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Development of methods for visualization of three-dimensional objects using augmented reality technology

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CONTENTS

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DEFINITIONS

The following terms are used in this dissertation together with the corresponding definitions:

Augmented Reality (AR) – one of many human-computer interaction technologies. Its specificity lies in the fact that it programmatically visually combines two initially independent spaces: the world of real objects around us and the virtual world recreated on a computer.

Virtual reality, (VR) - a highly advanced form of computer simulation that allows the user to immerse themselves in an artificial world and directly act in it using special sensory devices that link their movements to audiovisual effects. In this case, the visual, auditory, tactile and motor sensations of the user are replaced by their imitation generated by the computer.

Mixed reality - is a combination of virtual (VR) and augmented (AR) reality. It is activated with the help of special digital systems and either partially complements the perception of the environment, or completely changes it.

Three-dimensional space (3D space) - geometric model of the material world. This space is called three-dimensional, since it has three homogeneous dimensions - length, width and height, that is, three-dimensional space is described by three-unit orthogonal vectors.

3D visualization, object 3d visualization - is a visualization of individual objects that can be used as advertising images, illustrations, etc.

ABBREVIATIONS

API - Application Programming Interface
AR - Augmented Reality
JS - JavaScript
JSON - JavaScript object notation (object in JavaScript notation)
MT - Mixed Reality
REST - Representational State Transfer
SDK - Software Development Kit
SLAM - Visual Simultaneous Localization and Mapping (simultaneous localization and mapping)
UML - Unified Modeling Language
VR - Virtual Reality
IS - Information System
DBMS - Database Management System
IoT - Internet of Things
UAV - unmanned aerial vehicle

INTRODUCTION

The relevance of research. Currently, there is a further formation of the information society, in which the dominant activity is associated with the production of an information product.

How effectively a person can work with information depends on his integration into this society.

In addition, the information flows that modern specialists need to navigate are steadily increasing, stimulating the development of new technologies (a set of tools and methods) for working with information, i.e., information technologies.

The computer remains the main technical means of modern information technologies, the hardware and software of which make it possible to automate many information processes, including telecommunication interaction.

The globalization of virtual reality has led to the introduction of a new term "augmented reality" into scientific circulation.

If the current user interface technologies are focused mainly on the interaction of a person and a computer, then augmented reality with the help of computer technology offers an improvement in the human interface and the real world around.

The modern stage of augmented reality research began in the 1990s. Abroad, many works have been published on the relevance and serious potential of this topic. However, the development of consumer electronics has only now reached a level that can ensure the mass adoption of this technology.

Now, augmented reality is one of the most relevant objects for research, because the niche has not yet been filled by major players. However, in Kazakhstan this topic is not given proper attention.

But if we intensify scientific and practical research in this area for popularization and widespread implementation, then Kazakhstan can join the ranks of the main researchers.

The purpose of the study is to create a set of models and methods for assessing augmented reality traffic, as well as assessing the quality of perception of augmented reality applications by the user.

Research objectives.

To achieve the goal of the study, the following interrelated tasks were set and solved:

1) analysis of the current state in the field of augmented reality research, identifying the shortcomings of modern augmented reality systems and suggesting methods for their solution;

2) search and analysis of methods for visualization of three-dimensional objects and software for research purposes;

3) development of information system structures with interactive visualization technology using augmented reality;

4) search for a method for increasing the realism of displaying three-dimensional objects using augmented reality;

5) to implement an information system with interactive visualization technology using augmented reality in the form of a software-algorithmic complex.

The objects of research in the dissertation work are computer methods of information processing.

The subject of research is an information system with interactive visualization technology using augmented reality.

The theoretical and methodological basis of the research is research in the field of image processing and analysis, computer graphics and human-computer interaction.

In the course of the research, the works of both foreign and Kazakh scientists were used (R. Azuma, M. Billingharst, O. Bimber, D. Wagner, B. Victor, F. Kisino, T. Kodel, A. Kay, V.I. Loiko, S. Mann, P. Milgram, D. Mitsel, D. Ruskin, I. Sutherland, S. Siltanen, S. Finer, G. Fitzmaurice, D. Schmalstieg, D. Engelbart, A. Kuandykov, R. Uskenbayeva, Daineko E.A., Ipalakova M.T., Amirgaliyev B.Y., etc.), who made a significant contribution to the development of the theory of information systems, the development of issues of human-computer interaction, user interfaces and augmented reality.

Research methods. In the process of performing the work, methods of computer graphics and modeling were used.

Scientific novelty. The following main scientific results were obtained in the dissertation work:

1. A new classification of augmented reality applications is proposed, considering applications for the Tactile Internet and the Internet of Skills.

2. A method for representing augmented reality user traffic has been developed, consisting of three interrelated models: a service space model, a user perception area model, which is a part of the service space that a user can perceive at a particular point in time, and a mobile user behavior model that characterizes changes in his position and areas of perception.

3. A model of the user's service space has been developed, which differs in that when providing augmented reality services, in addition to an interactive data request at the user's request, the possibility of a predictive data request at the decision of the client application is also considered.

4. A model of the user perception area has been developed, characterized in that the predicted user perception area is represented as an ellipse built based on the probable user coordinates and the probable area of user perception of data, which makes it possible to provide at least 25% more efficiency than when using other figures.

5. A model of behavior of a mobile user of an augmented reality service moving in the environment of Internet of Things devices has been developed, which differs from the known ones in that the user is represented as a queuing system M/G/1, and the incoming stream is formed from K services available to the user, including video , text, graphics, speech, music, tactile sensations, etc., which makes it possible to calculate such systems using the queuing theory apparatus.

6. The distributions of the speeds of pedestrians, drivers and passengers of vehicles are determined, differing in that these distributions are used to obtain estimates of augmented reality user traffic.

The provisions submitted for defense

1. Methods for representing augmented reality user traffic based on three interrelated models: service space model, user perception area model, which is a part of the service space that the user can perceive at a particular point in time, and a mobile user behavior model that characterizes changes in his position and area perception.

2. Model of the user's service space, which considers, in addition to the interactive data at the user's request, the possibility of predictive data request according to the decision of the client application.

3. User perception area model, in which the predicted user perception area is represented as an ellipse based on the probable user coordinates and the probable user perception area, which makes it possible to provide at least 25% more efficiency than other figures.

4. Behavior model of a mobile user of an augmented reality service moving in the environment of Internet of Things devices, in which the user is represented as a queuing system M/G/1, and the incoming stream is formed from K services available to the user, including video, text, graphics, speech, music, tactile sensations, etc., which makes it possible to calculate such systems using the apparatus of queuing theory.

5. Augmented reality user traffic model with the user’s forward movement in the Poisson field under the conditions of determining the user’s perception area in the form of a sector, represented in the Kendall-Basharin classification, how $\frac{M(\alpha,r,\rho,v,\omega)}{G}/1$, when α – sector angle, r – radius, ρ – density devices in the sector, v– is the speed of the user's movement, ω –is the angular speed of rotation.

The practical significance of the research is the possibility of direct application of the developed information system in real business processes of design, trade and a number of other areas.

Publication of research results

The main provisions and scientific results of the work were reported and discussed at the seminars of the department "Computer Engineering and Information Security" of the International University of Information Technologies and at international scientific conferences:

The 13th International Conference on Control, Automation and Systems, ICCAS 2014 (South Korea, Busan, 2014);

The 10th International Conference on Future Networks and Communications / The 12th International Conference on MobiSPC 2015 (Belfort, France 2015).

The main results obtained during the dissertation work were published in 7 publications [1], of which 3 articles were published in publications recommended by the Committee this on control in the field of education and science of the Ministry of Education and Science of the Republic of Kazakhstan, 1 article was published in publications indexed by the Scopus database, 2 articles published in collections of international foreign conferences (South Korea, France).

Structure and scope of work

The structure of the work is determined by the goal and the sequence of solving the formulated tasks and is built according to the problem-thematic principle.

The dissertation consists of an introduction, four chapters, a conclusion, and a bibliographic list, which includes 40 titles of sources and literature used.

1 AUGMENTED REALITY, ITS PROPERTIES AND FEATURES

This chapter analyzes augmented reality applications and classifies them based on different criteria. Augmented reality devices are also being explored, making this technology different from all others.

1.1 Analysis of application areas of augmented reality applications

The term "virtual reality" (English virtual reality, VR) was introduced into mass circulation in the 1980s. J. Lanier is a computer specialist, entrepreneur and even a musician [1,p. 2]. After this moment, the term "virtual reality" has undergone many interpretations, but the most preferable is the definition developed by Valeria Kholodkova, a specialist at EligoVision, since the definition focuses on the visualization of information as one of the features of virtual reality. Virtual reality (English virtual reality, VR) is a technology that is built on the feedback between a person and the world synthesized by a computer, as well as the way a person visualizes the digital world, manipulates it, interacts with it [2].

The definition of augmented reality (AR) has also been introduced recently. The term was originally proposed by researcher Tom Codel in 1990, who at the time was working for Boeing. In 1997, Ronald T. Azuma, in his study on the various ways of using augmented reality, gave it a fairly capacious and simple definition - it is a system that:

- combines virtual and real.
- interact in real time.
- located in three-dimensional space.

Augmented reality, according to Azuma, is a kind of virtual reality, but with one caveat: AR integrates and complements the real world instead of completely replacing it, as VR does [3].

Many analytics companies are predicting an increase in the popularity of virtual and augmented reality technologies in modern culture. So, for example, according to BI Intelligence data, since the beginning of 2015, the growth of virtual reality devices will reach 99% per year, which, according to the forecast, will lead to the fact that by 2020 the volume of the market for virtual reality devices will be about $ 3 billion [4].

Analysts from ABI Research predict that the total number of VR/AR devices will grow to 65 million copies by 2020 [5].

These forecasts are quite justified, as the leaders of IT companies are already ready to invest huge amounts of money in the development of VR/AR. Facebook CEO Mark Zuckerberg comments on the VR market: “I've been looking forward to the day when we can finally immerse ourselves in virtual reality, and now the day has come. Everything is possible today” [6]. In addition, Mark Zuckerberg acquired Oculus for $2 billion, which creates a virtual reality helmet. Another example is Microsoft CEO Satya Nadela, who took over in 2014 and is already under his leadership. The company is making great efforts to promote its HoloLens augmented reality glasses. Microsoft itself speaks of HoloLens and Virtual Reality in general as a new stage in the evolution of computer science [7]. In addition to the companies such as HTC, Sony, Samsung, Google have entered the VR/AR research race.

Today, almost all available sectors of creative industries transmit visual information. Virtual and augmented reality technologies allow expanding the possibilities of information visualization and solving several problems with the help of this. But, before moving on to the consideration of problems and ways to solve them, we will consider the definition of creative industries and identify its main sectors.

One of the first countries to pay special attention to the creative industries was the United Kingdom. Since 1998, the country's department of culture has been engaged in this area, as a result, Britain is the world leader in terms of the degree of development of creative industries.

All existing sub-sectors of the creative industries convey visual information to a greater or lesser extent. Since modern VR/AR technologies serve to convey visual information, we will look at the problems associated with this area, using the example of three key sub-sectors (film industry, museum and exhibition activities and tourism) and analyze how they can be solved, or are already being solved with the help of VR/AR technologies.

Museums and gallery business. In the age of modern technology, when we began to receive information in various ways using a wide variety of devices, most museums have not adapted to reality and continue to transmit information using traditional methods to this day.

A new presentation of information in museums is also possible with the help of VR/AR technologies. The creation of virtual spaces will help to save on the creation of an interactive museum; besides, it adds some features that are quite difficult to implement. One example of the creation of a VR / AR museum is the "Palace of Schoolchildren" in the city of Astana. The museum helps children in choosing their future profession.

A smaller project is implemented by Great Gonzo Studio. The Great Gonzo team comes to various events and shows a new way of visualizing art objects, which is called "immersive painting" - a person, wearing a helmet, moves from real space to virtual space and finds himself, as it were, inside the picture, where he can explore it from different angles.

Tourism industry. The first and main problem of tourism during the COVID-19 pandemic is related to the impossibility of a person due to fear of travel or physical inability to travel, but there is a need for this.

This problem can be partially solved with the help of virtual and augmented reality. At the moment, the easiest way to implement it is to use immersive virtual reality using Google Street View or similar applications, of which there are a lot on the Internet. But, alas, this method cannot give a sense of travel since a person is not given the opportunity to move around space on his own without the help of an interface. As mentioned earlier, the presence effect in VR must provide all the sensations inherent in the normal movement of the body in space, otherwise the illusion will be lost, since the "picture" for the eyes will not be consistent with the experience of a person experienced in real life, constantly moving in space.

There is a second option, The Void, a startup that allows you to walk in a virtual space using a “holo-camera”, about 20 by 20 meters in size, where you can move freely in any direction. The creators of The Void have achieved the effect of unlimited space in virtual reality through a few tricks. For example, when a person wearing a vest turns 90 degrees, in virtual reality they turn only 80 degrees. This is almost imperceptible for the user but allows you to achieve the illusion of unlimited space, preventing the visitor from resting against the wall. He may think he is moving straight when he is walking in circles. In the future, this technology can be used to implement travel, and now, only high-quality content is missing.

Thus, the analysis of the three creative industries demonstrates the possibilities of VR/AR technologies in solving the problems of visual information transmission in the creative industries, as well as in solving various problems of society. As Mark Zuckerberg notes, commenting on a sensational photo from the World Mobile Congress in Barcelona, where the journalists in the hall did not notice him, carried away by watching the video in virtual reality, at that moment the glasses showed children playing football, and everyone who was in the hall was worried the same deep and personalized experience that could not be achieved with any other technology. Mark recalls that people are social by nature, so anti-social technologies simply do not have a chance of success [8]. An analysis of the experience of solving social problems of our time through VR / AR technologies is a perspective for researching this topic.

1.2 Classification of augmented reality applications

A person has a whole set of sensory organs that allow him to get an idea of the surrounding space. The augmented reality system is an intermediary between reality and a person, which means that at the output it must create a signal for one of these organs. Thus, the following systems can be distinguished by the type of information presentation:

1. Visual. These systems are based on human visual perception. The task of such systems is to create an image that can be used by a person to achieve his goals. This type of system is more common due to the peculiarities of human perception - the image for a person is more informative and understandable.

2. Audio. Systems of this type are focused on auditory perception. The features of such systems are considered in [5, p. 6]. As a rule, these systems are used as navigators. When a person reaches a certain place, they can give out various sounds. It is possible to use a stereoscopic effect, which allows a person to walk in the right direction, focusing on the sound source. An example of such a system is Hear&There [6,p. 8].

3. Audiovisual. These systems are a combination of the two previous types, but the audio information in them is of an auxiliary nature.

Augmented reality systems must receive information about the environment. It is based on this information that virtual objects are built. Each of these systems has a certain set of sensors - devices that allow you to record various environmental signals: sound and electromagnetic vibrations, acceleration, etc. For classification, it makes sense to separate sensors not according to the types of recorded physical quantities, but according to their purpose, since signals similar in nature can carry different information. The following systems can be distinguished by type of sensors:

1. Geolocation. Such systems are guided primarily by the signals of GPS positioning systems [7, p. 9]. In addition to receivers for such signals, geo positioning systems may be equipped with a compass and an accelerometer to determine the angle of rotation relative to the vertical and azimuth.

2. Optical. These systems work with the image obtained from one or more cameras. Cameras can move with or without the system.

Systems can vary in the degree of user interaction. In several systems, the user plays a passive role, he observes the reaction of the system to a change in the environment. But there are also systems that require active user intervention - he can manage both the operation of the system itself in order to achieve results and change virtual objects. On this basis, the following systems can be distinguished:

1. Autonomous. Such systems do not require user intervention to operate. The task of such systems is to provide information about objects. For example, such systems can analyze objects that are in the field of view of a person and provide background information about them. Also, systems of this type are used in medicine. For example, the Gait Aid system [9] is used to provide the brain with additional information by using virtual objects to help coordinate movements. This system is used by people with disorders of the musculoskeletal system.

2. Interactive. The operation of these systems is based on interaction with the user. Such systems give a different response to different user actions. Such systems need an input device. Such a device can be a touch screen of a mobile device, a tablet, or a special manipulator. The choice of input devices depends on the specifics of the system. If the user needs to perform simple actions with a virtual object, a simple pointing device is sufficient. In the case of simulating any real processes and performing complex manipulations with objects, special manipulators are used that have a different number of degrees of freedom. The PHANTOM devices [10] can serve as an example.

Interactivity can be expressed in different ways. There are systems that allow the user to actively change the virtual environment [11]. Basically, these are simulation systems of any real actions. They are used when the use of real objects is not possible. These can be, for example, medical simulators that allow novice doctors to develop the necessary skills [2, p. 5].

There are other systems where the user does not need to modify the virtual environment. Instead, the user chooses which virtual objects he wants to see. The user also can manipulate virtual objects, but not at the structure level, but at the display level, i.e., do, for example, affine transformations such as rotation, displacement, etc. This group includes various architectural systems [12], which allow you to see how a new structure or part of it will fit into the existing environment, as well as navigation and geographic information systems [13]. Such systems may, for example, show parts of objects of interest hidden by other buildings, information about selected objects, and so on.

Also, according to the degree of mobility, the following augmented reality systems can be distinguished:

1. Stationary. Systems of this type are designed to operate in a fixed location; the movement of such systems leads to a partial or complete suspension of their functioning.

2. Mobile. Systems of this type can be easily moved; often their movement is the basis of their function.

Belonging to a particular type is determined by the functions of the system. Thus, a surgical table simulator should not be mobile, since its task is to allow a person to work in conditions that are as close to real as possible. At the same time, the navigation system must be such that it can move with a vehicle or a person without creating additional costs for its movement.

Table 1.1 - classification of AR applications

Classification criterion	Types of AR Applications	AR application example
Information presentation types	visual system	Sketchand+
	Audio systems	Navigation information systems
	Audiovisual systems	Excursions with AR glasses
	Text or graphics systems	Applications of the Tactile Internet
	Holographic systems	GateBox smart home assistant
Object recognition methods	Geolocation	WallaMe
	With image recognition	Face recognition systems
	marker ones	Applications for museums
Ways for User Interaction	Autonomous	EyeDecide Diagnostics
	Interactive	Game ConductAR
Type of mobility	Stationary	Remote surgery VIPAR
	Mobile	SmartReality Drawings
Purpose of the service	Medicine	AccuVein
	Assembly, repair and maintenance of equipment	Instructions for diagnosing a breakdown
	Annotation and visualization	MaxReality Weather
	Robotic systems control	Automotive Diagnostics
	Games and entertainment	PokemonGo
	Trade	IKEA
	Education	Educational AR, SMART game
	Military industry	Visualization of operational information
Security type	Objects of increased danger	Smart Energy
	Safe objects	AMC Theaters poster
Degree of impact on the environment	Managers	Smart home Zac
	Informative	Interactive shopping center map

1.3 Augmented reality devices

The forms of displaying information and interacting with objects of the real and virtual worlds in AR applications are so diverse that the devices used to implement the applications are also very different. Among them are such as augmented reality glasses, projectors, lenses, tablets, helmets, and the most numerous categories of devices -

smartphones. A distinctive feature of augmented reality devices is the ability to communicate with other devices using various wireless technologies. The AR device recognizes the object and sends a request about it to the server via the communication network. Let's take a closer look at some devices.

1.3.1 Lightform Project

The Lightform scanner is a small device [14] and is shown in figure 1.1.

Figure 1.1 - Lightform Augmented Reality Projector

The Lightform AR device is designed for situations where the use of a helmet or AR goggles is not possible or practical. The device is a 3D scanner that allows you to create a three-dimensional map of the room in all details. The location of objects in space is fixed, stored in memory, and subsequently used as a projection surface.

Inside the device is a high-resolution camera that allows you to capture the smallest objects in the room and scan them, after which the Lightform application can display various information on the scanned surfaces. The device connects to any computer and projector via HDMI. On a computer, any image is processed and prepared for display in three dimensions. Having received information about the location of objects from Lightform, the computer sends the image to the projector, which renders a three-dimensional image. The Lightform Creator software allows you to edit the resulting images and how they appear on the surface by adding various effects or data.

So, an ordinary clock in the kitchen can display a hint that it's time to leave the house or make an important call. Houseplants can visually remind you that you forgot to water them today and what can happen to them. And lying in the bathroom, on the wall, you can watch movies or read e-mail. The device was planned to be used both at home and in commercial organizations.

Lightform works with stationary objects, in case of movement of the object, the projection image on it is broken. However, the company claims that the device quickly reconfigures and rescans the desired object in less than a minute. To ensure the speed of the device, high-performance hardware components are used that can independently perform calculations. To detail the space and analyze the geometry of the room, a high-resolution camera and algorithms based on artificial intelligence are used, which allows the scanner to accurately recreate the room with all the objects in it and capture even small movements of objects within it.

The advantages of this device include a compact size, the ability to project images on any surface, quick setup. The disadvantages include the lack of mobility, the need to connect additional equipment, and the relatively high cost.

1.3.2 3D SID Camera

Weeview, which is the manufacturer of the Eye-Plug, the world's first detachable 3D camera compatible with smartphones, has presented its new development of a 3D camera that superimposes special effects of augmented reality [15]. Innovative SID technology for stereoscopic viewing allows you to create your own world with incredible 3D content.

This camera is small and capable of recording 3D videos, with users being able to adjust video settings for optimal stereoscopic effects. To work with the SID camera, you need to download a mobile application that will allow you to implement functions such as live 3D broadcasting, bringing to the fore to increase individual objects in the video image, and for tracking an object in the video. The camera allows you to shoot video with a maximum resolution of 2880x1440 (3K) at 30 frames per second, as well as 32 MP photos with a resolution of 8064x4032. Two stereoscopic cameras have F2.4 lenses with a field of view of 1600. The novelty is equipped with a Wi-Fi adapter according to the IEEE 802.11n standard for wireless connectivity, a microUSB port for charging and a microSD card slot for storage. The appearance of the camera is shown in figure 1.2.

Figure 1.2 - SID Camera Appearance

Among the advantages of the camera, one can single out compact dimensions, the ability to shoot high-resolution 3D video and apply DR effects to it, connection to various devices, reasonable cost. However, inconvenience is the lack of a screen and the lack of sale. The project is under development, and the sale of devices is limited.

1.3.3 Intel RealSense 3D Camera

The augmented reality camera takes AR services and applications to the next level, opening almost unlimited possibilities. Intel was one of the first to offer its development. The camera was not released to the public but was distributed to various scientific and university laboratories for research and to determine possible applications for the camera. It is these cameras that are used in scientific and educational activities at the Department of Communication Networks and Data Transmission of the St. Petersburg State University of Telecommunications. prof. M.A. Bonch-Bruevich. In the future, Intel planned to embed such cameras in laptops, tablets, smartphones, and TVs [16]. The appearance of the camera is shown in figure 1.3.

Figure 1.3 - Intel Augmented Reality Camera

The Intel RealSense 3D Camera reads 78 points on a person's face and can detect any emotion a viewer experiences while watching a video. It consists of the front camera F200, which includes 2 cameras: the first shoots video in RGB color mode, the second is a stereoscopic infrared camera that allows you to capture the depth of the image. The operating range of the camera is not large up to 1.5 m, but it provides high accuracy in face and gesture recognition, which allows you to control various processes using hand and head movements. The scope of its application is extensive, one of the main areas is helping people with disabilities.

