AUTOMATION OF THE DESIGN OF THE CROSS-SECTION OF THE MANIPULATOR ARMS PROFILE

MILAN MIHOLA [1], ZDENEK ZEMAN [1], DAVID FOJTIK [2]

[1] VSB - Technical University of Ostrava, Department of Robotics, Ostrava, Czech Republic

[2] VSB - Technical University of Ostrava, Department of Control Systems and Instrumentation, Ostrava, Czech Republic

DOI: 10.17973/MMSJ.2021_10_2021092

e-mail: milan.mihola@vsb.cz

The design of the arms of industrial robots and manipulators is a demanding process both in terms of expertise and in terms of the time required. For these reasons, algorithms have been created, with the help of which it is possible to design cross-sections of individual arms of robots and manipulators not only from the point of view of maximum allowed deflection but also from the point of view of minimizing cross-sectional dimensions or minimizing the weight of arms. These algorithms were subsequently used in the development of the software tool RobotArmDesign, with the help of which it is possible to simplify and shorten the arm design process significantly. This tool also has a connection to the SolidWorks CAD system and its simulation tools through its API interface, making it possible to refine robot arms designs while maintaining significantly shorter design times than would be the case with commonly used procedures. This tool's capabilities were demonstrated in the design of a robot arm with an angular structure and five degrees of freedom.

KEYWORDS

Automation, robot, cross-section, arm, RobotArmDesign

1 INTRODUCTION

Robotics is a multidisciplinary branch of technology. Scientific teams around the world are involved in the development of both complete robotic devices and their subsystems. From the point of view of industrial robotics, attention is currently paid mainly to the field of control, as described, for example, in the articles [Azarfar 2018, Castillo-Garcia 2017, Prathab 2017]. However, the possibility of using optimization algorithms in designing kinematic structures of industrial robots and manipulators, as described in the articles, also comes to the fore [Ha 2018, Kumar 2017, Whitman 2019]. A somewhat neglected area is the possibility of automating the design process of both individual structural elements of robotic devices and entire mechanical systems. This is an area with significant potential in terms of creating better design proposals while significantly reducing the required design time of the equipment and the related improvement in work efficiency while reducing the costs associated with the actual design of the equipment.

Design of individual parts of industrial robots and manipulators is one of the most demanding processes, both in terms of the necessary expertise and time. For this reason, methodological procedures [Isermann 2002, Lindemann 2009, VDI 2004] and software tools [KISSsoft 2021, MITCalc 2021, Reddy 2016] are being developed, which can significantly facilitate and speed up selected parts of this process. The development aims to transfer known methodological procedures and own experience gained in designing industrial robots, manipulators, and other types of mechatronic devices into a software tool that would automatically generate 3D models of devices or their individual parts. The development of such software tool is very demanding. Therefore, it was divided into several stages. This article describes the stage of automation of the cross-section design of the arms of industrial robots and manipulators.

Due to the required accuracy of movement or positioning of this type of device, the developers strive to design their individual parts in such a way that they undergo as little deformation as possible. Depending on the shape complexity of the arms, it is possible to design their cross-sections, resp. their dimensions, in various ways, e.g. according to the appropriate analytical method or with the help of the finite element method. The use of analytical methods is more advantageous for simpler arms, where it is possible based on known relationships (e.g. according to Betti's theorem or its modification, according to Maxwell's theorem, according to the Method of integration of the differential equation of bending line, etc. [Bedenik 1999, Hearn 1997, Kurrer 2008, Panditta 2012, Panditta 2013, Przemieniecki 2012]) and required size of deflection, to design suitable cross-sections of the arms, resp. their dimensions. Analytical design methods are relatively fast. They also do not require specialized software tools, the acquisition of which is usually quite costly.

Finite element methods, which are used, for example, in strength analysis in many CAD systems, can also be used for simpler arms. Still, their advantages are mainly in more complex parts, with a more complicated distribution of loads, e.g. interaction of subsequent parts, where the procedures according to analytical methods would be too complex, or would not lead to the desired outcome. The disadvantages of this method of arms design include the need for specialized CAD systems and knowledge of working with them, sufficiently powerful computer equipment, and time. The strength analysis of one design variant of the proposed part can take tens of hours. For this reason, if possible and advantageous, it is advisable to consider a combination of these two approaches when designing the arms. The initial design of the arm profile and its dimensions would be carried out using a suitable analytical method, and only in the subsequent phase, the suitable CAD system would be used. In this way, it would be possible to significantly reduce the arm's total design time, thanks to the smaller number of required strength analyses.

Further reduction of design time can be achieved by automating this process. One possible way to do so is to use the application programming interface (API), which is often part of many CAD systems [Chen 2013, Lad 2014]. In this case, the SolidWorks CAD system is used, with the help of which it is possible not only to create and subsequently analyze selected parts of the proposed equipment but also to perform kinematic and dynamic analyses, the results of which are used in strength analyses.

Further reduction of design time can be achieved by automating this process. One possible way is to use an application programming interface (API), which is part of many CAD systems [Abidin 2019, Chen 2013, Lad 2014]. In this case, the SolidWorks CAD system is used, with the help of which it is possible not only to create 3D models [Reddy 2018a, Reddy 2018b], but also to perform their kinematic and dynamic analyzes. The results from these analyzes can then be used in strength analyzes or topological optimizations.

2 RESEARCH METHOD

Industrial robots and manipulators are among the devices that are often characterized by high dynamics of movement. At the same time, they can achieve outstanding movement accuracy of their end member or repeatable positioning accuracy. This carries increased demands on their construction and overall mechanical strength and durability [Yang 2016, Lynch 2017, Jazar 2010, Ceccarelli 2019]. Ideally, the individual mechanical elements of these devices would be designed as absolutely rigid bodies [Murray 1994, Xiong 2015, Grotjahn 2001, Ivanov 2018], i.e. without deformations caused by external loads or their weight. In the real world, however, we can only approach the properties of an absolutely rigid body for individual elements of the proposed mechanisms, using, for example, materials with better mechanical properties [Pandey 2017, Lee 1993], appropriately modifying the dimensions, shape or structure of the proposed mechanism elements or using optimization software tools [Rueda 2009, Yao 2019, Paška 2020]. At the same time, there is an effort to achieve the lowest possible weight, moments of inertia and dimensions of the proposed elements or the entire proposed device. Production costs also play an important role. It is, therefore, an optimization process, which involves a number of requirements and limitations.

