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# OBSAH

# ODDÍL 4. INFORMAČNÍ TECHNOLOGIE

## *§4.1 3D MODELLING USAGE FOR LIMB PROSTHETICS* (**Zavalniuk Ye.K.**, Vinnytsia National Technical University, **Romanyuk O.N.**, Vinnytsia National Technical University, **Chekhmestruk R.Yu.**, Vinnytsia National Technical University, **Bobko O.L.**, Vinnytsia National Technical University, **Reshetnik O.O.**, Vinnytsia National Technical University)

**Introduction**. Approximately one limb is amputated [1] every 30 s in the world, 2 million people [1], who have lost an upper or lower limb, live in the United States alone. Under normal conditions, the main causes of amputation are vascular diseases (54%) and injuries (45%) [1]. In order to partially restore active life, the prosthetics of patient is carried out. The problem of limb prosthetics became especially relevant after the beginning of a large-scale war, where up to 50,000 Ukrainians (2023) [2] underwent limb amputation.

The important characteristics of the prosthesis are compliance with the patient's characteristics, durability and flexibility of the material, ensuring a high degree of mobility and effective load distribution, affordable price. Three-dimensional modelling tools are used to design the optimal prosthesis for the patient.

The aim of the work. Conducting an analysis of the peculiarities of using 3D modelling for limb prosthetics.

**Main findings.** The main stages of limb prosthetics include assessment of the person's condition, preliminary rehabilitation, design, manufacture and adjustment of the prosthesis, training and rehabilitation of the person, care of the prosthesis.

Assessment of the condition of the residual limb is the first stage of prosthetics. The main methods of obtaining data [3] about the limb include anthropometric measurement, water displacement, magnetic resonance imaging (MRI), ultrasound measurement, computer tomography (CT), three-dimensional laser scanning, and optical scanning. The accuracy of the obtained data affects the quality of the prosthesis socket model, ensuring a uniform load on the prosthesis, choosing the optimal time to replace the temporary prosthesis with a permanent one, and the possibility of tracking the change in the residual volume of the limb.

The method of anthropometric measurements [4] is a standard way of collecting data on the residual limb. With the help of measuring devices (measuring tape), limb parameters such as length and circumference are determined. The method is cheap, measurement results are obtained in real time. The accuracy of the method is limited because the surface of the limb is uneven, the measurement results depend on the operator. The method is characterized by non-invasiveness and is more comfortable for the patient compared to other methods. Based on the measured data, it is possible to build an approximate model of the limb.

The water displacement method [4] is used only for measuring the volume of the limb. The residual limb is placed in a water volume, after which the volume of squeezed water is determined. The method is simple, cheap, provides a fairly accurate assessment of the volume of the limb. A significant drawback of the method is the possibility of contamination of the patient through water.

The MRI method [4] (magnetic resonance imaging) lies in obtaining images of the residual limb using the interaction of radio waves and atoms of a strong magnetic field. A highly accurate representation of the features of the limb surface is provided, the method is non-invasive. However, the cost of the equipment is high, the processing of the scan results is long.

The CT method [4] (computed tomography) is based on obtaining images of the limb based on the use of X-ray radiation. Limb scanning is faster than when using MRI, but data processing is also time-consuming. The method is minimally invasive, provides high-precision presentation of tissues, however, exposure to X-rays is present. The equipment is expensive.

Images obtained as a result of MRI or CT are the basis for building a three-dimensional model of the limb using special software tools, for example, 3D Slicer, OciriX [5].

The ultrasound method [4] ensures obtaining data about the limb in real time. At the same time, a certain amount of time is spent on data processing. The method is non-invasive, allows to accurately reproduce the surface of the limb. Equipment for ultrasound scanning is expensive but is cheaper than MRI and CT. The resulting images are more two-dimensional and less suitable for forming 3D models.

The use of laser scanning [4] lies in the versatile projection of a laser beam on the limb, on the basis of which its three-dimensional model is formed. The method is characterized by highly accurate representation of the shape of the limb, fast scanning, somewhat lengthy processing of the scan results, and non-invasiveness. The equipment is cheaper than when using CT and MRI.

Optical scanning [4] involves obtaining a three-dimensional model of the limb relative to its recorded external contours or projected grid patterns. The method, like the laser scanning method, is accurate, non-contact, relatively economical and fast.

