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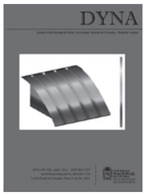

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The manufacture of a maxillofacial prosthesis from an axial tomography using simulation technologies with a virtual machine tool and four-axis machining

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Abstract
The surfaces of a personalized maxillofacial prosthesis were manufactured in a relatively short period of time and at a moderate cost. The surface topography was generated with a Computer-Aided Design system from the Computerized Axial Tomography of a maxillofacial area. The design of the machining manufacturing process, its simulation and verification, were facilitated by the use of a virtual machine tool equivalent to the real machine tool available. Finally, the manufacturing process was successfully achieved by using a conventional 3-axis vertical machining center equipped with a fourth external rotational axis. Using a 3-axis machine tool with an additional axis is less expensive than using a 5-axis machine. There is abundant literature on machining of free-form surfaces using a 5-axis machine tool, but there are few precedents for the manufacturing of this kind of surface using a 4-axis machine.

Keywords: process planning; simulation and verification of processes; multi-axis machining; free-form surface machining; prosthesis manufacturing.

Manufactura de una prótesis maxilofacial, a partir de una tomografía axial, usando tecnologías de simulación en una máquina herramienta virtual y maquinado de cuatro ejes

Resumen
Se fabricaron las superficies de una prótesis maxilofacial personalizada en un lapso de tiempo relativamente corto y con un costo moderado. La topografía de la superficie de la prótesis se recreó en un sistema CAD a partir de una tomografía axial computarizada. El diseño, la simulación y la verificación del proceso de fabricación por maquinado se facilitó gracias al uso de una máquina herramienta virtual equivalente a la máquina real disponible. El proceso de fabricación se ejecutó exitosamente en un centro de maquinado de tres ejes dotado de un cuarto eje de rotación externo. Una máquina herramienta de tres ejes con un eje adicional es menos costosa de operar que una máquina de cinco ejes. Es abundante la literatura sobre maquinado de superficies de forma libre usando máquinas herramienta de cinco ejes, pero hay pocos antecedentes sobre la fabricación de una superficie de este tipo utilizando cuatro ejes de movimiento.

Palabras clave: planificación de procesos; simulación y verificación de procesos; maquinado multiejes; maquinado de superficies complejas; manufactura de prótesis.

1. Introduction

A prosthesis is an artificial implant which replaces or substitutes a part of the human body while maintaining its functionality and aesthetic appearance [1,2]. Commands to generate surfaces, which are available in CAD systems, are insufficient to generate the complex geometry of an anatomically-shaped implant with precision. Nevertheless, it is possible to obtain complete geometric information on facial morphology with developments achieved in the automatic

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processing of three-dimensional (3D) data [3]. A custom-made implant that fits the patient´s anatomy exactly can be designed with precision because of the notable evolution of production technologies [4,5]. However, the efficacy of computer-aided technologies in the design and manufacturing of maxillofacial prostheses has not been completely tested [6].

Reverse engineering is a process that makes it possible to obtain a 3D virtual CAD model from an actual physical object [7]. Recent advances in reverse-engineering technologies are relevant in the manufacturing process of personalized prostheses. These advances make it possible to obtain a CAD model of the prosthesis by using the results of standard diagnostic tools like computerized tomography or magnetic resonance [4,8]. The surfaces of a maxillofacial prosthesis can be classified as free-form surfaces, and they are frequently fabricated by precision-casting of titanium alloys [4]. An alternative, in order to simplify the manufacturing process and reduce manufacturing time is to fabricate them by machining [1].

The definition of a free-form surface is more intuitive than formal. It can be defined as a surface that contains one or more regions with curvatures different from zero, that are non-quadratic and can be represented parametrically or discretized. Free-form surfaces are widely used in the automotive, aerospace and medical industries, and multi-axis machining is mainly used to produce them [9]. Nevertheless, milling by using a 5-axis machine requires considerable investment in equipment, specialized software to generate the cutting-path trajectories and a highly skilled programmer [10]. An alternative way to produce components with free-form surfaces is by using traditional 3-axis machine tools (low speed and low cost) equipped with a fourth external rotational axis [11].