In the case of the design of the arms of industrial robots and manipulators, we can proceed as follows. Suppose an industrial robot or manipulator is designed for a specific manipulation or technological task. In that case, it is possible to specify the trajectory of the manipulation object (OM) movement or specify a position of the selected point of the technological effector, resp. determine the rotation of the effector, relative to this trajectory over time. The area or areas in which the proposed device could be placed relative to the trajectory should also be specified. Based on this information, it is then possible to design a suitable kinematic structure of an industrial robot or manipulator and its basic dimensions. With repeated kinematic and dynamic analyses, it is then possible to gradually design individual parts of the device.

The design process of the arms of industrial robots and manipulators is divided into two main parts. A preliminary design of suitable types of cross-sections and their dimensions is performed using a selected analytical method in the first part. In the second part, the design is refined using the module for strength analysis of CAD system SolidWorks. In both parts of the design process, an iterative process is used, where the shapes and dimensions of the cross-sections of the designed arms are gradually adjusted until the required values of their deflections are reached.

2.1 Preliminary design of the arm profile

By using known analytical methods, it is possible to determine the angle of rotation and deflection of an arm loaded with various combinations of forces, bending moments, torques and other types of loads. This process's complexity depends on the number and location of supports, respectively embeddings, the combination and places of action of individual loads, the cross-sectional shape of the proposed arm, etc.

Within the preliminary design of the arms, the calculation procedure, according to the Castiglian theorem, is used, which is based on the deformation energies [Hearn 1997, Kurrer 2008]. To calculate the angle of rotation φ (rad) and deflection w (mm) according to this theorem, relations (1) and (2) apply.

$$\varphi = \frac{1}{E \cdot I} \int_L M(x) \cdot \frac{\partial M(x)}{\partial M} \cdot dx \tag{1}$$

$$w_b = \frac{1}{E \cdot I} \int_L M(x) \cdot \frac{\partial M(x)}{\partial F} \cdot dx \tag{2}$$

where E (MPa) is the modulus of elasticity in tension, I (mm^4) is the moment of inertia of the cross-section, $M(x)$ (N·mm) is the moment, $\partial M(x)/\partial M$ is the partial derivative of the moment according to the moment acting in the calculated point, $\partial M(x)/\partial F$ is the partial derivative of the moment according to the force acting at the calculated point, L (mm) is the length over which the integration takes place.

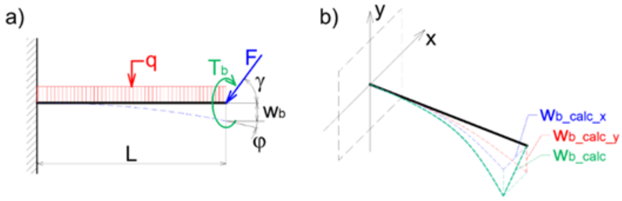

Figure 1. Embedded beam: a) load on embedded beam; b) deflections in individual planes and total spatial deflection

In the case of industrial robots and manipulators with an angular structure, which is the most frequently used kinematic structure of industrial robots today [IFR 2021], it is possible to count individual arms in the preliminary design as embedded beams (taking into account the required stiffness of rotary joints of robots), loaded at its end by forces and moments from previous parts of the proposed device, resp. from the load caused by the self-weight of the arms. Figure 1a) indicates the possible load of the embedded beam, resp. of the designed arm with a force F (N) acting at an angle γ (deg), a bending moment T_b (N·mm) and a continuous load q (N/mm). The magnitude of the moment $M(x)$ (N·mm) at the point of entanglement, based on which it is possible to determine the angle of rotation and deflection at the endpoint of the bending line of the beam, can then be calculated using equation (3).

$$M(x) = F \cdot \sin(\gamma) \cdot L + T_b + q \cdot \frac{L^2}{2} \tag{3}$$

The continuous load q (N/mm) can represent the external action force and the dead weight of the designed arm. In the case of a statically loaded beam, with a constant cross-section along its entire length, the magnitude of the continuous load is based on the density of the beam material ρ (kg/m^3), its cross-sectional area S (m^2) and the gravitational acceleration g (m/sec^2). It can be calculated using equation (4).

$$q = \frac{\rho \cdot S \cdot g}{1000} \tag{4}$$

However, in the case of a preliminary design of the arm profiles, it is also necessary to consider the dynamic effects based on their weight. For this reason, the previous relationship was modified to a different form (5), which is calculated by the sum of all accelerations (or their components) at the selected location of the beam (in the middle of the continuous load, or its part, which would be calculated) and in the direction of the investigated deflection of the proposed arm.

$$q = \frac{\rho \cdot S}{1000} \cdot \sum_{i=1}^{n} a_i \tag{5}$$

where n is the number of all accelerations (or their components) at the selected location of the beam.

In the design of the arm's cross-section and its dimensions, it is based primarily on the value of the maximum required allowable deflection. However, the calculated bending stress value is also compared with the allowable value for the selected arm material. The design algorithm, using an iterative process, during which the cross-sectional dimensions are gradually read from the knowledge base from the smallest to the largest, is shown in Figure 2.

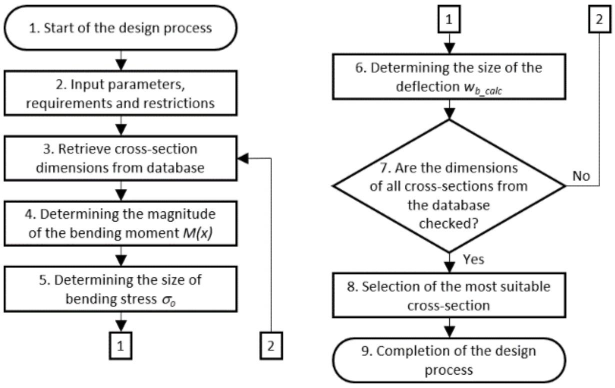

Figure 2. Algorithm for the preliminary design of arm cross-section dimensions

The design process is not completed when the arm's cross-sectional dimensions are found at which the calculated amount of deflection is smaller than required. Due to the effort to minimize the force effects on the following parts of the proposed device, cross-sections come to the forefront of the selection, with which it is possible to achieve the lowest possible weight of the arm. The maximum permissible external cross-sectional dimensions, or other requirements and restrictions defined at the beginning of the preliminary design, can also play an important role. For this reason, deflection calculations are performed for all cross-sections (or their dimensions) contained in the knowledge database. Only then is the final selection made based on other specified requirements and restrictions. In this way, it is possible to work on a more suitable type of cross-section and its dimensions than would be the case if the design were completed when the first cross-section of the arm was found in the database, with which it is possible to achieve less deflection than required.

