Concept for Construction of Unmanned Ferry Lines on Russia’s Inland Waterways

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Abstract. This article considers the prospects of building highly automated ferry lines on the internal waterways of Russia. To do this, the authors used the engineering-cybernetical approach to determine the basic provisions of the concept for the construction of unmanned ferry lines. The key provisions of the concept account for the integration of unmanned ferry lines in the river information and communications triad based on the hierarchical principle: the corporate river information and communications service - the river information service - the automated ship-traffic control system. The authors consider the prospects of using unmanned ferry lines on rivers where the navigation and information support for the unmanned ferry can be provided using radio technical facilities covering both the points of departure and destination. The authors also reviewed the arrangement of unmanned ferry lines for situations where the departure point and the destination are far from each other. This type of unmanned ferry line is suitable for reservoirs or large lakes.

Finally, the research work also provides a rationalization of the selection of the automation level for unmanned ferry lines following the terminology used by the work team for inland water transport of the Committee for the Inland Water Transport of the UN Economic Commission for Europe (UNECE).

1. Introduction

Currently, unmanned vessels are put to use in the water transportation sector all over the world [1-3]. This trend is evident in Russia’s water transport as well. The Central Commission for the Navigation of the Rhine (the world’s oldest international organization established in 1815) developed and approved the first international definition of the automation levels for inland navigation. It comprised 5 levels: from steering assistance (level 1) to complete automation (level 5, full autonomy) [4, 5]. These definitions were supported on the European level by the work team for inland water transport of UNECE. Russia (RF) is also developing a concept for unmanned navigation that is know as the A-navigation concept [6]. This concept is designed to create a uniform autonomous ship navigation safety system for Russia’s water transportation sector that would be based on modern technology, as well as digitalization, navigation, communications, artificial intelligence, and other solutions.
The creation of unmanned and self-piloted ferry lines for the inland waterways (IWW) of Russia is one of the most promising aspects of autonomous navigation deployment. It is made relevant by the great number of ferry lines on navigable rivers and lakes of Russia and large maintenance personnel.

Currently, the IWW of Russia have over 150 ferry lines in operation that cross the navigation pass, and the majority of them operate day and night. According to the preliminary assessment, the number of maintenance personnel and ferry crews can exceed 2500 people. Ferry lines have difficulties finding skilled employees as the regions with the most ferry lines on the IWW of Russia have poor infrastructure and thus are not very desirable for living.

Thus, we deem it feasible to increase the degree of automation of ferry lines on the IWW of Russia based on the A-navigation technologies, as well as modern digital and information technologies, and advanced precision navigation solutions. In this case, it is possible to improve the efficiency and reliability of ferry lines and reduce the impacts of human factors on the safety of navigation on the IWW of Russia.

Ferry line automation allows us to view them as a system. The first stage of creating any system is the development of a concept for its optimum structure. This is what we focused on in this research.

2. Methods and materials

To develop the concept for the construction of an unmanned or self-piloted ferry line, we used the methods based on the engineering-cybernetical approach to the design of complex systems [7, 8].

According to this approach, the designed system is reviewed as part of a complex hierarchic system rather than independently. The concept of a metasystem is used for the upper level of the hierarchy.

Concept research is required for the description of the key properties of the system designed. This requires to separate the system from the metasystem and rationalize its occurrence and properties determining the potential efficiency if the global goal of creating the system is achieved. To solve this problem, we need to describe the external complement.

The engineering-cybernetical methods are based on research hypotheses. These hypotheses are brought up when studying the metasystem because it is only possible to obtain a theoretical comprehension of a lower-order system's behavior at the metasystem level.

The proposed system behavior hypotheses are a component of the external complement of the metasystem that coordinates the system’s goals and behavior and the goals of metasystem activities. Thus, the external complement eliminates the arbitrary selection of system behavior rules being a logical closure that facilitates the high efficiency of the system in question.

This requires the selection of a rational system structure option so that the potential efficiency of this system in operation to achieve the goal would be at the highest. The concept research ends with the formation of rational requirements for the system that are based on detailed research of technical and techno-economic parameters.

