for direction of rotation part of connection mechanism of submodule, and $p_1 = 0, \pi/2, \pi$ for the main connection mechanism;***
- ***rotation around x-axis of value $p_2 = 0$ for main connection mechanism and $p_2 = 0{,}3398[rad]$ for direction of rotation part of connection mechanism of submodule;***
- ***displacement along z-axis of value $p_3 = 0$, for main connection mechanism and $p_3 = r_{cs}$, for for direction of rotation part of connection mechanism of submodule, where r_{cs} is the radius of the submodule of rotation;***
- ***rotation around the z-axis of the submodule degree of freedom and rotation of coordinate system to a local system of coordinate system of adjacent submodules of value $p_4 = q + s_i$, where si can be $s_1 = 0$, $s_2 = \pi/3$, $s_3 = -\pi/3$;***
- ***rotation around the x-axis of value p5, whereas for $d = 1$, $p_5 = 0$ and at $d = -1$, $p_5 = \pi$.***

The resulting transformation matrix from the LCS_b to $LCS_{i,j}$ has the form, where $d = 1$:

$$Ts_b^{i,j}(p_0, p_1, p_2, p_3, p_4, p_5, d) \qquad (10)$$

A transformation matrix from $LCS_{i,j}$ to LCS_b has the form, where $d = -1$:

$$Ts_{i,j}^{b}(p_5, p_4, p_3, p_2, p_1, p_0, d) \qquad (11)$$

The functionality and accuracy of transformation matrices has been verified by mathematical programs MathCad® and Matlab®, where the recalculation of transformation matrices for the two modules associated MG. Among them were subsequently obtained transformation matrix and position vectors x_i, y_i, z_i for each of the main LCS shown in Fig. 2, 3, 4. Followed by plotting the position of the LCS in the area at the bottom deflection module and comparing the tracks of the LCS program SolidWorks® COSMOSMotion found that the curve along which they move LCS are the same ie. transformation matrix that are properly designed to detect the exact position of each LCS.

Mathematical notation of transformation matrices for each sub-modules it allows sub-modules under the requirements of the role currently carried out by the system and yet still have the position vectors to any LCS structure in a momentary kinematic structure.

Connections allows to create different modules of the simplified base module. As an example, applications can shown kinematic structure in Fig. 5, which corresponds to gripping mechanism. Is highlighted in red kinematic structure. The kinematics has 11 DOF. Allows you to fit large and small loads. Maximum range is about 350 mm and 500 g load. To attach the small loads can be used jaw of connection mechanisms, which distance in a closed state is 7,5 mm.

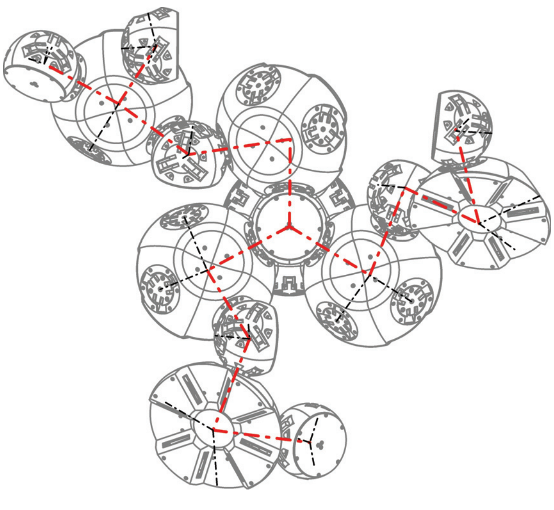
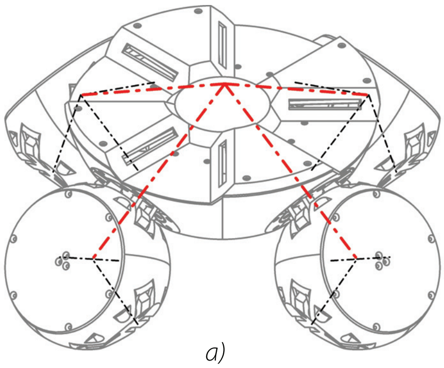
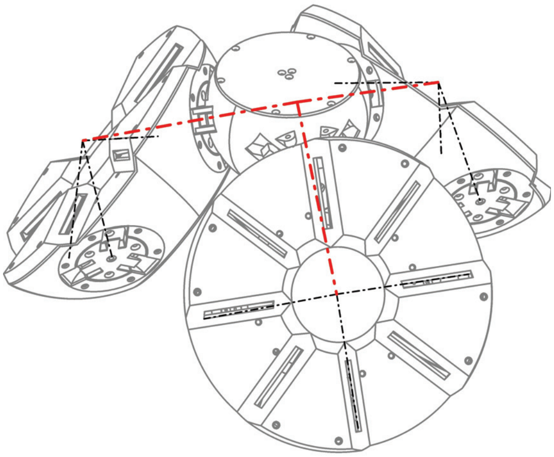


Fig. 5 *Active kinematic structure of opened module*



a)



b)

Fig. 6 *Two kinematic structures from submodules of rotation and submodules of connection*

CONCLUSION

Self-reconfigurable modular robotic systems have great potential application, but only if this system will replace a large number of specific robots. Our proposed system has features that allow replacing the large number of specific robots. The module supports a high degree of adjustability and also allows you to create the sub-modules and other modules resp. robotic systems that can work well in a reduced number of sub-modules. Fig. 6 is shown two kinematic structures formed only with sub-modules of rotation and sub-modules of connection. Fig. 6a is a module with four DOF, which is able to move across the surface without cooperation with other modules. On fig.6b module with the three DOF, this is able to move across the surface without cooperation with other modules. That these options module and its sub-modules are used is necessary to know the position vectors of LCS. To serve the transformation matrix presented in this paper.

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