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DEVELOPMENT OF COMPUTERIZED TECHNOLOGY FOR CREATING INDIVIDUAL RESPIRATORY PROTECTION EQUIPMENT USING 3D MODELING AND CAD

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The development of individual respiratory protective equipment (masks) during the coronavirus pandemic is a pressing issue. Modern design and manufacturing technologies make it possible to create masks that account for the unique anatomical features of each individual. However, existing mask configurations often fail to consider the specific characteristics of the wearer. Therefore, it is critically important to design masks tailored to the anatomical features of each person. This paper examines the design process for protective masks using modern computer technologies and an information-based model. The general approach and practical options for mask design are presented, taking into account the individual's features. The information model comprises six main stages for creating a protective face mask. To design a human head form, the photogrammetry method is employed, allowing the creation of a three-dimensional head form from two-dimensional photographs. Using retopology tools on the surface of the 3D head form, the basis for the mask frame is developed in the 3DS Max program. Subsequently, a three-dimensional solid model of the mask frame is created. The process of generating the solid model and testing the mask frame under mechanical stresses, such as changes in facial expressions, is conducted in Autodesk Inventor. To enhance the mask's secure attachment to the face, a version with ear hooks, similar to those used in eyeglasses, is proposed. Additionally, the design allows for the use of one or two filters, as in the Pitta mask. An automation subsystem for mask design is developed in the iLogic environment of Autodesk Inventor, based on the results of this study.

Keywords: Information model, mask frame, filtering element.

Introduction. During the coronavirus pandemic, the creation of customized respiratory protective equipment (face masks) has become a highly relevant issue. Modern computer-aided design and manufacturing technologies enable the production of masks tailored to the individual anatomical features of each person.

Designing face masks adapted to individual needs is not only important during pandemics but also under normal circumstances, such as for surgeons during surgeries, police officers while on duty, and other professionals requiring specialized protective equipment [1].

Literature Review. All individual protective products are divided into two major groups [2, 3]: disposable and reusable. Products from the first group are intended for single use and are disposed of afterward, while products from the second group are designed for long-term use, lasting up to several months. In this regard, reusable masks typically have lower penetration rates but come at a higher price. Both types of respiratory protective equipment are used not only for personal purposes but also in healthcare institutions, beauty salons, factories, and in cases of man-made threats. There is an extensive classification of these products.

Disposable masks are commonly used in the medical sector, cosmetology, and daily life. The maximum recommended duration for wearing such a mask is no more than 2 hours, after which it should be replaced with a new one. Traditionally, these masks consist of an outer layer and a filtering layer. Additionally, they may include a hydrophobic layer or film to prevent glasses from fogging. Some masks are equipped with a flexible aluminum strip to ensure a tight fit around the nose.

By filtration level, disposable masks are classified as follows:

- Double-layered: Basic masks with a protection level of up to 98%;
- Three-layered: Designed for everyday use, with a filter placed at the center;
- Four-layered: Surgical masks that provide protection against liquid penetration.

By material, masks are produced using:

- Cotton: Utilizing cotton filters;
- Spunbond: Offering high air permeability;
- Meltblown: Featuring an inner filtering layer;
- Self-made: Made from materials such as gauze, cotton, or linen.

By availability of additional features:

- With a valve: Includes an adjustable opening for moisture removal;
- Without a valve: Fabric with heat-absorbing properties;

In addition to these categories, reusable masks offer greater comfort and ease of maintenance [4]. They can be washed at high temperatures after each use without losing their protective effectiveness. For instance, the so-called Pitta mask is a filter made of foamed polyurethane that fits snugly to the face. This type of reusable mask can retain up to 90% of pathogenic microparticles. It can be washed and reused after drying but has a maximum lifespan of two months. These masks are significantly more expensive than disposable ones.

Masks with filters can provide up to five levels of protection:

Level 1 (air-permeable forming layer): Blocks larger particles;

Level 2 (activated carbon): Adsorbs chemical and virological pollutants;

Level 3 (powdered cotton): Filters out smaller particles;

Level 4: Enhances particle filtration;

Level 5 (nonwoven breathable material): Ensures breathability while maintaining filtration.

Contests for designing innovative types of masks are held in various countries. Experts assert that textile masks do not provide reliable protection against coronavirus. More effective protective equipment against biological threats includes respiratory masks, specialized filters, protective screens, and masks with advanced coatings. In the first year of the pandemic, numerous innovative protective masks were developed worldwide [5].

Papers [1-4] have reviewed different types of masks and provided recommendations based on expert opinions. However, these studies do not consider the individual anatomical features of the human face. The approach proposed in this study aligns with the second phase of competition: the creation of a new concept for protective masks.

