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DECISION SUPPORT SYSTEM FOR THE SAFETY OF SHIP NAVIGATION BASED ON OPTICAL COLOR LOGIC GATES

Victor Timchenko_1, Yury Kondratenko_2, Vladik Kreinovich_3

1. Introduction

- In the development of expert systems as part of modern DSS, various inference mechanisms based on certain rules, precedents. 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 methods, methods of expert evaluation, theory of game (see next slide fig.*a*) 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 (fig.*b*).
- The theory of fuzzy sets and fuzzy logic as been successfully applied in the development of intelligent DSS in transport logistics 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) (fig.*c*).

a)

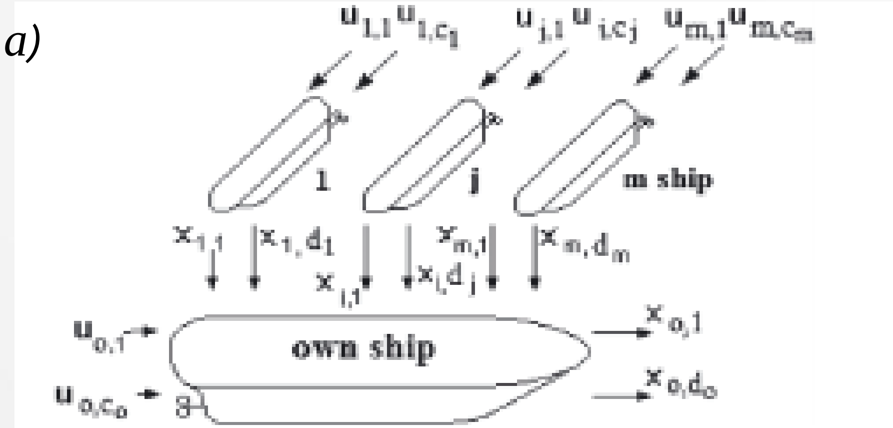


Fig. 5. Block diagram of a base dynamic game model

Lisowski, J.: Game and computational intelligence decision making algorithms for avoiding collision at sea. Proc.of the IEEE Int.Conf. on Technologies for Homeland Security and Safety, Gdansk, 2005, pp. 71-78

b)

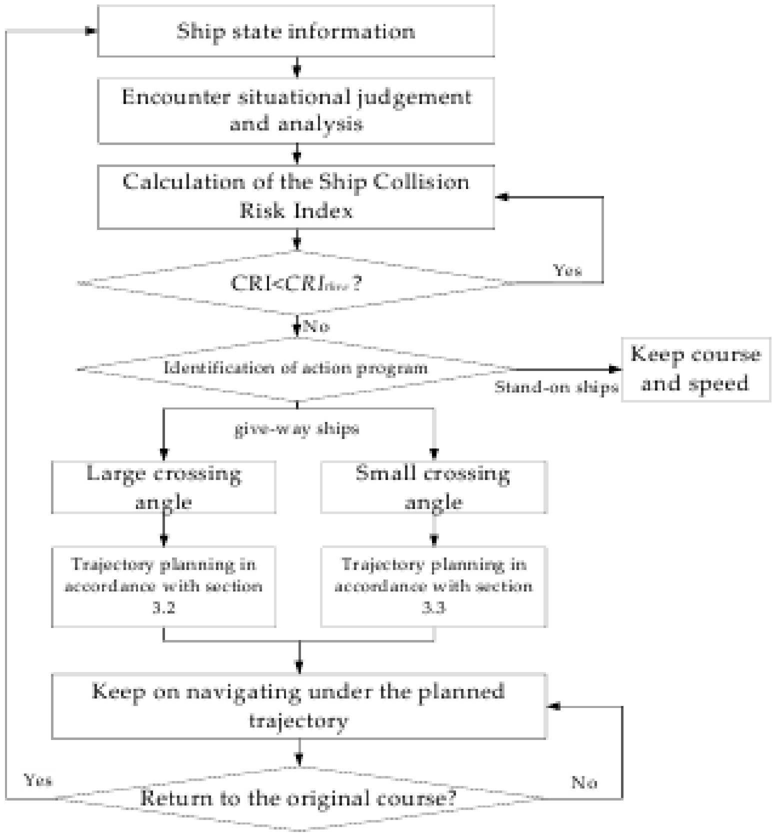
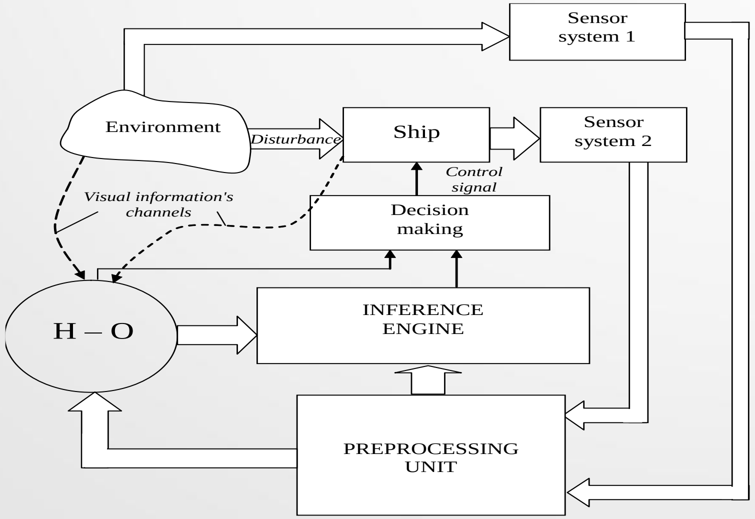


Figure 4. Trajectory planning procedure for the own ship (OS). Where *CRI* represents collision risk index, *CRI* refers to collision risk index thresholds.

Jinfen Zhang & et al., Multi-Ship Collision Avoidance Decision-Making Based on Collision Risk Index, Journal of Marine Science and Engineering, 2020, 8, 640

c)



Y. Kondratenko, S. Sidorenko, Ship Navigation in Narrowness Passes and Channels in Uncertain Conditions: Intelligent Decision Support, Studies in Systems, Decision and Control,(2022) 414: 475–493.

• Optical systems of fuzzy logical inference for parallel processing of many fuzzy rules based on the principles of using a spatial modulator of a Gaussian laser light source and a microprismatic system (see next slide, fig.*a*), a spatial light modulator with the implementation of various functions (fig.*b*), optical system with color filters for Boolean operations and paper printable memory (fig.*c*), etc. have been developed.