The efficiency of a complex system is understood as the most common property that is exposed through the category of goal and can be objectively assessed by the degree of its accomplishment taking into account the resource and time inputs [9].

Theoretical research activities focusing on the improvement of operational efficiency of systems can be divided into three classes depending on the problems they solve:

- developing structure and resource distribution options that would cover the highest potential needs (needs exceed resources);
- developing the system structure that would provide the most opportunities with the given resources (resources and needs are equal);
- minimizing resource consumption while covering the needs (resources exceed needs).

The selection of a specific efficiency improvement option for the designed system will depend on the goal-setting assessment of the metasystem.

To solve this problem, it is necessary to review the external and internal factors characterizing the operating conditions of the system. They can be divided into three groups:
factors determining the operating conditions of the systems (weather and climate condition, geographic location, availability of resources, state of infrastructure, operational restrictions, and the possibility of deliberate counteraction);
- system application methods (control methods, communication methods between elements, task and resource distribution among elements, the spatial and temporal sequence of works);
- system properties (resilience, controllability, capabilities, self-organization).

First of all, all of the factors are classified as uncontrolled, i.e. independent of the person making decisions, and controlled, i.e. the ones that designers may change as they will. The factors from the first group above are uncontrolled. The factors from the second group characterize the system's structure and application methods to implement key processes. The factors from the third group determine the quality of the system.

For the analysis of system efficiency, four different methodological levels of system analysis are introduced.
- Level I – composition-properties (elementary);
- Level II – structure-functions (aggregative);
- Level III – organization-behavior (systemic);
- Level IV – metasystem-activity (metasystemic).

The engineering-cybernetical approach combined the research of the second, third, and fourth methodological levels conducted during the organizational stage of problem-solving.

At the aggregative level, research activities focus on the operations conducted within system functions. The systems of this level usually have a simple structure and are viewed as the subsystems of the system designed.

At the systemic level, the research is focused on the designed system itself. This level deals with the efficiency of the system.

At the metasystemic level, the research focuses on global systems including the organizational and technical systems and their external environment.

Thus, this approach is based on the idea that the third-level system should be analyzed as an integral part of a metasystem rather than independently. The quality of the system in question is not only attributed to the properties of this system but the properties of the metasystem as well.

3. Results

We will review the operation of the information and communications system at the metasystem level. This is an upper-level system (metasystem) of the designed unmanned or self-piloted ferry line (UMFL). We will also see the role and the place of the UNFL in its structure.

The mentioned requirement for the improvement of navigation safety and efficiency on the IWW led to the requirement for the deployment of modern information and communications technologies in Russia to create the base for the deployment of the information and communications triad: the corporate river information service (CRIS) - the river information service (RIS) - the automated ship-traffic control system (ASTCS) [10].

The concept of River Information Services (RIS) is used on the IWW of the European Union, the USA, and some countries of South America. Its key component is the Vessel Traffic Service (VTS) [11].

The key functions of CRIS include providing the safety of navigation in transport corridors or different basins on Russian IWW, the creation of a uniform information and communications space involving all of the transportation process participants, facilitating the operation of the information and communications triad based on the hierarchy of CRIS-RIS-ASTCS.

RIS on the IWW of Russia are deployed using the basin principle. They are used to provide skippers, ship owners, and IWW basin administrations with a standard set of information services facilitating safe and economically efficient navigation and environmental protection.

ASTCS are responsible for navigation safety in their area of operation, traffic control, and provision of navigation and weather data to skippers.
River ASTCS do not cover all of the IWW of Russia. They only operate on some sections that are difficult to navigate. This, UMFL design shall take into account that some vessels will be subjected to ASTCS, and some will not. Therefore, the metasystemic requirements for the designed system will have some differences as well.

The common requirements to the designed AFL from both RIS and ASTCS will include the following:
- facilitating the reliable operation of ferry lines in the set mode;
- maintaining navigation safety in the area of UMFL operations at the current level or higher;
- providing the cyber security of the operations to prevent unauthorized access and control of the UMFL.

Besides, when UMFL operate under ASTCS, a radio channel must be created to exchange information between the subsystems of the UMFL that would not interfere with the existing ASTCS radio channels.

