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DEVELOPMENT AND 3D PRINTING OF VESSEL MODELS WITH AUTOMATED TRAFFIC CONTROL SYSTEMS

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The aims to enhance maritime navigation quality and safety by developing autonomous navigation systems that mitigate the negative impact of human factors through advanced software and hardware integration with servers and onboard controllers.

A pivotal challenge faced by researchers is to minimize the potentially negative implications of human factors in the context of vessel management, and to develop efficient mechanisms for software and hardware interaction with servers and onboard controllers.

From a methodological perspective, the research encompasses: a) the development of modules to refine management processes; b) the creation of simulation stands for comprehensive research; and c) the design of a detailed 3D model of the MSC Panaya container ship.

The principal outcomes of our study involve the creation of a detailed 3D model of the MSC Panaya container ship, based on factory blueprints. Utilizing advanced 3D printing technology and PLA plastic, physical models ready for field testing of the proposed technical solutions were successfully fabricated. After selecting and configuring a remote-control system for the ship model, it was ensured to be waterproof, maneuverable, and compatible with other components. Using the chosen remote-control system, the model could operate at a distance of up to 500 meters. Notably, the application of PID controllers assists in stabilizing the vessel under varying weather conditions and marine currents. Furthermore, approaches to optimize hardware components, including microcontrollers, sensors, and associated software, were explored. Emphasizing the development of autopilot systems for ship models up to 2 meters in size, it was discerned that compact sensors such as LIDAR, cameras, and sonars could be particularly beneficial for such vessel models. Additionally, communication systems and integrated GPS modules can simplify navigation and interaction.

The practical contribution of the study is reflected in the development and implementation of comprehensive technical solutions aimed at the optimal interaction of the ship model with water bodies, considering the dynamics of weather conditions and nuances of maritime navigation. Experimental testing under real conditions and modern control systems have augmented the efficiency of the model's operation. Prospects for further research include additional refinement of technical solutions and their adaptation to the needs of real ship systems.

Key words: *Autonomous navigation systems; human factor; ECDIS/AIS; 3D modeling; remote-control system; PID controllers; maritime navigation.*

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Introduction. The current state of navigation systems development, automated and intelligent means of controlling the movement of vessels, complex multi-parameter automatic modules requires continuous improvement of relevant information and formal models and methods to maintain the reliability and safety of navigation. The directions of development of this field determine the synthesis of new approaches, development of software and hardware for simulation and field experiments, aimed at identifying priorities in the science and technology of water transport.

The human factor is currently the weakest link in the vessel control system [1–3]. According to world statistics, it is the human factor that causes accidents and catastrophes at sea in 75–96% of cases. Modern approaches and organizational measures taken to strengthen the training and retraining of seafarers, amendments to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, and other IMO measures have not led to a significant reduction in accidents.

This is due to growing number of information sources that the captain (pilot) must process at the same time. It is the information and organizational load, the high level of responsibility is the reason for the increase in vessel accidents. Thus, today it is becoming increasingly clear that the most effective way to achieve the desired result is to reduce the impact of the human factor through introduction of modern information control systems for vessel traffic.

The study [4] points out that in practice there are many difficult situations when the International Regulations for Preventing Collisions of Ships of 1972 (COLREG-72) do not have clear answers and recommendations for the actions of another vessel in divergence and maneuvering. Usually, in such situations, the navigator makes decisions from his own experience, which significantly increases the level of danger in maritime transport. Ambiguity in situations where, for example, a vessel loses control, stops, or violates rules requires scientists to conduct multiple simulations and field research, mathematical and software processing of large data sets, which will further develop appropriate automated modules to support decision-making in complex and atypical situations.

The research presented in [5] is aimed at analyzing the probability of stability of vessel traffic, approaches based on the entropy of information about navigation states. Experts are directly involved in such situations, transforming their experience into a decision support information system. This area of research is also related to risk analysis, loss of balance of control actions, analysis of the degree of uncertainty of the navigation situation and thus supports the research areas of the research laboratory on an integrated approach to collecting experimental data. The difficulty of solving this problem remains quite high because expert opinion is not subject to the negative influence of human factors and this fact suggests that the scientific search to avoid it in difficult situations should continue.