Research Methodology. Nowadays, creating new objects in various fields, including medicine, is increasingly carried out using computer design technologies. The suggested approach for creating a mask involves the fulfillment of several successive stages. In the mask design and production process, various computer programs are applied. When designing new objects using computer technologies, it is important to build an information model. The information model generalizes the approach for design by applying different technologies, examples of which are presented in studies [7-9]. To optimize the design process, it is suggested to use an information model for creating face masks, which will contain all the information necessary for mask production. The result is developed into a mask design subsystem that considers the individual features of the human face. The design information model consists of six main stages, each divided into several sequential steps.

Let us describe in detail an algorithm of the information model for the discussed issue:

1. Stage – Data gathering and determining technology for creating a model of a human face.
   a. Determining the technology for producing a three-dimensional model of a human face.

   b. Determining equipment for scanning (photogrammetry) of the object under investigation.
   c. Conducting photogrammetry of the object and obtaining a mathematical model of the information model boundaries in the form of a point cloud.
2. Stage – Creating and optimizing the face model.
   a. Creating the initial three-dimensional surface model of the human head.
   b. Correcting form inconsistencies and optimizing the surface model of the face.
3. Stage – Modeling the mask configuration.
   a. Determining the technology for designing the mask frame.
   b. Retopology of the mask frame on the face model.
   c. Developing the model of the mask frame.
4. Stage – Form analysis and conducting stress simulations of the mask configuration.
   a. Analyzing the form and required stresses for the created solid mask model.
   b. Conducting static and dynamic stress simulations on the solid mask model.
5. Stage – Preparing mask production technology.
   a. Designing the mask configuration, taking into account the shape of the filtering element.
   b. Preparing the mask production technology based on the developed model.
   c. Creating the mask according to the developed technology.
6. Stage – Implementing and developing the automation subsystem for designing masks with different filter types.
   a. Summarizing versions of the mask configuration with different filter types.
   b. Conducting CAD analysis with an option for developing automation subsystems for object design.
   c. Developing an automation subsystem for designing masks with various frame configurations and filter types.

Let us consider in detail the general approach for mask design using the suggested information model.

At the first stage of creating individually tailored masks, we must obtain a 3D headform of a human face for which the mask will be designed. At this point, we are discussing building a 3D model, the real-life analogue of which cannot have an accurate description due to the infinite number of unique parameters. For such cases, 3D scanning and photogrammetry methods have been developed. The 3D scanning method requires specialized and often expensive equipment, such as 3D scanners. Photogrammetry, on the other hand, can be applied using consumer smartphones. It tracks points from different sources under consistent conditions and generates a 3D point cloud that forms the topology of the object. Information from each photograph is saved in a file, including height, camera rotation angle, and geospatial data. The program applies computer vision and photogrammetry techniques to find common points in multiple photographs. As a result, each pixel in a photograph is matched by color correspondence with others, and every match becomes a key point. If the key point is found in three or more photographs, the program constructs this point in space. The more such points, the better the coordinates of each point are defined in space. Therefore, the more overlap among photographs, the more accurate the resulting model. An overlap of 60–80% is considered optimal. The spatial coordinates of each point are calculated using the triangulation method: from every shooting point, a line of sight is automatically drawn to the selected point, and their intersection determines the required outcome [6]. Additionally, algorithms aimed at minimizing the sum of squares of errors are applied in photogrammetry. The Levenberg-Marquardt algorithm (or the damped least-squares method) is typically used, solving nonlinear equations by the least squares method. During the processing of photographs, an extended point cloud (a set of all 3D points) is created, which can be used to generate a surface consisting of polygons. Finally, resolution is calculated to determine which pixels in a photograph correspond to which polygons. To do this, the 3D model is unfolded into a surface, and the spatial position of a point is matched to the original photograph to set its color.

For example, the object is a human face. To make this method work, the face should be photographed from different angles under consistent conditions: the same state of the object (facial expression, position), the same surroundings, and the same material. Maintaining these conditions guarantees a more successful search for the same points in different photographs, enabling a more accurate representation of the human face in a 3D point cloud [10].

At the second stage, photogrammetry software is used to create a 3D model of the face. The obtained model is then imported into software designed for processing three-dimensional models, such as Autodesk 3DS Max or Maya. At this point, form inconsistencies are corrected, and the surface model of the object is optimized, ensuring the correct form of the created object. At the third stage, the mask configuration is modeled based on the obtained face model. This involves solving an inverse problem: the geometry of the mask structure is placed over the face. Retopology tools [11-12] can be used for this purpose. Retopology is the process of creating a new geometry over an existing one by altering its structure. First, a surface tangential to the face is built. The created surface of the mask base is then imported into a CAD system, where a three-dimensional solid model of the mask frame is developed.

