Florin - Felix RĂDUICĂ, Ionel SIMION, Elena IONIȚĂ

A STUDY ON PARAMETRIC DESIGN OF LINE TENDON BASED PROSTHETIC FINGER USING PROGRAMMING TECHNIQUES

Abstract: *In this paper we discuss the process of geometric modelling of a prosthetic finger using programming techniques. Along the design process OpenSCAD is used to model a prosthetic, one degree of freedom finger. As this is a prosthetic device, the ease of customization is taken into consideration. The type of prosthetic considered is a tendon design with flexible and rigid lines. First, we discuss the medical considerations that are needed to develop the model. Second, we discuss the assembly and function of the generated shape. The result is a downloadable geometric model of the finger assembly and the methodology used to generate the design.*

Keywords: *prosthetic finger, line tendon design, custom prosthetic, parametric design, upper limb prosthetic.*

1. INTRODUCTION

In recent years Computer-Aided-Design, CAD software has started to move from regular computer applications to a more advanced, platform-independent web-medium. This can be seen in Autodesk, Dassault Systèmes and other software design suites. The offered cloud solutions are moving the design process from Computer-Aided-Design CAD to an online variation that we termed Web-Aided-Design WAD in the future. The design information has also moved from a local computer to the online distributed network. The closed nature of the main design software applications combined with the WAD concept may lead to a designed product being published accidentally. Also, due to the novelty of this technology we have seen failures contributing to loss of data. Furthermore, the number of file types of designs has grown. The compatibility issues across proprietary software applications have increased. There can be a balance between the quality issues and the advantages of WAD that depending on the software package can be decided whether to choose it or not.

In another case we can consider the implementation of Free-Open-Source-Design-Software FOSDS which is community-developed, and the nature of the source-code allows improvement and customization to any user. Furthermore, the intellectual property can be either shared or maintained privately. Best of all, the compatibility issues between FOSDS are limited.

The research opportunity of FOSDS can be described through the following items:

- possibility of customizing the software application for the design intent;
- ability to access the implemented methods in case of a need for a broader understanding;
- compatibility with other research projects and the possibility of building upon earlier work;
- ease of contribution to existing projects as they are open-source and editable.
- extended lifespan of research projects as they are editable and high availability to contribute or propose other methods.

2. MEDICAL BACKGROUND

The human anatomy is a complex network of systems that work together to provide the needed function of the body. In this work we concentrate on the upper limb of the body, specifically on the index finger. The focus is on replicating as much of the lost function as possible. For a patient with an amputated finger the rehabilitation using a prosthesis leads to partial regain of function.

To provide most of the function, finger prosthetics focus on the human anatomy and try to replicate the structural integrity and function of the hand. This can be done with a custom prosthetic finger manufactured for the specific patient. This suits the needs and anatomy of the specific patient and helps rehabilitate and compensate a part of the lost function.

Items that are of interest for creating a prosthetic hand are presented in Figure 1 below, where the bones and joints of the human hand are illustrated.

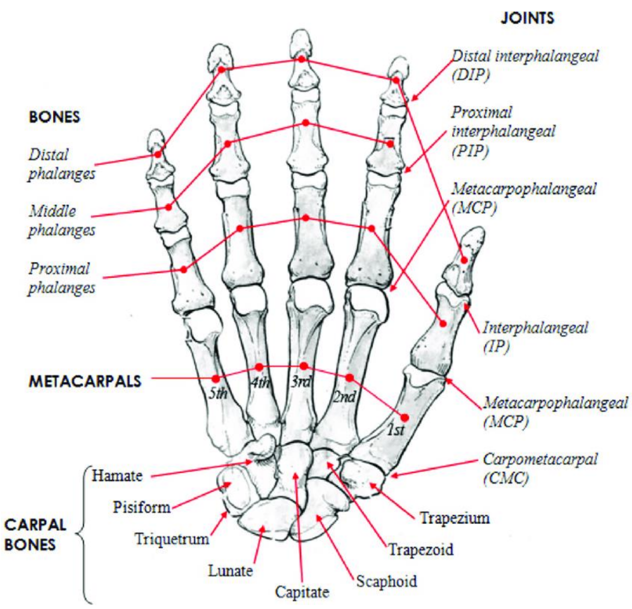


Figure 1 Human hand skeletal structure depicting finger bones joints metacarpals and carpal [1].

