DEPARTMENT OF DEFENCE

DEFENCE INSTITUTE „PROF. TZVETAN LAZAROV"

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VISUALIZATION OF AN ELECTRONIC BATTLEFIELD WITH ELEMENTS OF AUGMENTED REALITY

DISSERTATION ABSTRACT

for the acquisition of the educational and scientific degree Ph.D.
in the scientific specialty "Automated systems for information processing and management"

Research supervisor:
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The dissertation work was accepted and directed for defense after discussion by the Scientific Council of the Directorate "Development of C4I Systems" at the Institute of Defense "Professor Tsvetan Lazarov" with a protocol № 76/25.06.2024 г.

The dissertation contains an introduction, four chapters with results and conclusions to each of them, results and contributions of the whole work and a conclusion, set out in 135 pages of academic text, 57 figures and 5 tables, 9 appendices. The bibliography includes 111 titles in Bulgarian and English. The total volume of the dissertation is 165 pages.
The numbers of chapters, figures, tables, formulas and cited literature in the abstract correspond to those in the dissertation work. The numbering of the literature used in the abstract corresponds to that in the dissertation.

The defense of the dissertation will take place on 26 september 2024 14:00 hours in the hall 210 of the Defense Institute "Professor Tsvetan Lazarov", Sofia, at open session of a scientific jury in composition::

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Title:
Visualization of an electronic battlefield with elements of augmented reality

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

ACTUALITY

Scientific and manufacturing organizations engaged in projects in the interest of defense have long-standing traditions in creating, adapting and developing emerging and promising technologies. The ability to overlay additional digital information onto the end user's field of view is highly valued and used in specific military applications. Application of advanced visual perception of the situation, in combination with digital communication for remote data transmission is able to improve situational awareness according to modern concepts of network-centric organization of combat operations, improve understanding of tasks and serve to accumulate shared experience.

In general, the final effect aims to reduce reaction time in critical situations, proactively inform users of upcoming situations, shorten the command cycle for decision making. In the field of command and control systems, combat control systems and weapons control systems, developments based on such advanced technologies can be cited.

SUBJECT OF THE DISSERTATION

The subject of research in the dissertation is the application of information technology "augmented reality" to expand cognitive capabilities in a more modern presentation of elements of an electronic battlefield. The possible information technology approaches for the implementation of systems with augmented reality were studied, the interconnection with existing army information systems for command and control was studied, and the possibility of application in field conditions was evaluated.

OBJECT OF RESEARCH

The object of research is the creation of a model of an advanced electronic battlefield with basic visualization and augmented reality components, with a subsystem for identifying an object of interest in the field of view of an observer using an inertial sensor. On the basis of an analysis of the sources of errors in the identification of an object of interest, digital methods for stabilizing the readings of the inertial sensor have been determined. The possibilities for identification of objects from the order of battle and military infrastructure objects depending on their distance to the observer have been investigated.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the dissertation work is to propose an effective model for enhanced representation of electronic battlefield objects using augmented reality.

To achieve the thus defined goal, the following tasks are set for implementation:

• To carry out a review of known applications of augmented reality information technology in the civil and military fields;
• To determine the scope of applicability of augmented reality for application in training and combat conditions when identifying an object of interest and integrating additional graphic and/or textual information to support the performance of certain tactical tasks;
• To analyze the problems in the military application of augmented reality with a view to adaptation to existing army communication and information systems;
• To propose approaches and algorithms for accessing data for objects from the electronic battlefield;
• To create a formal mathematical model of the sensor subsystem and to propose an algorithm for field object identification;
• To evaluate the effectiveness of the proposed algorithm when performing field tasks.

II. BRIEF CONTENTS OF THE DISSERTATION

CHAPTER 1: Information technology for augmented reality

Combining elements of the real world with virtual aspects is called Augmented Reality (AR). It is a combination between virtual objects and the real environment surrounding us, i.e. complements reality rather than completely replacing it [7] .

Terminology definition from Ronald T. Azuma [89] "Augmented reality allows the user to see the real world, with virtual objects superimposed or combined with the real world". AR augments reality rather than completely replacing it.

The development of tools and technologies for gathering geospatial information, in parallel with the level of cartographic methods and GIS (Geographic Information System) technologies, allow the presentation of geospatial information from 2D maps in a much more accessible, useful and understandable way - in the form of realistic digital models. In fig. 1.4.a shows the sequence of information processing in a geoinformation application.

The identification of an object of interest can be by image, by marker or by position.

Although not yet introduced as standard equipment, a system known as IVAS (Integrated Visual Augmentation System) [54, 101]. IVAS is based

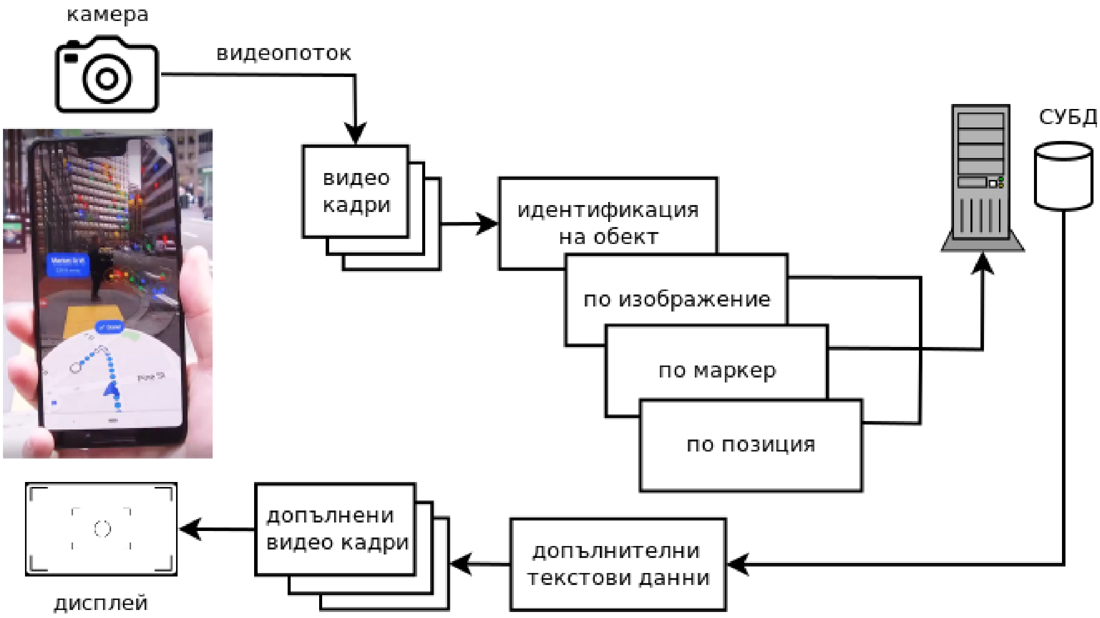

Fig. 1.4.a. Geoinformation application

on product Microsoft HoloLens [68] and will have an expanded range of capabilities, including night vision, thermal imaging, native/foreign target identification, access to navigational data, and more. Another system called FBCB2 (ForceXXI Battle Command Brigade-and-Bellow) [72], It was conceived in principle as a battle management system BMS (Battle Management System) of the US Army.

The publication [62], presents a mobile application in which data from an inertial sensor is combined with results from a visual recognition system to provide robust object tracking and orientation reporting. In fig. 1.6. is shown summarized by [62] the information interaction in object recognition with introduced digital filtering. This combination of different methods overcomes the disadvantages associated with applying one or another method separately. The visual recognition part uses an algorithm based on digital filtering, and for accurate localization, mathematical processing of data from an inertial sensor, which is mechanically coupled to the video camera, is applied. The cited material states that to achieve repeatability with good results, the individual components must be independently tested and precisely adjusted.

The application of the above-described method for military purposes, in order to supplement the sensor picture of a digital battlefield, can potentially lead to satisfactory results.

With the expansion of data processing capabilities and advanced graphical representation, the number of augmented reality applications used in the military is growing exponentially. An important technological component is known under the term "heads-up" display. In aviation, all important information (spatial orientation data, weapons pointing, recognized surroundings) is superimposed on the pilot's viewfinder, so that he does not have to look away from traditional display panels, and at all times the pilot has much more good situational awareness.

Similar development aimed at ground forces was carried out by the US Army Research, Development and Engineering Center (Communications-Electronics RD&E Center, CERDEC), which is actively exploring the potential of augmented reality technology.

Unmanned Aerial Vehicle (UAV) is increasingly being used in a variety of scenarios, recently increasingly in combat missions. Pilots trained and

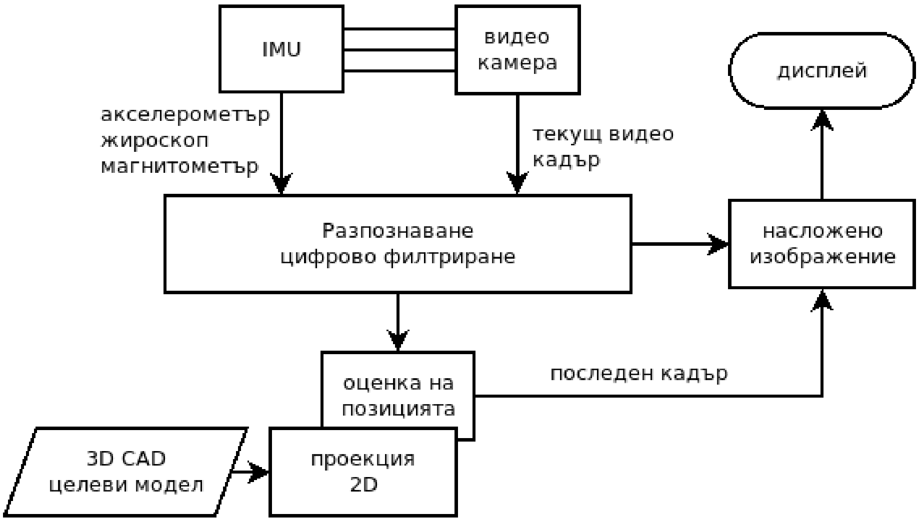

Fig. 1.6. Combined sensory-visual recognition

capable of operating traditional aerial platforms must adapt their skills to operate UAVs remotely from a Ground Control Station (GCS). The general arrangement of the GCS is to provide visual information on separate screens: one screen presents the video stream provided by the on-board video camera, while the other screen displays mission flight plan information and various information coming from other sensors.

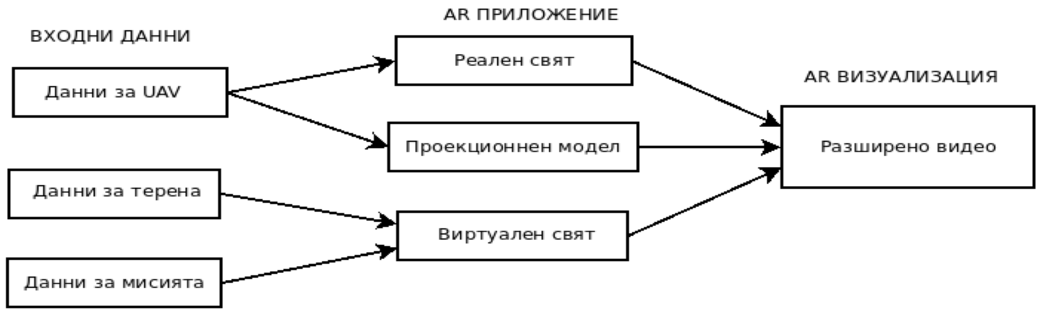

Fig. 1.11. Input data, virtualization and advanced video streaming

The UAV operator is subjected to an additional load because he has to monitor different screens. To avoid the burden of perceiving information displayed on two screens in the material [98] a system using AR technology is proposed. The AR system is designed to support UAV control in Medium Altitude Long Endurance (MALE) missions. It has two main functionalities: orientation for the movement of the UAV along the flight plan route and target identification.

