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Methods for Development of a Digital Twin of the Water Area for Navigation of Unmanned Vessels



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ABSTRACT

The article discusses a set of methods with which it is possible to form a digital twin of the water area for autonomous navigation of a river vessel to solve problems of modelling movement in the water area of an autonomous vessel under various environmental parameters (flow velocity, wind speed, etc.), including dynamically changing ones within the process of vessel's movement, to test algorithms for operation of an autonomous vessel under the conditions of emerging threats and emergency incidents. The proposed methods include aerial photography from unmanned aerial systems, airborne laser scanning and coordination of the results of their processing using geodetic equipment operating using global navigation satellite systems and serving to link all received spatial data into a single coordinate system to form high-precision digital twin components of water area, including the water's edge and part of surface elements.

To form the bottom part of a digital twin of the water area, a possibility was considered to use bathymetric survey data collected with a multibeam echosounder, as well as aerial photography data received from an unmanned aerial vehicle equipped with a high-precision geodetic receiver and an on-board inertial system for laying out bathymetric survey routes.

Keywords: digital twin of the water area, autonomous navigation, digital terrain model, digital bottom model, airborne laser scanning, aerial photography, water transport.

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INTRODUCTION

Currently, there is a growing interest in creation of automated unmanned (crewless) vessels all over the world [1]. Controlling an unmanned vessel is a complex technical problem, one of the components of which is a digital twin of the water area (DTWA), which contains all the data required for navigation of unmanned (autonomous) vessels [2].

In 2002, the concept of the digital twin was initially introduced as the model focused on the information about a product [the model was then referred to as «Mirrored Spaces Model»] by Michael Grieves, Professor at the University of Michigan [3, 4]. The term «digital twin» (DT) was officially adopted in 2010 when the US National Aeronautics and Space Administration (NASA) provided a detailed concept. This description refers to the integrated use of physical models, sensors, historical operational data, and additional relevant information to model interdisciplinary and multiscale processes. The goal is to create a virtual representation that can reflect the entire life cycle of the corresponding physical object [5]. Essentially, the proposed DT model includes three main components: a physical product, a virtual product, and the relationship between these two products.

Although the concept of the DT initially emerged in the aerospace and manufacturing fields, it has since evolved to extend its application to intangible processes such as smart cities [6], precision (personalised) medicine [7–9], Digital Earth, and even the metaverse [10–14]. DT was included in the top ten key technology trends in the digital industry in 2019 according to Gartner [15]. A striking example of the application of DT is the «Destination Earth» project, initiated by the European Union in March 2021. This initiative aims to create an extremely accurate Earth DT for continuous and accurate monitoring of the planet's health. Besides, it aims to promote high-precision forecasting of natural disasters and anthropogenic environmental degradation, as well as to study the socio-economic impacts of climate change and major natural disasters [13].

With development of DT technology, its range of applications has been gradually expanding to include the marine environment, thereby facilitating the emergence of a Digital Twin of the Ocean. To date, many applications of DT have been implemented under various scenarios [16]. For example, real-time DT systems for marine vessel operations have been developed using wave reconstruction and ship motion forecasting [17]. Application of DT technology allows creating high-fidelity modelling systems for underwater unmanned gliders [18].

Russian state standard (GOST) defines a «digital twin of a product» as «a system consisting of a digital model of a product and two-way information links with the product (if there is a product) and (or) its components»[1]. If we expand the concept of a digital twin beyond the scope of a «product», then the definition of «a digital twin as a digital (virtual) model of any objects, systems, processes or people, accurately reproducing the form and actions of the original and synchronised with it»[2], has become recognised. A digital twin is necessary «to simulate processes in the original object under certain conditions»[2].

According to the definition given in the Water Code of the Russian Federation, a water area is «a water space within natural, artificial or conditional boundaries», that is, some water surface limited conditionally or physically. However, the navigation process uses primarily information about the depths of the water area, bottom topography, flows, coastal navigational signs, obstacles, etc.