3. LITERATURE REVIEW

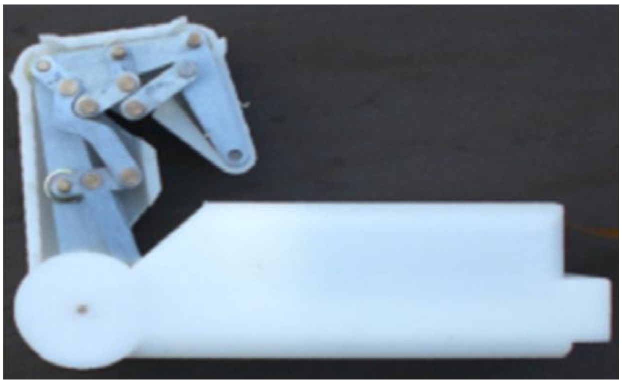
Considering that the human hand is equipped with 27 degrees of freedom DOF of which 4 DOF belong to the index finger [2] and these provide the full range of motion. On the other hand, most prosthetic fingers rely on linkage mechanisms based on one to three degrees of freedom [3] to provide most of the functionality.

3.1 Finger prosthetic with 1 DOF

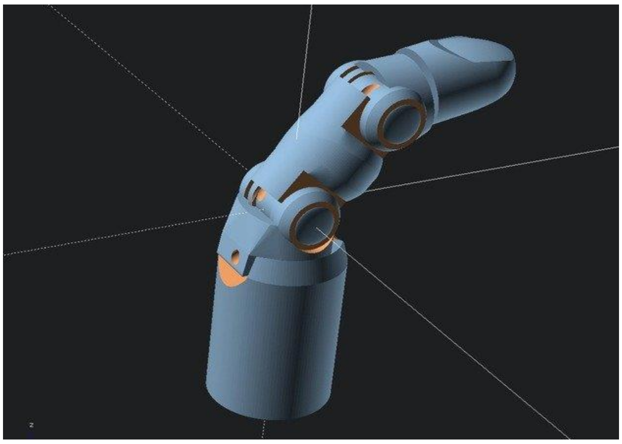
The prosthetic finger can be actuated using a four-bar linkage mechanism and some structural reinforcement. Such prosthetics have 1 DOF and an example is presented in Figure 2a below. The motion induced at the base of the finger is transferred through a series of links and joints to the middle and upper part of the finger. This leads to a closing motion for the finger. The arrangement is also called a stackable four bar linkage.

A prosthetic hand fitted with fingers that run using this type of mechanism can do a very limited number of grasping patterns. Although motion is limited the device presents a high degree of complexity. The assembly uses 3 parts as phalanges, 20 parts as links and 28 joints.

In Figure 2b we present a variation of the design that is also prepared for fabrication using additive manufacturing techniques.



a) Prototype of robotic index finger [4].



b) Knick's prosthetic finger [5].

Figure 2 Prosthetic finger mechanisms with one degree of freedom.

3.2 Finger prosthetic with 2 DOF

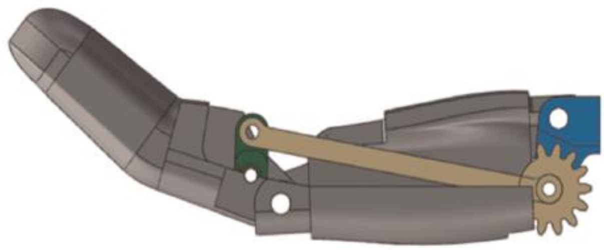


Figure 3 The 3D model of the UA finger [6].

In Figure 3 the 2 DOF design of a prosthetic finger is presented. The function of the finger is improved over the 1 DOF design. But the improvement comes with the collapse of the middle phalanx.

Using the linkage mechanism rather than the other tendon-based design allows the finger to do a larger range of gestures with a higher degree of force.

3.3 Finger prosthetic with 3 DOF

In Figure 4 a 3 DOF is presented. The extra degree gives it even more grasping capabilities then the other examples mentioned. The figure presents a prosthetic finger made with the help of additive manufacturing technologies.

The mechanism involved are contractable slider-cranks and stackable four-bar linkages. The technical design presents linkages in favor of line tendon designs.

Figure 4 Model of 3 DOF prosthetic finger [7].

3.4 Four bar linkage system

The four-bar linkage mechanism can be used to transmit motion. It can be by itself, or it can be used interlinked with other mechanisms. The resulting joint mechanism is a combination of the equations of motion of the two.

In the mechanical design of upper limb prosthetics, the number of joints is high.