In certain areas of prevention of negative manifestations of the human factor involved organizational approaches aimed at the cognitive mechanisms of the operator-navigator [6]. Interviews of seafarers in difficult situations are conducted, structural conclusions are drawn and guidelines are formed. However, even these measures do not give significant results, because the pilots during the interview and those who are directly on board are in different physiological states. In connection with these circumstances, the processes of situation analysis and decision-making are formed differently with different priorities and time for information processing. All this presupposes taking into account the conditions in which the decision-makers make decisions, the formation of individual models of decision-making, and so on. Thus, the time ranges of decision-making and the time of the maneuvering stages depend on the perception of the situation by the navigator [7]. This area of research is important because of the distortion of the processes observed during time maneuvering by the navigator. It is the perception of risk that affects the time distortion of the navigator and causes uncertainty in his actions, which introduces an imbalance in navigation safety.

Also, taking into account the significant economic losses caused by disruption of main waterways and canals, special attention should be paid not only to emergencies, but also to emergencies that have insignificant differences in maneuvers and difficult harbour crossings [8, 9]. In this case, the courses do not intersect and the rules of COLREG-72 are not violated. However, atypical actions and minor deviations from the vessel's established trajectories, speed, time maneuvering stages and limited sources of information for the captain's decision-making should be of concern for control and information support. In such circumstances, there is a high level of uncertainty in the set of indicators and parameters of the vessel, which signals the non-typical situation. In order to constantly monitor navigation situations, there is a need to create automated and intelligent control systems that will track even minor differences from the trajectories in predetermined locations.

Statistical surveys usually introduce a multi-navigation risk assessment system [10], which uses vessel risk profile inspection data, automatic identification system (AIS) data and expert judgment. The combination of data gives a complete situation that allows port operators to understand the situation in the maximum possible detail. However, the dynamic nature of maneuvering vessels and the difficulty of forecasting them in bad weather or abnormal situations should be taken into account. The combination of approaches significantly expands the analytical capabilities of the system, but requires the creation of new and mathematical models and methods of vessel traffic control and appropriate automated control systems. The creation of such systems will provide comprehensive support for individual vessels and the management of the local system of vessel traffic in the water area and increase the safety of navigation.

The research aims to enhance maritime navigation quality and safety by developing autonomous navigation systems that mitigate the negative impact of human factors through advanced software and hardware integration with servers and onboard controllers.

Main research material. To obtain new scientific solutions, build innovative integrated systems of human-machine interaction in the ergatic systems of maritime and inland water transport of Ukraine in the KSMA was established research laboratory "Development of decision support systems, ergatic and automated control systems for vessel."

The main task of the research laboratory is to conduct a set of scientific research related to the creation of latest automated control systems for vessel traffic and minimize the impact of human factors on these processes.

In the framework of the agreement with the Ministry of Education and Science of Ukraine for 2021 provides for the development of material and technical base of research laboratory and conducting on its basis a number of studies related to improving models and methods of vessel traffic control in divergence and maneuvering to mitigate negative consequences of human factors on vessel control processes.

The development of the material base of the research laboratory, its facilities with equipment for simulation and field simulation, provided a solution to a number of problems aimed at developing a simulation stand using information signals navigation Navi Trainer 5000. This allowed mathematical and software processing of signals from navigation sensors for the system of automated control of movement of vessels in difficult navigational conditions.

An important component of the successful application of new approaches and scientific ideas was the development of appropriate mathematical software for modules of automated control of vessel traffic with their subsequent use in identifying the risk of vessels collisions. This approach allowed the use of optimal programs of divergence and complex maneuvering, avoiding the manifestation of the human factor of captains [11, 12], but performing, at the same time, control functions under the general control of the navigator. In this case, the captain receives effective means of optimal control of the vessel's movement and has the opportunity in real time to choose the time of application of the appropriate automated modules at its discretion according to their qualifications.

All this allowed to develop a multi-module DSS, which comprehensively performs the task of identifying the navigation situation, calculated analysis of collision risks, by analyzing the positions of vessels and vectors of their relative motion, as well as models of human-machine interaction.

To obtain the results of scientific research carried out in the laboratory, the research was conducted in the following areas:

– research and development of decision support systems;

– research and development of automated vessel traffic control systems;

– research and development of ergatic systems in vessel control;

– use of navigation simulators, simulation stand modelling for research and development of these systems;

– study of the negative impact of human factors on the safety of traffic control.

The designated research directions of the laboratory are focused on comprehensive maintenance of navigation safety through the use of automation and the latest information technologies. This includes the development of decision support systems, automated vessel traffic control systems, ergatic systems in vessel management, the use of navigation simulators for research and development of these systems, and the study of the impact of human factors on traffic control safety.

The primary research focus of the laboratory is the development of automated systems and field models of vessels, which provide scientific data and results to enable maneuvers without human intervention, enhancing the accuracy and reliability of operations. These developed systems are also aimed at optimizing vessel traffic control and reducing the negative impact of human factors on this process. [13].

