The work is devoted to the study of factors influencing the reproduction of augmented reality elements.

The object of the study is technologically significant parameters of the influence on the process of reproduction of AR elements when pointing a phone or tablet camera at a special marker image. The main problem of the study is the lack of information regarding the technological process of creating AR products and a large number of parameters that should be taken into account when choosing a particular technological operation, since changes in these factors greatly affect the correct reproduction of AR elements and further use of such products.

The study determined that in recent years, research has shifted from the field of science to printing and entertainment. This is due to the capabilities of the technology, namely wow effect, content expression, ease of creation, etc., development of digital technologies and competition with digital products.

Also, a low level of research was revealed in the area of products with unstable usage conditions such as clothing, packaging, etc. This can be explained by the development of printing technologies and opportunities in this area only recently, the increase in the popularity of such products only in recent years and, as a result, insufficient knowledge in this area. However, such products are much more popular in the market, which is emphasized by a significant drop in the production of books, magazines, etc.

The results of studying the significance of factors in the marker reproduction processes made it possible to identify the most significant ones (marker parameters, material characteristics, usage conditions, etc.). A systematic and integrated approach to the influence factors of this study allows the development of methods for normalizing the process of creating AR products with unstable usage conditions, which makes it possible to produce workable and reliable products in any conditions

Keywords: augmented reality, augmented reality marker, marker reproduction

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RANKING OF TECHNOLOGICALLY SIGNIFICANT FACTORS DETERMINING THE QUALITY OF REPRODUCTION OF AUGMENTED REALITY ELEMENTS

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1. Introduction

The subject of the chosen research area is the reproduction of printed products containing augmented reality markers (hereinafter referred to as AR elements) with their subsequent reading in non-standardized conditions.

Augmented reality is a digital technology that allows you to integrate digital elements (text, illustrations, video, audio, animation, 3D objects, etc.) into the real world, in particular, printed products. To implement this technology, AR elements are printed in the form of marker objects on the surface of printed materials. Then these pictures are scanned and recognized using a camera of devices (phone, tablet, helmet, glasses, etc.). After that, these devices display virtual objects on the screen [1–3].

The chosen topic is quite relevant, since the application of this technology, especially in the field of printing, is a fairly new and, therefore, insufficiently studied issue. So, there are a large number of little-studied factors and especially their influence on processes that require systematization and in-depth study.

Augmented reality technology can be used both in products with stable and unstable usage conditions. The first group includes books, magazines, newspapers, etc., the second – clothes, cardboard and flexible packaging, outdoor and indoor advertising, and so on. In the first area, everything is deeply investigated – technologies that can be applied, requirements for augmented reality elements, conditions for correct reproduction, etc. All this is backed up by a number of studies. In the second area, there are a large number of factors that significantly affect the processes of reproduction of AR elements that should be taken into account when developing such products. However, clear stages of normalization of technological processes have not been developed, the influence of factors has not been studied. So, the degree of their significance in the process of forming the quality of such products has not been determined.

In the field of augmented reality, technologies for creating and reproducing AR elements can be singled out. The first category has been developed and researched throughout the existence of this sphere, and now its development has declined. The second category has become of interest to researchers only recently, as new areas of application, problems and conditions that affect AR reproduction require deeper study and systematization.

To correctly reproduce information during scanning, a number of conditions must be observed: strict correspondence of the imprint to the original image, appropriate color design, detailing of the marker pattern, etc. These conditions can be met if AR elements are scanned under normalized conditions. These are lighting, weather conditions, conditions for using products with augmented reality elements, properties of selected materials, etc. However, today many printed products containing AR elements are used in more complex non-standard conditions. Therefore, the reproduction of augmented reality elements, as well as the use of products in general, is influenced by various factors. These can be the strength properties of materials, resistance to abrasion and external conditions, unstable printing conditions, as well as compliance of the concept with usage conditions, and so on. All the smallest factors can become critical in the reproduction of augmented reality.

For valid reproduction of information, it is necessary to consider this technology as a complex interconnected system. It is described as follows: original layout with an AR element (electronic file) – printed material – imprint – reading system (AR element scanning) – reading conditions – augmented reality elements on the screen of the user's device. All these elements must be considered as a whole. However, current research takes place in the field of individual elements, not accounting for their interaction.

Determining the most significant factors and their mutual influence on the correctness of reading AR elements is an urgent task. First, without taking into account their influence, it is impossible to talk about the possibility of using such products in any conditions. Secondly, the influence should be considered comprehensively and systematically, since even a seemingly minor factor may have the greatest impact on the process and the degree of influence of each factor individually.

It can also be concluded that the results allow you to quickly determine and regulate the system of factors influencing the processes of AR reproduction and effectively respond to emerging problems at a minimal cost. In general, this makes it possible to produce high-quality products and apply them not only in traditional areas (games, printing, etc.), but also develop them for new ones – tourism, economics, politics, etc.

2. Literature review and problem statement

Research on the features of technologies for creating augmented reality elements was carried out. So, in [4], the use of marker-based augmented reality elements in mobile technologies was considered. Based on a survey, a number of factors were investigated (22 out of 100 possible ones were selected) that would affect such adoption among the population. The most significant of them were identified such as privacy and security. However, the factors considered were more global and related to the security of personal information. The parameters of devices, the characteristics of markers, etc., were not taken into account. In [5], on the contrary, the characteristics of the markerless technology and the features of its implementation were considered. The paper considered the features of introducing markerless technology in the educational process for the automation and control fields. It was determined that, unlike marker technology, markerless technology is easier to integrate into the educational process. The main reason is that there is no need for knowledge of programming languages to create AR elements and find ways to implement simple-type markers in products. A number of important factors in this process were also investigated. These include the distance to the marker, the position of the user's hands in space, the presence of stable Internet, etc.

The disadvantage of the above works is that the studies were carried out within one selected AR technology. So, research was conducted without considering the degree of factors' impact as a whole to establish requirements for the correct reproduction of markers under any conditions, despite the chosen technology. In addition, the factors influencing the reproduction of augmented reality elements were considered only on the one hand, without taking into account their complex effect.

A number of studies on the application of augmented reality in the educational sphere have been carried out.

In [6], the issues of introducing augmented reality into the educational process of non-engineering students and their perception of AR as a learning tool were considered. For this, a special test was developed and an experiment was conducted. The results of the study showed that this technology can significantly improve the test results. This is because the technology makes it easier to understand context or complex terms by visualizing examples. In addition, it was determined that such parameters as relevant actual context and simple user interface are significant factors influencing the students' perception of learning outcomes. The study took into account only visual factors (concept fit, marker design, etc.) and age factors (respondents' skill level).

The work [7] examined the features of using augmented reality technologies in the information and educational environment in universities. In the paper, the features of introducing AR elements were considered in general, and an analytical review of foreign experience was carried out. As a result, the main software was identified that allows using augmented reality technology – Unity, Vuforia, ARTool Kit, ARCore, etc. The main advantages and disadvantages of this technology are also found. The first group includes interactivity, ease of use, wow effect. The second – technical limitation of practical implementation, external conditions, etc.

In [8], the possibilities of applying augmented reality in medicine and the educational process in it were considered. This technology makes it easier to assimilate the material, understand and present various formulas and elements, assimilate information faster. It allows you to create, according to the author, an alternative learning environment. In addition, it was investigated that the use of this technology is much cheaper than, for example, virtual reality. This is due to the absence of the need to use expensive equipment and software, which in turn allows you to interact with digital content at any level of knowledge and skills. For the study, special test individual and group 3-stage tasks were developed. The results were evaluated using statistical methods. Positive

estimates of the introduction of augmented reality in the educational process were obtained – 69–88 % of respondents noted the convenience of such integration, 58–83 % were not opposed to such a combination.

In [9], a systematic analysis of trends and features of using augmented reality in education was carried out. The influence of the developed content on the results of educational achievements was also considered. The methodology of work was to conduct a bibliometric analysis using the Scopus library, paying attention to the educational sphere. As a result, a general picture of the introduction of augmented reality in education was formed.

In [10], the integration of augmented reality and the educational process was considered from a different perspective than in previous works. Researchers studied the most significant characteristics of augmented reality when applied in the educational field (programming training), as well as the main advantages and disadvantages. An in-depth systematic review of the literature was carried out to address the issue. This method allows a comprehensive understanding of the concept and characteristics of the technology. As a result, prospects for the development of the sphere and the need for further research were determined. However, parameters of devices used in this process, external usage conditions specific to a particular printed or electronic product or service have not been studied. They may affect the development of augmented reality in the future and the prospects for its application.

