Application of continuous carbon fiber reinforced composites in a modular system

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Abstract. The article deals with the development of the construction of a second generation robotic manipulator designed on a modular principle. The manipulator consists of 6 separate rotary modules interconnected by passive members of the structure. In previous generations of the module, the high weight of the overall assembly, which limited the movement properties, proved to be a problem. Modifications to the structure no longer allowed for further weight reduction. Therefore, a change was made to the materials used for the passive members of the structure. The aluminium alloy was replaced by a continuous carbon fiber reinforced composite produced by additive technology. Modelling and simulation in CAD software was used in the modification of passive members, which was necessary in order to be able to design and manufacture composite parts.

1. Introduction

Theoretical beginnings of the use of modularity in industry were developed in the seventies, but significant use of modular systems occurs only today [1]. Nowadays, modular systems are undergoing considerable development. New types of modular devices are appearing, their quality is increasing and new areas in which they are used are being added. Robotics is one of the industries in which the principles of modularity can be fully utilized. The goal can be to create a robotic device designed for a specific task (for example a snake that passes through a tunnel or a rolling belt to quickly cover an opening) or a robot designed for a specific job (for example a wrench, hammer or bridge). After completing a task, the modules in the structure can be disconnected and reused to create another device for another task [2].

An example of such robotic device based on the modular principle is a rotary module with an unlimited degree rotation (URM 02). It is a modular system, which by its construction allows to assemble machines and equipment designed for various tasks. Such machines are, for example, manipulators, industrial robots or robotic arms. It is possible to assemble machines for various applications from one type of module without modifications of an individual module or with only minor modifications. During the operation of the URM 02, the advantage is the possibility of using unlimited rotation of adjacent modules. The use of URM 02 modules or their assembly in the form of a manipulator is designed for handling work of industrial robots with lower dynamics of movement or after making certain modifications in production technology (e.g. auxiliary arm of production machine, tool change) [3, 4].
2. Theory
The article focuses on the development of a modular robotic system URM 02 and the optimization of the weight of certain members of the URM 02 structure by replacing metallic materials with composites reinforced with continuous carbon fiber.

2.1. Modular robotic systems
The theory that describes the definition of the general conceptual architecture of a modular robot is called the Axiomatic Design Theory (ADT) [5]. According to ADT, the basis of the general architecture of modular robotic systems is to create different configurations of the robot composed of modules in order to fulfill all the functional requirements for the operation of the robot. Then identify the design parameters of the structure, these must respect and suit the functional requirements [5, 6].

Diverse machines for different applications can be built from the same modules. Assembling robotic devices on the principle of modularity brings several advantages. Properly designed modular construction leads to simplification of production, assembly, handling, storage and service. Modularity allows not only individual configuration of the construction of robotic system but also gradual expansion and improvement of equipment according to current requirements [1, 5, 6].

By summarizing the functional and design requirements, a general list of design features of modular robotic systems is created [6]:

- A modular robot can consist of several joint and link modules. These modules can have different types and sizes. Link modules also include a base or top platform. Joint modules include an end effector.
- Joint and link modules can have several interconnection options, which can take place between any modules (joint / joint, joint / link, link / link).
- Joint modules are then divided into active (with motor) and passive (without motor).
- Link modules have two special types for connecting more than two modules. They are a hybrid connection module (connection between joint modules to create a hybrid robot) and a platform module (base platform).
- Some modules may have adjustable parameters, for example link modules may have adjustable geometry dimensions or active joint modules may have an adjustable starting position.

An example of a modular robot designed on the basis of the above-mentioned features is the H-ROS robot [7] (Figure 1) or the universal rotary module URM 02 described in the following chapter.

![Figure 1. H-ROS modular robot [7]](image-url)
2.2. Composites reinforced with continuous carbon fiber

Composites consist of at least two materials with different properties. By joining, they created a material which, with its latest properties, surpasses the original separate materials. The reinforcement placed inside significantly improves the mechanical properties and the matrix around the reinforcement creates the shape of the part and protects the reinforcement from the environment [10]. For the production of angular members for URM 02, 3D printing of the composite was chosen due to the simplicity, speed and accuracy of production. The Markforged Mark Two 3D printer (Figure 2) was used for production.

![Figure 2. The Markforged Mark Two 3D printer [11]](image)

The advantage of this 3D printer is the printing of continuous reinforcement of carbon fibers or HSHT (Figure 3) and thus obtain quality products with high strength (comparable mechanical properties with aluminium alloys) and low weight [11].