The research laboratory's work was focused on combining three key aspects: identifying the negative manifestation of the human factor and implementing the functions of the navigator's decision support system. Additionally, the laboratory emphasized the transition to automatic control of vessel traffic to prevent accidents and emergencies in maritime transport.

The automated systems being developed involve the use of an on-board computer with modular software focused on performance of individual functional tasks, the number of which can be scaled as required, as determined by modern control vessels practices. In this direction, work is already underway to create mathematical, algorithmic and software automatic separation module for many purposes, including maneuvering, module to increase the reliability of the vessel's traffic control system, module for optimal maneuvering in narrows and channels using the vessel's center of rotation and Pivot Point, management of redundant structures of executive devices.

An important area of the research work laboratory is software and hardware interaction with ECDIS and AIS servers, which will provide the full range of navigation data for multi-stage disaster forecasting, taking into account weather conditions.

The creation of a simulation stand as a research task, as well as further development of programs for the on-board controller of full-scale vessel models provides continuous monitoring of command devices and actuators by comparing the measured parameters of the vessel with their estimates in the virtual environment of Navi Trainer 5000 and during field experiments on water.

In the future, in addition to vessels with traditional control, research will be conducted to develop a module for optimal control of redundant structures of actuators used on military vessels, passenger vessel, special purpose vessels, platform support vessels and the platforms themselves. Redundant structures can be used to optimize control processes according to the selected target function. This makes it possible to improve traditional manual redundancy and increase the reliability of actuators and the maneuverability of vessel. However, redundant structures are also expected to be used for optimized control processes.

The focal point of the research laboratory's work is the development and application of a simulation stand based on the navigation simulators of the Kherson State Maritime Academy. This stand is created by integrating system units with information exchange software and the software of functional modules of the traffic control system into the local area network of navigation simulators. The developed simulation stand is aimed at developing and testing mathematical software for vessel traffic control systems using all the capabilities of training equipment (models of different vessels, targets, navigation equipment, sailing areas, weather conditions and equipment failures). Multi-parameter analysis of navigation data in real time with a discrete step in a split second allows you to form management decisions without delay.

The accumulated base of field experiments over several years of operations and maneuvers by navigators on navigation simulators allows to ensure high accuracy of data processing by nonlinear multiparameter mathematical and software tools, which increases the accuracy of decision support systems, their proximity to real conditions and reliability.

The relevance and choice of the proposed scientific approaches is supported by a number of modern studies of both domestic and foreign scientists. The difficulty of these studies is that the vessel has its inertia, according to its mass and length, and therefore the time to the nearest approach point (TCPA) is changing dynamically and navigation simulators are not able to fully convey all the physics and realism of processes. This makes it necessary to use models of vessel to be made using 3D printers, as provided in the research laboratory.

The plan to create a detailed and functional 3D model of a ship using SolidWorks:

1. Analysis of Theoretical Drawings
Tools: Use 'Sketch' for initial outlines based on drawings.
Commands: 'Import' for bringing in the factory drawings.
Functions: 'Measure' and 'Dimension' tools for accuracy.
2. Formation of 2D Contours
Tools: '2D Sketch' for creating the initial hull contours.
Commands: 'Convert Entities' to transfer 2D sketches into workable profiles.
Functions: 'Offset' and 'Trim' for adjusting and refining contours.
3. Creation of a 3D Base Surface
Tools: 'Surfaces' for generating the hull's 3D base.
Commands: 'Lofted Surface' for complex shapes.
Functions: 'Reference Points' for accurate spatial form creation.
4. Designing the Complex Surface of the Hull Bow
Tools: '3D Sketch' and 'Surface Tools' for the hull bow.
Commands: 'Swept Surface' for complex curved surfaces.
Functions: 'Cutting Planes' for detailed shaping.
5. Hull Modelling and Shaping Operations
Tools: 'Extrude', 'Revolve', and 'Sweep' for main hull shaping.
Commands: 'Shell' for hollowing out sections.
Functions: 'Fillet' and 'Chamfer' for smooth edges and transitions.
6. Formation of the Longitudinal Contour
Tools: 'Solid Bodies' for creating the main structure.
Commands: 'Boolean Operations' for subtracting and adding geometries.
Functions: 'Combine' for merging different parts.
7. 3D Modelling of Deck Superstructures
Tools: 'Assembly' for putting together different segments.
Commands: 'Mates' for aligning and positioning components.
Functions: 'Pattern' for replicating similar structures.
8. Combining Elements into a 3D Assembly Model
Tools: 'Assembly Modeling' for combining all ship components.
Commands: 'Insert Component' for adding individual parts.
Functions: 'Interference Check' for ensuring no parts clash.
9. Direct Production and Control
Tools: '3D Printing Prep' for preparing the model for printing.
Commands: 'Export to STL' for 3D printing compatibility.
Functions: 'Simulation' for testing the model's performance.