• A simple implementation of optical fuzzy logic gates will allow to focus on more complex tasks of creating a multi-level decision-making system:

• (a) 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;

• (d) assessment of the reliability of the decisions made;

• (e) to create the fuzzy information in the form of filters of the corresponding color;

• (g) to form the decision-making branches, etc.

- Optical systems of fuzzy logical inference for parallel processing of many fuzzy rules based on the principles of using a spatial modulator of a Gaussian laser light source and a microprismatic system (see next slide, fig.*a*), a spatial light modulator with the implementation of various functions (fig.*b*), optical system with color filters for Boolean operations and paper printable memory (fig.*c*), etc. have been developed.
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Implementation of optical gates for fuzzy sets and Boolean operations

a)

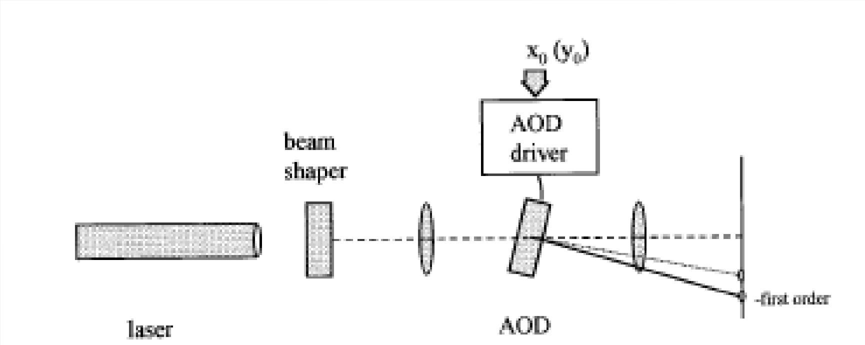


Fig. 7. One-dimensional setup for optical beam displacement by use of an AOD.

out (x \ y)	NVL	NL	NM	NS	Z	PS	PM	PL	PVL
PVL	NVL	NVL	NVL	NVL	NVL	NVL	NVL	NVL	NVL
PL	NL	NL	NL	NL	NL	NL	NL	NL	NL
PM	NM	NM	NM	NM	NM	NM	NM	NM	NM
PS	Z	Z	NS	NS	NS	NS	NS	NS	NS
Z	PS	PS	Z	Z	Z	Z	Z	NS	NS
NS	PS	PS	PS	PS	PS	PS	PS	Z	Z
NM	PM	PM	PM	PM	PM	PM	PM	PM	PM
NL	PL	PL	PL	PL	PL	PL	PL	PL	PL
NVL	PVL	PVL	PVL	PVL	PVL	PVL	PVL	PVL	PVL

Fig. 8. Rule scheme (9 × 9) for an inverted pendulum: x represents the pendulum tilt, y represents the first derivative of the tilt, and out represents the required cart displacement. P, positive; N, negative; Z, zero; L, large; M, medium; S, small.

E. Gur, D. Mendlovic, Z. Zalevsky, Optical implementation of fuzzy-logic controllers, Part I., Applied Optics, Vol. 37, No. 29 (1998) pp.6937-6945.

b)

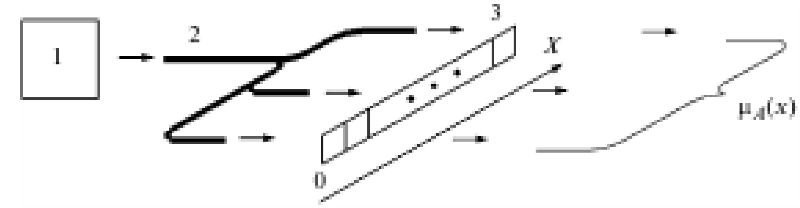


Fig. 1. Spatially distributed representation of the fuzzy membership function.

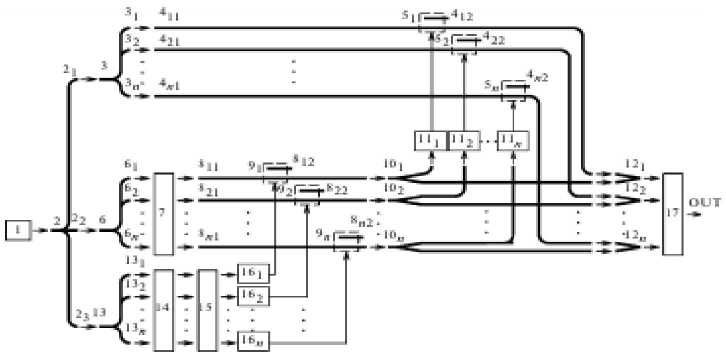
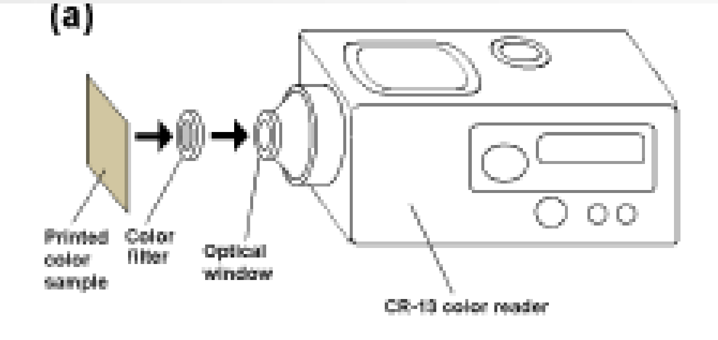


Fig. 2. The opto-electronic dephaser.

