The Architecture of Optical Logical Coloroid with Fuzzy Computing

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Abstract

The proposed approach for improving the efficiency of decision support systems provides for the formation and processing of an array of input data based on the use of light radiation of a certain color as a fuzzy variable - a quantum of logical information. This allows you to design a logic inference architecture by additive and subtractive converting a light emitter with appropriate color filters, measuring light in optical channels, and switching light emitters. For the synthesis of coloroid logical components of the computational architecture of decision-making systems, a logical structure of decisions, an algorithmic inference procedure, and optical circuit solutions have been developed to improve the reliability of decisions and estimates. Estimates of the effectiveness of the proposed approach are considered in terms of increasing the speed of processing logical information, ensuring high noise immunity of computational operations, and practical implementation of the proposed optical schemes of logical coloroids.

Keywords [1]

Information color quantum, architecture of logical fuzzy coloroid, light color filter

1. Introduction

Modern computers for solving many practical problems require even faster calculations, which can be provided by using several processors working in parallel. To speed up calculations, it is necessary to speed up each processor and / or increase the number of processors, as well as provide a high speed of information transfer between the various components of this processor. Since photons can move at the speed of light, the natural idea is to use photons, in particular ordinary light, to process information. Using a light can help with parallelization - it's easy to have a large number of light beams sending information in parallel. At present, great progress has been made in the implementation of the idea of optical computing and two main trends have formed.

The first trend is optoelectronic computational devices, in which optical components are used to transmit information (and even to perform some data processing tasks), while the more traditional semiconductor-based components transform optical signals into the usual electronic form and perform the remaining computational tasks on the resulting electric signals [1-5].

The second trend is to design all-optical computational devices in which all logic gates – the basis of modern computers – process optical information. Optical switching gates are based on the properties of interference, on the polarization and coherence of a light beam, and on using the properties of diffraction gratings and photonic crystals [6-12].

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It is possible to increase the processing speed of big data in tasks related to artificial intelligence, where a large amount of data comes from experts or measurements with low accuracy through the use of soft computing [13, 14]. For optical processing of fuzzy data, this will make it possible to take full advantage of the main advantages of optical computing: processing speed, compactness, and almost unlimited possibilities of parallelization [15-21]. A more detailed analysis of such systems, given, for example, in the work [22], shows that the main disadvantage of existing optical logic systems with fuzzy calculations is the a priori digital representation of fuzzy data (which significantly increases their processing time) and technological complexity.

Of interest is the use of optical logic devices in intelligent decision support systems of technological objects with a large amount of input information, the effectiveness of which is closely related to the speed and parallelism of information processing. Such objects include marine infrastructure facilities (ports, oil and gas terminals, shipping channels, etc.) with heavy vessel traffic. The resulting problems with the safety of ships and the environment require the development and improvement of hierarchically organized man-machine decision support systems for the implementation of safe traffic in the conditions of non-standard scenarios and the impact of intense random external disturbances on the ship [23-27]. Another infrastructural object of application of the decision-making system can be aircraft traffic control at a large airport to improve flight safety, which should include the creation of a database and their ranking according to the degree of impact on flight safety, inference systems, visualization of traffic control, taking into account dangerous traffic areas and aircraft conditions.

In operations with fuzzy variables, the use of a traditional computer with binary calculations leads to tens and hundreds of additional computational operations in the processing and storage of certain numerical values, equivalent to fuzzy variables. At the same time, in practice, for decision support systems in artificial intelligence systems, it is enough to have about seven gradations of input information (which generally corresponds to a scale of human assessment, for example, “critically hot”, “very hot”, “hot”, “warm”, “cold”, “very cold”, “critically cold”). This corresponds to a well-known color gradation, for example, we usually use red to describe a dangerous situation, green - the proximity of the absence of a threat, blue - the absence of a threat, and yellow - an intermediate degree of danger. Additional gradations of fuzzy variables can provide magenta and cyan. The main thing is that the conversion of color optical radiation with the use of light filters corresponds to the implementation of the basic logical operations necessary to create a computational architecture of color logical gates and, in the future, networks of artificial intelligence systems [22, 27].

Color filters are used to process the optical light emitter and make it quite simple to implement logic based on the additive and subtractive transformation of light emitter of a certain color. To build optical logic devices, you can also use the measurement of the length of light waves for their identification, the phenomenon of diffraction and interference and high-precision prisms, but this would significantly complicate the design and technological simplicity of optical devices.