In [11], an experiment was conducted to study the effect of an augmented reality application on the process of information perception by students in disciplines related to mechanical design. The study was carried out among students of engineering specialties, as well as bachelors of technical universities. Some of them were provided with an AR application that helped to understand information easier, and some passed the classic test without additional programs. The results of testing the developed application using quantitative and qualitative methods showed a generally positive estimate of the integration of the digital and real world. The experiment increased cognitive perception of information and knowledge in a simpler and faster way.

However, the development did not take into account the parameters of digital content, hardware features and characteristics of printing and printed materials. A comprehensive study of their impact on the test results of the developed application made it possible to create more flexible and versatile software that works in any conditions.

When studying all these works, their strong and fundamental results for the development of augmented reality and creation of applications with it were noted. However, these studies almost or completely did not take into account the factors influencing the reproduction of augmented reality elements and content perception. Only some parameters were considered, without taking into account their complex impact as a whole. This drawback may arise from the narrow focus of the work, which leads to a one-sided consideration of the problem and the lack of knowledge in this area due to its novelty. It can be overcome by the method considered in this paper, which is applicable to any field of augmented reality. All this makes it possible to produce quality products or conduct a training process, regardless of the chosen technology or influence factors.

The work [12] is devoted to the study of the features of using augmented and virtual reality and their impact on market relations. A general overview of the sphere was carried out, problem areas and issues were identified, and the prospects for using augmented reality in various fields were compared. In [13], a comparison was made between virtual and augmented reality. A special in-depth analysis was conducted on the application of these technologies in business and management. The work [14] analyzed recent studies on the development and application of augmented reality. A very deep comprehensive analytical review of papers in the field of architecture, engineering and construction was carried out regarding the application of augmented reality by various methods. Two main parameters of influence on the process of using AR applications were found – marker registration errors and user perception of information. Accordingly, a number of methods to overcome them in the future were discussed.

The results of the work revealed a variety of interesting possibilities for applying augmented reality technology in the outlined areas. This can be visiting websites, researching the project status, solving problems online, etc. In [15], the main areas of application of augmented reality based on industry experience were highlighted. Particular attention was paid to the study of AR glasses. The research was carried out using the prototyping method.

The results of the reviewed works made it possible to assess changes in the field of augmented reality. Also, they showed the prospects for AR implementation in various fields within 5–8 years. However, the field of printing and printed products, especially with unstable usage conditions, turned out to be unexplored. This may be due to the fact that when the works were published, the technology was little used in these industries, and therefore did not need a wide and in-depth study. Now many factors should be taken into account, since there are high requirements for the quality of printed products, which require systematization and detailing. This can be done using the methodology described in this study, which allows considering the influence of factors in a complex, developing and ordering them into a system. This also allows you to determine the significance of their impact and apply this knowledge in practice in any field.

Threats to the development of the sphere were also investigated [16]. During the study, 6 main problems were identified by the survey and questionnaire method related to the economic capabilities of users and their behavior psychology. On this basis, the ability to overcome them was determined. However, the definition of threats did not take into account the factors of manufacturing and using such products, which can significantly affect the opinion of respondents. This may be due to the limitations of the method used in the study and the impossibility to account for all items in one test.

In addition, the study of factors in classical printing was carried out using the graph method. In [17], the graph method was used to study methods to overcome the influence of factors emerging in the manufacture of printed products. By this method, the most significant of them were identified, their systematization and classification were carried out, a graph of an extended technological process and a partial process was constructed. All this allows you to optimize, facilitate and improve the technological printing process. The work [18] is devoted to the study of software testing processes in the field of printing. By the graph method, a hierarchy of influencing factors was determined and the most significant ones were identified. In particular, this is a restriction

on the use of a particular software when choosing a particular printing technology. In [19], the features of optimization of post-printing processes were deeply studied. Therefore, using the graph method, the features of each of the stages and the factors influencing them were determined. This allows you to design a variety of post-printing processes that are reliable under any conditions.

The results of these works made it possible to systematically and comprehensively consider the features and problems of the processes of traditional printing. However, in the context of augmented reality, such studies were not conducted. All this suggests conducting a study devoted to the placement of augmented reality elements on printed materials.

As already noted, augmented reality is a new technology, and therefore it is not well understood, especially in manufacturing products with unstable usage conditions such as clothing, packaging and outdoor products. In most cases, the study of this area focuses on the development of software for creating augmented reality elements.

There is little research on the reproduction of AR elements and parameters of this process. The AR reproduction is affected by many factors, such as external conditions, printing conditions, characteristics of printed materials, features of marker images.

The analysis of the work allows us to assert the need for the selected study, since it is relevant and appropriate in the current situation. This research will be new and will make an important contribution to the development of augmented reality. First, products with unstable usage conditions will be researched, which are little studied and unsystematized, but gaining wide popularity compared to classical types of products. Second, the studied influence of certain factors will make it possible to form a complete picture and develop recommendations for normalizing the marker recognition system. It can be defined as «original layout with AR element (electronic file) – printed material – print – reading system (AR element scanning) – reading conditions – augmented reality elements on the screen of the user's device». It consists of several subsystems (an AR electronic original marker, devices for developing and scanning markers, a print). Each requires research into a significant influence of factors on them and their complex impact as a whole. So, it allows the correct reproduction of markers under any conditions. In addition, the results of the reviewed works showed an insufficient study of the sphere of augmented reality in terms of the influence of factors on the processes of reproduction of augmented reality elements. This also necessitates research in this direction.

3. The aim and objectives of the study

The aim of the study is to determine the factors and the significance of their influence on the process of reproduction of augmented reality markers in any conditions. This allows developing recommendations for normalizing the original – printed material – print – marker scanning system, which in turn improves the technological process, making it more efficient, economical and simpler.

To achieve the aim, a number of objectives were accomplished in the work, namely:

– to perform a patent search to determine development trends in the chosen subject with a 10-year retrospective;

– to identify new areas of application of printed materials with augmented reality elements and determine marker reading features;

– to determine the metrological parameters of the «original layout with an AR element (electronic file) – printed material – print – reading system (AR element scanning) – reading conditions – augmented reality elements on the user's device screen» system;

– to evaluate the influence of factors on each other using the graph method;

– to form a system of the most significant parameters of influence on the process of reproduction of augmented reality markers, the control of which normalizes the process.

4. Research materials and methods

To determine trends in the development of augmented reality, an analytical research method was used when studying professional scientific and technical literature and information sources.

To identify the most significant metrological parameters of the «original layout with an AR element (electronic file) – printed material – print – reading system (AR element scanning) – reading conditions – augmented reality elements on the user's device screen» system, the following method was used (based on the graph method):

1. Determination of the system components and their main features.

2. Determination of the factors influencing the reproduction of each subsystem.

3. Building relationships among certain metrological parameters.

4. Building a reachability matrix based on a graphical representation of the relationships among certain factors of the components of the «original layout with an AR-element (electronic file) – printed material – print – reading system (AR-element scanning) – reading conditions – augmented reality elements on the user's device screen» system.

5. Evaluation of the reachability matrix using the analytical method.

6. Building a dominant hierarchical ordered model of influence criteria.

7. Determination of the most significant parameters of the components of the «original layout with an AR element (electronic file) – printed material – print – reading system (scanning an AR element) – reading conditions – augmented reality elements on the user's device screen» system.

8. Graphical presentation of the relationships among the parameters of subsystems, identification of factors that need to be normalized in the case of products with unstable usage conditions.

5. Results of research on the factors determining the quality of reproduction of augmented reality markers

5. 1. Conducting a patent search in the field of augmented reality

To determine the directions of development in the field of augmented reality, a patent search was conducted, the regulations of which are presented in Table 1. The distribution of patent search by year for the selected search subjects is presented in Fig. 1–3.

Table 1

Patent search regulations

Subject of search	Purpose	Countries	Classification indices	Retrospective	Sources of information
1. Augmented reality. 2. Augmented reality technology. 3. Software for creating AR elements. 4. Products with augmented reality elements. 5. Devices for reproducing augmented reality elements	Determining the directions of development of augmented reality	Republic of Korea; Federal Republic of Germany; USA; People's Republic of China, Japan, French Republic, Canada, United Kingdom of Great Britain and Northern Ireland	G06T19/00; G06T7/00; G06F1/16; G06F3/0346; G06F3/0488; G06F3/16; H04N5/232; H04R1/02; H04R1/10	10 years (2012–2021)	Internet resources: ep.espacenet.com, tgs.freshpatents.com, Google Patents

Areas of development of the industry were also analyzed to identify its weaknesses. Fig. 4 presents the distribution of patents by the main areas of application and years.