Alles M., Sokolov S.V., Kovalev S.M., Fuzzy Logical Control Based on Optical Information, Automatic Control and Computer Sciences, 2014, Vol. 48, No. 3, pp. 123–128.

c)



(D) Color prototypes

	O	A	B	AB
	OR	AND		
Filter A	A (1, 0)	A (1, 0)	AB (1, 1)	AB (1, 1)
Filter B	B (0, 1)	AB (1, 1)	B (0, 1)	AB (1, 1)
Filter AB	AB (1, 1)	AB (1, 1)	AB (1, 1)	AB (1, 1)
Filter Ā *NOT A*	O (0, 0)	O (0, 0)	B (0, 1)	B (0, 1)
Filter B̄ *NOT B*	O (0, 0)	A (1, 0)	O (0, 1)	A (1, 0)
Filter $\overline{AB}$ *A NOR B*	O (0, 0)	O (0, 0)	O (0, 0)	O (0, 0)

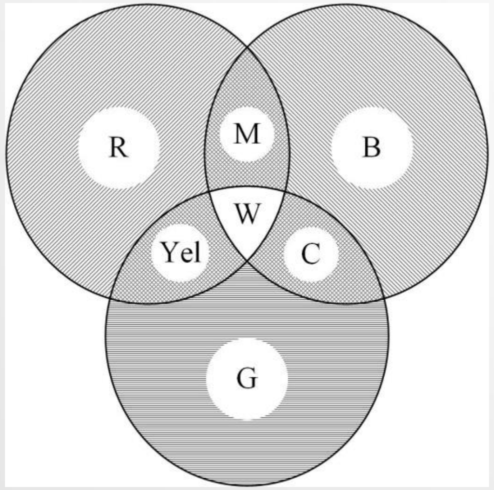
ABO color typing after filtering (a^*, b^*)

Tomonori Kawano, Printable Optical Logic Gates with CIELAB Color Coding System for Boolean, Operation-Mediated Handling of Colors Genetic and Evolutionary Computing (ICGEC), IEEE (2012) pp. 270-275.

2. Basic principles for constructing logical optical coloroids

- (a) from ultra-precise measurements where all these bits matter,
- (b) from a measurement with an accuracy of 10% (deviation),
- In the processors of traditional computers, all numbers are processed with very high precision, 64 or even 128 bits, regardless of whether these numbers come in:
- or (c) from estimate, when the expert can reliably distinguish between 7±2 different degrees.
- The more bits we use, the more logic gates we need to process this data, the more complex the design becomes.
- To process a single fuzzy degree on a traditional computer, we need to store and process a real number from the interval [0,1]. In practice, we only need to distinguish about 7 degrees. So, the natural idea is to use the optical phenomenon of color, in which we distinguish about 7 primary colors in the spectrum [V. Timchenko, Yu. Kondratenko, V. Kreinovich, Efficient optical approach to fuzzy data processing based on colors and light filter, International Journal of Problems of Control and Informatics, №4 (2022) pp. 1-17. To appear].

2.1. Operations of additive transformation of colors



A certain positive or negative color can be evaluated, for example, a negative color evaluation: red **R** - a clear danger, yellow **Yel** - a probable danger, magenta **M** can be defined as the proximity of a danger; positive color assessment: green **G** - near absence of danger, light cyan **C** – very probable absence of danger, blue **B** - absence of danger. 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:

W = R + G + B – "*positive decision*";

R – "*no*";

B –"*yes*";

G –"*probably yes*";

C = G + B – "*very probably yes*";

M = R + B –"*probably no*", *negative evaluation (for additional color)*;

Yel = R + G – "*very probably no*".

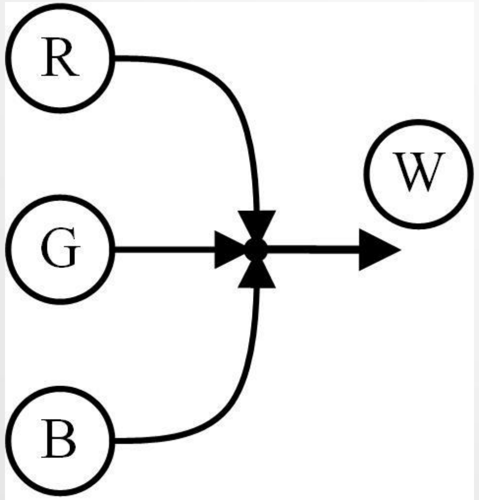
Implementation of the logical operation ***or*** (disjunction)

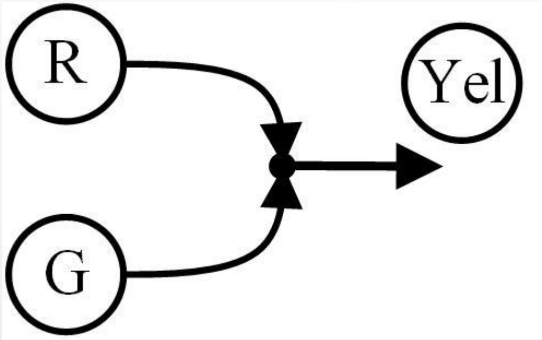
We assume that we have the spectral light emitters, ideal filters corresponding to all three basic colors (red, green, and blue) and all three additional colors (yellow, magenta, and cyan).
Combining the two lights of the same color does not change this color (idempotency property):

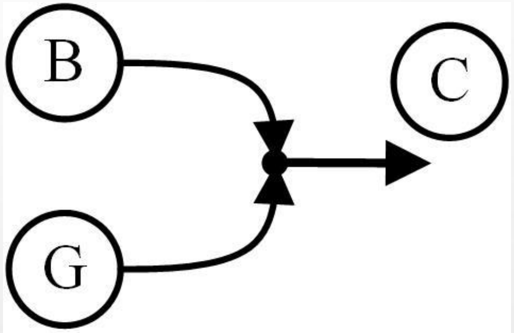
R + R = R; G + G = G; B + B = B.

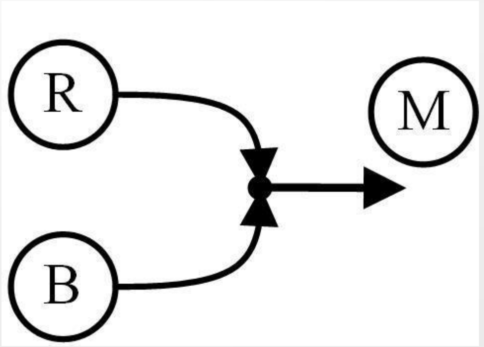
When all three colors **RGB** are combined, a white color **W** is obtained; red and blue - magenta **M** is obtained; red and green - **Yel**, and when green and blue - cyan **C**

R + G + B = W; R + G = Yel; R + B = M; G + B = C.