Creating a model MSC container vessel for field modelling. As part of the research laboratory "Development of decision support systems, ergatic and automated vessel traffic control systems" in 2021 was developed the 3D parametric model of the container vessel MSC Panaya Drawings according to accurate factory drawings (Fig. 1).

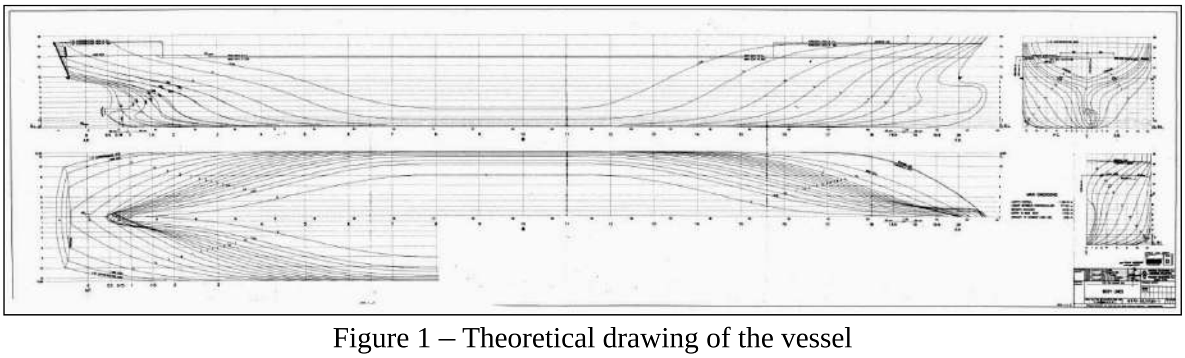

Figure 1 – Theoretical drawing of the vessel

Theoretical drawings of the vessel were analyzed and 2D contours of its hull with step-by-step transfer of mid-frames to 3D shape were formed (Fig. 2).

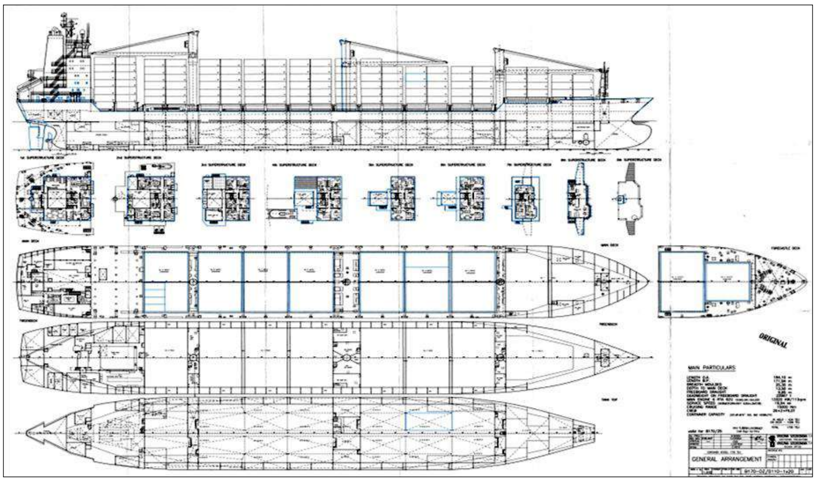

Figure 2 – Formation of the main geometric bases for 3D modelling

Having received the main contours of the vessel, it became possible to form a three-dimensional base surface of the hull. The geometry of the main forming surfaces and the number of reference points for the formation of spatial forms were taken into account (Fig. 3).

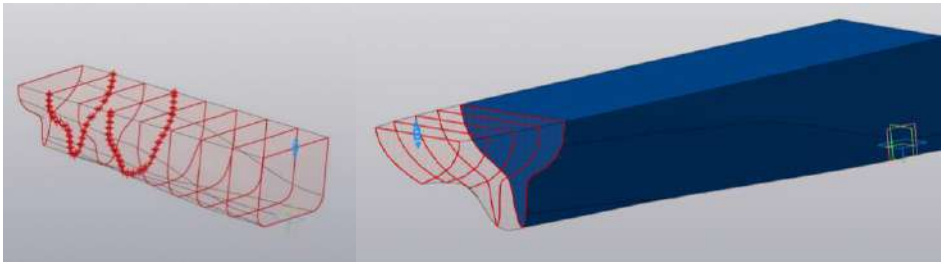

Figure 3 – Formation of the hull model in space

The complex surface of hull bow with the pitch and cutting planes is designed, which allows to most clearly define the complex spatial surface (Fig. 4).

