Decision Support System for the Safety of Ship Navigation Based on Optical Color Logic Gates

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Abstract

This work is devoted to the creation of effective optical-logical systems based on the use of light emitter of a certain color as a fuzzy variable - a carrier of logical information and the basis for constructing logical solutions by converting light radiation by appropriate light filters. The basic principles of optical transformations used in the construction of fuzzy logical gates (coloroids of various types) are considered. A multifactorial knowledge base is proposed for assessing the safety of navigation in conditions of limited water areas, the structures of logical optical coloroids. A two-stage decision support system for controlling vessel traffic is synthesized using the example of a shipping channel Lyman Rybosol.

Keywords [1]

decision support system, safety of ship, fuzzy logical gates, optical coloroid, light color filters.

1. Introduction

The analysis of modern ship control problems in conditions of increasing shipping intensity confirms the need to develop and improve hierarchically organized systems of automated ship traffic control. The structure of such systems should be based on a reasonable combination of the advantages of the capabilities of a human operator and an automatic control system. One of the promising ways to improve the efficiency of automated ship traffic management systems is the creation of human-machine decision support systems (DSS) [1-4] for the implementation of a safe movement trajectory in the conditions of the occurrence of non-standard scenarios and the impact on the ship of intensive random external disturbances.

Currently, it is impossible to solve the problem of creating a high-quality control system without taking into account the human factor [14]. A skilled human operator or a team of experts can replace a highly advanced and cost-effective system that can also cause a technological failure. At the same time, unqualified actions of a human operator can also lead to catastrophic consequences, blocking the necessary reactions of the automatic control system. It is obvious that the solution to such a complex technical task of ship control consists in finding a technological compromise and effective interaction between human operator and system. The development and improvement of software-algorithmic and hardware support systems for decision-making based on new methods, algorithms and approaches will significantly increase the level of maritime safety, taking into account insufficiently formalized factors, random disturbances and non-standard situations.

Statistical data on the accidents of the marine fleet emphasize the dominant influence of the human factor, in particular the psychophysical state of the human operator, on the safety of navigation and demonstrate the expediency of conducting scientific research in the field of improving human-machine systems. In the case of using DSS, the vessel control process is carried out by an automatic system [5-9] under the control of a human operator. At the same time, the automatic system

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determines situations that require increased control or the direct intervention of a human operator, and when making a decision, it relies on quantitative criteria for assessing the situation and expert assessments. In the development of expert systems as part of modern intelligent DSS, various inference mechanisms based on certain rules, precedents, etc. are used [10-11]. The formation of decisions in conditions of uncertainty is associated with the difficulty of determining many indicators and criteria in numerical form and requires the use of statistical and probabilistic methods, methods of expert evaluation, in particular, based on the approaches of Pareto, Bayes, Saati, etc. In general, expert evaluation methods allow, based on the experience of leading specialists, to rank indicators according to the share of their contribution to the solution of the existing problem by forming a matrix of ranked evaluations.

Many publications are devoted to the problems of safe navigation and avoiding collisions in marine practice [12-14]. In [15] authors propose a method of determining and visualizing safe motion parameters of a ship navigating in restricted waters; the importance of a risk-based approach to maritime safety is discussed in [16]; the maneuverings pace concept used in [17] for quantitative assessment of marine traffic environment; Lisowski [18] implemented dynamic games methods in navigator DSS or safety navigation providing avoiding collision at sea; the modified velocity obstacle method considered [19] for synthesis a collision avoidance DSS for ships; cooperative path planning algorithm for marine surface vessels is discussed in [20]; autonomous decision-making scheme with iterative observation and inference for multi-ship collision avoidance is presented in [21]; in [22] authors consider associative memory-based intelligent control of ship steering systems; safety evaluation of ship entering a harbor under severe wave conditions is discussed in [23].