In both cases, the existing RIS will serve as the UMFL metasystem because the RIS personnel can provide control, maintenance, repair, and logistical support of autonomous ferry lines.

At the systemic level of conceptual research, we reviewed the classification of ferry lines, the arrangement and behavior of UMFL, and their efficiency criteria.

Synthesizing an optimum UMFL is a problem whose solution requires the development of system structure options where the set goals are accomplished by the establishment of the optimum structure that would cover all needs with minimum resource consumption. Resources, in our case, include the number of specialists maintaining the system, the number and cost of data sensors, processors, and the interface connecting them, the required frequency range, the volume of traffic between system components, etc.

Thus, the efficiency criterion for the designed system is the minimization of resources spent on the arrangement of a UMFL.

The efficiency of the designed UMFL depends significantly on the design of the ferry crossing and the area where the UMFL is going to be used.

Figure 1 shows a typical IWW ferry line arrangement. A ferry crossing consists of the following: 1 – ferry landing; 2 – ferry; 3 – tug boat (used with dumb ferries).

IWW UMFL can be classified by their navigation areas as river and lake lines. Lake lines are more difficult in terms of arranging an AFL because they are much longer (about 40-50 km), which creates problems with the creation of radio channels for AFL control and management. In this situation, the most efficient UMFL arrangement option is the 2nd level of automation (partial automation) because the 3rd level of automation (remote control) may prove economically unfeasible due to the significant expenses associated with the establishment of reliable visual control, management, and telemetry channels.

Currently, there are not many such ferry lines. They include the following services: Petrozavodsk - Kizhi on Onega Lake; Ploiești - Konevets Island, Ploiești - Valaam island on Ladoga Lake, Sakhyurta - Orkhon on lake Baikal, Puchezh – Sokolskoye on Gorky Reservoir. The majority of ferry lines are river crossings of 0.1 – 2 km long.

In Russia, various ferry crossing designs are used for the transportation of goods and passengers across rivers, lakes, and reservoirs.
Figure 1. A typical IWW ferry line arrangement.

River ferry crossings are divided into cable-driven and cable-free crossings. In cable ferry crossings, the dumb ferry vessel moves along the cable or a chain strained across the river course (Figure 2). In this type of crossing, ferries can be moved manually using chain or cable winches installed on the hull of the ferry or tug boat, or by the river current.

Figure 2. Cable-driven ferry crossing (1 – jetty; 2 – ferry; 3 – cable).
Cable-free ferry crossings can be divided into two types depending on the type of vessel used: motor ferries or dumb ferries. For each type of ferry crossings, there are different arrangement options. Based on the suggested efficiency criterion for the designed system, cable-driven crossings should use the 5th level of automation (complete autonomy). For cable-free crossings with motor ferry vessels, the 3rd level of automation (remote control) is more feasible. Taking into account the conceptual analysis performed, cable-free motor-ferry crossings, which make up the majority of crossing on Russia’s IWW, can use the extended UMFL arrangement shown in Figure 3.

![Figure 3. Extended UMFL arrangement for rivers.](image)

The system comprises the operator’s control desk with the control and management module, on-shore control facilities (on-shore radars and automatic identification system, VHF radio station, video surveillance system) connected to the control desk via ground-line communications, jetties, and the ferry boat with the control module and navigation sensors, as well as the data processing and transmission module. This arrangement also requires reliable and protected operator-ferry-operator communications to receive telemetric data and send control commands. Besides, positioning precision during ferry movement must be at least 1-5 m. To achieve this, we can use the correction signals from the differential river subsystem of GNSS GLONASS/GPS transmitted over the range of 283.5-325.0 kHz by the control and adjustment station. To facilitate safe ferry mooring, it is necessary to use on-shore video surveillance and radar monitoring system. The precision of navigation positioning in this mode must be 10 cm or higher. TO achieve this, we can use the local real-time kinematic systems (RTK).

Both cable-driven and cable-free automated ferry crossings must include a signaling system that would promptly warn skippers that they need to slow down or stop because the ferry is running ( semaphore).

