AUTOMATION OF DESIGN OF ROBOTIC ARM

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Robotic arms are complex mechatronic systems. Therefore, their design requires knowledge and experience from various technical fields, such as mechanics, electrical engineering, electronics or control. From the view of the requirements placed on developers, the design of robotic arms is one of the more complex tasks. Unfortunately, there is a lack of necessary specialists in this field of technology. Therefore, ways are sought to help existing specialists in their work and, simultaneously, reduce the time needed to design the required equipment. At the same time, there are also sought ways to open the way to this issue for developers who do not yet have enough experience.

For this reason, algorithms and development tools have been developed to significantly simplify and reduce the time required to design robotic arms and simultaneously automate as much of this process as possible. The aim is to shorten the design time and achieve better results than in the case of designs according to classical procedures.

KEYWORDS

Design automation, algorithms, robot, SolidWorks, API

1 INTRODUCTION

The design of the robotic arm is based on the application for which it is intended. For that purpose, an additional module for the SolidWorks CAD system was designed to simplify the basic concept of robotic workplaces. Its function is described in the article [Boleslavsky 2022]. Commonly available industrial robots are used in this module. However, they are not optimized for the application.

For this reason, procedures are sought with the help of which it would be possible to design an optimized kinematic structure of the robotic arm. For example, articles [Huczala 2021, Kot 2021, Pastor 2021] are devoted to this issue, describing design procedures using various optimization algorithms. The output of these procedures is usually a simplified kinematic structure of the robotic arm, with optimized dimensions of individual links of the whole mechanism. However, the road to a device composed of real elements capable of handling the required load is still very long. As part of the research, software tools were gradually created, with the help of which it is possible to either automate or significantly simplify the design process of individual parts of robotic arms. The article [Zeman 2021] describes the software tool DrivePicker, designed to design power units. The article [Mihola 2021] describes the software tool RobotArmDesigner, designed to design cross-sections of individual arms of industrial robots and manipulators. However, these are still stand-alone tools for which it is necessary to prepare input data and subsequently evaluate the output data. Another goal is to connect both the already mentioned software tools and add other functions, with the help of which it would be possible to automate the design process of robotic arms as much as possible. Or at least minimize the need for developer intervention.

In the design process, there is not only relied on developed software tools but also the use of third-party resources. The most important is the SolidWorks CAD system, with which it is possible to create the 3D models of the designed devices and perform kinematic, dynamic and strength analyses, together with several other tasks. The connection of this CAD system is possible thanks to its application programming interface (API). For example, the articles [Reddy 2016, Reddy 2018a, Reddy 2018b] present the use of the SolidWorks CAD API in the design of bearings, gears or battery blocks. However, in the case of the design of robotic arms, its use will be significantly more extensive, and the advanced functions of this CAD system will be used.

2 RESEARCH METHOD

At present, robotic arm designs are considered only for object manipulation tasks. The design procedure is described in the form of a block diagram in Fig. 1.

