Design and 3D Printing of a Non-Anthropomorphic Articulated Mechanical Hand

A Bouachari[1], A. Haddad[2,*], and W. Leuchi[1]
[1]Mechanical Engineering Department, Faculté de Technologie, Université 20 Aout 1955, Skikda-21000, Algeria
[2]Laboratoire de Mécanique Appliquée des Nouveaux Matériaux-LMANM, Faculté des Sciences et Technologie, Université 8 Mai 1945, Guelma-24000, Algeria
*Corresponding author: akhhaddad@gmail.com

***Abstract*— The present investigation focuses on the design and 3D printing of a non-anthropomorphic articulated mechanical hand dedicated to dextral manipulation. A virtual dextral simulation workshop under 'Catia' and based on the functionalities that are integrated in it especially the module 'Digital Model/DMU kinematics' has been developed. Its application allows the design of a five-fingered hand inspired by existing ones, and can be mounted on a manipulator arm with six degrees of freedom. It was subsequently refined through the application of the module 'Human Builder' which manages the human grasping under 'Catia, and two cases of grasping have been successfully completed: a palmar grasping and a digito-palmar one with the possibility of the whole hand-arm to perform 'pick-and-place' tasks within a virtual environment. These simulations have proved promising as they allow considering a wide spectrum of interesting robotic tasks. The design developed in this way was 3D printed out (additive manufactured) and its commands tested. The results have been found very satisfactory.**

***Index Term*— Dextral manipulation, grasping, articulated hands, pick-and-place, 3D printing, command.**

I. INTRODUCTION

The faculty of grasping is very developed in the human being. It is generally seen as a set of kinematic chains connected to a base, and closed on an object in areas of contact that should be modeled [1]. There are mainly two kinds of gripping. Those said ‘of power’ or full hands that use the approach of stability and security, and the so-called fine or precision grips requiring sensitivity and dexterity. Grasping can be performed in a variety of ways, mainly because of the thumb's opposition to the other fingers of the hand [2]. An experimental assessment of the capacity of grasping for robotic and prosthetic hands controlled by a human operator has been investigated [3], and the control procedure followed has been shown to be similar in a preliminary test with two users.

The human hand behaves like an articulated mechanical system similar to a complex kinematic chain with a tree structure [4]. Its skeleton is formed by a complex assemblage of carp bones, metacarpus and phalanges whose joints vary according to the number of degrees of freedom (DOF) carried out. The long fingers have the same structure while the thumb is more complex [5].

The design of mechanical hands is often inspired by the morphology of the human hand. Developed to interact with the human environment, they are integrated to robots consisting of a mobile base equipped with one or two articulated anthropomorphic manipulator arms whose end is provided with a gripper capable of grasping objects of various sizes and geometries.

In the early 1980s, the grippers had only two fingers designed to hold the various tools needed to perform manufacturing operations. The first robotic hand designed for manipulation is the Salisbury one [6]. Its gripping model provided the basis for future dextral manipulation developments. Different grippers are currently used for different applications (welding, painting, assembly of printed circuit boards, repair-inspection in hostile environment etc.). However and because of the limited access of amputees to prosthetic devices in developing countries, new approaches for the design and 3D printing of non-assembly active hand prostheses using inexpensive 3D printers have been developed [7-8-9-10]. Moreover, an open-source 3D-printable dexterous anthropomorphic robotic hand brought about for deaf and deaf-blind users has been specifically designed to reproduce Sign Languages’ hand [11]. The ‘InMoov’ hand has been improved in order to enhance dexterity by adding abduction/adduction degrees of freedom of the thumb, index and middle fingers along with 3DOF parallel spherical joint wrist.

The articulated mechanical hands currently in use can indeed seize objects safely and apply both arbitrary forces and movements to those handled [12]. The four- or five-fingers mechanical hands facilitate the manipulation of objects because of their ability to reposition certain fingers on the object. Novel approaches for a hand prosthesis consisting of a flexible, anthropomorphic, 3D-printed replacement hand combined with a commercially available motorized orthosis that allows gripping [13] as well as soft robotic hands with monolithic structure have shown great potential to be used as prostheses due to their advantages to yield light weight and compact designs as well as their ease of manufacture [14].

Mechanical design determines the fundamental dexterity of the hand i.e. the kind of manipulation that can be performed when moving objects. The size and placement of the fingers will lead to the choice of the approach. Anthropomorphic hands are based on the direct transfer of grasping strategies from the human hand, and non-anthropomorphic hands will consider the fingers as identical and will therefore be arranged symmetrically.