![Figure 3. Example of reinforced composite part [11]](image)

The printer prints the reinforcement inside the plastic matrix. Onyx Filament consists of two parts: nylon and small carbon fiber particles. Onyx is used as a thermoplastic matrix for composite parts. The table compares the mechanical properties of Onyx and ABS plastic (Table 1). Markforged offers a choice of several reinforcement materials such as carbon fiber, Kevlar, HSHT, fiberglass. In the table
(Table 2) there is a comparison of the mechanical properties of the two most suitable materials for reinforcement. The comparison shows that carbon fiber was a suitable material for the production of parts for URM 02 as a reinforcement of the composite matrix [11, 12]

**Table 1. Mechanical properties of selected thermoplastics [12]**

| Material | Density (g/cm³) | Modulus of Elasticity (MPa) | Tensile Strength (MPa) | Deformation at Yield Strength (%) | Breakdown Stress (MPa) | Deformation at Break (%) |
|----------|----------------|-----------------------------|------------------------|----------------------------------|-----------------------|--------------------------|
| ABS      | 1.04           | 2095                        | 29.5                   | 1.8                              | 22.9                  | 16.3                     |
| Onyx     | 1.2            | 1401                        | 36                     | 25                               | 30                    | 58                       |

**Table 2. Mechanical properties of reinforced materials [12]**

| Material   | Density (g/cm³) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Tensile Stress at Break (%) | Flexural Strength (MPa) | Flexural Modulus (GPa) | Flexural Stress at Break (%) |
|------------|-----------------|------------------------|-----------------------|-----------------------------|------------------------|------------------------|-------------------------------|
| Carbon fibers | 1.4             | 800                    | 60                    | 1.5                         | 540                    | 51                     | 1.2                           |
| HSHT       | 1.5             | 600                    | 21                    | 3.9                         | 420                    | 21                     | 2.2                           |

3. **CAD model**

3.1. **Universal rotation module (URM 02)**

The presented solution (URM 02) is a modular system for assembling modular robots (Figure 4). The basic feature of the construction is the possibility of unlimited rotational movement of two interconnected modules. By connecting the modules, it is possible to assemble a manipulator with six degrees of freedom of movement. A higher number of interconnected modules means more degrees of freedom. Passive connecting members or extension arms can be connected between the modules. Which allows to achieve a large range of workspace and accurately achieve individual points in this space [4, 8]

![Figure 4. Rotary module with unlimited degree of rotation (right), manipulator assembly from URM 02 (left)](image-url)
URM 02 (Figure 5) is designed as a cylinder and all mechanical components (motor, gearbox, encoder, bearings) and electrical elements (batteries, control board, transmission board) are placed inside.

![Figure 5](image1.png)

**Figure 5.** Basic dimensions of URM module type L

Such placement does not prevent the unlimited movement of the modules and at the same time protects the components from damage and environmental influences. The modules are connected via a clamp coupling. Among the modules are the so-called angular members. Their function is to directly determine the possibilities of the manipulator's movement and the size of its workspace [4, 9]. From Figure 4 it is clear that the manipulator consists of 6 modules of 3 size series, i.e. L modules have the largest height, diameter and weight (Figure 5), M modules have smaller parameters, etc. and 5 angular members from 3 size series (Figure 6), i.e. the angular member L connects the two modules L, the angular member LM connects module L and module M, and so on.

![Figure 6](image2.png)

**Figure 6.** CAD model of angular member (left), section view (right)

URM 02 is the second generation of modules. When testing older versions, shortcomings were discovered that needed to be removed. The improvements were mainly weight reduction and improvement of mechanical functions. A relief of 1.8 kg was achieved by changing the roller bearings to plain bearings. By changing the internal construction, more space was achieved inside, which enabled better storage of electronics and the use of larger batteries. The interconnection system has also been changed. The locking pins were replaced by a clamp coupling.

Other changes that this article is about are changes to the angular members. The original parts made of aluminium weighed too much and needed to be lightened. The design changes did not allow
major modifications and therefore the material was replaced. Aluminium was replaced by a composite produced by additive technology.

3.2. Adjustment of angular members

The original design of the angular member did not allow its use in 3D printing. It consisted of four parts joined by corner welds. However, for 3D printing, it is better to design the component as a whole. This eliminates the need to use a binder that could be a weak link in the structure. The adjustment of the original angular member consisted of two things. In order to be able to reinforce the walls with carbon fiber, their thickness had to be increased from the original 3 mm around the whole component to 6 mm on the bottom and top and on the sides to 5 mm (Figure 7). Furthermore, the addition of supports inside as the component will be loaded primarily to bend.

![Figure 7. Modified construction for 3D printing (left), section view (right)](image)

To ensure the best possible mechanical properties of the infill, the density of the infill between the reinforcements was chosen to be 100%. This means more material used but at the same time higher component strength [13]. Continuous carbon fiber was added in three interconnected lines that copy the shape of the part. The orientation of the part during printing was chosen on the side in order to be able to place the reinforcement with carbon fibers in the direction of the greatest load and thus make maximum use of its excellent mechanical properties (Figure 8).

![Figure 8. Cross section of the internal structure of the angular member – plastic matrix (white), carbon fiber (blue), support (purple)](image)
4. Results

4.1. Weight optimization

After replacing metallic materials with continuous carbon fiber reinforced composites, construction modifications and producing angular members on a 3D printer, we were able to reduce the total weight of the components (Table 3) as shown in the table below. The graphical representation of weight optimization (Figure 9) is shown in the graph below.