The system of [98] is structured in three different modules, which is shown in fig. 1.11. One main module of the system is that of perception of input data; this module covers the processing of data coming from the UAV and the information available in the GCS. The virtualization module with the application of AR unites information from the real and virtual worlds, as well as ensures the achievement of visual coherence of the general information presentation. The module was developed using the OpenSceneGraph software library [83]. The advanced video stream module presents the operator visually with the information where the virtually added elements carry their semantic meaning.

In many of the solutions reviewed so far using AR technology, the main hardware component is the Microsoft HoloLens device [56] .

Virtual environment objects supported by AR are generally considered to be mostly 3D computer graphics models, but a majority of specialists accept another definition where virtual reality can consist of 2D computer modeled objects, text and images. There is a branch of the software industry that presents multimedia content, and visual search capabilities and similar developments are being promoted as applications of augmented reality.

Below are some concepts and terms that play an important role in AR information technology.

• Registration and Tracking describes the methods available for aligning a virtual object with 3D coordinates in the real view. In mobile applications, object tracking involves either location sensors such as GPS, a digital compass, and an orientation sensor (location-based tracking) or an image recognition system (optical tracking), or a combination of the two. Here, by the term orientation sensor we will understand a hardware module consisting of a gyroscope and a magnetometer.

• Virtual object. Some kind of digital content that is rendered by the AR application and superimposed on the real view. Typical content includes 3D models, 2D images, icons and text. A typical data flow in an AR application

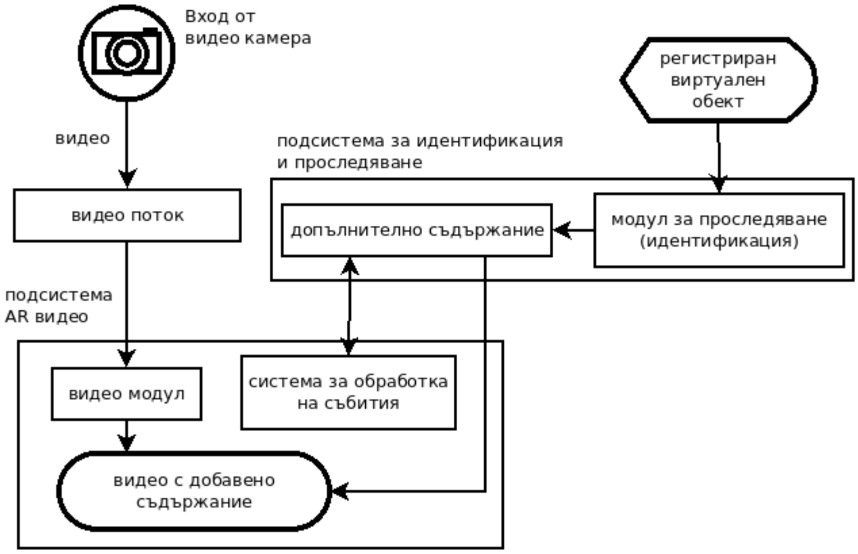

Fig. 1.16. AR application data stream

is shown in Fig. 1.16.

In the AR application concept, the key point is the identification and localization of a real object that will be part of the augmented reality. The tracking module of FIG. 1.16 (as shown in [45]) is responsible for identification where two methods are commonly used: optical tracking known as tag identification and location based tracking known as tagless identification.

The challenge in developing AR software is identifying and tracking a registered object. The use case of tag identification sequence is shown below in fig. 1.17, see also [45, 110]. The sequence is considered in the case where the mobile device is a smart phone. The first step occurs when the AR viewer observes the environment through a video camera. In step two, if the image is tagged or the desired object is in view, the AR software begins the identification process. In a third step, the observed picture is binarized and prepared for recognition. Here, the AR software searches the database (DB) to compare the presented picture with a pre-registered virtual object. If the match exists, then the corresponding virtual object is identified. The following fourth step is important in the case of an existing 3D object model. At this step, the AR software recognizes the spatial orientation of the marker and establishes a local coordinate system of the model.

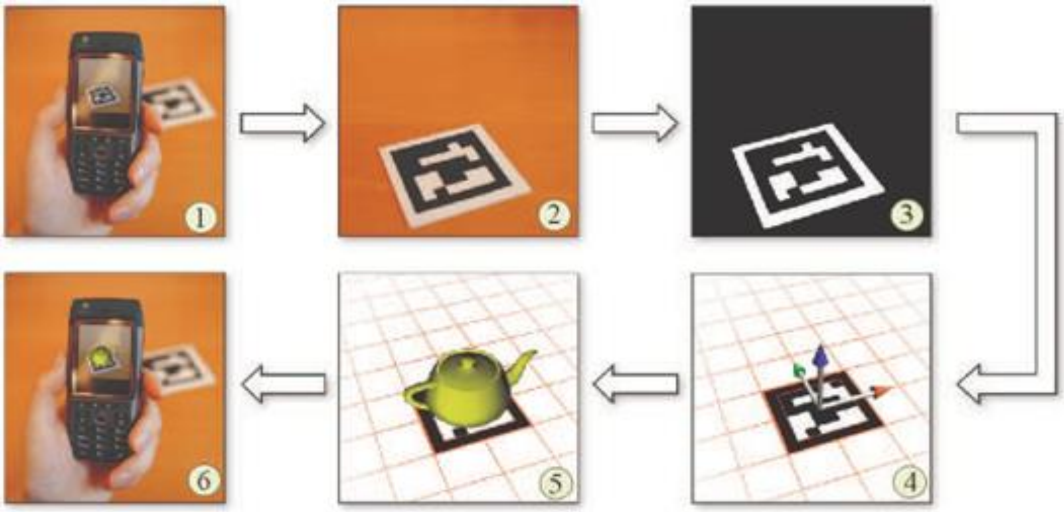

Fig. 1.17. Sequence in marker identification [45]

Marker identification is completed in a fifth step, when the corresponding 3D model is initialized with defined scale, position, and orientation. Finally (the sixth step), the AR software creates a complex video image in which a 3D image of the recognized object is added.

Usually, steps 3 and 4 cause problems in the tag identification approach described above. The solution to these problems lies in the application of effective image processing techniques, e.g. gradient approaches for still images or the standard KLT approach (Kanade-Lucas-Tomasi) [93] for video.

The second approach discussed for virtual object identification and tracking is tagless identification. The case of tagless identification based on geolocation is shown in Fig. 1.18.

Important preliminary steps are determining the position, determining the direction of the optical axis of the device camera, and extracting the geometric boundary data for each virtual object of interest. The latter is shown in fig. 1.18.

The current position of the viewer's mobile device is indicated in Fig. 1.18 as lon, lat and h. Here, lon and lat represent the geographic coordinates, longitude and latitude, and h is the altitude of the device's camera above the surface.

Determining the current position of the mobile phone using the built-in GPS module. The difficulty with this step can be the delay in initial setup and the inherent error of this class of devices. It should be noted that the height error can be significantly larger than the coordinate determination error.

For this case, the direction of the optical axis of the camera is usually represented by specifying the so-called Euler angles.

These three angles are estimated by the orientation sensors embedded in the mobile device. The magnetometer gives the azimuth (ie the orientation to north). The angle (to the "target location") can be determined by the gyroscope.

To determine whether the optical axis of the camera is within the boundaries of the 3D model of the object, it is proposed to apply the so-called ray tracing method. The proposed method computes determinants of square matrices. In the case of intensive calculations, it is important to reduce the time to determine the determinants of the above equation without interrupting the operation of the mobile device.

The analysis of problematic moments in previous experiments in the research field of the dissertation shows that the main and still not fully resolved question is related to the identification of the object of interest in the field of view of the mobile device with AR application.

Considered in its entirety, the real application of information technology products with AR implementation addressed in the security and defense

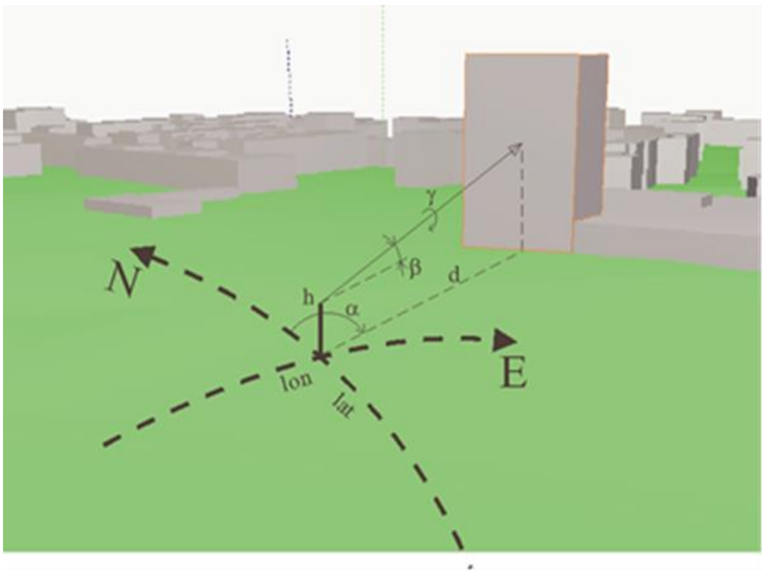

Fig. 1.18. Tagless identification based on geographic location [45]

sphere shows a set of different solutions in the field of hardware design, communication environment, optical, sensor and computing subsystems.

Scientific research and experimental work in the current dissertation work are limited within the scientific specialty "Automated information processing and management systems", which leads to the limitations:

• The subject of research are the problematic moments in the identification of an object of interest, related to the process of processing the primary sensory information from the IMU;

• The communication subsystem, in the part and access to databases of C2 systems, is computer simulated in a laboratory environment;

• The experimental activity used a material base available at the Defense Institute "Professor Tsvetan Lazarov", open source software products distributed under a free license and mobile communication devices available commercially.

The performed review of known AR applications in the civilian and military field allows to refine details of the research tasks set at the beginning of the current dissertation work.

In fig. 1.20 schematically shows the proposed extended battlefield model. The "Electronic Battlefield" figure shows components of "Command and Control Systems". The known and experimentally accessible PIKIS and C2PC are indicated as representatives of the C2 systems. It is accepted that there is a "Tactical Database" in which up-to-date and sufficiently accurate and detailed data is available on fielded own, friendly and foreign combat forces and assets. Data is available from military, technical and electronic intelligence systems.

In the present study, it is reported that the distributed systems use electronic map visualization. The transition to augmented representation of the electronic battlefield is an evolution of visualization approaches with the application of AR.