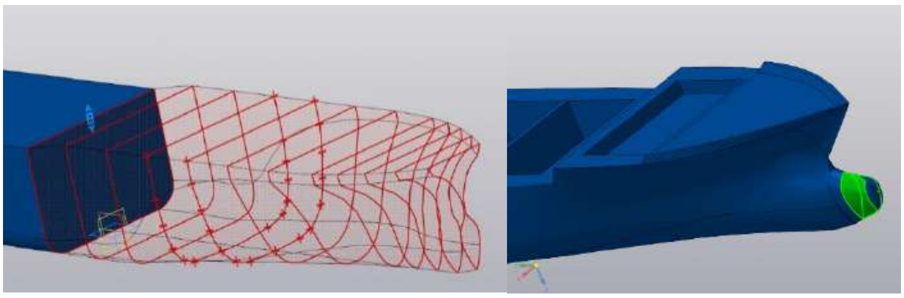

Figure 4 – Formation of the vessel bow

Hull modelling also involved a number of shaping operations (Fig. 5). As a result, the basis for the location of rudder pen and the inner propeller shaft was made.

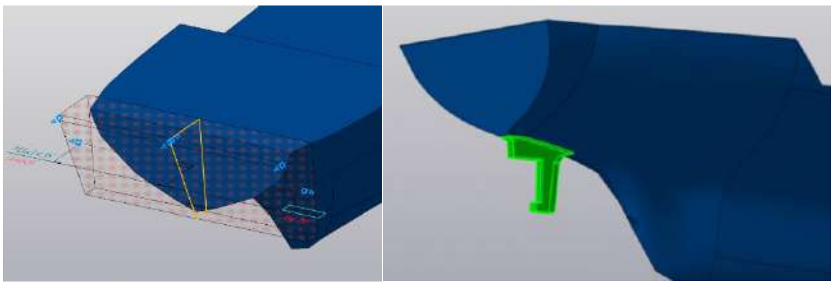

Figure 5 – Formation of the stern of the vessel

The next stage was the formation of the longitudinal contour of vessel as a solid object. Boolean subtractions were made from the surface of hull to build holds.

The next step was to perform 3D models of deck superstructures. The formed vessel segments have structural holes for stacking them and reproduce complex geometric shapes with high accuracy (Fig. 6).

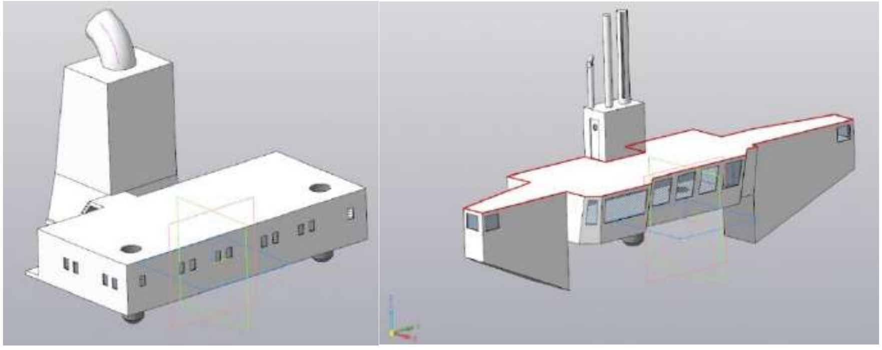

Figure 6 – Stages of deck superstructures formation

Subsequent segmental creation of the superstructure and other elements of the vessel allowed them to be combined into a 3D assembly model of the vessel (Fig. 7).

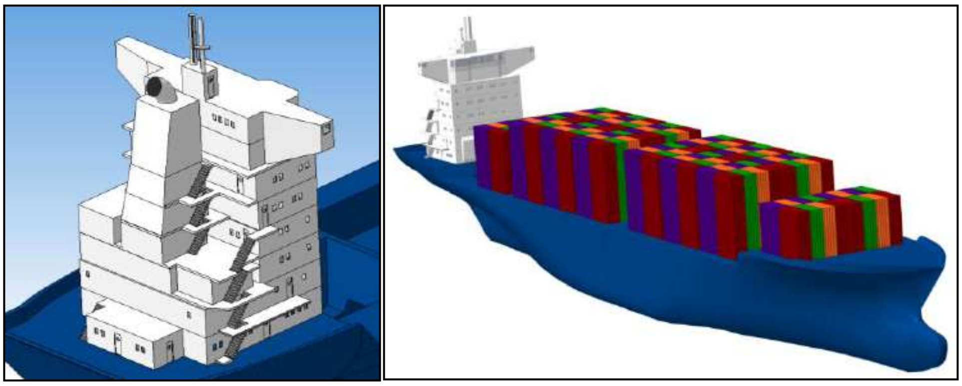

Figure 7 – Creating a 3D assembly model of the MSC Panaya Drawings

Built 3D parametric models allow you to go directly to the production of original model vessel using the latest information technology to control its movement.

