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RESEARCH OF METHODS FOR DETERMINING THE ACCURACY OF METROLOGICAL MEASUREMENTS

The object of research in this work are individual branches and processes of metrology, namely algorithms and methods of global positioning, analysis and research of individual processes, and their implementation in the software model to analyze their accuracy. The existing problem is that some methods or devices that produce results based on these methods are not accurate enough or their accuracy is affected by a number of factors that worsen the result.

During the work the methods and approaches of the global positioning system were analyzed, such as: precise point positioning, relative positioning of GPS, static and fast static GPS-shooting and Stop-and-go shooting. Approaches were also divided into static and kinematic. Among the methods, the method of precise point positioning was chosen, as the most common and used among ordinary GPS users, for more detailed research and analysis of accuracy. Development methods are based on the means of interaction with open GPS services, and C#, ASP.NET Core, Angular framework, and development environment Visual Studio Code and Visual Studio 2022.

In order to implement all the necessary functionality, the subject area was analyzed, the methods of determining metrological accuracy in general and within the system of global positioning as a direct object of work were considered. As a result of the work the analysis and modelling of the subject area was carried out, the methods of the global positioning system and the software system for the analysis of the accuracy of one of the GPS methods were investigated. The analysis results provided by the software help to understand the accuracy of the method and the GPS receivers that use it on different devices.

Keywords: *metrological measurements, global positioning system, precise point positioning, .NET, Angular.*

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1. Introduction

In recent years, more and more there is a trend in the automation of manual labor, and the technology that replaces manual labor is becoming more versatile and powerful. At first, computers only performed data calculations, then algorithmic tasks, and today, thanks to advances in machine learning, bioinformatics, the Internet, and increased computing power, they have become an integral part of human privacy [1]. Laptops, smartphones, tablets, smart homes are already a routine for each of us. Hundreds of tasks that were previously performed by a person with its own hands are now performed for it by machines. But not all.

The topic of this work, namely the study of methods for determining the accuracy of metrological measurements, was chosen precisely because many routine functions and processes performed during metrological work are still not automated or they are not good enough, as the work is done by a person. For example, many metrological distance measurements can be made by neural networks using computer vision, but people are still working on this. For example, in the Kharkiv Regional Scientific and Production Center or the Kharkiv Institute of Metrology, the All-Ukrainian State Scientific and Production Center for Standardization, Metrology, Certification and Consumer Rights Protection in Kyiv or in the same center in Lviv. Humanity already has the experience that machines can do work no worse than a person would do it manually, and even better, especially in those processes where accuracy is needed. And metrology is one of those industries where processes need precision.

Today, one of the important branches of science and industry is the study of space and objects. For example, SpaceX is actively studying the planet Mars: both its surface and atmosphere and geochemistry – for further colonization in the near future. An important role in these studies is played by practical methods of metrology, especially GPS methods. But space exploration is not the only area where these methods are actively used.

Thus, in Ukraine, for several months now, a war has been going on with the occupying troops of the army of the Russian Federation. Many cities and villages suffered partial or complete destruction, they became unsuitable for life in them. For example, in Kharkov, almost one thousand buildings were damaged, and in Mariupol, 90–95 % of all buildings, some villages cease to exist altogether. People are forced to flee their homes to the west of Ukraine or abroad, often taking with them only the essentials: documents, money, telephones and spare clothes. In such conditions, it is necessary to quickly navigate a new area, so they use GPS navigation applications to find their way to the nearest store, to the nearest city or city center, to find their relatives and friends, etc. The accuracy of geolocation is now very important, so this work is aimed at researching the methods of GPS positioning and GPS navigation, analyzing the GPS processes themselves, ways to improve them and create new ones. The urgency of the problem is aggravated by the fact that in connection with military operations, Starlink supplies its satellites to the territory of Ukraine. These satellites provide more opportunities and capacities, so their consideration and analysis can be a significant part of the work.

So, *the object of research* in the work are separate areas and processes of metrology, namely, algorithms and methods of the global positioning system, analysis and study of individual processes and their implementation in a software model to analyze their accuracy. The main subject of research is the GPS method of accurate positioning of a point and the errors of its results. *The aim of research* is a practical analysis of the accuracy of GPS methods using the developed software.

2. Research methodology

2.1. Domain Analysis. Metrology is the scientific study of measurements [2], establishing a common understanding of the units that are decisive in linking human activity [3].

Metrology can be divided into three sub-sectors: scientific metrology, applied and legal metrology.

