OPTIMIZATION OF THE UNIVERSAL ROTARY MODULE URM THROUGH ADDITIVE MANUFACTURING OF COMPOSITE MATERIALS

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The article deals with the ongoing development of the universal rotary module URM 02. The high weight of the components from which the modules are assembled proved to be a significant problem. As well as the weight of the connecting parts that are needed to assemble the manipulator or robotic arm. Design changes have resulted in a reduction in weight compared to older generations of modules, but in order for the manipulator to function properly, further weight reduction is required. The article describes the procedure for lightening components by changing the material and the design changes that result from it. The original aluminium alloy was replaced by a continuous carbon fibres composite produced using CFR (Continuous Fiber Reinforcement) additive technology. Here you should describe the paper idea in short.

KEYWORDS

Modular robotics, universal rotary module, weight optimization, additive technology, composite, carbon fibres.

1 INTRODUCTION

The universal rotation module with unlimited degree of rotation (URM) is a modular system from which it is possible to assemble various machines and equipment that need or can use unlimited rotation of modules in their operation. Such machines are, for example, manipulators, industrial robots or robotic arms (Figure 1) [Svetlik 2010]. One of the most important features of URM construction is its modular principle [Kuznetsov 2018]. It was fully used in the concepts and design of the module. This means that it is possible to assemble machines for different applications from one type of module without modifications of individual modules or with only minor modifications [Stofa 2018]. With the development of robots lightweight design plays an important role. Advantages are offered in various areas e. g., light arms are less dangerous in case of collision compared to heavier ones, energy efficiency of lighter arms is better. This means that weight optimization is one of the important processes of robot development [Albers 2007]. During development, the high weight of the manipulator parts proved to be a problem. Design modifications between the first and second generation of modules helped to reduce weight but not enough. Therefore, further weight reduction was realized by replacing some metal parts.

2 IMPROVING THE MECHANICAL PROPERTIES OF URM 02 MODULES

After assembling the kinematic structure of URM 02 and testing, it was found that weight reduction was needed to improve functionality and mechanical properties. This resulted in changes in the materials used to make the mechanical components. Until now, all mechanical components of the modules were made of metallic materials, namely aluminium alloys EN AW 6060 AlMgSi0,5 (outer module cover), EN AW 6082 AlMgSi1 (motor holder), EN AW 7075 AlZnMgCu1,5 (other parts of the module) [Nedal aluminium 2021]. These alloys no longer allow for further significant weight reduction by design modifications and will therefore be replaced by components made of composite materials. The use of composites for the production of components will bring the preservation of the required mechanical properties and at the same time will bring a significant reduction in the weight of the overall system of modules.

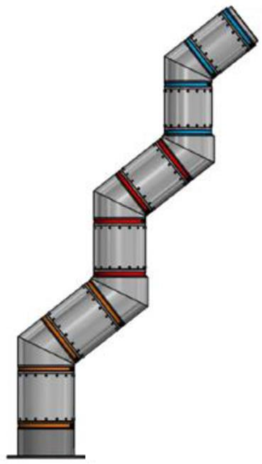

Figure 1. Manipulator assembled from modules URM 02

2.1 3D printing of composites

Composites are materials that consist of two or more materials simultaneously. The materials are divided into two types in the composite, namely the filling (matrix) and the reinforcement. The matrix creates the final shape of the part and at the same time protects the reinforcement from environmental influences. The reinforcement located inside the matrix improves the resulting properties of the composite with its better mechanical properties compared to the matrix material. Such a connection achieves mechanical properties that surpass the properties of the materials used separately [Tri-Dung Ngo 2020].