The choice of the method of obtaining data about the limb depends on the purpose of the measurement (modeling the socket, tracking the change in the volume of the limb), the patient's condition (presence of wounds), the material capabilities of the institution, the stage after amputation. A compromise solution in terms of equipment price, scanning speed, level of accuracy, and invasiveness is the use of laser and optical three-dimensional scanners [3, 6-8] (VIUScan, Artec Eva, Go!SCAN, Vistus 3D Body Scanner).

Based on the measured shape and volume of the limb, its three-dimensional model is built and the prosthesis is designed. The advantages of 3D modelling of prostheses are personalization (compliance of the prosthesis with the anatomical features and needs of a specific person), ensuring a high level of user comfort and functionality of the prosthesis, speeding up the process of designing and manufacturing the prosthesis, the possibility of optimizing the parameters of the prosthesis using machine learning methods, facilitating the design of complex prostheses with sensors and motors, the possibility of virtual testing of the designed prosthesis.

Common types of prosthesis structure design are: cosmetic, functional, modular, myoelectric, tendon, endoskeletal, exoskeletal, hybrid, bionic. Cosmetic prostheses are intended only to visually mask the loss of a limb. At the same time, functional prostheses ensure the restoration of the functions of the lost limb. Modular prostheses include a system of modules that can be adjusted depending on the needs of the user. Myoelectric prostheses involve controlling movement with electrical signals from the user's muscles. This ensures a more natural and precise movement of the patient. Tendon prostheses are designed to simulate the movement of the tendons of the limbs using a system of cables and blocks. Endoskeletal prostheses are formed by combining an internal metal frame and external cosmetic materials. Exoskeletal prostheses include an external rigid shell. Hybrid prostheses are a combination of different types, such as mechanical and myoelectric prostheses.

Bionic prostheses combine advances in robotics, medicine, and biomechanics to mimic natural limb movements. Prostheses of this type are controlled by reading electrical signals from the user's muscles with special sensors. High-precision reproduction of natural movements, such as flexion, extension, rotation, is ensured. For optimal use of bionic prostheses, their individual adjustment is carried out. Bionic prostheses can be characterized by the presence of additional functions, such as the presence of programmable modes of movement (running, walking, cycling), integration with mobile applications and neurointerfaces. In the production of these prostheses, durable and light materials such as titanium and carbon fibers can be used.

Automated design systems (CAD) are used to build models of prostheses [9-11].

For example, F. Ezigbo et al. [12], using the SOLIDWORKS system, designed a prosthetic hand that used solar energy. The prosthetic model consists of the following separate parts: hand (houses actuators for finger movement), fingers (connected by fibers distal phalange, proximal phalange, metacarpal bone), wrist (houses rotary actuator), forearm (houses electronics), elbow ( houses the actuator for movement of the forearm), the upper arm (the largest part of the prosthesis, the actuator acts as a shoulder joint). The created three-dimensional model of the prototype hand prosthesis was printed on a 3D-printer of the FDM (Fused Deposition Modeling) type, which uses a continuous supply of material thread to the extruder [13]. Polylactide (PLA) was chosen as the printing material. The SOLIDWORKS Simulation Xpress force simulation program was used to check the strength of the prosthesis. A force of 250 N was applied to each component of the prosthesis in the simulation, which corresponds to the fall of the prosthesis carrier. Safety factors were calculated for the components, giving the probability of maintaining the integrity of the prosthesis. Only for the fingers the calculated value was relatively low. At the same time, when falling, the impact force is distributed over the entire prosthesis, which increases its overall stability.

Another example is the construction of a three-dimensional model of the lower limb prosthesis socket based on CT images (Gubbala et al. [14]). With the help of software tools 3D Slicer and Embodi3D, the collection of CT images of the limb was transformed into a three-dimensional model in .STL format. Based on the

3D model of the limb, a model of the socket of the leg prosthesis was designed in the MeshMixer tool. Next, the models of the residual limb and the prosthesis socket were combined in the SOLIDWORKS application. A structural and dynamic analysis of the operation of the prosthesis was carried out using the Ansys framework. During the structural static analysis, a force of 500 N was applied to the prosthesis model and it was found out that the amount of deformation did not exceed $3.5 \cdot 10^{-6}$ m. The program also calculated the value of the von Mises stress, which is used to predict the fluidity of the material. During the dynamic simulation, the influence of the rapid movement of the limb in the direction of the socket on the deformation of the interface between them was investigated. The designed leg prosthesis was printed on a 3D printer using ABS plastic.