The information mechanisms of AR, oriented towards the extension of the presentation capabilities of the electronic battlefield, concentrate on providing an opportunity to:

• Access to the data contained in the existing tactical database;

• Identification, or matching of the elements of the order of battle found in the database with the combat machines and objects within the field commander's observation range;

• Determining the extent to which the AR system can be practically used in the field.

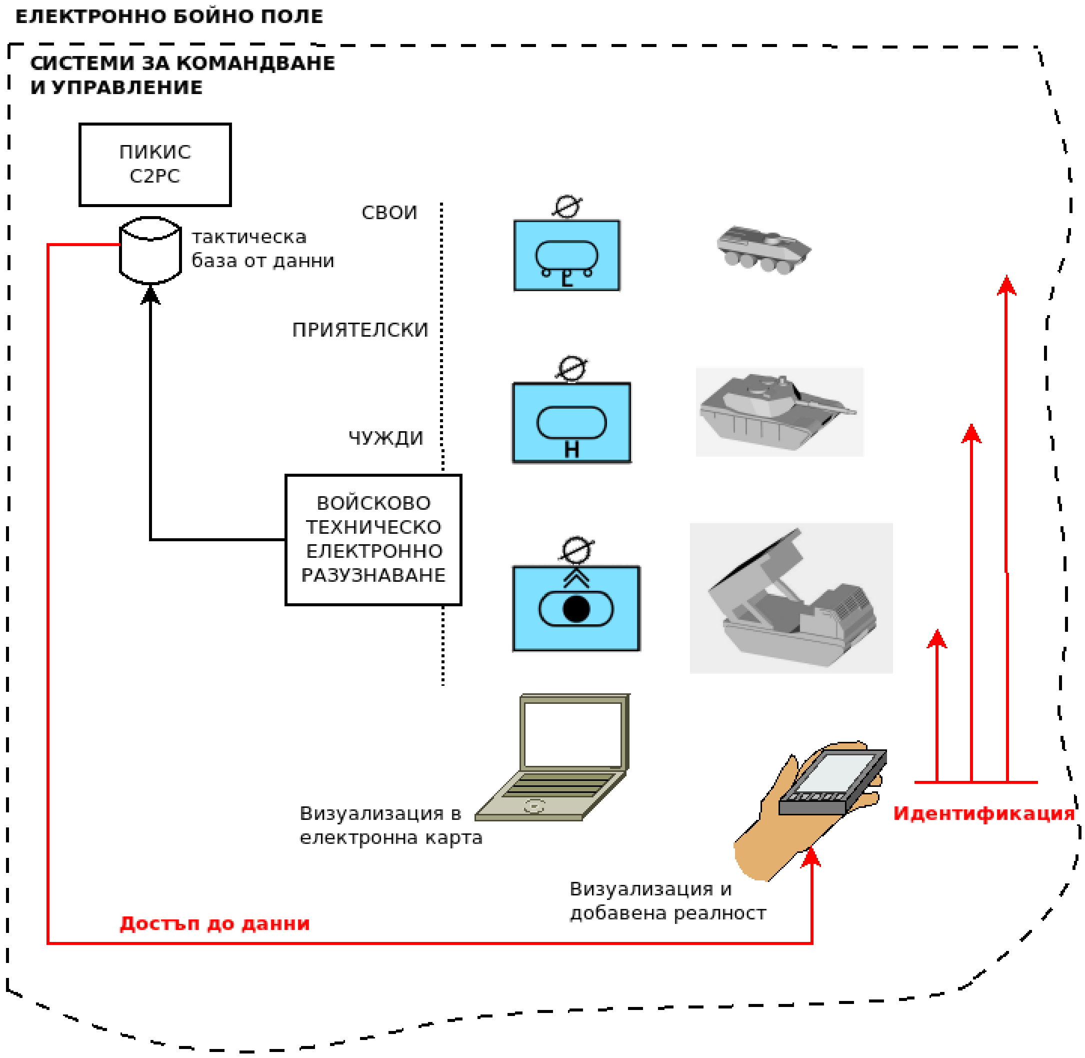

Fig. 1.20. Advanced electronic battlefield model

Conclusions and results.

In the considered area of information technology, there are prerequisites for a gradual transition to higher-tech principles for visualization and the realization of an advanced user interface, and this is a transition to software solutions with the application of augmented reality. The chapter presents views on important practical aspects of modern understandings of the electronic battlefield, by including elements of it in a video presentation from a mobile device in field conditions. An increase in the information capabilities of the command staff is achievable, which is the next step in moving to an increasingly high-tech defense.

• An advanced electronic battlefield model is proposed with an information flow to transfer specific data from existing C2 systems databases to the hardware part of field mobile systems with AR. Access to this type of data is sensitive information in combat conditions and can be made to own databases with the provision of the minimum necessary rights to read data.

• A minimum set of data is defined: geolocation of the element, affiliation and type of combat equipment unit to support the command staff in field conditions with additional textual information. A mobile device with an AR application is required, when pointing the device's camera at a field object, to display in the field of view that part of the data corresponding to the aimed object.

• The method for tagless identification using object geolocation data, the current position of the mobile device and its spatial orientation has been determined as suitable in the conditions of military application. The procedure for correct identification of a field object is of key importance for the applicability of AR in field conditions. Possible failures are related to the distortion of the sensor data for determining the spatial orientation, or the accumulation of computational error in the algorithmic implementation.

• Experimentation is needed to determine the extent to which AR technology will be useful in supporting command staff operations in field settings.

CHAPTER 2: Command and control systems and electronic battlefield

In the terminology related to military science, command and control systems occupy a significant place. In the process of introduction and ever-increasing sophistication, computer technology is becoming an invariable and essential part of decision support systems and paint control systems in general. A common feature of military computer systems is that, in one form or another, an electronic image is created of the objects and processes occurring in various military activities. The collection, storage and update support of structured information about the objects of the order of battle, combined with the advantages of electronic cartography allow us to talk about an electronic battlefield.

Modern war machines are more mobile, lethal and protected than their predecessors. The integration of more "on-platform" weapons, sensors, C4ISREW and active protection systems - if not managed properly - creates an unnecessary cognitive load on the combat vehicle crew [104].

The considered solution is a battery management system (BMS) in a networked environment and an integrated weapon. A centralized user interface combines all platform sensors and effectors, providing the commander and crew with a single interface for unified and/or integrated situational awareness acquisition. The combat control system functions at the platform level and at the crew level of the combat vehicle. The combat effectiveness of the system's co-operating units is increased through a modular architecture and extensive knowledge base, making it easier to integrate with various other platforms, sensors and end-effectors.

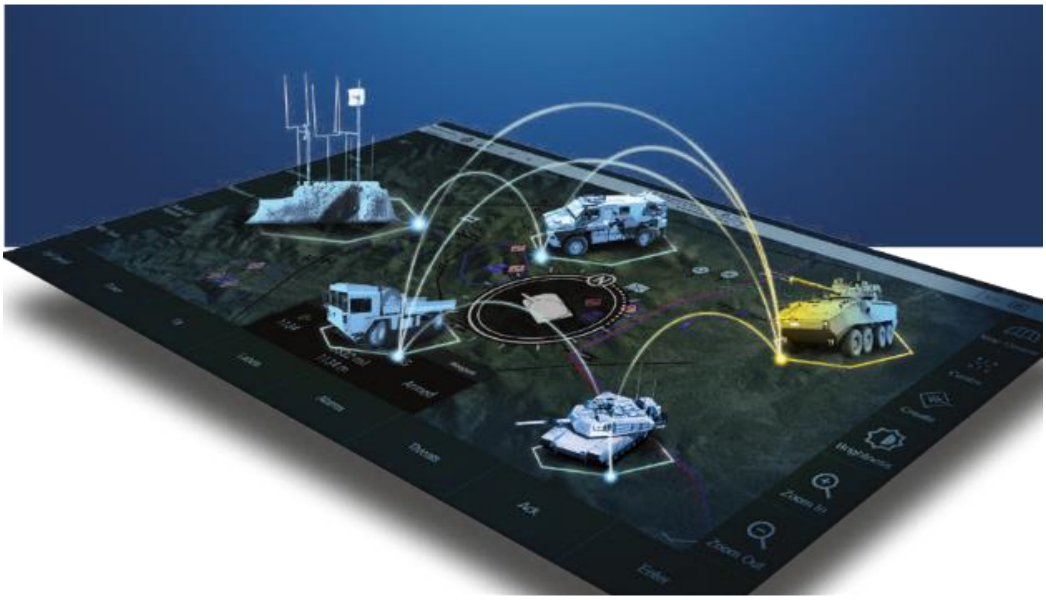

Fig. 2.2. Battle management system [104]

The integrated combat network solution for combat vehicles consists of complex building blocks, including end-to-end C2 applications, advanced computer terminals, tactical multimedia routers, and communications systems. Delivered a truly integrated battle network solution for today's combat platforms, through its state-of-the-art and conflict-proven solution. It integrates successfully in a variety of tracked and wheeled platforms and with the application of a wide range of weapon systems, sensors and communication means.

High-performance computing terminals are used, which work as tactical computers and displays with various software configurations and serve as a user interface for the crew of the combat machine. Commander and gunner capabilities have been expanded, including video motion detection, tactical overlays displayed on video, and visual exchange between tactical computer displays.

The integration of a weapon into a BMS is multi-factorial and performs basic functions such as:

• Seamless integration and interaction of sensors, mechanisms and communication systems.

• Unified Human Machine Interface (HMI) for common operational picture, weapon activation and sensors.

• Artificial Intelligence (AI) decision support tools to reduce cognitive load on commanders and crew.

• Target data distribution in near real time.

• Ease of integration with autonomous platforms, unmanned aerial vehicles and mechanisms.

The command and control system is designed to support CP (Common Picture) units deployed in a single operational scenario in the execution of their activities. It is designed to support commanders and their staffs to act in a coordinated and cooperative manner, and to be used in a variety of operational situations (humanitarian, peacekeeping, peace enforcement, conflicts, etc.).

One of the main objectives of the system is to improve the time for the preparation of messages, orders, reports, through the use of highly automated and user-friendly tools, as well as the time for data transmission between or within the headquarters through the efficient use of available means of connection.

In the case of AR software development for a military purpose, without specific requirements for the manufacturer and the version of the RDBMS (Relational DataBase Management System) used, it is recommended to implement or ensure sufficient compatibility with a single logical data model.

Based on published freely available materials [103], the logical model of the relationships in the recommended database is known as the Command and Control Information Exchange Data Model (C2IEDM).

The top-level logical structure of C2IEDM is presented in Fig. 2.4.

In terms of its geographic location, the object is identified by LOCATION. On the other hand, LOCATION is composed of a specific COORDINATE-SYSTEM and an additional VERTICAL-DISTANCE and can be a time-varying quantity. ACTION denotes a unique characteristic with which we describe the spatio-temporal behavior of the object. From an augmented reality perspective [31] (Fig. 2.6), a given ITEM in the scope of the video image can be supplemented with textual information such as AFFILIATION, ADDRESS and CONTEXT. The OBJECT-TYPE in the C4I system is a specific military symbology, while in the AR system it can be a more realistic 3D model.