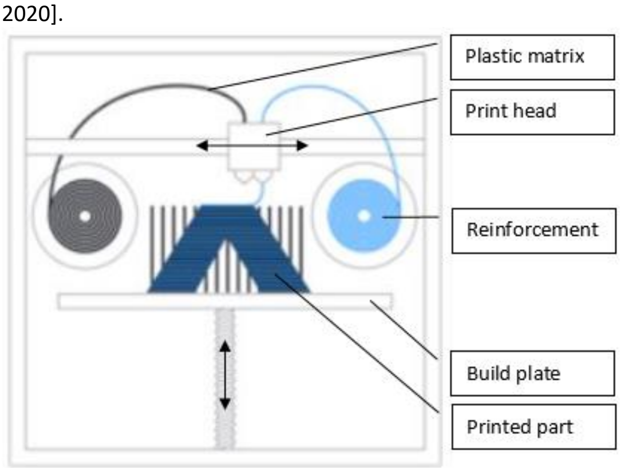

Figure 2. 3D composite printing scheme

For the production of parts of URM 02 was selected 3D printing of the composite instead of other considered manual production due to greater simplicity, speed and accuracy of production [Dobransky 2019]. The main reason, however, is the need to produce a component with a complex shape, which would be difficult to produce by hand [Dobránsky 2015] even by conventional machining process. A Markforged 3D printer labeled Mark Two was used to print components for use in a universal rotary module. (Figure 3). The biggest advantage of this 3D printer is the ability to printing of continuous reinforcement from carbon fibres or HSHT (High Strength High Temperature Fiberglass) materials and thus achieve quality products with high strength and low weight in the same time [Markforged 2021].

Figure 3. 3D printer Markforged Mark Two [Markforged 2021]

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 commonly used ABS plastic (Table 1). The comparison shows that Onyx was the appropriate material for the production of parts for URM 02 as a composite matrix.

Mechanical properties	ABS	Onyx
Density (g /cm^3)	1,04	1,2
Modulus of elasticity (MPa)	2095	1401
Tensile strength (MPa)	29,5	36
Deformation at yield strength (%)	1,8	25
Breakdown stress (MPa)	22,9	30
Deformation at break (%)	16,3	58

Table 1. Mechanical properties of suitable composite matrix material [Markforged 2021]

When printing, a reinforcement made of a material with better mechanical properties than a plastic matrix is inserted into the plastic matrix. 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 [Beniak 2018]. Carbon fiber is a rigid and strong fiber, whose properties are comparable to aluminium 6061, which means that components made of this material are light but can withstand high loads.

Mechanical properties	Carbon fibers	HSHT
Density (g /cm^3)	1,4	1,5
Tensile strength (MPa)	800	600
Tensile modulus (GPa)	60	21
Tensile stress at break (%)	1,5	3,9
Flexural strength (MPa)	540	420
Flexural modulus (GPa)	51	21
Flexural stress at break (%)	1,2	2,2

Table 2. Mechanical properties of reinforcement materials [Markforged 2021]

3 CONSTRUCTION ADJUSTMENT

The solved component of the construction is the so-called curvature (angular member), which is inserted between two modules (Figure 4), which interconnects and at the same time directly determines the possibilities of movement and the size of the working space of the manipulator or robotic arm composed from URM 02 modules.

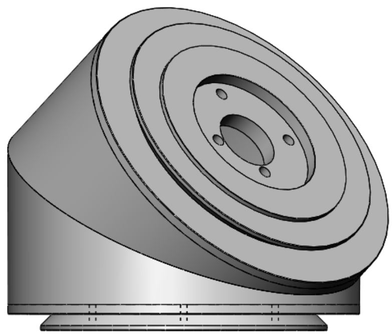

Figure 4. CAD model of the angular member

The original angular member was analysed by the finite element method to identify deficiencies. The simulation conditions were subsequently applied to the component, i.e. fixture from the bottom to match the connection to the module and load applied from the top [Bozek 2018]. The direction and magnitude of the force simulates the anticipated load acting on the component when placed in the manipulator assembly. The magnitude of the force in this case is chosen to be 1000 N. Subsequently, a finite element network was applied and the analysis was started.

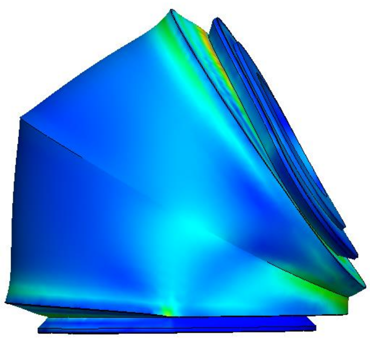

Figure 5. Finite element analysis of the angular member in its original shape

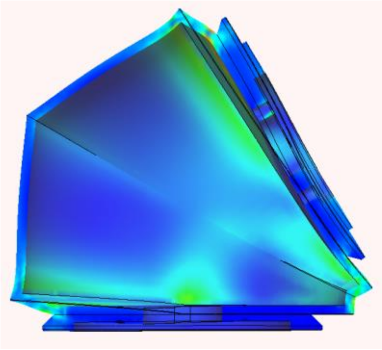

Figure 6. Finite element analysis of the angular member in its original shape in cross section

Deficiencies are seen in the joints as the component consists of four separate parts joined by welding. Therefore, it is a suitable solution to produce a component from one piece using a significantly lighter material, which will also meet the required mechanical properties [Stejskal 2020]. For this reason, the part will be manufactured from a fiber composite by 3D printing. The original design of the curvature did not allow its use in 3D printing [Beniak 2020]. 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 (Figure 7) [Pollak 2020]. The adjustment of the original curvature 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 [7].