At the fourth stage, form analysis and stress simulations of the mask configuration are conducted. The material type and its properties are selected for the solid model. Modern CAD systems allow simulations of various stress types on created models. Stress analysis is required to account for facial expression changes during conversation, ensuring the mask fits tightly to the face.

At the fifth stage, mask production technology is prepared. Appropriate types of filtering elements are selected. It is suggested to use a replaceable filtering element that can be temporarily fixed to the basic mask frame using a sticky layer or a fixing mechanism. This allows the filtering element to be replaced after two hours of use. Alternatively, separate filters, such as those used in Pitta masks, can be applied, which can be washed in disinfectant fluid or replaced as needed. Once the filtering element type is defined, the mask production technology must be determined. Additive manufacturing using 3D printers is considered one of the most appropriate solutions. Modern 3D printers can use various materials to form an object [13, 14]. After producing the mask frame, an elastic layer is applied to the inner surface to reduce skin irritation and discomfort during extended use.

At the sixth and final stage, an analysis of available mask frame configurations and filtering elements is performed. The most suitable CAD system is selected for developing an automation design subsystem for the product.

Therefore, the general approach for creating protective masks using an information model has been studied in detail.

Results. The design of the protective mask using an information model is demonstrated in the presented example.

At the first stage, the required software for implementing photogrammetry is identified. To create a three-dimensional headform using the photogrammetry method, a variety of programs can be used.

In this research, the construction is performed using Regard3D, a free, open-source photogrammetry program. To create the headform, 100 photographs were taken, based on which the model boundaries are defined, and a point cloud of the future object is formed. In Regard3D, the point cloud is generated and serves as the core for the headform design.

At the second stage, the point cloud is edited in the Regard3D program before being forwarded to generate the three-dimensional surface of the object.

As a result of photogrammetry and point cloud correction, a three-dimensional surface headform is obtained (Fig. 1). Further editing of the headform is carried out using another software product – Autodesk 3DS Max.

Fig. 1. Three-dimensional surface model of a human face

At the third stage, the generated headform is imported into Autodesk 3DS Max, where the mask frame design process begins. For this purpose, it is recommended to use retopology tools. Retopology enables the creation of new geometry over an existing one by modifying its structure.

Using retopology tools, new geometry is placed over the face model, using it as a foundation (Fig. 2). This approach allows for precise placement of the new object and facilitates further modifications. It is also crucial to maintain the correct topology of the 3D model, which should consist exclusively of quadrilaterals. This ensures compatibility with subdivision modifiers, enabling the creation of a high-poly model while allowing a return to its previous state for further updates, if needed.

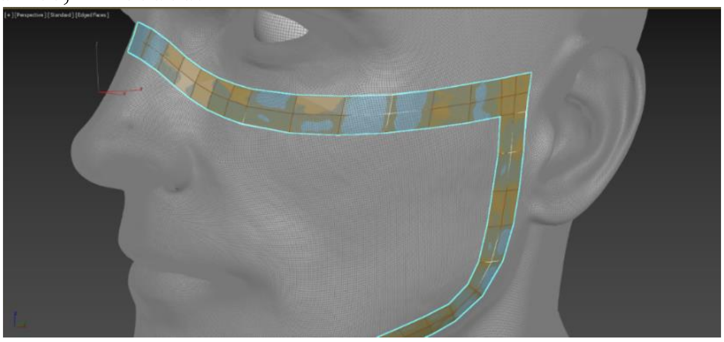

Fig. 2. Mask frame retopology

This toolbox facilitates the design of the mask frame shape, which can be easily modified later. Using the obtained mask frame configuration, a solid model is developed in Autodesk 3DS Max (Fig. 3). Managing the model's topology allows the design to be exported into CAD modeling programs (experiments in this study were conducted using the Autodesk Inventor Pro CAD system). This enables the performance of various stress tests, the selection of physical materials, the configuration of settings for 3D printing, and more.