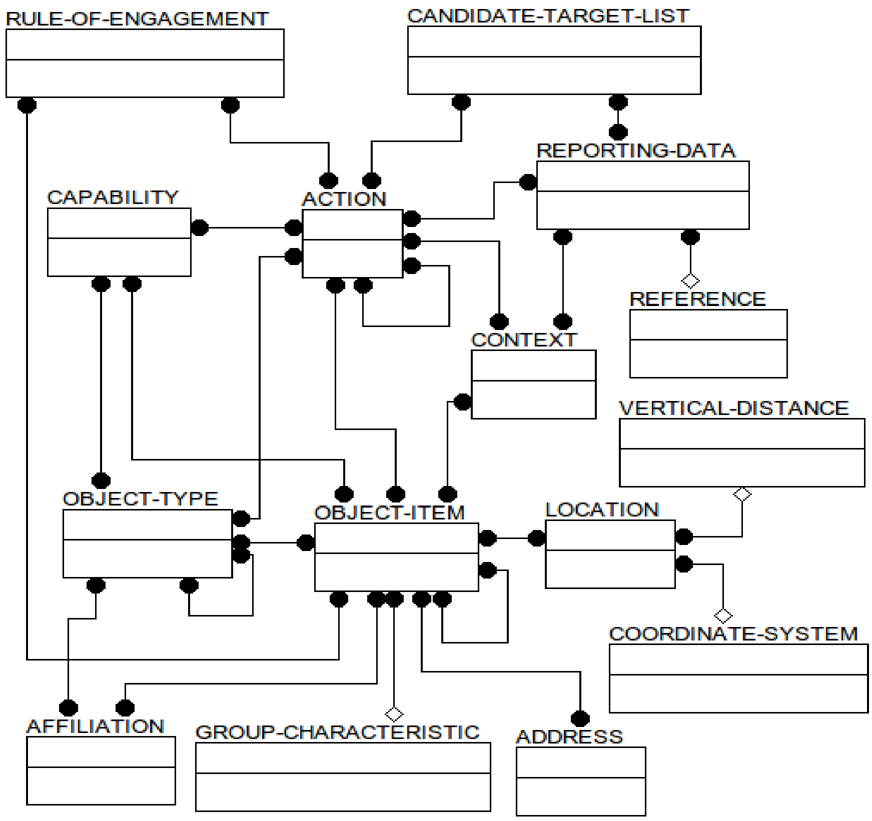

Fig. 2.4. Logical structure of C2IEDM [103]

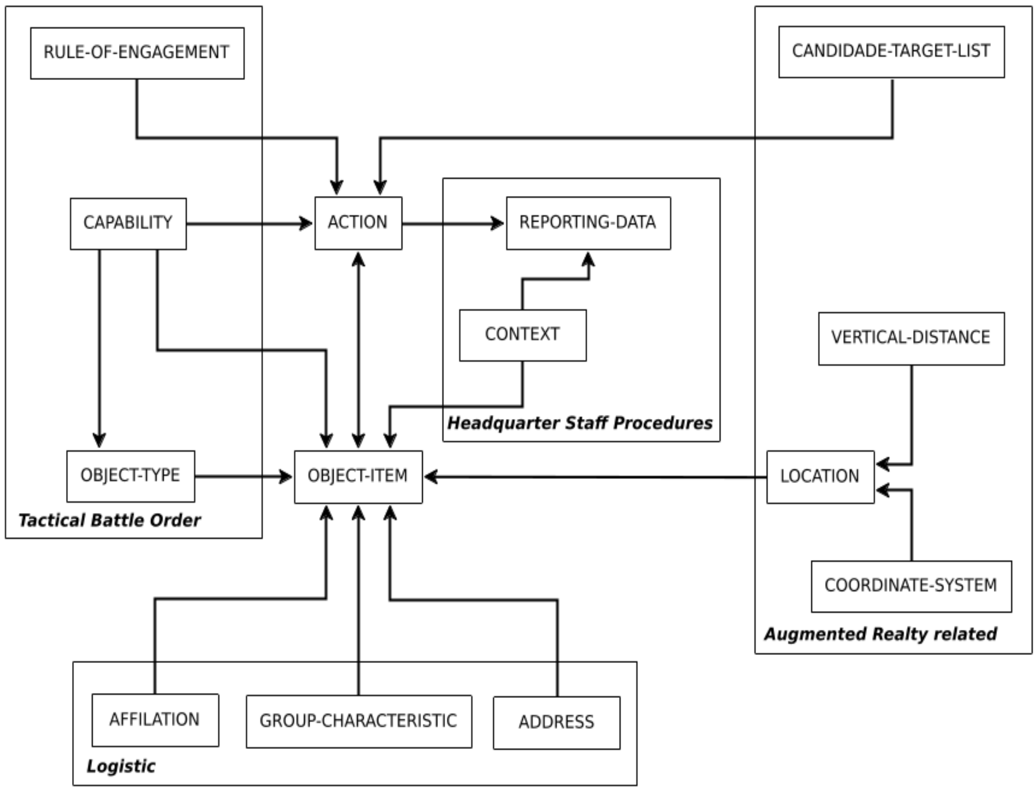

Fig. 2.6. A database linked to an AR system

The detailed analysis of the reduced logical structure of the data brings to the fore the main functional relationship ITEM-ACTION-LOCATION.

Analysis of approaches to information exchange.

The above-presented principles of information exchange between individual functional modules in different C2 systems give a general idea of the complexity of organizing such an exchange. In general, the following approaches are widely used:

- Formatted text messages;
- Database replications;
- Local database;
- Central/coalition database;
- Program gateway.

The approach of information exchange with formatted text messages was used in some of the examined cases as the main or substitute data channel. Different implementation options can be followed: regarding the encoding of the textual information – different standards; in terms of physical exchange at a lower level - via e-mail systems or file transfer protocols. The existence of different standards for encoding text messages is a difficult point for continuing the research of this dissertation.

Exchange through database replication can be defined as more technological from an informational point of view. Information technologies of RBDMS are sufficiently developed to cover requirements not only in the civil but also in the military domain. At the software level, there are proprietary as well as freely available and open source APIs (Application Programming Interfaces) that enable local as well as remote access to information from the RDBMS.

Application of a software gateway is a universal approach to achieve relative compatibility and exchange of information between different information systems. Successful attempts to implement a programmatic gateway to one degree or another boil down to implementing software APIs. A software gateway can be referred to as the next level in the increasingly complex setup for automated data exchange between systems from different manufacturers and based on different RDBMS and/or formatted text systems.

Common to all described approaches to information exchange is that for their legal implementation in favor of a third party, in the case of extended information exchange to AR systems, it is necessary to provide access rights and system settings.

Access to a centralized database

In fig. 2.15 schematically presents the information exchange sequence between a C4I system and a mobile device with an augmented reality application. Detailed data and a description of the experimental work are given in the publication [19]. For the purposes of the experiment, a test environment consisting of a base computer (BC), a virtual machine (VM) and a mobile computer (MC) was created.

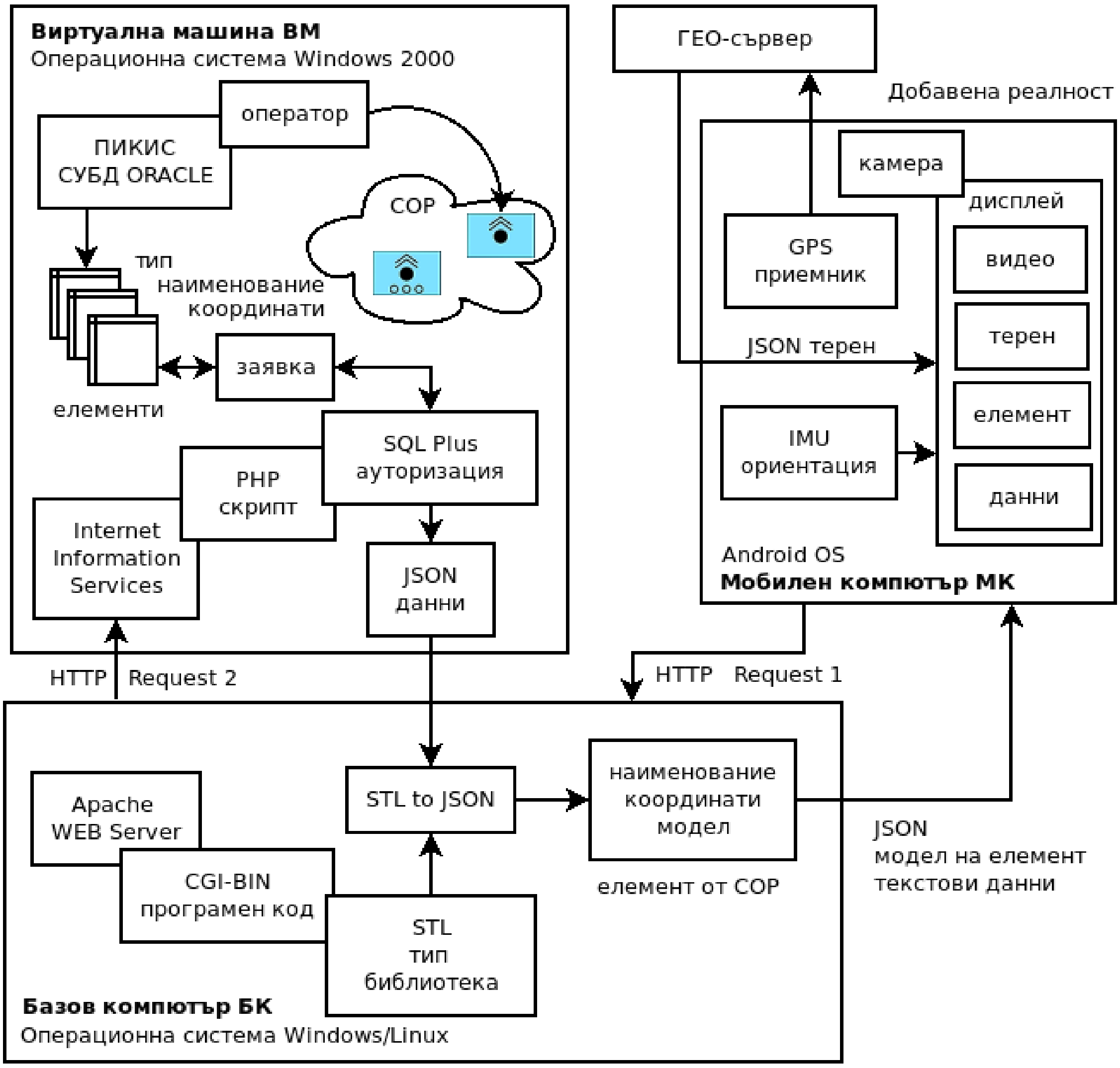

Fig. 2.15. Exchange of data from DBMS PIKIS

BC and VM components are located on one physical computer platform. A test version of the PIKIS software product with C4I system functionality is installed on the VM. The VM machine runs Windows 2000, Internet Information Services (IIS) and PHP WEB programming language code are additionally configured on this machine. The SQL Plus executable module is part of the PIKIS installation package.

