The Module for a Self-Reconfigurable Robotic System

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Abstract—The article presents design of a new type of a module for self-reconfigurable robotic system. The designed module is a complex unit consisting of fifteen sub-modules. The module is able to connect to other modules, sub-modules of others modules or split itself to sub-modules to perform a desired action. This article presents the process of module shape design to maximize the usable volume with acceptable force power effect between sub-modules. Moreover, the article presents the first physical version of the module, which was designed to verify proposed kinematics of the module and for experimental verification in three types of predefined movements.

I. INTRODUCTION

Self-reconfigurable robotic systems are devices able to adapt their shape and kinematic structure for a newly defined condition in which they are located, or for newly created tasks, which has been defined. The basic element of these systems is a module. Shape, possibilities and autonomy of the overall system is defined by these modules. These systems may work in a lattice [3] or a chain structure [5, 6, 8]. Some of them are able to work in both structures [9, 12, 13]. Both these structures have advantages and disadvantages [1, 9].

Self-reconfigurable systems have applications in the situations and tasks where many special robots are required or where space and all necessary actions that must be taken are not known in advance [1].

II. DESCRIPTION AND PRESENTATION OF MODULE PERFORMANCE

These systems are based on modules and therefore we can process design of such systems by two possible methods. The first method is Top – Down (TD), where all properties of the system are defined and from that we can get definition of module or types of modules. The other method is Down – Top (DT), when a module or modules are designed and then we can get all properties of the system.

In our design of a module called Multi-Group (MG), we used the TD method. The main idea was to create a system able to work in lattice and chain structures. System that will be able to change its own shape and properties, able to work in group of modules and where modules can work like a single unit with the ability to change its own kinematic structure. Create a module able to split itself to sub-modules able work independently, module able to detect own failures, overloading and also able to partially, if not fully, self-repair. For this reasons we have chosen the cube shape as a base shape of the module. This shape has advantages like the symmetry in 3D and possible six connection surfaces-places. It was necessary to design a sufficient number of degrees of freedom (DOF) for maximum number of connection places.

Based on reviewing of previous works from different authors [1,2,3,4,10,11] and a created comparison of possibilities of existing modules, we decided to apply an axis of rotation into the cube volume diagonal, like in this module [4], but for all the diagonals, not just one of them, Fig. 1a. A module with four axes of rotation will still have six connection surfaces and obtain useful movement possibilities, like one of “Rubik’s cube” type cube called “Skewb” [15]. On the other hand, four axes of rotation applied in module will increase the structural complexity of module. Every rotation axis needs a plane perpendicular to the axis and these planes divide the module into fourteen sub-modules, Fig. 1.

To avoid collision states during rotation around an axis, it is necessary to make some geometrical modifications of the module. These modifications are based on possible moves that the module must perform. When one half of the module is turning around some axis (Fig. 2), there is an intersection with the vertices on modules connected to the main module. Gray color shows the removed collision volume. Vertices of the removed pyramid volume lie in the center of cube base edges. When the collision volume is removed, the cube shape transforms into a cuboctahedron shape.

Figure 1. Basic shape with four axes of rotation

Figure 2. Collision volume of module
If two neighboring modules make movement in free axes like on Fig. 3a, modules are in intersection between vertices of the moving halves of modules. Gray color shows the removed collision volume, Fig. 2. The external radius of the module after collision volume removal is:

\[ R = \frac{3L}{8} \]  \hspace{1cm} (1)

Where: \( L \) - length of cube edge.

In an ideal state, the modifications of shape are sufficient for module collision prevention. The resulting possibly usable volume of the module represents 80.65 % of the basic cube volume. The module is divided into 14 parts and to achieve movements around all basic axes it is necessary to have another sub-module in the center of the module.

Other sub-modules will move around this core sub-module. Six sub-modules are the modules of connection because they are able to make connections with other modules. Eight sub-modules are the sub-modules of rotation because they allow rotation motions of all cover sub-modules.

To achieve the movement of one half of the module relatively to another, 32 pairs of connection mechanisms in a single module are needed, and further 6 connection mechanisms are needed to provide connections with the neighboring modules.

The number of connection mechanisms is very high for a module with 4 DOF. But a module divided into this number of sub-modules allows expanding possibilities of the module exactly as it was defined at the beginning of the design – the ability to change the module kinematics and to split itself.

To use these properties, we need to add 4 DOF to the sub-module of connection. Together with the main axis rotation it is 28 DOF. And another geometric modification of all sub-modules must be made to avoid collision states during motion of the module. There are two possible options for modifications; the first option is without any interactions between volumes, Fig. 3a, but with a big gap in place for connection mechanism. The second option is with the interactions between the core sub-module and sub-module of connection, Fig. 3b. The intersection volume in the second option is removed.