Based of fairly well-known facts, one can make some prediction that artificial intelligence systems should have fairly simple information processing algorithms (because the excessive complexity of the algorithms “absorbs” the achievable information processing speeds, and a comparison of the development of human and artificial intelligence confirms this - a person thinks with fairly simple algorithms, but "scrolls" them an extremely large number of times). At the same time, to achieve the goals of the development of artificial intelligence, it is necessary to have the possibility of almost unlimited parallel work and the very approximately processing speed of the order $10^{16} \div 10^{18}$ Hz. Now such prospects seem possible only for fairly technologically simple implemented optical logical systems with information processing in the form of fuzzy sets. To achieve the indicated information processing speed, an optical logic device for 12 logical fuzzy operations should be able to perform $10 \div 10^{3}$ binary operations at the size of the physical implementation (at the level of a modern transistor per gate - $r = 25\ 10^{-3}\mu) \approx 12 * r$, which, according to this estimate seems quite achievable. An important advantage of optical logic circuits is their high resistance compared to semiconductor components to various kinds of electromagnetic, thermal, and radiation interference in the processing and transmitting information.

The main attention in this work will be paid to the development of a computing architecture for decision support systems as an integral part of artificial intelligence high-speed and robustness components based on the representation of fuzzy information in the form of a certain information color quantum and optical processing using color filters as the simple technological implementation of logical gates.

2. Basic optical operations for the transformation of color information

It is well known and widely used in color photography and, further, in color television that combinations of the three basic sets of colors: red, green and blue (RGB) allow you to create any color, including white (light). The absence of light (and of course color) is perceived as black (light). In addition to the primary colors in photography and television technology, additional (secondary colors) colors are widely used: yellow, magenta and cyan (YMC).

Consider logical solutions, for example, based on expert ratings, and form a system for identifying the primary and secondary colors as a combination of positive Y (yes) and negative N (no) expert ratings and possible solutions. Interpretations of combinations of basic colors can be naturally associated with the combinations of the corresponding degrees of confidence [22] (Table 1).

Table 1
Degrees of confidence

Color	Degrees of confidence
$\{R\} = \{N\}$	*"no"*
$\{G\} = \{YN\}$	*"probably yes"*
$\{B\} = \{Y\}$	*"yes"*
$\{W\} = \{R\} + \{G\} + \{B\} = \{YYNN\}$	*"positive decision"*
$\{C\} = \{G\} + \{B\} = \{G, B\} = \{YYN\}$	*"very probably yes"*
$\{M\} = \{R\} + \{B\} = \{R, B\} = \{NY\}$	*"probably no"*
$\{Yel\} = \{R\} + \{G\} = \{R, G\} = \{NNY\}$	*"very probably no"*
$\{Blc\} = \{W\} - \{R\} - \{G\} - \{B\} = \{0\}$	*"no decision"*

The operations of addition and subtraction of color, given in Table 1, can be naturally interpreted as the operations of union (disjunction) and intersection (conjunction) of sets (logical statements, operations).

Suppose we have perfect filters that match all three main colors and all three additional colors, and that the light emitters used are spectral monochromatic. An optical transformation (Fig. 1) of the form $\{W\}$ can be defined as a simple (ordinary) solution under contradictory conditions (which can also be roughly attributed to the estimate $\{G\}$).

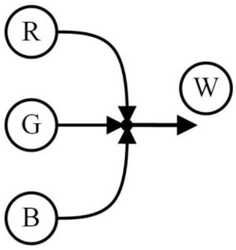

Figure 1: Optical transformation RGB

In works [22], the authors proposed to describe the main transformations of the color light emitter and filters using a 3 × 3 matrix representation of color information

$$\{R\} = diag(R, 0, 0);\ \{G\} = diag(0, \mathrm{G}, 0);\ \{B\} = diag(R, 0, B);$$
$$\{Yel\} = diag(R, \mathrm{G}, 0);\ \{M\} = diag(R, 0, B);\ \{C\} = diag(0, \mathrm{G}, \mathrm{B}); \quad (1)$$
$$\{W\} = diag(R, G, B};\ \{Blc\} = \mathrm{diag}(0, 0, 0).$$

We will distinguish between evaluations and, in fact, decisions in the decision-making process. The assessment will be determined by the accumulation or change of current information and take the values $\{R\}$, $\{G\}$, $\{B\}$, $\{Yel\}$, $\{C\}$, $\{M\}$. The positive and negative decisions $\{W\}$ and $\{Blc\}$ will be defined as a logical conclusion made based on estimates.