The need to reduce the number of motors is so that the device is lightweight and the complexity of the control system is lowered as well. Usually, for low-cost upper-limb prosthetics we find stackable four-bar linkage mechanisms that limit drastically the number of motors used. The disadvantage is that the number of degrees of freedom is also lowered.

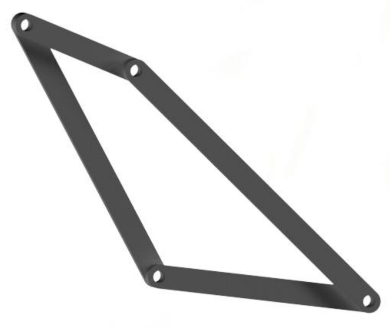


Figure 5 Four bar linkage.

The four-bar linkage seen in Figure 5 is a mechanism that allows actuation of the finger joints. We use it to reduce the number of motor required for the joints of the hand.

4. LINE TENDON BASED INDEX FINGER PROSTHETIC MODELLING

Figure 6 Proximal phalanx as exported from OpenSCAD.

In the case of line tendons, we modeled a 3-piece finger in OpenSCAD. The programming language on which the software relies, offers a coding editor and a render window. When we compile the code, we can see the result on the render window. In order to organize the code variables may be used. The functions used to generate the geometry are prebuilt to accommodate a unit system and provide good control of the render window.

In the following sections we discuss the modeling and general methodology used that lead to the geometry and we compare with standard modeling practices.

To get the desired shape in Figure 9 of the proximal phalanges we used a series of built-in functions from OpenSCAD. The procedural programing language allowed us to start from a basic shape and build upon it as we took the following steps:

1. Build the basic shape of a cylinder;
2. Remove middle material to get hinges shaped;
3. Remove side-material to fully define the hinges;
4. Make a tunnel through the base shape;
5. Make pin hole through the hinges;
6. Fillet edges of hinges to allow travel;
7. Generate the half of the geometry;
8. Make a function to call the geometry into other documents or programs;
9. Call function to generate render view;
10. Create new function with the 2 symmetry parts joined into one.

This allowed us to build the shape of the proximal phalanges (Figure 6). The first part of our assembly has been generated in code. The symmetrical part is equipped with hinges on one end to attach to the palm area. At the other end it can be attached to the next part of the assembly which is the middle phalange (Figure 7). The part can be assembled via a bolt or other fasteners. The fully assembled part can be placed in an assembly as one unique part (Figure 8).

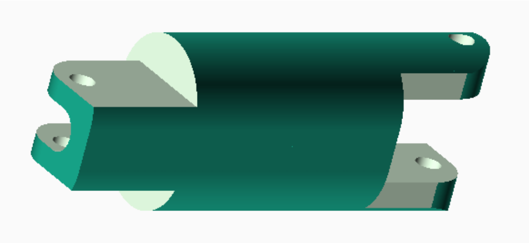


Figure 7 Index Media Phalanx as exported from OpenSCAD.

In the case of the middle phalange the modeling considered a way to attach to the existing proximal phalange. The hinge solution was again used. The assembly will use a bolt or other fastener.

Figure 8 Distal phalanx as exported from OpenSCAD.

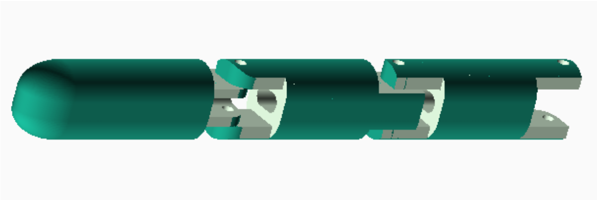


Figure 9 Assembly of index finger as exported from OpenSCAD.

The line tendon system relies on a series of wires that move the phalanges. One of the wire is rigid and is used to actuate the device. The second wire is flexible and is used to readjust the finger to the normal position.

Systems like these have the advantage of not being very complex. When broken they are easily serviceable. The person wearing such a device can easily maintain it.

A disadvantage is the limited movement capabilities. When the device is not correctly wound the main function is disactivated and the device is unusable.