It follows that a digital twin of a water area is a copy made in a virtual environment of the underwater and coastal parts of the water area, as well as its water column, sufficient as for its completeness and reliability for autonomous navigation, and which is a synthesis of 3D models of these parts, cartographic and semantic information about objects located on them and dynamic processes occurring on their territory.

With the help of DTWA, it is possible to solve a range of problems, comprising, for example, modelling the movement in the water area of an autonomous vessel under various environmental parameters (flow velocity, wind speed), including those dynamically changing during movement, testing algorithms for operation of an autonomous vessel under the conditions of emerging threats and emergencies [19], modelling vessel routes depending on tasks (fastest route, most economical route), use in navigation for precise positioning of the vessel by comparing data from external sensors with data from the DTWA data [20] and for choosing further actions depending on the situation and current tasks.

The objective of the study was to reveal a set of methods which allow to form a digital twin of the water area for autonomous navigation of a river

[1] GOST R [State Standard] 57700.37–2021 «Computer models and simulation. Digital twins of products. General provisions».

[2] What are digital twins and where are they used // RBC Trends. [Electronic resource]: https://trends.rbc.ru/trends/industry/6107e5339a79478125166eeb?from=copy. Last accessed 22.12.2023.

vessel, to solve problems of modelling movement in the water area of an autonomous vessel under various environmental parameters, including dynamically changing ones within the process of vessel's movement

RESULTS

Objects and Structure of the Digital Twin of the Water Area

For successful functioning of DTWA, it should be filled with all the data used for vessel navigation. The main requirement for DTWA data is that all data must be interconnected and located in a single coordinate system. The components of DTWA in relation to changes in coordinates in space and their shape are divided into static, transitional and dynamic ones. Besides, within DTWA, dynamic objects depend on factors which are variable quantities that influence the state of the object.

Static DTWA objects include objects that do not change their spatial position. These include most man-made objects – bridges, piers, navigational signs, dams, etc. Also, in most cases, the coastline can also be classified as a static object.

Transitional DTWA objects include objects that are able to change their shape and coordinates over time. As a rule, these are objects that move and change shape in rivers under the influence of channel flows. Also, transitional objects should include some of the man-made objects, such as buoys, bacons, marks, etc. that change their position depending on the wind and flow, as well as with each new navigation due to errors in place where the floating mark is anchored.

Dynamic DTWA objects include objects moving within the water area: vessels, ferries, floating obstacles, etc. The movement of dynamic objects depends on factors which are variables influencing the state of the object: velocity and direction of flow and wind.

The components of DTWA are combined into a single data structure, which is a collection of data elements between which certain connections are established, as well as a method to organise data for more efficient use. The data structure within the digital twin of the water area represents attribute information embedded in each layer of each component.

Layers or objects are indicated by the following three types of signs: area (polygonal), linear, and point ones.

Area signs mark objects depicted on a map scale, that is, those whose dimensions (length, width and area) can be measured on the map, for example, a large lake, river, etc. Regulatory documents previously gave the following definition: «An area sign consists of an outline the depicted object and of the background colouring, colour shading or grid of identical icons filling it. The outlie of objects is shown on the map with solid lines or dotted lines in accordance with their outlines on the ground»[3].

Linear symbols depict narrow, extended objects, the width of which can be neglected on the map scale, and the lengths of which are expressed on the map scale (railway tracks, roads, watercourses, power lines, product pipelines and other objects).

Point objects are objects located only at one point in space on a map scale (lonely trees, houses, wells, points of the state geodetic network). Point objects can be designated by the coordinates of their location.

Depending on the required scale of the plan being formed, the same object can be depicted in different ways, that is, when creating a large-scale plan, the object can be indicated by an area symbol, and when creating a small-scale plan, it can be indicated by a point symbol.

Each layer contains its own attribute information, which in turn is divided into 2 types: positional and non-positional.

Positional information describes the position of objects in space in two-dimensional or three-dimensional coordinates.