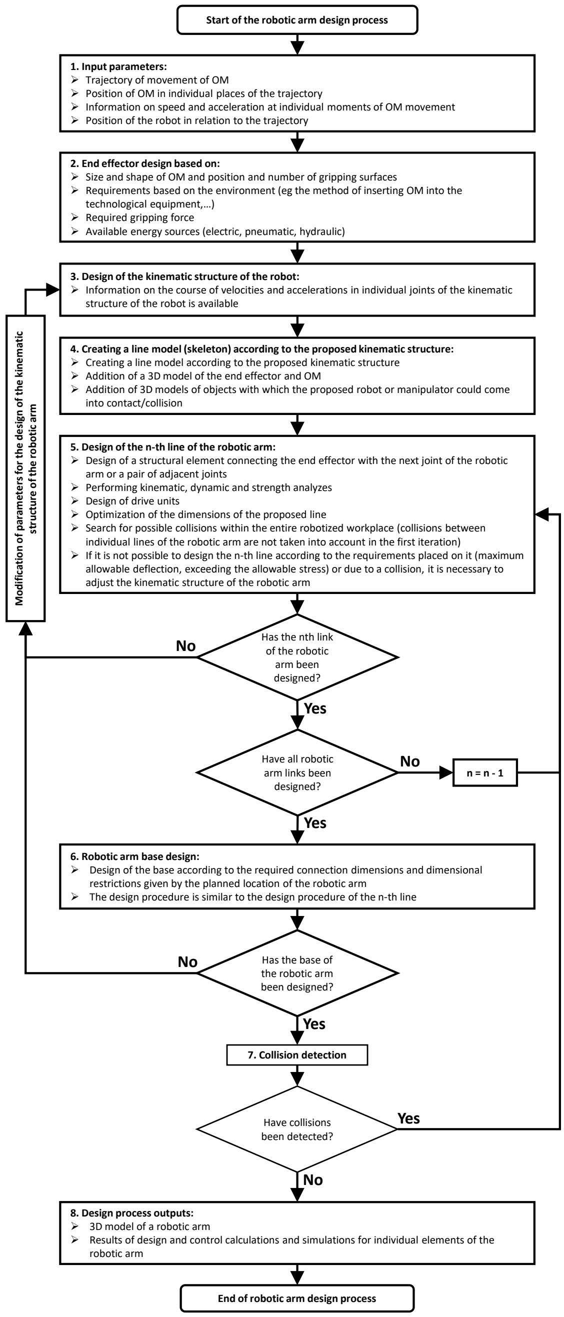

Figure 1. Block diagram of the robotic arm design process

In the first step, the input data for the design of the robotic arm is defined (parameters of the manipulation object (OM), trajectories of its movement, information about the speed and acceleration of the object of manipulation during movement, the position of the base of the robotic arm, etc.). In the second step, a suitable end effector is designed. Currently, software tools of individual end effector manufacturers are used for this design. Based on this information, the robotic arm's kinematic structure is designed in the next step, using genetic algorithms or artificial neural networks. The kinematic structure designed this way is then transferred in the form of a skeleton to the SolidWorks CAD system. In the following steps, the individual elements of the robotic arm are gradually designed. Suppose it is impossible to design the robotic arm according to the given kinematic structure, the algorithm returns to the third step according to Fig. 1 and the design of a new kinematic structure is initiated. When designing a new kinematic structure, the input parameters are adjusted in such a way as to reflect the reasons for the failure of the previous design steps.

2.1 *Creation and use of skeletons*

The proposed kinematic structures are usually obtained in the form of simplified 3D models or line kinematic structures. These are then converted into solid skeletons using the SolidWorks CAD API. The motion links between the skeleton's parts correspond to the proposed device's links. Together with 3D models of the object of manipulation and the end effector, the skeleton forms the basis of the robotic arm, on which kinematic and dynamic analysis are subsequently performed.

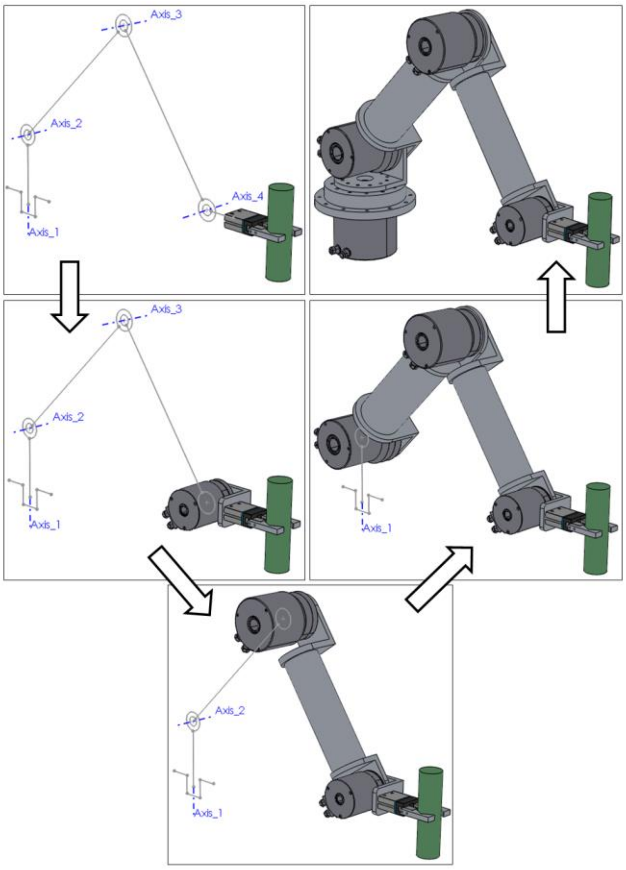

Figure 2. Demonstration of a skeleton with 4 DOF and its gradual addition to the designed elements of the robotic arm

The results of these analyses are then used in designing individual drive units and structural elements of the robotic arm. Fig. 2 shows the design procedure of a robotic arm with 4 DOF. From the skeleton to the final 3D model.