Let's define for each color quantum the corresponding numerical weight (confidence) value for the circular scale [0÷1]. For example,

$$\{R\}(0);\ \{\mathrm{Yel}\}(0.25);\ \{G\}(0.55); \{\mathrm{C}\}(0.75); \{B\}(1); \{M\}(0.45); \{R\}(0), \quad (2)$$

which corresponds to the location of the color on the inner hexagon of the circular spectrum.

Of course, combining two or more lights of the same color does not change that color

$$\{N\} + \{N\} = \{N\};\ \{\mathrm{YN}\} + \{YN\} = \{YN\}; \{Y\} + \{\mathrm{Y}\} = \{\mathrm{Y}\}. \quad (3)$$

Taking into account the idempotence property (3), three repeated combinations are excluded. There are 6 estimates $\{R\}$, $\{G\}$, $\{B\}$, $\{Yel\}$, $\{C\}$, $\{M\}$ and one decision $\{W\}$. Figures 1,2 shows the optical schemes for white and secondary colors at the output of coloroids.

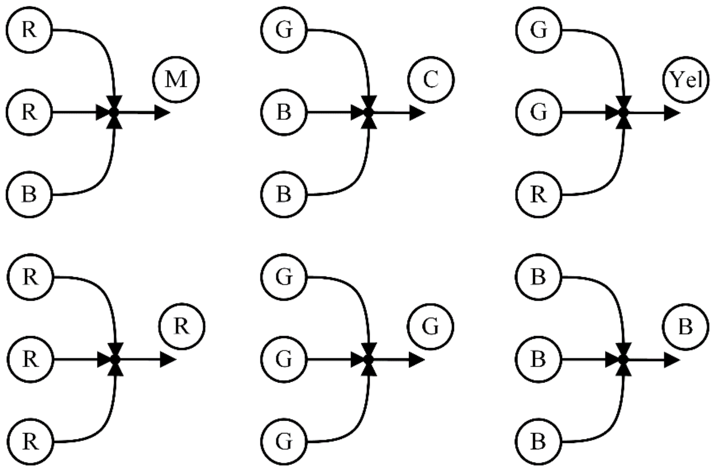

Figure 2: Optical schemes of output for summing coloroid

3. Implementation of the architecture of optical logical coloroid

3.1. Development of a logical coloroid for decision separation

Subtractive transformation of light emitters using light filters forms a blocking (subtraction) of the corresponding color. For example, a red filter blocks the green and blue components,

$$\{YYNN\} – \{YN\} - \{Y\} = \{N\}, \quad (4)$$

a blue filter blocks the green and red components

$$\{YYNN\} – \{YN\} - \{N\} = \{Y\}, \quad (5)$$

a green filter blocks the blue and red components

$$\{YYNN\} – \{Y\} - \{N\} = \{YN\}, \quad (6)$$

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 F_1

$$\{YYNN\} - \{Y\} = \{NNY\}, \quad (7)$$

we can similarly have a cyan filter F_2 for which

$$\{YYNN\} - \{N\} = \{YYN\}, \quad (8)$$

and a magenta filter F_3 for which

$$\{YYNN\} - \{YN\} = \{NY\}. \quad (9)$$

If we block all three color components, we end up with a black (Fig.3, a)

$$\{\mathrm{YY}NN\} – \{Y\} – \{YN\} – \{N\} = \{0\}. \quad (10)$$

When a white light emitter (Fig.3, b) passes through a yellow filter, the blue color is blocked, passes through a magenta filter, the green color is blocked and the output is red

$$\{\mathrm{YY}NN\} - \{Y\} - \{YN\} = \{N\} \quad (11)$$

through the yellow filter and cyan filter (Fig.3, c), the blue and red color is blocked, and the output is green

$$\{\mathrm{YY}NN\} – \{Y\} – \{N\} = \{YN\}, \quad (12)$$

through the magenta and cyan filter (Fig.3, d), red and green and red are blocked, and the output is blue color