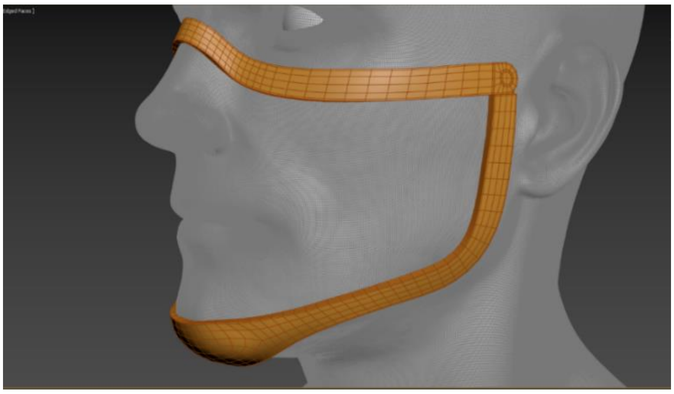

Fig. 3. Solid model of a mask frame in Autodesk 3Ds Max

At the fourth stage, the reliability of the mask structure is evaluated. The configuration of the mask frame consists of two main parts, which are hingedly connected. This design ensures that the mask can be used regardless of changes in facial expression or speech by the wearer. The lower part of the mask fits snugly against the chin, while the upper part is secured on the bridge of the nose.

Stress simulations are performed on all parts of the mask and their connections using Autodesk Inventor Pro software. These simulations verify the reliability of the mask configuration under mechanical stress and evaluate its fixation on the face. Once the material for the mask's basic structure is determined, the design is tested for resistance to external forces and potential displacement caused by changes in facial expressions during conversation. Adjustments to the mask structure can be made based on the testing results.

A three-dimensional solid model of the mask frame created in Autodesk Inventor Pro is shown in Fig. 4.

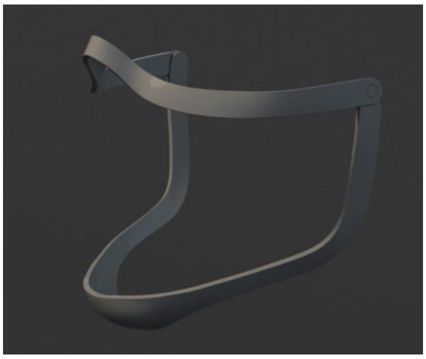

Fig. 4. Three-dimensional solid model of a mask frame in Autodesk Inventor Pro

At the fifth stage, the type of filtering element is defined, which determines the method of attaching it to the basic mask structure. Let us consider the simplest example involving a replaceable multi-layered filtering element. This element can be pre-manufactured, taking into account the shape of the basic mask configuration.

The filtering element is attached to the basic structure using a sticky layer, which can be applied to either the filtering element, the basic structure, or both. To ensure more reliable fixation, an additional securing element can be applied over the filter.

If necessary, the mask configuration can be adjusted to improve the secure attachment of the filtering element. Separate filters, similar to those in Pitta masks with one or two filters, can also be used.

Once the filtering element is defined, the technology for producing the mask frame is developed. Additive manufacturing using a 3D printer is selected as the core technology in this experiment.

The process of creating the object using a 3D printer can be simulated in the Autodesk Inventor HSM program. Using cloud computing technologies, the parameters of the required

3D printer are downloaded, and the simulation of the mask frame manufacturing process is conducted.

If complications arise during the simulation, the program suggests appropriate configuration corrections or the addition of extra fixing elements. The final version of the mask after the simulation of 3D printing is shown in Fig. 5.

Once the mask is designed, it is placed on a headform for testing. During the tests, the mask is carefully positioned to ensure accurate placement. The resulting image of the mask on a face is shown in Fig. 6.

To guarantee more secure fixation, a version of the mask with ear hooks, similar to those used in eyeglasses, is proposed (Fig. 7). Variants with separate filtering elements are presented in Fig. 8: (a) single filter and (b) double filter.