A hybrid optimization algorithm for vessel collision prevention and marine collision avoidance radar using dynamic windows is presented in [24]. In [25], the authors consider an approach to generate route plan templates for vessels using AIS data, and work [26] deals with speed-optimized vessel routing and scheduling. Modeling, simulation, and experimental testing of various navigation situations are powerful tools for researching safe navigation and collision avoidance in maritime practice [27-30]. The theory of fuzzy sets and fuzzy logic [31-34] has been successfully applied in the development of intelligent DSS in transport logistics [35,36] and in planning the trajectories of vessels when passing through sea narrows and channels and in conditions increased intensity of external disturbances (wind, sea waves, currents, etc.) [37-40]. At the same time, researchers showed interest in the implementation of optical gates for fuzzy sets. Optical-electronic systems of fuzzy logical derivation for parallel processing of many fuzzy rules based on a spatial light modulator with the implementation of various functions, the principles of using a spatial modulator of a Gaussian laser light source and a microprismatic system, etc. have been developed [41-47]. The use of optical logic elements in artificial intelligence systems or, to some extent, in decision-making systems involves the processing of a large amount of data and a multi-level decision-making process. Using a binary encoding and calculation system for the simplest data input and output task requires hundreds of binary arithmetic operations, which naturally reduces performance.

The approach proposed by the authors is that the efficiency of optical logic systems can be maximized if the color of the light emitter is directly used as a fuzzy variable. In this case, the optical processing of color information, which reflects different degrees of evaluation of input data, is greatly simplified and can be implemented on the properties of the additive and subtractive color system using simple light filters. A simple implementation of optical fuzzy logic gates will allow (a) to focus on more complex tasks of creating a multi-level decision-making system: forming classes of task complexity and their classification features; (b) to construct the appropriate structure of the optical logic fuzzy device for each class of problems; (c) to optimize the structure of optical logic fuzzy elements; assessment of the reliability of the decisions made; (d) to create the fuzzy information input systems in the form of filters of the appropriate color; (e) to form the decision-making branches, etc.

The purpose of this work is to study the possibilities of using optical logic systems with the implementation of fuzzy logic algorithms in the creation of intelligent DSS to increase the efficiency of ship’s navigation traffic in maritime practice.

2. Basic principles for constructing logical optical coloroids

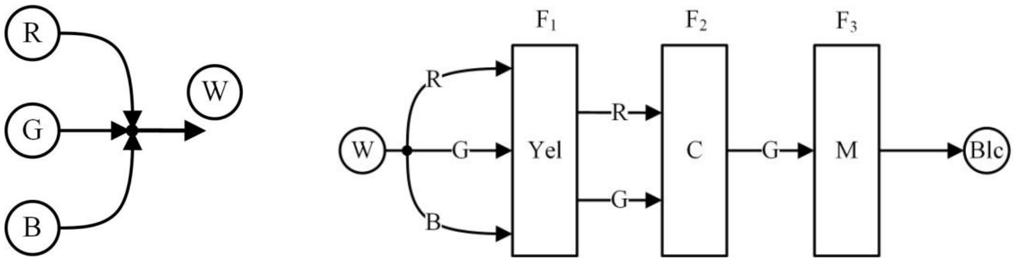
It is well known that all visible colors can be obtained by an appropriate combination of the three primary colors: red **R**, green **G** and blue **B**. When we have no colors, this is perceived as black **Blc**. When all three colors are combined in equal proportions (Fig. 1, *a*, *b*), a white color **W** is obtained;

when red and blue are combined, magenta **M** is obtained; when red and green are combined, it is yellow **Yel**, and when green and blue are combined, it is cyan **C**:

$$\mathbf{R}+\mathbf{G}+\mathbf{B}=\mathbf{W};\ \ \mathbf{R}+\mathbf{G}=\mathbf{Yel};\ \mathbf{R}+\mathbf{B}=\mathbf{M};\ \mathbf{G}+\mathbf{B}=\mathbf{C}. \tag{1}$$

Suppose there are perfect filters corresponding to all three primary colors (red, green and blue) and all three composite colors (yellow, magenta and cyan). Of course, combining two or more lights of the same color does not change that color:

$$\mathbf{R}+\mathbf{R}=\mathbf{R};\ \mathbf{G}+\mathbf{G}=\mathbf{G};\ \mathbf{B}+\mathbf{B}=\mathbf{B}.$$



a) *b*)

Figure 1: The logical structure of coloroids of the first type

An optical transformation of the form (1) (Fig.1*a*) can be defined as a simple (ordinary) solution under contradictory conditions (which can also be approximately attributed to the **G** estimate).