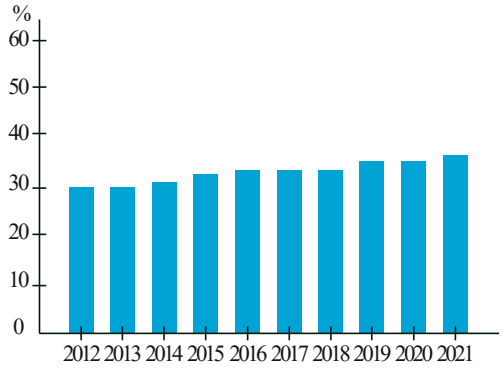

Fig. 1. Distribution of patents by year for the patent search subject «augmented reality as a product»

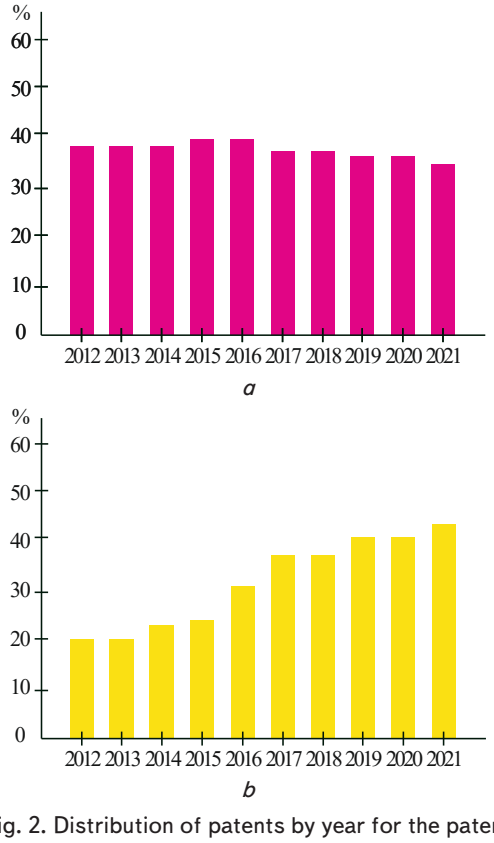

Fig. 2. Distribution of patents by year for the patent search subject: *a* – augmented reality technology; *b* – software for creating augmented reality

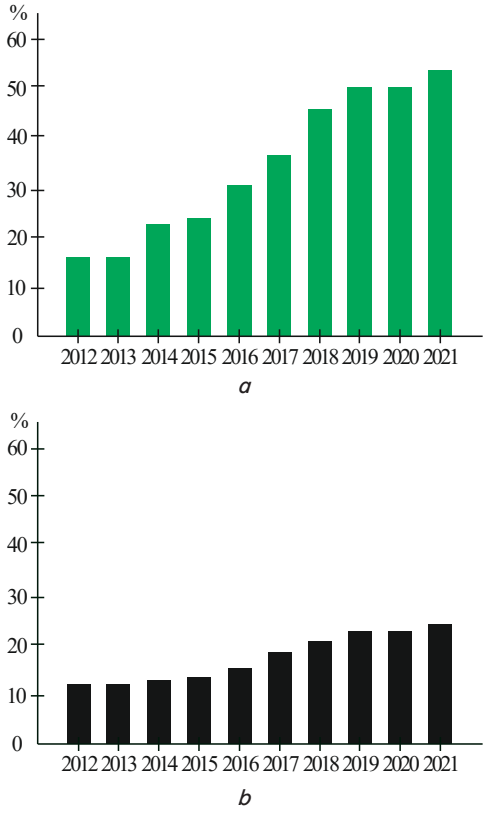

Fig. 3. Distribution of patents by year for the patent search subject: *a* – products with augmented reality elements; *b* – devices for reproducing AR elements

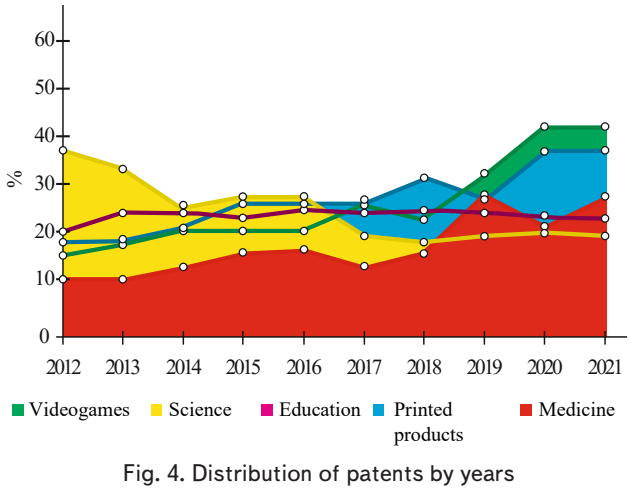

Fig. 4. Distribution of patents by years and areas of application

Based on the results of the patent search and literary review, the following conclusions were drawn:

– the topic of augmented reality is relevant. However, studies were carried out on individual elements of the technology and were not considered as a whole;

– stable patenting on the search subjects «augmented reality technologies» and «augmented reality» indicates that the technology has reached a «plateau». This suggests that the market is saturated with new products, which requires the correct selection of technologies, taking into account all influencing factors and, as a result, a more detailed study;

– stagnation in the segment of patenting «devices for reproducing AR elements» demonstrates market saturation and reduced interest in its development, since at this stage, augmented reality does not require sophisticated demonstration equipment;

– the steady growth of patenting in the field of products with augmented reality elements shows the market's interest in using printed products with these elements;

– the main areas of application of augmented reality, as evidenced by the largest number of patents in them, are video games, science, education, printed products (printing) and medicine;

– at the beginning of its development, this technology developed mainly in 2 areas – science and education. This may be due to the development of research on this topic and the level of technologies being created;

– the rapid development of augmented reality in the field of video games took place in 2014 and continues to develop. This may be due to the development of digital technology and the digital sphere in general;

– since 2018, another area where augmented reality has become widespread and interesting for research is printing (printed products). This may be due to developers' attention to the ability of augmented reality to draw attention to products, expanding their capabilities and attracting more and more potential buyers. As can be seen from the analysis, the use of AR elements in printed materials is developing. This is also because there are still many obscure points and factors that affect processes and are poorly understood. They need deep research and systematization. Therefore, the number of patents in this area is growing.

To develop a system of factors using the described methodology, it is first necessary to conduct a more detailed study of the scope of augmented reality application in order to identify really important and little-studied ones having many weaknesses and requiring deeper analysis.

5. 2. Defining the areas of application of augmented reality

The main areas of application of augmented reality are identified and systematized. Based on the results, the following classification of products to apply augmented reality elements was developed, shown in Fig. 5, 6, respectively.

It was also determined that:

a) the following product categories with augmented reality elements are popular among potential users:

– textile products – 30 %;

– packaging – 40 %;

– street advertising – 20 %;

– books, magazines, newspapers – 10 %;

b) the distribution of research in these areas is as follows:

– textile products – 65 %;

– packaging – 11 %;

– street advertising – 12 %;

– books, magazines, newspapers – 11 %.

As can be seen, the products that are now popular are little explored. Therefore, they need a more detailed study to determine the factors affecting the reproduction of markers. In addition, this allows them to be further standardized in order to reduce the possibility of errors when using such products.

The directions of research in the field of augmented reality technologies were also identified, since the degree of research on this issue affects the quality of the manufacturing processes. It also determines the quality of finished products as a whole. The direction of research in this area has moved to the field of technologies for reproducing augmented reality markers. This is due to the development of the digital sphere, the emergence of new devices for reproducing augmented reality elements, their parameters and features of work.

The results make it possible to narrow the research area to printed products with augmented reality elements with unstable usage conditions with the study of factors affecting the validity of the chosen marker reproduction technology. This kind of products is most vulnerable to the presence or absence of many conditions. But at the same time, they have not been deeply studied, specified, systematized and normalized, although such products are now the most popular. So, further research will be carried out for this area.

5. 3. Determination of the metrological parameters of the «original layout with an AR element (electronic file) – printed material – print – reading system (AR element scanning) – reading conditions – augmented reality elements on the user's device screen» system

5. 3. 1. Determination of the system components and their main characteristics

In the reproduction of products with AR elements, it is necessary to single out individual production stages and their components. This is the creation of digital content that is not directly related to the release of a printed product, designing products with AR elements, pre-printing preparation and printing of products. In addition, the process of testing markers for reproducibility on a reader is very important. The valid reproduction of information in this operation is significantly affected by the reading conditions: lighting, device parameters, camera characteristics, material indicators, printing technology, etc.