Legal metrology is the part that deals with the regulatory requirements for measurements and measuring equipment for consumer protection and fair trade.

In applied metrology, the science of measurement is being developed for manufacturing and other processes that ensure the suitability of measuring instruments, their calibration and quality control. Accurate measurements are very important in the industry as they affect the cost and quality of the product, as well as reduce the possibility of missing and further costs.

Scientific metrology is the backbone of all sub-sectors and concerns the development of new measurement methods, the creation and verification of standards, and the communication of these standards to users through finished products. This kind of metrology is considered to be the highest level of metrology, which aims for a high degree of accuracy.

Metrological activities are coordinated by national laboratories, such as the National Institute of Standards and Technology (NIST, USA) and the National Institute of Metrology, Quality and Technology (Inmetro, Brazil), coordinated at the international level by the International Bureau of Weights and Measures [4]. Standardization is also coordinated by the International Organization for Standardization, along with other organizations such as the Versailles Project for Advanced Materials and Standards (VAMAS). The main goal of VAMAS is to support trade in high-tech products through international joint projects. These projects are focused on providing the technical basis for the development of codes of practice and specifications for advanced materials [5, 6].

From the description of the sub-sectors, the scientific one should be singled out, since it studies and regulates the accuracy of metrology methods. This work is a scientific study of individual parts of metrology and belongs to the sub-sector of the same name.

Within the framework of this work, such a part of metrology as a global positioning system should be considered in more detail. GPS is a US-owned utility that provides users with positioning, navigation, and timing services. This system consists of three segments: the space segment, the control segment and the user segment. Initially, the US Space Force developed, maintained, and operated the space and control segments. But now private business (for example, SpaceX) is also doing this.

The space segment consists of a group of active satellites transmitting one-way signals giving the current GPS satellite position and time.

The control segment consists of monitoring and control stations around the world that maintain the satellites in their correct orbits through command maneuvers and correct the satellites, download updated navigation data, and maintain the health and status of the satellite constellation.

The user segment consists of the GPS receiver equipment that receives signals from GPS satellites and uses the transmitted information to calculate the user's three-dimensional position and time [6, 7].

GPS positioning can be done in one of two ways: point positioning or relative positioning. GPS point positioning uses a single GPS receiver that measures coded pseudorange to instantly determine the user's position if four or more satellites are visible on the receiver. The expected horizontal positioning accuracy from civilian code receivers decreased from about 100 m when selective availability was enabled to about 22 m when selective availability was not enabled. GPS positioning is mainly used when relatively low accuracy is required. This includes recreation and navigation programs with low accuracy [8].

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However, GPS relative positioning uses two GPS receivers tracking the same satellites at the same time. If both receivers track at least four common satellites, then it is possible to get a level of positioning accuracy from a centimeter to several meters. Carrier phase and/or pseudo-range measurements can be used in GPS relative positioning depending on accuracy requirements [9]. The first provides the highest possible accuracy. GPS relative positioning is used for high-precision geodesy and mapping applications, geographic information systems (GIS), and precision navigation.

GPS point positioning, also known as standalone, requires only one GPS receiver. That is, one GPS receiver simultaneously tracks four or more GPS satellites to determine its own coordinates with respect to the center of the Earth. Almost all GPS receivers currently available on the market are capable of displaying their location coordinates.

To determine the position of the receiver point at any time, it is necessary the satellite coordinates, as well as a minimum of four ranges of up to four satellites. The receiver receives the satellite position via a navigation message.

GPS relative positioning, also called differential positioning, uses two GPS receivers that simultaneously track the same satellites to determine their relative positions. Of the two receivers, one is selected as a reference or base receiver, which remains stationary in place with precisely known coordinates [9]. The other receiver, known as the rover or remote receiver, has unknown coordinates. The rover's receiver can be movable or stationary depending on the type of GPS operation.

Relative positioning requires a minimum of four common satellites. However, tracking more than four common satellites at the same time will improve the accuracy of the solution for determining the position of the GPS [6]. Carrier phase and pseudorange measurements can be used in relative positioning. Various positioning methods are used to provide a post-processing or real-time solution.

Static GPS surveying is a relative positioning method dependent on carrier phase measurements [4]. It uses two (or more) fixed receivers simultaneously tracking the same satellites. One receiver, the base receiver, is installed over a point with precisely known coordinates as a survey monument. Another receiver, the remote receiver, is positioned over the point whose coordinates are being sought. The base receiver can support any number of remote receivers, provided that a minimum of four common satellites are visible at the base and remote locations.