Cameras of AR and other manufacturers are known, for example, the company Kinect, which develops its solutions to a greater extent for business tasks and computer games.

1.3.4. "Smart" contact lenses

Smart Contact Lenses or “smart” contact lenses have been on the market for quite some time and have already generated a wave of interest among developers of AR applications. Due to their convenience and practicality, they can replace many AR devices and compete with augmented reality glasses. Lenses are small enough to put on and you get access to various AR services, while AR glasses do not always have the necessary functions and need to be connected to a smartphone, which creates some inconvenience.

One of the advantages of Smart Contact Lenses is the ability to take snapshots since contact lenses project an image directly into the wearer's eye. It speeds up the exchange of information between the user and the server and improves feedback.

Contact lenses consist of a set of elements, which are a set of microcircuits and microelements. Among them, we can distinguish a solar cell module, electrical connectors, a biosensor module, an ANF sensor reading circuit, a power-consuming module, a translucent display and a micro lens array, antennas for receiving and transmitting, a display driving circuit, a radio circuit, and a power conversion circuit. A diagram of a smart contact lens is shown in figure 1.4.

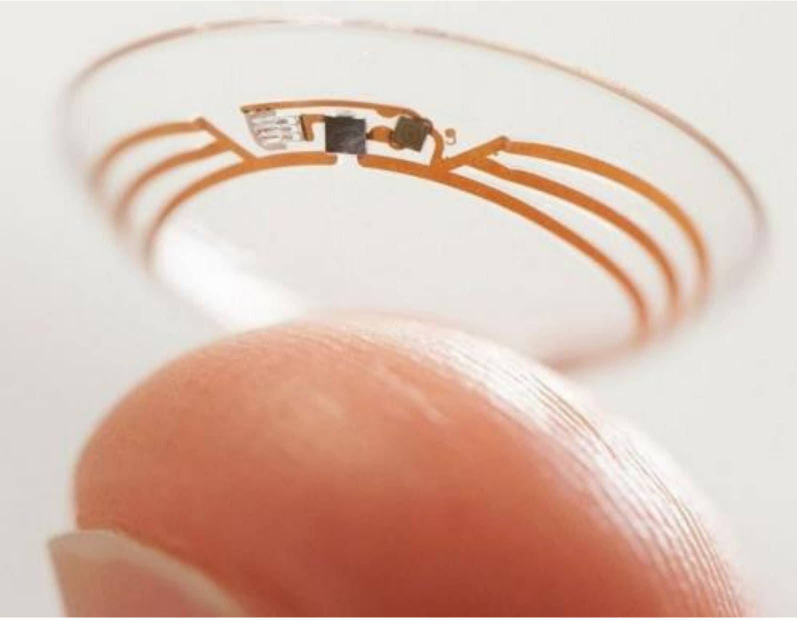


Figure 1.4 - Schematic of a smart contact lens

Smart contact lenses work according to the following principle. The antenna, located at the periphery, collects radio frequency energy that comes from a separate portable transmitter. The power conversion circuit provides constant current so that other parts of the system can be powered and sends instructions to the display control circuit. The display is in the center and can consist of both LEDs that turn on and off as needed, and liquid crystal elements, the transparency of which will be modulated by the control circuit. An energy storage module, which can be shaped like a large capacitor, is connected to the solar cell, and provides a pulse to the lens. The biosensor models the surface of the cornea, performs analysis, and provides data to the telecommunications module for transmission to an external device and further to the network. All information is transmitted via a wireless network using built-in antennas to the user's smartphone or tablet for further processing [17].

Google was one of the first to get involved in the development and creation of smart contact lenses and patented the results of its work. Contact lenses developed by Google allow you to measure blood sugar levels and monitor the condition of diabetic patients. Google Smart Contact Lens perform their function using a wireless chip and a miniature glucose sensor that analyzes the state of aqueous humor in the eye. The electronics in the lens are sandwiched between two soft layers of lens material. Google is also planning to add tiny LEDs that will alert users when their glucose levels reach certain thresholds.

In 2019, engineers from the IMT Atlantique University of Technology from France presented their development of smart contact lenses, which are shown in figure 1.5 [18].

Figure 1.5 - An example of a smart contact lens

The contact lens is autonomous and contains a micro battery. The micro battery can power the lens for several hours, which at that moment transmits information wirelessly or reproduces data. This development will allow a deeper study of cognitive functions and advance research in the field of human-machine interaction. The main difficulty in creating the lens was the development of a flexible and very small power source. The engineers say that the use of graphene-based flexible electronics will expand the functional potential of lenses, for example, add additional vision and integrate computing devices.

1.3.5 Augmented reality glasses

In general, AR glasses are a headset for smartphones running on various operating systems, in particular Android. The devices look like ordinary glasses, which consist of a transparent display that is worn on the head and is located just above the right eye, and a high-resolution video recording camera. The smart glasses also contain an audio output, a battery, a mini-USB, on/off buttons for the device, a minicomputer consisting of a touch panel, a microphone, a camera, and a small display.

The glasses can send audio signals directly to the inner ear. The battery life is calculated for a day without recharging with the device fully functioning. Basically, energy is spent on data transmission via wireless technologies such as Wi-Fi, mobile network, Bluetooth, sometimes, depending on the complexity of the task and the principles of the application, the energy spent on its execution may increase. The built-in computer supports navigation functions - GPS, and Google Glass DR glasses contain a memory capacity of 12 GB, which is synchronized with the Google cloud. The built-in camera allows you to take photos and shoot videos with different quality, usually 5 megapixels and 720p HD video. The display reproduces images with an average resolution of 640x360 pixels.

Augmented reality glasses are multifunctional, by connecting to a smartphone and accessing the global network, they can implement AR applications of varying degrees of complexity and are also simple and easy to use. There have been a lot of goggle options on the market lately and with each new version they are getting smaller and more powerful.

In 2018, the Consumer Electronics Show was held in Las Vegas, USA, dedicated to the latest technical developments, and new equipment in the field of augmented reality was presented there [19]. Google Glass glasses, presented earlier, had several shortcomings, which were analyzed and considered by the manufacturers of AR glasses. The main idea was to project content onto the glasses themselves, which reduces their size and makes everything look more like regular glasses. Consider some examples of DR points [20]. The development of Canadian researchers North Focals is shown in figure 1.6.

Figure 1.6 - Points AR North Focals

Glasses primarily perform their main function - improving vision, so the developers paid special attention to the fashionable design of glasses. North uses special technology to scan the face and get perfect eye measurements to improve DR performance. Also paired with glasses, the user receives a small ring, which is used to navigate through the Focals menu. The glasses can play text messages, music, and maps. To popularize glasses around the world, developers have set a relatively low price.

Another example of AR glasses, released by Vuzix, can indeed be called a finished commercial product. Vuzix Blade glasses are practically the same as real glasses, shown in figure 1.7.

Figure 1.7 - AR glasses Vuzix Blade

For comparison, we can say that these glasses are like first-generation smartwatches, not everything is fully thought out, but even now it is interesting and convenient to use them. Things like music control, camera, image viewing, some games are already implemented, and a real-time transcription application has also been launched. The display is well made, photos look crisp and bright, there is an 8-megapixel camera and 4 GB of memory that can be filled with anything, but the continuous operation time is about 3-4 hours.

Solos has come up with a version of the DR glasses that is suitable for people with an active lifestyle, such as cyclists. The goggles have a small display that allows you to see a lot of useful data in real time, including speed, cadence, heart rate and power zones. Points are shown in figure 1.8.

Figure 1.8 - Solos DR glasses

The glasses are expected to work with existing fitness apps and offer navigation and are Bluetooth compatible with other cycling kits. The goggles have been tested by the US Cycling Team and found to be lightweight and comfortable, with positive reviews.

Like Solos, Israeli company Everysight has built up years of experience in military head screens and has created its own AR smart glasses for cyclists. With smartphone-like internals, the Raptors DR goggles use an OLED-based projector system to power a display that, along with a host of built-in sensors, can display mapping data, heart rate information, and other ride information. They also have a camera offering action camera style footage and voice commands to use the hands-free features. They cost more than the Solos, but they're easy to use, include a great display, and have the nice addition of workout modes to get the most out of your connected smart devices. The advantages of this model include a long battery life of up to 8 hours, a 13.2MP front camera allows you to shoot HD video and photos, equipped with an intuitive touch panel, cyclists can switch between different shades of the visor depending on the weather. On the negative side, when combined with additional accessories, these goggles can be expensive.

Figure 1.9 - Eyesight Raptor

The Epson MOVERIO BT-300, shown in figure 1.9, also known as the MOVERIO BT-300 FPV, does away with the clunkiness of its predecessor and offers a more sophisticated pair of AR goggles. They are lighter than the previous model, but not yet perfect - these are high-quality augmented reality smart glasses with impressive features and affordable pricing.

This model uses a much sharper OLED display with HD 720p resolution and a 5-megapixel front camera. They are also powered by quad-core Intel Atom processors, and Android OS allows self-development of AR applications.

Figure 1.10 - Epson Moverio BT-300 DR glasses

Epson smart glasses have always been focused on business, but the BT-300 has expanded their scope a bit. There is also a UAV version that can be used to control a quadcopter. Benefits include a high-resolution OLED display, UAV control software version, long battery life, and a dedicated controller. However, there are also disadvantages, they include a small viewing angle and memory, limited to 32 GB microSD card. The considered examples of AR glasses are far from all the developments that are on the market today. Obviously, research will continue and soon we will observe new technological solutions for both general and narrowly focused applications. Perhaps one of the most colorful and understandable features of AR glasses would be to expand human-machine interaction in the field of entertainment. Panasonic's sports concept illustrated such an example based on a football game scenario. During a match, fans will be able to view a player's profile and sports analytics graphically overlaid on the pitch and participate in a range of new activities in real time, such as attack formation prediction. Figure 1.10 shows the development of Panasonic AR.

Figure 1.11 - Panasonic DR match broadcast

Table 1.2 summarizes the most popular AR glasses available on the market today [21]. The rating is based on an analysis of the technical capabilities of the presented models, as well as an analysis of reviews on TechRadar, Wareable, CNET and Amazon resources.

Table 1.2 - Analysis of augmented reality glasses models

AR glasses model	Producing country	Viewing angle, 0	Year of issue	Cost, $
Epson moverio BT-300	Japan	23^0	2016	699,0
Everysight Raptor	Israel	-	2018	649,0
Google Glass Enterprise Edition	USA	-	2017	1 800,0
Kopion SOLOS	USA	$10{,}68^0$	2016	499,0
ODG R-7	USA	30^0	2017	2750,0
Toshiba dynaEdge AR-100 Viewer	Japan	-	2018	18999,0
Vizix Blade Smart Glasses	USA	-	2018	1000,0
ThirdEye Gen X1	USA	40^0	2017	1299,0
Vuzix M300	USA	20^0	2016	999,0

As can be seen from the presented table, the cost of points varies over a wide range. The pricing policy is largely due to the purpose of the devices, battery life, compatibility with other smart devices and the supported feature set.

1.3.6 Holographic smartphone

The augmented reality market is replenished with new devices every year, and these are not only well-established AR glasses. In 2018, the first holographic smartphone developed by RED appeared and was called Hydrogen One, shown in figure 1.12.

Initially, RED specialized in the production of high-quality cameras. As conceived by the authors, the distinctive feature of the smartphone and its main advantage was the ability to view various content in three-dimensional format without wearing AR glasses [22]. To do this, you need to activate the H4V mode, and the holograms will appear in front of the screen.

Figure 1.12 - Smartphone with a holographic screen

Also, the smartphone allows you to take three-dimensional photos and instantly display them, watch movies in 3D without the use of special glasses or headsets. The most attractive feature for users is the function of displaying video calls in holographic mode, i.e., you can talk in real time with the hologram of the interlocutor. At the same time, a “surround sound” effect has been added to the smartphone's speakers, which gives the impression of hearing sounds that are far away or approaching. However, the controversial design and rather high price of $1300 led to low sales. There were also complaints about the quality of the holographic image. In this regard, the company decided to close this project and, after analyzing the errors, proceeded to create a new smartphone with hologram support called Hydrogen Two.

To implement AR applications, in addition to specialized devices, it is necessary to interact with other elements of the service, for example, servers, databases, through a communication network. In the next section, promising technologies for organizing

AR services will be considered.

1.4 Problems of augmented reality

Each type of augmented reality system has its own set of problems. For audio systems, the main problem is the tracking of a person's head, since the reproduced sound will depend on how the head is turned or tilted. There are several approaches to determining the position of the head:

1. determining the position relative to the fixed platform;
2. determining the position relative to the rotating of the planet Earth;
3. determining the position relative to an arbitrary movable platform.

In [6,p. 5], for each of the above cases, coordinate systems are introduced and expressions for determining these coordinates are described. However, no matter what coordinate system we use, it is necessary to attach sensors to the human head, based on the readings of which the coordinates will be calculated; for visual systems, the main problem is pattern recognition in the image. This is necessary to identify the environment, depending on which virtual objects are built. A person thinks in categories - some collective images with which he compares visible objects. The same must be done for augmented reality systems. Currently, there are no systems capable of recognizing any object. Each specific system can identify only a certain group of objects, determined by the purpose of the system. An overview of methods for identifying objects in an image is given in [7,p. 6].

The identification process is reduced to the following steps:

1. construction of the contour (shape) of the object;
2. construction of a one-dimensional function from a two-dimensional form of an object;
3. comparison of the obtained function with the standard for its identification.

However, another problem arises here - the classification of objects for setting standards. For example, let's take an object like a house. This category may include a small one-story warehouse, and a skyscraper. At the same time, the standards of such objects will differ significantly.

When developing mobile systems, specific problems also arise. There are two trends here: the desire to make the device as small as possible and to provide the processing power necessary to ensure the operation of the system in real time. Moreover, these trends are opposing - if we want to get a high-performance system, we will have to put up with an increase in its size and vice versa. Therefore, less resource-intensive algorithms are used for mobile systems, even if this leads to a decrease in accuracy.

There are also several problems that are common to all augmented reality systems. These are the problems associated with building virtual objects:

1. organization of storage of virtual objects and means of access to it;
2. ensuring the necessary degree of realism of virtual objects;
3. coordination of virtual objects with the scene.

The augmented reality system can operate with a whole set of virtual objects that are reproduced depending on the specific situation. Therefore, it is necessary to organize the storage of objects in such a way that the system can get quick access to them. An object can be stored in any form suitable for subsequent interpretation: a function or description of a construction method, a list of polygons for graphic objects, an image, a sound file. The way objects are represented largely depends on the purpose of the system and its limitations. The choice or development of a presentation method is also one of the problems of augmented reality systems.

Systems for various purposes impose their own limitations on the required degree of realism of objects. Ideally, virtual objects should be indistinguishable from real ones, but the current level of technological development does not allow this to be achieved. Therefore, at present, augmented reality systems operate with objects that are close to real ones.

No matter how realistic a virtual object is, it must fit into the scene. For graphic objects, this means selecting the correct perspective, scale, brightness; for sound objects - a selection of volume, synchronism with other sounds. In addition, it is necessary to superimpose an object on a real image or sound in such a way that it does not fall out of the overall picture. In addition, the scene is not static, it changes depending on the user's actions. Therefore, the augmented reality system should provide tracking of the position of real objects on the stage and move the associated virtual ones after them. As a result, another problem arises - the tracking of image elements. In this case, it may be necessary to track not one, but several objects at once, which can move not only relative to the user, but also relative to each other.

High performance systems can be used to solve many of these problems. However, they are not mobile and are often not available to everyone; they cannot be used directly. But based on high-performance systems, it is possible to organize a computing service that would solve the following tasks:

1. identification of objects by image fragments;
2. searching for the necessary virtual objects in the storage and adjusting their parameters;
3. merging virtual objects with fragments of the scene;
4. changing the representation of the object to ensure less resource consumption when it is played on a specific end device.

With this use of high-performance systems, the tasks of mobile devices will include capturing the environment and rendering augmented reality for the user. The operation of the system will consist of the following stages:

1. Determining the contours of objects of interest to the user of the image on a mobile device. Each of these circuits will be assigned a label, the position of which the device will track.
2. Sending the contours and their contents to the server for processing.
3. Processing by the server of received data, identification of objects and construction of virtual objects. Each of these objects is a certain sequence of bytes in the device's memory, based on which you can build an image of the object. It can be a function for procedural objects, vertices, and textures for polygonal objects, and so on.
4. Sending finished objects, accompanied by a mark ID on the original image.
5. Reproduction of virtual objects.

1.5 Problem statement

With the advent of mass mobile devices such as smartphones and tablet computers that have the necessary characteristics to run applications with augmented reality, it has become possible to simultaneously solve both the main disadvantages of modern AR systems: lack of mobility and mass distribution. At the same time, to ensure mass distribution, an appropriate approach to the design of the user interface is also required, which allows the user to use the software without special training.

Accordingly, the enlarged task of this study is to improve the methods and algorithms for interactive visualization using AR in accordance with the following principles:

1. Mass availability.
2. Realism.
3. Functionality.

This study is focused on the mass introduction of augmented reality technology. In accordance with this principle, modern mass-produced mobile devices will be considered as platforms for applying the results of the study. And solutions to issues of organizing user interaction will be developed considering the requirements of users without special training.

For the full implementation of augmented reality technology, virtual objects must be integrated into the real environment as realistically as possible. At the same time, the main obstacle is the limited hardware and computing capabilities of mass devices.

It is necessary to fully reveal the potential of augmented reality technology in solving practical problems.

Conclusion on chapter 1

1. Augmented reality technology has a significant potential for improving modern user interfaces.
2. At the present stage, characterized by the spread of smartphones and tablet computers, there are prerequisites for the mass introduction of augmented reality technology.
3. A comparative analysis of visualization systems using AR was carried out, which showed their shortcomings in terms of realism, functionality, and user interaction. As a result, the objectives of the study were formulated, which are to eliminate the corresponding shortcomings.
4. To solve the tasks set, it is necessary to search and analyze the existing tools for the development of augmented reality for the possibility of using it for research purposes.

2 MODELS OF APPLICATION OF AUGMENTED REALITY TECHNOLOGY

In this chapter, several models of AR services are proposed depending on the specifics of the applied area, which imposes its own characteristics on the type and amount of transmitted information, methods for generating requests about objects and displaying information to the user.

The purpose of providing the AR service is to bring to the user the maximum possible amount of additional information. To achieve this goal, one should consider the user's ability to perceive various types of messages with varying degrees of their informativeness.

2.1 Service Model

According to most definitions, the provision of an augmented reality (AR) service consists in introducing additional information into the field of human perception. In the general case, the appointment of AR to facilitate the solution of various problems associated with perception, analysis, and management. Figure 2.1 shows an example of an AR star chart (StarChart). The difference between a simple map or an interactive map is that its display is associated with the position of the device in space (pointing it to a certain point in the sky), i.e., supplemented by the results of user information processing.

Figure 2.1 - An example of augmented reality when looking at the starry sky (StarChart)

In a more general case, the process of providing an AR service can be considered as an interactive interaction of the user with application functions that analyze the state of his environment and provide him with additional information, as shown in figure 2.2.

Since the intended purpose of the AR is to provide the user with additional contextual information, the quality of its provision should be considered in terms of the degree to which this goal is achieved, which can be characterized as:

- the degree of compliance of the additional information provided with the needs of the user (compliance with the intended purpose, volume, detail, etc.);
- the degree of susceptibility of the provided data (video data, graphics, sound, tables, text and other elements of the user interface, the quality of their presentation);
– the timeliness of providing additional information.

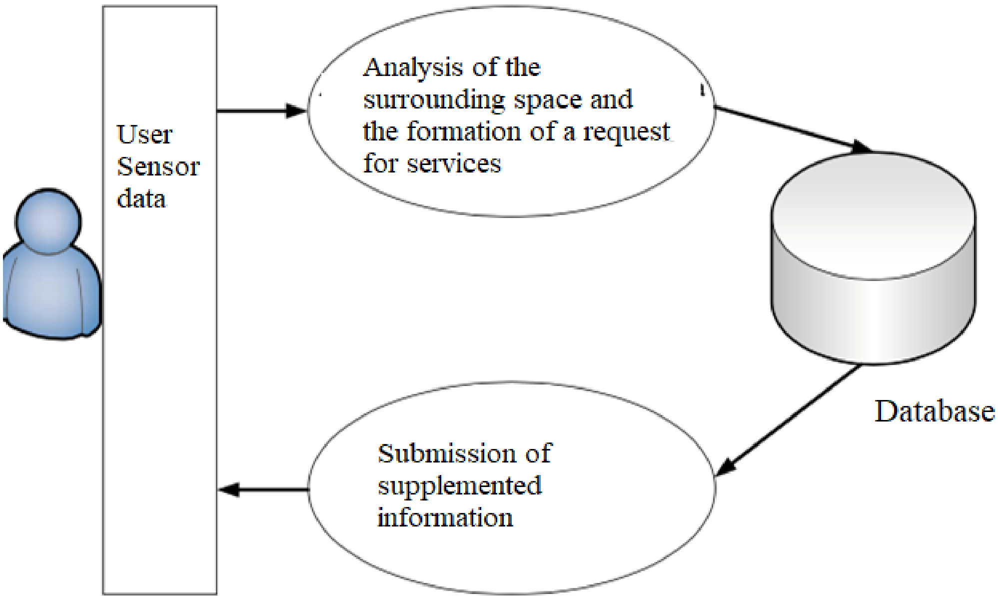


Figure 2.2 - User interaction with application functions

2.1.1 Interaction model of the main elements in the provision of AR services

The implementation of the AR service may be different, depending on the technical means used. The set of these tools necessarily includes a subscriber device, which can be a smartphone, tablet PC, multimedia glasses, a helmet, etc., which allow organizing a user interface, obtaining data about the environment, and having a sufficiently high performance of a computing device. However, in many applications, for example, it is impractical or impossible to store all additional information, as well as to perform all user data processing by the resources of the mobile device. Therefore, the next element of the AR is the infocommunication component (communication network), which provides the delivery of additional information to the user, databases and, possibly, servers that perform some of the functions of processing user information, as shown in figure 2.3. If there are Internet of Things (IoT) sensors in the user's environment that can provide useful information, D2D technology can be used to directly connect the subscriber device with them.