5. LINKAGE BASED INDEX FINGER PROSTHETIC MODELLING

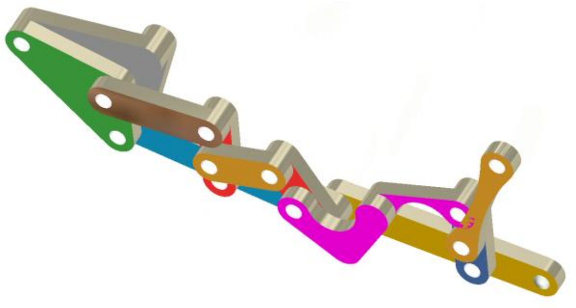
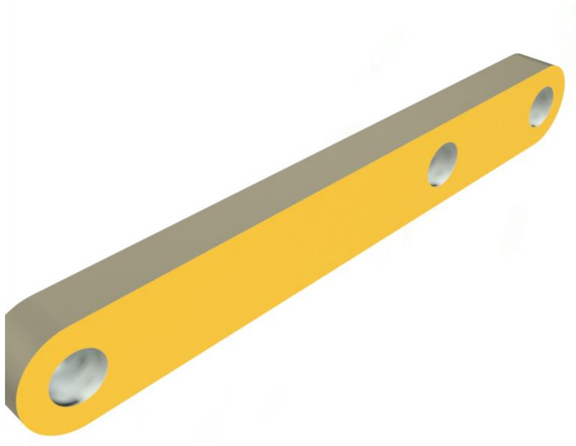


Figure 10 Finger assembly.



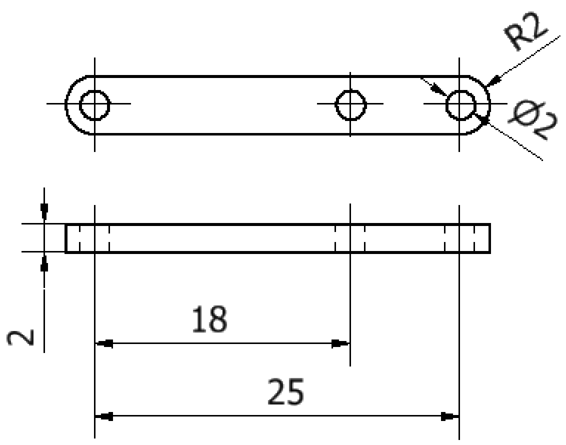
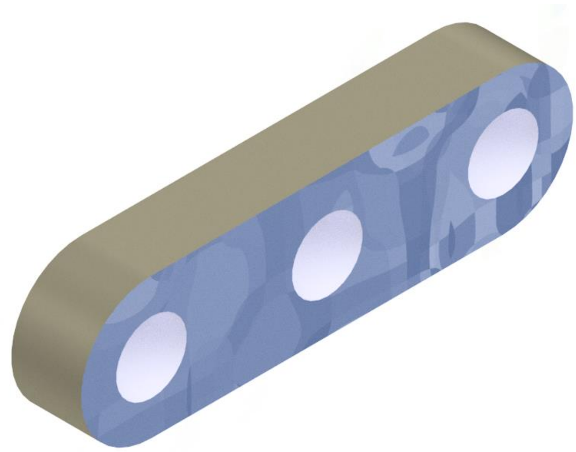


Figure 11 First four bar linkage frame component.

In Figure 11 we see the frame element. The frame is the first element of the first four bar linkage. It's placed horizontally and has the rocker connected on it. It also connects to the second frame of the second four bar linkage. The crank element of the first bar linkage also connects to it (Figure 10).

The rocker in Figure 12 allows the mechanism to move since it is connected to the frame and to a mobile rod that has a translational movement. It also connects to the connecting rod element. This completes the first four bar mechanism of the two which are connected in series.



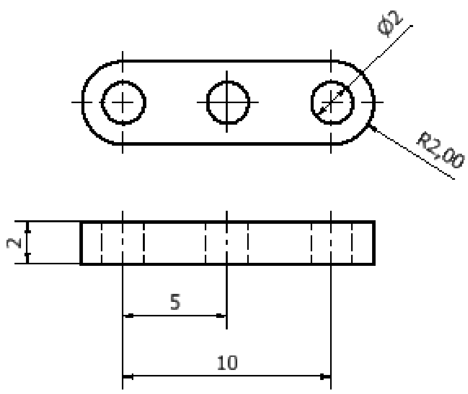


Figure 12 First rocker component of the first four bar mechanism.

In Figure 13 we see the mobile rod. This rod is ment to be connected to an actuator device. The rod puts in motion the serie of four bar linkages. The motion from the mobile rod gets transfered through the first four bar linkage and up to the second four bar linkage and reaches the tip.