Fast static surveying is a carrier phase based relative positioning method similar to GPS static surveying. That is, it uses two or more receivers that simultaneously track the same satellites. However, with a fast static survey, the base receiver remains stationary over the known point throughout the entire observation session. The rover receiver remains stationary over the unknown point for only a short period of time, and then moves to another point, the coordinates of which are being searched [4]. Similar to a static GPS survey, the base receiver can support any number of bikes.

Stop-and-go surveying is another method of relative positioning based on the carrier phase. It also uses two or more GPS receivers simultaneously tracking the same satellites: a base receiver that remains stationary over a known point, and one or more rover receivers [4]. The rover receiver moves between unknown points and makes a short stop at each point to collect GPS data. Data is typically collected at a recording rate of 1 to 2 seconds for approximately 30 seconds per stop [9]. Like the previous methods, the base receiver can support any number of bikes. This method is suitable when the survey includes a large number of unknown points located in the vicinity (i. e., within 10–15 km) of a known point.

2.2. Research and analysis of solution methods. For the study and analysis of GPS methods in the previous section, all methods were considered and their description was given, as well as existing systems, their functionality and characteristics were analyzed.

Among the GPS positioning approaches, methods such as point positioning, relative positioning, static GPS surveying, fast static GPS surveying, and stop-and-go surveying have been considered. Among the methods of tracking in time, static, kinematic and continuously operating have been described. And although they do not differ much in terms of accuracy, the places and purposes of their use are quite different.

At first, GPS was used for military and government achievements, but it soon began to be used in industrial and daily affairs. Today, global positioning is used to explore space and space objects. For example, fast static GPS surveys and stop-and-go surveys are often used for space exploration, and point positioning is often used for everyday purposes.

However, there are many obstacles for practical analysis and research of many methods, such as having a GPS rover or a static reference receiver, or even several. But to study the positioning of a point, it is enough to have one GPS receiver, which is in every phone, so this method will be the central object of practical and analytical research.

Let's consider in more detail the method of positioning a GPS point. Precise Point Positioning (PPP) is a global navigation satellite system (GNSS) positioning method that calculates very accurate positions with errors of only a few centimeters in good conditions. PPP is a combination of several relatively sophisticated GNSS position refinement methods that can be used with near-consumer-grade hardware to produce near-survey-level results. PPP uses a single GNSS receiver, unlike standard Real-Time Kinematic (RTK) methods, which use a temporarily fixed base receiver in the field as well as near a rover. PPP methods overlap somewhat with DGNSS (differential global navigation satellite system) positioning methods, which use fixed reference stations to quantify system errors.

The PPP solution depends on the GNSS satellite clock and the orbit corrections generated by the network of global reference stations. After calculating the corrections, they deliver them to the end user via satellite or via the Internet. These corrections are used by the receiver resulting in decimeter level or better positioning without the need for a base station.

PPP provides accuracy down to 3 cm. A typical PPP solution requires a certain decimeter rendezvous time to eliminate any local drifts such as atmospheric conditions, multipath environment and satellite geometry. The accuracy actually achieved and the required convergence time depend on the quality of the corrections and how they are applied in the receiver.

The precise positioning of a point relies on two common sources of information: direct observables and ephemeris. Direct observable data is data that the GPS receiver can measure on its own. Ephemeris is accurate measurements of the orbits of GNSS satellites made by the geodetic community with global networks of ground stations.

The fine point positioning algorithm is a point positioning technique that uses:

– exact satellite orbits and clock instead of satellite broadcast corrections;
– very accurate additional error models;
– sequential filtering of two-frequency pseudoranges and those observed on the carrier phase.

Through this processing, PPP is able to calculate the exact position of the receiver along with the clock, path delay, and initial phase ambiguity for all satellites.

Precise positioning of a point can be thought of as an approach to global position since its positional solutions refer to a global reference frame. As a consequence, PPP provides much greater positioning consistency than the differential approach, where the position decision is relative to the local base station(s).

3. Research results and discussion

3.1. Modeling and software implementation details. Modeling of the developed system is performed using UML. This will help to display the functionality and internal structure of the software and system.

UML is a general-purpose design and modeling language for software engineering designed to provide a standard way to visualize system design.

When developing the system, diagrams of the following types were created:

– diagram of use cases;
– class diagram;
– deployment diagram.

Use Case diagram – a diagram that reflects the relationship between actors and use cases and is an integral part of the use case model that allows describing the system at a conceptual level (Fig. 1).

On the diagram, it is possible to see a list of user actions using the system. A user is a person using a web application to analyze the accuracy of the PPP GPS method on their device.