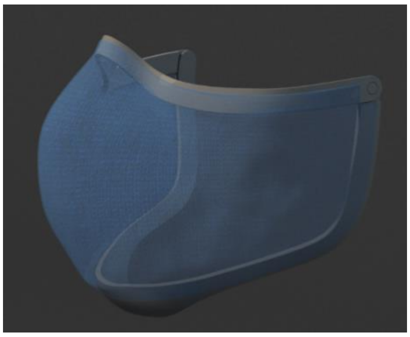

Fig. 5. Finished mask

Fig. 6. Mask put on a face **Fig.7.** Mask with ear hooks

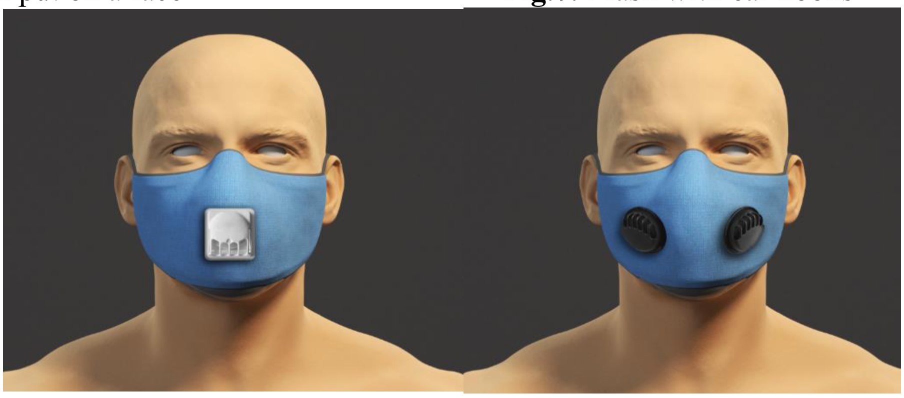

Fig. 8. a) Single filter mask b) Double filter mask

At the final sixth stage of the information model, an automation subsystem for designing masks is developed based on the required parameters obtained during the previous stages. The integrated design automation tool in the Autodesk Inventor CAD system, the iLogic environment, was used to create this subsystem. The presented subsystem streamlines the process of generating an appropriate template for the face mask. An interface window of this subsystem is shown in Fig. 9

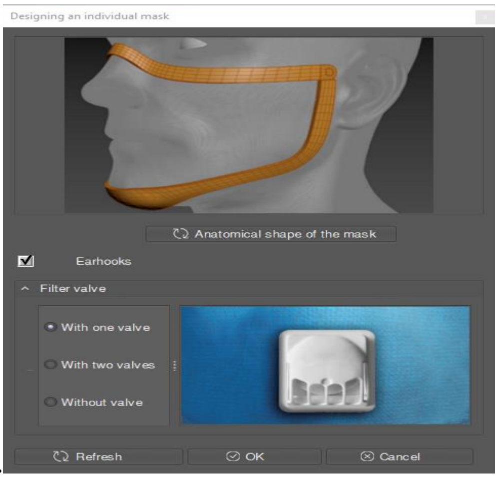

Fig. 9. Subsystem interface window

Conclusions. This study presents a general approach to protective mask design that considers the individual features of the human face. An information model of the created object is utilized in the mask design process. The information model encompasses all the sequential stages of mask creation and includes the possibility of developing an automated design subsystem. The construction of real protective mask prototypes with different replaceable filters is discussed in detail. To improve the reliability of mask fixation on the face, the addition of ear hooks, similar to those used in eyeglasses, is suggested.

Applying an information model in the mask creation process reduces the time required for design, increases accuracy, and helps avoid errors in the developed model. The presented versions of protective face masks address the issues outlined in the Mask Innovation Challenge program. The innovative mask design method based on the information model can also be applied to other similar objects. The development of the mask design subsystem will facilitate their implementation. Further research on this topic aims to design reusable masks that can accommodate a variety of filter types.

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РОЗРОБКА КОМП'ЮТЕРИЗОВАНОЇ ТЕХНОЛОГІЇ СТВОРЕННЯ ІНДИВІДУАЛЬНИХ ЗАСОБІВ ЗАХИСТУ ОРГАНІВ ДИХАННЯ З ВИКОРИСТАННЯМ 3D МОДЕЛЮВАННЯ ТА САПР

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Розробка індивідуальних засобів захисту дихання (маски) під час пандемії коронавірусу дуже актуальна. Сучасні технології проектування та виготовлення дозволяють створити маски з урахуванням індивідуальних анатомічних особливостей кожної людини. Докладно розглянуті різні типи захисних масок та їх конструкції. Наявні конструкції масок не враховують індивідуальних особливостей кожної людини. Тому надзвичайно важливо створити маску відповідно до анатомічних особливостей кожної людини. У даній роботі розглядається процес створення захисної маски із використанням сучасних комп'ютерних технологій із застосуванням інформаційної моделі. Розглянуто загальний підхід та варіанти практичної реалізації створення маски з урахуванням індивідуальних особливостей людини. Інформаційна модель включає шість основних етапів створення захисної маски. Для створення моделі голови людини використано метод фотограмметрії, коли за двовимірними фотографіями формується тривимірна модель голови людини. За допомогою технології ретопології на поверхні тривимірної моделі голови у програмі 3DS Max створюється основа несучого каркаса маски. Створення твердотільної моделі та перевірка несучого каркаса маски на механічні навантаження при зміні міміки обличчя проведено в Autodesk Inventor. Для більш надійного кріплення маски на обличчі запропоновано варіант із завушинами, як у окулярів. Розглянуто варіант встановлення одного або двох фільтрів як у масці Питта.
За результатами дослідження було створено підпрограму автоматизації проектування створеної маски у середовищі iLogic Autodesk Inventor.
Ключові слова: інформаційна модель, каркас маски, фільтрувальний елемент.