The BC computer is the main component in the test setup. In the present case, it runs under Linux Ubuntu 18 operating system, but there is no explicit requirement for the specific operating system type. The system component Apache WEB server has been added to the BC configuration and a CGI-BIN folder has been declared, in which the program code created for the purposes of the experiment is located. An important part of the provision here is the library of typical three-dimensional models of the COP elements that are subject to visualization in the augmented reality system.

The mobile computer, referred to as MK, is a smartphone with an Android operating system. The experiments were conducted on several different smartphones, with different versions of the mobile operating system. Android 4.2 and Android 11 mobile operating system variants were tested. A test mobile application created for the purposes of this experiment was installed on the MK system. The mobile application of the so-called "Electronic Battlefield". The application actively uses the built-in video camera, GPS and Inertial Measurement Unit (IMU) sensors and wireless connectivity of the mobile device.

Access to systems with a local database

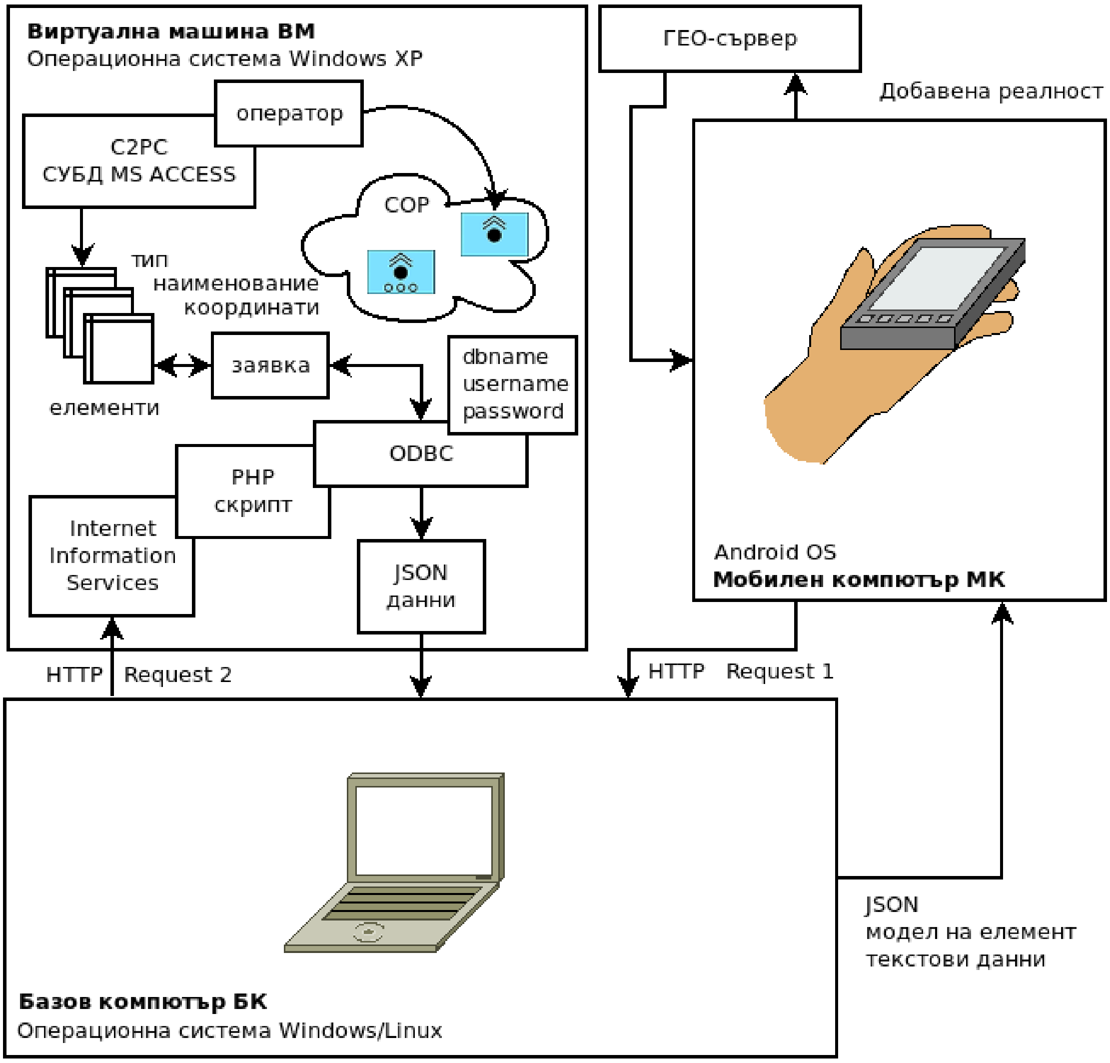

Fig. 2.17. Exchange of data from DBMS C2PC

A good example to consider for a local database access solution is the well-known C2PC software system.

Shown in fig. 2.17, the software subsystems BC and MK are borrowed from the data access method described above. It differs in the type of DBMS used, which in the local database case considered here is MS ACCESS. The virtual machine on which the C2PC system is installed is under the management of the Windows XP operating system, with configured IIS and scripting language for programming in the WEB environment PHP. Access to the local database is provided using the standard ODBC (Open Database Connectivity) programming interface.

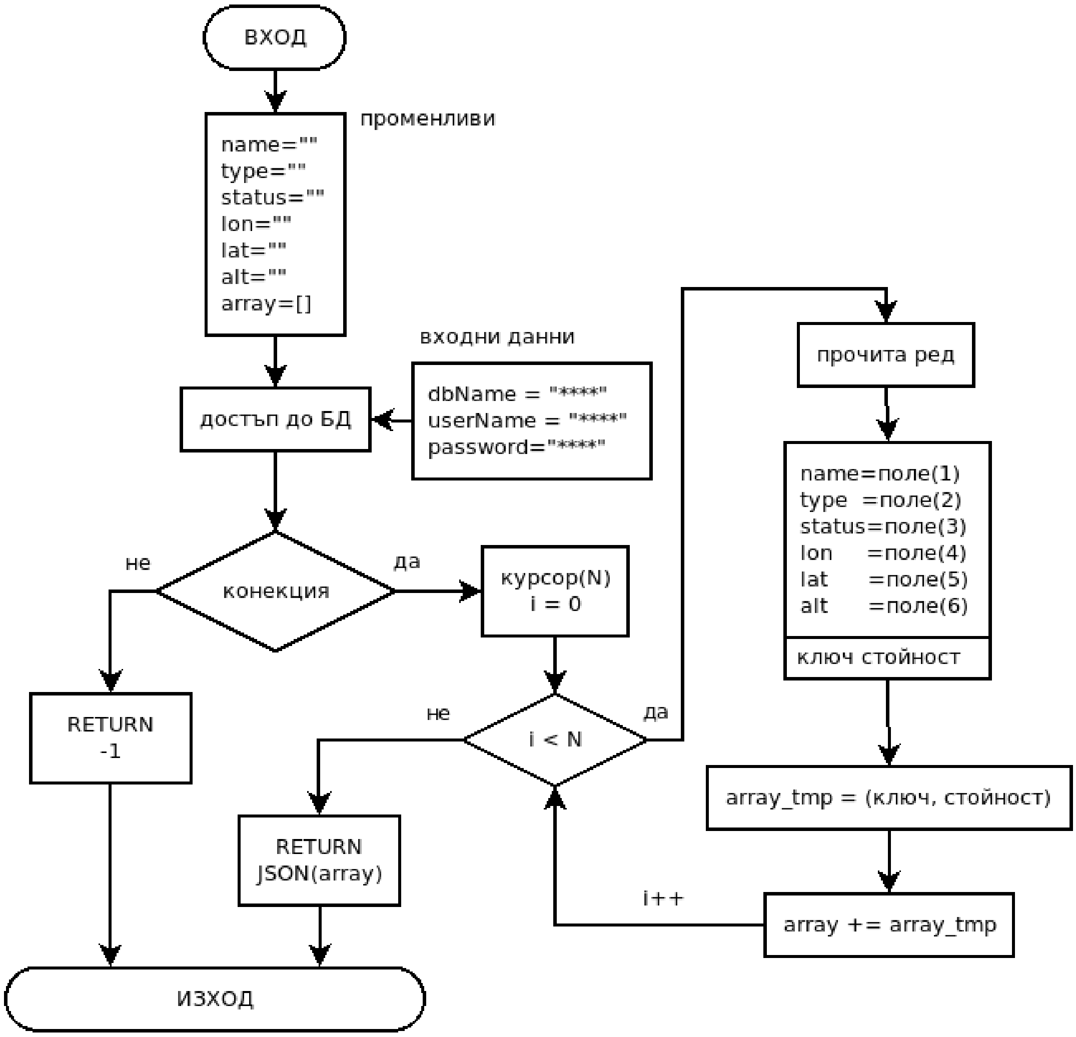

Fig. 2.21. Local database access algorithm

The use of the ODBC interface in combination with the PHP programming language requires the presence of an ODBC driver installed in the operating system to access the MS ACCESS database.

The one shown in fig. 2.21 algorithm reflects the action of the program code that accesses the local database, reads data, and formats the JSON-type information structure necessary for the operation of the augmented reality module.

Variables are defined to identify an object from the database (name, type, status), and related to this object positional characteristics (lon, lat, alt). The database is accessed with the parameters in the variables dbName, userName, password, which are set to the necessary and correctly defined values. The array variable is the array in which the program stores the values extracted from the database.

The connection to the database with the passed parameters may or may not succeed. If the connection fails, the program exits without result and returns a value of -1 to the calling process.

Upon successful connection to the database, a cursor is formed containing N retrieved records (rows) with the data expected for the object. A loop is formed with control variable i, with initial value i=0. In the body of the loop, each subsequent line is read from the cursor, and the fields contained in that line are assigned to the corresponding variables. A temporary associative array array_tmp is formed, in which each of the elements has the format "key → value". The temporary array is appended to the array variable, the loop control variable i is incremented by one. The loop exits when the number of retrieved records N is reached. The last step is to form the formatted JSON text string and return it to the calling process.

Conclusions and results

Computer and information technologies occupy their place in military affairs. Primarily, as command and control systems and battle management systems, we see the creation of extensive databases, carriers of the most complete information possible about battlefield objects. The background visualization capabilities of electronic mapping systems speak to the existence of an electronic battlefield.

- The concept of "electronic battlefield" is defined as the gathering capability of visualization systems with the application of electronic cartography and the corresponding information contained in information arrays and database management systems.
- The structure and functional features of military communication and information systems are revealed in sufficient detail. From the given examples of field command and control systems, as well as battle management systems, a general quality of the considered systems has been deduced: electronic map-based visualization of elements of the order of battle.
- The need to switch to a new type of interface for intensive use of the accumulated data from the composition of the electronic battlefield, applicable in a field setting, has been determined. A prerequisite for moving to AR information technology is providing access to relevant databases.
- As a result of analysis of recommended MIP-type DBs, it is shown that the necessary information structures and relationships sufficient to trigger the AR information mechanism are available.
- A review of existing data storage and exchange systems was performed in the form of replication, formatted messages, program gateway. An adequately functioning information mechanism for accessing data in existing C2 systems at the RDBMS level has been defined.
- Proposed algorithm and experimental results for accessing centralized and local databases.