We can block some primary colors if apply filters. For example, a red filter blocks the green and blue components, allowing only the red to pass through; this can be described as $\mathbf{R}=\mathbf{W}-\mathbf{G}-\mathbf{B}$. We can also write similar expressions describing the blue filter $\mathbf{B}=\mathbf{W}-\mathbf{R}-\mathbf{G}$ and the green filter $\mathbf{G}=\mathbf{W}-\mathbf{R}-\mathbf{B}$. We can also have a yellow filter that blocks the blue components of the white light and keeps only the red and green components, which form the yellow light filter $\mathbf{W}-\mathbf{B}=\mathbf{R}+\mathbf{G}=\mathbf{Yel}$; we can similarly have a cyan filter for which $\mathbf{W}-\mathbf{R}=\mathbf{G}+\mathbf{B}=\mathbf{C}$ and a magenta filter for which $\mathbf{W}-\mathbf{G}=\mathbf{R}+\mathbf{B}=\mathbf{M}$.

If we block all three color components, we end up with black color (Fig.1*b*):

$$\mathbf{W}-\mathbf{R}-\mathbf{G}-\mathbf{B}=\mathbf{Blc}. \tag{2}$$

For a simple (ordinary) solution, we denote the optical scheme (Fig.1*a*) as the logical coloroid of the first type 1a (coloroid1a), and the optical scheme (Fig.1*b*) as the logical coloroid of the first type 1b (coloroid1b). When a yellow light emitter (for example) passes through a red filter, the green color is blocked, and the output is red

$$\mathbf{Yel}-\mathbf{G}=\mathbf{R}, \tag{3}$$

through the green filter, the red color is blocked, and the output is green

$$\mathbf{Yel}-\mathbf{R}=\mathbf{G}, \tag{4}$$

through the blue filter, red and green are blocked, and the output is black (i.e., the absence of light emitter) color

$$\mathbf{Yel}-\mathbf{R}-\mathbf{G}=\mathbf{Blc}. \tag{5}$$

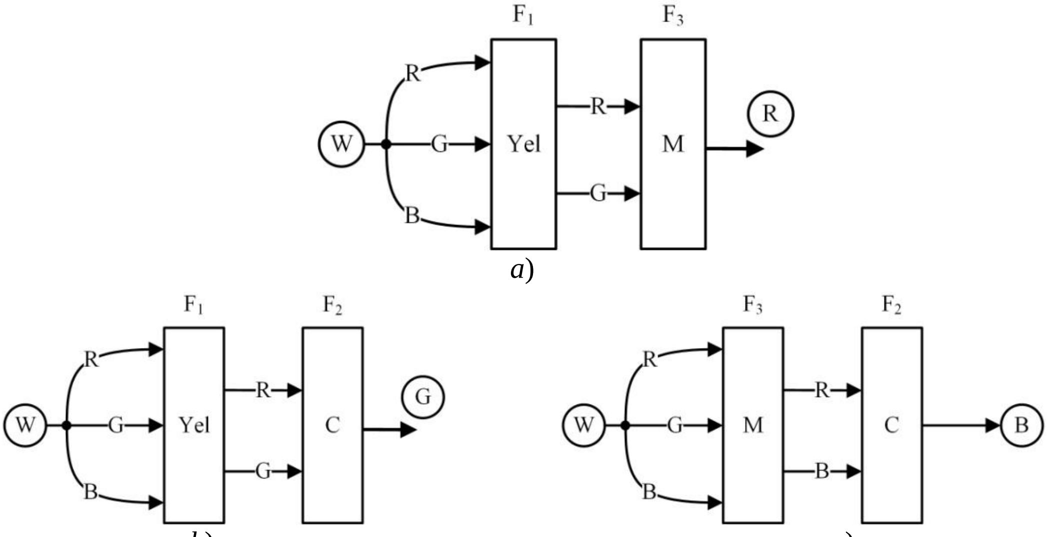
Similar dependencies can be obtained for other combinations of the color of the light emitter and the light filter (F_1, F_2, F_3). In particular, by combining **Y**, **C**, and **M** filters, it is possible to separate the main colors (Fig.2, *a* -*c*). A certain positive or negative color can be evaluated, for example, a negative color evaluation: red **R** - a clear threat, yellow **Yel** - a probable threat, magenta **M** can be defined as the proximity of a threat; positive color assessment: green **G** - near absence of threat, you can continue further: light cyan **C** – very probable absence of threat, blue **B** - absence of threat. Basically, the white color W determines a positive evaluation (such as having a decision), the black **Blc** - a negative one (for example, the absence of a decision). Interpretations of combinations of basic colors can be naturally associated with the combinations of the corresponding degrees of confidence [47]:

W = **R** + **G** + **B** “***positive decision***”;
C = **G** + **B** “***very probably yes***”;

M = **R** + **B** “***probably no***”, negative evaluation (for additional color); (6)

Yel = **R** + **G** “***very probably no***”;

Blc = **W** – **R** – **G** – **B** “***no decision***”.



a)

b) *c*)

Figure 2: Transformation of the light emitter by color filters

In work [47], the authors propose an expanded optical scheme of a logical coloroid second type (coloroid2) (Fig.3, Level - evaluation; S - a white light emitter) with three levels of evaluation of the decision-making process. Level 1 can give, for example, for primary evaluations **R, G**, **B** the formation of white light **W**. After the secondary evaluation (by Level 2) by the system of light filters, it is proposed, upon receipt, for example, of the white light emitter, to introduce a third group of experts who control of the system of light filters, which, for example, with a tertiary evaluation Level 3 of the form **C**, **M**, **Yel** will give light **Blc** at the output, i.e. no decision and further search for a new decision. For example, for the primary evaluation **R**, **R**, **R** at the output of the Level 1, red light emitter **R** is formed, which passes through the filters **M**, **Yel**.

For the primary evaluation, for example, **R**, **R**, **B** magenta light **M** is produced at the output of the optical gates of Level 1. This light will pass through the filters **M**, **Yel** of Level 2, where the magenta light emitter will be blocked by the yellow filter **B** (remains **R**), and through the filters **M**, **C** of the secondary evaluation Level 2, where magenta light emission is blocked by **R** with a cyan filter (remains **B**)

M – B = R; **M – R = B.**

When passing through a **Yel**, **C** filter, magenta will be blocked (5)

M – B – R = Blc.

At the output of optical devices of Level 2, the sum of red and blue light **R + B = M** is formed. In this case, at the Level 3, the light emitter **M** will pass (for example, for a filter system of level 3 **Yel**, **C**, **M**) filter **Yel**, the output will be **R**, which will then be blocked by filter **C**, that is, we will get **Blc** at the common output. The proposed logical transformation schemes (for example, in the formulas of 1-5) and estimates of information data (6), using appropriate light filters, color information flows are the basis for building a DSS for the safety of ship navigation.

3. Synthesis of the decision support system

The conducted analysis of the factors affecting the safety of the vessel movement in the canals, and the processing of statistical data of accidents of the world fleet when moving in limited water areas made it possible to form the color values of the danger levels according to each criterion, summarized in Table 1. It is accepted that the safest level corresponds to the grade "**B**", the most dangerous - "**R**", “decision *Yes* - vessel passage allowed”, “decision *No* - Stop”.