Printing 3-D model of the MSC vessel. The designed 3D models of vessels were exported to Ultimaker Cura and the printing parameters and corresponding settings were determined (Fig. 9).

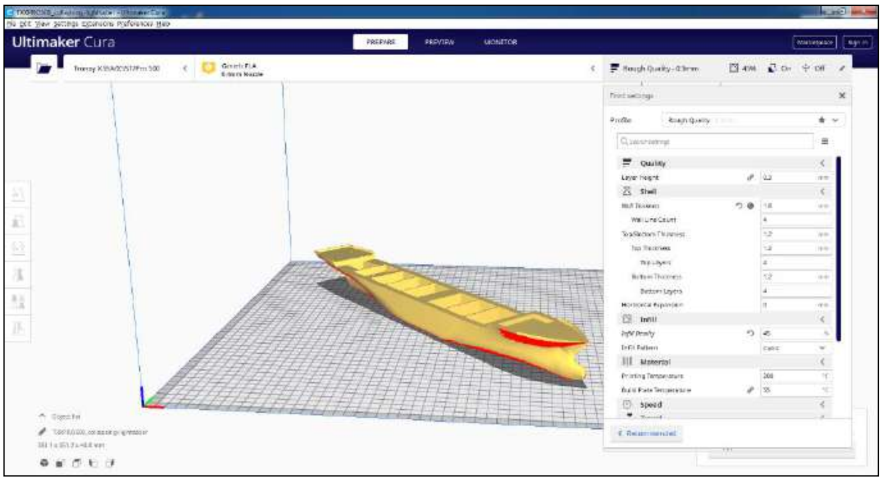

Figure 9 – Configuring print settings in Ultimaker Cura

The obtained indicators of vessel model made by 3D printing allowed to obtain control software trajectories (Fig. 10).

In order to print certain parts of spatial physical model of the vessel, a 3D printer was purchased – Tronxy 500 pro (Fig. 11). The main feature of this printer is that it allows you to print components of vessel models of a sufficiently large size. This 3D printer was purchased for the needs of laboratory.

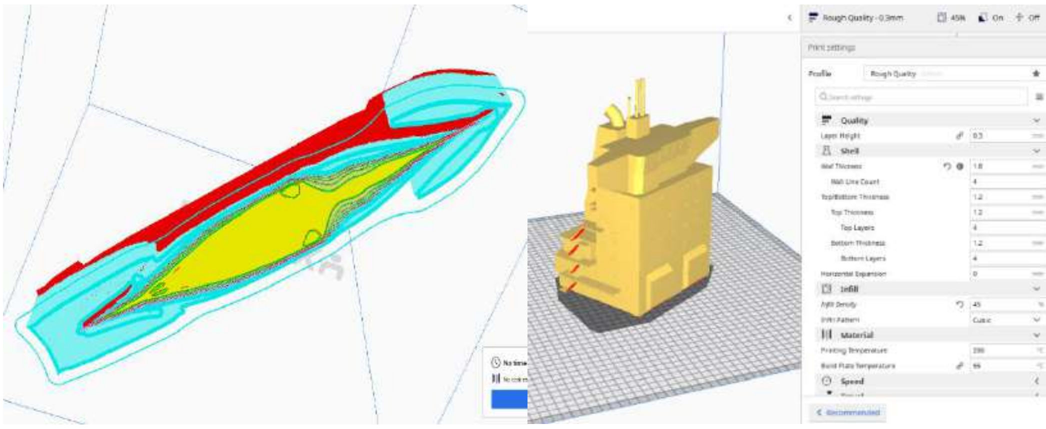

Figure 10 – Formation of the executive path for 3D printing (G-code)

The dimensions of printed components of the vessel allow for electronic means to control and determine its own position relative to other target-vessels.