CHAPTER 3: Augmented reality for an augmented electronic battlefield

The conducted studies and the analysis carried out in the first chapter bring out the method for markerless identification of an object from the battlefield as possibly applicable in the field conditions used in combat missions. In the process of markerless identification, it is necessary to take into account the positions of the objects of interest, the position of the mobile device with the AR system and, last but not least, the direction (direction) connecting the observer to the observed object.

The sensor subsystem including GPS satellite navigation and inertial navigation sensor IMU is responsible for the localization of an object of interest in markerless identification in an AR system.

The mathematical theory for adequate processing of inertial data is widely discussed in a number of literature sources [79, 90]. Let's assume our IMU is 9-DoF ie. it has a three-axis gyroscope, accelerometer and magnetometer.

A basic mathematical model is shown below in the text [75] of dependencies when reading gyroscope and accelerometer readings.

Gyroscope model:

$$\omega = \widehat{\omega} + \mathbf{b}_{g,t} + \mathbf{n}_g \qquad (3.1)$$

Here, in expression (3.1), ω is the angular velocity measured by the gyroscope with respect to the instantaneous axis of rotation, and ωˆ is the ideal angular velocity that we want to derive, $b_{g,t}$ is the deviation in the gyroscope readings that changes with time (drift) and other factors such as temperature, ng is the intrinsic noise.

Accelerometer model:

Accelerometer readings are represented by the expression:

$$\mathbf{a} = R^T(\hat{\mathbf{a}} - \mathbf{g}) + \mathbf{b}_a + \mathbf{n}_a, \qquad (3.2)$$

where, $\hat{a}$ is the ideal acceleration to be taken into account in the post-processing of the data, g denotes the influencing ground acceleration in the chosen coordinate frame, b_a and n_a respectively reflect the perturbations in the accuracy of the readings caused by temperature changes and the intrinsic noise of the device. The designation R^T in matrix form indicates the relative position of the device's local coordinate system relative to a selected reference coordinate system.

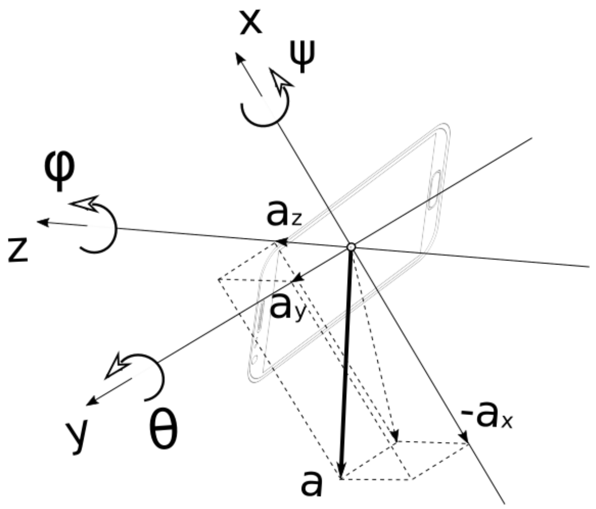

Fig. 3.1. Orientation angles and mobile device

Determining the orientation of the mobile device in space is reduced to the calculation of the so-called orientation angles, or borrowing terminology from aircraft flight control, these are azimuth, roll and pitch. In the case where accelerometer data is to be used, the constant ground acceleration directed towards the center of the earth is the basis of trigonometric calculations which give the instantaneous roll values (engl. roll φ) and pitch (engl. pitch θ) on the mobile device [33]. The readings of the magnetometer determine the azimuth value (engl. yaw ψ).

In fig. 3.1. the coordinate system attached to a mobile AR device is shown. Applying the accelerometer readings, presumably at rest and acting on ground acceleration, the pitch values θ and roll φ are determined by dependencies (3.3, 3.4) in a spin sequence ZYX.

$$\theta = \tan^{-1}\left(\frac{a_z}{\sqrt{(a_y^2 + a_x^2)}}\right) \tag{3.3}$$

$$\varphi = \tan^{-1}\left(\frac{a_y}{a_x}\right) \tag{3.4}$$

The application of the projections a_x, a_y, a_z of the ground acceleration a to determine the orientation angles, at rest of the mobile device in the trigonometric interpretation from the expressions (3.3, 3.4) are affected by the additional disturbing factors, sources of errors, according to the expression (3.2).

Alternatively, the orientation angles in motion can be determined by integrating the angular values of the rotation of the mobile device obtained from the gyro sensor readings.

$$\theta_{n+1} = \theta_n + \omega_y \Delta t \tag{3.5}$$

$$\varphi_{n+1} = \varphi_n + \omega_z \Delta t\ , \tag{3.6}$$

where n is the previous value of the specified angle, n+1 is the current value of the specified angle, Δt is the time constant for performing the numerical integration. Expressions (3.3 ... 3.6) agree [33] and reflect an independent determination of "Eulerian" angles. This form of expression allows for mathematical uncertainty in borderline cases known as „gimbal lock“.

Considering primarily the determination of roll and pitch, all necessary output data can be obtained from the sensors [11, 53, 62] from both the accelerometer and the gyroscope, independently of each other.

Complementary filter.

One of the methods [73] to reliably determine the spatial localization of the device is the unification of the data that is acquired when taking the readings of the gyroscope and the accelerometer.

Taking into account the fact that the two considered sensors have an opposite tendency to accumulate error in the measurements, the application of a complementary filter (Fig. 3.2) increases the reliability of the calculated roll and pitch angles.

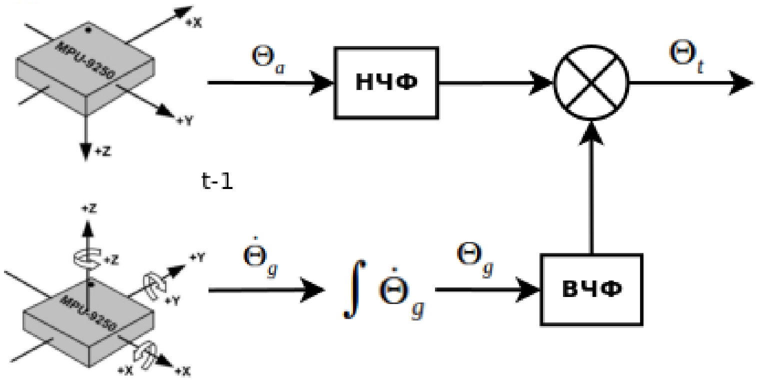

Fig. 3.2. Complementary filter

The general appearance of the expression [41] to determine the filtered value of an orientation angle relative to one of the axes in principle is:

$$\Theta_t = (1- \tau)\, \Theta_a + \tau\, (\Theta_{t-1} + \Theta_g), \tag{3.7}$$

where:
Θ_t– filtered orientation angle value;
Θ_{t-1} – previous value;
Θ_g– instantaneous value according to the gyroscope;
Θ_a– instantaneous value according to the accelerometer;
τ – time ratio factor.

Let s ω and a denote the output measured data of the gyroscope and accelerometer, expressions (3.8, 3.9).

$$\omega = [\omega_x, \omega_y, \omega_z]^T, \tag{3.8}$$

where ω_x, ω_y and ω_z are the projections of the angular velocity along the three axes of the local coordinate system.

$$a = [a_x, a_y, a_z]^T, \tag{3.9}$$

here a_x, a_y and a_z are the projections of the acceleration along the three axes of the local coordinate system.

Applying a low-pass filter to the accelerometer readings is represented by the expression (3.8):

$$\hat{a}_{t+1} = (1-\alpha)a_{t+1} + \alpha\hat{a}_t \tag{3.10}$$

Applying a high-pass filter to the gyroscope readings is represented by the following expression (3.9):

$$\hat{\omega}_{t+1} = (1-\alpha)\hat{\omega}_t + (1-\alpha)(\omega_{t+1} - \omega_t) \tag{3.11}$$

In expressions (3.8, 3.9) with $\hat{a}$ and $\hat{\omega}$ the established (filtered) values of the readings at successive moments of time are indicated t and t+1.

Taking into account (3.3 … 3.6) dependence (3.7) for each of the two orientation angles acquires the form:

$$\theta_t = (1-\tau)\theta^a_{(\hat{a}x,\hat{a}y,\hat{a}z)} + \tau\left(\theta_{t-1} + \theta^g_{(\omega_y\Delta t)}\right) \tag{3.12}$$

$$\varphi_t = (1-\tau)\varphi^a_{(\hat{a}x,\hat{a}y)} + \tau\left(\varphi_{t-1} + \varphi^g_{(\omega_z\Delta t)}\right) \tag{3.13}$$

Expressions (3.12, 3.13) are an extended form of the one shown in [73]. It is considered that the angle values obtained from the gyroscope readings (θ^g, φ^g) are relatively constant with time, while the angle values obtained with the accelerometer readings (θ^a, φ^a) subject to occasional momentary deviations. The coefficient τ типично приема стойности:

$$0.5 < \tau < 1.0, \tag{3.14}$$

as its practically determined value, leading to a stable and adequate determination of the orientation angles, also depends on the value of the integration interval Δt.

In applications responsible for practice, the exact operating values for the coefficient τ and the time interval Δt are determined experimentally [61].

Kalman filter

For the operation of the complementary filter discussed above, a parameter is introduced that determines which of the two sensors, the gyroscope or the accelerometer, is more important for the accuracy of the determined orientation angles. This parameter is subject to adjustment depending on the application of the sensors and does not always give optimal indicators. Another type of digital filtering approach known as a "Kalman filter" (engl. Kalman Filter, KF) [60] would theoretically achieve an optimal result.

We consider a system in which coordinate reference systems denoted by are distinguished I, W and B. Inertial (I), immovable (W) and the sensory body (B). In most cases the coordinate systems I and B match. When transforming from one coordinate system to another, a special notation is used, for example ${}^{B}_{A}X$ means the transformation of the quantities X from the coordinate system A to the coordinate system B. The expected result of the application of KF is to determine the values of the orientation angles $[\varphi, \theta, \psi]^T$ in the coordinate system W.

Part of the terminology adopted when designing KF systems is "state". This term means a vector of time-varying quantities [74] to describe the parameters of a given system. An important position of the work of KF is to carry out an assessment of the condition. The estimation is performed by looking for the minimum of the squared difference between the state estimated in the previous step and the assumed "correct" state.

When using KF, the aim is to estimate a given state by taking the data from one or more sensors and having a model of the process in the system in its dynamics. The Kalman filter dynamically estimates the state (also called "updating") by taking into account both the process model and the magnitudes of the sensor measurements. Some of the quantities describing the state may not be measurable, such as the gyro drift value. The process can still be updated, such a state in which not all quantities are known is called an "extended state".

Kalman filter works in steps which are process update and measurement update. In the update step of the process, the sensor-measured quantities and the system dynamics are used, thereby predicting the future state. The future state also changes over time, with a deviation proportional to the error introduced by inaccuracies in the process model. In the measurement update step, the KF uses the measurement values of another complementary sensor to correct the error in the predicted state. Since the readings of each of the sensors cannot be considered perfectly accurate, the pattern of the noise characteristics of the sensors must be accounted for. The behavior of the sensors is also reported through a matrix of average values and a covariance matrix.