In addition, modelling and simulation of manufacturing systems and their technological operations have been developed to emulate the physics of the process, thus reducing the cost of production tests [12]. Many contemporary systems for computer-aided machining (CAM) include software to implement virtual models of machine tools with a high degree of realism. It is possible to simulate the machining process accurately with a virtual machine tool because this makes it possible to verify the kinematics of cutting-tool trajectory as well as to check for collisions, servomechanism dynamics, and tool-changing and work-material clamp devices [13-15]. These simulation characteristics are especially useful in the planning of manufacturing processes involving machine tools with more than three axes.

This study shows the process carried out in order to obtain the geometry of a maxillofacial prosthesis and its manufacturing in which a 4-axis milling machine was used instead of precision casting. The topography of the surface was generated with a CAD-CAM system from a computerized axial tomography. The design, simulation and verification of the manufacturing process was made in a virtual machine tool equivalent to the real three-axis machining center with an external rotational fourth-axis. The manufacturing process was achieved as planned and the surfaces of the prosthesis were obtained successfully. The operation of the machine tool used is less expensive than that of a 5-axis machine tool. Interestingly, no precedent was found in the literature regarding the manufacturing of free-form surfaces using a 4-axis machine tool.

2. Materials and Methods

2.1. CAD model of the surface

A file in STL (Standard Tessellation Language) format was obtained from the computerized axial tomography of a human maxillofacial area. This STL file approximates the surface to a set of discrete plane triangles, but this format does not represent a solid model with information about volume, center of mass and moments of inertia [16]. In order to obtain the solid model of the prosthesis, the CAD module of the NX-Siemens-PLM software was used, which has the capacity to generate continuous surfaces using the B-REP (Boundary Representation) method. Based on control points that were obtained from the STL file and using the B-REP tool, it was possible to generate a set of patches of interconnected surfaces and, finally, a compound surface which enclosed the STL model.

In order to guarantee surface smoothness and homogeneity, the first condition that must be met is contact or coincidence in position (G0) on the borders of the surface patches. To ensure geometric continuity or smoothness, the direction of the tangents (G1) [17] must also coincide. Fig. 1 illustrates the analysis of position and tangency (geometric continuity) on one of the borders between some of the surface patches. The condition of tangency can be assessed by reflection analysis; continuity exists if there is a smooth transition between two adjacent patches of geometric patterns. A complete 3D-model was generated after verifying the conditions of position and tangency on the borders of the set of surface patches in which the geometry of the STL file was enclosed.

2.2. Surface manufacturability analysis

Fig. 2 shows how the workpiece orientation was defined relative to the CAD reference system. The center of mass and the axes of the main moments of inertia of the workpiece were aligned with the axes of the Work Coordinate System (WCS). For a surface generated by a machining operation, the specifications of geometrical and dimensional tolerances, as well as the absence of interferences between the cutting tool and the surface [9] must be ensured.

During the machining of a free-form surface, global or local interferences can appear as shown in Fig. 3a, 3b. A draft analysis of the concave surface was undertaken, placed in the previously defined orientation and taking into account a vertical machining center with three degrees of freedom. Several zones of interference were found and identified with dark gray as shown in Fig. 3c. The conditions of interference detected demonstrated the need to use a machine tool with more than three degrees of freedom.

A curvature analysis was carried out on the model surfaces to determine the maximum admissible radius for the cutting tools. Fig. 4 illustrates that the smallest radius begins at 2.0 mm. Based on this information, the ball-nose cutting tools to be used in the roughing process (diameter 8.0 mm), in the semi-finishing process (diameter 6.0 mm), and in the finishing process (diameter 4.0 mm) were chosen.