The use of such products as a whole depends on changes in the metrological characteristics in each process. They can affect the marker pattern, color design, and clarity of the elements. This, in turn, affects the accuracy of digital content reproduction on the screen of a phone or tablet when pointing its camera at the marker. The most important thing in this process is the maximum correspondence of the imprint marker to the original marker. If the imprint marker changes under the influence of factors, then the possibility to reproduce it decreases. The analyzer camera, comparing the image in the device's memory with the scanned one, cannot find a match between them and the content is not reproduced.

Therefore, the reproduction of printed materials with AR elements should be considered as a complex system, with the identification of interrelated factors that determine the correctness, and sometimes the possibility of information reproduction.

This system has three subsystems: digital content subsystem, hardware subsystem and imprint subsystem. The first includes all digital content of the augmented reality element. The second serves to create and reproduce augmented reality elements. The third includes the imprint itself, material, ink, control system, conditions, etc.

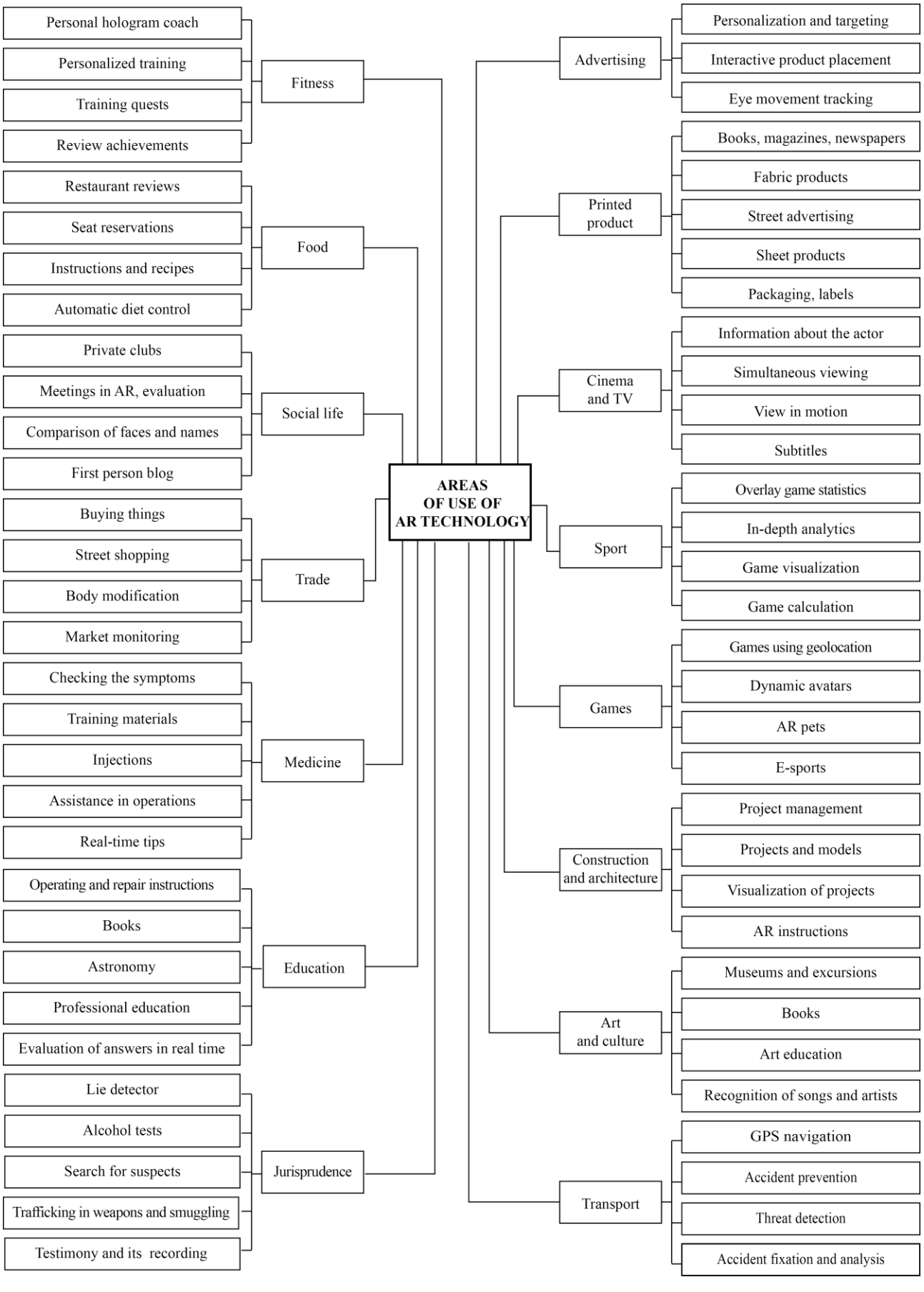

Fig. 5. Areas of application of augmented reality

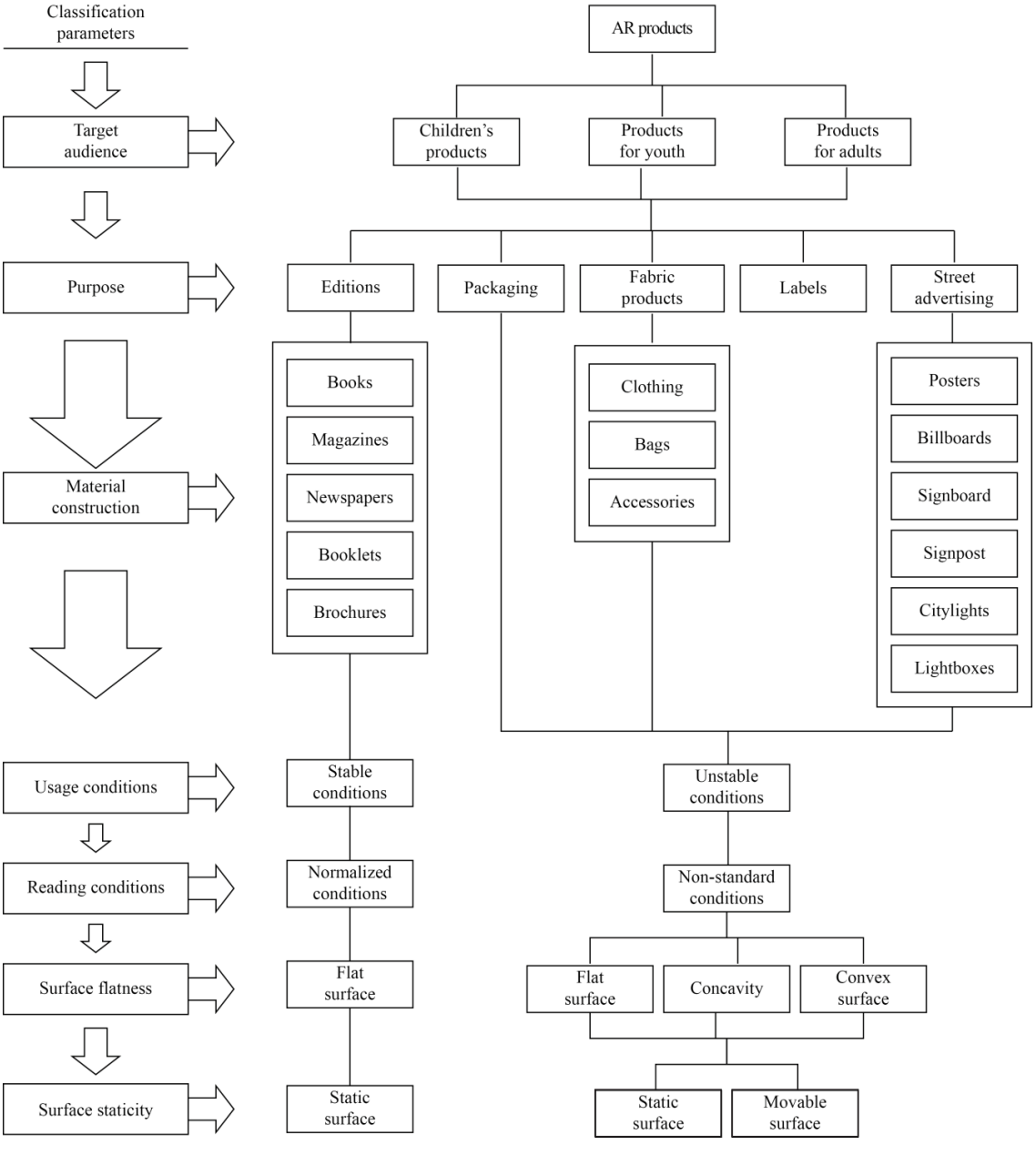

Fig. 6. Classification of products with augmented reality elements

The first subsystem has the most general requirements for normalization, since its parameters have the least impact on the process of marker reproduction, affecting only the quality of reproduced content. In the second subsystem, minimum hardware performance values can be controlled, which qualitatively affect the reproduction of markers. The third subsystem has the most significant impact on the reproduction process, since the possibility to read and then reproduce digital content generally depends on the correct selection of its components. Therefore, this subsystem is considered in detail.