Usable volumes for different types of \( l_m \) are shown on Fig. 4a. \( l_m \) is the length from the center of module to a minor axis; \( l_m = 25 \) to 60 mm. The dimension \( l_m \) influences the radiiuses of each sub-module (\( r_c, r_r, r_{co} \)) and their volumes. Fig. 5a shows all input parameters for the calculation: 1 – external shape of the module (\( L = 100 \) mm), 2 – first geometrical modification of the module, 3 – second geometrical modification of the module (\( R \) is radius), 4 – sub-module of connection (\( r_{co} \)), 5 – sub-module of rotation (\( r_r \)) and 6 – core sub-module (\( r_c \)). The chart on Fig. 4b shows the changing volume of sub-modules in the second option.

Evaluation and comparison of these options and comparison of remaining volumes of sub-modules shows that the appropriate length is \( l_m = 46.25 \) mm, in a module with \( L = 100 \) mm. The usable volume of all sub-modules is 56.17 % of the cube volume. This volume ratio is not the largest that can be achieved. But with this \( l_m \) the volume of the sub-module of rotation is the largest and location of the axis of rotation in sub-modules of connection is suitable for adding an actuator to it.

The modified collision volume of module, Fig. 5, limits the size of module space by about 43.83 %. Any manufacturing inaccuracies and the design of construction will increase this number.
In order to rotate the module parts around different axes and in order to divide the module into individual sub-modules, it is necessary to properly allocate active and passive parts into all sub-modules.

We consider using a male-female connection mechanism between sub-modules and a genderless connection mechanism between modules, Fig. 6. The connection mechanism between sub-modules can be connected with rotation by 120° and between modules by 90°.

The connection mechanism between sub-modules is based on the free volume space between sub-modules, respectively; shape of these free spaces defines the possible shape and principle of function of the connection mechanism. While sub-modules are connected like on Fig. 7a, the usable space is different from the space which can be occupied while the sub-modules are connected like on Fig. 7b. Connection of these spaces shows, Fig. 7c, that it is possible to use this free space to create sub-modules connection mechanisms like three-finger gripper, Fig. 7d, with 120° between fingers. For that reason, the connection mechanism between sub-modules can by connected with a 120° rotation. The finger side of the connection mechanism is “male” and the other side is “female”.

A. Sub-module of core
This sub-module has eight male sides of connection mechanisms and four degrees of freedom. On Fig. 8a (green) are DOF and male connectors and on Fig. 8a (red) are male connectors only. Such distribution of active parts will be sufficient to ensure the rotation around the axis and connection to neighboring sub-modules.

B. Sub-module of rotation
The sub-module of rotation acts as a passive module with no degrees of freedom and with four connection places. Three of the connection places are active male connectors, Fig. 8 (green), and one is a female connector, Fig. 8 (red).

C. Sub-module of connection
This sub-module has four degrees of freedom and five connection places. Four of them are female passive connectors. In same place where the four sub-modules connection mechanisms are, is placed a DOF, Fig. 8 (green). Connection between modules is provided via a genderless connector, Fig. 8 (blue).

The spaces in Fig. 8 are not determining the amount of space that is designed for the construction. They only show a place where the given part will be located.
IV. MOTION SIMULATION

The designed module has high motion potential given by the high number of DOF and number of connection mechanisms. To achieve motion on a physical module it is necessary to know the values of the required mechanical parameters. For that reason motion simulations were made in an Adams-based simulation system to find these values.

Since it is not defined how quickly the module can move and it is necessary to determine whether the values of torque and reaction forces are radically changing with the rotation speed, we chose the response variable actuator speed, Fig. 9. The given characteristic of the actuator is applied to all simulations.

Three series of calculations were done:
1. Changing size of the module from $L = 100$ mm to $L = 300$ mm in 20mm steps, while also changing the testing assembly: occupation of connection places on the moving module, Fig. 10.
2. Changing the number of connected modules at one connection place from 1 to 10 by 1, for a fixed size of the module $L = 100$ mm.
3. Changing the number of connected sub-modules in a chain at one connection place of the sub-module core, for $L = 100$ mm and the number of connected sub-modules ranging from 1 to 14, with step 1.

All calculations were made with a full volume of modules and sub-modules and with density of material $1000 \text{ kg/m}^3$.

The calculations were done in SolidWorks – Motion, which supports dynamics calculations and uses the MSC ADAMS engine. As a result, the maximum values for individual torques and forces in connection places were obtained.

The results were processed into graphs showing the maximum values for needed torques, Fig. 11a, and the maximum needed connection force between the core and the moving half of the module, Fig. 11b, for the first series of calculations.