II. MORPHOLOGY OF THE HUMAN HAND

The skeleton of the human hand is constituted by the complex assembly of the carpal, metacarpal and phalanges bones. The joints located between these bones vary in terms of the number of DOF they hold that should correlate the number of axes of rotation linked to them. Figure 1 illustrates these bones, and the number of DOF linked to each joint is mentioned. For the long fingers (index, major, annular and little finger) that develop the same structure, the MC joint shows only one DOF. The PP and DP joints have two DOFs each. Every joint produces a flexion-extension movement while solely the PP joint generates the adduction-abduction movement [5].

Compared to the long fingers, the thumb has a more complex structure as its MC, PP and DP joints develop three, two and one degrees of freedom respectively. The MC joint produces a flexion-extension movement and allows a rotation of the pastern. The PP thumb joint is similar to its corresponding long finger ones. It produces the flexion-extension and the adduction-abduction movements. The DP joint only produces flexion-extension movements. All these movements are produced at the level of the pattern and phalanges. Some movements produced in the carpus are limited in amplitude. They are not taken into account in the modeling of articulated hands [15-16].

Fig. 1. Human hand skeleton [15].

III. ANTHROPOMORPHIC ROBOTIC HANDS

A. Description of an articulated hand

The hand behaves like an articulated mechanical system [4] i.e. a complex kinematic chain with a tree structure as represented in Figure 2.

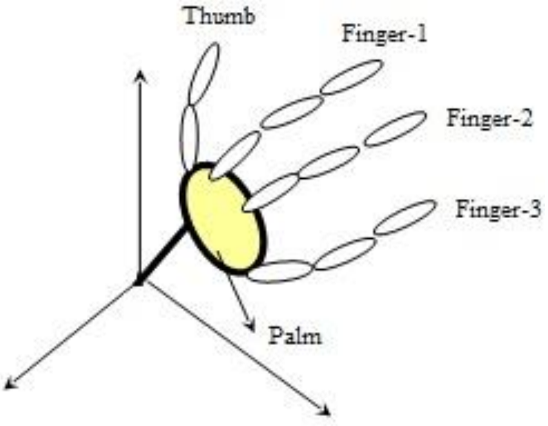
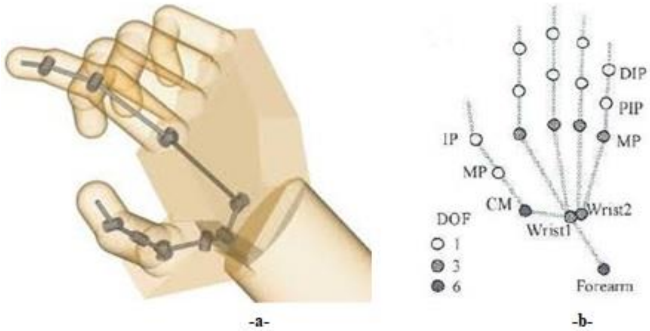


Fig. 2. Aborescent structure of the human hand [4].

On the kinematic diagram of the human hand shown in Figure 3, each articulation is represented by a pivot connection. The long fingers have an articular chain formed of four links including a metacarpal and three phalanges while the thumb comprises only one articulated chain of three links including a metacarpal and two phalanges as shown by [17] and described by [18].



-a- -b-

Fig. 3. Setting up and assembling finger joints. (a) Kinematic model of thumb and index; (b) Kinematic model of the hand [18].

B. Purpose and classification

Anthropomorphic robotic hands are generally classified according to their degree of under-actuation. The 'actuators-joints' report will evaluate the ability of a hand to independently control its joints. When the number of actuators is equal to that of the joints, the hand is said to be fully actuated. This results in abilities that go beyond the simple pre-tension of an object.

The main motivation for all these developments is that a multi-fingered hand or a poly-articulated hand can offer an interesting solution in terms of dexterity, versatility and adaptation to the shape of the object. Such a hand will be able to execute the input of various objects, and will be able to offer great potential in terms of dexterous manipulation [20] and repositioning [21] of the object in the hand.