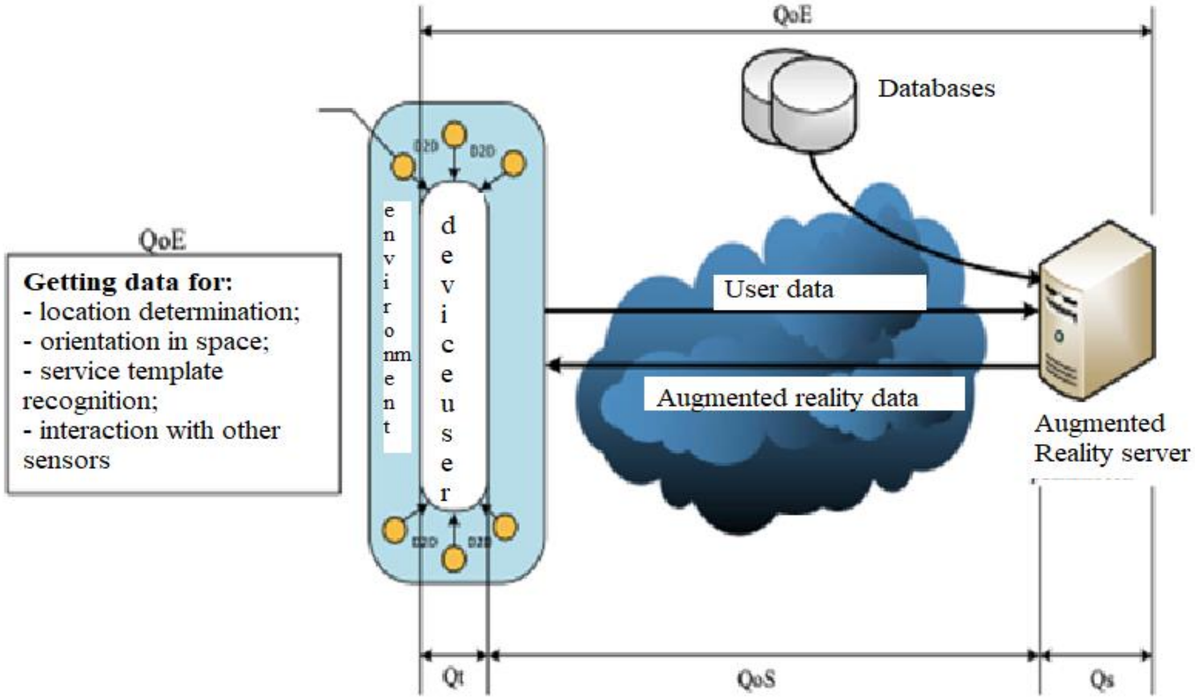


Figure 2.3 - Interaction of the main elements in the provision of the AR service

The main elements that ensure the quality-of-service perception by the user are the AR user device, the AR service server, databases, and the communication network. All elements interact through a communication network (with IoT devices, D2D communication is also possible). In this system, the main task of ensuring the quality of service is the distribution of functionality and data between the client application of the user's device, the service server, and databases. This distribution is reflected in the execution time of data processing functions, the time of data delivery through the communication network and the traffic generated in the network.

2.1.2 Quality of AR service delivery

As mentioned earlier, the quality of the augmented reality service is associated with providing the user with additional contextual information about the object. Therefore, to understand the user's satisfaction with the service, it is necessary to determine the degree of compliance of the additional information provided with the user's needs, the degree of susceptibility of the data provided, and the timeliness of providing additional information.

The AR service is interactive, so the timeliness of providing information is one of the most important factors that determine its quality. Timeliness is characterized by the time between an event associated with changes in the state of the environment or the user and an event characterizing the availability of additional information to the user. This time (delay) is determined by several components, such as:

− time of obtaining data about the environment (polling of state sensors, video, etc.) and their processing;

− time of data delivery to the service server (if necessary);

− time of data processing by the service server;

− time of data delivery to the user;

− time of data submission.

When organizing a service with the participation of a server, data is requested and transmitted to the user when the state of the environment changes (changes in the environment in the field of view/perception of the user). Change identification can be performed, for example, based on the analysis of data about the coordinates of the device and its orientation in space, object recognition by analyzing video data, etc.

2.2 AR traffic model

To describe the traffic produced by the service, it is necessary to link the amount of data transmitted by the user and the user when his environment changes. To do this, we introduce three models:

− service space model;

− user environment model;

− model of behavior.

Under the service space we will understand the information model of the physical three-dimensional space in which the user of the service can be. The information model includes a description of some objects located in this space $X = \{\bar{x}_1\}$ $X = \{\bar{x}_1, \bar{x}_2, \dots, \bar{x}_n\}$ where n is the total number of objects.

The user environment model is a subspace of the service space, i.e. part of the space limited by the possibilities of perception (the model of these possibilities). The environment, as a rule, is tied to the position of the user in the space of the service and includes many objects X={ $X = \{\bar{x}_1^{(U)}, \bar{x}_2^{(U)}, \dots, \bar{x}_k^{(U)}\}$ where k is the number of objects in the user's area of perception.

The behavior model describes changes in the position of the user and his environment in the service space. Changes in the user's environment can occur both as a result of the user's movements and the movements of objects in the service space. A change caused by the appearance of a new object in the user's environment leads to a request for data about this object.

The service implementation algorithm should provide the following functions:

− identification of the environment change event and calculation of the change parameters;

− request for information about changing the environment;

− data acquisition and display.

A possible data exchange diagram is shown in figure 3.4.

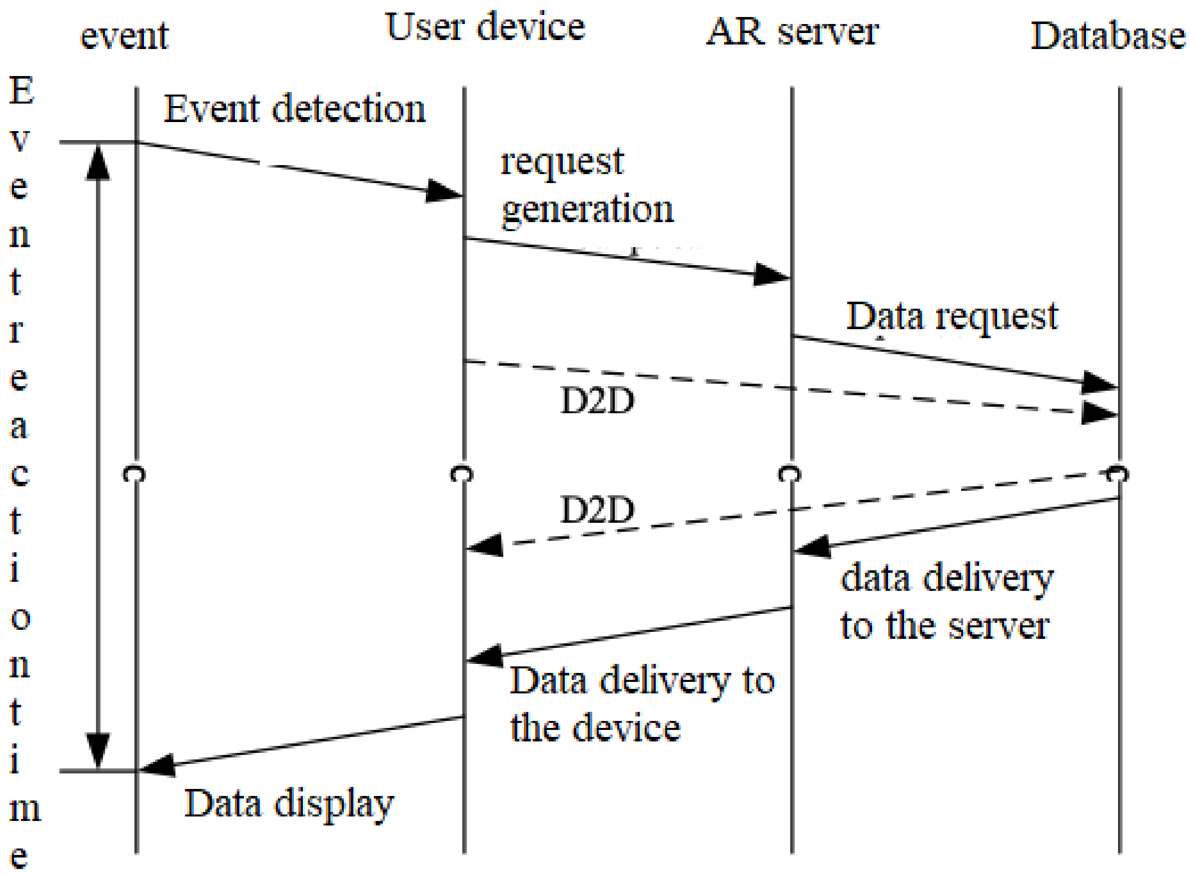


Figure 2.4 - Diagram of data exchange in the provision of AR service

Since the environment, as well as the space of the service, is a limited (perceptual) physical three-dimensional space, changes in it can be described as a stream of events associated with the appearance of objects in it. Objects can enter through its boundaries due to the movement of these boundaries or the objects themselves.

Obviously, the characteristics of the flow will depend on the distribution and characteristics of objects in the service space, as well as the characteristics of the user's movement.

2.2.1 User environment model

Let's assume that the objects in the service space are randomly distributed (from a Poisson field) and immobile, only the user is mobile. Then, changing the position of the user is equivalent to changing his environment. Given the properties of the service space and environment, this change can be described by volume or area. Consider the 2D version and describe the user's environment with a circle of radius r, and the user's movement speed v will be considered constant. Then, in time t, the change in the environment will be determined by the number of new objects in the area that defines the user's environment.

Let us estimate the number of new objects in the environment during time t as

$$n(t) = \tilde{S}\big(L(t)\big)p \qquad (2.1)$$

where $\tilde{S}\big(L(t)\big)p$ – area of environment change;

p – object density (objects/м^2)

Figure 2.5 shows a model illustrating the movement of the user and the change in his environment. Moving the circle representing the user's environment from the starting point by a distance L results in a sickle-shaped area (shaded area) that defines the environment change. Objects in this area are identified according to the service provision algorithm, because of which requests for additional information are generated.

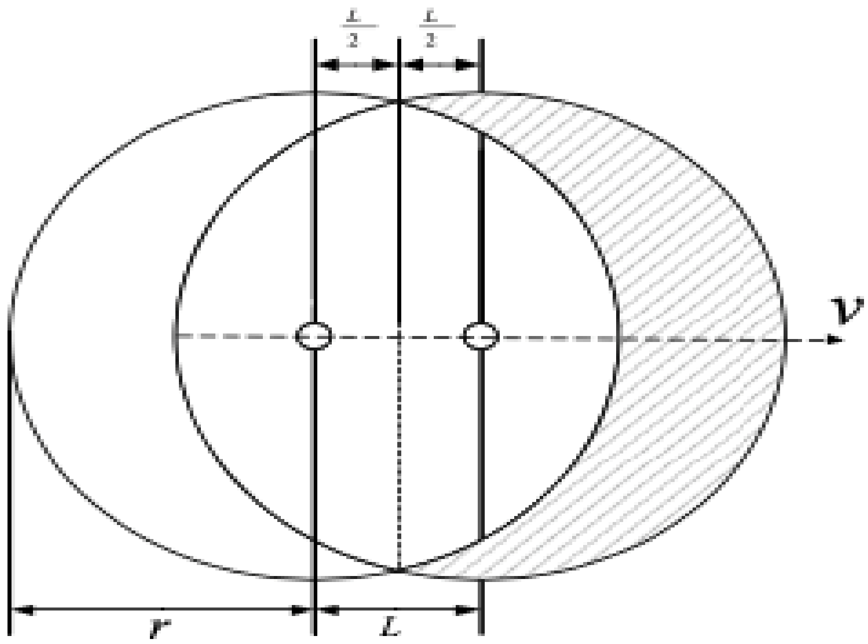


Figure 2.5 - Diagram of data exchange in the provision of AR service

From the above figure, the area of the shaded area can be determined by formula (2.2).

$$\tilde{S}(L) = \pi r^2 - 2\left(r^2 \arccos\left(\frac{L}{2r}\right) - \left(\frac{L}{2}\right)\sqrt{r^2 - \left(\frac{L}{2r}\right)^2}\right) \qquad (2.2)$$

The number of new objects in the area can be defined as

$$n(t) = \tilde{S}(L)p \qquad (2.3)$$

where p – density of objects (objects /м^2).

Considering this process in dynamics, i.e., when the user moves, a stream of events (requests for data) takes place.

The intensity of the flow of events (requests for data) can be defined as the number of objects in a small increment of the area of the figure under consideration.

$$\lambda_r = \frac{d\tilde{S}(L)}{dL}|L = 0^{pv} \tag{2.4}$$

где p – density of objects (objects /м^2)
v - travel speed (м/с).
The derivative of expression (3.2) at the point $L = 0$

$$\lambda_r = \frac{d\tilde{S}(L)}{dL}|L = 0^{2r} \tag{2.5}$$

Then, considering (2.4) and (2.5)

$$\lambda_r = 2rpv \tag{2.6}$$

Considering the properties of the Poisson field adopted for the model, the number of objects in a certain limited area is random, distributed according to the Poisson law and depends only on the area (or volume) of the area under consideration. Therefore, for the accepted model, the flow of requests will be the simplest flow, for which the probability of receiving k requests in a time interval t will be defined as

$$p_k = \frac{(\lambda_r t)^k}{k!} e^{-\lambda_r t} = \frac{(2rpvt)^k}{k!} e^{-2rpvt} \tag{2.7}$$

The flow of traffic generated because of the provision of a service is determined by the flow of responses to data requests. In general, the response can be either a single data packet or a stream of packets (transmission of video or audio data). The intensity of this flow can be described as

$$\lambda_S = \lambda_r n \tag{2.8}$$

where η – the average number of packets required to complete a request.

When transmitting video data, s can exceed the intensity of requests by tens and hundreds of times. Considering the quality requirements, this leads to a significant increase in the requirements for the bandwidth of the communication network.

The physical dimensions of the user's environment are generally commensurate with the range of the wireless technologies used to establish PANs, such as the Wi-Fi family of standards. Many objects of AR services (elements of urban infrastructure, vehicles, household appliances) can be equipped with access nodes and the necessary data that can be provided to users. Therefore, a possible solution that provides a significant reduction in traffic to the communication network can be the use of D2D technologies. In such a case, data traffic can be delivered directly from the entity to the user terminal as shown in figure 2.4 (dotted line). The intensity of this flow will be determined as

$$\lambda_S = \lambda_r n_{D2D} \tag{2.9}$$

where $n_{D2D} = (1\text{-}\gamma)n$, γ – share of environmental objects supporting D2D technology.

The use of D2D technologies is possible only when the service objects are the physical objects mentioned above, which can be equipped with appropriate communication nodes. A relatively wide range of services still require interaction with remote databases and solving quality assurance problems.

2.2.2 Sectoral user environment model

Today there are many augmented reality applications that can be divided into six large groups: medicine; assembly, maintenance, and repair of complex equipment; adding various information to existing objects; control of robots, unmanned aerial vehicles, etc.; gaming and entertainment industry; military. There are several applications that allow the user to control various engines and devices, inform drivers about the traffic situation, and control the UAV. Flying sensor networks (FUSN) based on drones are gaining popularity with the advent of the Industrial Internet of Things (IoT). Among the sectors that show the greatest interest in the introduction of the industrial Internet are mining, engineering, agriculture, and transport. It is widely believed that device data collection and data analysis are the core ideas of FUSN. For some applications, such as area surveillance, cameras can be mounted on UAVs.

The pilot controls the actions of the UAV through the AR device (goggles or helmet) using turns and tilts, Figure 2.6. A camera is installed on the UAV, the video stream is displayed on the AR device, which is located on the pilot's head. Based on the video stream, the pilot can determine the location of the UAV and can control both the UAV itself and the camera to change the viewing angle.

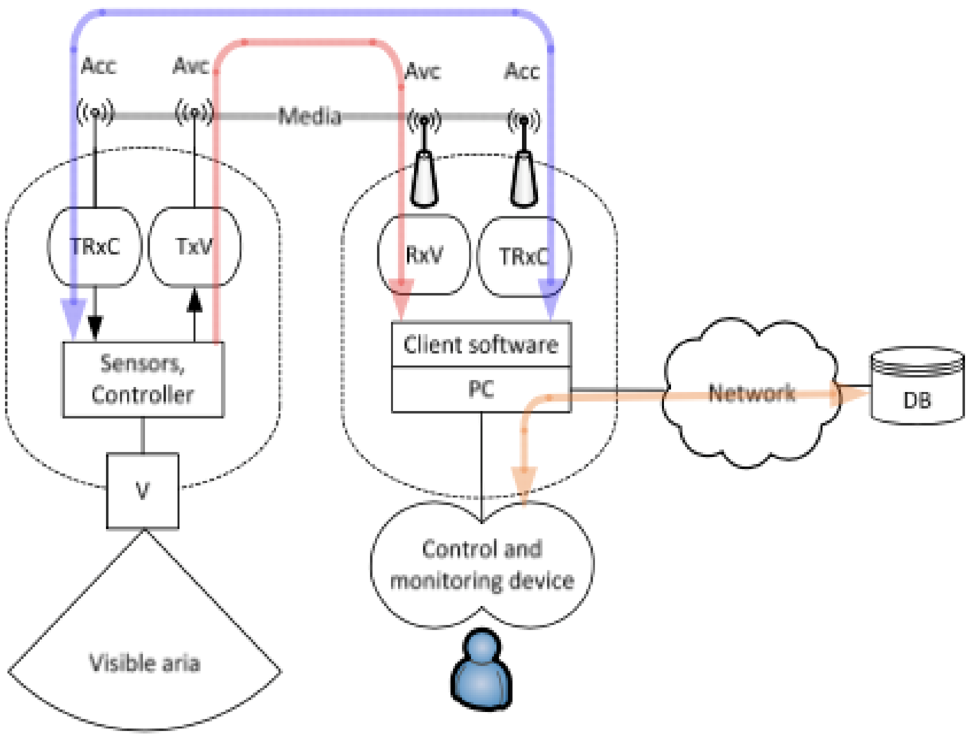


Figure 2.6 - Interaction of the main elements in the provision of AR services using UAVs

In the case when information about the user's environment is an image obtained using a video camera installed on the UAV, to determine the area of limitation of the user's environment, the motion features of this device and the transmitting video camera should be considered.

Consider a 2D version of the environment (ground objects) and describe the user's environment with a sector of radius r. Such a model is closer to the real situation than the circle model discussed earlier because a video camera has a limited viewing angle, and possibly a relatively high linear speed of movement limits the possibilities in terms of all-round visibility. The linear velocity of the UAV movement v will be considered constant. Then, in time t, the change in the environment will be determined by the number of new objects in the area that defines the user's environment.

As an example, when using a UAV, the environment model can be a map of the area with conditional, textual, and graphic images or designations of objects. The high-speed video transmission channel is more susceptible to changes in reception conditions than the low-speed control signaling channel. In the event of a decrease in the quality of the video transmission channel, the image presented to the user can be replaced by a map of the area, which is available on the local server.

Figure 2.7 shows a model illustrating the movement of the user and the change in his environment. Moving the sector representing the user's environment from the starting point by a distance L results in the formation of an area (shaded area) that defines a change in the environment. Objects in this area are identified according to the service provision algorithm, because of which, requests for additional information are generated.

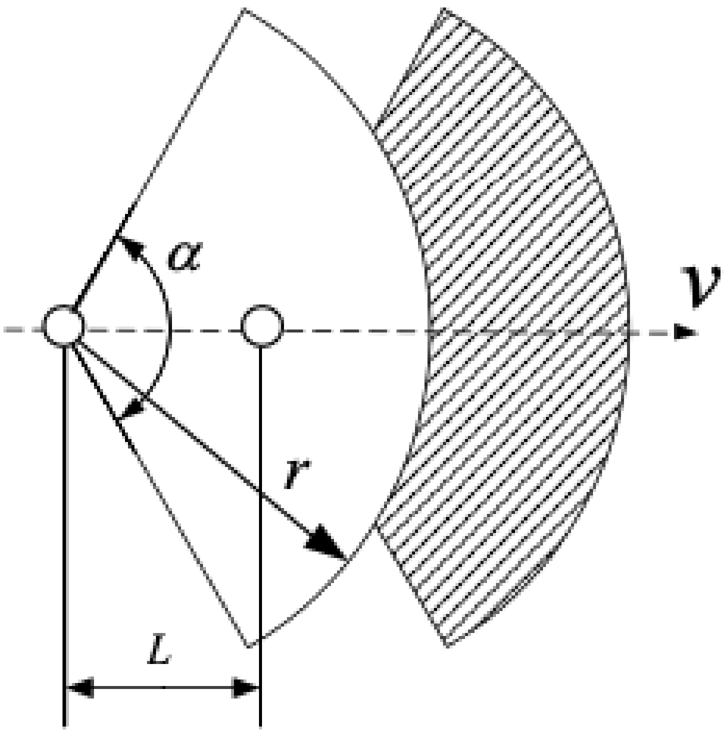


Figure 2.7 - Changing the environment during translational motion

From the above figure, the area of the shaded area can be determined by the formula (2.10).

$$\tilde{S}(L) = \tilde{S}(r)\text{-}\tilde{S}(r\text{-}L) = \begin{cases} \frac{a}{2}(2rL\text{-}L^2) L \leq r \\ \quad \frac{ar^2}{2} L > r \end{cases} \tag{2.10}$$

The number of new objects in the area can be determined by formula 2.3.

Considering this process in dynamics, i.e., when the user moves, a stream of events (requests for data) takes place.

The intensity of the flow of events (requests for data) can be defined as the number of objects in a small increment of the area of the figure under consideration and calculated by formula 2.4.

Derivative of expression (2.10) at a point $L = 0$

$$\frac{d\tilde{S}(L)}{dL}\Big|L = 0^{=a(r-L)}\Big|L = 0^{ar} \tag{2.11}$$

Then in view of (2.4) and (2.11)

$$\lambda_r = arpv \tag{2.12}$$

Considering the properties of the Poisson field adopted for the model, the number of objects in a certain limited area is random, distributed according to the Poisson law and depends only on the area (or volume) of the area under consideration. Therefore, for the accepted model, the flow of requests will be the simplest flow, for which the probability of receiving k requests in a time interval t will be defined as

$$p_k = \frac{(\lambda_r t)^k}{k!} e^{-\lambda_r t} = \frac{(arpvt)^k}{k!} e^{-arpvt} \tag{2.13}$$

Along with the translational movement, the device can perform rotational movements. The rotational motion model is shown in figure 2.8.