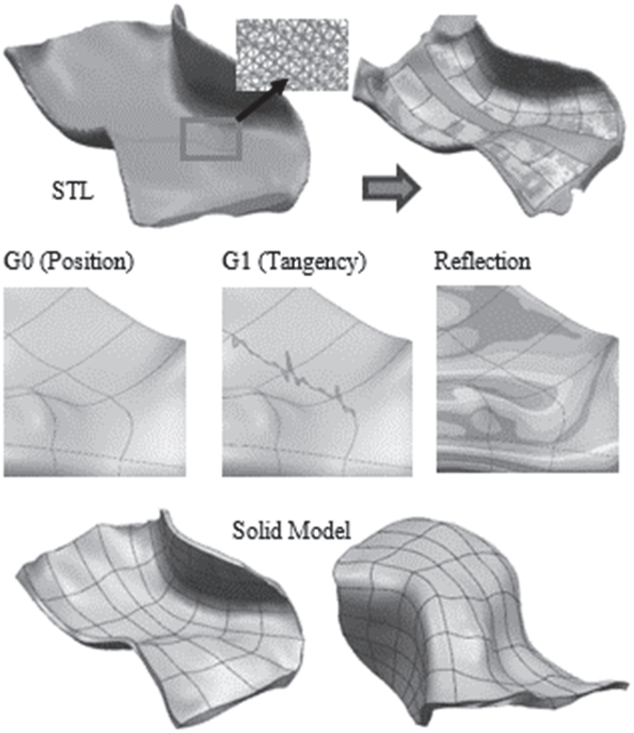

Figure 1. Prosthesis CAD model generation from STL file using the B-REP method.
Source: The authors.

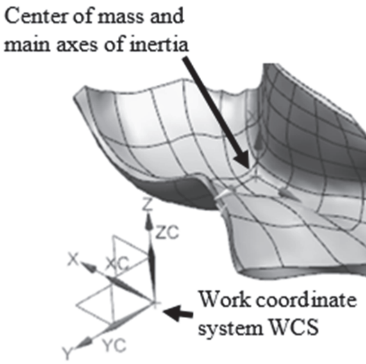

Figure 2. Workpiece orientation relative to the work coordinate system
Source: The authors.

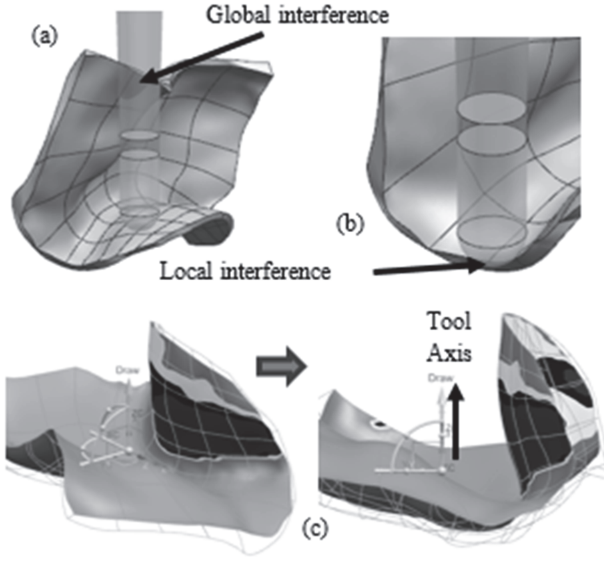

Figure 3. Global (a) and local (b) interferences; draft analysis of the prosthesis (c).
Source: The authors.

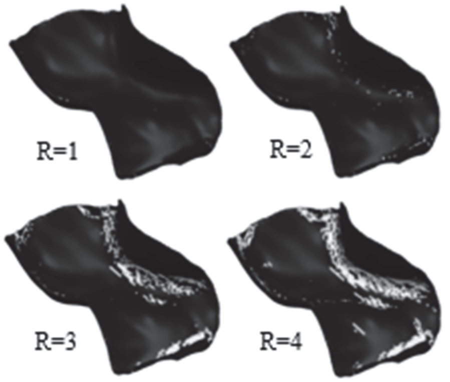

Figure 4. Curvature analysis for minimal tool radius [mm].
Source: The authors.

2.3. Work material, machine tool and process parameters

The work material selected was a bar of 12L14 steel. Functional materials such as titanium alloys, cobalt-chromium-molybdenum alloys or stainless steel were not used due to the fact that the main objective of this study was to verify whether it was possible to make the prosthesis with the available technology.

The machine tool used was a Leadwell V-20 vertical machining center with three axes, with a maximum rotational frequency of the spindle of 8000 min^{-1}, and power of 5.5 kW. The machining center was equipped with a fourth rotational axis (Golden Sun CNC-151R) with maximum rotational frequency of 22 min^{-1}, maximum torque of 225 Nm and angular precision of 0.001º. The Fanuc 0MD machine-tool controller controls all four axes simultaneously, so the prototype was manufactured with a machine tool with four degrees of freedom (CMV-4DOF).