coloroid1a

Let's imagine a light emitter and filter of a certain color in the form of a 3 × 3 diagonal matrix:

$$\mathbf{R}=\begin{pmatrix}R&0&0\\0&0&0\\0&0&0\end{pmatrix}\quad \mathbf{G}=\begin{pmatrix}0&0&0\\0&G&0\\0&0&0\end{pmatrix}\quad \mathbf{B}=\begin{pmatrix}0&0&0\\0&0&0\\0&0&B\end{pmatrix}\quad \mathbf{Yel}=\begin{pmatrix}R&0&0\\0&G&0\\0&0&0\end{pmatrix}$$

$$\mathbf{M}=\begin{pmatrix}R&0&0\\0&0&0\\0&0&B\end{pmatrix}\quad \mathbf{C}=\begin{pmatrix}0&0&0\\0&G&0\\0&0&B\end{pmatrix}\quad \mathbf{W}=\begin{pmatrix}R&0&0\\0&G&0\\0&0&B\end{pmatrix}\quad \mathbf{BLc}=\begin{pmatrix}0&0&0\\0&0&0\\0&0&0\end{pmatrix}$$

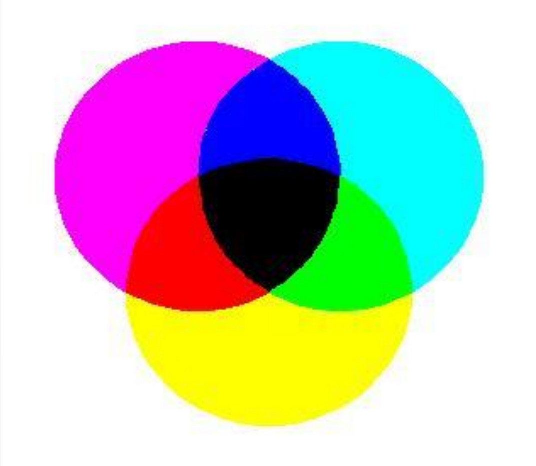
The additional operation of sets, for example

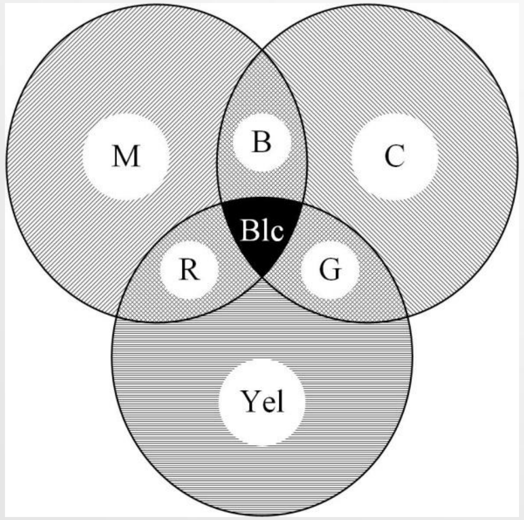
$$\mathbf{W}=\begin{pmatrix}R&0&0\\0&0&0\\0&0&0\end{pmatrix}\vee\begin{pmatrix}0&0&0\\0&G&0\\0&0&0\end{pmatrix}\vee\begin{pmatrix}0&0&0\\0&0&0\\0&0&B\end{pmatrix}=\begin{pmatrix}R&0&0\\0&G&0\\0&0&B\end{pmatrix}$$

We can also describe the *idempotency property* in these terms; for example, for red

$$\mathbf{R}=\begin{pmatrix}R&0&0\\0&0&0\\0&0&0\end{pmatrix}\vee\begin{pmatrix}R&0&0\\0&0&0\\0&0&0\end{pmatrix}=\begin{pmatrix}R&0&0\\0&0&0\\0&0&0\end{pmatrix}$$

2.2 Operations of subtractive transformation of colors





IMPLEMENTATION OF THE LOGICAL OPERATION ***AND*** (CONJUNCTION)

We can block some basic colors if we apply filters. For example, the **R** filter blocks **G** and **B** components

$$\mathbf{R = W - G - B};$$

the **B** filter

$$\mathbf{B = W - R - G}$$

the **G** filter

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

We can also have a **Yel** filter that blocks the **B** components of the **W** light and keeps only the **R** and **G** components, which form the **Yel** light filter (light filter F_1)

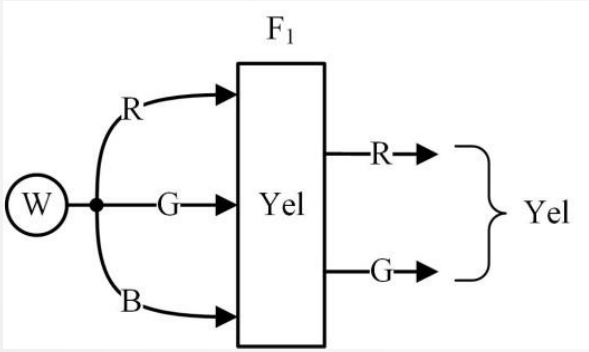
$$\mathbf{W - B = R + G = Yel};$$

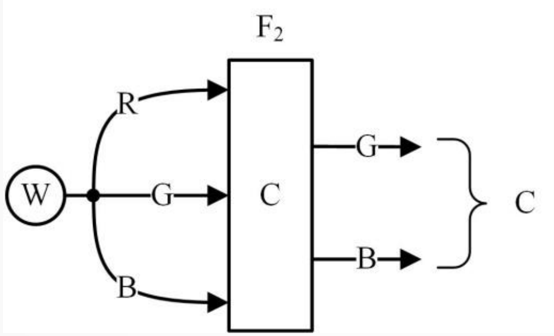
we can similarly have a **C** filter (F_2) for which

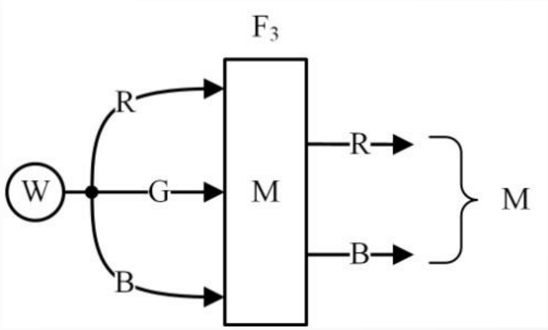
$$\mathbf{W - R = G + B = C}$$

and a **M** filter (F_3) for which

$$\mathbf{W - G = R + B = M.}$$







When a **Yel** light emitter passes through a **R** filter, the **G** color is blocked, and the output is **R**