In the case of linkage systems there are several advantages regarding precision. If the movement is applied mechanical through a motor then the resulting displacements lead to precise finger movement. In this case finger elements need to be in a certain tolerance so that the precision is meat. Otherwise the precision is lost if the parts are poorly manufactured. The manufacturing process used can be an advantage and a disadvantage at the same time. It can provide low cost parts that aid in providing the prosthetic to a wider variety of patients. The disadvantage is that if the manufacturing process has a lack in precision and the parts are not usable. The movemenet is not precise and the device cant be controlled.

In the case of this device an external force needs to be applied to the linkage system. Usually this is in the form of a electric motor. The actuation is done through myoelectric sensors placed on the patients body. The electric impuls generated by a muscle can be delivered as an input signal to the motor. The disadvantage here is that this requires multiple electric and electronic components to function.

Figures 14-20 illustrate in 3D representation and double orthogonal projection the component elements of the first and second four bar linkage mechanism.

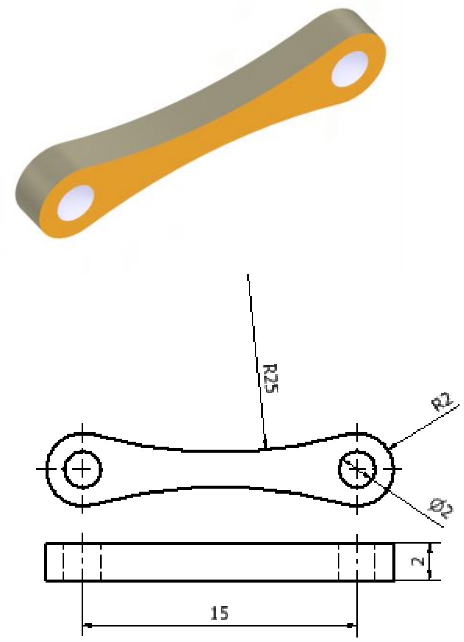


Figure 13 Mobile rod connected to first four bar linkage.