2.4. Verification and simulation of the manufacturing process

The Integrated Simulation and Verification (ISV) module of NX-Siemens-PLM software was used to make a virtual model of the vertical machining center and its accessories as shown in Fig. 5. The assembly made it possible to simulate the manufacturing process with a high degree of realism and to verify the correct generation of the programmed toolpaths, as well as to detect any conflicts in numerical control programming and collisions between setup accessories [18].

It is possible to define pairs of technological components with the ISV module, the main purpose of which is to detect possible interferences between them in the simulation process.

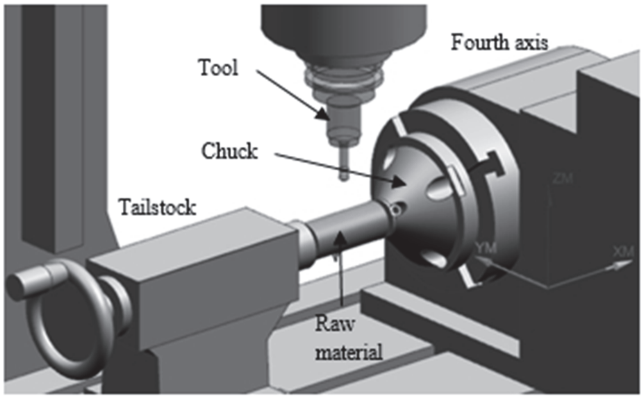

Figure 5. Virtual machine tool setup
Source: The authors.

It is essential to make sure there are no collisions between components such as the chuck, the tailstock, the tool holder, the work material, the spindle and the fourth external axis. The pairs are indispensable not only for detecting any possible collisions between technological agents but also for evaluating any possible in-process collisions between the workpiece and the cutting-tool body. This is in fact the most critical situation to be detected in a multi-axis machining process.

Following the preliminary planning process, the setup of work material, cutting tools and clamping devices was mounted in the virtual machining center. The cylindrical work material was aligned with the 'x' axis of the machining center and fixed between the chuck and the tailstock (Fig. 5).

A first roughing process with an end milling cutter was done taking account of the material removal shape element volume criteria (MRSEV) [19] that resulted in volumes V1, V2 and V3 shown in Fig. 6a. After that, a second roughing process was performed using a cavity-mill strategy, which took into account a constant depth cut in z-axis (Fig. 6b). For semi-finishing and finishing of the convex surface, ball-nose milling cutters and variable contour cutting strategies were used based on the normal vector to the surface. These strategies were made possible by using the fourth external rotational axis; i.e. four simultaneous axes were employed. Fixed-contour cutting strategies with three axes were applied for the concave surface; the work-piece was oriented in such a way as to permit the access of the cutter (strategy 3+1 axis), with position angles of 0º, -10º and 25º (Fig. 6c).

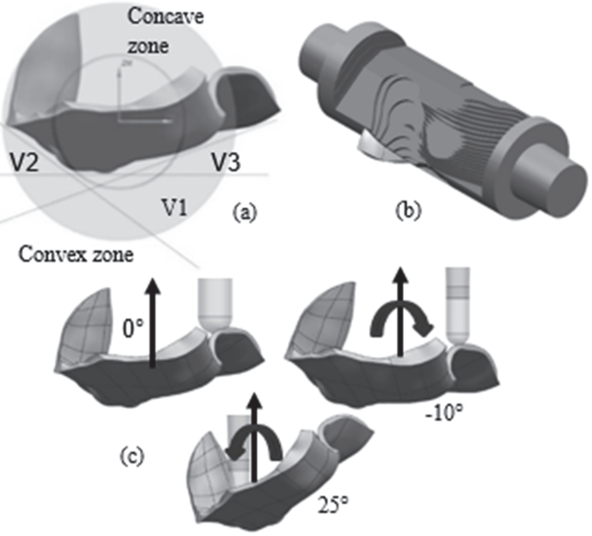

Figure 6. (a) and (b), roughing process. (c) 3+1 strategy for machining of concave surface.
Source: The authors.