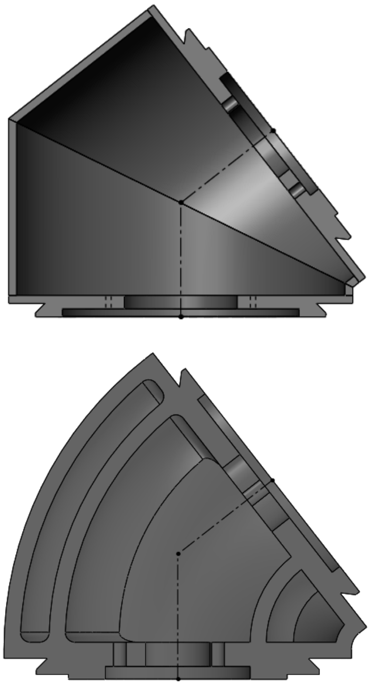

Figure 7. Original angular member (top) and modified construction for 3D printing (bottom) in cross section

After modifying the CAD (Computer-aided design) model, it was necessary to set the print parameters and the resulting composite using the Eiger software supplied with the printer. The surface of the component, the wall and the filling around the layers of carbon fiber are extruded from plastic. The minimum thickness of the surface layers is 4, i.e. 0.5 mm which in this case cannot be changed. The wall thickness was set to 0.8 mm. To ensure the best possible mechanical properties of the infill, the density of the infill between the reinforcements was chosen to be 100% (Figure 10). This means more material used but at the same time higher component strength [Baron 2018].

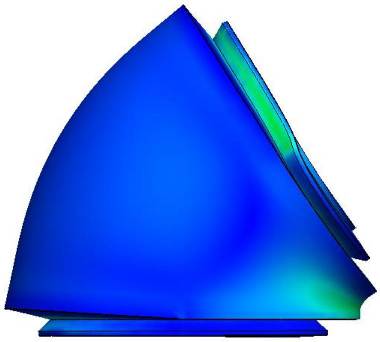

Figure 8. Finite element analysis of the angular member in its modified shape

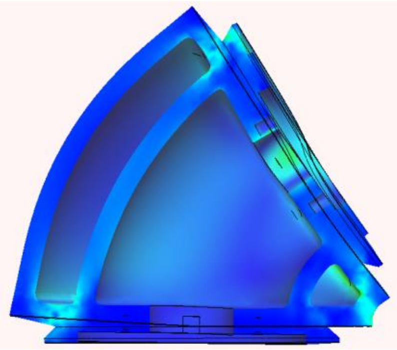

Figure 9. Finite element analysis of the angular member in its modified shape in cross section

Continuous carbon fiber was added in three interconnected lines that copy the shape of the part (Figure 10). 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. The modified angular element was analysed by the finite element method for comparison with the original member. The boundary conditions were the same in both cases (Figure 8 ,9). The results of the analysis show the reduction of the maximum stress from 200 MPa to 80 MPa and the elimination of problematic parts of construction of the angular member.

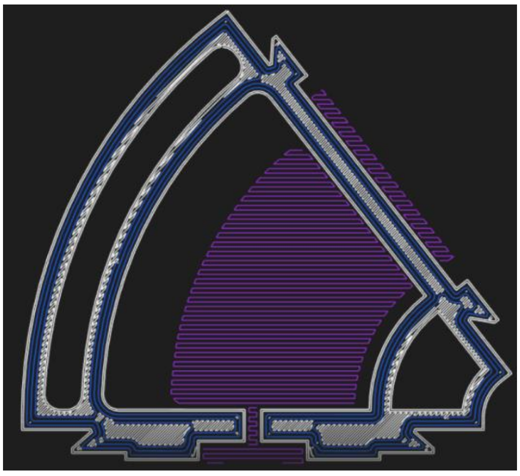

Figure 10. Cross section of the internal structure of the angular member - plastic matrix (white), carbon fiber (blue), support (purple)

4 EFFECT OF ADJUSTMENTS ON MANIPULATOR CONSTRUCTION

The same adjustments as described in Chapter 3 were made on all components necessary for the complete assembly of the manipulator with 6DOF (degrees of freedom) of movement in space.