Non-positional information includes qualitative characteristics of objects (semantic data) and quantitative ones (statistics). Non-positional information is represented as text and/or numeric parameters. In most cases, when working directly with data, the type of object is marked and identified by its attribute parameters (for example, a bridge has a name and is identified by construction materials (reinforced concrete, metal, stone, wood), width, height, presence of navigable spans, number of navigable spans).

Thus, the attribute information of objects of various components of DTWA will contain the following data:

• Positional data – the position of an object in space: *X, Y, Z*. This type of information is most applicable to point objects, however, for area and linear objects it is also possible to display spatial information as attributes by creating a separate point layer with vertices extracted from a polygon or line.

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[3] Order of the Ministry of Regional Development of the Russian Federation dated January 31, 2007, No. 4 «On approval of the Requirements for methods of displaying point, linear and area objects on maps (diagrams) provided for by the Regulations on the composition of territorial planning schemes of the Russian Federation».

• Non-positional data – semantic and statistical description of an object: object number, object name, object characteristics, connection with the spatial nature of the object (area, perimeter, width, height).

Methods for Forming a Digital Twin of the Water Area

The collection of spatial data to form a digital twin of the water area is carried out simultaneously with several techniques: by airborne laser scanning, aerial photography, ground geodesy and bathymetric survey.

Airborne laser scanning, aerial photography, and ground geodesy are used to create elements of the coastal and surface parts of DTWA, while bathymetric survey is used for underwater part of DTWA.

Airborne laser scanning

Airborne laser scanning (ALS) or lidar survey is a technology that allows creating digital terrain models, digital relief models and three-dimensional models of objects based on the obtained point clouds.

This method is the fastest, most complete and reliable way to collect spatial-geometric information about the area. The essence of the airborne laser scanning method is the process of recording the *X, Y, Z* coordinates for each reflection. Due to this, the result is a spatially defined terrain model.

The airborne laser scanning method is carried out using a rotating mirror on the lidar module, the angle of rotation of which is measured by an encoder mounted on the rotation axis of the mirror. An encoder is a rotary sensor that has a special turntable, divided into sectors, due to which this design allows quickly determining the angle of rotation. When the aircraft moves, the scanning laser beam is directed at various terrain objects in a plane perpendicular to the axis of rotation of the mirror. The reflected signal of the scanning laser beam hits the mirror and is recorded by the radiation receiver, and then converted into the usual coordinates *X, Y, Z*.

The result of airborne laser scanning is a cloud of laser reflection points (LRP), which is subsequently converted into a point cloud with sufficient density for subsequent creation of digital models.

One of the most important stages of ALS data processing is dense cloud classification. This process allows dividing the point cloud into classes, which further simplifies the process of working with data. The essence of classifying a dense point cloud is placing a group of points according to various criteria into a certain class. This process is automatic but requires control.

Aerial photography

«Modern aerial geodesy is based on methods for collecting geospatial information from moving carriers, that is on digital aerial and space photography, methods of direct geopositioning and methods of digital transformation of the results of conditionally static and dynamic surveys of objects to their static models in a given coordinate system» [21].

«An orthophotoplan is a photographic plan of the area with an accurate geodetic reference, obtained by aerial photography with subsequent conversion of aerial photographs (from a central projection to an orthogonal one) based on an effective method of their differential orthophototransformation» [22] and is a topographic digital photoplan compiled from orthophotos obtained following orthorectification. An orthophotoplan is created within the framework of nomenclature sheets or within specified boundaries and is characterised by a certain nominal spatial resolution.

The process of creating an orthophotoplan consists of several stages: phototriangulation, linking with ground-based control, clarification of external orientation parameters of images, orthorectification of images [23].

The final stage in constructing an orthophotoplan is orthorectification of images. Orthorectification is a mathematically rigorous transformation of the original image (shot) into an orthographic projection and elimination of distortions caused by terrain, shooting conditions and camera type.