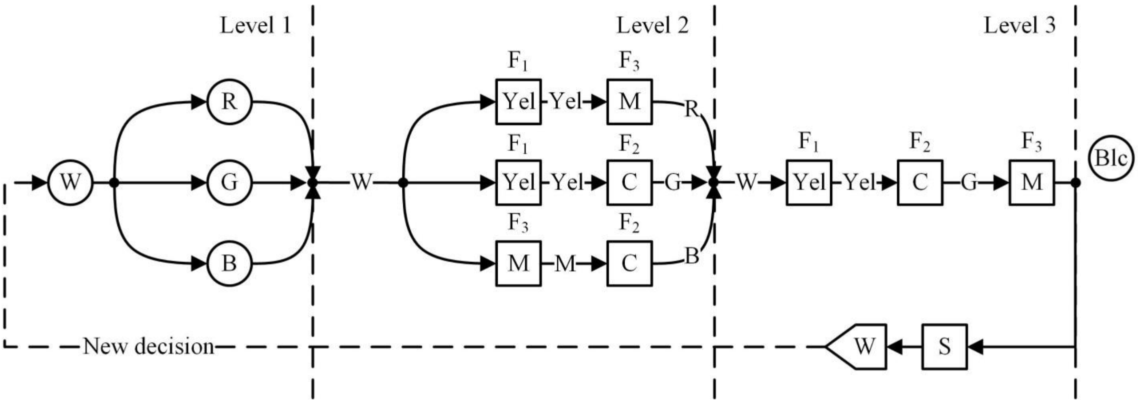


Figure 3: The logical structure of coloroids of the second type

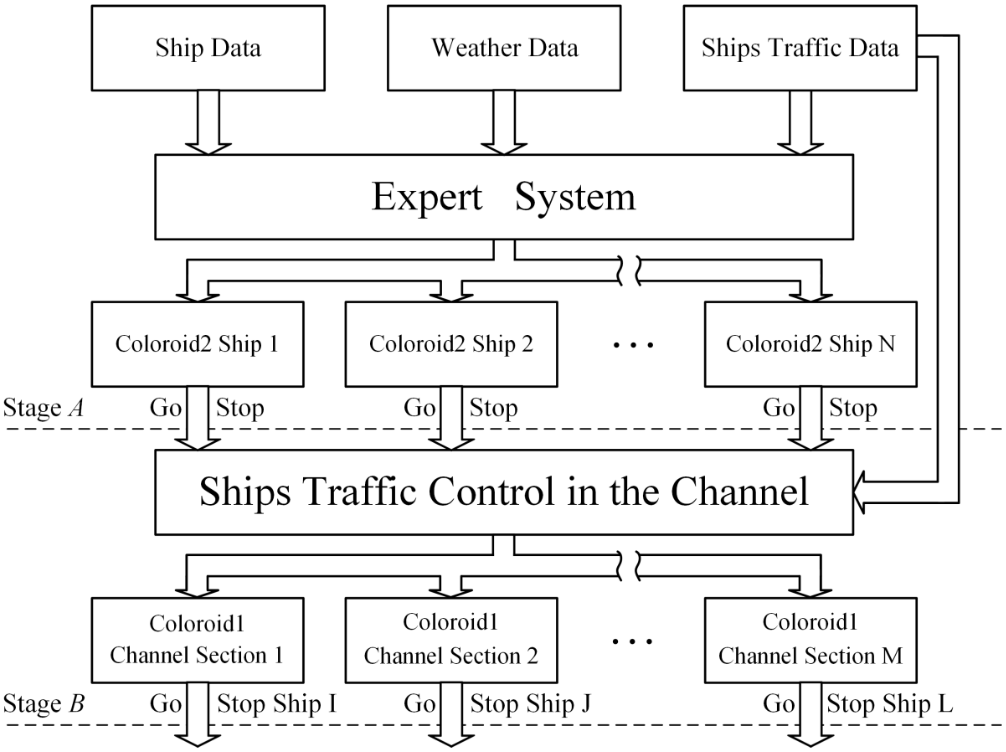


Figure 4: Structure of the DSS

The structure of the proposed DSS (Fig.4) includes two stages *A* and *B*. At the first stage *A*, based on the data on the vessel entering the navigation channel (for example Lyman Rybosol, Mykolaiv region), weather conditions with a forecast for 6 hours, information on the total number of vessels in the channel, the system, based on the use of coloroid2, makes a decision on permission to enter or stop with anchorage until a change in negative traffic and/or weather conditions. At the second stage *B*, the process of vessel traffic in the navigation channel is estimated, taking into account information about each of the vessels in difficult sections of the channel decisions, based on the use of coloroid1a, are made to increase the degree of traffic safety.

Let's apply further coloroid2, and, for example, according to the proposed scheme (Fig.5), see to the table and Fig.3, estimates and decisions follow: Level 1: Factor 1 – **R**; Factor 2 – **B**; Factor 3 – **G,** output – **W,** "***decision*** *Yes*". Level 2: upper line: Factor 10.-**Yel**; Factor 7 – **M**; middle line: Factor 12 – **Yel**; Factor 8 – **C**; lower line: Factor 9 – **M**; Factor 11 – **C**, output – **W,** "***decision*** *Yes*". Level 3: Factor 5 – **Yel**; Factor 4 – **C**; Factor 6 – **M**, output – "***decision No", Stop.***

This decision was taken from the Level 1 decisions for ratings: Storm, Daylight, Visibility 1000-2000 m; further decision Level 2 for ratings: Winter, Age of the vessel 15-20 years, The number of vessels in the channel moving in the opposite direction with a draft of more than 8 *m* > 3, Bulk or General, Partially satisfactory; decision Level 3 for ratings: Actual draft > 10.30, cargo, with ballast or Bulk, Maximum length of the vessel >200 *m*. It should be noted that in the case of factor 6 score as **C**, **G** (the length of the ship is less than 200 *m*) the input score will be **G**, "***Go to channel***".