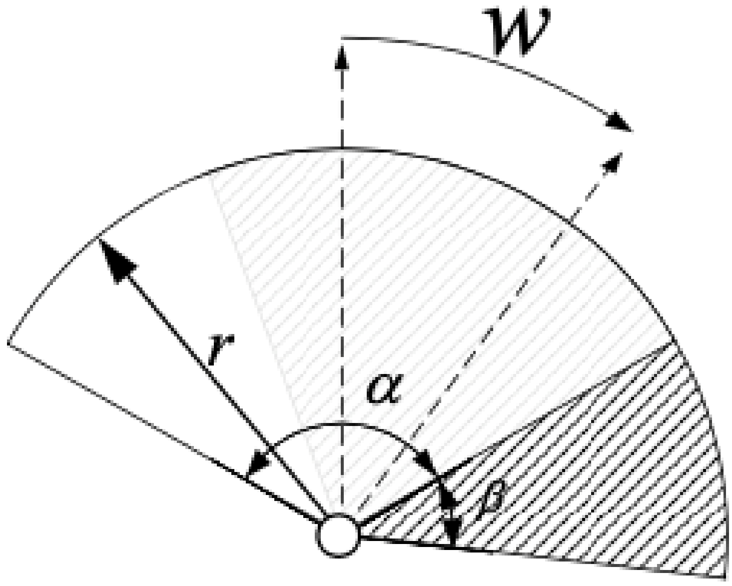


Figure 2.8 - Changing the environment when turning

The area of the shaded area can be determined by the formula.

$$\tilde{S}(\beta) = \tilde{S}(0) - \tilde{S}(\beta) = \begin{cases} \frac{\beta r^2}{2} \beta \leq r \\ \frac{ar^2}{2} \beta > r \end{cases} \quad (2.14)$$

The number of new objects in the area can be defined as

$$\lambda_r = \frac{r^2 pw}{2} \quad (2.15)$$

where ρ is the density of objects (objects/ м2), β– is the rotation angle (rad), α is the viewing sector angle (rad). When considering this process in dynamics, i.e., when the user moves, a stream of events (requests for data) takes place. Its intensity can be defined as the number of objects in a small increment of the area of the figure under consideration.

$$\lambda_r = \frac{d\tilde{S}(\beta)}{d\beta} |\beta = 0^{pw} \quad (2.16)$$

where ρ– is the density of objects (objects/m2), w – is the angular rate of turn (rad/s). Derivative of expression (3.14) at the point β= 0

$$\frac{d\tilde{S}(L)}{dL} |\beta = 0^{\frac{r^2}{2}} \quad (2.17)$$

Considering (2.16) and (2.17)

$$\lambda_r = \frac{r^2 pw}{2} \tag{2.18}$$

Considering the Poisson field model, the flow of requests will be the simplest flow for which the probability of receiving k requests in a time interval t will be defined as

$$p_k = \frac{(\lambda_r t)^k}{k!} e^{-\lambda_r t} = \frac{(\frac{r^2 pw}{2} t)}{k!} e^{-\frac{r^2 pw}{2} t} \tag{2.19}$$

Figure 2.9 shows the ratio of the angular rate of turn (rad/s) and the linear speed of movement for equal traffic intensity for viewing angles $a = \frac{\pi}{2}$ and $a = \frac{\pi}{2}$

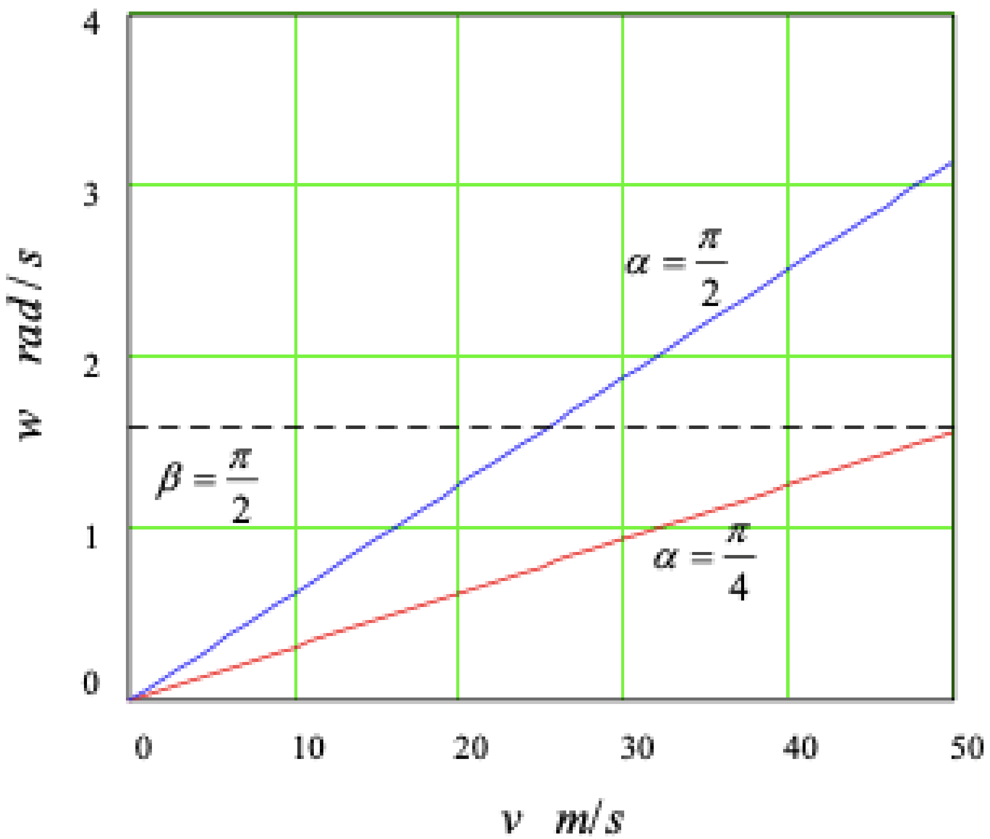


Figure 2.9 - Ratios of the angular rate of rotation and the linear speed of movement for equal flow intensity

For example, when turning through an angle β=π2 in 1s, the traffic intensity is equivalent to the traffic intensity of linear traffic at a speed of 50m/s (180 km/h). In this example, the radius is set to 50m. Such a ratio of the generated traffic and the peculiarities of the UAV movement should be considered when choosing a method for implementing the selection and delivery of data.

The model considered above makes it possible to analyze the traffic of the augmented reality service without being tied to the method of implementing the service, both in terms of the server and client components. The specific implementation method can significantly affect the nature of the traffic produced. The implementation is characterized by the distribution of data processing functions between client and server applications, as well as the ways in which data is selected. This is the organization of the buffer memory (cache) of the client application, determining its size, data update rate, generating data requests considering the traffic forecast. Managing these settings allows you to select the most appropriate resource usage mode based on the requirements and behavior of the client application or device.

2.2.3 User behavior (movement) model

To study the user's movement model, applications were considered that add information to objects of a different nature. We considered a user who walks around the city in augmented reality glasses and needs to receive information about the surrounding buildings. This may be a historical note on a building of architectural value or a floor plan of a shopping center, indicating the shops or menus located in it, and the presence of visitors in the restaurant.

Smart City AR service model (or in AR points)

At present, technologies provide a person with a whole range of new opportunities that were not available decades ago, and their implementation seemed impossible. However, even now they are gradually being introduced into our daily life and have become an integral part of it. Every year, developments reach a new level, doing a lot of useful things: they can recognize a person’s face, his voice, facial expressions, and gestures, as well as determine emotions and mood.

Most technologies are focused not only on the entertainment side of life, but, above all, on bringing benefits to people and simplifying their activities. Recently, augmented reality has become more and more of interest to IT experts, developers of games and applications on the Android and iOS platforms, as well as marketers. This technology allows a person to receive information in completely new ways, combining both virtual and real, and does it in simple and visual ways. It transforms real world objects in a different quality, revealing them to the user on the other hand.

The user's interest in augmented reality services poses new challenges for operators who provide this type of service. They must maintain the network at the proper level and provide the required values of QoS and QoE indicators. To implement such services, it is necessary to revise approaches to building communication networks, as there are several works that consider a new type of communication - D2D and a new principle of networking - SDN networks.

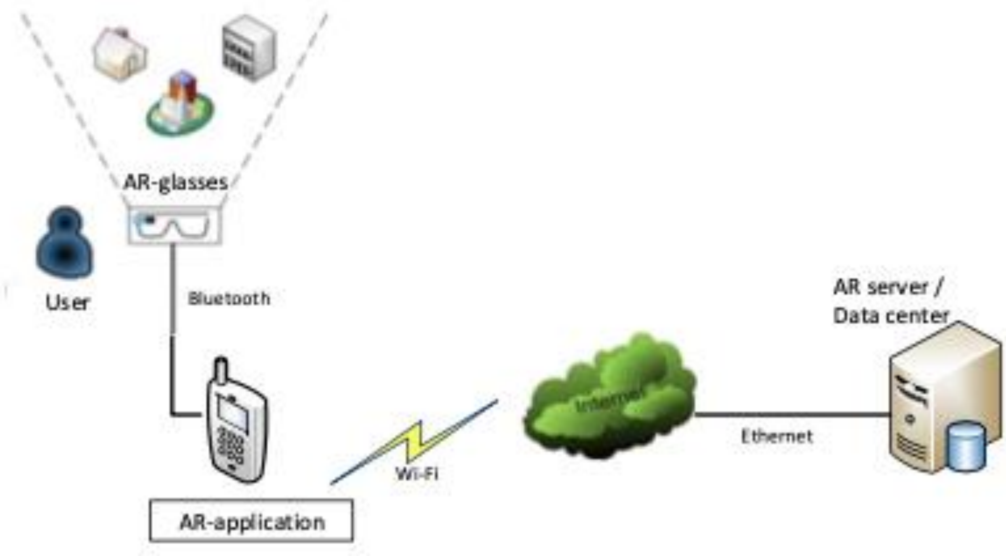


Figure 2.10 - Scheme for providing AR service in AR points

In addition to the scenario described above, objects within the user's field of view can directly transmit information about themselves. This could be a bus timetable if the user has selected a bus stop object or a store's opening hours. Various technologies can be used for this, such as Wi-Fi and D2D communications. It should also be considered that data can come from objects without user intervention. Those, the user does not select the object about which he wants to receive information, but simply looks around and the glasses read data from all surrounding objects.

User Perception Model

The user of the augmented reality service receives a certain amount of additional information in the form of messages of various types: text, graphics, speech, sound, tactile and, possibly, other types. Messages are entered into the user's environment and are available for perception.

Let's make the following assumptions:

- the user can adequately perceive a certain amount of information μ per unit of time (intensity of perception of information);

− the intensity of perception of information is different for different types of messages (text, graphics, voice, sound, tactile sensations) μ_k, k=1...K;

− messages are in the user's environment for some limited time t;

− messages of various types appear (arrive) in the user's environment independently of each other at random time;

− the user is able to select a message according to the degree of its significance (priority);

- the user can interrupt processing (perception of the current message) when a more significant message arrives.

With the assumptions made, the user model can be described by the QS model with the choice of requests according to their priorities (with relative priorities), as shown in figure 2.11.

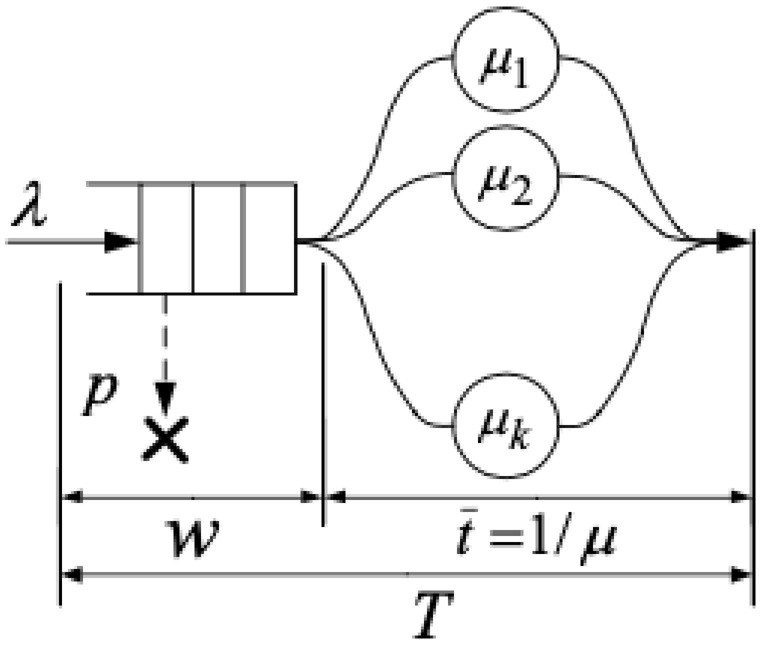


Figure 2.11 – AR user model

With that said, the service time is random, and the service time distribution is determined by a mixture of distributions.

$$f(x) = \sum_{i=1}^{k} \xi_i p_i(x) \tag{2.20}$$

где $p_i(x)$ – probability density of the service time of the k message type; $0 \le \xi_i \le 1$

$$\sum_{i=1}^{n} \xi_i = 1$$

the probability of receiving a message of the i-th type.

As noted above, in the general case, the AR information perception model can be described by a queuing system. Let us consider the use of a model of the form G/G/1 with priority servicing of requests for its description. Considering the random nature of the placement of elements and the nature of the user's movement, we can assume a more particular case of M/G/1 [7,p. 5], which, under the indicated conditions, can be quite close to the real situation. The average waiting time to start service for priority (type) p in each system can be defined as

$$w_p = \frac{\sum_{i=1}^{k} \lambda_i M(t_i^2)}{2(1-\theta_p)(1-\theta_{p-1})} \tag{2.21}$$

where λi – intensity of message flow of i-th priority (type);

μi – intensity of service (perception) of messages of the i-th priority (type);

$M(t_i^2)$– second initial moment of the time distribution function

$$\theta_p = \sum_{i=1}^{p} \frac{\lambda_i}{\mu_i} \quad (2.22)$$

servicing messages of the i-th priority (type); p λi

Approximation of the message waiting time distribution of the i-priority type can be described by the expression

$$h_p = (t) \approx 1 - p > 0^{\theta^{-\frac{p>0}{w_p}}} \quad (2.23)$$

For the simplest flow, the probability of delay in the queue is numerically equal to

$$p > 0 = p = \sum_{i=1}^{k} \frac{\lambda_i}{\mu_i}$$

K λi to the value of load intensity p>0

Knowing the perception time distribution (2.22), we can determine the system parameters based on the waiting time requirements. Wait time and service time determine the time during which messages will be accepted by the user. Time of perception of the message of the i-th type

$$T_i = w_i + \overline{t_i} \quad (2.24)$$

where is the average service time

$$\bar{t}_i = \frac{1}{\mu_i}$$

System requirements can be given as a probability λ_{0i} того, что время waiting for a message will not exceed a certain threshold value T_{0i}

$$h_p = (T_{oi}) = p(t < T_{0i}) = \lambda_{0i} \quad (2.25)$$

The choice of the latency threshold T_{0i} can be made from various considerations, depending on the characteristics of the service and the significance of the messages. As a characteristic approach, one can proceed from the fact that the waiting time should not exceed the time spent by the message in the user's environment, i.e., the time of its existence.

The residence time of a message in the user's environment is determined by the residence time of the corresponding object in it and depends on the user's behavior. For example, if the user's environment is given by an area bounded by a circle with a radius R, then with a rectilinear and uniform user movement, Figure 2.12, with a random distribution of objects, the path passed by the object in the perception area will be a random variable with a probability density:

$$g(d) = \frac{1}{\pi R \sqrt{1-(\frac{d}{2R})^2}} \quad (2.26)$$

and mathematical expectation:

$$M[d] = \bar{d} \quad (2.27)$$

user environment area

With the user's movement speed v, the time the object stays in the area will also be a random variable with a probability density

$$q(t) = \frac{1}{\pi R \sqrt{1-(\frac{v}{2R})^2}} \quad (2.28)$$

and mathematical expectation:

$$M[t] = \bar{t} = \frac{4R}{\pi v} \quad (2.29)$$

The graph of the probability density (2.23) is shown in figure 2.12.

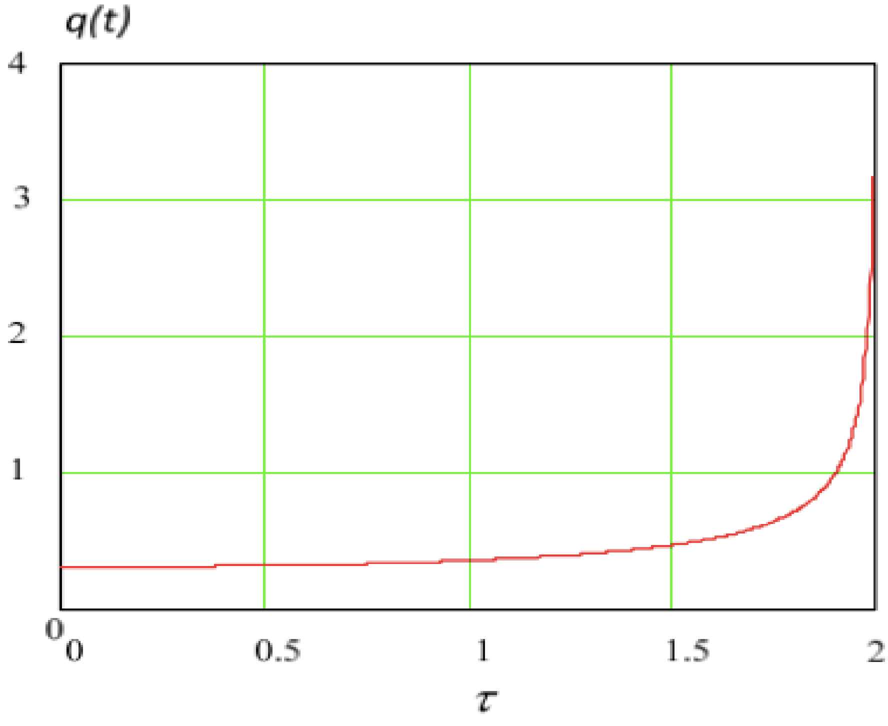


Figure 2.12 - Time spent by an object in the user's field of vision

Expressions (2.27) and (2.28) make it possible to estimate the residence time of objects in the area accessible to the user and choose an adequate threshold value for expression (2.24).

The task of constructing the system in this case will be to choose the values of the system parameters for which condition (2.24) is satisfied. These parameters are the share of messages of each type and how they are formed. Consider next the service delivery model.

AR Service Delivery Model

The provision of an augmented reality service consists in providing the user with additional information about his environment in the form of a certain set of messages. The volume of this information is determined by the data contained in the service database and can also be obtained from local storage located directly on objects located in the communication zone user.

If there are n objects in the user's environment provided with some information $I_j, j = 1 \ldots n$.. The total amount of information will be defined as $\mathrm{I} = \sum \mathrm{I_j}$. Information about each object $j_j = 1$ can be presented as a message $m_j$which is formed according to some rules $m_j = R(I_j)$ The rules for generating a message include the method of presenting the message and the method of its formation. As the ways of presenting messages, for example, presentation in the form of text, graphics (pictograms), speech, sound, tactile impact, and other presentation methods can be selected. The method of forming a message assumes the construction of a message based on the available information about the object and the requirements for the size of the message. For example, a text message may be detailed or abbreviated, a picture message may contain a photograph, a plan or a short pictogram, and the like.

Thus, the rules for the formation of a message can be defined $R\left(I_j, U\right) = \left\{M_k\left(I_j, U\right), k(U)\right\}$, where Ij defines the message construction method for the selected presentation method k, and the presentation method, as well as the method of its formation, depends on the user's state data $U(k = 1 \ldots K)$, where K the number of possible ways to present the message. The state (behavior) of the user affects both the choice of the message type and the process of its formation. The purpose of this process is to select the type of message and its informativeness to get the most benefit from the additional information provided to the user. The amount of information in the generated message is equal to. $I_k = M_k\left(I_j, U\right)$.

Let's make the following assumption: the user can adequately perceive a certain amount of information μ per unit of time (intensity of perception of information). The intensity of information perception is different for different ways of forming messages (text, graphics, voice, sound, tactile sensations) $k = 1 \ldots K$.

The formation of a message about the AR object is shown in figure 2.13.

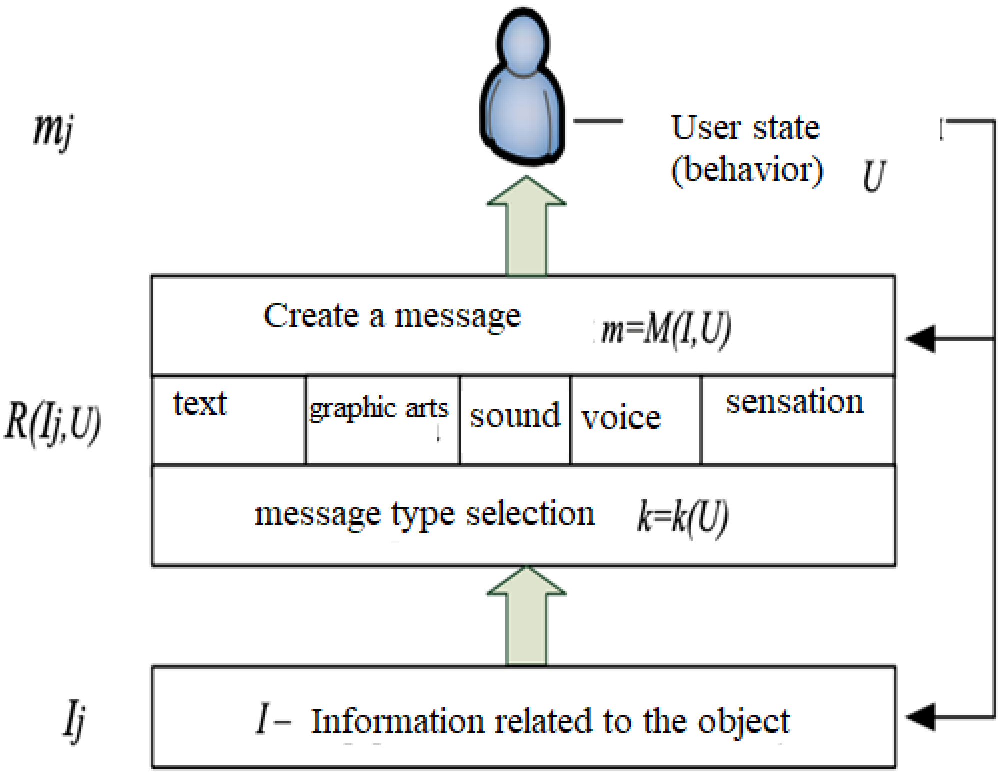


Figure 2.13 - Formation of a message about the AR object

Thus, it is a random variable whose distribution depends on the distribution of message types. We believe that the message m_j is in the user's perception area for some time t. This time depends on the parameters of the environment area and the nature of the user's movement, as shown above. Thus, service delivery parameters, such as message presentation methods and the amount of information in a message, affect the number of messages perceived by the user, and hence the perceived amount of information.

Let us estimate the share of messages perceived by the user through the waiting time distribution function (2.24). Then choosing the value T_0, based on the user's movement characteristics (2.27) and (2.28) it is possible to formulate the objective function

$$\{M,k\} = \arg(\max_{k,M}\left(h_p,(T_{0i})I_p\right) \quad (2.29)$$

$k = 1..K$;

$M = M(I,U)$;

where I_p – the amount of information in the message.

The ways of presenting messages and the amount of information in the message affect the number of messages perceived by the user, and therefore the perceived amount of information.

Let us estimate the share of messages perceived by the user through the waiting time distribution function (2.24). Then, choosing the value T_0, based on the characteristics of the user's movement (2.27) and (2.28), we can formulate the objective function.

The search for the maximum objective function is to achieve the maximum amount of information perceived by the user for a given time interval T_0. This is achieved by choosing message types $k = 1..K$ of their representation method $\mathrm{M(I, U)}$.The method of presenting the message determines the amount of information in the message (detailed, abbreviated, brief, etc.). The choice of a message presentation method, in the general case, requires separate consideration. In this paper, we assume that $\mathrm{M(I, U)}$is a discrete function whose value is a message that can be presented in three formats: detailed, abbreviated, and short formats. The choice of this or that format is determined by the solution of problem (2.29).