The designed arm need not be subjected to a load in only one plane passing through its deflection line, as indicated in Figure 1a). In such a case, it is necessary to distribute the force and moment effects into two suitably designed, mutually perpendicular planes passing through the beam's deflection line. The design of the beam cross-sectional dimensions would then proceed again according to the algorithm in Figure 2. However, the inspection of the maximum deflection would be performed in both mutually perpendicular planes. The total deflection *wb_calc* (mm) would be calculated using equation (6), where *wb_calc_x* (mm) and *wb_calc_y* (mm) are the calculated partial deflections in individual, mutually perpendicular planes (Figure 1b)).

$$w_{b\_calc} = \sqrt{w_{b\_calc\_x}^2 + w_{b\_calc\_y}^2} \tag{6}$$

The design of the arm cross-section would further proceed as described above. However, the value of *wb_calc* would be compared with the value of the required maximum allowable deflection.

2.2 *Arm design using CAD software*

The arm of an industrial robot or manipulator with a pre-designed cross-section and its dimensions is then subjected to strength analysis in the CAD environment of the SolidWorks system. It is possible to perform strength analyses in two ways, as a separate element or as one of an assembly model's elements in motion analysis. In the first method, the arm is analyzed as a statically loaded embedded beam. In the second method, the proposed arm is analyzed within the entire motion cycle of the industrial robot or manipulator, within a selected part of this cycle, or at specified times of this cycle. Changes in applied loads during the movement cycle are reflected in the analysis here. This is a computationally demanding process and, therefore, more time-consuming than the arm's strength analysis as a separate element. In this article, only the first method will be considered. The arm design process algorithm is indicated in Figure 3, which, as in the case of the preliminary design, is an iterative process.

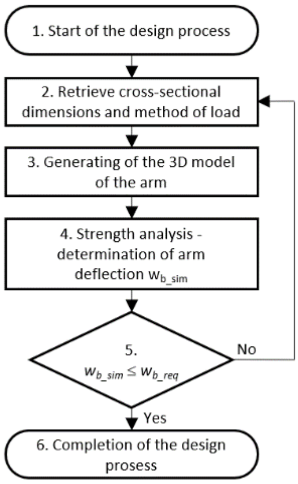

Figure 3. Algorithm of the arm profile design process using FEM

In the first iteration, a 3D model of the arm is created based on a preliminary design, which is then subjected to strength analysis, based on which the deflection of the arm *wb_sim* (mm) is determined. If this value is less than the required deflection *wb_req* (mm) value, the following strength analysis will be subjected to an arm of smaller cross-section, resp. lower weight, which was no longer suitable in the preliminary design. If this arm does not comply, the design process will be completed with the most appropriate cross-section from the preliminary design. If this arm is also suitable, the same procedure will continue until a cross-section of dimensions is found, which would no longer be suitable from the required deflection point of view. The last, dimensionally suitable cross-section will be marked as the most suitable cross-section, and thus the design process will be completed.

Otherwise, if the arm based on the preliminary design dimensions does not meet the required deflection, the strength analysis will be subjected to the arm of a larger cross-section, resp. higher weights in the order specified in the preliminary design. If this arm is not suitable either, this procedure will be repeated until a dimensionally suitable cross-section is found in terms of the required deflection. That will complete the design process.

The time required for this process depends on the complexity of the analyzed 3D model, its size, the fineness of the mesh used in the given strength analysis and the number of iterations. However, at least two iterations will always be performed. The process of creating a 3D model of the arm, preparation and performance of strength analysis, and subsequent comparison of the achieved results with the required results, can be automated using the API of CAD system SolidWorks [Chen 2013, Lad 2014].

2.3 *RobotArmDesign software tool*

To speed up and simplify the design of the arms of industrial robots and manipulators, the algorithms and calculation procedures mentioned above were converted into the software tool RobotArmDesign (Figure 4).

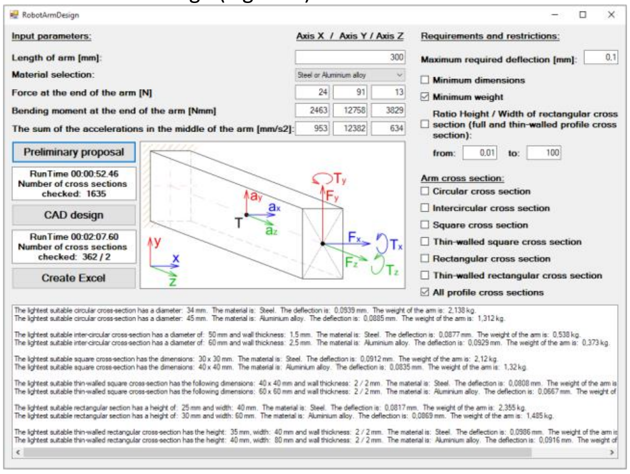

Figure 4. RobotArmDesign software tool

When designing an arm, you must first specify its length and the material from which it is to be made. Subsequently, the magnitudes of the loading forces and moments at the end of the arm and the acceleration at its centre of gravity are entered. Then it is possible to select either one of the available profiles of the proposed arm, or to allow selection from all available profiles stored in the database. Before starting the design using the "Preliminary proposal" button, it is necessary to enter the proposed arm's maximum permissible deflection value. Before starting the design, it is possible to check the arm's design options with minimum external dimensions or minimum weight. In the case of rectangular cross-sections, it is possible to enter restrictions regarding their height and width ratios.

When the preliminary design is complete, the RobotArmDesign software tool lists the matching profiles in the lower window, including their weight and deflection size. In the window below the "Preliminary proposal" button, the time of the preliminary design of the arm cross-section and the number of analyzed cross-sections are listed. The maximum pre-design time (on a computer configured with an AMD Ryzen 5 2600X processor, 16GB of RAM, a graphics card equipped with an NVidia GeForce GTX 1650 chip, and a 500GB SSD) will not exceed 1 minute.

By using the "CAD design" button, it is possible to design the arm cross-section, including its strength analysis in the CAD environment of the SolidWorks system. However, in this case, it is necessary to limit the selection to only one specific type of cross-section, one explicit material and select one of the options "Minimum Dimensions" or "Minimum weight". After pressing the "CAD design" button, the RobotArmDesign software tool first proceeds according to the algorithm indicated in Figure 2. After performing the preliminary design, the procedure follows the algorithm indicated in Figure 3. An example of the strength analysis result is shown in Figure 5. window of the RobotArmDesign software tool. In the window below the "CAD design" button, the design time of a suitable cross-section of the arm and the total number of analyzed profiles are then listed. The maximum design time depends on the number of strength analyzes performed. In most cases (up to five strength analyses performed) it does not exceed 10 minutes.