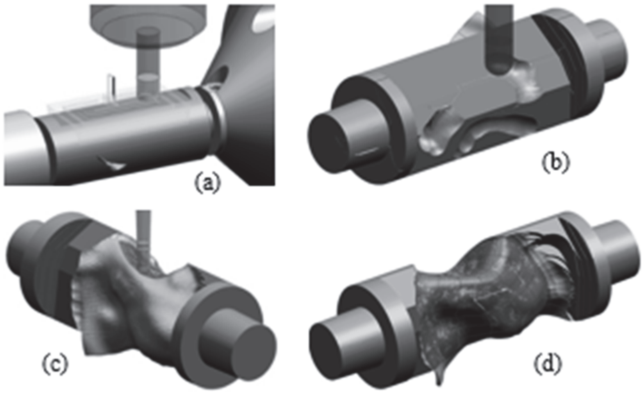

Figure 7. (a) Roughing trajectories verification, (b) Collision detection, (c) Surface finish verification, (d) final convex surface.
Source: The authors.

3. Results

The simulation of cutting-tool path trajectories and material removal were completed according to the process plan. The absence of interferences between the cutting tool with the devices and with the work and machined surfaces (Fig. 7a) was also verified. An example of virtual collision between the in-process workpiece and the cutting tool is illustrated in Fig. 7b. Fig. 7c, 7d show the simulation of the finishing process and the final convex surface obtained. Fig. 8 summarizes the methodology applied in designing and planning the process.

The manufacturing process was executed in the actual machine tool after having been designed, simulated and verified in the virtual machine tool, including verification of the trajectories of each cutting tool and verification of the absence of collisions between the setup components.

The manufacturing program was carried out without any problems, in accordance with the strategies and results established in the designing process. Fig. 9 shows the concave and convex surfaces obtained and verified in the virtual machine tool, and the same surfaces obtained in the actual setup. The manufacturing time estimated in the virtual process was 18 hours and 52 minutes; the real time spent was 15% higher. The main reasons for this difference were a feed adjustment during the machining process and programmed stops after each tool-change to verify the correct performance of the process.

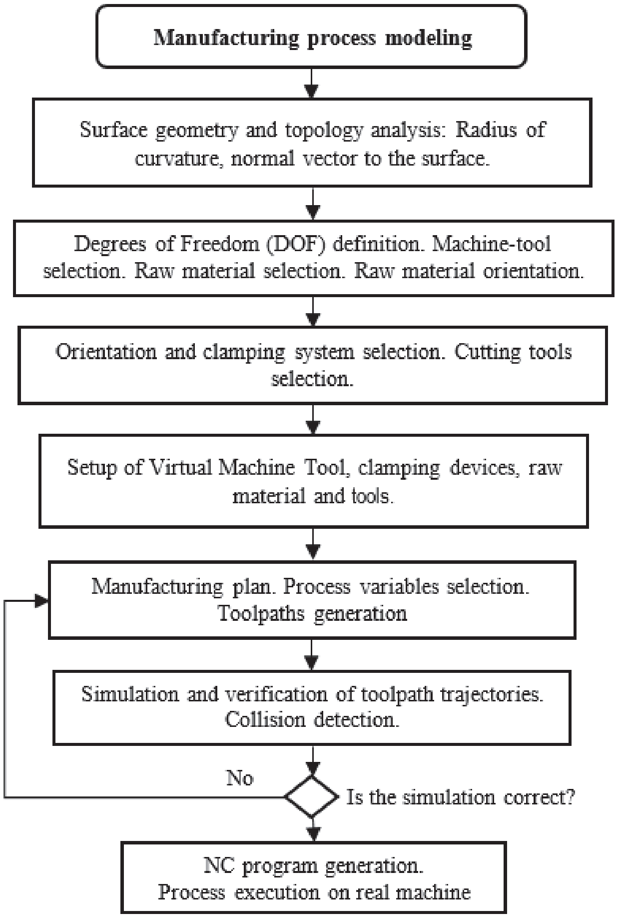

Figure 8. Manufacturing process workflow.
Source: The authors.

4. Discussion

Multi-axis machining of free-form surfaces is a complex task which requires the latest tools developed for product modelling, process planning and machine-tool emulation.

Given that the efficacy of computer-aided technologies in the design and manufacturing of maxillofacial prostheses has not been completely tested [6]; we explored the integration of several technologies to achieve the engineering design and the manufacturing of the complex geometry, typical of prosthesis parts, as have other authors [8,17].