5. 3. 2. Determination of factors influencing the reproduction of each subsystem

In the imprint marker subsystem, we can distinguish the factors influencing the reproduction of AR elements, which can be divided into certain groups:

a) factors corresponding to the characteristics of the printed material: c1 – color of the printed material (CPM); c2 – density of the printed material (DPM); c3 – flexibility of the printed material (FPM); c4 – texture of the printed material (TPM); c5 – presence of additional coverage (PAC); c6 – material resistance to external factors (MREF);

b) factors corresponding to the characteristics of the printing ink: c7 – ink viscosity (IV); c8 – ink gloss (IG); c9 – ink transparency (IT); c10 – ink resistance to external factors (IREF);

c) characteristics of the imprint marker: c11 – marker size (MS); c12 – marker pattern detail (MPD); c13 – marker and background contrast (MBC);

d) external usage conditions: c14 – lighting intensity (LI); c15 – lighting uniformity (LU); c16 – light temperature (LT); c17 – flatness of the surface with a marker (SF); c18 – staticity of the surface with a marker (SS); s19 – weather conditions (WC); c20 – presence of additional protective element (APE); c21 – storage conditions for products with a marker (PSC);

e) printing conditions: c22 – printing method (PM); c23 – image resolution (IR); c24 – line reproduction accuracy (LRA); c25 – number of colors (NC).

In the subsystem of devices for creating and reproducing AR elements, the factors can be identified, which affect not only the reproduction process, but also the imprint system factors:

a) parameters of hardware for creating augmented reality elements (PC, graphic tablet): b1 – amount of operating memory (RAM); b2 – amount of hard disk memory (ROM); b3 – amount of video memory (AVM); b4 – display diagonal (DD); b5 – number of reproduced colors (NRC); b6 – screen brightness (SB); b7 – screen contrast (SC);

b) parameters of hardware for reproducing augmented reality elements (smartphone, tablet): b8 – amount of memory (AM); b9 – number of reproduced colors (NRCR); b10 – screen resolution (SR); b11 – distance and focus parameters (DFP).

In the subsystem of the electronic original, we can single out such a parameter as the amount of memory of the resulting augmented reality element. It has the greatest impact on the parameters of the device subsystem and their correct selection.

Based on certain factors, a system of the most significant parameters of influence on the reproduction of AR markers is formed in the study, the control of which normalizes this process. For this, it is necessary to rank the influence of factors based on building relationships between metrological parameters, forming a reachability matrix and creating a dominant hierarchical ordered model of influence criteria.

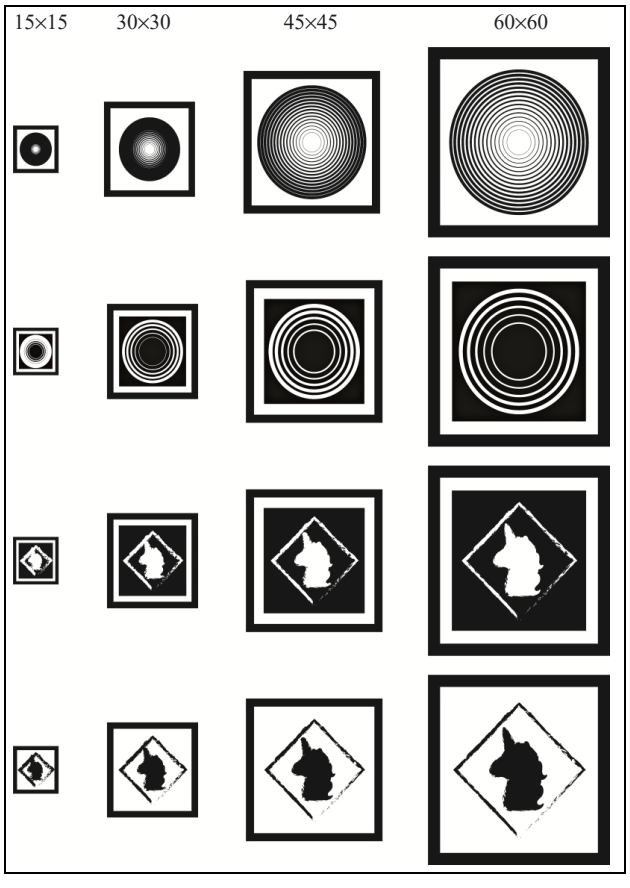

Fig. 7. Sample for performing marker reproduction testing

5. 4. Ranking the influence of factors on each other

To accomplish the objectives set in the previous section, the influence of factors on each other was ranked using the graph method as follows [20, 21]:

1. Building a system of relationships between the above factors using the Adobe Illustrator software based on a survey of experts (21) of various skill levels – students, teachers, printing specialists. The survey used both the respondents' experience and the experiment by scanning test samples (Fig. 7) of different sizes and types in real conditions and assessing the influence of factors on this process.

The assessment was carried out by the following system:

– 2 – high level of significance of the factor influence;

– 1 – medium or insignificant level of influence;

– 0 – almost no influence of the factor on the reproduction process or none at all compared to others.

The created system of relationships is shown in Fig. 8.

2. Next, a reachability matrix is constructed based on Fig. 8. The average value was also calculated and the recalculation was carried out for the «original layout with an AR element – printed material – imprint – reading system – reading conditions – AR elements on the user's device screen» system.

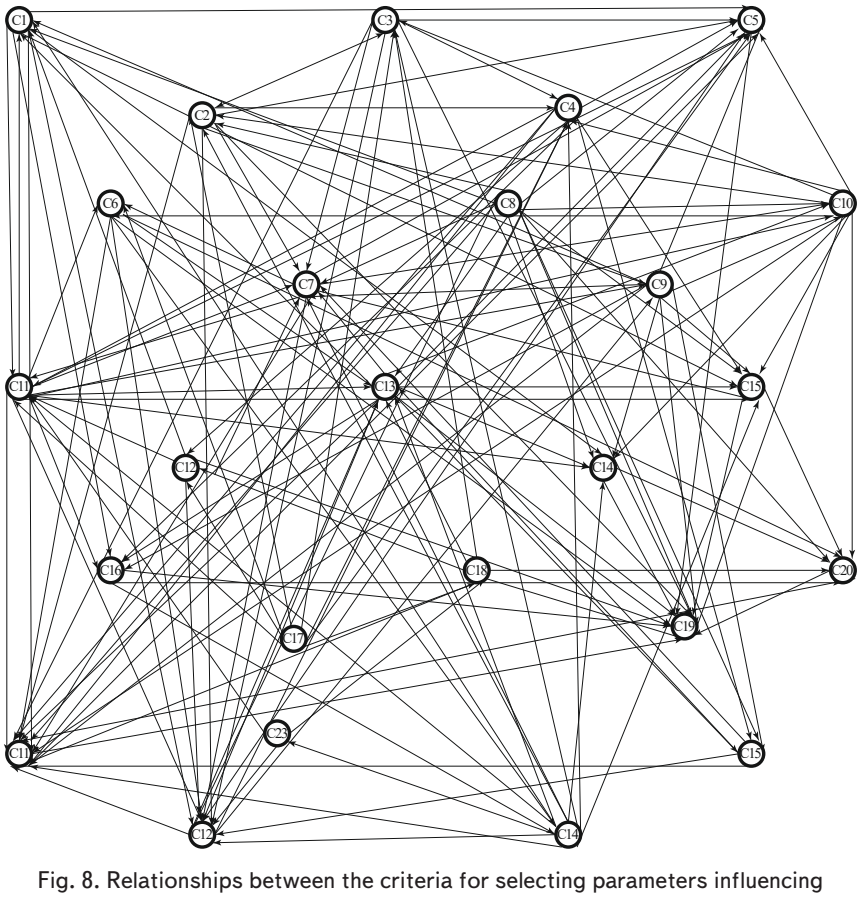

Fig. 8. Relationships between the criteria for selecting parameters influencing the marker reproduction process

This was done using (1), (2) as follows:

$$R=\left[r_{ij}\right], \quad (1)$$

where R – reachability in the graph, $i=j=1, 2, 3, 4...n$; n – an integer number of graph vertices; $r_{ij}=1$, if vertex x_j is reachable from x_i, $r_{ij}=0$, if vertex x_j is unreachable from x_i.