Through the 'Shadow' hand shown in Figure 4-a, anthropomorphic approaches were adapted to robotic manipulation. With its twenty DOFs, this hand offers unique analogies with the human hand. Developed by Shadow and the UPMC [22], it is equipped with force and position sensors as well as sensitive ultra-touch sensitive sensors located at the fingertips and using industry standard interfaces. The Shadow hand can easily be used as a tele-operation tool. It can also be easily mounted on a range of arms as part of a robotic system and perform various seizures (Figure 4-b-c-d-e).

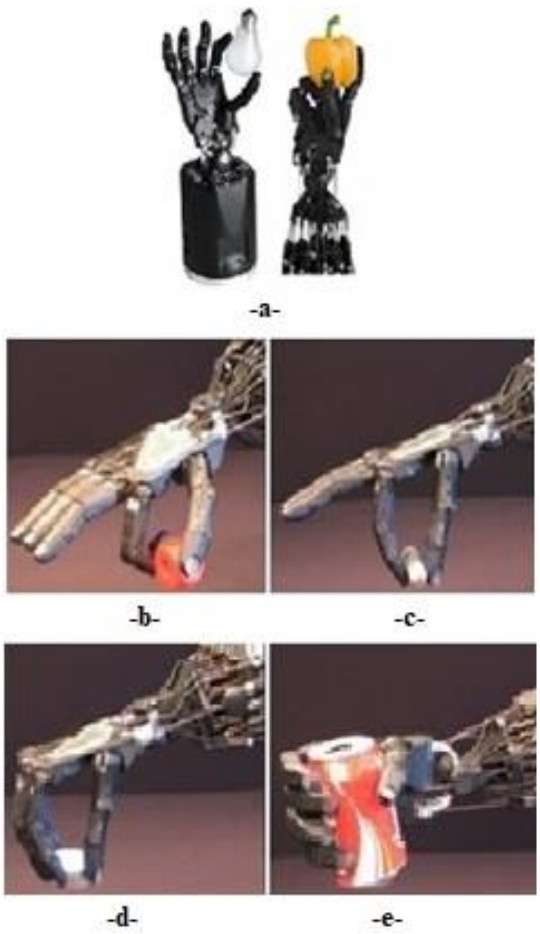


Fig. 4. The shadow hand. (a) Shadow dexterous hand E1 ; (b) 2-finger pinch input ; (c) 2-finger precision input ; (d) Precision input with all fingers ; (e) Power grasp [19].

C. *Robotic hands and dexterous manipulation*

The topic related to dextral manipulation might seem obsolete, especially considering the fact that the manipulation of objects in an industrial environment has existed for many years particularly in the automotive industry. In fact, it is precisely in this sector that the need for research and innovation is most in demand. Two main reasons guide R&D in this sector and are mainly represented by:

1. The fact that the simple problem of the 'recognition-capture-assembly' cycle for industrial components is still not solved outside academic institutions. Indeed, most simple cases are now considered (objects of elementary form, separate objects, known ambient light ... etc.). Nevertheless, many developments such as those related to objects of complex shapes are still necessary.
2. The case of some complex tasks that can only be realized by involving a human operator in the loop.

Many laboratories are still interested in the development of robotic hands along with dextral manipulation in robotics. Nearly a hundred mechanical hands are nowadays available around the world. Some have been developed by industrialists while others have been in academic laboratories.

The UTAH/MIT hand [23] remains a reference in the history of dexter manipulation in robotics because of both its innovative nature at the time of development and its bio-inspired design. This hand was developed at the University of Utah's Center for Engineering Innovation in collaboration with the Computer Science and Artificial Intelligence Laboratory of the Massachusetts Institute of Technology. It has four modular fingers with the thumb opposing the three long ones, and each having four DOF (the little finger was considered not necessary and was thus sacrificed for ease of handling).

Figure 5 shows the UTAH/MIT hand also known as the Jacobsen hand [23]. Its kinematic diagram is illustrated in figure 5-b that shows the separation of the joints of each finger allowing the routing of the tendons. The friction exerted on the tendons was found to leading to a limited lifespan. They have therefore been replaced by flat belts that generate a stress separated by axial torsions (figure 5-c). A complex system of tactile sensors is integrated at the end of the fingers and in the palm [23].