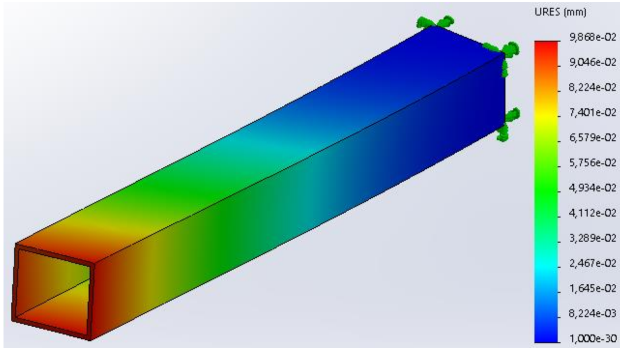

Figure 5. Result of strength analysis of the arm of a rectangular thin-walled cross-section

The "Create Excel" button can be used to export the results of the preliminary design of the arm cross-section to a pre-prepared MS Excel file and then view these results in graphs (Figure 6) showing the dependencies between the dimensions of available cross-sections in the database and deflections at a specified load. They also plot the relationship between the given cross-sections' dimensions and their weight, for a given arm length.

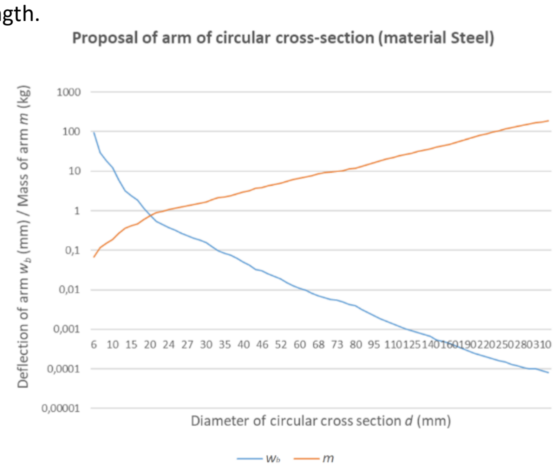

Figure 6. Dependence of the size of the deflection of the full circular cross-section arm and its weight for the specified load and all diameters listed in the profile database

3 RESULTS AND ANALYSIS

Functionality and benefits of the algorithms mentioned above, respectively RobotArmDesign software tool was verified on the manipulation task indicated in Figure 7. A robot with an angular structure and 5 degrees of freedom was designed to manipulate a cylindrical object with a diameter of 52 mm, a length of 200 mm and a weight of 3,313 kg. The length of the trajectory is 1314,16 mm, and OM travels it in 3 seconds.

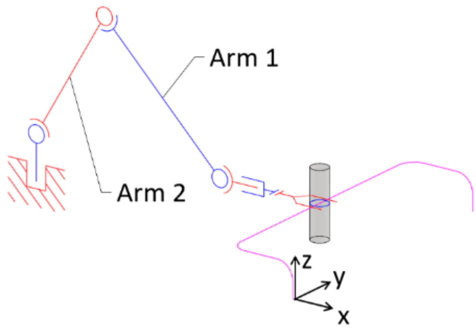

Figure 7. Design of the kinematic structure of the manipulator

Based on the robot's kinematic structure, the object of manipulation and repeated kinematic and dynamic analyzes in the CAD environment of the SolidWorks system, the individual elements of the robot were gradually designed. Starting with the end effector and ending with the robot base. The previously created Drive Picker software tool was used to design the Harmonic Drive units of the CanisDrive series. 3D models of structural elements related to power units were generated with the help of a previously created knowledge base. The following graphs (Figure 8) show the forces, moments and accelerations required to design Arm 1 arm, obtained from a dynamic analysis of the proposed device. The length of this arm is 300 mm.

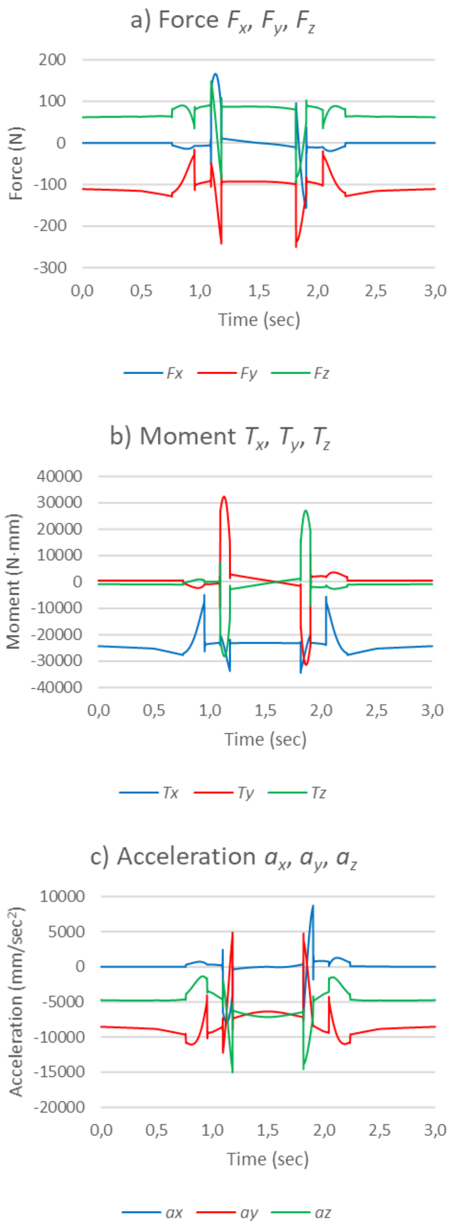

Figure 8. Graphs with courses of: a) forces *Fx*, *Fy*, *Fz*; b) moments *Tx*, *Ty*, *Tz*; c) accelerations *ax*, *ay*, *az*

Table 1 shows preliminary dimensional designs for individual types of cross-sections (including the indication of the arm's final weight), for Steel and Aluminum alloy materials, at selected moments of OM movement. For each type of cross-section, material and time, two values are given, the minimum size of a suitable cross-section and the cross-section's size with the lowest achievable weight, for the required maximum deflection of 0,01 mm. If a suitable cross-section is not found, there is a dash in the table column.

In the second and third columns of Table 2, for each type of cross-section and materials, the cross-sections' dimensions are given (again for the minimum size of a suitable cross-section and the cross-sectional size with the lowest achievable arm weight). It also shows the sizes of the calculated deflection and the number of sizes checked within the given type of cross-section. The fourth column shows the percentage difference in weight between the arms of a given type of cross-section with the smallest dimensions and the smallest weight.