Under these conditions, problem (2.29) is an optimization problem for a discrete objective function. The method of dynamic programming can be used as a method for solving it.

Modeling the movement of the user of the augmented reality service

AR terminals can be various devices, both general-purpose (smartphones, tablet computers, laptops) and specialized (augmented reality glasses, projectors, etc.). The main function of the AR service is the delivery to the consumer of information that is useful to him in certain conditions. Methods for identifying such conditions and methods for delivering information can be very different. A generalized AR service model is shown in figure 2.14.

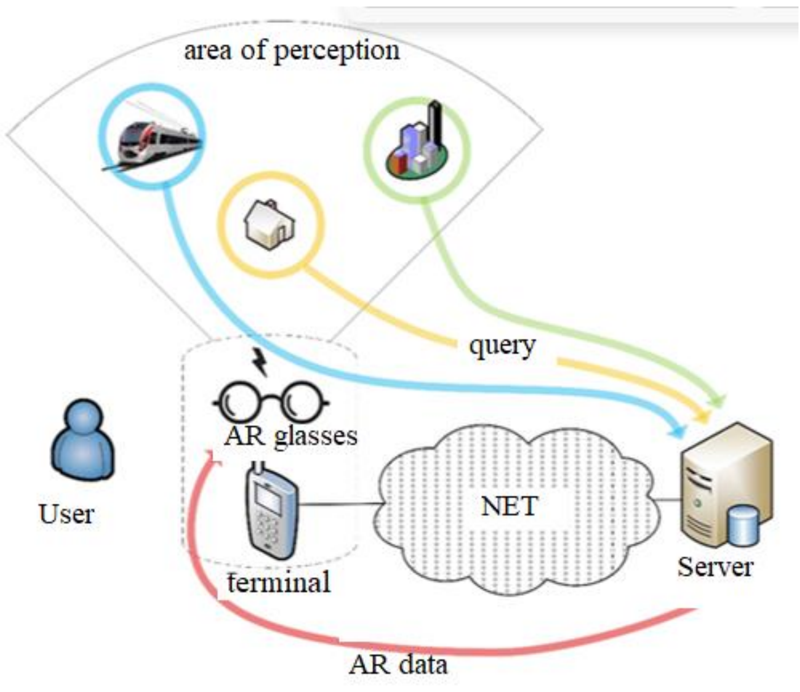


Figure 2.14 - Generalized augmented reality service model

There are also different ways of presenting information. Most AR services involve the transmission of information using visual messages (text, icons, color, image brightness, etc.), although other forms of data representation (voice, sound, tactile sensations) are possible in some applications. Thus, the organization of the AR service is a complex task, the solution of which is largely determined by the applied orientation.

For the target space, we will take the user's environment, where objects are located, information about which is contained in the AR database and can be requested. As conditions that determine the need for this or that information, we will consider the position of the user in his environment, as well as the characteristics of the movement. For example, when using a service such as maps or a navigator, the user is free to move. At the same time, the only characteristic of its position in the surrounding space is its coordinates, the change of which serves as the basis for requesting data. Depending on the user's coordinates, the smartphone application loads the map data, and periodically loads the necessary data during the user's movement. If the data loading is delayed, the information on the map becomes out of date. The value of the information decreases and becomes zero when the user leaves the area displayed on the map.

Obviously, the quality of perception by the user of the service depends on the timeliness of information delivery, and the requirements for the delivery process depend on the nature of the requests, i.e., on the way it moves, which, of course, will be different for a pedestrian and a car driver on a high-speed road. To eliminate the risk of untimely delivery of data, for example, by using a navigator application, all map data can be pre-placed on the user's device (offline maps). However, this method is good only for one of the services, and besides, it is applicable if the data is unchanged for a long time: it is not advisable to store information about traffic jams on the terminal. Additional AR information, which is information about the current state (this can be, for example, an x-ray of a patient during surgery), is not subject to storage at all. Thus, to organize an AR service and ensure its quality, it is necessary to consider the traffic model, which, in turn, is determined by the user's behavior and the methods of generating data requests.

Data model

AR data serves to bring to the user some information that he may need in a real situation. The information represented by these data is associated with specific objects. Thus, there is a one-to-one correspondence between objects and data containing certain information.

Let the set of AR objects be equal to $O = \{o_1, o_2, K, o_n\}$ where n is the number of objects, information about which is contained in the AR system. Then there is also a set of AR data $D = \{d_1, d_2, K, d_n\}$ and there is also such a mapping of the set of objects to the data set $f: O \to D$, where each element o_i is associated with elements of the set D.

An element d_i in the general case is a set of data that includes information about the corresponding o_i object. This data set may contain various forms of message presentation, such as text description, graphic image, icons, video, and audio recordings, etc., which can be accessed by the user. A more detailed and deep classification of data is also possible, depending on the specifics of the service provided. In this work, we restrict ourselves to stating the presence of the data block itself d_i.

The set of AR objects itself is in fact a set of certain features, based on which these objects can be identified, i.e., is a set of features of the o_i object. Such a set may include, for example, geographic coordinates, viewing directions, geometric dimensions, and elements necessary for object image recognition. For AR services for different purposes, for different terminal options, requests and user behavior, there may be different sets of features of different objects. Here we will also restrict ourselves to stating that such a set of features of an object exists.

The form of the mapping function f is determined by what is required for the service. In general, f should establish a correspondence between a set of features and data about an object. Naturally, in the general case, it is impossible to set a unique condition for f, and a uniqueness condition for features. Even when it comes to biometric data, there is a non-zero probability of matching error. Thus, mapping rules must also consider the requirements of a particular service.

To summarize what has been said: a data model is a description of the sets of features of objects and data about these objects, as well as the corresponding rules for displaying these sets.

User model

The user model is one of the most essential elements in service modeling. Since the user is the subject for which the service is created, such a model should reflect its main characteristics of behavior and perception, which set the requirements for the technical parameters of the service. It is the perception of messages (information) and the behavior that determines the need for information that serve as factors in the choice of methods for organizing and providing services.

The ability to perceive various forms of message representation determines the choice of means for organizing the (generally) human–machine interface. Such a choice should be based on studies of the characteristics of human perception of various forms of presentation of messages, as well as the ability to perceive several messages in various conditions. This is a separate area of research. In this case, we focus on the user's behavior, namely, on the behavioral features associated with the nature of data requests. This component of the user model allows you to identify the features of the request traffic and data traffic of the ARR service.

When describing the user model, we proceed from the following assumptions:

1. The user is a person, and the user terminal is AR glasses, a smartphone or other portable wearable device connected to a communication network and having a graphical interface (screen) with the user.

2. We consider a typical user whose behavior is determined by the most probable (typical) situations. This model does not claim to be completely general since there are many special (specific) areas and situations in which user behavior can differ significantly from the typical one. Such applications require specific models.

3. When constructing a behavior model, we examine only those features that determine the nature of data requests. These include those that manifest themselves in such an effect on the AR device that can be assessed using sensors and input devices currently available.

Let us describe the parameters that can be measured or entered by the AR device. In general, these include:

1) sound, without recognition of the source and content;

2) sound, with source and/or content recognition;

3) photo or video (without object recognition);

4) photo or video (with object recognition);

5) manipulations with the input device (touch screen, etc.);

6) position of the device in space (GPS coordinates or other global positioning systems);

7) orientation of the device in space (orientation in the Earth's magnetic field);

8) illumination data;

9) temperature data.

The given set of data is typical, individual devices may show a wider set of data, for example, fitness bracelets (“smart watches”), etc.

The AR service is provided through the interaction of the AR client application running on the mobile device and the server. Requests for data are made by the client application. In this case, the request for AR data can be both interactive, i.e., at the request of the user, and predictive - at the decision of the client application. In the first case, the user makes a request in some prescribed way, by touching the screen, moving the manipulator, or by voice command. In the second case, the request is made automatically by the client program based on the analysis of user or environment actions, for example, moving to a point with different coordinates, turning the subscriber device, hitting a certain target object in the observation area, etc.

Thus, the nature of data requests can be very diverse, which significantly depends on the specifics of the service. When building the model, we will analyze only requests initiated by the application, i.e., automatically, based on the analysis of some properties of user behavior. Let's consider the most characteristic properties inherent in most modern applications and services, namely: the movement of the user and the change in the position of the device in space.

Under such conditions, the request is initiated when the user's coordinates or the position of the subscriber device in space changes. Since the data must be delivered in a timely manner (when they are expected to be needed), they should be requested based on some forecast. The initial data for the forecast can be the parameters of the user's behavior until the moment when the request is made. It is obvious, for example, that when a driver moves in a car on a high-speed road, it is advisable to prepare data considering the speed and direction of movement.

In general, we can say: in a particular situation, different data have different probabilities of being in demand. This is determined by the behavior of the user, his movement.

Speaking about the user's movement (change of his coordinates in three-dimensional space), we assume that the data request is formed when the AR object enters the user's surrounding space. Such an event can be registered by the sensors of the subscriber device, if it is possible and provided by the service, or after accessing the AR database. In the second case, the AR DB should be accessed when the user's coordinates change. Obviously, a certain threshold value of this change should be chosen, since changes in the coordinate estimate occur not only due to the user's movement, but also by chance - due to the presence of an error in the functioning of the positioning system. In addition, the size of this change may depend on the density of AR objects in the space under consideration.

For example, if the user's environment is given by an area bounded by a circle with radius R, then with its rectilinear and uniform movement (figure 2.16), with a random distribution of objects, the path traveled by an object in the perception area will be a random variable with a probability density equal to:

$$g(d) = \frac{1}{\pi R\sqrt{1-\left(\frac{d}{2R}\right)^2}} \quad (2.30)$$

and mathematical expectation:

$$M[d] = \bar{d} = \frac{4}{\pi}R \quad (2.31)$$

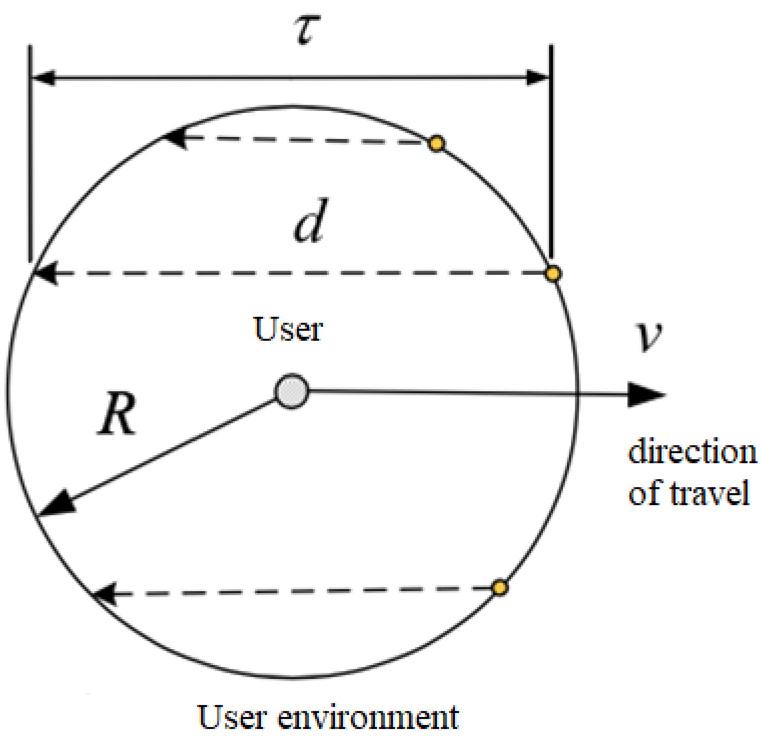


Figure 2.15 - The model of the rectilinear movement of the user

With the user's movement speed v, the time the object stays in the perception area will also be a random variable with a probability density:

$$q(t) = \frac{1}{\pi R\sqrt{1-\left(\frac{v}{2R}\tau\right)^2}} \quad (2.32)$$

and mathematical expectation:

$$M[t] = \bar{\tau} = \frac{4R}{\pi v} \qquad (2.33)$$

The graph of the probability density (3.32) is shown in figure 2.17.

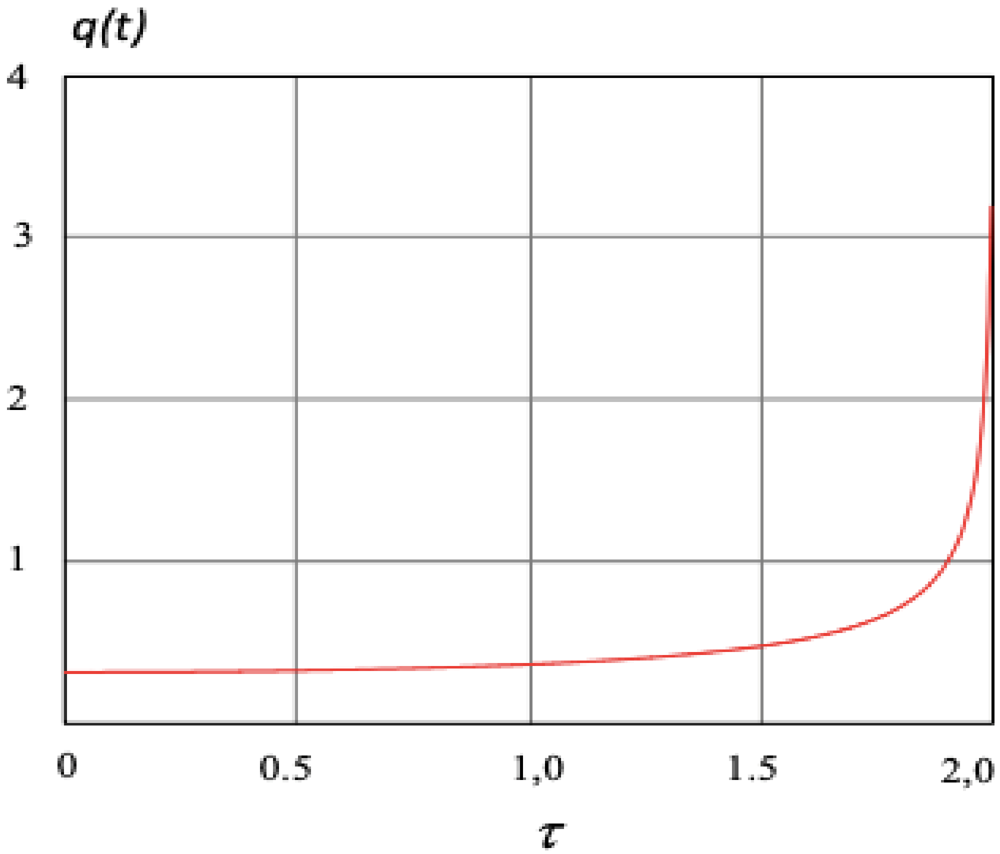


Figure 2.16 - The probability density of finding an object in the user's environment

Expressions (2.32) and (2.33) make it possible to estimate the time spent by objects in the area accessible to the user. The task of constructing the system in this case will be to choose the values of the system parameters for which condition (2.33) is satisfied. These parameters are the share of messages of each type and how they are formed.

Consider next the service delivery model. Note that it is not entirely correct to focus only on rectilinear movement: all users (pedestrians, passengers of various types of public transport, passengers, and drivers of vehicles) have different speeds. Therefore, we consider several models of the speed of movement as random variables.

Figure 2.18 shows the probability density of the speed of a pedestrian, obtained based on the experiment - by analyzing the movement according to the monitoring data of its geographical coordinates.

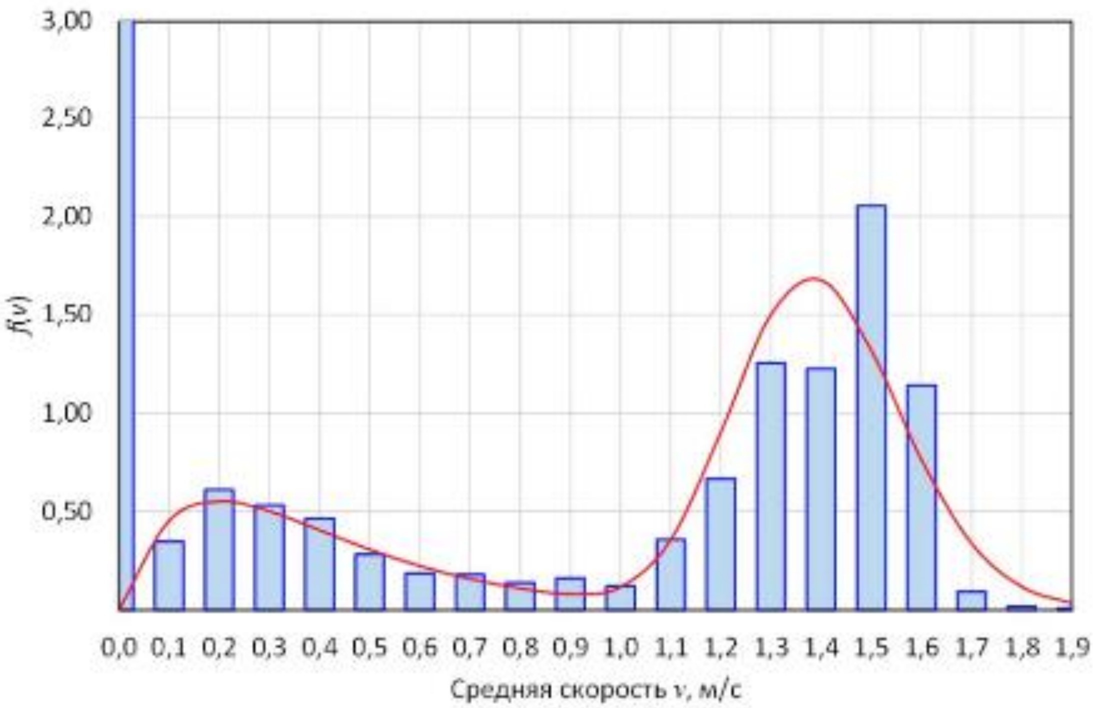


Figure 2.17 – Probability density of average pedestrian speed estimates

The resulting histogram has three distinct modes: 0; 0.4 m/s (1.4 km/h) and 1.4 m/s (5.0 km/h). These modes obviously describe three characteristic types of pedestrian movement: waiting (permitting signal of a traffic light, transport, etc.), slow movement (when waiting for transport, walking step), normal movement (on the sidewalk).

The histogram in figure 2.18 is approximated by the sum of two gamma distributions and a delta function:

$$f(v) = \eta_1 \delta(0) + \eta_2 \frac{v^{k_1-1}}{\theta_1^{k_1}\Gamma(k)} e^{-\frac{v}{\theta_1}} + \eta_3 \frac{v^{k_2-1}}{\theta_2^{k_2}\Gamma(k)} e^{-\frac{v}{\theta_2}}, \eta_1 + \eta_2 + \eta_3 = 1, \quad (2.34)$$

where η_1, η_2, η_3– empirical coefficients;

$k1, k2, \theta1, \theta2$– distribution parameters.

Figure 2.19 shows the empirical histogram and the probability density of the speed of the car in difficult traffic (during rush hour). The histogram has several modes, the actual number of which is difficult to calculate. These modes are determined by the average traffic speeds characteristic of a car stream in various states: free movement, movement when avoiding an obstacle, passing an intersection when driving "in a traffic jam" (acceleration, movement and stopping in line at the intersection). There can be a different number of characteristic situations – at least three modes can be distinguished in the experimental data.

According to the distinguished modes, we construct the probability density function. As in the previous case, we will consider the situations described above, which determine the different nature of the movement by random and independent events. Then the probability density function can be represented as a weighted sum of the probability densities of each of the considered types of motion.

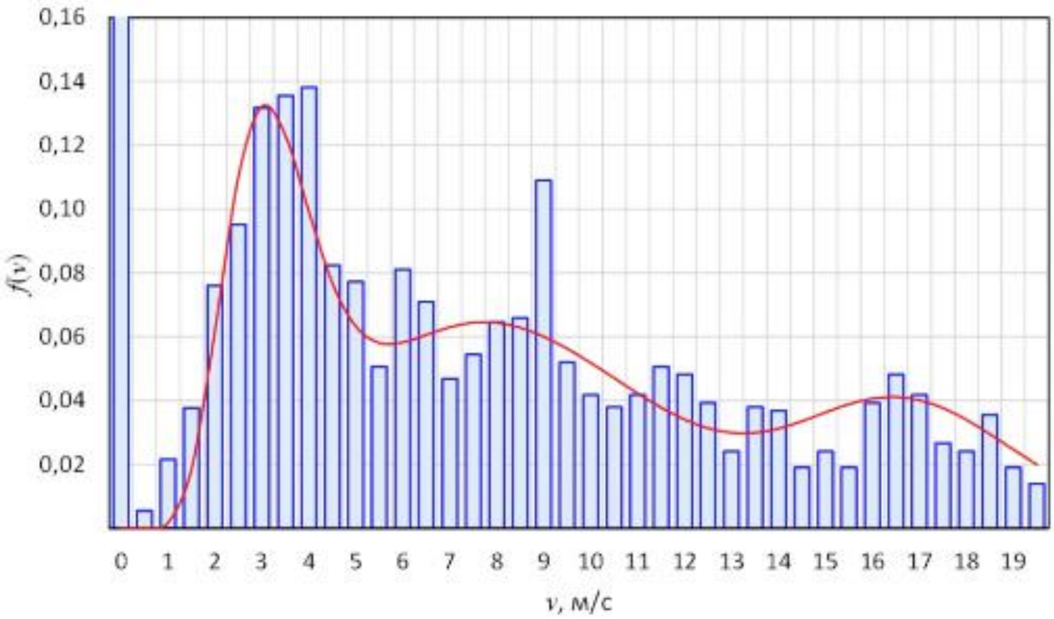


Figure 2.18 - The probability density of estimates of the average speed of the car in difficult traffic

The probability density in this case is equal to

$$g(v) = \eta_1 \delta(0) + \eta_2 \frac{v^{k_1-1}}{\theta_1^{k_1}\Gamma(k)} e^{-\frac{v}{\theta_1}} + \eta_3 \frac{v^{k_2-1}}{\theta_2^{k_2}\Gamma(k)} e^{-\frac{v}{\theta_2}} + \eta_4 \frac{v^{k_3-1}}{\theta_3^{k_3}\Gamma(k)} e^{-\frac{v}{\theta_3}} \quad (3.35)$$

$$\eta_1 + \eta_2 + \eta_3 + \eta_4 = 1$$

где $\eta_1, \eta_2, \eta_3, \eta_4$– empirical coefficients;

$k1, k2, k3, \theta1, \theta2, \theta3$ – distribution parameters.