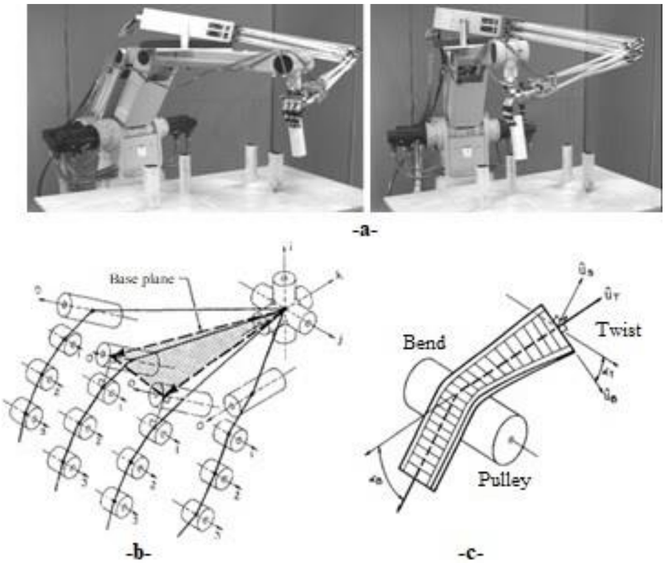


Fig. 5. The UATH / MIT hand. (a) Objects handling ; (b) Kinematics ; (c) Flat belt [24].

IV. DESIGN AND ASSEMBLY OF A FIVE FINGER ARTICULATED HAND

This section looks at the steps necessary to design and 3D print a five-fingered mechanical hand that comprises a palm, four long fingers and a thumb. Its kinematics is similar to that of the human hand represented in figure 6.

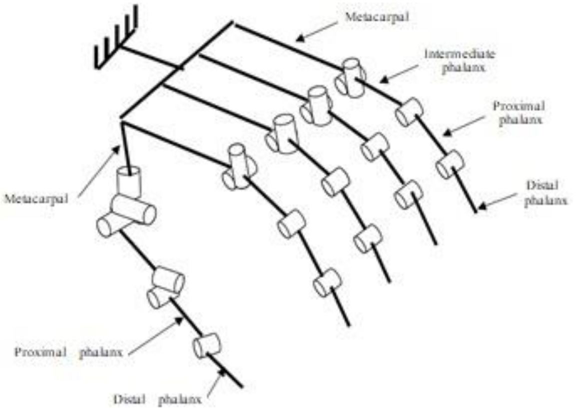


Fig. 6. Kinematic diagram of the human hand.

Each joint is represented by a pivot link. Long fingers have an articular chain made up of four links (a metacarpal and three phalanges). Instead, the thumb comprises only an articular chain of three links represented by a metacarpal and two phalanges [17].

In order to obtain a silhouette close to the five-fingers hand represented, sketches were carried out through the application of the design workshop of 'Catia'.

A. Design of long fingers

Each long finger integrates three phalanges whose sizes are smaller than those of a human hand. The initial implementation of an arbitrary form was carried out with the aim of developing three different designs whose assembly will constitute the phalanges of each finger (Figure 7).

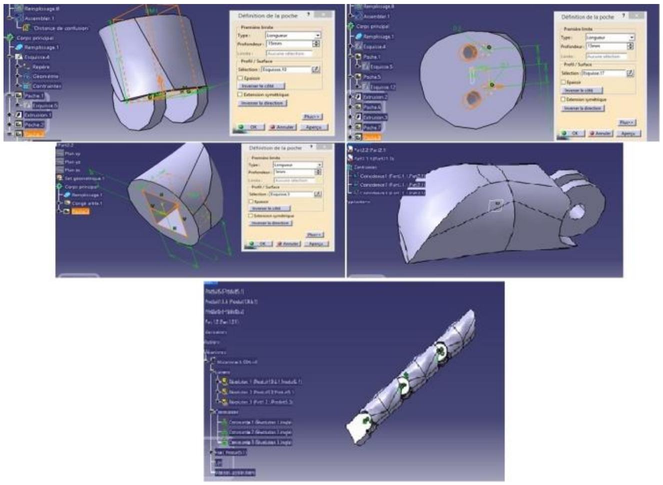


Fig. 7. Design and assembly of the phalanges of a long finger [24].

B. Thumb design

The thumb whose design steps are illustrated in figure 8 is different from that of the long fingers as it is based on the technique of shifting the plane defined during the first phase of its development.