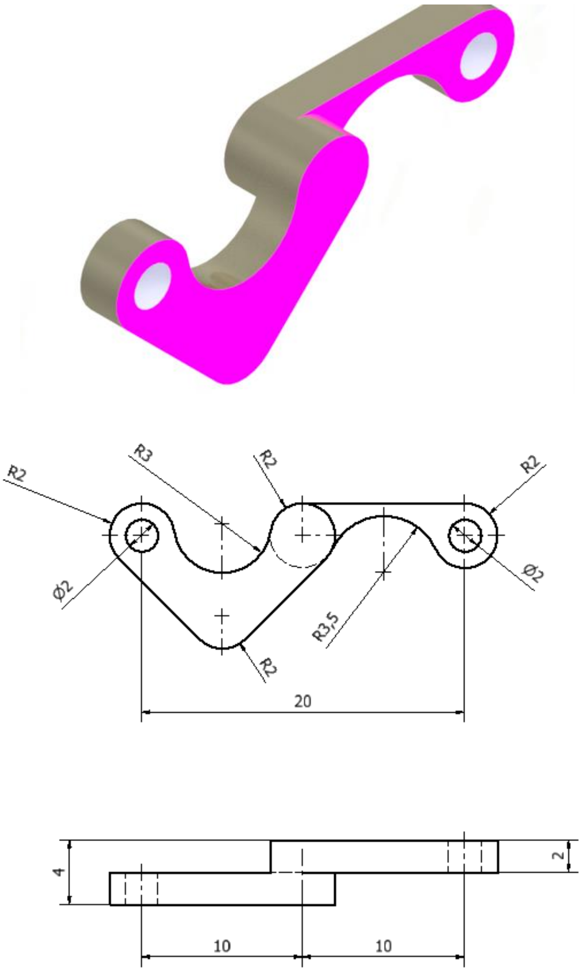


Figure 14 First connecting rod of the first four bar linkage

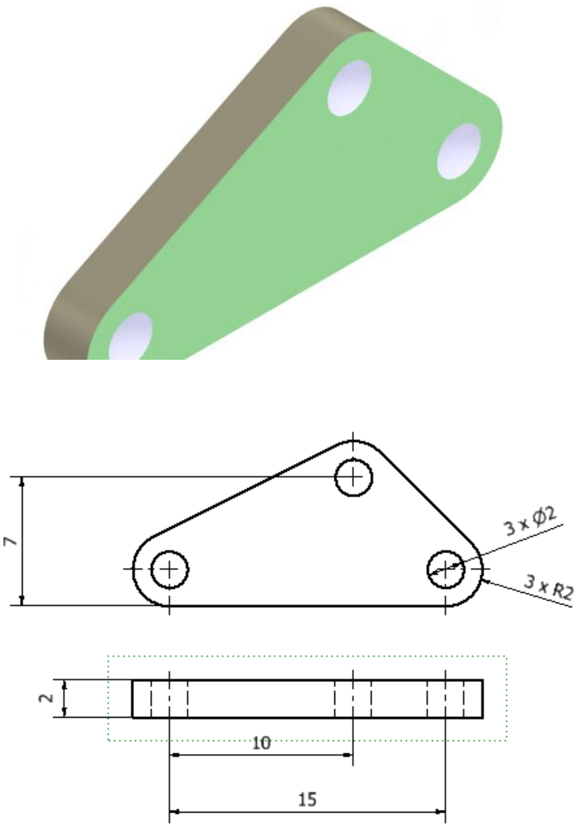


Figure 15 The crank element of the second four bar linkage.

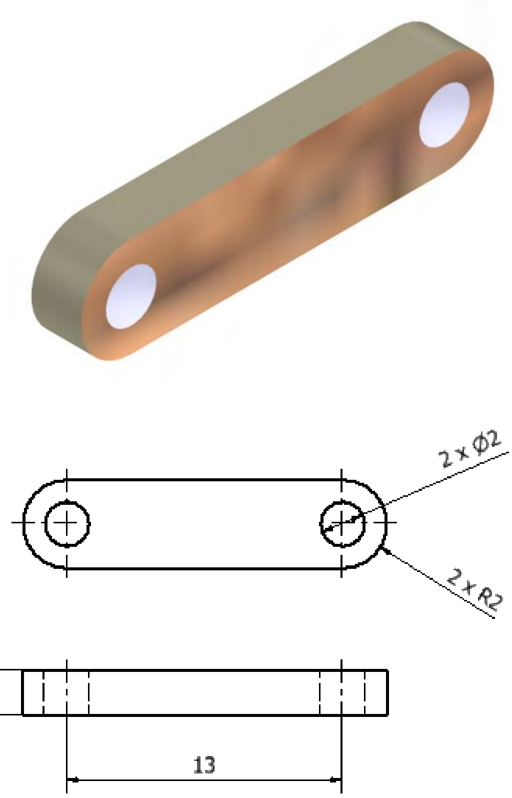


Figure 16 The connecting rod element of the second four bar linkage.

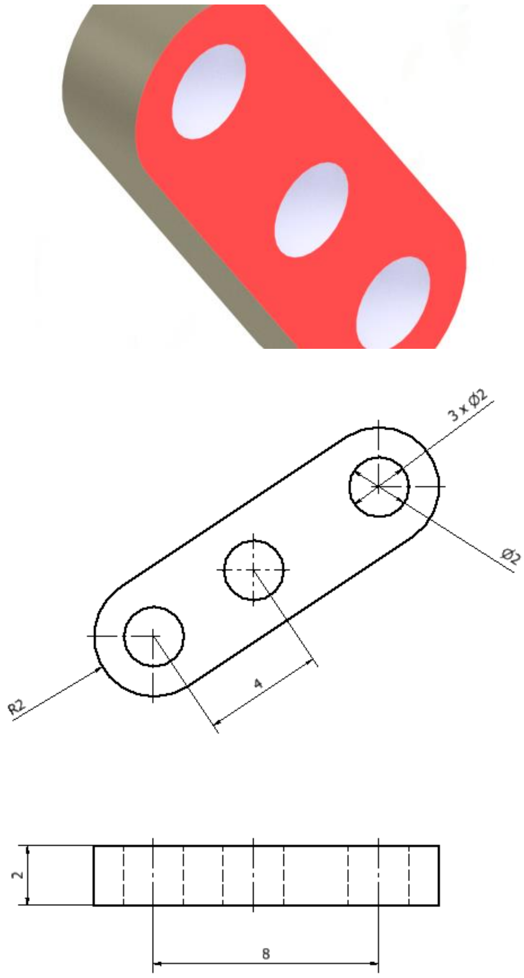


Figure 17 The crank for the first four bar linkage and rocker of the second four bar linkage.