The maximal needed values of torque and connection force for the second series of calculation are shown on Fig. 11c,d and the maximal needed torque for the third series of calculation is shown on Fig. 11e.

The obtained values give us an initial idea of needed torques for actuators and forces in the connection mechanism. Based on these values, the first physical model of the MG module was designed and was used for some experiments to determine whether collisions occur during motion or not. The model includes actuators to provide rotary motion in the main and minor axis and manual connection mechanisms. The connection mechanisms are designed just for connection of the sub-modules.
V. INITIAL DESIGN

The initial design was based on data provided in the previous section of this article. Constructions of sub-modules consist of components printed on a 3D rapid prototyping machine, parts from laser cutting and fasteners (bolt, nuts and washers). Based on values, Fig. 11, the module has the base length \( L = 250 \text{ mm} \). We chose this size, because we wanted to verify the movement possibilities and collision conditions at the lowest possible price. For this length and the required load of sub-modules, we used servos from Hitec®. These actuators are much cheaper but bigger than Maxon® or Faulhaber® for the same required load value. HS7985MG actuators (torque 12.4 kg.cm at 6 V) were used for the main axes were used; HS5085MG (4.3 kg.cm torque at 6 V) were used for the minor axes. These properties satisfy the requirements identified in the motion analysis.

All sub-modules are created in simplified versions. Sub-module of core has got two active axes and six connection points. These are sufficient to verify the collision detection and partially the physical possibilities of the whole module.

The sub-module of rotation contains four male connection places, which are represented by 3xM5 nuts. For reactions that occur during the motion, this design is sufficient, Fig. 12b.

The sub-module of connection has got two active axes and 4 connection places. The sub-module does not have any connection mechanisms to connect with neighboring modules, Fig. 12c.

The entire design was verified by the FEM calculation method so that the weight of all parts is the lowest possible with a sufficient strength and rigidity of the structure, for the defined types of experiments.

VI. EXPERIMENTS

To verify the collision detection and physical possibilities of the designed module MG, three types of experimental movements were chosen. These experiments are the basic movements that the module must handle. The actual types of experiments are:

1. Movement with sub-modules connected in serial structure – to verify if there is a collision or not, Fig. 13a.
2. Movement with sub-modules connected in serial structure with parallel motion – to verify if there is a collision or not, Fig. 13b.
3. Rotation around main axes of the module – relocating the sub-module of connection from front to back, Fig. 13c.

In the first experiment the module makes the desired movement in a defined structure of sub-modules. The movement occurred in three types of possible combinations of movements of actuators:

1. Movement with both actuators together.
2. Movement with the first actuator and then with the second one.
3. Movement with the second actuator and then with the first one.
The third experiment was divided into two parts. The first part is to move the sub-module from front (with black actuators) to the top of the module. The second part is to move the same sub-module from top of the module to its back, Fig. 14c. In the base state all sub-modules in a module are connected to its neighboring sub-modules. So the module has fixed state, without any DOF. To ensure this movement, 6 connections must be disconnected in a plane perpendicular to the rotation axis before the first part of the move. After the first part, all connections must be established (fixed state of the module) and other 6 connection must be disconnected in a plane perpendicular to the second axis. At the end of the second part of move, all connections are reestablished (fixed state of the module).

VII. CONCLUSION

Based on the presented experiments, it was discovered that there was undesirable abrasion between sub-modules during the performance of the defined movement. This was due to the inaccuracy of production of individual parts, which made gaps in the shaft drive, and also because of the low stiffness of the proposed design elements. This knowledge will be used in the design of the second version of the MG module.

The second version of the module will have sensors to detect the neighboring sub-modules, an automatic connection mechanism and other sensors to determine the exact position and orientation of the module in space. The ongoing development of the connection mechanism for connection with neighboring modules shows that it is possible to provide automatic connection between modules. Simultaneously with the development of a new design, software is being developed, to support self-reconfiguration for $n$ number of modules in one system and coordination of $n$ number of individual systems. This software will serve as a test program for algorithms and test of control for use in modules and sub-modules.

A self-reconfigurable system has a huge potential for its application in various application areas. This application is effective only if these systems are able to replace more specific robots to solve the same problem. Therefore it is necessary to design these systems so that they are able to fulfill this requirement. The introduced principle shows the MG module for self-reconfigurable system. It will be able to operate in its basic function in the “cube” shape and lock its shape so that it can create a fixed part of the system without the need for a brake on the actuators after the automatic connection mechanism will be part of it. The module will be able to rebuild its own shape and create a new module without the need to re-construct additional modules. Such a complex module will be able to cover a wide range of applications of robotic tasks.

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