Table 1
Traffic safety assessment factors for each vessels with danger levels

Main Factor	Level of danger	Additional Factor	Level of danger
1. Wind speed		7. Age of the vessel, years	
No wind (0-1 *m* /c)	**B**	0-3	**B**
Light wind (1-6 *m* /c)	**C**	3-10	**C**
moderate wind (4-11 *m*/s)	**G**	10-15	**G**
Strong wind (11-17 *m*/s)	**M**	15-20	**M**
Storm (>17 *m*/s)	**R**	>20	**Yel**
2. Time of day		8. Classification of the vessel by destination	
Daylight	**B**	Passenger	**G**
Dark time of day	**Yel**	Bulk	**C**
3. Visibility, м		Tanker	**G**
<100	**R**	General	**C**
100-500	**Yel**	Helpful	**B**
500-1000	**M**	9. Ship condition	
1000-2000	**G**	Excellent	**B**
2000-3700	**C**	Good	**C**
>3700	**B**	Satisfactory	**G**
4. Type of cargo		Partially satisfactory	**M**
No cargo, no ballast	**Yel**	10. Season	
No cargo, with ballast	**C**	Summer	**C**
Bulk	**C**	Autumn	**M**
General	**G**	Winter	**Yel**
Oil/fuel	**M**	Spring	**M**
5. Actual draft		11. Time of continuous work of the crew, mon.	
<8	**C**	<1	**Yel**
8-10	**G**	1…6	**C**
10-10.30	**M**	>6	**M**
>10.30	**Yel**	12. The number of vessels in the channel moving in the opposite direction with a draft of more than 8 *m*	
6. Maximum length of the vessel, *m*			
<170	**C**	0	**C**
170-200	**G**	1-3	**M**
>200	**M**	>3	**Yel**

The obtained estimates can be used as a basis for correcting the basic speed of the ship in the channel to a safe for the given situation, characterized by the values of the relevant factors. To better relate to conventional fuzzy logic, where the degree of confidence takes values from the interval [0, 1], each color can be assigned a corresponding numerical value from that interval. For example, **R** (0); **Yel** (0.25); **G** (0.55); **C** (0.75); **B** (1); **M** (0.45); **R** (0), which corresponds to the location of the color in the inner hexagon of the circular spectrum, when counted counterclockwise. Thus, the recommended speed of the ship will take into account the correction factor corresponding to the basic one, which will be determined for a ship with a **B** rating. Another possible decision of the operator may be to order the vessel to be escorted by a tug, which reduces the level of traffic danger by 1-2 levels from the priory assessment.

The second stage *B* of vessel traffic control in the channel is formed taking into account the simultaneous movement of N vessels (Fig.6) in the channel with the corresponding safety level estimates obtained at the first stage. An analysis of the factors affecting traffic safety for the considered stage of vessel traffic made it possible to identify the most important:

- the number of vessels simultaneously on the most difficult sections of the channel;
- a summary assessment of the safety of vessels located simultaneously in the most difficult sections of the channel;
- navigational complexity of the section (presence of bends, turns, narrowing, etc.).