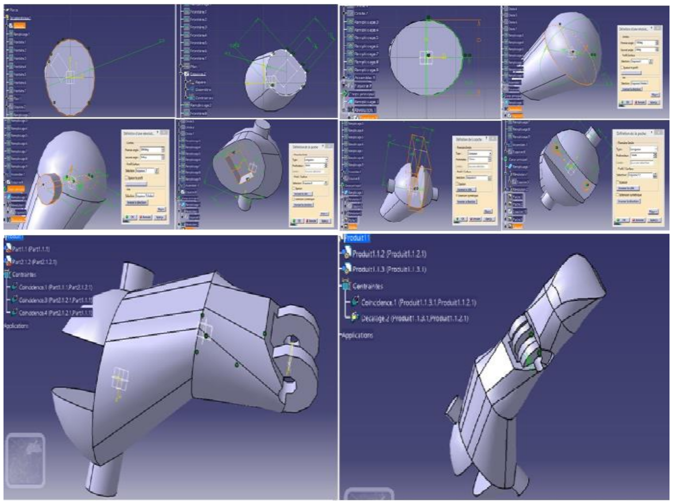


Fig. 8. Design and assembly of the phalanges of the thumb.

C. Palm design

The design of the palm is carried out in three steps. The first step is concerned with the design of the inner part of the palm while the second deals with the design of the dorsal one. The grooves and pockets represent the last step in the design. Figure 9 outlines the different phases of the design, and shows the end result.

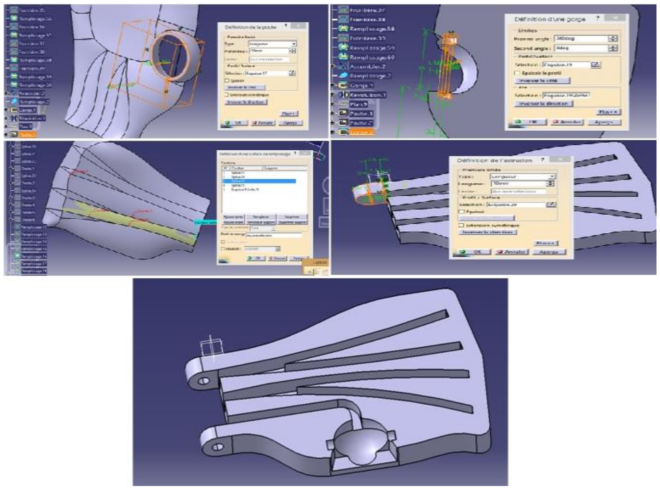


Fig. 9. Hand palm design.

D. Assembly of the hand

The digital mockup/DMU platform simulates the kinematics of an assembly with one or more DOFs. It has been applied to simulate the assembly of the hand designed earlier. It defines the mechanical connections through a generation of a mechanism before illustrating the diverse commands to finally simulate them.

For the same product, several mechanisms can be created and arranged to control the one or more DOFs of the system according to the analysis to be carried out.

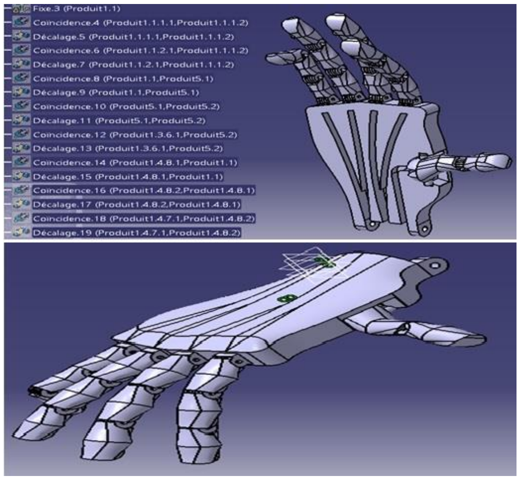


Fig. 10. Hand assembly via digital model / DMU kinematics.

The assembly of the hand has been carried out so that the palm grooves coincide with the finger joints. The fingers' phalanges were assembled with the palm using a pivot connection and brought together by the applications of the necessary stresses. The inner and outer parts of the palm were the last pieces to be assembled. These steps in the design of the articulated mechanical hand have been carried out on the Catia-V5 software. They are illustrated in figure 10.

V. HUMAN GRASPING UNDER 'CATIA'

The human hand possesses five fingers with only the thumb having the ability to oppose the long fingers. It integrates the index used for pointing, the middle finger which is the longest, the ring finger and the little finger. Because of its many bones and joints, the hand is able to develop extreme versatility in terms of mobility and agility.