Ground geodetic control

To accurately link airborne laser scanning and aerial photography, it is necessary to perform a geodetic control of the coastal part of DTWA test site by measuring the respective coordinates of the centres of aerial survey ground control points within the territory of airborne laser scanning and aerial photography. It requires preliminary placement of those ground control points intended for aerial survey at points with known coordinates for the purpose of subsequent accurate coordinate reference of the results of photogrammetric processing of airborne laser scanning and aerial photography materials.

It is recommended to use as those ground control points the objects that have «unchangeable outline on the ground, are contrast with the surrounding background and are clearly visible on aerial photographs». «It is recommended to reliably mark ground control points. If necessary, ground control points are painted on the road surface. The shape of a ground control point must ensure an unmistakable determination of its centre», and therefore it is recommended to use «ground control points such as «target», half-cross or cross»[4].

The location of ground control points for aerial survey must comply with the principles below:

– On rectangular areas, ground control points are located according to the «envelope» pattern, which provides for installation of at least five control points; four control points are installed at the corners of the rectangle, and one is placed in the area where the diagonals intersect. With an increase in the geometric complexity of the boundaries of aerial photography area, in the complexity of building area and terrain, the number of control points should increase with a uniform distribution within the survey area and in each corner zone (Pic. 1).

• When surveying a linearly extended object, ground control points are located in pairs at the beginning and end of the surveyed site and then along the site route at least every 500 m along the axis (Pic. 2).

• «When designing several flight missions with planned overlap zones, it is necessary to install at least 2 ground control points within the overlap zone. When the width of the overlap… is more than 1 km, it is recommended to install ground control points at least every 250 m»[4].

• «In areas with a height difference of more than 20 m, it is recommended to install additional control points at characteristic turning points»[4].

• The preferred placement of control points is at ground level.

• There should be no objects above the control point that block it from aerial photography at nadir point, including trees, contact networks and power line wires.

• No control points should be placed near high objects, including fences, poles, trees, etc.

It is advisable to measure the coordinates of the centres of ground control points using geodetic-grade GNSS equipment in the differential correction mode to reduce the measurement time.

Differential correction is a technique for improving the accuracy of GNSS data collected. The differential correction method consists of improving the accuracy of the GNSS receiver by taking into account navigation corrections received from third-party sources. As a rule, to single out corrections, a GNSS receiver is used that is fixedly located at a point with known coordinates (base station). This allows to isolate the «noise» of the main signal due to various distortions (inhomogeneity of the atmosphere, interference from static and moving objects, signal reflections), generate corrections and transmit them via a communication channel to a second mobile receiver (rover), used to measure points with unknown coordinates, which allows eliminating errors in the coordinates obtained on the mobile receiver and determining its coordinates with greater accuracy.

The essence of performing real-time GNSS geodetic measuring (RTK, Real Time Kinematic) is that the base station receives differential corrections from each satellite in orbit to which it is connected, processes these differential corrections online, and transmits them (via mobile or radio communications) to the rover.

As a result of these actions, the rover, which has received corrections, automatically refines its location, displays differentially corrected coordinates on the screen, and records these coordinates into the catalogue when performing direct measurements.

In the case of GNSS measurements followed by office processing with PPK (Post-Processed Kinematics), the base station records all differential corrections received from the satellite, while the rover records telemetry.

Further, in office conditions, the file with differential corrections is combined with the rover telemetry using specialised software, an ephemeris file is added to them, and processing is performed.

This results in a catalogue of refined geodetic measurements.

It is also possible to post-process GNSS measurements taken in RTK mode in case the signal transmitting differential corrections from the base station to the rover is interrupted. The rover, even after signal loss, will continue to record telemetry data, which will allow post-processing to obtain a catalogue of measured points.

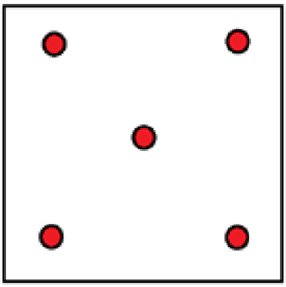
Bathymetric survey

Bathymetric surveys on water bodies (rivers, lakes, reservoirs and in the coastal zone of the sea) are carried out to map the bottom topography. Depending on the expected complexity of the bottom topography, a network of measurement points is formed along which depths are subsequently measured.