At the aggregative level of the concept research, we reviewed the key operations performed by UMFL and their subsystems. The key operations include cargo loading/unloading and passenger boarding/drop-off, mooring, maneuvering when moving to and from the jetty, moving along the set route, and navigation safety.
control. Therefore, UMFL should comprise a navigation safety control subsystem, a movement control subsystem, and a maneuvering and mooring subsystem.

4. Discussion

The operational mode of ferry lines is determined depending on the intensity of waterway traffic. The technical operation of ferry crossings is carried out by on-shore maintenance personnel. The operation of a ferry line requires the following set of employees: 1 ferry line manager, 1 mechanic per each shift, 1 engine fitter, 1 welder, 1 carpenter (if wooden structures are used), 1 worker, and 1 technician. Ferry vessels are currently staffed to perform the following functions: watchkeeping, vessel and mechanism control, required monitoring, passenger safety control, vehicle placement and bracing, mooring, etc. depending on the parameters of the boat and the rated data on the number of crew members on watch. The Regulation on the Minimum Manning of Motorized Transport Ships is used to determine the number of crew members for vessels used in ferry crossings. The crew of motorized ferries must contain a skipper-mechanic (with alternate skippers and mechanics for different shifts), 2-4 sailors depending on the freight-carrying capacity of the ferry, and the loading/unloading methods used on it, etc. For tugboats, the crew must have a skipper-mechanic (alternate skippers and mechanics for different shifts), and 1 sailor. Dumb ferries must have a skipper (alternate skippers for different shifts), sailors (road workers): 2 people for ferries carrying up to 80 tons, 3 people for ferries carrying between 80 and 300 tons, and 4 people for ferries carrying over 300 tons. To arrange a ferry line operating 24 hours a day, it is necessary to have 2-3 shifts.

Therefore, to operate a 24-hours motorized ferry line, the number of maintenance personnel and ferry crew may reach 28 people. Thus, the transition of UMFL may have a significant economic effect in many cases.

There are 20 cable-driven ferry crossings in the UDWS of European Russia and the rivers of Siberia and the Far East, which is 14% of the total number of various crossings. We suggest using the 5th level of automation for them because this will only require the creation of an automated mooring subsystem. Thus, the automation costs will be at the minimum, and the efficiency of UMFL deployment compared to manual controls will be the highest.

At the same time, cable-driven ferry crossings should not be used on rivers with ship traffic or rivers that are wider than 100 meters. The use of this type of ferry crossing on rivers that are wider than 400 meters is unfeasible.

For cable-free motorized ferry crossings of 2 km long or less should have the 3rd level of automation because it is easy to create reliable telemetry, visual control and management channels is easy in this case. At the same time, full automation will require significant costs, which does not satisfy the key efficiency criterion of the designed system.

The selection of 2nd or 3rd level of automation for cable-free crossings with dumb ferries requires additional research because we are uncertain whether the combination of a tug boat and a ferry can comply with the requirement for maintaining the current level of navigation safety under the remote control mode.

The ferry line operator needs a VHF radio station to exchange information with the vessels passing by or with control center dispatchers if the crossing is located in an area controlled by the ASTCS.

The control desk for the UMFL must be located so that it would provide the reliable information exchange between the elements of the UMFL and the components of upper-level systems. The control desk of UMFL must be able to run operator authentication algorithms to prevent unauthorized access to the UMFL. Besides, if the IWW basin with the UMFL is controlled by an ASTCS or a RIS, higher-level systems must receive information about the UMFL operations. ASTCS must receive the dynamic data on ferry movement in real-time, as well as the telemetric data on the state of the power plant and the key systems of the ferry. RIS may require only the schedule and the operating mode of the UMFL.
5. Conclusion

The introduction of UMFL requires the availability of on-shore support infrastructure. Some elements of this infrastructure can be found on some of the river basins in the UDWS of European Russia. They include the network of control and adjustment stations of GNSS GLONASS/GPS, on-shore VHF radio communications networks, and automatic identification systems. In the future, we may consider using the Russian wide-area satellite augmentation and monitoring system to facilitate precise positioning. The introduction of UMFL will also require the development of suitable boat designs, as well as amending the existing and preparing new regulatory documents.

Despite the obvious problems with development and introduction, unmanned ferry lines remain a promising concept of inland water transportation, and they are going to take a fair share of river traffic.

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