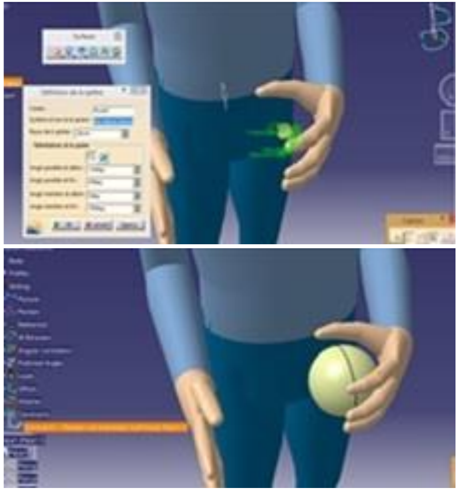


Fig. 11. Selection of the hand with spherical posture via 'Catia's 'Human-Builder' module.

Among the essential functions of grasping are those called

The simulation of the movement functionality of the hand mechanism with the posture selection shown in Figure 11 has been performed using the 'Human Builder' module under the environment 'Catia'.

Among the essential functions of grasping are those called palmar, digito-palmar, termino-terminal, pulp or subtermino-lateral. Two of these functions, relating to the palmar and digit palmar grasping functions, have been simulated and are shown in figure 12.

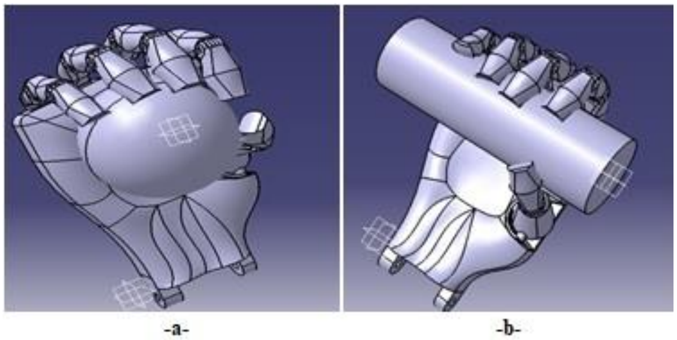


Fig. 12. Grasp. a-Palmar grasp and b- Digito-palmar grasp.

A. *Palmary and digito-palmar grasps*

Used for grasping voluminous objects, palmar grasping requires significant forces. Indeed, wide objects usually introduce difficulties to develop extensive forces. Palmar grasping is shown in Figure 12-a.

The digit-palmar grip is more refined, and requires a frank opposition of the long fingers to the palm of the hand. The thumb is used to lock the grasp as illustrated in figure 12-b.

B. *Control of the articulated hand*

A more complex task than the previously described functions is represented by the dextral manipulation that requires the pick-and-place of an object. It is illustrated in figure 13 and consists of three essential steps, the first being the 'approach' carried out by the movements of the shoulders, elbow and wrist. It allows the hand to be positioned in the ideal position authorizing the control of both the speed and the distance leading a final adjustment. It is illustrated in figures 13-a and 13-b.

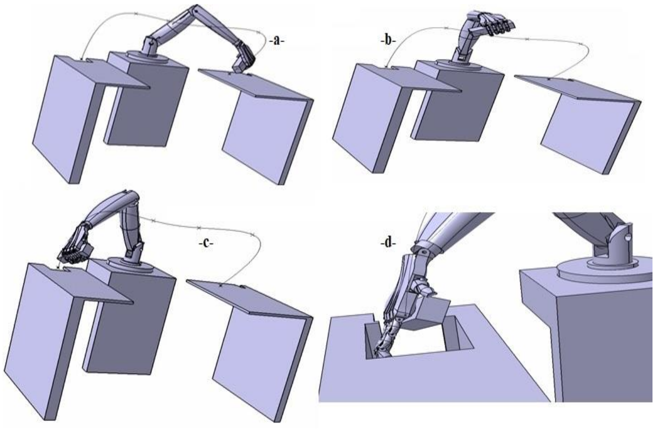


Fig. 13. Simulation of the robotic task pick-up of an object.

The second step is represented by the 'choice of the type of catch' and is generally carried out at the same time as the 'approach'. The position of the fingers adapts to the shape of the object, and the clamping force is regulated by the sensors (c.f. figure 13-c).

Finally, the object has to be delivered at the chosen position. It is the 'release' step displayed in figure 13.d. It allows freeing the hand in order to deposit the object, throw it, move it away or bring it closer.