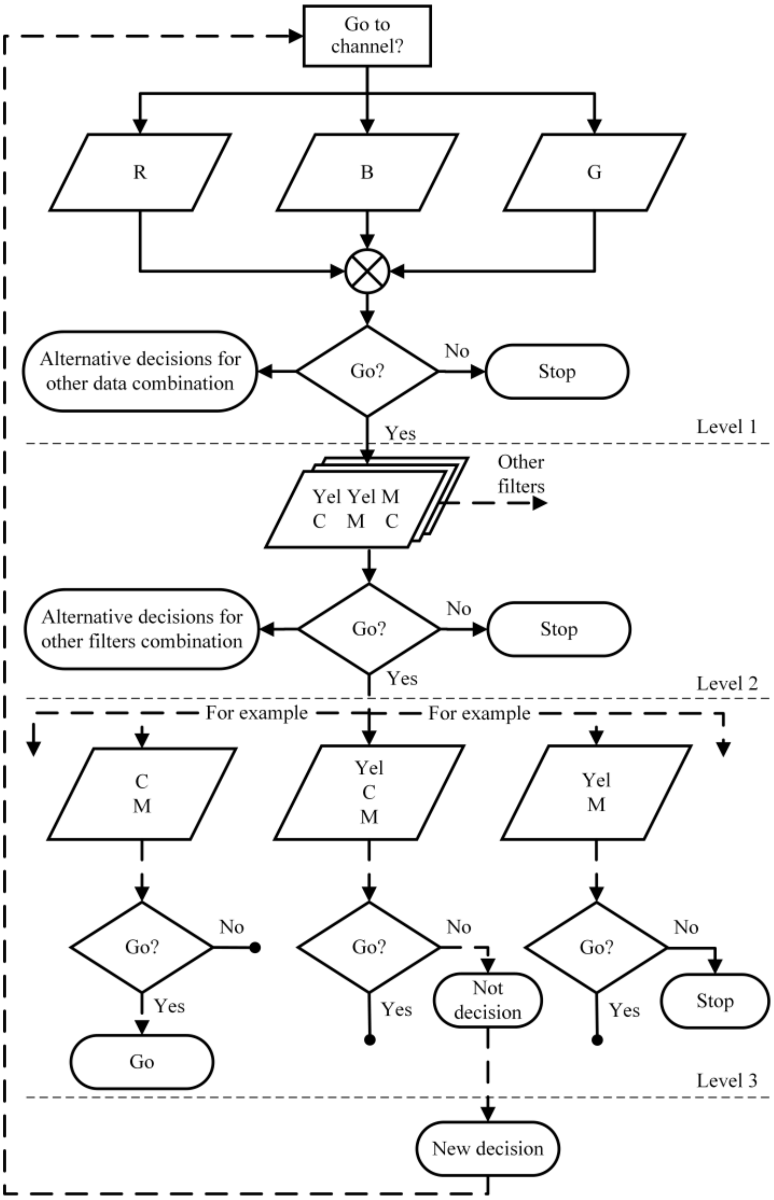


Figure 5: Block diagram of logical inference

It is assumed that the a priori estimate of the safety level of a vessel already moving in the channel, as well as weather conditions, do not change during the movement through the channel.

The navigation situation in this case, associated with the movement of ships between sections of the canal, is dynamically changing and, unlike the first stage of decision-making, when an expert assessment is made within a few hours before the ship approaches the canal, a decision is required in the "On-line" mode. In this case, for the operational assessment of traffic safety, a table for assessing traffic safety factors (Table 2) and type coloroid1a (Fig.1*a*) are proposed. As a final decision, when assessing the situation at level **R**, it is considered to bring the ship with the lowest safety level in the corresponding section of the navigation channel to the adjacent anchorage in the direction of travel until the level of danger in this section of the channel decreases.