The input to KF work is the current state:

$$\mathbf{x}_t = \begin{bmatrix} \varphi_t \\ \theta_t \\ \psi_t \\ \mathbf{b}_{g,t} \end{bmatrix}, \tag{3.15}$$

where the state vector **x** is determined at time t and so on:

with $\mathbf{b}_{g,t}$ the deviation in the gyroscope readings is indicated.

Step 1: The current sensor measurements of the magnitudes from the gyroscope are obtained ${}^{I}\omega_t$ and from the accelerometer ${}^{I}\mathrm{a}_t$.

Step 2: Predicted future state, taking into account the dynamic model of the system (process update).

$$\hat{\mu}_{t+1} = \mathbf{A}_{t+1}\mu_t + \mathbf{B}_{t+1}\mathbf{u}_{t+1} \quad , \tag{3.16}$$

$$\hat{\Sigma}_{t+1} = \mathbf{A}_{t+1}\Sigma_t\mathbf{A}_{t+1}^T + \mathbf{Q}_{t+1} \ , \tag{3.17}$$

where: μ_t, Σ_t denote the averaged values and the covariance matrix of the state over time, respectively t;

$\hat{\mu}_{t+1}$ and $\hat{\Sigma}_{t+1}$ denote the mean values and the covariance matrix of the state over time t+1;

$\mathbf{Q}_{t+1}$ stands for modeled noise matrix;

$\mathbf{A}_{t+1}$ stands for the dynamics of the process, a mathematical model of the transition from state at time t to time t+1. It is represented as:

$$\mathbf{A}_{t+1} = \begin{bmatrix} 1 & 0 & 0 & -\Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & -\Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & -\Delta t \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3.18}$$

where Δt is the time interval between two consecutive measurements t and t+1.

$\mathbf{u}_{t+1}$ stands for the vector of the measured state, in the case considered here it is the rate of change of the orientation angles in a coordinate system W. It is represented as:

$$\mathbf{u}_{t+1} = \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}. \tag{3.19}$$

The transformation of the state vector from the I to W coordinate systems is shown by the expression:

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \mathbf{R}^{-1} \quad {}^{I}\omega_t \ , \tag{3.20}$$

Where **R** stands for rotation matrix:

$$\mathbf{R} = \begin{bmatrix} \cos\theta & 0 & -\cos\varphi\sin\theta \\ 0 & 1 & \sin\varphi \\ \sin\theta & 0 & \cos\varphi\cos\theta \end{bmatrix}. \tag{3.21}$$

$\mathbf{B}_{t+1}$ means the correspondence between the measured state vector (in the angular velocity dimension) to the state vector (in the orientation angle dimension). It is represented as:

$$\mathbf{B}_{t+1} = \begin{bmatrix} \Delta t & 0 & 0 \\ 0 & \Delta t & 0 \\ 0 & 0 & \Delta t \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \quad (3.22)$$

Стъпка 3: Update measurement. In this step, the orientation angles are measured taking into account the sensor values obtained from the accelerometer. They are applied to move to the next, corrected state by merging data.

$$\mu_{t+1} = \hat{\mu}_{t+1} + \mathbf{K}_{t+1}(\mathbf{z}_{t+1} - \mathbf{C}\hat{\mu}_{t+1}), \quad (3.23)$$

$$\Sigma_{t+1} = \hat{\Sigma}_{t+1} - \mathbf{K}_{t+1}\mathbf{C}\hat{\Sigma}_{t+1}, \quad (3.24)$$

where: $\mathbf{K}_{t+1}$ expresses a change in the degree of correlation in sensor readings;

C refers to a transition from the current state to the next stable state;

Expressions (3.15 … 3.24) are representations of the KF by [74] and $\mathbf{z}_{t+1}$expresses the angular values of the orientation angles determined from the current readings of the accelerometer applying the dependencies (3.3, 3.4).

Mobile application software architecture with augmented reality capabilities.

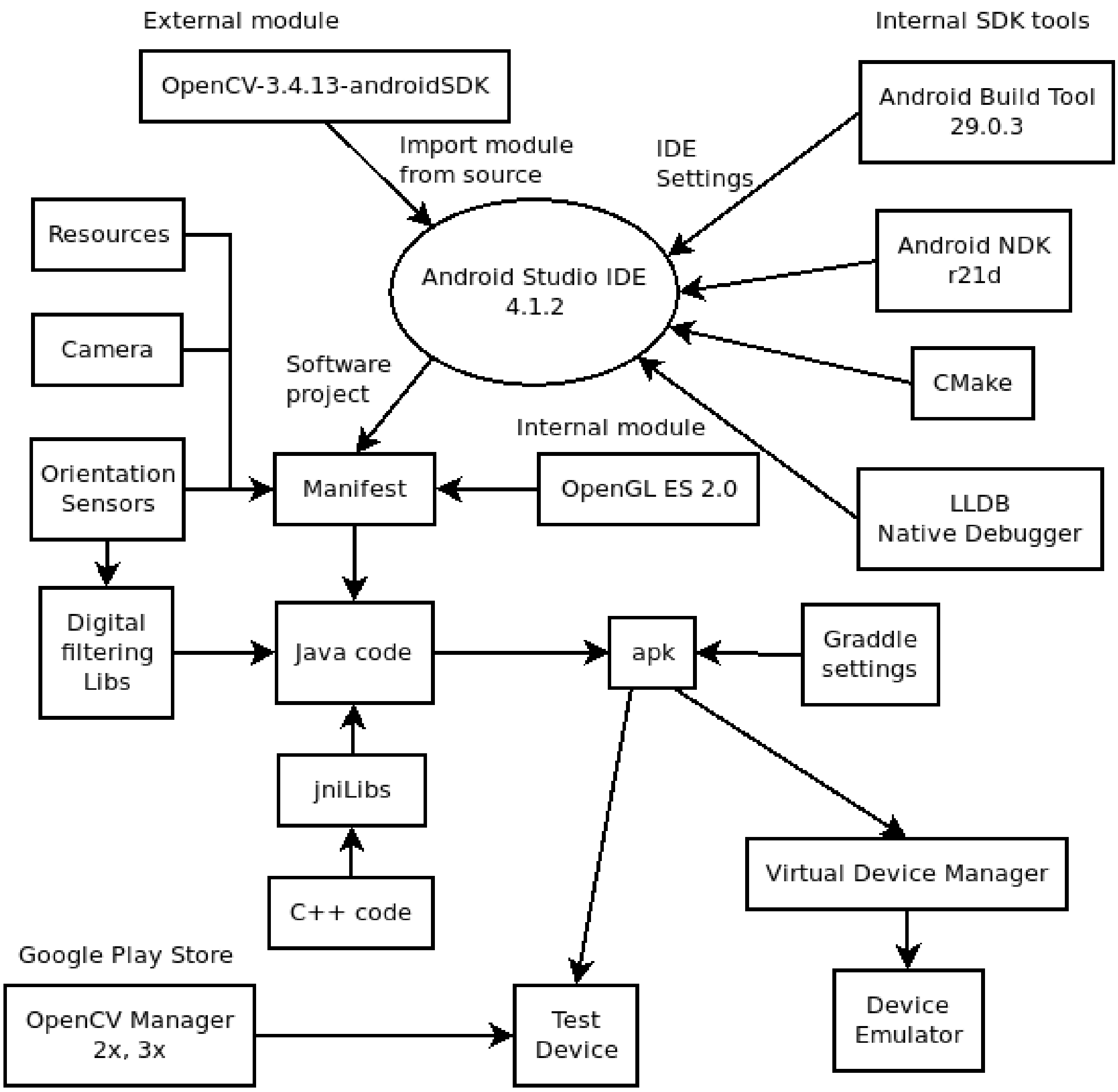

Fig. 3.3. Mobile application software architecture

In fig. 3.3 presents a software architecture of a mobile application designed to present augmented reality elements.

A key component in the software architecture proposed by the author is the freely distributed product Android Studio. Included specifically for this application are Digital filtering Libs - software libraries for digitally filtering the readings of inertial source orientation sensors [50, 92]. In the visualization process of the test AR application, additional textual and graphical information is required to be overlaid on a video frame. In the course of the experimental work on the present scientific research, it turned out to be practical, in addition to the additional received textual information, to also visualize the three-dimensional digital model of the terrain of the immediate surroundings, as well as the identified objects of interest from the order of battle, represented by their own animated three-dimensional model.

The created Android application is functional in a simulated environment and has been tested using Android Emulator as well as real mobile devices from different manufacturers.

Fig. 3.11. Screenshot of the app running

In fig. 3.11, the view of a part of the test area, a photo with the camera of a real mobile device and the result of the operation of the application in Android Emulator mode are shown sequentially.

Algorithm for markerless object identification from the electronic battlefield

The mathematical apparatus presented in the first chapter and expressions (1.1, 1.2) is a working setup for conducting tagless identification using geographic location.

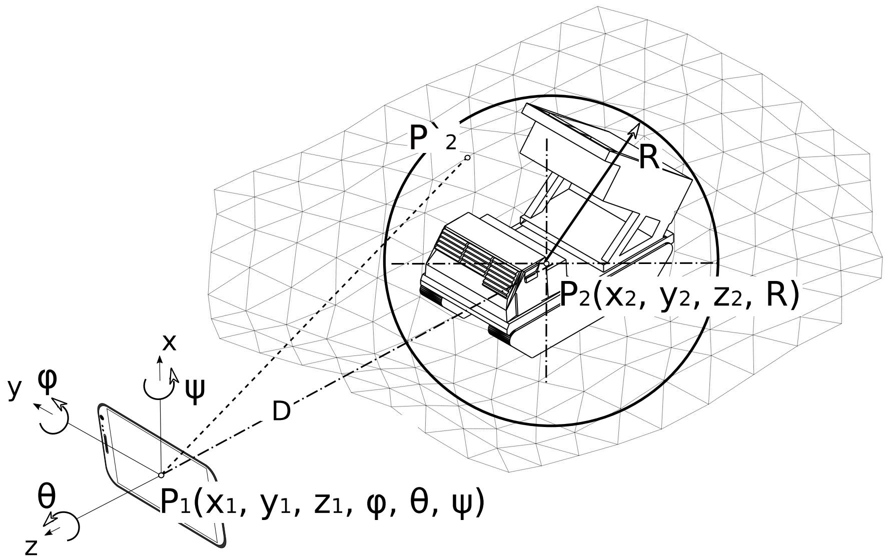

Fig. 3.12. A bounding-sphere markerless identification setup

The ray tracing method returns multiple possible solutions, and each of the resulting solutions needs to be further refined to fit within the desired geometric boundaries.

In the present study, a markerless identification algorithm is proposed using a bounding sphere.

Shown in fig. 3.12, we assume that we know the position and spatial orientation of the observer, position P_1. The characteristics of $P_1(x_1, y_1, z_1, \varphi, \theta, \psi)$ are received from the mobile device's built-in sensors.

The position P_2 (x_2, y_2, z_2) of the object of interest is determined by reference to the relevant database.

Input data P_1, P_2.