In the fifth and sixth columns of Table 2, the dimensions are given for each type of cross-section and material, again for the minimum size of a suitable cross-section (the size of the cross-section with the lowest achievable arm weight) designed using strength analyzes performed in SolidWorks CAD. Again, it shows the deflection sizes and the number of sizes checked within the given cross-section. However, there are two values, separated by a slash. The first indicates the number of sizes of a given cross-section, checked in the preliminary design. The second (after the slash) shows the number of strength analyzes performed to find a cross-section of suitable dimensions.

It is clear from Table 2 that for this particular case, it was necessary to perform only two strength analyses for most cross-sections. Overall, it could be concluded that it is possible to obtain a cross-section of the arm either dimensionally satisfactory or close to the preliminary design process's desired result.

Figure 9 shows the structural designs of the Arm 1 arm according to the cross-sections in Table 2, including flanges whose connection dimensions correspond to the respective designed rotary joints of the robot (a) ∅78, material Steel; b) ∅110, Aluminum alloy material; c) ∅90x10, material Steel; d) ∅140x10, material Aluminum alloy; e) 70x70, material Steel; f) 100x100, material Aluminum alloy; g) 80x80x8, material Steel; h) 120x120x3, material Steel; i) 60x90, material Steel; j) 80x120, material Steel; k) 120x80x6, material Steel; l) 100x120x3, material Steel.

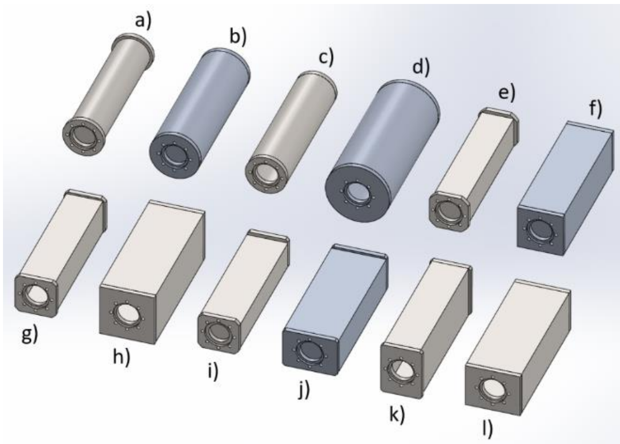

Figure 9. Arm 1 designs

If we compare the proposed cross-sections of the arms only from the point of view of the arm's weight, it is evident that the thin-walled ones perform significantly better than the solid ones. Aluminium alloy arms are also lighter than steel arms. But they also have larger external dimensions. The larger external dimensions of the proposed arm are not problematic from the point of view of the actual construction or the robot's planned deployment. It is more appropriate to use thin-walled cross-sections made of Aluminum alloy and thus achieve its lower weight. Otherwise, the use of Steel or full cross-sections is more advantageous (in the case of full cross-sections, there is significantly more space for possible subsequent topological optimization than thin-walled cross-sections).

Time (sec)	0,75	0,96	1,135	1,183	1,82	1,87	2,05	2,25
Circular (Steel)	∅72mm (9,588kg)	∅ 70mm (9,063kg)	∅78mm (11,25kg)	∅78mm (11,25kg)	∅78mm (11,25kg)	∅78mm (11,25kg)	∅50mm (4,624kg)	∅72mm (9,588kg)
	∅72mm (9,588kg)	∅ 70mm (9,063kg)	∅ 78mm (11,25kg)	∅78mm (11,25kg)	∅78mm (11,25kg)	∅78mm (11,25kg)	∅50mm (4,624kg)	∅72mm (9,588kg)
Circular (Aluminium alloy)	∅100mm (6,48kg)	∅90mm (5,248kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅65mm (2,738kg)	∅100mm (6,48kg)
	∅100mm (6,48kg)	∅90mm (5,248kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅110mm (7,84kg)	∅65mm (2,738kg)	∅100mm (6,48kg)
Intercircular (Steel)	∅80x10mm (5,179kg)	∅80x10mm (5,179kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅51x10mm (3,033kg)	∅80x10mm (5,179kg)
	∅90x5mm (3,144kg)	∅ 90x5mm (3,144kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅90x10mm (5,919kg)	∅80x2mm (1,154kg)	∅90x5mm (3,144kg)
Intercircular (Aluminium alloy)	∅120x10 mm (2,851kg)	∅120x5 mm (1,49kg)	∅120x10 mm (2,851kg)	∅140x10 mm (3,369kg)	∅140x10 mm (3,369kg)	∅120x10 mm (2,851kg)	∅80x5mm (0,972kg)	∅120x10 mm (2,851kg)
	∅140x4 mm (1,41kg)	∅ 140x4 mm (1,41kg)	∅150x5 mm (1,879kg)	∅150x5 mm (1,879kg)	∅150x5 mm (1,879kg)	∅150x5 mm (1,879kg)	100x3mm (0,754kg)	∅140x4mm (1,41kg)
Square (Steel)	65x65mm (9,95kg)	65x65mm (9,95kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	45x45mm (4,769kg)	65x65mm (9,95kg)
	65x65mm (9,95kg)	65x65mm (9,95kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	70x70mm (11,54kg)	45x45mm (4,769kg)	65x65mm (9,95kg)
Square (Aluminium alloy)	90x90mm (6,683kg)	80x80mm (5,28kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	60x60mm (2,97kg)	90x90mm (6,683kg)
	90x9mm (6,683kg)	80x80mm (5,28kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	90x90mm (6,683kg)	60x60mm (2,97kg)	90x90mm (6,683kg)
Thin-walled square (Steel)	80x80x5 mm (3,532kg)	80x80x4 mm (2,864kg)	80x80x8 mm (5,426kg)	80x80x8 mm (5,426kg)	80x80x8 mm (5,426kg)	80x80x8 mm (5,426kg)	50x50x5 mm (2,12kg)	80x80x5 mm (3,532kg)
	100x100x3 mm (2,741kg)	100x100x3 mm (2,741kg)	100x100x3 mm (2,741kg)	120x120x3 mm (3,306kg)	100x100x3 mm (2,741kg)	110x110x3 mm (2,741kg)	70x70x2 mm (1,281kg)	100x100x3 mm (2,741kg)
Thin-walled square (Aluminium alloy)	120x120x4 mm (1,531kg)	120x120x4 mm (1,531kg)	-	-	-	-	75x75x5 mm (1,155kg)	120x120x4 mm (1,531kg)
	120x120x4 mm (1,531kg)	120x120x4 mm (1,531kg)	-	-	-	-	100x100x2 mm (0,647kg)	120x120x4 mm (1,531kg)
Rectangular (Steel)	50x70mm (8,243kg)	40x70mm (6,594kg)	50x90mm (10,6kg)	50x90mm (10,6kg)	50x80mm (9,42kg)	60x90mm (12,72kg)	30x50mm (3,532kg)	50x70mm (8,243kg)
	12x120mm (3,391kg)	20x100mm (4,71kg)	50x90mm (10,6kg)	50x90mm (10,6kg)	20x110mm (5,181kg)	50x100mm (11,76kg)	8x90mm (1,696kg)	10x130mm (3,062kg)
Rectangular (Aluminium alloy)	50x100mm (4,125kg)	40x100mm (3,3kg)	80x120mm (7,92kg)	80x120mm (7,92kg)	50x120mm (4,95kg)	80x120mm (7,92kg)	50x60mm (2,475kg)	50x100mm (4,125kg)
	20x150mm (2,475kg)	40x100mm (3,3kg)	80x120mm (7,92kg)	80x120mm (7,92kg)	20x150mm (2,475kg)	80x120mm (7,92kg)	12x100mm (0,99kg)	15x150mm (1,856kg)
Thin-walled rectangular (Steel)	60x80x6 mm (3,617kg)	60x80x5 mm (3,062kg)	80x100x5 mm (4,004kg)	80x100x4 mm (3,24kg)	50x100x6 mm (3,9kg)	80x100x5 mm (4,004kg)	30x60x4 mm (1,545kg)	60x80x6 mm (3,617kg)
	60x100x3 mm (2,176kg)	50x100x3 mm (2,035kg)	100x120x3 mm (3,024kg)	80x120x3 mm (2,741kg)	80x120x3 mm (2,741kg)	80x120x3 mm (2,741kg)	20x80x2 mm (0,904kg)	60x100x3 mm (2,176kg)
Thin-walled rectangular (Aluminium alloy)	40x150x4 mm (1,201kg)	40x150x4 mm (1,201kg)	-	-	50x180x4 mm (1,465kg)	-	60x80x4 mm (0,871kg)	40x150x4 mm (1,201kg)
	34x200x3 mm (1,129kg)	34x200x3 mm (1,129kg)	-	-	34x200x3 mm (1,129kg)	-	40x120x2 mm (0,515kg)	34x200x3 mm (1,129kg)