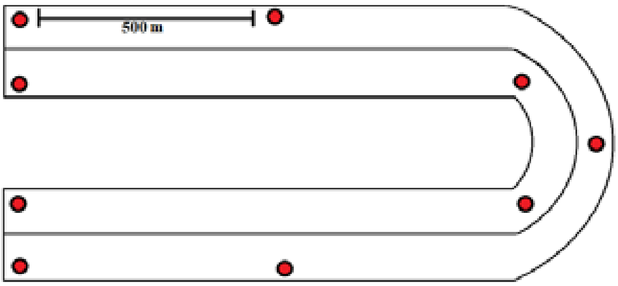
Survey is made along routes located in such a way as to minimise the workload while respecting a given accuracy of underwater relief surveying [24].

Optimisation of bathymetric survey routes can be carried out on the basis of aerospace survey, since

[4] ODM 218.9.017–2019. Road Industry Methodological Document. Methodological recommendations for performance of aerial phototopographic works using unmanned aerial vehicles during surveys for the purpose of construction and reconstruction of highways. Federal Road Agency (ROSAVTODOR). Moscow, 2021.



Pic. 1. Location of ground control points for the area aerial photography [performed by the authors].



Pic. 2. Location of ground control points for the corridor aerial photography [performed by the authors].

the visible part of the solar spectrum is well transmitted by water and, as a result, allows one to estimate the depth with good accuracy [25]. Limiting factors for determining bottom relief using aerospace methods include water transparency (turbidity), lack of good lighting, and the presence of disturbances (ripples) on the water surface.

Modern bathymetric survey is carried out, as a rule, using a multibeam echosounder (MBES) [26], which performs three-dimensional mapping of the bottom topography based on data from sonar scanning the bottom in a plane perpendicular to the direction of movement of the carrier. At the same time, for correct binding of bathymetric survey data, the MBES carrier must accurately determine its position in space. Determination of the carrier's position in space is carried out, as a rule, using GNSS methods, either in RTK or PPK mode.

Modern hydroacoustic equipment, together with «software for hydrographic works, makes it possible to collect and process data on the bottom topography with high accuracy» [27]. Hydroacoustic equipment can be installed on «hydrographic and specialised vessels,.. autonomous and remotely controlled underwater vehicles» [27].

«The data collected and processed by the onboard hydroacoustic system characterise the unique features of the bottom topography, usually represented by an array of depths with geographic coordinates. The obtained depth values are characterised by uncertainties caused by the difference between the calculated and actual values of the speed of sound in water, and due to acoustic dispersion and absorption by bottom soil» [27].

MBES is one of the most modern, effective and most informative systems for performing area hydroacoustic surveys and thus merits attention regarding its use for navigation purposes of unmanned autonomous vessels.

The MBES sensor is mounted on the bottom of the vessel. Such a location helps obtaining more accurate data and reduces the impact of various noise and distortions on the signal. The installed MBES, using transducers, emits short acoustic pulses in the direction of the bottom of the water area, forming radiation patterns: wide (120°–150°), located perpendicular to the vessel's progress, and narrow one (about 1° for high-precision systems), located along the vessel's course.

«Thus, the system performs spatial filtering of acoustic pulses reflected from various discrete areas of the bottom of the water area along the scan path, called irradiation spots, or beam flare spots» [28]. So, based on the delay time of the acoustic pulse and the angle of arrival of the beam, the bottom topography digital twin is formed.

BRIEF CONCLUSIONS

Thus, to create a digital twin of the water area, it is advisable to use combined methods of collecting information. To form the coastal part of DTWA and surface elements, it is effective to use a point cloud and three-dimensional models constructed from aerial photography and airborne laser scanning data with georeferencing based on ground control points measured by geodetic GNSS receivers. Besides, aerial photography data can be used to plot bathymetric survey routes.

To form the bottom part of DTWA, it is advisable to use MBES bathymetric survey data.

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