Then for the matrix elements located diagonally, $R=1$, since they are reachable by themselves through a path of length 0. Then the first-order elements $\Gamma^{+1}(x_i)$ are vertices x_j, which can be reached from vertices x_i through a path of length 1. The same dependence is possible for elements of other orders. Then $\Gamma^{+p}(x_i)$ is a set of vertices x_j that can be reached from vertices x_j by a path of length p.

Since x_j can be reached from vertex x_i through a path of length 0 or 1 or 2, ..., or p, then the reachability formula has the following form (2):

$$R(x_i)=\{x_i\}\cdot\Gamma^{+1}(x_i)\cdot\Gamma^{+2}(x_i)\cdot\ldots\cdot\Gamma^{+p}(x_i). \quad (2)$$

It follows that $R(x_i)=T^{+}(x_i)$. That is, the set of vertices x_j that can be reached from vertices x_i through a path of a certain length can be represented as a transitive closure of the latter. Then to construct the matrix, it should be taken into account that $r_{ij}=1$ in the case when $x\in R$ (x_i) and $r_{ij}=0$ in the opposite case.

To evaluate the survey results and build a general reachability matrix, Microsoft Excel calculations of average values of respondents' estimates were used in terms of: values within 1–2 – 1, up to 1 – 0 (Fig. 9). An example of estimating one of the samples is given in Table 2.

3. Estimation of the reachability matrix using the analytical method for the set of vertices C (Table 3).

4. Building a dominant hierarchical ordered model of influence criteria (Fig. 10) using Adobe Illustrator software.

M =

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	1	0	0	0	0
2	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0
3	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	1	0	0	1
5	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
7	0	0	0	0	1	1	1	0	0	1	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0
8	1	1	0	0	1	0	1	1	0	1	0	0	0	1	1	0	0	0	1	1	1	1	0	0	1
9	1	1	0	0	1	0	1	0	1	1	0	0	0	1	1	1	0	0	1	0	1	1	0	0	1
10	0	1	1	1	1	1	0	0	0	1	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0
11	1	0	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	0	1	1	0	0	0
12	1	0	0	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
13	1	0	0	0	1	1	1	1	0	1	0	0	1	1	1	1	0	0	1	0	1	1	0	0	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0
17	0	1	1	1	1	1	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
22	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0
23	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	1	0	0
24	1	1	1	1	0	1	1	0	0	0	1	0	1	1	1	1	0	0	0	0	1	1	1	1	0
25	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	1

Fig. 9. Binary reachability matrix M' for the set of vertices C

Table 2

Example of estimating the significance of factors for the first sample

No. of factor	Respondents' estimate																					
	Students (9 people)									Teachers (7 people)							Printing specialists (5 people)				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	1	2	2	2	1	2	1	1	0	0	0	2	1	1	0	1	2	1	1	0
2	1	2	1	1	2	0	2	1	1	1	1	0	0	0	2	2	1	1	2	0	0
3	2	1	0	0	2	2	1	0	2	2	0	2	0	2	1	0	0	0	1	1	1
4	1	2	0	2	1	0	2	2	1	0	1	1	0	0	1	1	0	0	2	2	0
5	2	0	2	0	2	0	1	1	0	0	1	2	2	1	2	2	0	2	0	2	1
6	1	0	1	0	1	1	0	1	0	2	0	0	2	0	1	1	2	0	1	2	1
7	2	0	2	1	0	1	2	1	1	1	0	0	1	2	0	0	0	0	2	0	0
8	0	2	2	0	2	2	2	1	2	2	0	0	1	1	0	2	0	2	0	2	0
9	2	2	0	1	0	2	2	2	1	2	1	2	1	0	0	1	1	2	1	2	2

Continuation of Table 2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
10	2	2	1	1	2	1	0	2	0	0	0	0	1	2	0	1	1	0	2	1	1
11	0	2	0	2	1	2	2	0	1	0	1	2	0	2	0	1	2	1	1	2	0
12	2	0	1	1	2	0	1	1	0	1	2	0	2	2	2	1	0	1	0	1	2
13	1	0	2	1	0	2	2	1	1	0	2	0	2	2	0	1	2	1	2	0	0
14	0	1	1	1	0	0	1	2	0	0	2	2	1	0	2	1	0	2	2	0	1
15	1	0	2	0	2	2	1	2	2	0	1	2	1	0	1	1	0	2	0	1	1
16	0	0	1	2	1	0	1	0	0	1	2	0	1	0	1	2	0	0	0	2	0
17	1	0	1	1	0	1	2	1	0	1	0	0	2	0	2	0	0	1	1	0	2
18	2	0	1	0	1	2	1	1	0	2	2	1	1	0	1	0	0	0	1	2	1
19	2	0	0	2	1	1	1	1	0	1	1	1	2	1	1	0	0	1	0	2	2
20	0	0	0	0	1	1	1	2	0	2	0	0	1	0	1	0	0	0	1	2	1
21	1	1	0	0	1	1	1	0	2	2	1	1	0	1	2	1	1	1	1	0	0
22	2	2	1	2	2	1	1	0	2	1	0	2	1	1	0	0	2	1	0	0	0
23	2	0	1	1	1	0	2	1	0	0	0	1	2	2	2	2	1	1	1	0	2
24	0	2	2	0	2	1	2	0	0	0	2	1	1	1	2	1	0	1	1	0	1
25	1	2	2	0	0	0	1	2	2	1	2	0	0	2	0	1	0	1	0	0	1

Table 3

Iteration of the analysis of the binary reachability matrix *M′*

No. of level	*i*-th element	$L(c_i)$ – reached vertices	$P(c_i)$ – previous vertices	$L(c_i) \cup P(c_i)$
Defining the first hierarchy level				
a	1	1, 5, 14, 15, 16, 18, 21	1, 8, 9, 11, 12, 13, 22, 24	1
	2	2, 4, 5, 7, 19, 21, 22	2, 3, 8, 9, 10, 17, 24	2
	3	2, 3, 4, 5, 7, 19, 21, 22	3, 10, 17, 18, 24	3
	4	4, 14, 15, 16, 21, 22, 25	2, 3, 4, 5, 10, 11, 12, 17, 24	4
	5	4, 5, 19, 21, 22	1, 2, 3, 5, 7, 8, 9, 10, 11, 13, 17	5
	6	2, 3, 4, 5, 6, 19, 20, 21, 22	6, 7, 10, 11, 13, 17, 24	6
	7	5, 6, 7, 10, 11, 18, 21, 22	2, 3, 7, 8, 9, 12, 13, 24, 25	7
	8	1, 2, 5, 7, 8, 10, 14, 15, 19, 20, 21, 22, 25	8, 13	8
	9	1, 2, 4, 5, 7, 8, 9, 10, 13, 14, 15, 16, 19, 21,22, 25	9, 11	9
	10	2, 3, 4, 5, 6, 10, 14, 15, 19, 20, 21	7, 8, 9, 10, 11, 13	10
	11	1, 4, 5, 6, 9, 10, 11, 13, 14, 15, 16, 18, 21, 22, 25	7, 11, 12, 17, 23, 24	11
	12	1, 4, 11, 12, 18, 19, 22	12, 17, 18	12
	13	1, 5, 6, 7, 8, 9, 10, 13, 14, 15, 16, 19, 21, 22, 25	11, 13, 18, 22, 24, 25	13
	14	14, 19, 20	1, 4, 8, 9, 10, 11, 13, 14, 24	14
	15	15, 19, 20	1, 4, 7, 8, 9, 10, 11, 13, 15, 24	15
	16	16, 19, 20	1, 4, 9, 11, 13, 16, 24	16
	17	2, 3, 4, 5, 6, 11, 12, 17, 22	**17**	17
	18	1, 2, 3, 5, 11, 12, 13, 18, 19, 20, 21	17, 18, 23	18
	19	19	2, 3, 5, 6, 8, 9, 10, 12, 13, 14, 15, 16, 18, 19, 20, 21	19
	20	19, 20, 21	6, 8, 10, 14, 15, 16, 18, 20	20
	21	19, 21	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 18, 20, 21, 22, 24, 25	21
	22	1, 21, 22	2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 22, 23, 24, 25	22
	23	18, 22, 23	23, 24	23
	24	1, 2, 3, 4, 6, 7, 11, 12, 13, 14, 15, 16, 20, 21, 22, 23, 24	**24**	24
	25	7, 17, 12, 13, 21, 22, 25	4, 8, 9, 13, 25	25