Generalizing the two considered cases, we can assume that the probability density of the movement of a pedestrian, car or public transport passenger is determined by the expression

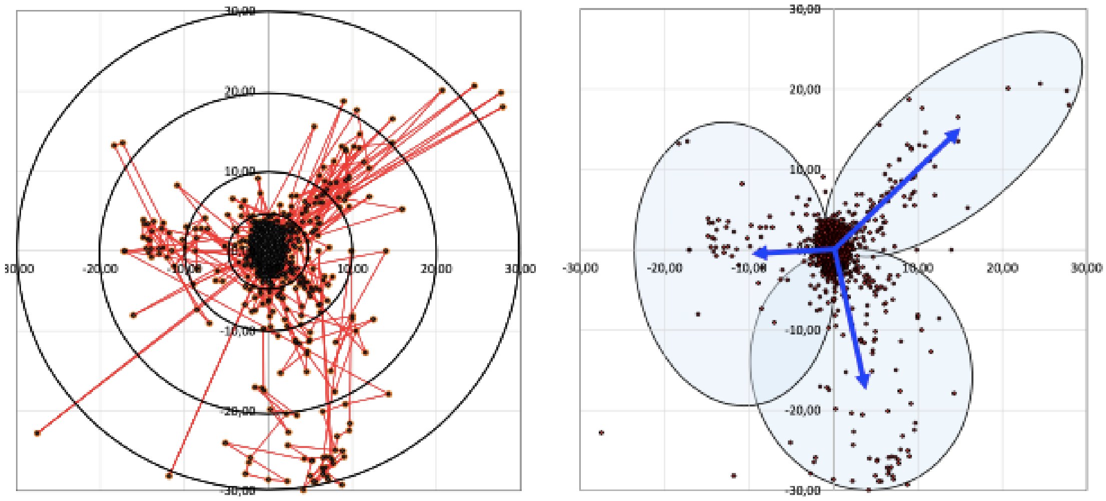
$$h(v) = \eta_0 \delta(0) + \sum_{i=1}^{N} \eta_i \frac{v^{k_1-1}}{\theta_i^{k_i}\Gamma(k)} e^{-\frac{v}{\theta_i}}, \sum_{i=0}^{N} \eta_i = 1, \quad (3.36)$$

where η_i– empirical coefficients;

k_i, θ_i– distribution parameters;

N– number of modes.

Figure 2.20 shows the changes in coordinates during the observation time. Each point corresponds to one reading, the readings are taken with an interval of 1 s. Neighboring readings are connected by lines. Figure 2.20, b illustrates the main directions of movement that took place during the observations. The obtained data are divided into three clusters (highlighted in the figure by ovals), for each of which a vector is constructed, formed by averaging over the direction and distance.



a - is the sequence of changing coordinates; b - the main directions of movement

Figure 2.19 - Change of coordinates during observations

The obtained clusters are characterized by the closeness of the values of both counts and the time for which they were obtained, i.e., each vector can be associated with a continuous time interval during observations. From the analysis of Figure 2.20, it follows that the most probable transitions are made in the direction of the object's movement.

Consider movement in one direction, i.e., one of the selected clusters. In this case, the area of probable changes in the position of the object can be described by a single ellipse. The distribution of the probability of a point getting into the user's environment can be represented by a two-dimensional normal distribution

$$p(x,y) = \frac{1}{2\pi\sigma_{x,}\sigma_{y}\sqrt{1-p^2}} e^{-\frac{1}{2(1-p_i^2)}\left(\frac{(x-\bar{x})^2}{\sigma_x^2} - p\frac{2(x-x)}{\sigma_x\sigma_y} + \frac{(y-\bar{y})^2}{\sigma_y^2}\right)} \quad (2.37)$$

where $\bar{x}, \bar{y}$ – average values for the corresponding coordinates;

σ_x, σ_y– root-mean-square deviations (RMSD) for the corresponding coordinates;

ρ - correlation coefficient between x and y

The probability density for the data obtained during the experiment and shown in figure 2.20 (if the motion processes described by different clusters are independent) can also be expressed by a multimodal distribution with a probability density.

$$\beta(x,y) = \sum_{i=1}^{K} \eta_i \frac{1}{2\pi\sigma_{x,}\sigma_{y}\sqrt{1-p^2}} e^{-\frac{1}{2(1-p_i^2)}\left(\frac{(x-\bar{x})^2}{\sigma_x^2} - p\frac{2(x-x)}{\sigma_x\sigma_y} + \frac{(y-\bar{y})^2}{\sigma_y^2}\right)} \quad (2.38)$$

Figure 2.21 shows the probability density of the position of the object according to the experimental data (see Figure 2.20). Figure 2.21, b shows a contour diagram of the probability density of one of the directions of movement (clusters), described by formula (2.37).

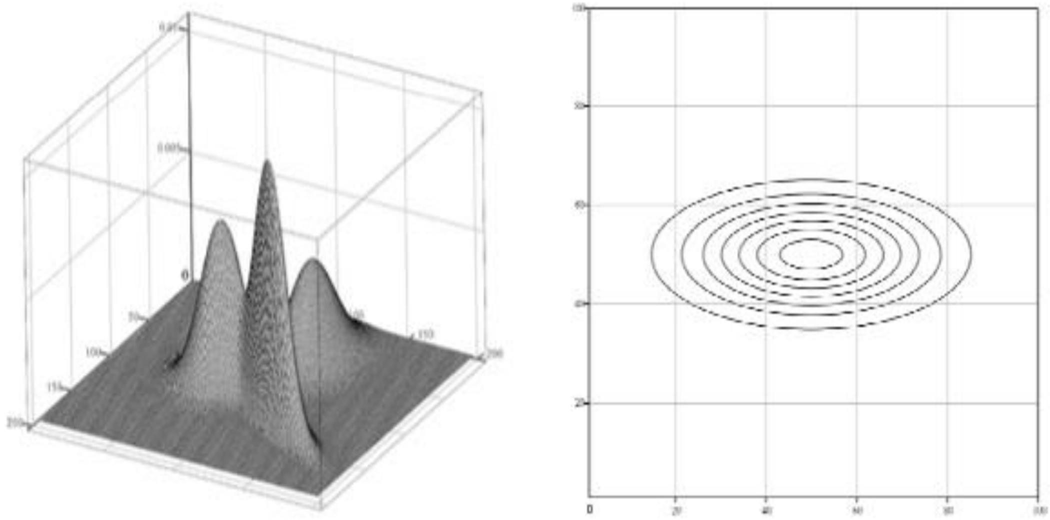


Figure 2.21 - Probability density obtained from experimental data (a), and a model of one of the directions of movement (b)

Let us write the probability of hitting the object o in the target area, according to the properties of the probability density function:

$$p(0 \in C) = \iint_C f(x,y)dx, dy, \quad (2.39)$$

where f(x,y)– probability density function determined according to (2.37) or (2.38), depending on the considered type of motion;

C - target area (ellipse). Suppose that when forming a request for AR data about objects in the user's environment, the required probability is determined that the requested objects will be in the target area p_0. Then the target area will be defined by an ellipse with the following parameters:

$$C = \arg\left\{\iint_C f(x,y)dx, dy = p_0\right\} \quad (2.40)$$

The solution of expression (2.40) is a rather complicated task, therefore, in practical cases, you can use the 3σ rule for the semi-axes of the scattering ellipse. In this case, the probability of hitting the ellipse is at least p0 > 0.99. The expression for the scattering ellipse has the form

$$\frac{(x-\bar{x})^2}{\sigma_x^2} + \frac{2p(x-x)(y-\bar{y})}{\sigma_x\sigma_y} + \frac{(x-\bar{y})^2}{\sigma_x^2} = \xi^2 \quad (2.41)$$

When forming a data request, one should consider the size of the user's perception area, which was described by a circle with a radius R (see Fig. 2.16). Figure 2.22 shows the target query area (red line) obtained from the scatter ellipse (2.41) (blue line).

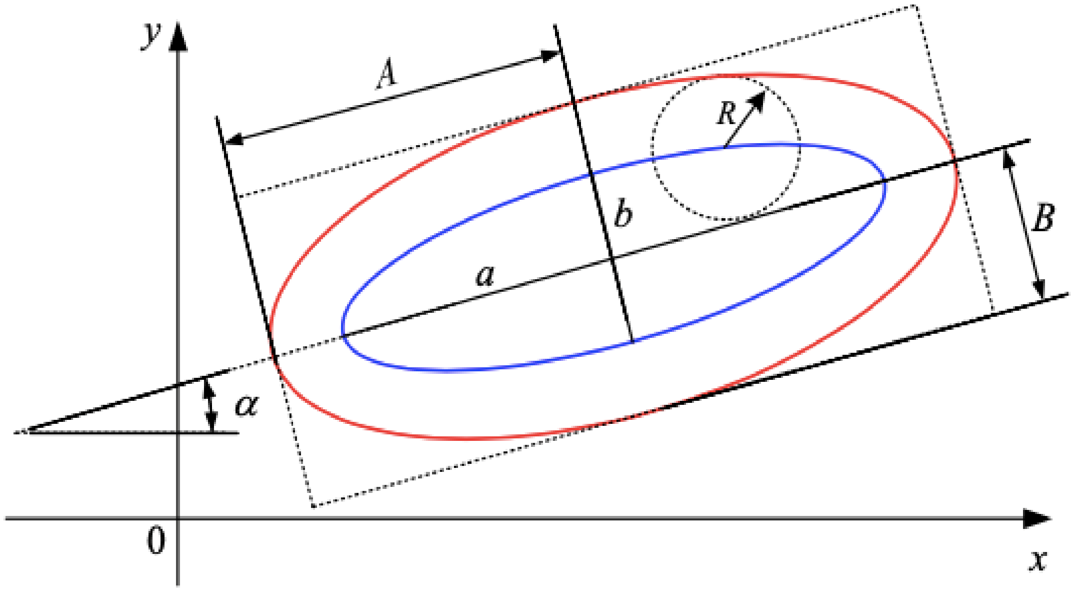


Figure 2.22 - Target area for requesting augmented reality data

Considering the rule 3σ we determine the parameters of the scattering ellipse:

$$a = 3\sigma_x, b = 3\sigma_y, A = a + R, B = b + R, tg2a = \frac{2p\sigma_x,\sigma_y}{\sigma_x^2 - \sigma_y^2} \qquad (2.42)$$

where a, b – semiaxes of the scatter ellipse (probable user coordinate);

A, B – semiaxes of the target area of the data request (probable area of user perception).

Since it takes a finite time to request data, their delivery and display, it is advisable to consider some size redundancy in the ellipse parameters (let's call it ΔR), then at the speed $\bar{v}$ and data delivery time td we get:

$$\Delta R = \bar{v} t_d \qquad (2.43)$$

Further, we will assume that the amount of redundancy is considered in the value of R itself.

In practical implementation of the service, to simplify calculations, the request area may be approximated by a rectangle in which an ellipse representing the target request area is inscribed.

Thus, for the formation of requests for AR data, parameters are required that can be calculated from data on the user's coordinates obtained at certain time intervals. $X = \{x_1, x_2, ...\}, Y = \{y_1, y_2, ...\}$, on the basis of which the necessary values are determined $\bar{x}, \bar{y}, \sigma_x, \sigma_y$.

Their values at the moment of time corresponding to the k sample (interval) can be calculated as a sample mean and standard deviation.

When implementing the service, the characteristics of the traffic will depend on the method of generating requests. If the AR objects are distributed randomly and uniformly in the service area, then the number of requests (objects) for the data request time interval t_0 (in seconds) will be determined by the area of the target area of the SC request and the speed of the user's movement: $\lambda = \theta SC t_0$, where θ– AR object density (objects /м2).

One of the parameters required for the organization of the service is the time interval for updating the AR (request) data, which can be found from (3.41) as t_0. To do this, you need to set the intensity of requests λ_0, at which the system meets the delivery time requirement. Meaning λ_0 depends on the requirements for delivery time and the performance of the server (servers) of the AR system. To select it, the model of a queuing system (QS) can be used.

Augmented Reality Data Selection Method

For AR services focused on searching for data about objects based on geographic coordinates, the user movement model, as shown above, serves as a tool that allows prediction and predictive selection of data, including determining that a data request can be generated based on geographic coordinates of objects. included in the region bounded by an ellipse with parameters (3.42).

The parameters σ_x, σ_y and ρ can be obtained from experimental data, i.e., in the process of providing the service. The work on evaluating these parameters and generating a request is performed by the client application of the user's terminal.

The generalized algorithm of this method is represented by the following sequence of basic operations:

1. Initialization of initial values and other preparatory actions.

2. Obtaining estimates of coordinates and speed x_i, y_i, v_i for the i-th sample, for which the functionality of the client terminal is used. We believe that these capabilities include all the necessary operations associated with the calculations and pre-processing of these values.

3. Selecting the type of movement based on speed data. For this purpose, the average value of the speed over k observation intervals (sample) and its comparison with the types of movement characteristic of the user or service (for example, with the speed data given above) can be used. The purpose of this stage is to determine such a value of the speed of movement, which should be guided by when forming a request for the choice of ΔR (2.43) and a time interval t_0. This value can be taken, for example, from those considerations that the speed of movement does not exceed a certain value with a given probability. To solve the problem, it is proposed to use a hypothetical distribution (probability density) obtained from expressions (2.34) or (2.35) as a component that determines the mode for a given type of motion.

4. Calculation of RMS σ_x, σ_y and correlation coefficient ρ for the last k readings.

5. Calculation of the coordinates of the ellipse according to (2.42), formation and sending of a request with the appropriate parameters.

6. Obtaining AR data and using them.

7. Waiting for the end of the interval t0; go to point 1.

The above method provides predictive delivery of AR data to the client terminal, which makes it possible to reduce the time for providing messages to the user.

Obviously, the volume of the requested data, and, consequently, the traffic and delivery time are proportional to the area of the geometric figure that is used in the formation of the request. In this sense, the shape of the shape that bounds the target area chosen for the request affects the amount of AR data that is selected and transmitted, while the amount of payload data probably affects the amount requested.

It is quite difficult to determine the amount of useful data (perceived and used by the subscriber without the use of expert assessment methods). Therefore, we will assume that all data that falls into the user's perception area (a circle of radius R) is useful with a certain probability. The proposed model just describes this region as an ellipse with parameters (2.42).

Then the effectiveness of using the model can be estimated by a simple ratio of the areas of the figures used for the query. It is obvious that all figures that have a larger area than a given ellipse (described around the ellipse, Figure (2.23) lose in efficiency, and those with a smaller area (inscribed in the ellipse) lose in terms of the probability that all useful data will be delivered.

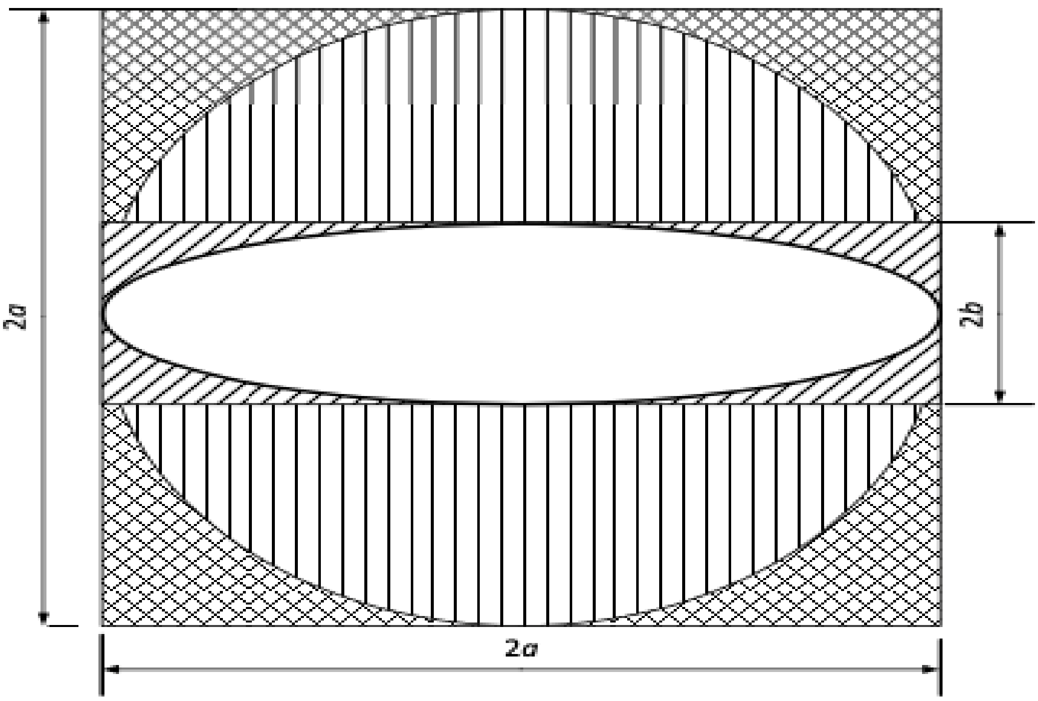


Figure 2.23 - Comparison of an ellipse with other forms of the query target area

When considering only larger area shapes such as a square, circle, and rectangle, $b/a,\ \pi/4, (\pi b)/(4a)$ the efficiency of using an ellipse is for a circle, rectangle, and square, respectively. It is obvious that the most efficient "simplified" form of the target area among the considered alternatives is the rectangle described around the ellipse: in relation to it, the gain exceeds 25%.

2.4 Choosing a 3D visualization development environment

Visualization is one of the most developed aspects in the implementation of augmented reality technology. Many existing solutions can be applied to implement the part of augmented reality technology related to three-dimensional visualization.

As one of the most low-level options, it is possible to directly use OpenGL - a specification for writing applications that use two-dimensional and three-dimensional computer graphics. It serves to develop three-dimensional graphics for most mobile devices. However, the use is time consuming.

There are also various graphics engines that allow you to develop complex applications with simpler means. These include Ogre3d, UnrealEngine, Unigine.

During the search and analysis, the Unity development environment was chosen as the basis for the software implementation of the system. It is a high-level development environment for applications and games. Includes a powerful GUI editor and a graphics engine optimized for mobile devices. Unity is a cross-platform development tool and allows you to compile a project with one source code and resources for leading mobile platforms such as iOS, Android, Windows Phone.

Unity uses the FBX 3D model format. Most modern tools for creating three-dimensional models, such as 3dsMax, Maya, support export to this format. In most cases, models are transferred correctly.

User scripts can be written in any .NET programming language and compiled into regular managed assemblies (DLLs).

There are built-in compilers for C#, UnityScript, and Boo. At the same time, there is the possibility of organizing an interface with external code.

The pluses also include an active developer community and many ready-made developments and extensions.

2.5 Conclusions on the second chapter

In connection with the introduction of the latest IT technologies not only in commercial organizations, but also in the lives of users around the world, new services are emerging that require a special approach to organizing network operation, as well as ensuring its optimal functioning. In this chapter, it was considered how one of these technologies, called "augmented reality", changes the principles of delivery and reproduction of information to the user.

1. A model of the AR service is proposed, based on the main criteria for assessing the quality of the provision of the AR service are formulated, characterized by the degree of compliance with the intended purpose, the degree of susceptibility of the data provided and the timeliness of the provision of information.

2. A model of interaction of the main elements in the provision of AR services is proposed, considering the presence of IoT devices in the user's environment, the use of a communication network, including D2D communications, and the possibility of using UAVs.

3. When evaluating such an indicator of the quality of the AR service as the timeliness of data delivery, the user is asked to take into account the following components: the time of obtaining data about the environment and their processing;

time of data delivery to the service server; time of data processing by the service server; time of data delivery to the user; data submission time.

4. A methodology for representing augmented reality user traffic has been developed, characterized in that three interrelated models are used to represent traffic: a service space model, a user perception area model, which is a part of the service space that a user can perceive at a particular point in time, and a user behavior model characterizing changes in its position and area of perception.

5. An augmented reality user traffic model has been developed when the user's perception area changes in the process of its movement, characterized in that when the user moves forward in the Poisson field, the user's perception area is represented as a sector and in the Kendall-Basharin classification this model is written as follows – , where α – sector angle, r is the radius, ρ is the density of devices in the sector, v is the user's movement speed, ω is the angular rotation speed.

6. A model of a mobile user of an augmented reality service moving in the environment of Internet of Things devices has been developed, which differs from the known ones in that the user is presented as a queuing system, and the incoming stream is formed from K services available to the user, including video, text, graphics, speech , music, tactile sensations, etc., which makes it possible to calculate such systems using the queuing theory apparatus.

7. A model for the provision of AR services has been developed, considering the methods of providing messages and the amount of information transmitted, which makes it possible to estimate the amount of information perceived by the user.

8. A model of the user's movement is proposed, built based on experimental data, which considers the peculiarities of his movement in the urban environment - both as a pedestrian and as a vehicle passenger. The model can be used both for modeling the service (simulating the movement of users), and in the process of its implementation (when forming the parameters of data requests).

The distributions of the speeds of pedestrians, drivers and passengers of vehicles are obtained, differing in that these distributions are presented in the form of multimodal ones to obtain estimates of the augmented reality user's traffic.

9. A method for providing augmented reality services with a circular view is proposed, which differs in that, in addition to an interactive data request at the request of the user, the possibility of predictive data request according to the decision of the client application is also taken into account, while the predicted area of user perception is represented as an ellipse built on the basis of probable coordinates user and the likely area of data perception by the user, which makes it possible to provide an efficiency of at least 25% greater than when using other shapes.

3 DEVELOPMENT OF INFORMATION SYSTEM WITH TECHNOLOGY OF INTERACTIVE VISUALIZATION BY AUGMENTED REALITY

3.1 Application of augmented reality, UAVs and SDN for VANET applications

VANET (Vehicular Ad Hoc Network) networks have proven themselves well in the exchange of traffic between road users. However, VANET capabilities are not always enough to solve modern problems. SDN technology, which is based on the division of traffic into management and data transmission tasks, complements VANET. This section proposes a model for controlling traffic lights along the entire route of special vehicles (ambulances, fire brigades ...), in which an unmanned aerial vehicle acts as an SDN controller. The model also considers the possibility of using augmented reality technology when controlling traffic lights in order to reduce the inconvenience of other road users associated with the need to pass special vehicles [10, p. 87].

Currently, VANET networks are one of the important directions in the development of Ad Hoc networks. At the same time, in recent years, VANET networks and their applications are increasingly being considered in complex applications with other new telecommunication technologies. Thus, the use of UAV (Unmanned Aerial Vehicle) unmanned aerial vehicles can often significantly improve the functioning of the VANET and / or expand the functionality of this network. The use of augmented reality applications also provides new opportunities for VANET, especially in conjunction with the use of UAV. At the same time, in most VANET applications, including when using UAVs and AR, the VANET network architecture is built based on software defined networks (SDN). To select a rational VANET network architecture, many authors use clustering methods.

Next, we consider the traffic light control model in VANET in the presence of priority service. Quite a lot of attention is paid to the issues of traffic light control in the VANET network. At the same time, it is emphasized that the control of traffic lights in the VANET network, in comparison with existing traffic light switching systems at intersections, makes it possible not only to reduce delays in the movement of cars [23], but also in urban conditions to reduce CO2 emissions [24]. The article [25-40] notes that the use of a traffic light control system can increase the capacity of intersections by 42%.

3.1.1 VANET model with priority service

This section discusses the traffic light control model in the presence of priority service. Priority service means that there is a cluster of cars that moves at a constant speed and for which, throughout the route of its movement, the presence of traffic lights at intersections in the state of unimpeded passage of this cluster of cars must be ensured, as shown in figure 3.1.