VI. 3D PRINTING AND ASSEMBLY OF HAND

A. *Model Preparation-3D Printer 'FabLab'*

The printing is carried out on a FABLAB-2 type FDM (Fused Deposition Modeling) Printer. The printer accepts 'STL' 3D files prepared by its open ware software 'Cura', and reads from its SD card reader. The FABLAB-2 3D printer shown in Figure 15 is produced by the company of the same name, and uses the FDM modeling technique by deposition of molten material.

B. *Preparation, 3D printing and hand assembly*

The model is saved into 'STL' format and exported to 'Cura'. The desired pattern 3D printing is performed using the filament wheel that is controlled by the printing board.

Fig. 15 3D printer of 'FABLAB' and its printing board.

The filament layer thickness measures the height of each addition of material as additive manufacturing or 3D printing processes are based on the stacking of layers. This is one of the essential technical characteristics of every 3D printer. The layer thickness is equivalent to the resolution along the z- axis which is the vertical manufacturing axis.

Fig. 16. Printed parts and various gripping functions [16].

Once imported into 'Cura', the 3D model is automatically created and printed. Figure 16 displays the different parts printed along with the hand and its main gripping functions.

VII. CONCLUSIONS

Articulated mechanical hands are becoming more and more analogous to human hands and as a result are capable of performing operations they were unable to accomplish before. They therefore offer interesting solutions, and provide mobile manipulators with a versatile dexterity comparable to that achieved by a hand with several fingers. They are capable of performing a variety of seizures allowing the reduction of the terminals. Four- and five-fingers mechanical hands facilitate the manipulation of objects through their wide possibilities of repositioning fingers on them.

The present research investigates the design of a non-anthropomorphic articulated mechanical hand dedicated to dextral manipulation. It is therefore essential to obtain a silhouette close to the human hand with four long fingers and one smaller opposed to them. Each long finger consists of three phalanges whose size is smaller than that of the human hand while the thumb had only two phalanges and therefore a different kinematics.

The application of the 'DMU/Kinematics' module of the 'CATIA' design software allowed the control of the hand design enabling it to adhere to the kinematics specifications dictated by both the mechanical hand and the manipulator arm.

The simulation of the grasping was performed using the 'Human Builder' module of 'CATIA' specifically developed for the purpose of modeling human grasping. Illustrations under this software enabled the visualization of the mechanical hand designed performing robotic gripping operations similar to that of humans such as palmar and finger-palmar. Moreover, the virtual workshop developed that simulates the mechanical hand mounted on a manipulator arm gripping an object and exercising a robotic 'pick-and-place' task in this virtual environment may be considered as one of the main contributions of this work.

On the basis of the results obtained that enable complex protocols close to that of a human hand, 3D printing of the hand has been carried out satisfactorily. It allows wide range of applications that should be performed.

REFERENCES

[1] C. Reboulet, “Modélisation des robots parallèles. Techniques de la Robotique”, *Architecture et Commande*, pp 257–284, 1988.

[2] C.M. Seguna and M.A. Saliba, “The mechanical and control system design of a dexterous robotic gripper”, 8th IEEE International Conference on Electronics, Circuits and Systems, 3, pp 1195-1201, 2001.

[3] I.L. Harillo and A.P. González, “System for the experimental evaluation of anthropomorphic hands. Application to a new 3D-printed prosthetic hand prototype”, International Biomechanics, 4:2, pp. 50-59, DOI:10.1080/23335432.2017.1364666, 2017.

[4] D. Osswald and H. Wörn, “Mechanical system and control system of a dexterous robot hand”, Proceedings of the IEEE-RAS International Conference on Humanoid Robots, 8, 2001.

[5] E. Brown and A. Vardy, “Articulated human hand model with inter-joint dependency constraints”, *Computer Science*, 6752, pp 8–9, 1998.

[6] K. Salisbury and B. Roth, “Kinematic and force analysis of articulated mechanical hands”, *Journal of Mechanical Design*, 105, pp 35–41, 1983.

[7] K.F. Gretsch, H.D. Lather, K.V. Peddada, C.D. Deeken, L.B. Wall and C.A. Goldfarb, “Development of novel 3D-printed robotic prosthetic for transradial amputees”, *Prosthet Orthot International*, 40(3), pp.400-403, DOI:10.1177/0309364615579317, 2016.

[8] J.S. Cuellar, G. Smit, P. Breedveld, A.A. Zadpoor and D. Plettenburg, “Functional evaluation of a non-assembly 3D-printed hand prosthesis”, *J. of Engineering in Medicine*, Vol. 233(11), pp. 1122-1131, DOI:10.1177/0954411919874523, 2019.