Most previous research in multi-axis machining have been concerned with tool path computation for 5-axis CNC machines, and very little research has been done for 4-axis [9,11]. Several works on prosthesis machining have been written on the use of 5-axis machining [1,8,17], but no research was found regarding the manufacturing of prosthesis surfaces using a 4-axis machine tool as we did in this work. As the operation of a 4-axis machine tool is less expensive than that of a 5-axis machine tool; the cost of the prosthesis could also be reduced.

5. Conclusions

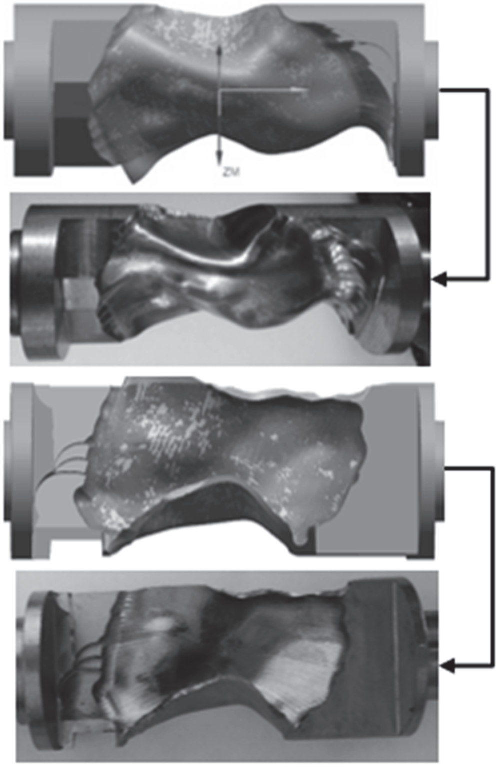

Figure 9. Virtual and actual convex surfaces (Top). Virtual and actual concave surfaces (Bottom).
Source: The authors.

The geometry of the free-form surfaces of a customized maxillofacial prosthesis and its subsequent manufacturing process were achieved in a relatively short time with moderate costs through the integration of an axial tomography using simulation technologies in a virtual machine tool and four-axis machining.

The topography of the surfaces was obtained with the NX-Siemens CAD software system from a STL file obtained with a computerized axial tomography. The tools for verifying surface quality, especially in terms of continuity and tangency, were essential in this process.

A virtual machine-tool equivalent to the actual machining center equipped with a fourth external axis made the design, simulation and verification of the machining process easier. Said virtual machine made it possible to undertake a realistic simulation and to detect some setup mistakes. A digital simulated process contributes to reducing the wasted time in manufacturing and to calculating the process time.

The manufacturing process was carried out in a 3-axis machining center equipped with a fourth external axis. The operational cost of this machine is less than that of a 5-axis machine. According to the results of this work, 4-axis machining technology is a viable way to produce free-form surfaces like those found in maxillofacial prostheses.

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References

[1] Ferreira, P., Relvas, C. and Simões, F., Analysis of machining operations of a femoral prosthesis using CAM applications. Key Engineering Materials, (554-557), pp. 2029-2037, 2013. DOI: 10.4028/www.scientific.net/KEM.554-557.2029.

[2] Plazas, C.E. and Perilla, J.E., The past, present and near future of materials for use in biodegradable orthopaedic implants. Ingeniería e Invetigación [Online], 31(2), pp. 124-133, 2011. [date of reference November 29th of 2015]. Available at: http://www.revistas.unal.edu.co/index.php/ingeinv/article/view/23471/24323

[3] Tsuji, M., Noguchi, N., Ihara, K., Yamashita, Y., Shikimori, M. and Goto, M., Fabrication of a maxillofacial prosthesis using a computer-aided design and manufacturing system. Journal of Prosthodontics, 13(3), pp. 179-183, 2004. DOI: 10.1111/j.1532-849X.2004.04029.x.

[4] Singare, S., Liu, Y., Li, D., Lu, B., Wang, J. and He, S., Individually prefabricated prosthesis for maxilla reconstruction. Journal of Prosthontics, XX, pp. 1-6, 2007. DOI: 10.1111/j.1532-849X.2007.00266.x.