2.2 *n-th link design procedure*

The design of individual parts of the robotic arm is an iterative optimization process. Changing the dimensions or one of the parameters of one element can affect the design of the previous and next element. Fig. 4 is a block diagram showing the design procedure of one robotic arm line and corresponding drive units. During this process, drive units are repeatedly designed, and kinematic, dynamic and strength analyses are performed. In the case of the first iteration of the design, collisions between the individual lines of the robotic arm are not taken into account. Only collisions between the robotic arm and the elements of the workplace are taken into account. In this way, a preliminary design of the arm is obtained. Only after the complete design have the collisions been checked within the individual elements of the robotic arm (Fig. 1, step 7). The preliminary draft can also be considered final if no collisions are found. However, if collisions are found in this step, the second iteration of the design begins. All possible collisions within the workplace are already considered in this and other iterations. The goal is not only to design a functional device but also to optimize it in terms of weight, dimensions or both, depending on the specific assignment.

The design process is divided into two main branches. The first is intended for line design where the distance between the axes of the joints does not exceed a distance corresponding to four times the diameter of the previous power unit (in the case of a line connecting the end effector and the next joint is calculated with a distance corresponding to four times the body length of the end effector). In this case, it is assumed that the link will consist of one piece of material. However, if this distance is greater, the link will consist of three parts, a pair of consoles and a profile that connects them.

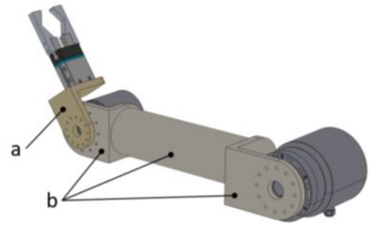

Figure 3. Examples of a link consisting of: a) one part; b) three parts

In previous publications [Mihola 2021, Zeman 2021], software tools for designing drive units and cross-sections of line profiles have been described. These software tools have been modified so that the robotic arm design process can be automated. However, their functionality remained unchanged. Procedures have been newly created to automate strength analyses of any structural elements of robotic arms. Based on them, procedures for dimensional optimization of these structural elements were developed. Procedures for finding collisions have also been newly created for both within the robotic arm and the entire workplace. In the block diagram of Fig. 4, only kinematic and dynamic analyzes are no longer fully automated.

The input data for these analyzes are automatically taken from the previous design steps and prepared in the required form. It is also possible to automatically define selected elements of these analyzes. The results of these analyzes are then automatically converted into the form needed for the next steps of the design process. The full automation of this part of the process is prevented by occasional problems with the CAD API of the SolidWorks system (not all the required actions are performed). It is therefore necessary to manually check the definition of these analyzes and their possible correction. But these are exceptional cases.