Figure 3.1 - Architecture of interaction of network elements

The simplest implementation of such a priority passage of cars is to switch all traffic lights on the route to the green state for this cluster in advance. However, with a sufficiently long route, this leads to unjustified delays for other vehicles located at this intersection, as well as to the impossibility of timely passage of the intersection, for example, by ambulances. To reduce the waiting time for cars in ordinary clusters, as well as to ensure timely passage of intersections by ambulances, the following model is proposed, based on the use of the VANET network, augmented reality, and the architecture of software-defined networks, shown in figure 3.2.

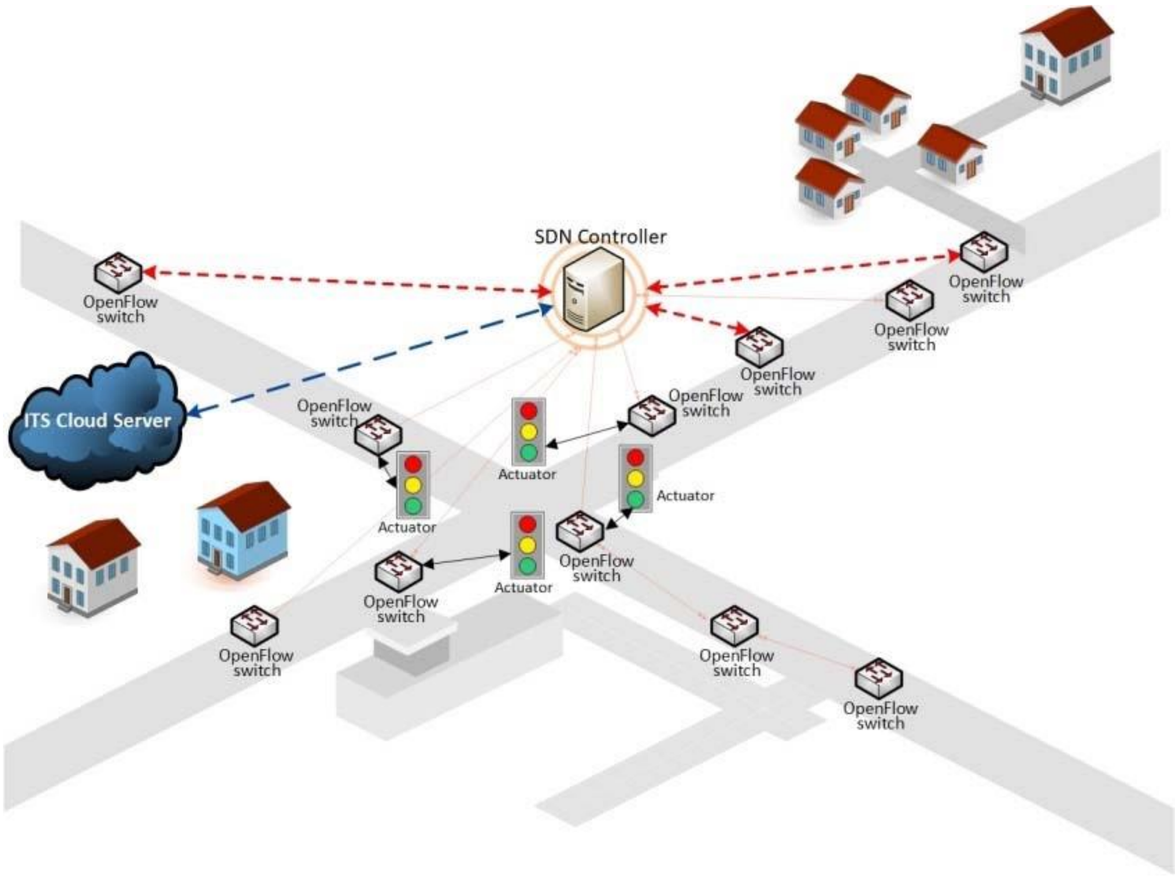


Figure 3.2 - SDN architecture

Note that in the proposed structure, the UAV performs the functions of an SDN network controller, the peripheral modules of which are in the cars of the priority cluster. The image from the UAV is received on augmented reality glasses by the assistant driver, which allows him to know the speed and other parameters of the movement of ambulances and other similar vehicles.

3.1.2 Traffic control algorithm.

Assume that the travel time of vehicles of the considered cluster along the route T is determined as the sum of the travel time of individual elements of the route T_{ik}.

$$T = \sum_{i=1}^{k} T_i \quad (3.1)$$

where i = 1 ... k number of the segment, k - the quantity of route segments.

The control task is to ensure a minimum delay in the arrival of a given vehicle through the road network using automatic traffic control devices, when interacting with them via a wireless network of the IEEE 802.11p standard (VANET). The task can be described as the problem of choosing the shortest route, i.e. reaching $min(T)$ by choosing the optimal route P among the set of possible routes {P}.

For a formal description of the model, we represent the road network in the form of a graph *G*, the vertices of which are the intersections - *v*, and the arcs of the road - *e*. In the general case, there is a directed graph. It should be noted that this graph can include only those vertices and arcs (intersections and roads) that can be used in the route. Each arc of the graph is assigned a number that characterizes the distance between intersections or the time it takes to travel this distance c_i. The solution to the problem consists in a dynamic (interactive) search for the shortest (in terms of distance or time) path by points of the beginning and end of the route. The peculiarity of solving this problem is that it is necessary: firstly, to determine the coefficients that consider the time of passage of the route element, considering the possibility of control, secondly, to determine the time for giving control signals (schedule or control plan) and thirdly, to be able to rebuild route at any current position of the vehicle m.

We assume that the beginning of the route is at the vertex s, and the end of the route is at the vertex t.

Proposed algorithm:

1. The current position is equal to the beginning of the route m = s.
2. Finding the shortest path between the current position and the end of the route $P_{min} = \{v_1, v_2, \ldots, v_k\}$
3. Formation of the list of times of switching on the permitting signal of traffic lights in the direction of the vehicle (control schedule) $L = \{\tau_1, \tau_2, \ldots, \tau_k\}$
4. Transmission of control signals (enabling signal activation) for the next i-th section of the route.
5. Waiting for a signal of readiness (unavailability) of the i-th element of the route during the travel time on sections up to the i-1 section of the route, inclusive.
6. If ready, following to element i of the route, $i = i + 1, m = i$. After passing the i-th element of the route, the control action is canceled (transfer to the normal operating mode).

Otherwise, go to n. 2.

7. If the destination point is reached (m = t), then stop, Otherwise, go to step 4.

At the beginning of the algorithm, the initial position of the vehicle is set (item 1), then the search for the shortest path between the current position and the destination is performed. For this purpose, any of the known algorithms for finding the shortest path in a graph can be used. In this case, preference should be given to heuristic algorithms, which can significantly reduce the search time. In addition, templates (variants) of routes obtained in advance can be used. After finding (choosing) the path, the sequence and time of transmission of control signals (turning on the enabling traffic signal) on the route elements are formed. This sequence is built in chronological order of the selected moments of transmission of control signals. The time (moment) of transmission of the control signal is selected based on the time required for the vehicle to arrive at a given route element and the time required to clear the intersection from passing vehicles.

$$t_i = \max\left(t_{i,}^{(arr)} \tau_i\right) \tag{3.2}$$

where, $t_i^{(arr)}$ is the time of arrival of the vehicle to the i-th element of the route;

τ_i is the time required to free the route element from associated vehicles (or increase its throughput). In the general case, $\tau_i = f(a, r)$ where **a** is the intensity of car traffic, **r** are the parameters of the route element (intersection, road). The description of this functional dependence is a separate task that requires certain research and field experiments. In our case, we will assume that a known function $f_i(a)$ is assigned to each of the vertices of the graph. Such a function can be specified, for example, by a table obtained experimentally. Traffic intensity **a** can be determined by various methods: statistically (according to schedule), using monitoring tools (stationary cameras, video cameras/cameras placed on the UAV, messages from other means of monitoring real traffic).

The effectiveness of the application of control actions is quite easy to evaluate by simplifying the route model to a multiphase QS, with the number of phases equal to the number of route elements, and vehicles as a flow of applications at its input. For example, with an exponential distribution of the service time (passage of the section) and the simplest flow at the entrance, the route passage time can be described as

$$T = \sum_{i=1}^{k} \left(\frac{p_i \bar{t}_i}{1-p_i} + \bar{t}_i \right) \tag{3.3}$$

Where $p_i = \lambda_i t_i$ is the load on the i-th phase,

λ_i is the flow rate at the i-th phase,

t_i– time of service (travel) of the i-th section,

k - the number of sections in the route.

When applying a control action on the i-th element, the value of t_i changes, namely, it leads to a decrease in this value. Consequently, there is a decrease in the value of T. This can be seen from the expression above. Thus, the travel time along the route is significantly reduced, the degree of this decrease can be determined when scheduling control actions. This is achieved by a timely increase in the throughput of the route elements, up to the complete release of the route elements from associated transport. The main advantage of this method is that the control action (allowing traffic signal) is produced within the minimum required time, which minimizes the impact on car traffic.

This section discusses the provision of priority passage of vehicles with special signals. Often this creates inconvenience to other road users because they must wait for a long time until the motorcade passes. This is due to the fact that traffic lights switch long before the approach of cars with special signals.

A model of timely traffic light control is proposed. VANET technology was chosen as the base for the implementation of control functions. To better manage the scalability and flexibility of the VANET, it is complemented by SDN technology, where the UAV acts as a controller.

For visual assessment of the situation and control, the model uses augmented reality technology. The video stream received from the UAV can be supplemented with the necessary current information, for example, the speed and intensity of vehicle traffic on crossing streets, vehicle dimensions, etc.

Within the framework of the proposed model, an algorithm has been developed for choosing the optimal route of movement by minimizing the time of arrival at a given point.

3.2 Investigation of the interaction of augmented reality applications and UAV control methods

In this section, we study the interaction of augmented reality applications and control methods for unmanned aerial vehicles. To conduct the study, an experimental stand was developed and during the experiment, the UAV was controlled by means of augmented reality technology. At the same time, the quality of service of the transmitted traffic was assessed and a subjective assessment of the quality of perception by observers was carried out. The study determined the characteristics of the network connection required for a given perceptual quality when controlling the UAV through augmented reality application [5,p. 6].

Controlling unmanned aerial vehicles in urban areas is a difficult task, since unforeseen obstacles can arise on the route of the UAV, which must be quickly detected and avoided. For the widespread introduction of UAV systems, it is necessary to solve the problem of ensuring reliable and timely control of the vehicle. In flying sensor networks, UAVs are actively used as a flying segment that collects data from ground sensors and delivers them to a server for further processing. Flying sensor networks turned out to be popular in the field of agriculture, when it is necessary to control a large area, in industry, when it is necessary to monitor hard-to-reach and remote objects, for example, gas pipelines, and have also proven themselves as routers that are used to quickly deploy a network in crowded areas.

It is customary to distinguish between three types of UAV control: manual, automated and automatic. In the first case of manual control, the UAV pilot is based on information received in the video image format from the UAV camera. With this control, augmented reality technology and tactile Internet applications can be applied to facilitate control tasks. Augmented reality allows you to add virtual data to objects of the surrounding physical world using specially designed display devices augmented reality glasses. The tasks of tactile internet include delivery of information on the impact of the network on an object at a remote distance and sending a response back. Obviously, with such an exchange of data, the delivery delay should be as low as possible.

When controlling the UAV, the pilot changes the position of the UAV in space by turning or tilting his head through the augmented reality application, based on the video that comes from the camera installed on the UAV to the AR display device.

To ensure stable control of UAVs using augmented reality applications, it is necessary to ensure the solution of the following tasks:

- transfer data on changes in the position of the pilot's head from the AR device to the UAV;
- to carry out continuous transmission of video images from the UAV camera to the AR device;
- ensure the fulfillment of the specified characteristics of the network;

- assess the quality of perception in the implementation of the UAV control process using the AR application.

3.2.1 Features of data transmission when controlling UAVs.

As mentioned earlier, the pilot controls the movements of the UAV and the video camera installed on it by tilting and turning the head, i.e., changes in its position in space. During the experiment, the camera was placed on the UAV so that only rotation along the vertical axis was ensured; therefore, to ensure the maximum viewing radius, it was necessary to rotate the UAV itself in the required direction. AR goggles are worn by the pilot, and they display video stream from the UAV camera. Thus, the pilot sees the objects surrounding the UAV and can change the location of the UAV, thereby moving the camera in the desired direction. For normal operation of the pilot, it is necessary to ensure not only a high-quality display of the video stream on the AR device, but also transmit a timely response to changes in the position of the controller's head to the UAV and the camera.

Thus, the response of the UAV must correspond to the commands of action; for example, when the head is tilted down, the camera must change its position and turn down as quickly as possible, so that the video stream is comfortable for the pilot to perceive. To accomplish this task, a gyroscope and an accelerometer installed on the AR device are used. Data from the accelerometer and gyroscope about the change in the angle of inclination or rotation of the pilot's head are transmitted to the UAV, which, in turn, understands this command as a control command and transfers it further, depending on the destination. Figure 3.3 shows the model of interaction between the AR device and the UAV.

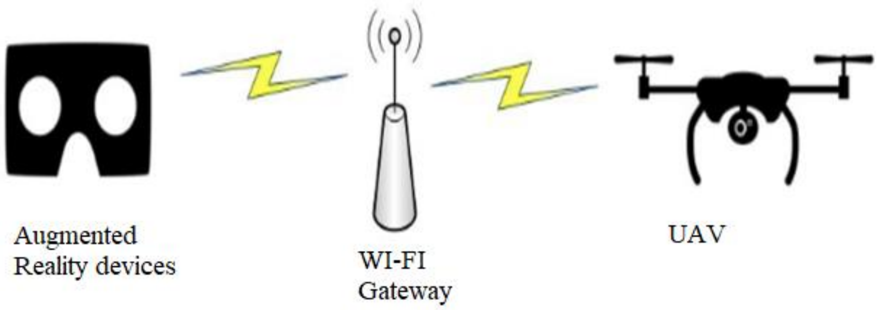


Figure 3.3 - Model of interaction between the AR device and the UAV

However, video is a large volume of traffic and requires adequate bandwidth. In this experiment, you may encounter interference in the communication channel. Also, the quality of video information transmission is affected by such indicators of the quality of service as the level of loss and delivery delays. The deterioration of the values of these indicators leads to failures in the control of the UAV and greatly affects the quality of perception of the pilot and the control decisions made by him, since they are carried out based on video data received from the UAV camera. Based on the above, for the study, a model of interaction (figure 3.3) of an augmented reality device and a UAV was developed, in which Wi-Fi technology of the IEEE 802.11n standard was selected as a wireless data transmission technology. Within the framework of this standard, it is possible to transfer large amounts of data with a bandwidth of up to 150 Mbit / s, which is more than enough to solve research problems.

The following is a study of the influence of the network service quality indicators on the quality of the pilot's perception in the AR system when controlling the UAV.

3.2.2 Conducting an experiment to control a UAV using an augmented reality application and analyzing the results

The expert is wearing augmented reality glasses, which display the video stream coming from the camera located on the UAV. The expert turns his head in different directions, including up and down, thereby changing the direction of the camera position. Thus, the viewing angle changes, and other video information is displayed. The task of the expert is to subjectively assess the response of the UAV and the quality of the modified video image in the AR glasses when applying the control action. Three scenarios of the experiment were implemented, in each of which the influence of changes in network characteristics, such as latency, loss and decrease in bandwidth, on the quality of perception was investigated. For each scenario, 20 experiments were performed. To obtain adequate estimates, the experts were shown a reference case in which no degrading effects on the network were introduced, i.e., as close as possible to ideal data transmission conditions.

For the reference case, the Hurst parameter was also calculated, and its value turned out to be 0.61, which indicates a self-similar structure of the transmitted traffic. To simplify the analysis of the results of the experiment, when transmitting the reference sequence, a subjective assessment of the quality of perception was set equal to 5 points on a five-point scale. In the first scenario, the effect of increasing delay on the quality of perception was investigated. The results are shown in table 3.1.

Table 3.1 - Experimental results with increasing delay

Delay, ms.	Subjective assessment on a five-point scale	Hurst parameter values
No delay	5,0	0,61
10-30	4,4	0,60
50-150	3,8	0,59
150-250	2,7	0,56
250-350	2,1	0,52

Table 1 shows that with delivery delays not exceeding 100 ms, the quality of video stream perception by an expert remains at an acceptable level, however, when controlling a UAV with such a delay value, several difficulties arise. Due to the data lag, the pilot (in our case, the expert) does not understand at what moment exactly it is necessary to change the movement or stop, thus, the control is carried out at random without visual control, the commands are transmitted with a delay, and, therefore, the response is returned with a delay. In this example, the Hurst parameter correctly establishes the relationship between the values of service quality indicators and subjective assessments of the quality of perception in the AR systems. Obviously, with delays above 150 ms, UAV control by means of an augmented reality application is not possible.

The second scenario involved adding losses to the communication channel between the UAV and the augmented reality device. Table 3.2 shows the results of this experiment.

Table 3.2 - Experimental results with an increase in the level of losses

Bandwidth, Kbps	Subjective assessment on a five-point scale	Hurst parameter values
With no restrictions	5,0	0,61
Up to 1700	4,9	0,61
Up to 1500	3,6	0,56
Up to 1000	2,7	0,55
Up to 500	1,7	0,49

According to the assessments of the quality of perception and the value of the Hurst parameter presented in table 3, a critical decrease in bandwidth affects the quality of user perception in augmented reality systems. As well as in the two previous cases, there are difficulties in controlling the UAV, because the expert (pilot) ceases to possess up-to-date information about the movement of the UAV and the objects surrounding it. All data transmitted with long delays, some of them are lost, and an expert wearing augmented reality glasses starts to feel dizzy.

The study found that augmented reality applications can be used to control unmanned aerial vehicles. However, it should be borne in mind that control takes place in real time, therefore, it is necessary to fulfill certain requirements for the characteristics of the network to ensure timely and comfortable control of the UAV based on current video information. In this section, we investigated the influence of network performance indicators on the quality of user perception in an augmented reality system when transmitting video images for control tasks from a UAV camera. Based on the results obtained, it was found that in a network with minimum delays of up to 100 ms, control of a UAV using an augmented reality application is possible without losing the quality of perception and control accuracy.

3.3 A typical model for managing Internet of things based on augmented reality technology

This section describes the framework for using augmented reality technology as an interface for interacting with the IoT for monitoring and control.

It presents the main functional elements, interaction protocols and approaches to implementing the interaction of IoT devices using AR technologies over the network.

Augmented reality technology allows virtual 2D / 3D graphics to be displayed in additional layers of information about real-life objects, which expands the possibilities of interaction with the virtual world and data.

As a result of the intensive development of the concept of the Internet of Things (devices, systems, infrastructure, applications, etc.) and its widespread implementation in various areas of human activity (industry, healthcare, education, agriculture, entertainment, etc.) in order to increase information content and process automation, it is of interest to use augmented reality technologies as a new type of interface for monitoring and controlling IoT.

To solve this issue, it is necessary to determine the general structure of the augmented reality application in relation to the tasks of controlling and monitoring devices and the IoT system. Monitoring the operation of IoT devices and systems using augmented reality means observing data created in the virtual world and displayed in real life when looking at a physical object (thing). Controlling the operation of devices and systems of the Internet of Things using augmented reality consists in transmitting control commands that are generated from the AR terminal.

There are two ways to transmit control actions to the AR-terminal:

- If the AR-terminal is a device such as a smartphone or tablet with a touch screen, then control requests are generated when interacting with virtual objects by pressing on the touch screen.
- If the AR terminal is a device without a touch screen, for example, the AR glasses, the control is carried out through the interface of the voice assistant.

After transmitting the control request, the AR-terminal generates a request to the AR-server, and then AR-server interacts with the IoT-server and transmits the necessary information. Figure 4 shows a general diagram of the implementation of augmented reality applications for managing and monitoring devices and systems of the Internet of Things.

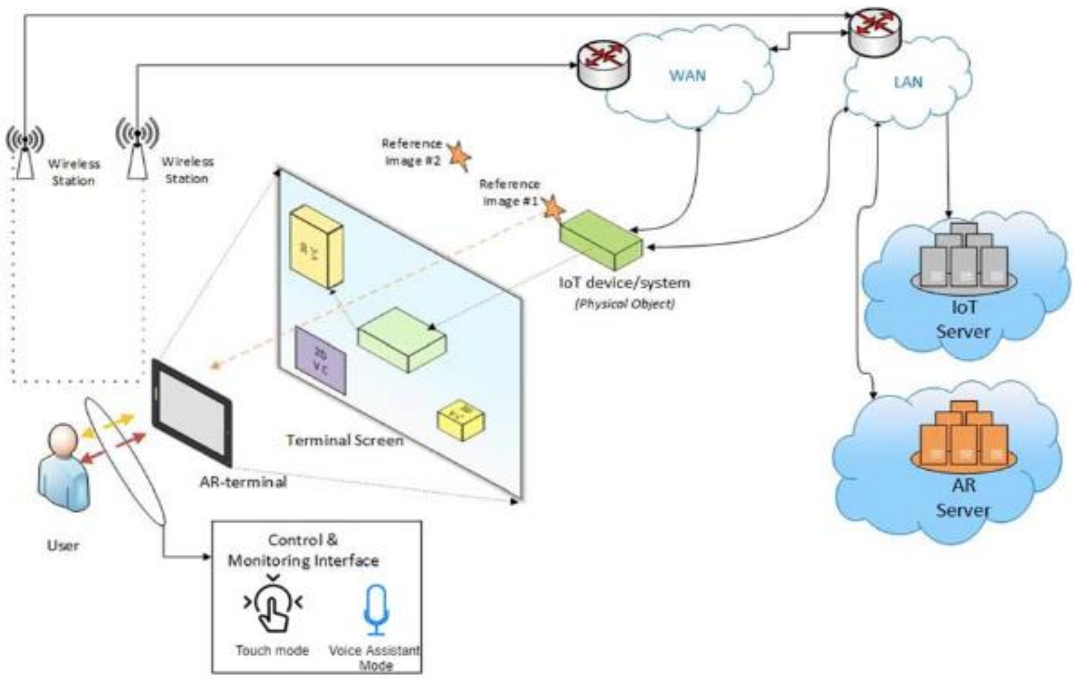


Figure 3.4 - General scheme of implementation of AR applications for managing and monitoring IoT devices and systems

3.4 Classification of IoT applications for AR technology

We define a set of IoT applications for which the AR technology can be used to implement the control and management functions. IoT applications can be divided into groups based on the classification of functions that a given application or service implements. Services can be implemented based on one or several applications. The functions that an IoT application performs can be divided depending on the areas of human and society life in which the application is applied.

1) Classification of IoT applications for integration with AR technology based on the scope:

a. Medicine and healthcare
b. Ecology
c. Agriculture
d. Commerce and retail
e. Education
f. Fire safety
g. Safety
h. Environment
i. Automobile transport
j. Smart city
k. Appliances

2) Classification of IoT applications for integration with AR technology based on the hazard level of objects:

a. high-risk facilities (nuclear power plants, hospitals, etc.)
b. safe facilities (shops, games, etc.)

The use of augmented reality to control and monitor IoT systems and devices at high-risk facilities requires special attention to ensuring security.