In addition, the company Osteonica [15] uses three-dimensional modelling in the manufacturing of personalized endoprostheses. These prostheses are usually used to replace damaged bone tissue (for example, a knee or hip joint). A three-dimensional endoprosthesis model is built on the basis of CT images. When building the model, the anatomical features of the patient are taken into account. After approval of the designed model, it is printed on a "titanium" 3D printer. In addition, printing 3D models enables rapid prototyping at the pre-operational planning stage.

It is reasonable to use 3D printers for the manufacturing of less expensive prostheses (Fig. 1), which is especially relevant in countries with a poor population (0.5% of the world's population needs prosthetics [6], but only 1 person out of 10 can get a prosthesis [16]). Obstacles [17] to the mass use of 3D printing in prosthetics include the limited ability of using popular prosthetic materials (polyethylene, polypropylene, titanium, aluminum), lower durability compared to traditional prostheses, lack of professionals who assemble prostheses from printed parts, lack of 3D printers in underdeveloped countries, lack of appropriate standards for the manufacture of prostheses. However, besides the standard use of polylactide and ABS plastic, new flexible materials for 3D printing (thermoplastic polyurethane) are spreading, and 3D printers are becoming more common in different countries.

*Fig. 1 Created using 3D printers prostheses [18]*

The usage of 3D printing for manufacturing the prosthetic prototypes is widespread. When using the prototype, the optimal parameters of the future permanent prosthesis are determined. At the same time, potential problems in the design of the prosthesis are revealed. The availability of the technology provides rapid iterative production of new prototypes, which provides more opportunities for selecting a personalized prosthesis design.

In general, the most common materials for 3D printing of prostheses (Fig. 2) are polylactide (PLA), ABS plastic, nylon, thermoplastic elastomer, thermoplastic polyurethane, carbon fibers, biocompatible polymers, titanium, and stainless steel. Polylactide is a common and environmentally friendly material, but it is subject to the destructive effects of high temperatures and loads. ABS plastic is characterized by greater resistance to external factors. Nylon is a strong material suitable for making flexible parts of prostheses. Thermoplastic elastomer and polyurethane are suitable for the creation of soft parts of prostheses in contact with the skin. Carbon fibers allow the production of prostheses that are both light and durable, so they are ideal for the development of sports prostheses. Biocompatible polymers are used when it is necessary to integrate the prosthesis with living tissues. Metals such as titanium and stainless steel are used to produce particularly durable prostheses. In particular, they are used in the manufacture of bone implants.

*Fig.2 Prosthesis manufacturing using 3D printing [19]*

In addition to selecting a prosthesis based on the model of the residual limb, it is possible to design a prosthesis using a three-dimensional model of a healthy limb (method of symmetrical data acquisition [6]). The advantage of the symmetrical method is that the weight, shape, load distribution of the limbs usually correspond to each other. Then, a three-dimensional scan of the limb with subsequent application of affine transformations is sufficient for the design of the prosthesis.

After the prosthesis is installed, the patient undergoes rehabilitation and learns to use the prosthesis. When training to use a prosthesis, especially a prosthesis of the lower limb, there is a significant risk of injury to the patient. The use of virtual reality means provides the safest possible training for the patient. For example, the products of the Virtetic company (Fig. 3) [20] are specially designed for training prosthetic patients who have lost an upper or lower limb.


*Fig.3 Prosthesis usage learning using Virtetic virtual technologies [20]*

Typical exercises in the virtual environment are "Pick and Cook" (using a prosthetic arm to cook a barbecue), "Paintball City" (playing paintball with a prosthetic arm), "Blocks and Boxes Challenge" (training a prosthetic arm with boxes and blocks), "Giant foosball" (the patient plays a foosball character and uses a prosthetic leg), "Management of phantom pains" (soothing visualizations of the presence of lost limbs are used).

Prospects for the development of three-dimensional modeling and printing in the field of prosthetics include increasing the accuracy and speed of adaptation of the prosthesis to the anatomical features of each person, reducing the time and cost of prosthetics based on 3D printing, developing new strong and durable materials for 3D printing, integrating the prosthesis model with artificial intelligence tools and health monitoring systems, facilitating the patient's rehabilitation process.

**Conclusions.** The usage of three-dimensional modelling in the field of prosthetics allows to accurately represent the shape and parameters of the remaining limb, design a prosthesis according to the unique characteristics of the patient, assess the ability of the prosthesis to withstand the load, and facilitate the patient's rehabilitation process.

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