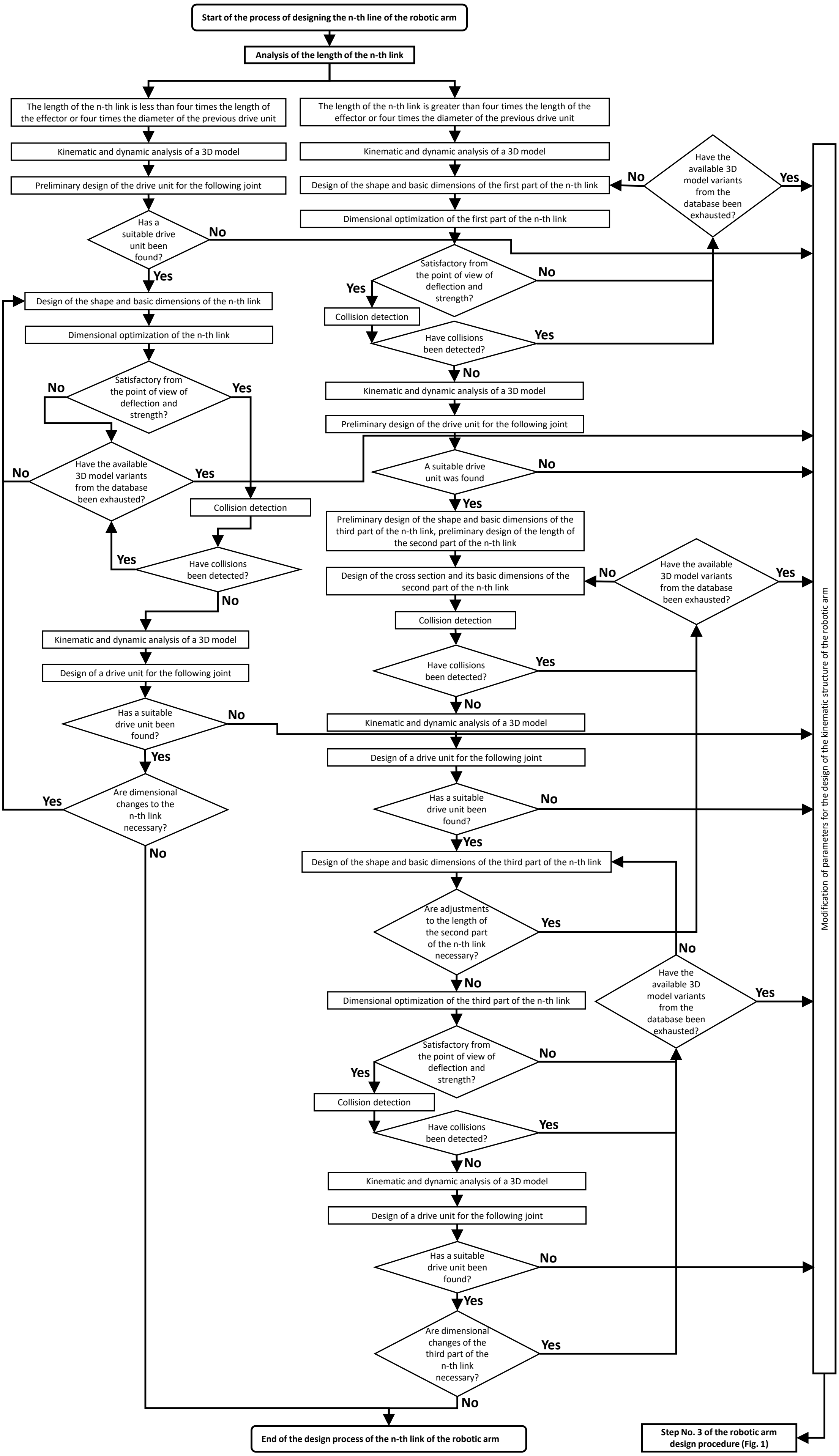

Figure 4. Block diagram of the design process of the nth line of the robotic arm

2.3 Dimensional optimization of structured elements

Design studies can be performed within the SolidWorks CAD system. Within them, it is possible to define the range of individual dimensions of the proposed structural element, the method of loading, the required result (e.g. the maximum amount of deformation of the element), and other requirements (e.g. to minimize the weight of the proposed element). However, the ability to define a Design Study through the SolidWorks CAD API is very limited. This means significant limitations in terms of the possible automation of this phase of the design process. Therefore, an alternative solution was created. The optimization procedure is described in the form of a block diagram in Fig. 5.

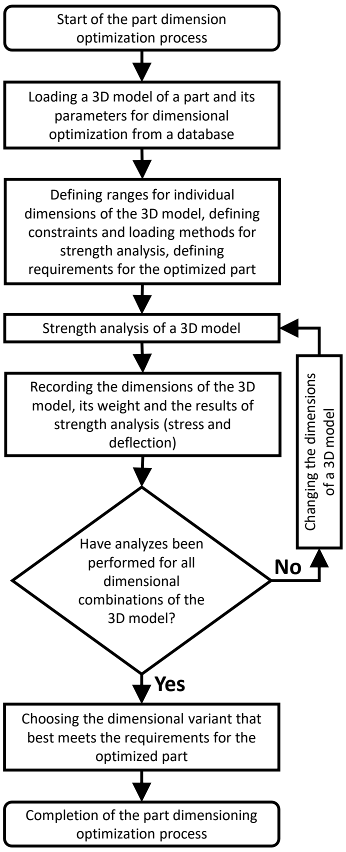

Figure 5. The procedure of dimensional optimization of individual structural elements of the robotic arm

This step performs strength analyses for all proposed dimensional combinations of a given structural element. Then the dimensional variant that best meets the requirements for the given structural element is automatically selected. The time required for this process depends on the complexity of the component, the number of analyzes performed, etc.