Table 1. Preliminary design of the dimensions of the cross-sections of the arms at selected moments of OM movement

Cross-section	Minimum dimensions (preliminary proposal)	Minimum weight (preliminary proposal)	Weight reduction in (%) (preliminary proposal)	Minimum dimensions (SolidWorks analysis)	Minimum weight (SolidWorks analysis)	Weight reduction in (%) (SolidWorks analysis)
Circular (Steel)	∅78mm (11,25kg) [0,0098mm] NoCSCh*: 74	∅78mm (11,25kg) [0,0098mm] NoCSCh: 74	0,0	∅78mm (11,25kg) [0,010mm] NoCSCh: 74 / 2	∅78mm (11,25kg) [0,010mm] NoCSCh: 74 / 2	0,0
Circular (Aluminium alloy)	∅110mm (7,84kg) [0,0075mm] NoCSCh: 31	∅110mm (7,84kg) [0,0075mm] NoCSCh: 31	0,0	∅110mm (7,84kg) [0,008mm] NoCSCh: 31 / 2	∅110mm (7,84kg) [0,008mm] NoCSCh: 31 / 2	0,0
Intercircular (Steel)	∅90x10mm (5,919kg) [0,009mm] NoCSCh: 164	∅90x10mm (5,919kg) [0,009mm] NoCSCh: 164	0,0	∅90x10mm (5,919kg) [0,010mm] NoCSCh: 164 / 2	∅90x10mm (5,919kg) [0,010mm] NoCSCh: 164 / 2	0,0
Intercircular (Aluminium alloy)	∅140x10mm (3,369kg) [0,0063mm] NoCSCh: 95	∅150x5mm (1,879kg) [0,0093mm] NoCSCh: 95	44,2	∅140x10mm (3,369kg) [0,008mm] NoCSCh: 95 / 2	∅140x10mm (3,369kg) [0,008mm] NoCSCh: 95 / 3	0,0
Square (Steel)	70x70mm (11,54kg) [0,0089mm] NoCSCh: 25	70x70mm (11,54kg) [0,0089mm] NoCSCh: 25	0,0	70x70mm (11,54kg) [0,010mm] NoCSCh: 25 / 2	70x70mm (11,54kg) [0,010mm] NoCSCh: 25 / 2	0,0
Square (Aluminium alloy)	90x90mm (6,683kg) [0,0099mm] NoCSCh: 18	90x90mm (6,683kg) [0,0099mm] NoCSCh: 18	0,0	100x100mm (8,25kg) [0,007mm] NoCSCh: 18 / 2	100x100mm (8,25kg) [0,007mm] NoCSCh: 18 / 2	0,0
Thin-walled square (Steel)	80x80x8mm (5,426kg) [0,0091mm] NoCSCh: 78	120x120x3mm (3,306kg) [0,0058mm] NoCSCh: 78	39,1	80x80x8mm (5,426kg) [0,010mm] NoCSCh: 78 / 2	120x120x3mm (3,306kg) [0,008mm] NoCSCh: 78 / 2	39,1
Thin-walled square (Aluminium alloy)	-	-	-	-	-	-
Rectangular (Steel)	60x90mm (12,72kg) [0,0071mm] NoCSCh: 368	50x100mm (11,76kg) [0,0099mm] NoCSCh: 368	0,0	60x90mm (12,72kg) [0,009mm] NoCSCh: 368 / 2	60x90mm (12,72kg) [0,009mm] NoCSCh: 368 / 2	0,0
Rectangular (Aluminium alloy)	80x120mm (7,92kg) [0,0068mm] NoCSCh: 276	80x120mm (7,92kg) [0,0068mm] NoCSCh: 276	0,0	80x120mm (7,92kg) [0,009mm] NoCSCh: 276 / 2	80x120mm (7,92kg) [0,009mm] NoCSCh: 276 / 2	0,0
Thin-walled rectangular (Steel)	80x100x5mm (4,004kg) [0,0092mm] NoCSCh: 362	100x120x3mm (3,024kg) [0,0075mm] NoCSCh: 362	24,5	120x80x6mm (5,313kg) [0,009mm] NoCSCh: 362 / 5	100x120x3mm (3,024kg) [0,010mm] NoCSCh: 362 / 2	43,1
Thin-walled rectangular (Aluminium alloy)	-	-	-	-	-	-