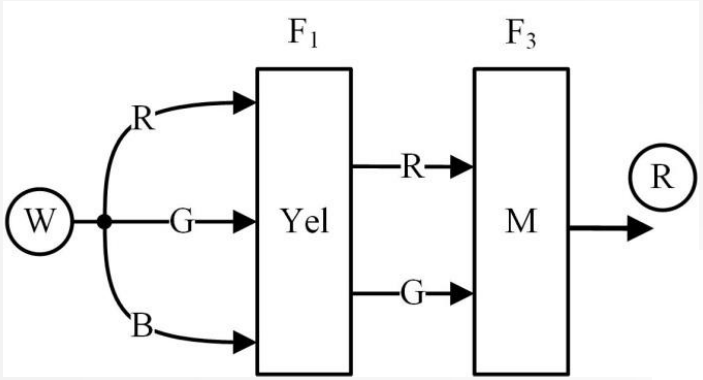
$$\mathbf{Yel - G = R,}$$

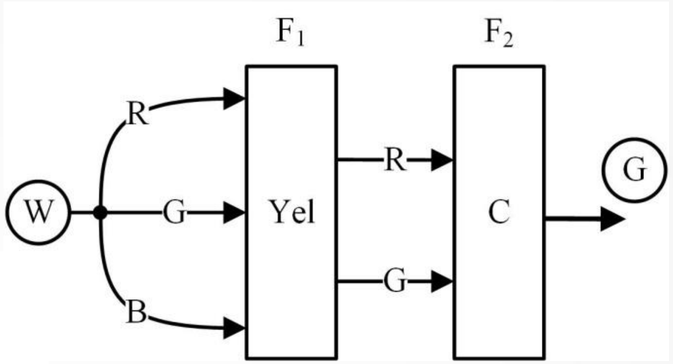
through the **G** filter, the **R** color is blocked, and the output is **G**

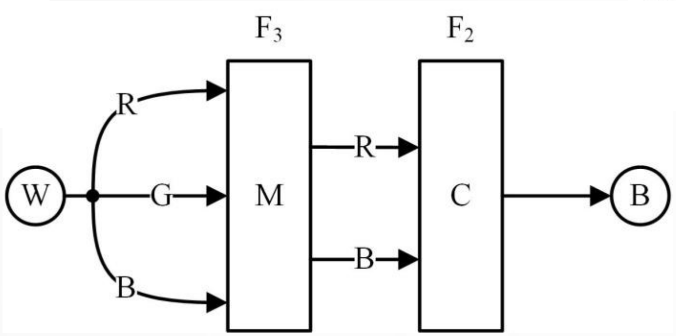
$$\mathbf{Yel - R = G,}$$

through the **B** filter, **R** and **G** are blocked, and the output is black (i.e., the absence of light emitter) color

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

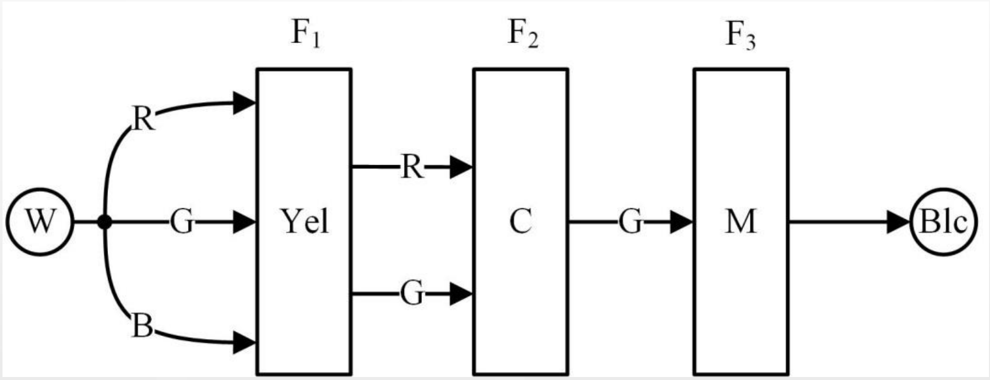






Implementation of the logical operation ***not*** (negation)

The negation operation for the main solutions $\mathbf{W} = \neg\mathbf{Blc}$ can be implemented on the basis of an optical scheme of the form (coloroid1b)



The operation of conjunction will be determined by multiplying the corresponding sets (and taking into account the idempotency). For example, for yellow

$$\mathbf{Yel} = \begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix} \wedge \begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Then we get the following representation of *white light emitter passing through the* **Yel** *filter*, considering

$$\begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & B \end{pmatrix} \wedge \begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

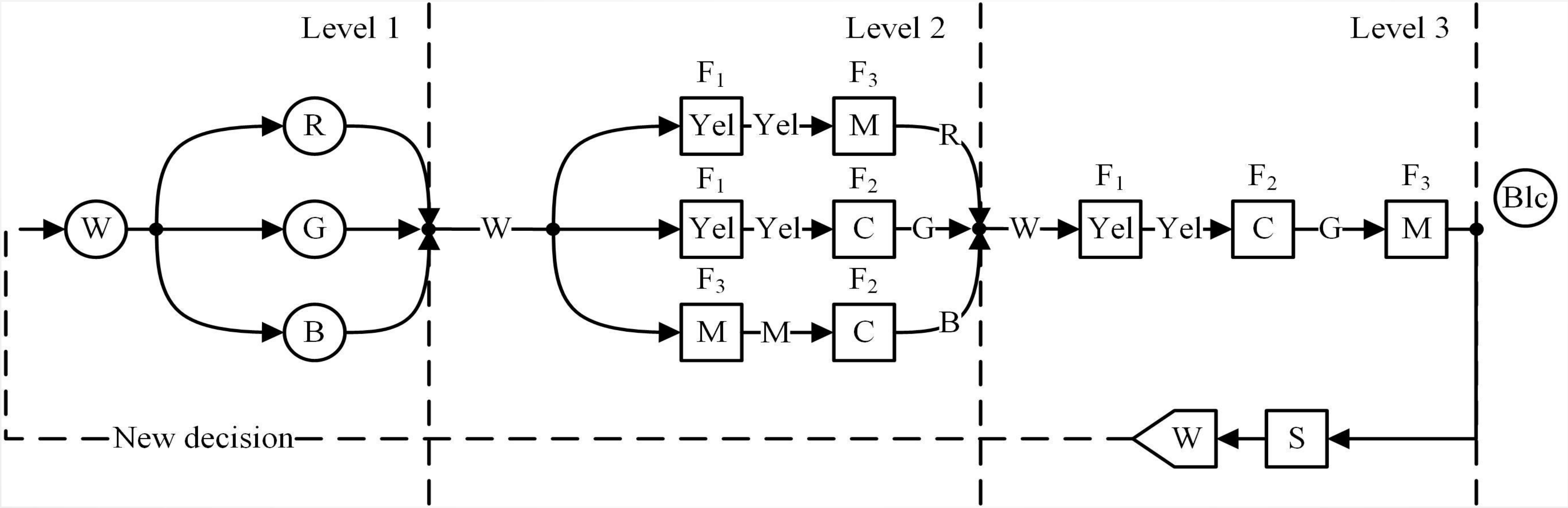
The resulting yellow light then passes through a light filter **M**