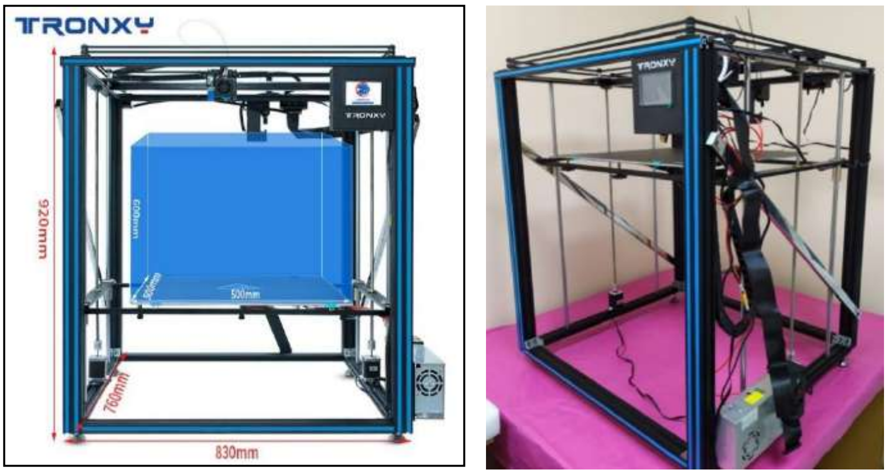

Figure 11 – Schematic and full-scale image of a 3D printer

The dimensions of vessel model components during 3D printing are sufficient to print the hull in 4–5 approaches and several approaches (5–9) for other elements of the 3D model (Fig. 12).

Figure 12 – 3D printing processes of vessel models

The 3D model control system is used for creating detailed vessel models with actuators and onboard controllers. The use of PLA plastic for 3D printing with a diameter of 1.75 mm, which is sufficiently resistant to water, temperature, its physical and mechanical properties has significantly improved the durability and reliability of the 3D model.

To create physical models of vessels, equipped with actuators and on-board controllers, necessary equipment was purchased for field modeling of vessel traffic. Vessel models, created on a

3D printer, are equipped with an automated control system including sensors and mini-controllers. (Fig. 13).

a *b* *c*

Figure 13 – A set of equipment for the current assembly of 3D vessel model:
a – transmitter/receiver; *b* – servomechanism; *s* – propeller

These models are valuable for testing complex navigational scenarios in field experiments, offering control visibility and cost-effectiveness.

Implementing these approaches in field research is crucial for forecasting and preventing maritime accidents. The next step is analyzing the feasibility of autonomous navigation technologies, particularly for smaller vessels (up to 1.5–2 meters). This involves examining sensors, algorithms, control systems, communication infrastructures, and interfaces, and adapting them to small vessel specifications.

A high-quality navigation system is essential for the proposed model, with sensors providing critical environmental data. The GPS system ensures precise location detection, essential for tasks like maneuvering and rescue operations. Autopilot systems offer enhanced navigation precision, distance coverage, and operation under challenging conditions. These systems are characterized by safety, obstacle avoidance, and efficient navigation in complex zones [21].

The radio-controlled model used the FS-i6X transmitter and the FS-iA6 receiver. The FS-i6X Transmitter, designed for remote control of vessels, offers stable connection and compatibility with multiple simulators. The FS-iA6 Receiver receives signals and controls the vessel model's servomechanisms [22]. Key features include stability, flexibility, and quality reception.

After configuring the radio control system, the model was waterproofed, ensuring operation within a 500 to 1500 meters range. Maneuverability was enhanced by additional channels in the FS-i6X. All components, including motors and sensors, were chosen for compatibility with the control system [23].

PID controllers were applied for stabilization and maneuverability, with a graphical interface displaying PID settings, maps, and diagnostic information. The vessel model's interaction with the marine environment and weather conditions was also considered vital. Research in real conditions, simulating scenarios, and testing control systems refine the model's operation, ensuring reliability and safety.

The radio control system's main components were scrutinized for compatibility and functionality. Integration with the controller and practical tests were conducted under various conditions. The ATMega2560 microcontroller was analyzed for potential integration of additional devices, alongside sensor testing and software ergonomics evaluation [24].

Development of autopilot systems for ship models, particularly those up to 2 meters, focused on compact sensors and algorithms. LIDARs, sonars, and miniature cameras were deemed essential, along with adapted trajectory planners and stabilization systems. Communication systems for data exchange and compact GPS modules were integrated, with wireless interfaces for interaction [25].

Therefore, the main aspects include the use of modern 3D printing for the development of vessel models, the integration of complex control systems, including sensors, PID controllers, and radio control. Besides the technical details, it is important to ensure practical testing and optimization for the safety and efficiency of the models. This approach has allowed for obtaining more accurate data for prediction and prevention of accidents in natural experiments.