The main action that the user performs is manually entering data about its location using Google Maps and requesting the system to analyze the accuracy of the GPS method.

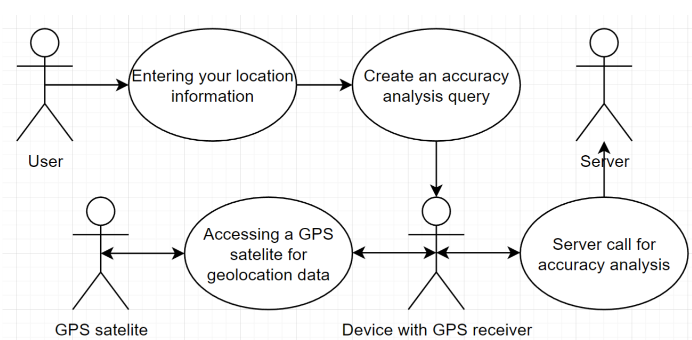

Fig. 1. Diagram of use cases

In the diagram, it is also possible to see a device with a GPS receiver that is accessing the satellite to get its location data. A GPS satellite that responds to a device request and sends the necessary data. The actor in the diagram is a server that receives requests from the client side (a device with a GPS receiver), processes them, and sends the result back.

Fig. 2, 3 show the class diagrams of the server and client parts, respectively.

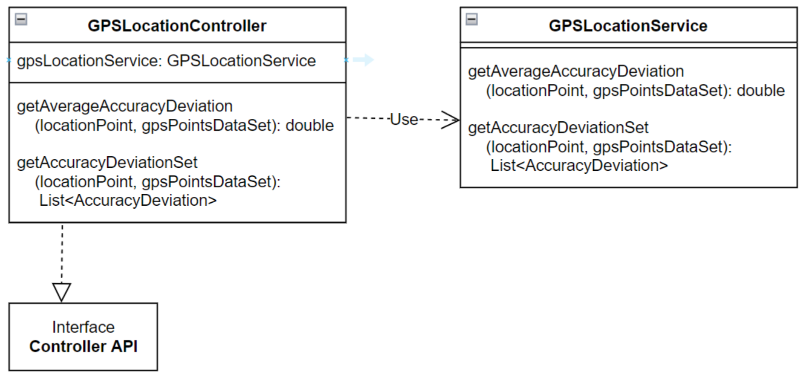

Fig. 2. Class diagram of the back end

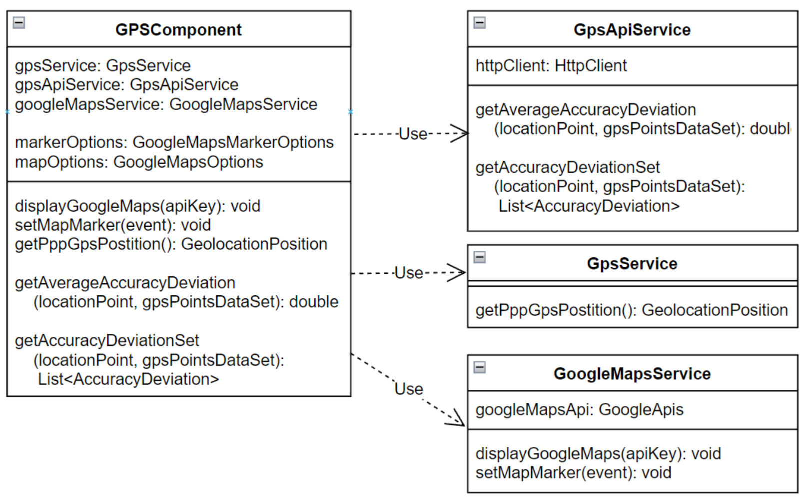

Fig. 3. Class diagram of the client side

A class diagram is a type of static structure diagram that describes the structure of a system by showing its classes, their attributes, operations or methods, and the relationships between objects.

Here is the ControllerAPI interface that allows the GPSLocationController class to communicate with the web client using the REST API. The GPSLocationController class has two methods getAverageAccuracyDeviaton and getAccuracyDeviationSet and a gpsLocationService field. The GPSLocationService class has similar methods in which it implements the logic for calculating GPS accuracy. In the client-side class diagram, the main class is GPSComonent, which represents the logical part of the HTML page.

The diagram also shows components such as:

– GPSApiService is responsible for creating REST requests to the backend;
– GpsService is responsible for finding geolocation using the PPP method of GPS;

– The GoogleMapsService is responsible for connecting to the Google API, configuring Google Maps, and responding to the user creating their location marker on the map.