$$\begin{pmatrix} R & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & 0 \end{pmatrix} \wedge \begin{pmatrix} R & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & B \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

And light filter **C**

$$\begin{pmatrix} R & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \wedge \begin{pmatrix} 0 & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & B \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \mathbf{Blc}$$

The logical structure of coloroids of the second type



Level 1 (Level - evaluation; S - a white light emitter)) can give, for example, for primary evaluations **RGB** 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 **W**, to introduce a third group of experts who control of the system of light filters, which, for example, with a 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.

Operations by the logical coloroid can be described in the following matrix form:

1.

$$\mathbf{W} = diag(R,0,0) \vee diag(0,G,0) \vee diag(0,0,B) = diag(R,G,B)$$

2.

Light filter **Yel**,**M**

$$diag(R,G,B) \wedge diag(R,G,0) \wedge diag(R,0,B) = diag(R,0,0)$$

light filter **Yel**,**C**

$$diag(R,G,B) \wedge diag(R,0,B) \wedge diag(0,G,B) = diag(0,0,B)$$

light filter **M**,**C**

$$diag(R,G,B) \wedge diag(R,G,0) \wedge diag(0,G,B) = diag(0,G,0)$$

3.

$$\mathbf{W} = diag(R,0,0) \vee diag(0,G,0) \vee diag(0,0,B) = diag(R,G,B)$$

4. Light filter **Yel**,**M**,**C**

$$diag(R,G,B) \wedge diag(R,G,0) \wedge diag(R,0,B) \wedge diag(0,G,B) = diag(0,0,0) = \mathbf{Blc}$$

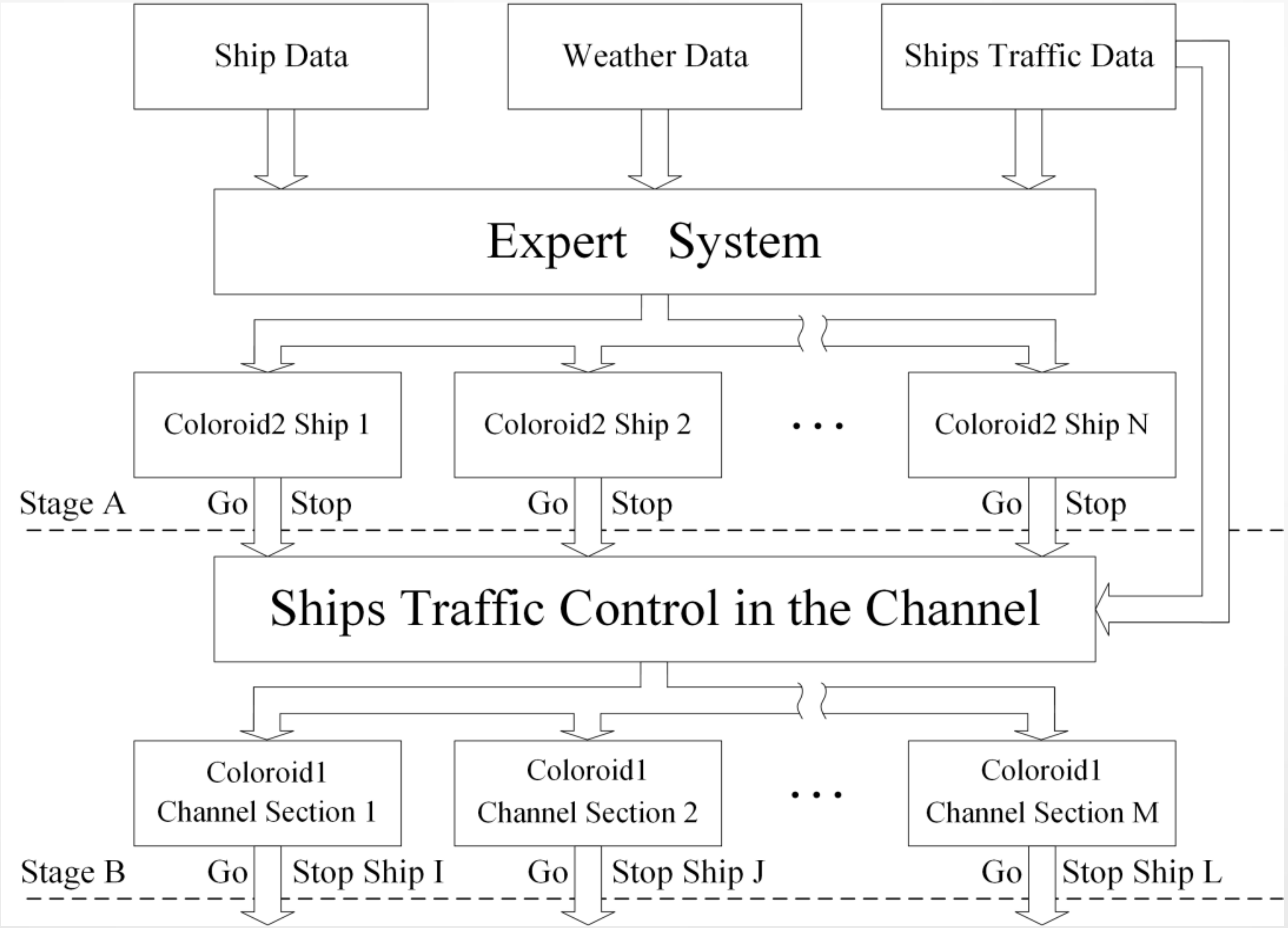
3. Synthesis of the decision support system

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 (factor), summarized in Table 1. It is accepted that the more safest level corresponds to the grade "**B**", the most dangerous - "**R**", "decision *Yes* - vessel passage allowed (Go)", "decision *No* - Stop".