Conclusions

The research aimed at developing autonomous navigation systems for maritime vessels primarily focuses on minimizing the negative impact of human factors in vessel management and fostering efficient software and hardware interaction with servers and onboard controllers. The methodology involves developing modules for refining management processes, creating simulation stands, and designing detailed 3D models, such as the MSC Panaya container ship.

Significant achievements include the creation of a detailed 3D model of the MSC Panaya, using advanced 3D printing technology and PLA plastic. This enabled the construction of physical models ready for field testing. The models, equipped with radio control systems, were made waterproof, maneuverable, and compatible with various components, functioning up to a distance of 500 meters. The application of PID controllers was crucial for stabilizing the vessel under diverse weather conditions. The research also explored approaches to optimize hardware components, including microcontrollers, sensors, and software.

Development of autopilot systems was a key focus, especially for ship models up to 2 meters, incorporating compact sensors like LIDAR, cameras, and sonars. Communication systems and integrated GPS modules were also considered vital for simplifying navigation and interaction.

The practical contribution of this study is reflected in the development of comprehensive technical solutions for optimal interaction of the ship model with aquatic environments. Experimental testing in real conditions and modern control systems have enhanced the efficiency and reliability of the model's operation.

Thanks to the developed complex, cadets were able to practice the main and most complex maneuvers regarding ship motion control in a real-world setting. It was determined that the speed of performing maneuvers on simulators increased by 11%. Additionally, obtaining terminal reactive indicators, individually tailored to each navigator, covered up to 63% of all operations. The limits of controllability of ship models were also identified, and conditions were determined in which it was proposed to switch to automatic control, which in 9% of cases prevented critical situations that could lead to the cessation of traffic in straits.

Future research prospects include further refinement of these technical solutions and their adaptation to real ship systems, thereby advancing the fields of maritime navigation and autonomous vessel control.

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РОЗРОБКА ТА 3D-ДРУК МОДЕЛЕЙ СУДЕН ДЛЯ СИСТЕМ АВТОМАТИЗОВАНОГО УПРАВЛІННЯ РУХОМ

Мета дослідження полягає у підвищенні якості та безпеки морської навігації шляхом розробки автономних навігаційних систем, які пом'якшують негативний вплив людського фактору за допомогою розширеної інтеграції програмного та апаратного забезпечення з серверами та бортовими контролерами.
Ключовою проблемою, яка стоїть перед дослідниками, є мінімізація потенційно негативних наслідків людського фактору в контексті управління судном, а також розробка ефективних механізмів взаємодії програмного та апаратного забезпечення із серверами та бортовими контролерами.
У методологічному плані дослідження передбачає: а) розробку модулів для удосконалення процесів управління; б) створення симуляційних стендів для комплексного дослідження; і в) дизайн деталізованої 3D моделі контейнеровоза MSC Panaya.
Основні результати нашого дослідження полягають у розробці детальної 3D моделі контейнеровоза MSC Panaya, що створена на основі заводських креслень. З використанням передових технологій 3D друку та пластику PLA, вдалося створити фізичні моделі, готові до польового тестування запропонованих технічних рішень. Після вибору та налаштування радіокеруючої системи для моделі судна, було забезпечено її водонепроникність, маневреність та сумісність з іншими компонентами. Використовуючи обрану радіокеруючу систему, модель могла діяти на відстані від 500 метрів. Важливістю є застосування PID контролерів, які допомагають стабілізувати судно в умовах змінних погодних умов та морських течій. Додатково було вивчено підходи до оптимізації апаратних компонентів, включаючи мікроконтролер, сенсори, а також відповідне програмне забезпечення. Зробивши акцент на розробці автопілотних систем для моделей кораблів розміром до 2 метрів, було виявлено, що компактні сенсори, такі як LIDAR, камери та сонари, можуть бути особливо корисними для таких моделей суден. Крім того, системи комунікації, а також інтегровані модулі GPS, можуть спростити навігацію та взаємодію.
Практичний внесок дослідження виявляється в розробці та впровадженні комплексних технічних рішень, які спрямовані на оптимальну взаємодію моделі судна з акваторією, враховуючи динаміку погодних умов та особливості морської навігації. Експериментальне тестування в натуральних умовах та сучасні системи керування дозволили збільшити ефективність роботи моделі. Перспективи подальших досліджень передбачають додаткове удосконалення технічних рішень та їх адаптацію до потреб реальних судових систем.
Ключові слова: *автономні навігаційні системи; людський фактор; ECDIS/AIS; 3D моделювання; радіокеруюча система; PID контролери; морська навігація.*

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