2.4 Collision search procedure

The SolidWorks CAD system is also equipped with functions for finding collisions between individual elements of the 3D model. However, the possibilities of these functions are also quite limited. Moreover, their control via API is also problematic. For this reason, a custom collision detection algorithm was built (Fig. 6). It is based on a combination of kinematic analysis of the proposed device and a function for finding intersections between individual elements of the 3D model.

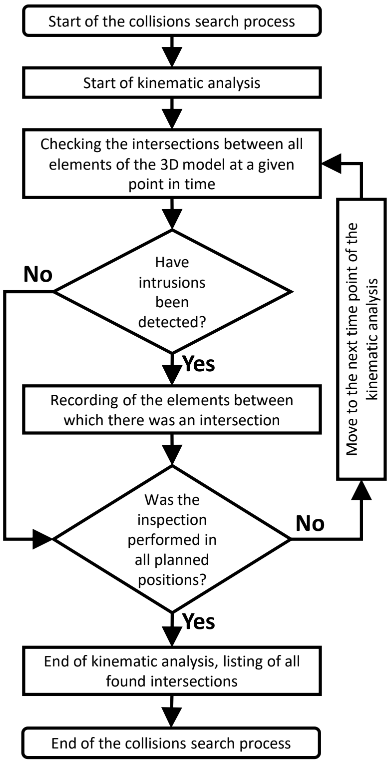

Figure 6. Block diagram of the collision search algorithm

Kinematic analysis is divided into smaller time periods. In each time period, a check is made to see if there is a mutual intersection of volumes between the individual elements of the 3D model. If not, it is continued to the next time period. If so, it is recorded which elements intersected and what its volume is. It is then continued to the next time period. This procedure is repeated until the entire kinematic analysis is completed. If no intersections have been found, it is possible to proceed to the next design step of the robotic arm. If intersections have been found, it is necessary to return to one of the previous design steps and adjust its input parameters.

3 RESULTS AND ANALYSIS

The algorithms described in Chapter 2 were used to design a robotic arm whose skeletal kinematic structure is indicated in Fig. 7. This kinematic structure with 5 DOF was designed for manipulation with a cylindrical object with a diameter of 52 mm, a length of 200 mm and a weight of 3.33 kg. The movement time of the manipulation object from the starting position to the target position is 4 seconds. The length of the trajectory is 1348 mm.

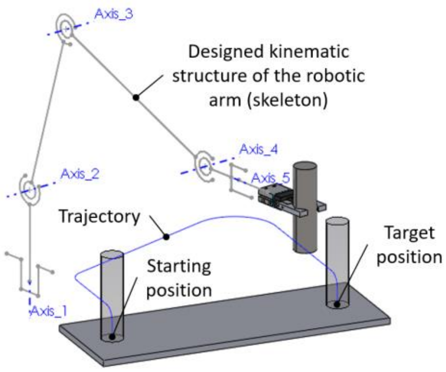

Figure 7. Kinematic structure with 5 DOF and trajectory of the object of manipulation

Based on the results of kinematic and dynamic analyzes, individual elements of the robotic arm are designed. In the case of structural elements, the effort is to find the most suitable ratio between the element's dimensions and its weight. All this while maintaining its sufficient rigidity. Fig. 8 is an example of a bracket line 3 in which the axis drive four is mounted.

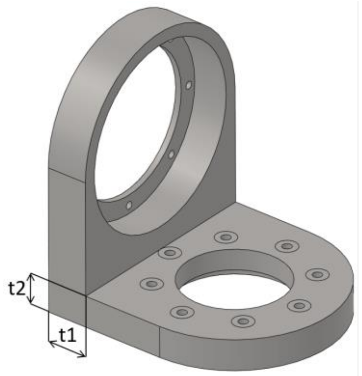

Figure 8. Link 3 Console

The basic dimensions of this element are based on the dimensions of the drive unit, designed using the DrivePicker tool. Dimensions t1 (ranging from 7 to 20 mm) and t2 (ranging from 7 to 15 mm) were used in the dimensional optimization. This corresponds to performing 128 strength analyzes. Fig. 9 is a graph showing the dependence of the maximum deformation of the proposed element on these dimensions at maximum load.