[5] Sánchez, J., Hernandez R.J. and Torres, J.E., The mechanical design of a transfemoral prosthesis using computational tools and design methodology. Ingeniería e Investigación [Online], 32(3), pp. 14-18, 2012. [date of reference November 29th of 2015]. Available at: http://www.revistas.unal.edu.co/index.php/ingeinv/article/view/35934/37227

[6] Eggbeer, D., Bibb, R., Evans, P. and Ji, L., Evaluation of direct and indirect additive manufacture of maxillofacial prostheses. Proceedings of the Institution of Mechanical Engineers, Part H : Journal of Engineering in Medicine, 226(9), pp. 718-728, 2012. DOI: 10.1177/0954411912451826.

[7] Kiatpanichgij, S., Afzulpurkar, N. and Kim, T., Three-Dimensional model reconstruction from industrial computed tomography-scanned data for reverse engineering. Virtual and Physical Prototyping, 9(2), pp. 97-114, 2014. DOI: 10.1080/17452759.2014.883475.

[8] Chang, C.C., Lee, M.Y. and Wang, S.H., Digital denture manufacturing - An integrated technologies of abrasive computer tomography, CNC machining and rapid prototyping. International Journal of Advanced Manufacturing Technology, (31), pp. 41-49, 2006. DOI: 10.1007/s00170-005-0181-z.

[9] Lasemi, A., Xue, D. and Gu, P., Recent development in CNC machining of freeform surfaces : A state-of-the-art review. Computer-Aided Design, 42(7), pp. 641-654, 2010. DOI: 10.1016/j.cad.2010.04.002.

[10] Suh, S.H., Lee, J.J. and Kim, S.K., Multiaxis machining with additional-axis NC System: Theory and development. International Journal of Advanced Manufacturing Technology, [Online]. (14), pp. 865-875, 1998. [date of reference November 29th of 2015] Available at: http://link.springer.com/article/10.1007%2FBF01179075

[11] Shan, C., Chen, X., Duan, W., Wang, W. and Liu, W., Four-axis tool orientation smoothing for spiral machining of blades based on step length. Proccedings of international conference on innovative and manufacturing, 2014, pp. 245-250.

[12] Altintas, Y., Kersting, P., Biermann, D., Budak, E., Denkena, B. and Lazoglu, I., Virtual process systems for part machining operations. CIRP Annals - Manufacturing Technology, 63(2), pp. 585-605, 2014. DOI: 10.1016/j.cirp.2014.05.007.

[13] Kadir, A.A., Xu, X. and Hämmerle, E., Virtual machine tools and virtual machining—A technological review. Robotics and Computer-Integrated Manufacturing, 27(3), pp. 494-508, 2011. DOI: 10.1016/j.rcim.2010.10.003.

[14] Altintas, Y., Brecher, C., Weck, M. and Witt, S., Virtual machine tool. CIRP Annals - Manufacturing Technology, [Online]. 54(2), pp. 115-138, 2005. [date of reference November 29th of 2015] Available at: http://www.sciencedirect.com.ezproxy.unal.edu.co/science/article/pii/S0007850607600225

[15] Abdul-Kadir, A. and Xu, X., Towards high-fidelity machining simulation. Journal of Manufacturing Systems, 30(3), pp. 175-186, 2011. DOI: 10.1016/j.jmsy.2011.04.004.

[16] Bianconi, F., Bridging the gap between CAD and CAE using STL files. International Journal of CAD/CAM, [Online]. 2(1), pp. 55-67, 2002. [date of reference November 29th of 2015] Available at: http://www.ijcc.org/on-line(pdf)/2(1)55-67.pdf

[17] Chaves-Jacob, J., Linares J.M. and Sprauel, J.M., Increasing of surface quality in friction free-form surfaces of knee prosthesis. CIRP Annals - Manufacturing Technology, 60 pp. 531-534, 2011. DOI: 10.1016/j.cirp.2011.03.059.

[18] García-Barbosa, J.A., Arroyo-Osorio, J.M. and Córdoba-Nieto, E., Simulation and verification of parametric numerical control programs using a virtual machine tool. Production Engineering, 8(3), pp. 1-7, 2014. DOI: 10.1007/s11740-014-0534-2.

[19] Gupta, S., Kramer, T., Nau, D., Regli, W. and Zhang, G., Building MRSEV models for CAM applications. Advances in Engineering Software, 20(2-3), pp. 121-139, 1994. DOI: 10.1016/0965-9978(94)90054-X.

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