Table 1. Design of cross-sections using strength analysis and comparison with the results of preliminary design (*NoCSCh - Number of Cross-Sections Checked)

Based on the achieved results, the Arm 1 arm was designed from a square thin-walled cross-section measuring 80x80x8 mm, made of Steel. Its weight is 44,3 % greater than in the case of using a rectangular thin-walled cross-section measuring 100x120x3 mm, which was the best in terms of weight. But from the point of view of the cross-section's external dimensions, this is a significantly more compact solution, better corresponding to the dimensions of the joints, resp. other parts of the proposed robot. Due to the excessive external dimensions, aluminium

alloy profiles were not considered, despite the significantly lower achievable weights than the final solution.
Similarly, the Arm 2 arm was designed. A rectangular thin-walled cross-section with dimensions of 100x80x3 mm, made of Steel, was designed for this arm based on the achieved results. Figure 10 shows the resulting 3D model of the robot, including the OM and its trajectory.

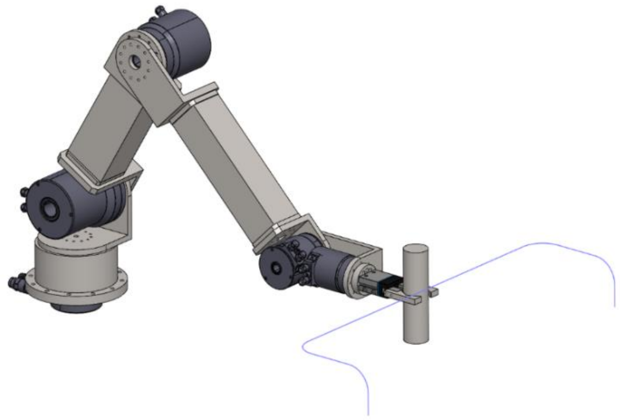

Figure 9. 3D model of the robot arm

At the time of writing, no information was available on a similar way of designing the arms of industrial robots and manipulators or similar structural elements. Commonly used design procedures, or available software tools, were designed to solve partial tasks within the described issues. By modifying them with regard to the design of the arms of industrial robots and manipulators, interconnection, the addition of other necessary algorithms, and subsequent creation of the software tool RobotArmDesign, enabling the design of a suitable cross-section of arms of robots and manipulators, can be considered unique. At the same time, not only was the required reduction of time and reduction of design complexity achieved but also the way was opened to automate the design process of complete arms of industrial robots and manipulators.

4 CONCLUSIONS

This article contains three main parts. The first describes calculations and algorithms, which can significantly not only reduce the design time of the arms of industrial robots and manipulators, but also achieve significantly better results in terms of their final dimensions or weight than in the use of classical design procedures. At the same time, the proposed algorithms can serve as inspiration for automating the design of other structural elements not only in the field of robotics. The second part describes the software tool RobotArmDesign, built on the basis of these calculations and algorithms and using the simulation tools of the CAD system SolidWorks to refine the design of the arms. The third part is devoted to verifying the functionality of the proposed algorithms, respectively the software tool RobotArmDesign. The achieved results show a significant benefit both from the point of view of shortening the design time of the arms and from the point of view of choosing a suitable cross-section or material from which it would be made. The RobotArmDesign software tool has therefore proved its worth in terms of possible practical use.

ACKNOWLEDGMENTS

This article was developed with the support of the project Research Centre of Advanced Mechatronic Systems, reg. no. CZ.02.1.01/0.0/0.0/16_019/0000867 in the frame of the Operational Program Research, Development and Education.

REFERENCES

[Abidin 2019] Abidin Z.F.Z., Zahid M.N.O. Real time object customization in CAD system. Indonesian Journal of Electrical Engineering and Computer Science, August 2019, Vol.15, No.2., pp 1066-1075. ISSN 2502-4752

[Azarfar 2018] Azarfar A. Self-tuning Fuzzy Task Space Controller for Puma 560 Robot. International Journal of Robotics and Automation, December 2018, Vol.7, No.4., pp 273-282. ISSN 2089-4856

[Bedenik 1999] Bedenik B.S., Besant C.B. Analysis of Engineering Structures. Chichester: Horwood Publishing, 1999. ISBN 9781898563556

[Castillo-Garcia 2017] Castillo-Garcia F.J., Rea P., Gonzalez-Rodriguez A., Ottaviano E. On the Design of a 4 Degrees-of-freedom Pick and Place Cable Suspended Parallel Manipulator. International Journal of Robotics and Automation, December 2017, Vol.6, No.4., pp 286-302. ISSN 2089-4856

[Ceccarelli 2019] Ceccarelli, M. and Gasparetto, A. Mechanism Design for Robotics: Proceedings of the 4th IFToMM Symposium on Mechanism Design for Robotics. Switzerland: Springer International Publishing, 2019. ISBN 978-3-030-13107-4

[Chen 2013] Chen T., Yan X.X., Yu Z.H. The Research and Development of VB and Solidworks-Based 3D Fixture Component Library. Applied Mechanics and Materials, February 2013, pp 300-301:301-305. ISSN 1660-9336

[Grotjahn 2001] Grotjahn, M., Daemi, M. and Heimann, B. Friction and rigid body identification of robot dynamics. International Journal of Solids and Structures, 2001, Vol.38, Issues 10–13., pp 1889-1902. ISSN 0020-7683

[Ha 2018] Ha S., Coros S., Alspach A., Bern J.M., Kim J., Yamane K. Computational Design of Robotic Devices From High-Level Motion Specifications. IEEE Transactions on Robotics, October 2018, Vol.34, No.5., pp 1240-1251. ISSN 1552-3098

[Hearn 1997] Hearn E.J. Mechanics of Materials 1. 3th ed. Oxford: Butterworth-Heinemann, 1997. ISBN 9780750632652

[IFR 2021] IFR International Federation of Robotics. [online]. Available from: https://ifr.org/

[Isermann 2002] Isermann R. Mechatronic design approach. In: Bishop RH. The Mechatronics Handbook. Boca Raton: CRC Press, 2002.