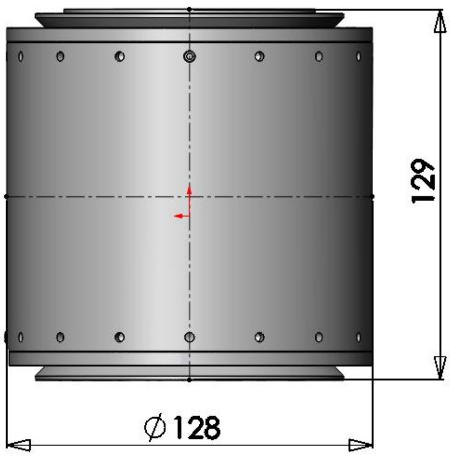

Figure 11. Basic dimensions of module URM 02 type L

From Figure 1 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 8), M modules have smaller parameters, etc. (Table 3) and 5 angular members from 3 size series, i.e. the angular member L connects the two modules L, the angular member LM connects module L and module M, and so on. (Table 4).

Module	L	M	S
Height (mm)	129	119	109
Diameter (mm)	128	118	108
Weight (g)	1811,22	1574,66	1299,34

Table 3. Parameters of URM 02 modules

The parameters of all original angular members made of aluminium alloy and new modified angular members made of composite can be found in the Table 4.

Original angular member	L	LM	M	MS	S
Diameter (mm)	128	128	118	118	108
Weight (g)	563,9	551,29	491,59	477,09	415,73
Modified angular member	**L**	**LM**	**M**	**MS**	**S**
Diameter (mm)	128	128	118	118	108
Weight (g)	330,2	322,59	271,17	262,55	215,74

Table 4. Original and modified parameters of angular members

Via optimization process (new shape and material) we have been able to reduce the total components weight as is shown below (Figure 8):

L: 563,92 – 330,29 = 233,63 g (41,43 %)

LM: 551,29 – 322,59 = 228,7 g (41,49 %)

M: 491,59 – 271,17 = 220,42 g (44,84 %)

MS: 477,09 – 262,55 = 214,54 g (44,97 %)

S: 415,73 – 215,74 = 199,99 g (48,11 %)

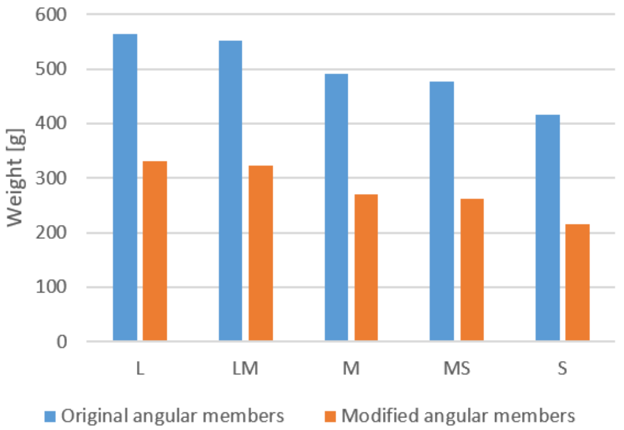

Figure 12. Weight comparison of the original and modified angular members

Weight reduction of the manipulator assembly:

The manipulator consists of 2 L modules, 2 M modules and 2 S modules. These are connected by all five angular members from the Table 4. The total weight of the modules is 9370.44 g. The total weight of the original angular members is 2499.65 g. The total weight of the adjusted parts is 1402.34 g. The saved weight on the angular members is 1097.31 g which is 43.89%. The resulting weight of the manipulator with the original curves is 11,870.06g. The final weight of the manipulator with modified curvatures is 10,772.78g.

5 CONCLUSIONS

The article was focused on the modification of interconnecting members of modules (curvature) URM 02. The reason for the modifications was to reduce the weight of the parts because the high weight of the system limits the functionality of the manipulator assembled from URM 02 modules. The means of reducing the weight was to change the materials used. The aluminium alloy was replaced with a continuous carbon fiber reinforced composite material. The production of parts was realized by additive technology, which required certain design modifications described in the article. For all parts, the weight was reduced by more than 40%, which results in a reduction from the original combined weight of 2499.65g to 1402.64g, which represents a relief of 43.89%.

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