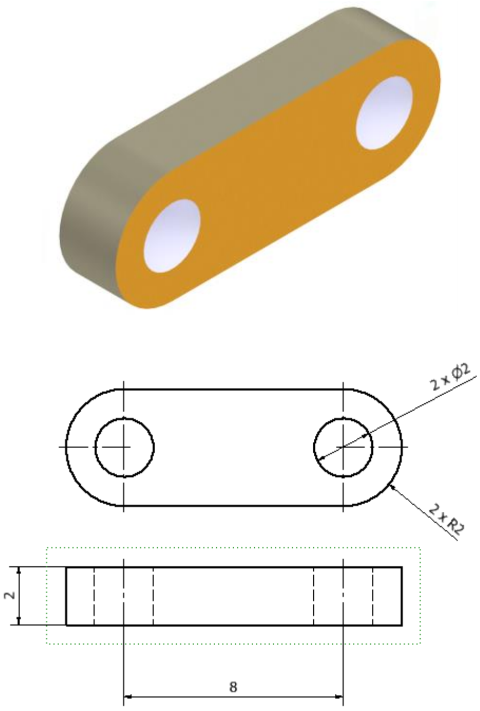


Figure 18 The connecting rod between the first and second four bar linkage.

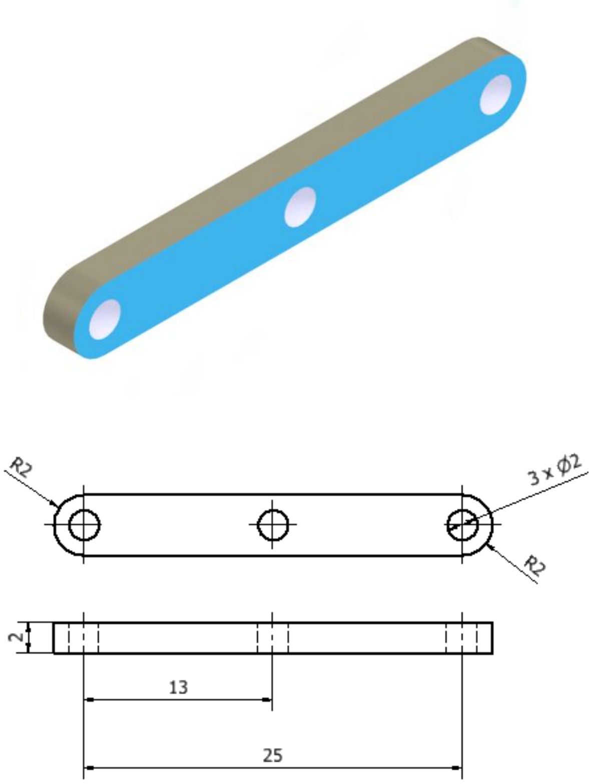


Figure 19 The frame element of the second four bar linkage.

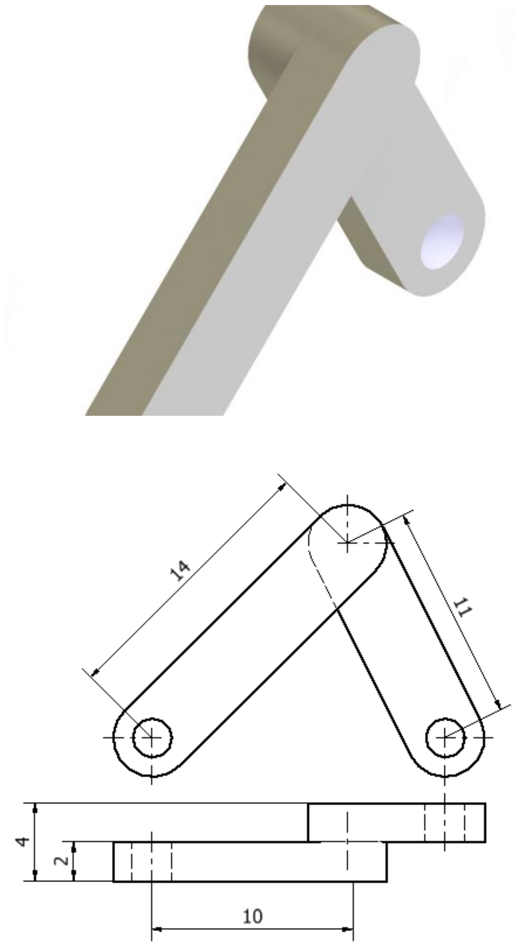


Figure 20 The locking rod for the second four bar linkage.

6. CONCLUSIONS

In OpenSCAD the environment allows us to program scripts that can be rendered. In one windows we can design the code and in another we can view the resulted rendered image.

In a full featured CAD package like Autodesk Inventor the endless array of tools allows us to develop design ideas even for open source modeling.

When working with free open source software for 3D modeling the complexity is high. But the resulting model can be edited by a larger number of people.