Within the range of dimensions t1 and t2, the weight of this element ranges from 0.666 to 1.446 kg. With a requirement for a maximum allowable deformation of 0.01 mm, a variant with dimensions t1 = 14 mm and t2 = 9 mm, with a maximum deflection of 0.0098 mm and a weight of 0.991 kg, was selected as the most suitable. Other structural elements of the robotic arm were designed similarly.

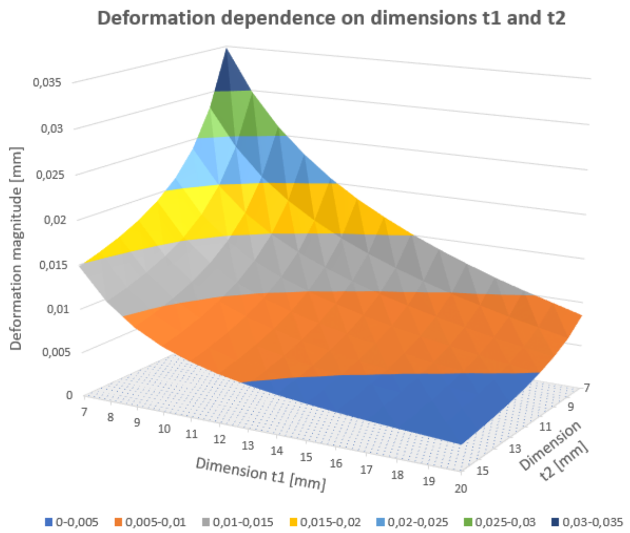

Figure 9. Graph showing the dependence of the amount of deformation on the dimensions t1 and t2

The procedure for designing the robotic arm in the first iteration is indicated in Fig. 10. Then, gradually, the individual components and drive units of the CanisDrive type from Harmonic Drive SE were designed.

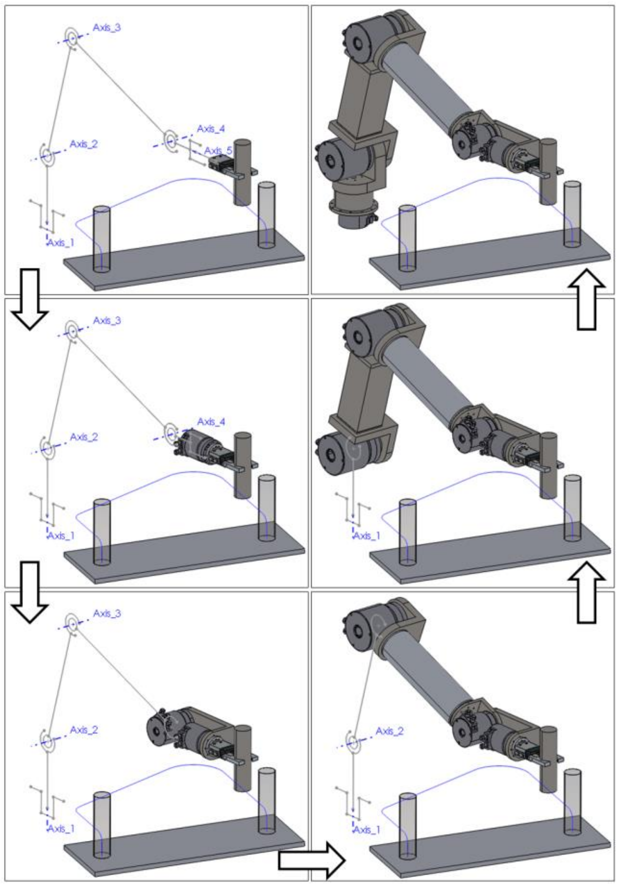

Figure 10. The first iteration of the robotic arm design

In the first iteration of the design, collisions between the individual elements of the robotic arm are not taken into account. If no collision is found in step 7, according to the block diagram in Fig. 1, the robotic arm design process is successfully completed. In this case, however, a collision was found between lines 2 and 3 (Fig. 11).