3) Classification of IoT applications for integration with AR technology based on the way of interaction with the IoT device:

a. Management through AR
b. Monitoring through AR
c. Control and monitoring through AR

3.5 Classification of IoT devices for the implementation of object identification systems

We will define the classification of reference images that can be used to identify or recognize a physical object (IoT devices and / or systems) and formulate general recommendations for the use of various methods for recognizing IoT objects in different areas of human activity. The reference image performs the function of identifying the observed object. Since there are many solutions for identification now, the following classification is proposed.

The classification is determined by the following recognition methods:

a. Based on reference image.

b. Based on the coordinates of the location of devices and systems of the Internet of Things and the AR-terminal.

c. Based on the reference image and coordinates of IoT devices and systems, as well as the AR terminal.

The first approach allows you to uniquely identify the object of the physical world (device or IoT system) to which the reference image is attached. To obtain augmented reality data without delays and distortions, factors such as the size of the device's camera, the complexity of the reference image, etc. must be considered. A QR code can be used as an example of a reference image for quick identification.

In the second case, identification is carried out based on data from the sensors of the AR-terminal: accelerometer, gyroscope, magnetometer, GPS receiver, etc. This approach shows a high percentage of errors in recognition and is not recommended for use on high-risk facilities. Also, this approach is not recommended for use in enclosed spaces, as well as with a high density of IoT devices.

In the third case, it is proposed to use a combined approach to improve the identification accuracy, as well as to minimize the risk of replacing the reference image. Thus, the identification of an IoT device or system is based on the reference image and coordinates of the IoT device, as well as the position of the AR terminal.

Conclusions on the third chapter

The concept of the Internet of Things has opened many opportunities in terms of creating new services. Today, many applications have been developed that can make everyday life easier. There are also several well-proven solutions for various fields of human activity, for example, in the housing and utilities sector, medicine, and the oil and gas industry.

With the advent of augmented reality technology, these possibilities have expanded. Augmented reality allows you to sort of create layers for the real world. Anything can be presented to the user of augmented reality in different ways, depending on the degree of access to this or that information, the information content that the user wants to receive, the type of data being added, etc. Since, according to forecasts, the number of IoT devices will be about 300-500 per person, the issues of network resource allocation, traffic offloading from the network and identification of IoT objects using cloud services are very popular.

1. It has been established that the main indicator of the quality-of-service provision is the response time, i.e. the time from the moment the user's environment is changed to the moment the desired message is presented to the user. This time depends on the distribution of the functions of providing the service among the executive elements.

2. To minimize the response time to changes in the user's environment, a hierarchical structure of resource allocation is proposed when providing augmented reality services.

The hierarchical model makes it possible to localize a significant proportion of data and traffic, which saves communication network bandwidth resources.

3. A new four-level structure of the system for providing augmented reality services has been developed based on a modified multi-level edge computing system (MM-MEC), using the device-to-device interaction technology, D2D.

4. A method for offloading traffic for a network that provides augmented reality services based on a multi-level edge computing system with four levels of traffic offloading has been developed, which allows not only to ensure that the requirements for a delay of 5ms are met, but also to reduce losses by several times compared to existing ones. methods for all major augmented reality services: circular video streams, multiplayer games, and augmented reality web applications.

6. A model has been developed for the timely control of traffic lights based on VANET networks, supplemented by SDN technology, where a UAV is used as a controller, and augmented reality is used for faster and more accurate assessment of the traffic situation.

7. A study was made of the interaction between augmented reality applications and UAV control methods, within the framework of which an experiment was conducted to evaluate the quality of perception of the video stream by the pilot and the efficiency of controlling the quadcopter by the pilot wearing AR glasses.

8. The structure for monitoring and controlling IoT devices and systems using AR technology is described. Several examples of the integration of augmented reality technology and the concept of the Internet of things for the provision of services in various areas of human activity are considered.

9. Explored the possibility of introducing the latest AR and IoT technologies to increase the information accessibility and interactivity of art objects, which, in turn, helps to attract younger visitors and, at the same time, preserve cultural heritage sites for future generations.

4 IMPLEMENTATION OF RESEARCH RESULTS

4.1 Scope of application of the developed information system

As mentioned above, AR, as a new stage in the development of the interface, has the potential to improve human-computer interaction in various areas. AR visualization brings novelty to the process of visual planning.

The results of the study can be applied to create systems using augmented reality technology for a number of industries. First, the field of landscape design was chosen for approbation.

Visualization of objects in the context of their application in real time and in real size can be effectively applied both in the design process when selecting and arranging objects, and when demonstrating a design project to a client. At the same time, a properly designed graphical user interface will speed up and simplify the work of the designer and thereby increase the number of iterations within an identical time interval.

Based on the presented information system, a prototype of an application was developed for visualizing objects used in landscape design using augmented reality.

It is important that the more natural approaches to the user interface offered by the AR allow not only specialists, but also the mass consumer to receive the benefits of technology. Visualization of objects by means of AR can be used to support the decision-making of buyers when purchasing goods. The user is given the opportunity to visualize the object in the place in the room or in the open area where he plans to place it, and interactively view the object from any angle. It does not require preliminary three-dimensional modeling of the environment.

This way of viewing goods by potential buyers is more effective than viewing two-dimensional images of the goods in various printed and electronic catalogs, as well as in the form of a three-dimensional model isolated from the context: rendered on an irrelevant background or in some abstract interior. Visualization using augmented reality allows the user to better perceive the real dimensions of the object, being able to instantly compare it with other known objects located in a known interior.

The application in the field of trade in interior items was considered. For this, possible models of interaction with customers using augmented reality tools were developed. A study was also conducted among customers of furniture stores about loyalty to the use of the application with augmented reality.

4.2 Models of interaction with customers when using augmented reality technology in trading

4.2.1 Interaction with printed products

When using printed products (catalogues, brochures, leaflets, etc.), the algorithm will look like this:

1) A potential buyer (user) receives the usual printed products with information about the product, which may include images, descriptions, prices, information about the store, and more. Among other things, products may contain a block informing the user about the availability of an application that he can install on a mobile device and view the offered goods directly in the intended context of use: for example, interior.

2) The user installs the application on the mobile device.

3) The user selects the product of interest by means of the usual interaction with paper media.

4) The user uses as a model identifier either a QR code printed on one of the pages of printed products (for example, a product page), or other elements (including combinations of elements): an image or part of an image, text or part of it, the entire full page, full spread.

The user uses as a marker (or initial calibration image):

- landing page (one of the pages of printed products: for example, a page with a description or photo of a product);

- a dedicated page (e.g., a cover, or spread, or a special insert, possibly larger than the printed matter used). If the user has the technological capability, the marker (or the initial calibration image) may not be used. The main advantages of this model are:

High intuitiveness of use. This option minimizes user rejection caused by rejection or insecure knowledge of information technology.

The user searches for the model of interest by interacting with printed products.

Paper products are easier and more familiar to deliver to the user. The shortest preparation time to start using.

No need for the user to specifically print the marker.

The main disadvantages of this model are:

1. The need for the user to have printed materials

2. The lack of the possibility of interactive interaction with information on paper (filtering, searching)

3. Special requirements in the manufacture of printing (minimization of glare)

4. Obsolescence of information in printed matter

4.3.2 Website interaction

The user uses the website to search and obtain information about the goods for the first time.

A website provides more opportunities for designing and implementing an interface than a mobile application. An example is the ability to develop a structurally complex yet visually comprehensible menu using the available screen space (e.g., monitor) compared to the limitations of the small screen size of a mobile phone.

When working with a website, the user can use the usual techniques: for example, adding bookmarks, working with multiple tabs. When searching, the functions of filtering products by various characteristics (price, size, material, color, and others) are available. A mouse and a full-size keyboard are used to enter information.

Working with the website is more familiar to the user and allows you to offer more functionality.

After the search for the product of interest has been made, the user, using a mobile application, scans the QR code of the corresponding product posted on the website and thereby selects this product in the application. This allows you not to duplicate the user's actions to search in the application for a product already found on the site. If there is no relevant content related to this product in the device’s memory, the relevant information is downloaded or updated.

Further, the user visualizes the product in a real environment, can visually evaluate the product from any angle, evaluate its dimensions, choose a place for installation, choose the color scheme that is most suitable for the environment.

After evaluating the product in the application, the user returns to the site and makes a purchase of the selected product.

Thus, this model offers a logical continuation of the process of selling in an online store.

In addition, the advantages of this model include:

- use of existing developments (website);
- the possibility of saving on costs associated with the development of some functionality of the mobile application;
- ease of changing the content of the site.

The disadvantage may be considered the impossibility of use in the absence of a PC from the user.

4.2.3 Static views and remote use

Using the application, the user takes photographs of one or more angles of the place of the intended installation (use) of the product. Pictures are taken in such a way as to include spatial information (for example, information about the plane of the floor, walls, as well as three-dimensional information about other objects in the environment). For this, hardware is used that allows obtaining spatial information (stereo cameras, spatial sensors, etc.). If necessary, one or more markers (known calibration images) are preliminarily added to the scene.

The user, if desired and technically possible, can perform a full three-dimensional scan of the room (environment) or part of it.

Further, the user has the option to also visualize various products in the context of their use, but there is no need to maintain the camera angle of the device (e.g., hold the tablet while standing in a certain place in the room). Moreover, there is no need to be directly next to the place of intended installation (use) of the product, but to use the application remotely in any convenient place.

The following case stands out. The user, being on the sales area of the seller, can personally examine the product, visually and tactilely assess the texture of the materials, try the product in action (sit on a chair, lie down on a bed) and take advantage of other offline sales benefits.

At the same time, he can quickly view the product in a context saved in advance (for example, in his interior). As a product identifier for the application, a QR code applied to the price tag, product, or other materials related to the product (labels, leaflets, etc.) or the price tag itself, product, or relevant materials can be used. The user, having studied the product live and becoming interested in it, opens the application, scans the product identifier, and thereby selects this product in the application. This allows you not to duplicate the user's search actions in the product application. If there is no relevant content related to this product in the device's memory, the relevant information is downloaded or updated. Next, the user selects the desired view from the previously saved ones, and the product is visualized according to the same principle as if the user were working with the application directly in the place where the product is visualized (for example, the interior).

The user also can use other sources to quickly enter information in order to search for products in the application (printed products, website, outdoor advertising).

This model is generally more suitable for advanced users such as interior designers. A specialist can work on a project, trying different interior items, color schemes, etc. At the same time, when using this model, it is possible, choosing a product in an offline store together with a client, to quickly demonstrate this product in the interior being developed.

The advantages of this model include:

1. No need to be directly in the place where the product is visualized.

The disadvantages of this model are:

1. Relative difficulty in understanding and implementation by an untrained user.

2. According to the results of informal surveys, this model finds the least support among users.

4.3 Determination of customer loyalty to the use of augmented reality

To determine customer loyalty to the use of augmented reality in furniture sales, we use the NPS methodology.

The satisfaction of consumers and customers (customer satisfaction), as well as their loyalty, is an important success factor in any business. Regular measurement of satisfaction and its evaluation of a service or product, monitoring of changes will allow you to give an objective assessment of the company's performance. One of the indicators of customer loyalty is the NPS index. NetPromoterScore or NPS is an index for determining consumer loyalty to a product or company (readiness to recommend index), used to assess readiness for repeat purchases. literally can be translated as "net support index". The NPS methodology as a tool for measuring customer loyalty was proposed in 2003 by Fred Reichheld in the Harvard Business Review magazine. Having set out to identify which indicators are most strongly associated with customer loyalty, the economist analyzed huge amounts of data. After the analysis, it was concluded that the willingness to recommend the company to your friends and acquaintances is most strongly correlated with actual loyalty. The NPS methodology is based on the willingness to recommend a company as the only indicator of loyalty.

For several years of existence, this technique has gained wide popularity in the world due to its simplicity and efficiency. Management decisions are made based on NPS measurements.

The essence of the methodology for measuring customer loyalty in the NPS model is quite simple. It is built based on two main questions asked by the company's clients. The first and main question: "How likely is it that you will recommend company X to your friends/acquaintances"? The client rates on a scale from 0 to 10, where 10 means “definitely recommend”, and 0 means “definitely do not recommend”. Further, based on the answers, customers are divided into three groups:

"Promoters" - rated 9 and 10. These are customers who are highly loyal to the company and are very likely to recommend it to their friends.

"Neutrals" - those who gave ratings of 7 and 8. They are considered "passive" customers who are not sure that they will recommend the company.

"Criticists" - those who gave ratings from 0 to 6 - are dissatisfied customers who would rather not recommend the Company to their friends / acquaintances and may dissuade using its services (figure 4.1).

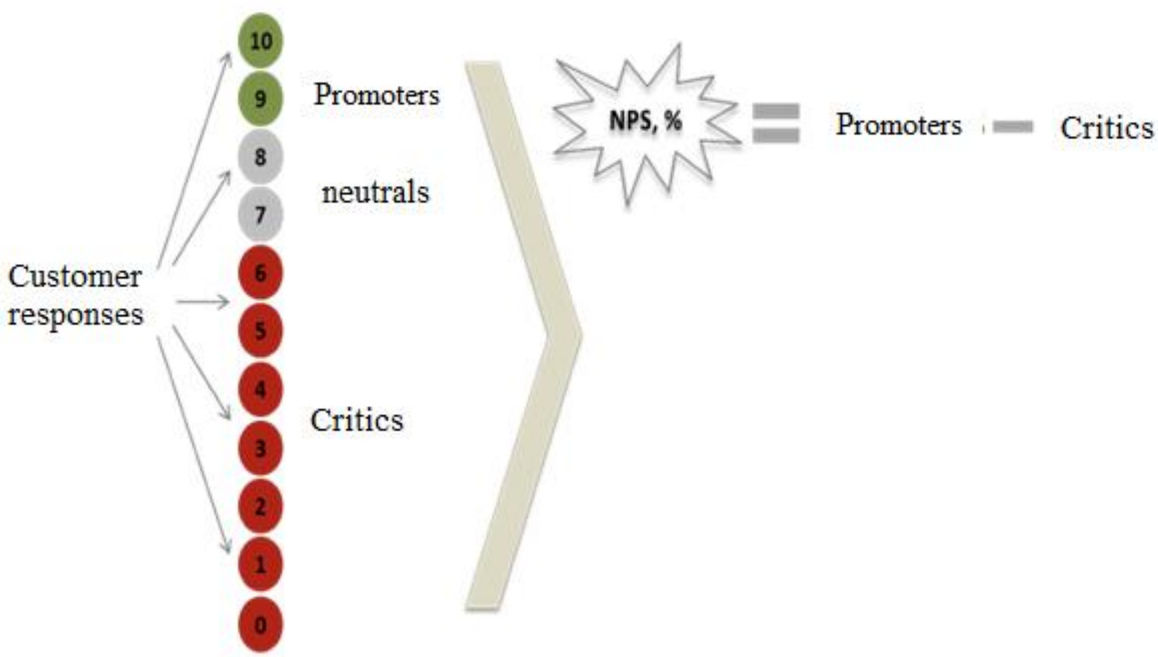


Figure 4.1 - Levels of customer loyalty in the NPS methodology

The NPS index is calculated as the difference between the percentage ratio of "promoters" and "critics" and shows the level of customer loyalty. The final value can vary from -100 (if 100% of the company's customers are "critics") to +100% (if all customers are "promoters").

The choice of the NPS methodology is due to the simplicity of execution since it requires one question to be asked to calculate the indicator. Also, the NPS score is measurable and comparable.

The aim of the study is:

- identifying the attitude of potential consumers to the AR application;

- determining the degree of consumer loyalty to the use of the AR application when buying furniture;

During the study, visitors to furniture stores were interviewed. Visitors were shown the possibilities of the AR application when choosing and buying furniture and were also invited to use it on their own in the trading floor. After the demonstration, the respondents were asked to rate from 0 to 10 how much they enjoyed using the AR app and how willing they were to recommend it to their friends or acquaintances. Where 10 meant that the respondent would definitely recommend, and 0 would definitely not recommend. During the study, 100 people were interviewed, the results are shown in table 4.1.

Table 4.1 - Survey results

Satisfaction with use	
Group Name	Total Group Percentage (%)
Critics (0-6)	5
Neutrals (7-8)	20
Promoters (9-10)	75
Probability of recommendation	
Group Name	Total Group Percentage (%)
Critics (0-6)	15
Neutrals (7-8)	20
Promoters (9-10)	65

After analyzing table 4.1, according to the degree of satisfaction, 5 answers were in the range from 0 to 6 (criticism), which is 5% of the respondents. 20 answers were in the range from 7 to 8 (neutrals), which is 20% of the respondents, 75 answers of the respondents were in the range from 9 to 10, which is 75%.

As can be seen from Table 4.4, in terms of the likelihood of a recommendation, 15 responses were in the range from 0 to 6 (criticism), which is 15% of the respondents. 20 answers were in the range from 7 to 8 (neutrals), which is 20% of the respondents, 65 answers of the respondents were in the range from 9 to 10, which is 65%.

The NPS index is calculated by the formula:

$$\frac{number\ of\ promoters - number\ of\ critics}{number\ of\ respondents} \text{x}100$$

As a result, we get (65–15/100)*100 = 50 (probability of recommendation);

Therefore, the NPS index for this criterion is 50.

As a result, we get (75–5/100) * 100 = 70 (satisfaction with use).

A positive NPS index indicates that among the potential consumers of the AR application, the share of “promoters” exceeds the share of “critics”, and, therefore, when implemented, there is the potential to create and increase the customer base through loyalty alone (“customer brings customer”). Also, an NPS of 50 indicates that there is no risk of customer churn due to anti-recommendations. It is believed that companies with a very high positive NPS index (conditionally +50 and above) can increase their customer base by themselves, and advertising activity can be reduced. But at the stage of application implementation, advertising activity is necessary.

4.4 Comparative analysis of software products that have appeared on the market in recent years using visualization by means of augmented reality

The study described in this paper began in 2013. During this time, several other AR visualization systems for mobile devices were also released to the market, which confirms the relevance of the chosen direction.

The developed information system was compared with other existing systems, including those that have appeared recently. The results of the comparison showed that the application of a scientific approach to the development of the system provided an advantage over competitors.

The developed methods for organizing lighting and preliminary preparation of three-dimensional models made it possible to significantly increase the realism of visualization of objects. The use of an independent shading texture provides a realistic rendering of objects' own shadows resulting from global illumination. The technique for implementing a static drop shadow also makes it possible to simulate the drop shadow of an object in real time without additional resource costs, and thereby visually increases the realism of embedding in a real environment.

Thanks to the developed algorithms, the principles of organizing the object storage structure and approaches to designing a graphical interface, the system provides for real-time changes in various parameters of complex composite objects.

The developed mechanism for changing the position of objects using gesture input methods allows you to move and rotate objects with high accuracy and sensitivity by touching the touch screen.

Designed in accordance with the results of the study, the graphical user interface provides high speed and ease of interaction with the system.

The system supports working simultaneously with several objects on the screen. The function of suspending the video stream is implemented. The leading mobile operating systems iOS, Android and Windows are supported.

4.5 Prospects for the development and use of visualization systems using augmented reality

Soon, new major breakthroughs in the development of augmented reality systems are expected.

The emergence of new types of computer vision sensors will make it possible to implement a number of important functions, such as correct occlusions and interaction with surrounding objects, as well as significantly simplify the process of use, which can play a decisive role in the mass dissemination of technology.

Other perspectives are related to the improvement of head devices such as goggles or helmets. Several companies are actively developing in this area (e.g., Meta, MagicLeap). The most compelling indicator of the significant prospects for technology are the actions of the largest companies. So, Apple acquired the Israeli developer of spatial sensors PrimeSense, as well as the major German developer of augmented reality - Metaio. Intel is developing the RealSense solution, a sensor system for mainstream mobile devices. A division of Google is working on the so-called Tango project, the essence of which is to develop new ways to orient computers in space. Microsoft has introduced and is developing the HoloLens augmented reality helmet.

Of course, there are no objective reasons for the development of exclusively head-mounted displays. And the future of augmented reality can be associated with the development of new types of three-dimensional displays that do not require additional means for viewing.

It should be noted that the system developed during this study is modular, and the solutions found are universal. The system remains compatible and fully functional with new, potentially improved types of tracking, and is not limited to use on hand-held devices (smartphones and tablets).

The development of augmented reality systems, of course, is also associated with the general level of computer technology: the resolution of displays, the capacity of batteries, the computing power of processors, etc.

With the help of modern multimedia tools, the approach to the organization of historical and memorial complexes can be completely revised. It is possible to create qualitatively new virtual reconstructions of events using animation and sound tools.

In the military, augmented reality technology has a significant potential for application, providing all kinds of visual support to personnel and improving the coordination of units.

The potential for applications in many other areas has been identified, including architectural visualization, construction, education, etc.

4.6 Conclusions on the fourth chapter

1. The results of the study can be applied to create systems using augmented reality technology for a number of industries. Approbation was carried out in the areas of landscape design and trade in interior items.

2. Approbation of the results of the study in the field of landscape design showed a high technical, economic, and social effect from the introduction of the developed information system in the processes of attracting and servicing customers.

3. The developed system has great potential for application in trade. Models of interaction between a manufacturer and a mass consumer using augmented reality were described.

4. A comparison of the developed system with the existing ones was carried out, which showed that the use of a scientific approach in the development made it possible to provide an advantage in terms of performance over competitors.

5. The development of visualization systems using augmented reality is ensured by the constant improvement of technical, algorithmic and software tools, as well as the interest in this area of the world's leading IT companies.

CONCLUSION

This work is devoted to the issues of visualization and information processing the improvement of the visualization of three-dimensional objects using augmented reality technology. The concept of augmented reality offers a more advanced user interface for visualization due to the combination of natural ways to control the change of an object's angle and render in a real context.

When the computer graphics system reproduces the conditions of monocular observation, the volume of the image, the spatial position of objects is perceived in the synthesized image due to the linear perspective, obstruction of some objects by others, the nature of the shadows and the change in tone across the image field. Essential for the perception of volume and space is the previous experience of observation, due to which the user involuntarily "completes" the three-dimensional structure of the observed scene. Thus, the visualization offered by augmented reality in a real environment familiar to the user contributes to a better perception of three-dimensional objects.

A feature of the work is the focus on the mass introduction of augmented reality. To do this, modern mass-available mobile devices were considered as platforms for applying the results of the study: smartphones and tablet computers.

The main results of the work done are:

1) the current state in the field of augmented reality research is analyzed, the shortcomings of modern augmented reality systems are identified and methods for their solution are proposed;

2) methodological, algorithmic and software tools for the purposes of the study are determined;

3) the structure of the information system with the technology of interactive visualization by means of augmented reality has been developed;

4) methods have been developed to increase the realism of displaying three-dimensional objects using augmented reality;

5) an approach to changing the parameters of augmented reality objects during visualization is proposed;

6) developed a methodology for preparing and storing three-dimensional models for realistic visualization on mobile devices;

7) developed a mechanism for manipulation of virtual three-dimensional objects in space;

8) practical recommendations are given on the design of the user interface for visualization by means of augmented reality;

The developed methods and algorithms can be used directly in the design of software products for use in real business processes of trade, design, as well as in several other areas.

The results of this work confirm the great importance of augmented reality in the development of human-computer interaction and its decisive role on the way to the next user interface paradigm.

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