- The structure of the proposed DSS includes two stages *A* and *B*. At the first stage *A*, based on the data on the vessel entering the navigation channel (for example Liman 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 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.

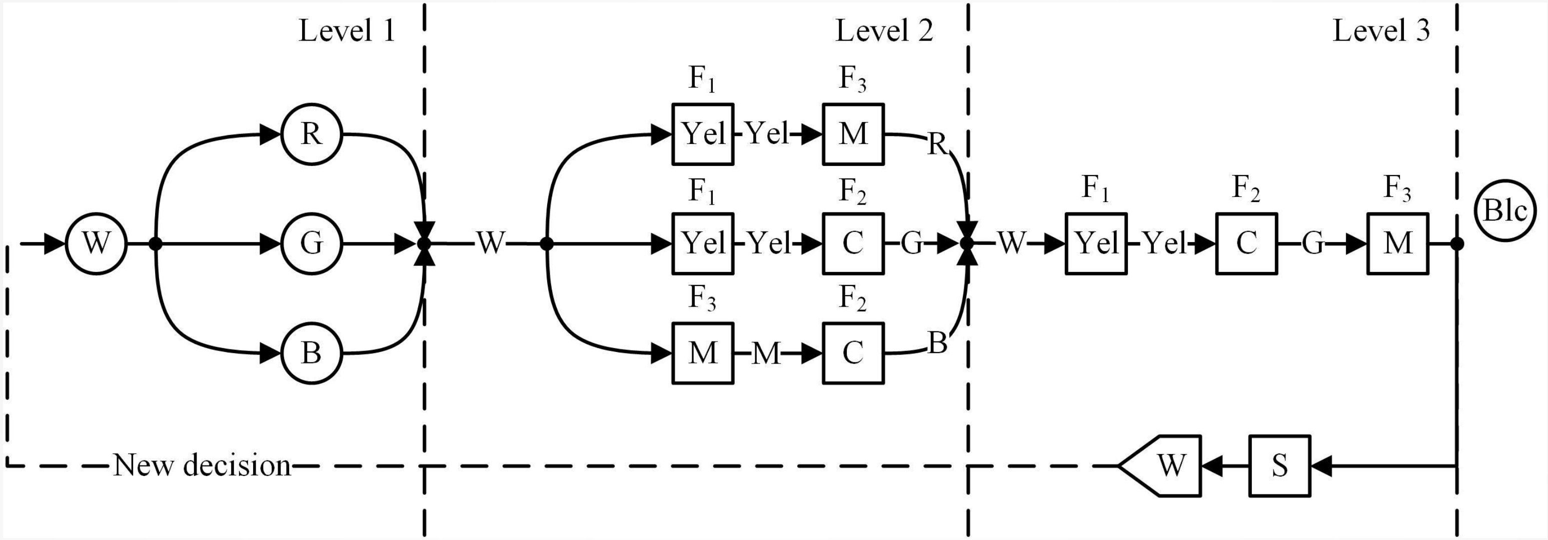
Structure of the DSS



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* /c)	**G**	10-15	**G**
Strong wind (11-17 *m* /c)	**M**	15-20	**M**
Storm (>17 *m* /c)	**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**		**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**