[Ivanov 2018] Ivanov. A.I. Theoretical Matrix Study of Rigid Body Absolute Motion. The International Journal of Engineering and Science, 2018, Vol.7, Issue 6, pp 1-8. ISSN 23-19-1805

[Jazar 2010] Jazar, R.N. Theory of Applied Robotics: Kinematics, Dynamics, and Control (2nd Edition). US: Springer, 2010. ISBN 978-1-4899-7760-1

[KISSsoft 2021] KISSsoftAG. [online]. Copyright ©2021 KISSsoft AG [cit. 15.05.2021]. Available from: https://www.kisssoft.com/en

[Kumar 2017] Kumar S., Rani K., Banga V.K. Robotic Arm Movement Optimization Using Soft Computing. International Journal of Robotics and Automation, March 2017, Vol.6, No.1., pp 1-14. ISSN 2089-4856

[Kurrer 2008] Kurrer K.E. The History of the Theory of Structures: From Arch Analysis to Computational Mechanics. Berlin: Ernst & Sohn, 2008. ISBN 978-3433018385

[Lad 2014] Lad A.C., Rao A.S. Design and Drawing Automation Using Solid Works Application Programming

Interface. International Journal of Emerging Engineering Research and Technology, October 2014, Vol.2, No.7., pp 157-167. ISSN 2349-4395

[Lee 1993] Lee, D.G., Jeong, K.S., Kim, K.S. and Kwak, Y.K. Development of the anthropomorphic robot with carbon fiber epoxy composite materials. Composite Structures, 1993, Vol.25, Issues 1–4, pp 313-324. ISSN 0263-8223

[Lindemann 2009] Lindemann U. Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden. Berlin: Springer-Verlag, 2009. ISBN 978-3-642-01423-9

[Lynch 2017] Lynch, K.M. and Park, F.C. Modern Robotics: Mechanics, Planning, and Control. Cambridge: University Press, 2017. ISBN 1316609847

[MITCalc 2021] MITCalc - Mechanical, Industrial and Technical Calculations. [online]. Available from https://www.mitcalc.com/

[Murray 1994] Murray, R.M., Li, Z. and Sastry, S.S. A Mathematical Introduction to Robotic Manipulation. UK: CRC Press, 1994. ISBN 978-0849379819

[Pandey 2017] Pandey, M., Srivastava, A.K. and Maurya, P. Design & Analysis of Robotic Arm's Part for Carbon Composite Material. International Journal of Advance Research, Ideas and Innovations in Technology 3, 2017, Vol.3, No.5., pp 97-106. ISSN 2454-132X

[Panditta 2012] Panditta I.K., Wani M.M. Deflection of Structures using Principle of Quasi Work. International Journal of Aerospace Sciences, 2012, Vol.1, No.5., pp 85-91. ISSN 2169-8872

[Panditta 2013] Panditta I.K. Deflection of Structures using Modified Betti's Theorem. International Journal of Aerospace Sciences, 2013, Vol.2, No.1., pp 11-13. ISSN 2169-8872

[Paška 2020] Paška, Z., Rojicek, J., Ferfecki, P., Fusek, M., Heczko, D. and Krys, V. Methodology of Arm Design for Mobile Robot Manipulator Using Topological Optimization. MM Science Journal, 2020, Vol.2020, issue June, pp 3918-3925. ISSN 1803-3126

[Prathab 2017] Prathab T.R., Malar R.S.M.,Ahilan T. A Method of Extended Jacobian and Firefly Algorithm for the Kinematic Analysis of Planar Robots. International Journal of Robotics and Automation, June 2017, Vol.6, No.2., pp 141-150. ISSN 2089-4856

[Przemieniecki 2012] Przemieniecki J.S. Theory of Matrix Structural Analysis. Revised edition. Dover: Dover Publications, 2012. ISBN 978-0486649481

[Reddy 2016] Reddy E.J., Sridhar C.N.V., Pandurangadu V. Research and development of knowledge based intelligent design system for bearings library construction using SolidWorks API. Advances in Intelligent Systems and Computing. India: Springer, 2016. ISBN 978-3-319-23257-7

[Reddy 2018a] Reddy E.J., Rangadu V.P. Development of knowledge based parametric CAD modelling system for spur gear: An approach. Alexandria Engineering Journal, December 2018, Vol.57, No.4., pp 3139-3149. ISSN 2249–6890

[Reddy 2018b] Reddy E.J., Venkatachalapathi N., Rangadu V.P. Development of an approach for Knowledge-Based System for CAD modelling. Materials Today: Proceedings, January 2018, Vol.5, No.5., pp 13375-13382. ISSN 2214-7853

[Rueda 2009] Rueda, J.D. and Angel, L. Structural analysis of a delta-type parallel industrial robot using flexible dynamic of ANSYS 11.0. 2009 35th Annual Conference of IEEE Industrial Electronics, 2009, pp 2247-2252. ISSN 1553-572X

[VDI 2004] VDI-Fachbereich Produktentwicklung und Mechatronik. Entwicklungsmethodik für mechatronische Systeme. Berlin: Beuth Verlag, 2004.

[Whitman 2019] Whitman J., Choset H. Task-Specific Manipulator Design and Trajectory Synthesis. IEEE Robotics and Automation Letters, April 2019, Vol.4, No.2., pp 301-308. ISSN 2377-3766

[Xiong 2015] Xiong, Z., Zhuang, C. and Wu, J. Rigid-Body Motions. In: Nee A. (eds) Handbook of Manufacturing Engineering and Technology. London: Springer, 2015. ISBN 978-1-4471-4669-8

[Yang 2016] Yang, C., Ma, H. and Fu, M. Robot Kinematics and Dynamics Modeling. In: Advanced Technologies in Modern Robotic Applications. Singapore: Springer, 2016. ISBN 978-981-10-0829-0

[Yao 2019] Yao, P., Zhou, K., Lin, Y. and Tang, Y. Light-Weight Topological Optimization for Upper Arm of an Industrial Welding Robot. Metals, 2019, Vol.2, No.2., pp 1020-1048.

CONTACTS:

doc. Ing. Milan Mihola, Ph.D.
VSB - Technical University of Ostrava, Department of Robotics
17. listopadu 2172/15, Ostrava-Poruba, 708 00, Czech Republic
+420 596 995 445, milan.mihola@vsb.cz,
https://www.fs.vsb.cz/354/en

Ing. Zdenek Zeman
VSB - Technical University of Ostrava, Department of Robotics
17. listopadu 2172/15, Ostrava-Poruba, 708 00, Czech Republic
+420 596 991 209, zdenek.zeman@vsb.cz
https://www.fs.vsb.cz/354/en

Ing. David Fojtik, Ph.D.
VSB - Technical University of Ostrava, Department of Control Systems and Instrumentation
17. listopadu 2172/15, Ostrava-Poruba, 708 00, Czech Republic
+420 596 994 193, david.fojtik@vsb.cz
https://www.fs.vsb.cz/352/en/