Determining the distance between the observer and the object D with the expression:

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (3.25)$$

Determining the position of a test point $P_2^`(x_2^`, y_2^`, z_2^`)$ with the expressions:

$$x_2^` = (s\theta s\psi + c\theta c\psi s\varphi)z_1 + (c\theta s\varphi s\psi - c\psi s\theta)y_1 + c\theta c\varphi x_1 - D(s\theta s\psi + c\theta c\psi s\varphi), \quad (3.26)$$

$$y_2^` = (c\psi s\theta s\varphi - c\theta s\psi)z_1 + (s\theta s\varphi s\psi + c\theta c\psi)y_1 + c\varphi s\theta x_1 - D(c\psi s\theta s\varphi - c\theta s\psi), \quad (3.27)$$

$$z_2^` = c\varphi c\psi z_1 + c\varphi s\psi y_1 - s\varphi x_1 - Dc\varphi c\psi, \quad (3.28)$$

where “s” stands for sin(), “c” stands for cos().

Determination of the radius R of the bounding sphere:

$$R = \frac{\max(\Delta x_m, \Delta y_m, \Delta z_m)}{2}, \quad (3.29)$$

where $\Delta x_m, \Delta y_m, \Delta z_m$ are determined from the data obtained from the 3D model of the object of interest.

Checking that the test point falls within the bounding sphere:

$$dist(P_2, P_2^`) < R, \quad (3.30)$$

Where with dist() is a marked procedure for determining the distance $P_2, P_2^`$ by expression-like dependency (3.25).

The variance in the angular readings of the sensors from the IMU, even after being processed by the previously discussed digital filters, complementary and Kalman filters, has its perceptible effect on the test point deviation. In fig. 3.15 shows a diagram obtained in the course of a test experiment to evaluate the impact of digital filtering.

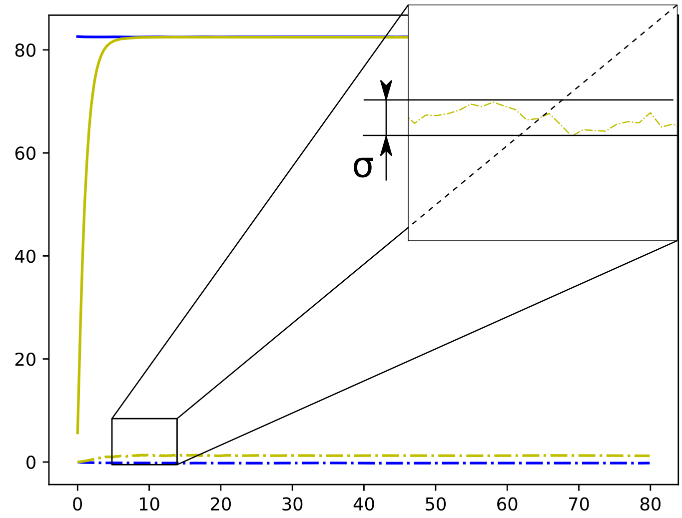

Fig. 3.15. Variance plot in accounting for values of orientation angles

In the course of the experimental work, the specialized Android application was supplemented with possibilities for testing the operation of the digital filters and a diagnostic subsystem.

As shown in fig. 3.16, the software control interface allows switching the type of digital filter currently in use. At the same time, the application screen reflects current operating values, between which is the dispersion in orientation angles $[\varphi, \theta, \psi]^T$ and the corresponding bias in markerless identification for a given distance to the observed object. The diagnostic data stream is documented via a wireless digital link to a purpose-built data server.

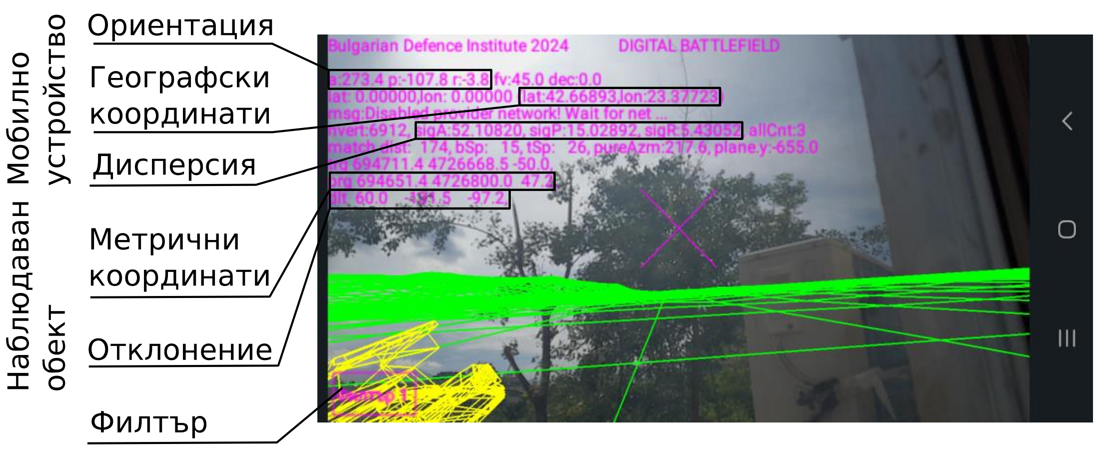

Fig. 3.16. Diagnostic data in the experimental Android application

On the table 3.2 certain numerical values are presented for the maximum distance d at which markerless identification works, depending on an average value of the dispersion of angular deviations σ_a, and specific radius R_a in different types of digital filtering.

Table 3.2. Applicability results

Digital filter	Angular dispersion	Object of interest	
		Standard target R_a=2.003 m	**MLRS M270 R_a = 3.717 m**
Off	$\sigma_a=2.57^0$	d=44.68 m	d=82.91 m
Complementary	$\sigma_a=0.25^0$	d=451.87 m	d=838.55 m
Kalman	$\sigma_a=0.80^0$	d=142.38 m	d=264.22 m

Conclusions and results.

Mobile devices with a built-in camera, display, positioning and orientation sensors, and wireless connectivity are suitable for supporting commanders' field work. One such device is the common type of smartphone or tablet.

• Object of interest identification is a major component in the AR application process. An identification method, tagless identification of geolocation principle, is adopted, which makes demands on the IMU type sensor.

• A basic mathematical model of the operation of the IMU is presented.

• The possible sources of instability reflecting on distorted and wrong readings of gyroscopic and accelerometric sensor are analyzed.

• The necessity of applying systems for digital filtering of the sensor data is brought out.

• A mathematical apparatus is presented to clarify the action of two types of digital filters: complementary and Kalman filter.

• A software architecture and object model of an application for a mobile device with an Android operating system is proposed. A selection of information structures was made to reflect the terrain, as well as various objects from the order of battle, as well as engineering and construction ones.

• An algorithm for markerless identification of objects from the order of battle is proposed.

• A test application was created to conduct experimental work. A practical verification of the tagless identification algorithm was carried out through field experiments. AR information technology shows good results when supplementing the image from the video camera with a three-dimensional model of the surrounding environment.

• A study was conducted on the influence of digital filters on the degree of applicability of AR in field conditions. Numerical data on the range of stable identification of objects from the order of battle are presented.

• The applicability of AR information technology as an enhanced electronic battlefield interface in the range of tactical mission performance has been demonstrated.

CONCLUSION

Information technology for augmented reality is a modern attempt to expand the functionality of various visualization systems. The possibilities of attaching specific textual and graphic information to real objects observed in the field of view of a video camera and a significant development in aid of eased perception of the surrounding picture. The examples of the application of AR in almost all spheres of human activity presented in the present study show the high potential of the considered information technology.

In the aspect of military application, AR has taken place in various training and specific planning activities. The conducted study found that no data have been published regarding the applicability of AR for immediate support of commander activities in field conditions and during training-combat missions. A model for advanced representation of electronic battlefield objects with the application of AR is proposed.

The presence of highly developed communication and information systems and battle management systems allow us to talk about an electronic image of objects from the battlefield - this is called an electronic battlefield in the present study. There are developed systems of the RDBMS type to the C2 systems, which at the information-physical level support the necessary data and form the electronic battlefield. An overview of the information exchange and distribution systems functionally necessary for the operation of C2 systems shows their great variety and different implementation approaches. Given the research objective, the data required for advanced visualization of objects from the electronic battlefield is achieved with organized access to the RDBMS of C2 systems.

Programmatic access to databases typically used in a local and centralized scenario is algorithmized. Tests were conducted to extract the data required for AR operation, with reference to ORACLE type DB and ACCESS type DB.

As one of the problematic moments in applying AR technology for extended presentation is the choice of method for identifying an object of interest in the observed surroundings in field conditions. The method for tagless identification using geolocation is defined. Weaknesses inherent to this method related to determining the exact location and orientation angles of the mobile device used for the AR system are analyzed. A basic mathematical model of an IMU-type sensor subsystem embedded in the mobile device is selected. An analysis of the sources of errors in the readings was made. The application of digital filters has been proposed in order to increase the reliability of sensor readings. A mathematical apparatus of the action of a complementary digital filter and a Kalman filter is presented. An original algorithm for markerless identification of a field object of interest having its electronic image in the existing electronic battlefield is proposed.

An algorithm is proposed to evaluate the performance of AR in field conditions. A software experiment was conducted and the limit distances at which markerless identification of objects from the order of battle is possible, as well as engineering and construction objects, with an example of a mine-explosive enclosure, were established. The workability of the proposed model for extended representation of objects from an electronic battlefield with the application of augmented reality in the scope of tactical tasks has been proven.

List of contributions in the dissertation

Scientific and applied contributions

1. The general principles of building applications with augmented reality in the process of information processing are defined.

2. An analysis of problematic moments of the functioning of computer applications for augmented reality, oriented for application in the military sphere, was carried out. A major problem related to the identification of an object of interest in an operator's field of view has been identified. A model of an advanced electronic battlefield is proposed.

3. Methods of data exchange and storage in army command and control systems are analyzed. Algorithms have been created for access to databases in a centralized and local version.

4. A formal model of an embedded sensor subsystem for inertial navigation is presented. An analysis of the sources of errors in sensor data processing was performed. Digital filtering methods have been applied in order to increase the reliability in operation of the sensor subsystem.

5. An architecture of a software application aimed at implementing augmented reality has been created. An algorithm for markerless identification of an object from the electronic battlefield has been developed. An analysis of the effectiveness of the algorithm applied to different types of objects from the composition of the electronic battlefield in field conditions was carried out.

Applied Contributions

1. Experiments were carried out on data extraction from the DBMS of army command and control systems for the purpose of subsequent visualization in augmented reality systems.

2. Numerical values are determined for the distance at which the capabilities of the built-in sensor subsystem allow the application of augmented reality technology to various objects of the order of battle in field conditions.

List of publications related to the dissertation work:

1. Kolev A., Pavlova L., Military applications with augmented reality, CIO ICT Media vol.7, year XV, ISSN 1312-5605, Sofia 2020, pp. 93-95, 2020

2. Pavlova L., Visualization of an electronic battlefield, CIO magazine, issue 3, year XVII, Sofia, April 2021, pp. 94-95, ISSN 1312-5605

3. Alexander Kolev, Lili Pavlova, Augmented Reality in an Enhanced Command and Control Application, Information & Security: An International Journal 50, no. 2 (2021): 180-192. https://doi.org/10.11610/isij.50223

4. Pavlova L., Engineering enclosures of the locality and electronic battlefield, ARTDEF 2023, Sofia, pp. II-97 – II-104, ISSN 2815-2581

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