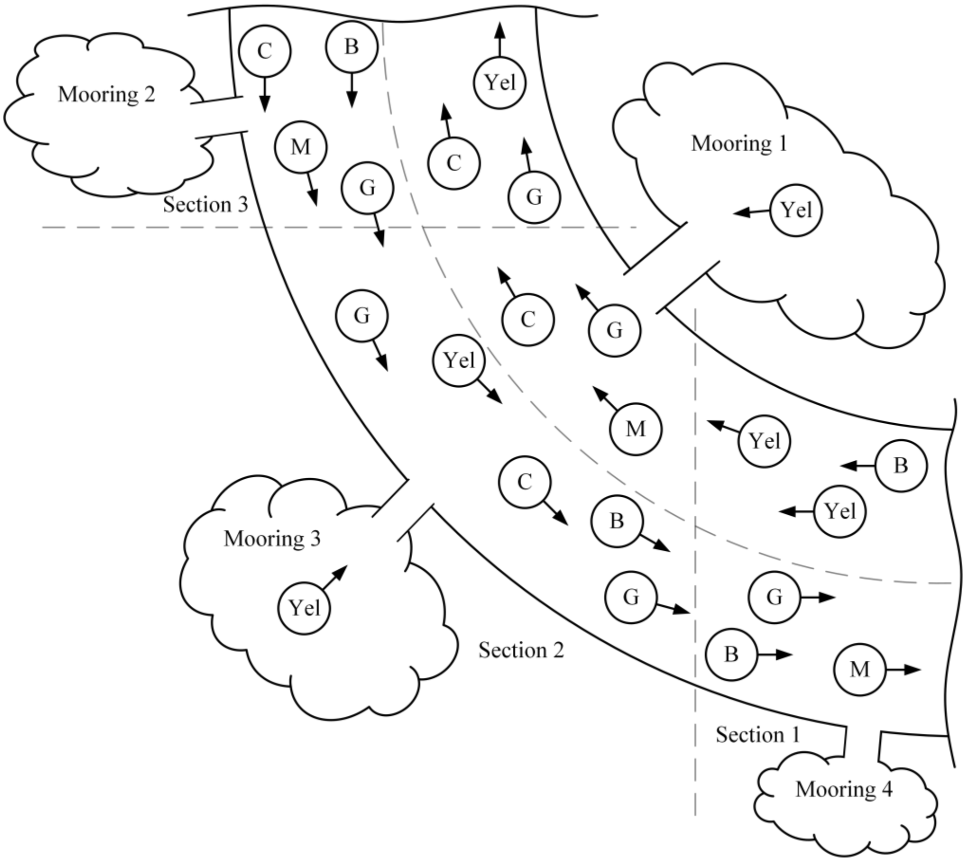


Figure 6: Scheme of vessel traffic in the shipping channel

Table 2
Traffic safety factors for sections of canal

Factor	Level of danger	Factor	Level of danger
1. Number of ships at the same time		2. Overall ships danger rating	
2-3	**B**	**C**, **B**	**B**
4-5	**G**	**W, M**, **G**	**G**
6-7	**R**	**Yel**	**R**
3. Navigational complexity of the canal section			
		Less difficult	**B**
		Difficult	**G**
		Very difficult	**R**

At the output of the coloroid1a, we get seven possible decisions (Fig.1*a*, Fig.7) **R**, **G**, **B**, **M**, **Yel**, **C**, **W**. In the case of **R** or **Yel** assessment of the navigational situation in the corresponding section of the navigation channel, the vessel with the lowest level of safety, for example **Yel**, is recommended to be taken out of the channel to the anchorage. With higher scores **G**, **B**, **M**, **C** or decision **W**, the movement of vessels continues in the same traffic or with the recommended speed reduction for assessment **G**, **M** or decision **W**.

4. Conclusion

Based on the safety category, the required level of qualification of the pilot who will guide the ship in the channel is determined, and an integrated correction factor is also set to correct the permissible, safety parameters of the ship's movement and channel boundaries. At a sufficiently low level of the safety category, the operator includes an interactive information channel of communication with a block of external experts and receives an additional assessment of the situation, which is also entered into the DSS. Expert evaluation is carried out on the basis of a survey of experts, who give the appropriate traffic safety score to the state of the vessel. Representatives of the state maritime pilot service, port supervision and other qualified specialists can act as experts.

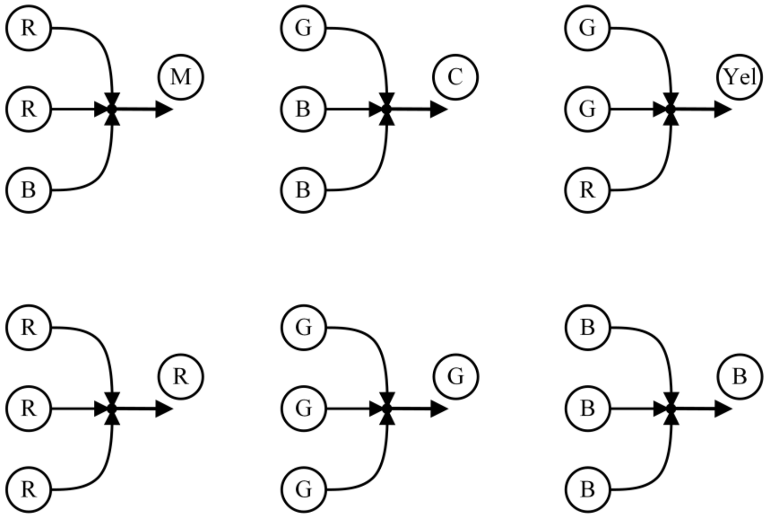


Figure 7: Optical circuits of logic decisions

The advantage (*a*-*d*) of the proposed information system for decision-making is the possibility of serial-parallel processing (*a*) of a large amount of information with high performance (*b*), a robustness (*c*) of data processing, a high degree of visualization (*d*) for a human operator of current information about the navigation situation, as well as an increase in the efficiency of the decision-making process.

The developed ship traffic safety control system significantly expands the capabilities of the radar navigation method, as well as electronic map systems based on the analysis of complex information on factors that significantly affect traffic safety. The use of the proposed DSS makes it possible to significantly reduce the accident rate of ship traffic, reducing the losses of ship owners and insurance companies. The development of a similar system is possible for large objects, for example, the flight control of large airports.

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