Table 3. Mechanical properties of reinforced materials

| Angular member size type | L    | LM   | M    | MS   | S    |
|--------------------------|------|------|------|------|------|
| Original weight (g)      | 563.92 | 551.29 | 491.59 | 477.09 | 415.73 |
| Weight after optimization (g) | 233.63 | 228.7  | 220.42 | 214.54 | 199.99 |

Figure 9. The graphical representation of weight optimization

5. Conclusion

Weight optimization is important in the design of robotic devices for several reasons. Lighter construction has lower energy requirements, better functionality, better movement properties, etc. The article describes the design of a modular robotic system URM 02 and its components from which it is possible to assemble a manipulator or a robotic arm. During the development, shortcomings were found, limitation of functionality caused by the high weight of components. The means of reducing the weight was to change the materials used. The aluminium alloy originally used for all components was replaced by a continuous composite material reinforced with carbon fibers produced by additive technology. The article focused mainly on one important component of the manipulator assembly, namely the angular member (passive member), which is used to interconnect the individual URM modules. The manipulator assembly contains five angular members of different sizes, depending on which two modules are interconnected. These angular members have undergone design modifications for production on a 3D printer, which are described in detail in the article. With such modification and subsequent production, we managed to reduce the weight of angle members by an average of 40%.
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References
[1] Modulárny svet. Modular world. Available online: https://www.engineering.sk/strojarstvo-extra/3850-modularny-svet (accessed on 20.7.2021).
[2] Gilpin, Kyle, and Daniela Rus. “Modular Robot Systems.” IEEE Robotics & Automation Magazine 17.3 (2010): 38-55. Web. 3 Feb. 2012. Gilpin, Kyle, and Daniela Rus. “Modular Robot Systems.” IEEE Robotics & Automation Magazine 17.3 (2010): 38-55. Web. 3 Feb. 2012. © 2011 Institute of Electrical and Electronics Engineers.
[3] Svetlík, J., Demec, P., Turisová, R. Rotating module for the construction of modular machines, Proceedings utility model registration. Industrial Property Office of the Slovak Republic 2010. Number 99-2010.
[4] Lukáš Hrivnáč ... [et al.]. Development of first and second generation of rotary module with an unlimited degree rotation. 2020. In: MM Science Journal. - Prague (Czech Republic). MM Publishing č. March (2020), s. 3861-3864 [print, online]. - ISSN 1803-1269.
[5] Štefano Nolfi and Dario Floreano, "Evolutionary Robotics" in The MIT Press, Cambridge, Massachusetts: MIT Press/Bradford Books, 2000.
[6] Z. M. Bi, W. J. Zhang and S. Y. T. Lang, "Modular robot system architecture," 7th International Conference on Control, Automation, Robotics and Vision, 2002. ICARCV 2002., 2002, pp. 1054-1059 vol.2, doi: 10.1109/ICARCV.2002.1238569.
[7] Carlos Uraga - From connected robots to connected components - Modularity has arrived. 21.12.2017. Available online: https://medium.com/@curaga1/from-connected-robots-to-connected-components-modularity-has-arrived-f8ac9d480cd3 (accessed on 20.7.2021).
[8] Štefan Ondočko ... [et al.] - Inverse kinematics data adaptation to non-standard modular robotic arm consisting of unique rotational modules. 2021. In: Applied Sciences. - Basel (Švajčiarsko) : Multidisciplinary Digital Publishing Institute Roč. 11, č. 3 (2021), s. 1-15 [online]. - ISSN 2076-3417.
[9] Pollák, M. - Kaščák, J. - Tóróková, M. - Kočiško, M. - Dobránsky, J.: Topological Optimization of a Supporting Part of a 3D Printer Pad. In: Manufacturing Technology. - Ústí nad Labem (Česko) : Univerzita Jana Evangelisty Purkyně v Ústí nad Labem Roč. 20, č. 4 (2020), s. 492-499. ISSN 1213-2489.
[10] Dobránsky J. et al.: The influence of the use of technological waste on the mechanical behavior of fibrous polymer composite. In: Composites Part B: Engineering : An International Journal. - Amsterdam (Holandsko) : Elsevier Roč. 166 (2019), s. 162-168 [print]. - ISSN 1359-8368.
[11] Markforged. 3D printing basics: “3D Printer Types & Technologies“. Available online: https://markforged.com/resources/learn/3d-printing-basics (accessed 20.7.2021).
[12] Markforged. 3D Printing Materials. 2020. Available online: https://markforged.com/materials (accessed 20.7.2021).
[13] Tomáš Stejskal ... [et al.] - Establishing the Optimal Density of the Michell Truss Members. 2020. In: Materials. - Basel (Švajčiarsko) : Molecular Diversity Preservation International Roč. 13, č. 17 (2020), s. 1-16 [online]. - ISSN 1996-1944.