$$\{\mathrm{YY}NN\} - \{YN\} - \{N\} = \{Y\}. \quad (13)$$

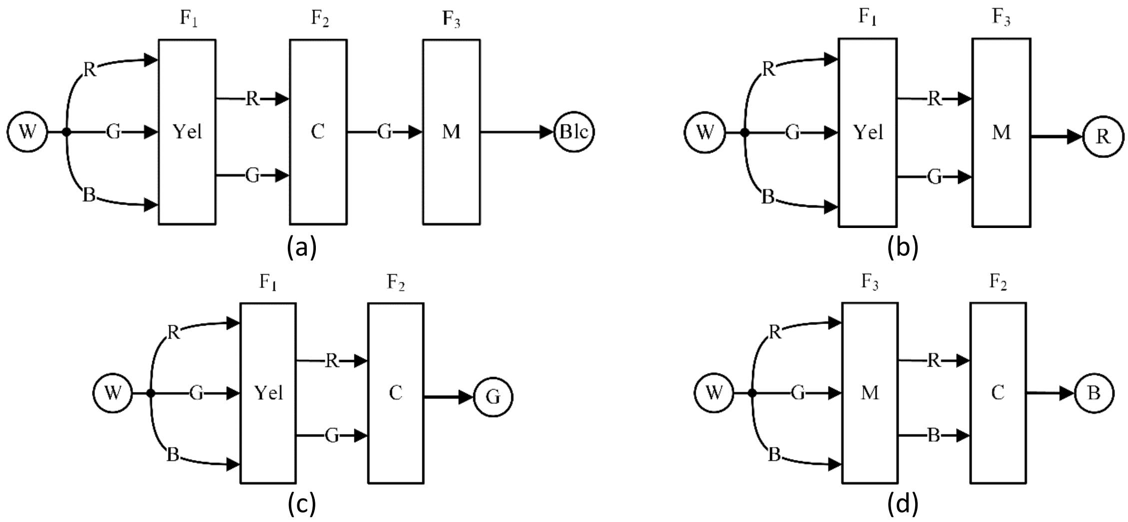

Figure 3: Optical schemes of subtractive coloroid

Consider logical operations (Table 1) for the summing coloroid (Figure 1, 2). If we consider the property of idempotence (3), then we obtain the following distribution of estimates (Table 2).

Table 2
Output color quantum

Number	Equation	Quantum
I	$\{C\} = \{G\} + \{B\} + \{B\} = \{YYYN\}$	$\approx \{YYN\}\,(a)$
	$\{C\} = \{G\} + \{G\} + \{B\} = \{YYYNN\}$	$\approx \{YYN\}\,(b)$
II	$\{Yel\} = \{R\} + \{G\} + \{G\} = \{NYNYN\}$	$\approx \{NNY\}$
	$\{Yel\} = \{R\} + \{R\} + \{G\} = \{NNYN\}$	$\approx \{NNY\}$
III	$\{M\} = \{R\} + \{B\} + \{B\} = \{NYY\}$	$\approx \{NY\}$
	$\{R\} + \{R\} + \{B\} = \{NNY\}$	$\approx \{NY\}$
IV	$\{R\} = \{R\} + \{R\} + \{R\} = \{NNN\}$	$\approx \{N\}$
V	$\{G\} = \{G\} + \{G\} + \{G\} = \{YNYNYN\}$	$\approx \{YN\}$
VI	$\{B\} = \{B\} + \{B\} + \{B\} = \{YYY\}$	$\approx \{Y\}$

Some of the primary information is lost (excluding of the estimate by formula (V) Table 2). Let's analyze each position of the estimates in detail. For the formula (I), when using the numerical equivalent of the corresponding color quantum (2), we obtain, respectively, the average estimates of 0.85 for the first formula (I *a*) and 0.7 for the second formula (I *b*). The accepted output estimate of 0.75 is lower than the first one (which can be attributed as to a more pessimistic estimate for decision-making, which will lead to the need for further refinement of the estimate). In relation to the score of 0.7, the final score will be overestimated by approximately 6.7%, which, taking into account the already necessary further refinement of the score, will not significantly affect the decision. Analysis of the formulas (II-IV) shows approximately the same ratios and general conclusion. Also, similar conclusions can be attributed to formula (V), which does not change mathematically, but requires clarification in the essence of the assessment itself as "*probably yes*". At the same time, formulas (IV, VI) can be considered as firm confident estimates for making a decision, taking into account the fact that the estimates were made by highly qualified experienced experts (let's call it a simple decision or a solution of a simple task that does not have a significant impact the overall result of the decision).