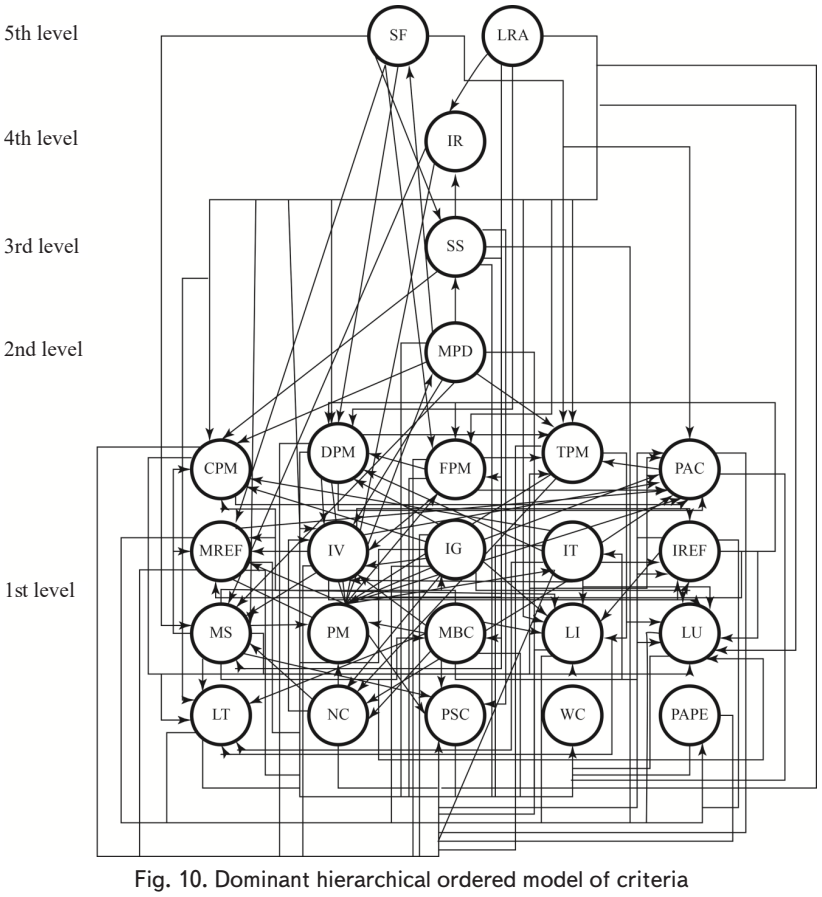

Fig. 10. Dominant hierarchical ordered model of criteria influencing marker reproduction

The last step was to determine the most significant parameters of the components of the «original layout with an AR element – printed material – imprint – reading system – reading conditions – AR elements on the user's device screen» system.

From the analysis of Fig. 8, 10, it can be concluded that this imprint subsystem with an AR marker has many significant factors. The most influential ones are the color, density, flexibility, texture of the printed material; the presence of additional coverage; material and ink resistance to external factors; ink viscosity, gloss and transparency. In addition, such parameters as the marker size; marker and background contrast can be added. Special attention should be paid to the lighting intensity; lighting uniformity; light temperature; weather conditions; the presence of additional protective element; storage conditions for products with a marker; printing method; number of colors.

These parameters are used to form a system of the most significant parameters influencing the process of reproduction of augmented reality markers.

5. 5. Formation of a system of the most significant parameters influencing the process of reproduction of augmented reality markers

To form a system of influencing factors, the most important parameters of the original – printed material – print – marker scanning system components were determined. On this basis, the relationships between the parameters of the subsystems were graphically presented, and the factors that need to be normalized in the case of products with unstable usage conditions were determined.

Then the system of factors is as shown in Fig. 11.

As can be seen from Fig. 11, the most important parameter influenced by the imprint subsystem is the distance and focus of the smartphone or tablet camera. This is due to the fact that the minimum focusing distance of the device camera depends on the correct setting and choice of the imprint subsystem parameters. This implies the possibility of further scanning, recognition and reproduction of augmented reality markers.

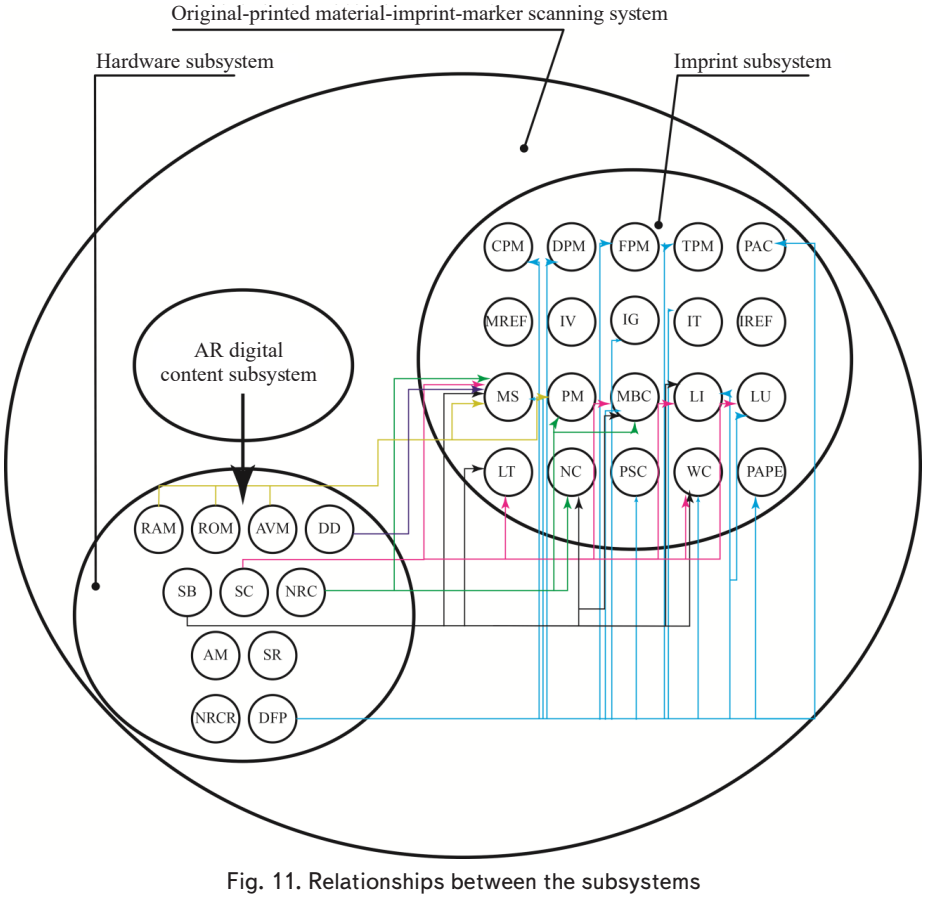

Fig. 11. Relationships between the subsystems of the original — printed material — print — marker scanning system

The digital content subsystem as a whole affects the hardware subsystem. The main system parameter – data volume – affects the memory capacity of the hardware for creating AR elements and hardware for reproducing them. The content and its features affect the choice of the minimum number of reproduced colors, the brightness and contrast of the display, as well as display resolution.

6. Discussion of the results of research on the factors determining the quality of reproduction of augmented reality markers

The results of the patent search (Fig. 1–4) made it possible to see an overall picture of the development of augmented reality, as well as to determine the problems and directions of research.

This area has attracted the attention of many researchers and continued to develop and be studied rapidly since 2016. This is due to the rapid development of digital technologies in this period and the emergence of new opportunities for expressing digital and printed products. It was also investigated that such areas as software for creating augmented reality elements and augmented reality products are being studied more. In the field of augmented reality technologies, researchers are more interested in the technologies for reading and reproducing markers, while research into technologies for creating elements has somewhat stopped. In addition, marker reproducing devices are being explored rather slowly, since at this stage the use of such products does not require new sophisticated equipment.

Augmented reality technology is used in various fields, but most of all in the following 5 ones – science, education, medicine, video games and printed products (printing). As can be seen (Fig. 4), in the beginning, this technology developed mainly in the first 2 areas. This was associated with the development of research on this topic and the level of technologies being developed. Over time, according to the level of knowledge accumulated, it became possible to apply this technology on a large scale in the field of computer games. Then, with the development of digital technologies, the rapid use of augmented reality in printed materials began.