Angular 13 is used to write the client side, and ASP.NET Core is used to create the server side. In Fig. 4 it is possible to see the deployment diagram.

For communication between the server and client parts, the REST API standard based on the HTTPS protocol is used. Hypertext Transfer Protocol Secure (HTTPS) is an extension of the Hypertext Transfer Protocol (HTTP). Used for secure communication over a computer network and is widely used on the Internet [10].

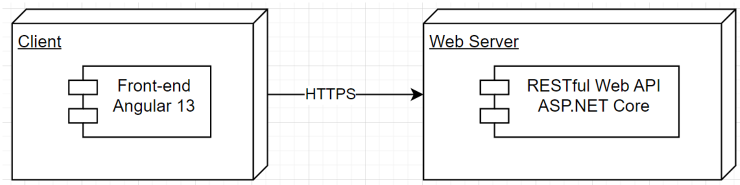

Fig. 4. Deployment diagram

An application has been created as software that can be used to analyze the accuracy of GPS methods and GPS receivers of a client device.

The functionality of the application is very simple, but it implements the necessary tasks. On the client side, using the GPS receiver of the client device and the implemented method for precise point positioning, the geoposition is read and, using Google Maps, the user manually marks the most accurate location.

A user-marked point reads longitude and latitude data up to fifteen decimal places for greater accuracy. Further, using the GPS method and TypeScript tools, the point at which the global positioning system sees the user is read many times and written to the data array. This data, together with the data from the manually marked point, is sent to the server side, where the average error is calculated and the result is returned back to the client side.

Also, keep in mind that most computers and laptops do not have a GPS receiver, so their location is determined using an IP address. This positioning can deviate up to several hundred meters, so it only makes sense to use this application on a device that has a GPS receiver.

3.2. Experimental research and software testing. Software testing is a process of technical research designed to discover information about the quality of a product in relation to the context in which it will be used. Testing methods include the process of finding bugs or other defects, as well as testing software components. The number of possible tests even for simple software components is quite large, so when developing a web application, unit testing and API testing were carried out.

API testing was done with smoke testing and Postman. Smoke testing is pre-testing to detect simple failures that are severe enough to, for example, reject a future release of software. Smoke tests are a set of test cases that cover the most important functionality of a component or system that are used to evaluate whether the main functions of the software are working correctly [11].

In order to test the individual components of the system, unit testing was carried out. On the client side, unit testing was done using standard Angular functions and the Jasmine and Karma libraries. For unit testing on the server side, several unit tests were created using the NUnit library.

During the development of the software, experimental studies of the accuracy of GPS devices for different devices were carried out. The results can be seen in Table 1.

According to the Table 1 it is possible to understand that the method of determining using the IP address is very inaccurate, and may deviate by several hundred meters, as described in the third section. The PPP method is quite accurate and differs only from the specifications of the GPS receiver. As noted in the analysis of existing systems, Apple Maps is a fairly accurate application due to the good technical characteristics of the GPS receiver in the iPhone.

The results of the analysis reflect only the deviations of the Precise point positioning method under normal conditions in the urban space and only on the three devices indicated in Table 1.

Table 1

Analytical test results

Device	Number of tests performed	GPS method	Average deviation (in meters)
Notebook Lenovo Thinkbook 15	200	Definition by IP address	319.53
Smartphone Samsung Galaxy A10	200	Precise point positioning	3.62
Smartphone iPhone 13	200	Precise point positioning	0.76

It should be noted that more tests are needed for a more detailed analysis. And also for practical use, the quality of the GPS receiver, weather conditions and terrain should be taken into account. The study of the above factors in the accuracy of the PPP may be a further development of the analysis.

4. Conclusions

As a result of the work, a study of the subject area of metrology was carried out using the example of GPS methods. The expediency of developing a system for analyzing the accuracy of the Precise point positioning method is substantiated, the principles of its operation are described, the main functions are identified, and software for assessing accuracy is implemented.

For software development, UML diagrams have been created, namely use case diagram, deployment diagram, and class diagram for back-end and front-end. Software testing methods of smoke testing for server API via Postman and unit testing method for all logical parts of the program are described.

200 tests were carried out on three devices and the accuracy on each of them was determined. The method of geopositioning using the IP address turned out to be rather inaccurate and its average error is more than 300 meters. The PPP method turned out to be quite accurate (within a few meters), and its quality depends on the quality of the GPS receiver.

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