[9] B. Phillips, G. Zingalis, S. Ritter and K. Mehta, “A review of current upper-limb prostheses for resource constrained settings”, Proc. of the 5th IEEE global humanitarian technology conference-GHTC, Seattle, pp.52–58, 8–11 Oct. 2015.

[10] V. Francis, S. K. Singh, R.G. Bhonde, YH. Tichkule, V.S. Gupta and S.P. Farande, “Adaptation of 3D Printing Technology for Fabrication of Economical Upper Limb Prostheses”, In: Phanden R.K., Mathiyazhagan K., Kumar R., Paulo Davim J. (eds) Advances in Industrial and Production Engineering. Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-33-4320-7_77, 2021.

[11] A. Bulgarelli, G. Toscana, L.O. Russo, G.A. Farulla, M. Indaco and B. Bona, “A Low-Cost Open Source 3D-Printable Dexterous Anthropomorphic Robotic Hand with a Parallel Spherical Joint Wrist for Sign Languages Reproduction”, *Int. J. of Advanced Robotic Systems*, vol. 13, issue 3, pp. 1-12, DOI: 10.5772/64113, 2016.

[12] R.M. Murray, Z. Li and S. Shankar, “*A mathematical introduction to robotic manipulation*”, CRC Press Book, 1984.

[13] J. Baron, S. Hazubski and A. Otte, “3D Multi-Material Printing of an Anthropomorphic, Personalized Replacement Hand for Use in Neuroprosthetics Using 3D Scanning and Computer-Aided Design: First Proof-of-Technical-Concept Study”, *Prosthesis*, 2(4), pp. 362-370; DOI:10.3390/prosthesis2040034, 2020.

[14] A. Mohammadi, J. Lavranos, H. Zhou, R. Mutlu, G. Alici, Y. Tan, P. Choong and D. Oetomo, “A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities”, PLOS ONE 15(5), DOI:10.1371/journal.pone.0232766, 2020.

[15] S. Cobos, M. Ferre, and S. Uran, “Efficient human hand kinematics for manipulation tasks,” in IEEE International Conference on Intelligent Robots and Systems, pp. 22-26,2008.

[16] I.M. Bullock, J. Borras and A.M. Dollar, “Assessing assumption in kinematic hand models: a review”, IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), June 24-27; Rome, Italy. pp. 139–146, 2012.

[17] J.N. Gaborieau, “Calcul des efforts dans une prise par empaumement pour des conditions anthropomorphes-Domaine de charge optimale en vue de la planification de mouvements de rotation de la main”, PhD dissertation, Medical Sciences, Poitiers Univ, 1996.

[18] A. Bouachari, H. Tebbikh and A. Zaatri, “Etude Cinématique de la Préhension d’une Main Mécanique”, 4ème Congrès International de Conception et Modélisation des Systèmes Mécaniques, Hammamet, Tunisia, 2011.

[19] F. Rothling, R. Haschke, J.J. Steil and H. Ritter, “Platform portable anthropomorphic grasping with the bielefeld 20-dof shadow and 9-dof tum hand”, IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 2951–2956, 2007.

[20] R. Quintero “Conception et attribution à la manipulation dextre dynamique pour les aspects conceptuels et de commande en ligne optimale”, PhD dissertation, Poitiers Univ., 2013.

[21] A. Bouachari and A. Haddad, “Conception et Performances de Mains Mécaniques Articulées: Revue de l’Etat de l’Art”, Journées d’Etudes Techniques-Association Franco-Maghrébine de Mécanique et des Matériaux-AF3M, Marrakech, Morocco, pp 51-57, 2018.

[22] G.A. Bekey,R. Tomovic and I. Zeljkovic “Control architecture for the Belgrade/USC hand, Dexterous Robot Hands”, Springer-Verlag, New York, pp. 136-149, 1990.

[23] S.C. Jacobsen, E.K. Iversen, D. Knutti, R. Johnson and K. Biggers, “Design of the Utah/M.I.T. dexterous hand”, IEEE International Conference on Robotics and Automation, 3, pp 1520-1532, 1986.

[24] W. Leuchi, “Optimisation conceptuelle d’une main mécanique articulée non anthropomorphe”, Master2 dissertation, Mechanical Engg Dept, 20 Août 1955-Skikda Univ., Algeria, 2018.