A study of the application of augmented reality (Fig. 5–6) gave the following results: augmented reality occupies many niches, but one of the new and increasingly popular is printing. According to Fig. 6, two large groups of products to apply elements of this technology can be distinguished – products with stable and unstable and non-standardized usage conditions. According to Fig. 6, there are 4 main and currently most popular types of products – books, clothes, street advertising and packaging.

The main type of products on which augmented reality can be applied are books, newspapers, magazines, leaflets, booklets, brochures, etc. This is the «traditional» application of such technology. The manufacture and use of such products provide for stable conditions with certain requirements for the processes and materials used without significant environmental impact on the marker characteristics. This is the most studied area in terms of the development of augmented reality.

However, the digital sphere is capturing more and more users. Therefore, traditional printed products fade into the background. Such types of printed products as packaging, labels, fabric products and street advertising come to the fore, which will be popular and demanded in any case. But, analyzing the review and search conducted, there are almost no studies of products with unstable usage conditions.

As noted above, another application is packaging and labeling. They have more unstable usage conditions than the previous type of products. It can be the shape of the object, its chemical composition, which have an effect when in contact with the printed marker, material characteristics (strength, flexibility, color, etc.), and so on.

The next fairly new direction in the application of augmented reality is clothing and fabric products. This is a new area that will gain popularity in the future. It allows you, for example, to try on selected clothes or shoes according to your parameters or find out interesting information about the product composition and the company. This type of product also has unstable conditions for creation and use, which should be controlled and standardized. First of all, the possibility of repeated mechanical friction and interaction of the marker with chemicals during washing should be taken into account. In addition, fabric characteristics (porosity, flexibility, «staininess») and color fading over time should be taken into account, which can affect the reading and reproduction of markers.

Another type of products that can use augmented reality is outdoor advertising products – posters, billboards, signs, etc. They have the most unstable usage conditions, which are not sufficiently studied, since this area is only gaining popularity. Therefore, this area requires a detailed study and development of requirements for their regulation and control. In particular, the thermal effect on color reproduction and fading, the presence of glass and the effect of glare on marker reading and reproduction should be taken into account. Also, one should not forget about the possibility to scan markers in dynamics, chemical exposure, wind and moisture effects, flexibility of materials, etc.

The results of the study of using augmented reality in the printing industry demonstrate that popular types of products (textiles, packaging) are poorly explored. They have more issues and impacts to consider when designing AR elements, but they are much less investigated than books having stable usage conditions. In addition, it was determined that now research in the field of AR technologies is carried out more for reading technologies, since there are many development technologies and they have already been deeply investigated.

The graph method used (Fig. 8–11, Tables 2, 3) and its results made it possible to see a picture of the impact on the process of reading and reproducing AR markers and highlight the most significant factors influencing the original – printed material – print – marker scanning system. Correct adjustment of the optimum values of these parameters affects not only the use of finished products, but also the implementation of the manufacturing process as a whole. The most significant factors are the color, density, flexibility, texture of the printed material; the presence of additional coverage; material and ink resistance to external factors. Also, it should not be forgotten about the viscosity, gloss, transparency of the ink. In addition, marker size; marker and background contrast are important. Special control is required for lighting intensity and uniformity; light temperature; weather conditions; presence of additional protective element; storage conditions for products with a marker; printing method; number of colors. These factors are crucial in the reproduction of digital elements encrypted in the marker. No matter how unusual and interesting the product is, no matter how powerful and optimally calibrated the hardware is, everything

depends on the characteristics of materials, environmental and printing conditions.

Comparing the results with the works of other researchers [4–8], it can be concluded that they can supplement and deepen them. Then, the development of test objects will take into account not only the level of respondents' knowledge, but also the system of factors influencing the experimental results.

Also, the results allow overcoming the drawback [9, 10] that the studies were carried out within one selected technology, without considering them in a complex to determine requirements for the correct reproduction of markers under any conditions, despite the chosen technology. In addition, the factors influencing the reproduction of augmented reality elements were considered only on the one hand, without taking into account their complex effect. In this study, the factors and their influence are considered comprehensively and systematically. This approach allows the development of high-quality products using any technology that is valid in any conditions.

Also, these results allow expanding the level of knowledge in classical printing. Compared to [17–19], they make it possible to qualitatively combine the printing and digital areas, accurately embedding into each other without the probability of non-reproduction of elements.

The difference of the study from others is that it highlights the factors influencing the reproduction of AR elements on printed products in non-normalized scanning conditions.

Further studies of the influence of these technologically significant factors on the process of reproducing augmented reality elements make it possible to determine their optimal values. This, in turn, helps to create a system for normalizing these metrological characteristics of the original – printed material – print – marker scanning system for products with unstable usage conditions.

7. Conclusions

1. It was determined that augmented reality is a rather interesting topic, which is still rapidly developing and being researched. This is supported by the number of patents and papers reviewed during the study. It was found that most of the studies consider augmented reality as a product (35 %), products with augmented reality elements (25 %) and «augmented reality technology» (40 %). At the same time, there is stagnation in the segment of patenting «devices for reproducing AR elements» (10–12 %) as there is no need for complex and expensive reproduction equipment. All that is needed is a user's phone or tablet with special software. Also, a shift in patenting by topic from the scientific sphere to entertainment, as well as the addition of AR elements to printed products, was found. Namely, the number of patents in the field of science decreased from 70 % to 25 % (from 2014 to 2021) and in the field of entertainment and printing increased from 25 % in 2012 to 50 % (starting from 2018). The results obtained allowed us to assert that the regulation of the process of reading augmented reality markers from printed materials in unstable conditions is an urgent scientific task. The main explanation is the emergence of a new group of problems – a variety of factors causing errors in content reproduction, and, as a result, the search for possible ways to overcome them.

2. Consideration and identification of the main areas of application of augmented reality and the study of their features made it possible to define problematic and little-studied ones. It was found that with the development of digital technologies and the use of AR elements to increase the informativeness and attractiveness of products, the list of printed products containing augmented reality elements has expanded. However, the conditions for their use are most often not standardized and unstable. This leads to uncertainty and possible misreading. Therefore, the use of augmented reality markers on products with unstable usage conditions (70 % of sales compared to traditional) is a poorly studied issue (35 % of research compared to traditional). That is, there are a number of factors affecting the operation of the «original layout with an AR element (electronic file) – printed material – imprint – reading system (AR element scanning) – reading conditions – AR elements on the user's device screen» system.

3. To determine the metrological parameters of the system, it was divided into three subsystems. This is the subsystem of the digital original, hardware for creating and reproducing markers and the imprint subsystem. In each of them, the factors of influence on the reproduction of augmented reality elements were determined. For example, in the hardware subsystem, these are device parameters (memory size, resolution, etc.), digital original – file size, imprint – material parameters, usage conditions, etc. The influence of each subsystem on the entire system was determined. This made it possible to identify the most influential one, which requires the most in-depth and detailed research – this is the imprint subsystem. As it was determined, it has the largest number of non-normalized factors that require study and control. Five groups of technologically significant factors were identified, namely, parameters of the printed material, ink characteristics, marker features, external conditions and printing conditions.

4. Under the presented methodology, based on the graph method, the selected technologically significant factors were ranked. The ranking was carried out by the experiment involving 21 experts of different skill levels (students, teachers, printing specialists) using a test sample on different materials. Respondents determined the influence of the factors based on their own experience and actual participation in the experiment. The data were processed by the described method, and the significance of the factors was studied. As a result, a 5-level system of the imprint subsystem factors was determined. The results revealed that the most significant factors are related to the first level of the system. These include parameters of printed materials, external usage conditions (lighting, weather conditions and usage conditions), printing parameters (printing method and number of colors). In addition, the parameters of other subsystems were determined and their influence on each other and on the factors of other subsystems was found. The results are explained by objective and subjective assessments of the significance of factors relative to each other and the possibility to reproduce augmented reality markers when their values change.

5. Building relationships between the parameters of subsystems made it possible to comprehensively understand the problem posed and form a common system of the most significant parameters of influence on the process of reproducing AR markers. These include material characteristics (flexibility, smoothness, density, etc.), marker indicators (size, color), and product usage conditions (lighting, weather conditions). A group of important factors, such as reading parameters (distance to the marker, camera focusing parameters, etc.) and amount of augmented reality data can

also be highlighted. By minimizing and optimizing the values of certain technologically significant factors in accordance with the characteristics of the selected product, it is possible to develop recommendations for normalizing the process of reproducing markers for products with unstable usage conditions under any conditions. Further experimental studies on this topic will concern quantifying and developing technological instructions and recommendations, which can be applied in practice for the manufacture of augmented reality products in any conditions.

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