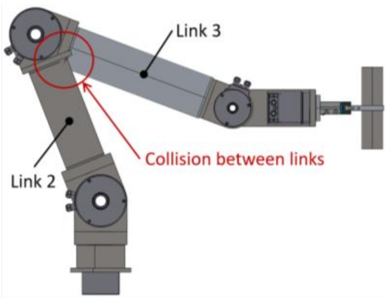

Figure 11. Collision between links 2 and 3

Thus, the second iteration of the proposal was started. During it, collisions between the individual elements of the robotic arm were also taken into account. The collision was found only between links 2 and 3. The part of the robotic arm relating to axes 5 and 4 could therefore be left unchanged. Collisions with link 2 and the dimensions designed in the first iteration were also considered in the design of link 3. The result of the design in the second iteration is shown in Fig. 12.

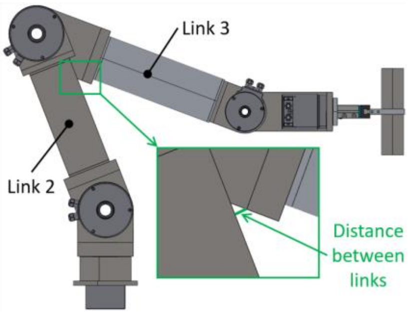

Figure 12. Modified link 3 as part of the next iteration

Compared to the original design, the length of the connecting profile of link 3 was shortened by 70 mm, and the wall thickness was reduced from 4 mm to 3 mm. At the same time, the bracket at the drive unit in axis 3 was extended by the same length. To maintain the required rigidity of this element, the wall thickness was increased by 2 mm. The resulting minimum distance between links 2 and 3, indicated in Fig. 12, is 10.5 mm. No other problem areas were found in the second iteration. Therefore, the design process could be completed successfully. The final design of the robotic arm is shown in Fig. 13.

Two types of materials were considered when designing the robotic arm's structural elements. Aluminum alloy AL 6063 T6 and steel AISI 4340 (they are color-coded in Fig. 13). The resulting weight of the robotic arm is 40.7 kg, and its maximum reach is 1303 mm. Used drive unit sizes are 14A (axis 5), 17A (axes 1 and 4) and 25A (axes 2 and 3).

In this case, two iterations were needed to achieve the final design. In the second iteration, designing all parts of the robotic arm was no longer necessary. This further reduced the time required for the overall design. The computer assembly, consisting of an AMD Ryzen 5 5600 processor, NVidia GeForce 1650 graphics card, 16 GB of RAM and a 500 GB SSD, took approximately 16 hours to design. Approximately 95% of this time took the strength analysis of the structural elements of the proposed robotic arm. In the case of manual design, a similar result could be achieved in a much longer time. Depending on the chosen procedures, the level of optimization and the experience and knowledge of the development staff.

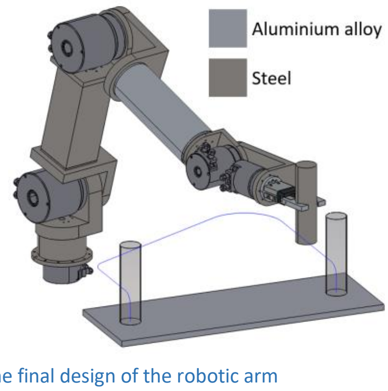

Figure 13. The final design of the robotic arm

4 CONCLUSIONS

The paper aimed to describe algorithms designed for the process of automatic design of robotic arms. It is evident that this is a demanding process in terms of the necessary knowledge and experience and the time required. Significant attention is paid to dimensional optimization of individual structural elements of robotic arms, focusing on minimizing weight while maintaining sufficient rigidity. This makes it possible to design drive units with lower power requirements and reduce the overall weight of the robotic arm. That would lead to a lower electricity consumption of the proposed arm during operation.

The functionality of the proposed algorithms was subsequently presented on the example of a robotic arm with 5 DOF. It took two iterations to reach the final design, totaling 16 hours. Approximately 95% of this time (ie 15.2 hours) was spent performing 3900 strength analyses. Another 20 minutes was spent checking that the kinematic and dynamic analyzes were set up correctly (in this case there were no issues with the SolidWorks CAD API and all settings were set up correctly). The remaining time was devoted to the other steps of the design. Using standard procedures, a similar result would be achieved in several hundred hours, depending on the experience of the developer. Thus, the presented design process turns out to be very effective.

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