Rapid prototyping tools can allow development of engineering solutions to aid in the effort of giving access to advanced prosthetics to more people.

The value gained by using paid closed source software is the ease of modeling and extended functionality. But the number of people who may be able to edit the model is restricted to those that have a license.

In the event of publishing modelled work online the 2 possibilities of sharing lead to a crowd effort. This can add value and expertise to a part or assembly.

Open-source modeling with the aid of programming is a good method of adding improvements to an existing model. Thus generating a new and improved version which is available to all to use or improve.

In the case of 3D printing the work done on parts published online has lead to improvements in part quality for those using the technology.

Programming in CAD leads to letting other engineers like software engineers to improve the code even if they are not specialized in industrial design. A multidisciplinary approach to CAD can further improve the design efforts.

Medical devices have a lot to benefit from both 3D printing and open models. The iterations done has permitted improvements in design.

Limitations of open-source software sometimes inhibit the design process. The lack of a full featured open-source software is inhibiting development.

Looking at line tendons as a solution for 3D printed prosthetics is an option. The downside to this is the lack of precision. The low cost makes it ideal for low-income families in need of a prosthetic.

The linkage systems are one of the more precise methods of movement. The downside to this is that you need more precise tools to get the precision required for movement.

Development communities meet online to collaborate in developing hardware and software together. The benefit of this is improvement of existing solutions and new ones.

Practical developments to models can improve the development of low cost prosthetics so that low income families can benefit from them.

The social and economic impact of low-cost prosthetics can lead to a better life for patients with mobility disability.

Developing online projects can lead to a continuous development of ideas. When a developer moves on the work can be further developed by someone else interested in the field.

REFERENCES

[1] Nanayakkara, V., Cotugno, G., Vitzilaios, N., Venetsanos, D., Nanayakkara, T., Sahinkaya, M. N. (2017). Th*e Role of Morphology of the Thumb in Anthropomorphic Grasping: A Review.* Frontiers in Mechanical Engineering, Vol. 3, No. 1, (June 2017) pp 1-21, Electronic ISSN: 2297-3079.

[2] Rahman, A., Al-Jumaily, A. (2013). *Design and Development of a Bilateral Therapeutic Hand Device for Stroke Rehabilitation.* International Journal of Advanced Robotic Systems, Vol. 10, No. 405, (July 2013) pp 1-12, Online ISSN: 1729-8814.

[3] Kashef, S. R., Amini, S., Akbarzadeh, A., (2020) *Robotic hand: A review on linkage-driven finger mechanisms of prosthetic hands and evaluation of the performance criteria.* Mechanism and Machine Theory, Vol. 145, No. 103677 (March 2020) pp 1-17, ISSN: 0094-114X.

[4] Jang, G., Lee, C., Lee, H., Choi, Y., (2013*) Robotic index finger prosthesis using stackable double 4-BAR mechanisms.* Mechatronics, Vol. 23, Np. 3, (April 2013) pp 318-325, ISSN 0957-4158.

[5] Brookins N., (2016) *Knick's Prosthetic Finger v3.5.5* available at: https://www.thingiverse.com/ Accessed: 2022-02-22.

[6] Li, X., Huang, Q., Chen, X., Yu1, Z., Zhu, J., Han, J. (2017). *A novel under-actuated bionic hand and its grasping stability analysis.* Advances in Mechanical Engineering, Vol. 9, No. 2, (March 2017) pp 1–13, ISSN 1687-8132.

[7] Yoon, D., Choi, Y. (2017*). Underactuated Finger Mechanism Using Contractible Slider-Cranks and Stackable Four-Bar Linkages*. IEEE/ASME Transactions on Mechatronics, Vol. 22, No. 5, (October 2017) pp 2046 - 2057, Doi: 10.1109/TMECH.2017.2723718.

Authors:

Asist. Prof. Florin – Felix RĂDUICĂ, University POLITEHNICA of Bucharest, Faculty of Aerospace Engineering, Department of Engineering Graphics and Industrial Design, E-mail: felix.raduica@upb.ro

Prof. Ionel SIMION, University POLITEHNICA of Bucharest, Faculty of Aerospace Engineering, Department of Engineering Graphics and Industrial Design, E-mail: ionel.simion@upb.ro

Lect. Elena IONIȚĂ, University POLITEHNICA of Bucharest, Faculty of Aerospace Engineering, Department of Engineering Graphics and Industrial Design, E-mail: elena.ionita@upb.ro