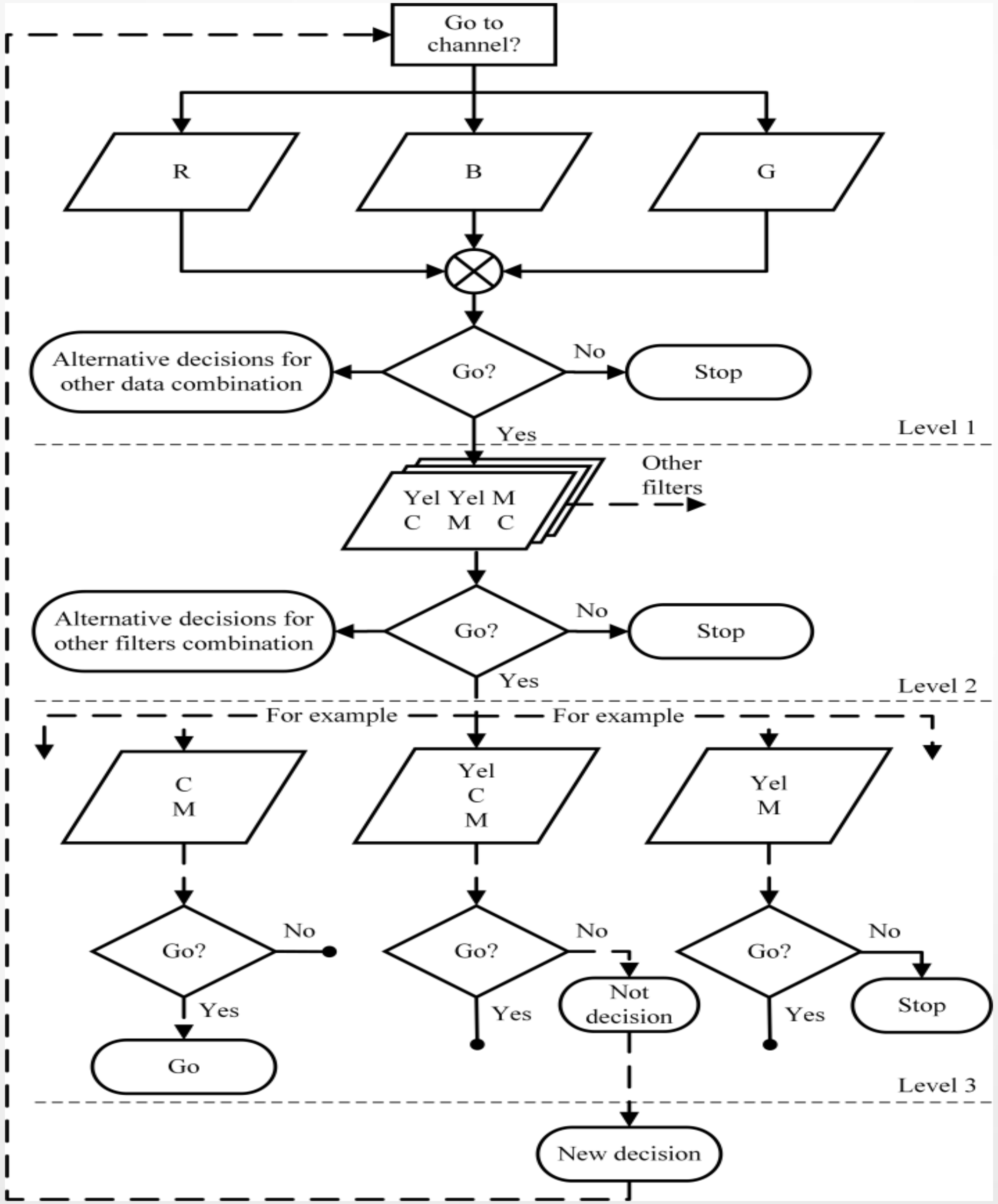
re-scheme



Let's apply further coloroid2, and, for example, according to the proposed scheme see to the table, 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 following 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**".*

Block diagram of logical inference



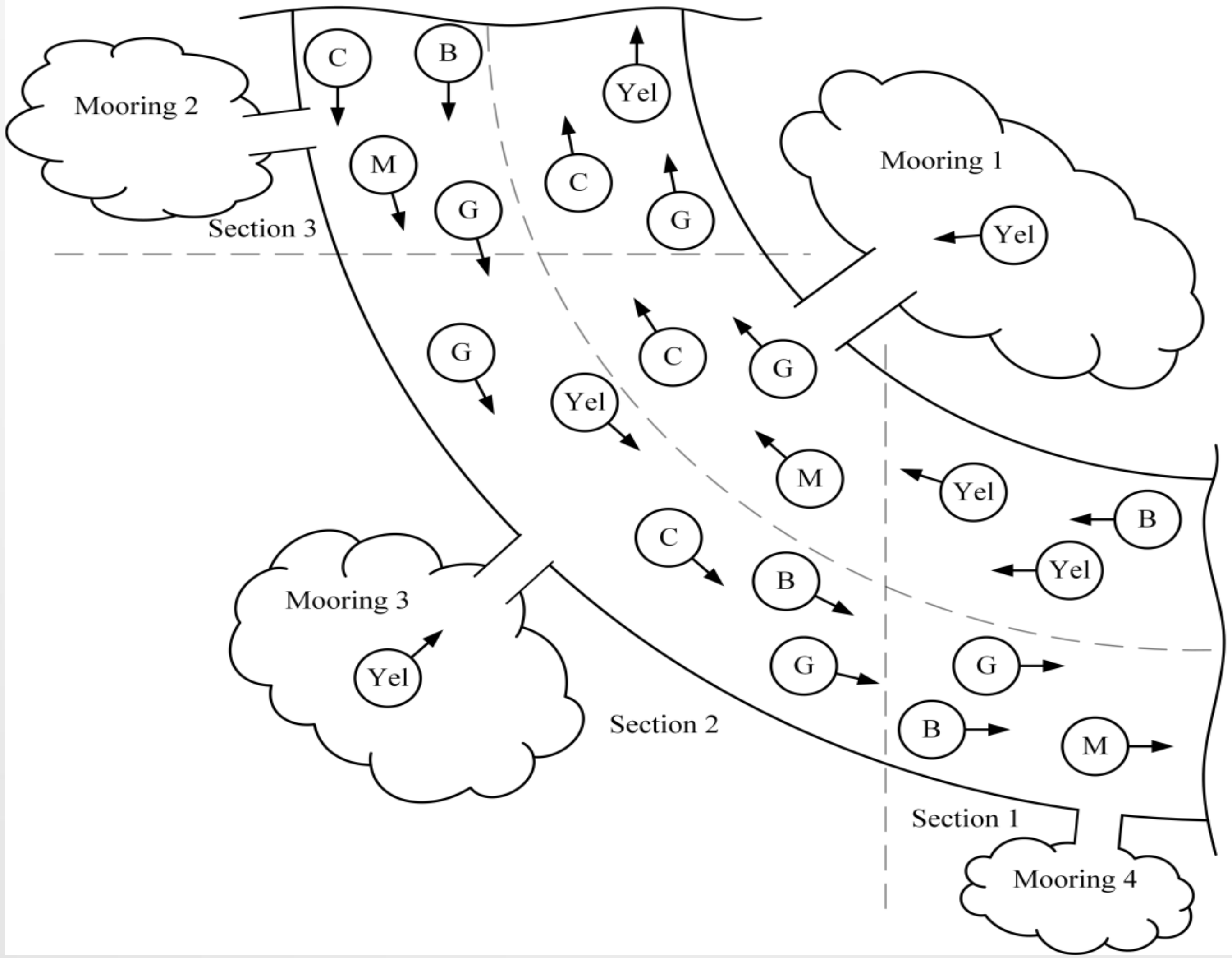
The obtained estimates can be used as a basis for correcting the basic speed of the ship in the channel to a safe for the given situation. Each color can be assigned a corresponding numerical value from the interval [0,1]. For example, **R**(0); **Yel** (0.25); **G** (0.55); **C** (0.75); **B** (1); **M** (0.45); **R**(0), Thus, the recommended speed of the ship will take into account the correction factor. *Another possible solution for the operator may be to order the vessel to be escorted by a tug*.

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**

The second stage *B* of vessel traffic control in the channel is formed taking the movement of N vessels in the channel with the corresponding safety level estimates obtained at the stage *A*. An analysis of the factors affecting traffic safety for the considered stage of vessel traffic made it possible to identify the most important (Table 1) :- the number of vessels on the most difficult sections of the channel;- a summary assessment of the safety of vessels located in the most difficult sections of the channel;- navigational complexity of the section (presence of bends, turns, narrowings, etc.).

Scheme of vessel traffic in the shipping canal



At the output of the coloroid1a, we get seven possible decisions **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 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.
- 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 pilotage service, port supervision and other qualified specialists can act as experts.
- *The advantage of DSS based on high-speed optical coloroids is the possibility of serial-parallel processing of a large amount of information with high performance, a high degree of visualization for a human operator of current information about the navigation situation, and as a result, 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 example, for the flight control of large airports.*

THANKS!