The same simple solutions include the output information quantum $\{W\}$, obtained as a result of conflicting estimates (with one negative estimate, one positive estimate, and a third estimate that supported a positive estimate), and take it as the final solution, precisely defined as simple, of the problem. At the same time, it is obvious that the estimates $\{R\} = \{NNN\}$, $\{B\} = \{YYY\}$ are more accurate and firmly, and when solving a more complex problem, they can be taken as the final ordinary solution, and the remaining estimates $\{W\}$, $\{C\}$, $\{M\}$, $\{G\}$, $\{Yel\}$ send for further refinement in the inference procedure of final solution using subtractive transformation formulas (4-13).

Thus, we are talking about the synthesis of an optical logical coloroid with a blocking circuit (Fig.4, CB – contact block; Bl – blocking device with of very short time delay τ; NO – normally opened contacts; NC – normally closed contacts; S1, S2 – light sensor), which makes it possible to select color quanta $\{R\}$ and $\{B\}$ at the output of the coloroid. Simplify the problem, and hence the optical architecture, by assuming that the scores are approximately equal to

$$\{Yel\} = \{NNY\} \approx \{R\} = \{N\}, \quad \{C\} = \{NNY\} \approx \{B\} = \{Y\}. \tag{14}$$

The output signal from the summing coloroid is fed to the color filter $\{M\}$, at the output of which we obtain, according to formulas (11-13), the following color quanta (Table 3) in matrix form (1).

Table 3
Output color quantum

Input Color	Equation
$\{W\}$	$diag(R,0,B) * diag(R,G,B) = diag(R,0,B)$
$\{R\}$	$diag(R,0,B) * diag(R,0,0) = diag(R,0,0)$
$\{B\}$.	$diag(R,0,B) * diag(0,0,B) = diag(0,0,B)$
$\{G\}$	$diag(R,0,B) * diag(0,G,0) = diag(0,0,0)$
$\{C\}$	$diag(R,0,B) * diag(0,G,B) = diag(0,0,B)$
$\{M\}$	$diag(R,0,B) * diag(R,0,B) = diag(R,0,B)$
$\{Yel\}$	$diag(R,0,B) * diag(R,G,0) = diag(R,0,0)$

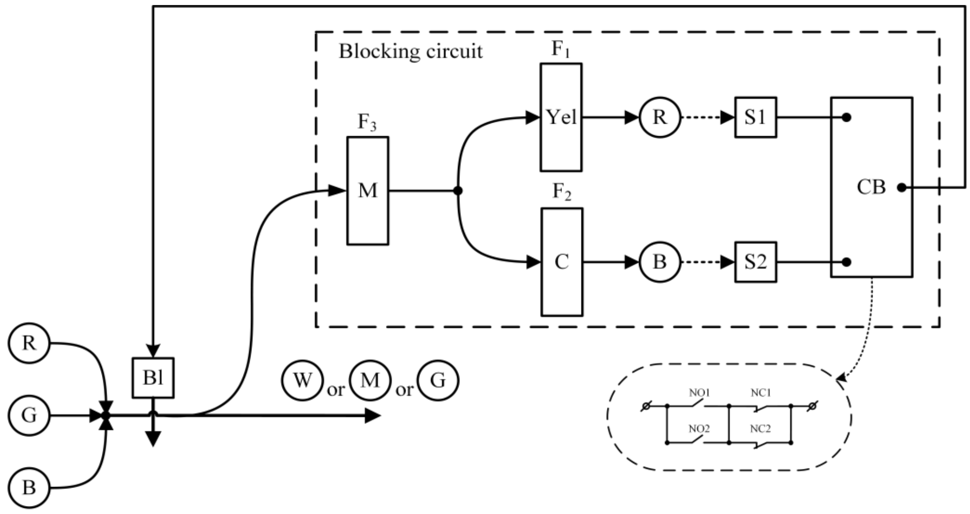

Figure 4: Optical schemes of summing coloroid with blocking circuit for RGB input

Further, the output color quantum (except for $\{G\}$, which gave an empty quantum $\{Blc\}$ at the output), enters the parallel-connected filters $\{Yel\}$ and $\{C\}$, forming two light channels, and are transformed by the following transformations, respectively for $\{M\}$, $\{R\}$, $\{B\}$ (Table 4).

Table 4
Operations by the logical coloroid

N	Equation
I	$diag(R,0,B) * diag(R,G,0) = diag(R,0,0)$
II	$diag(R,0,B) * diag(0,G,B) = diag(0,0,B)$
III	$diag(R,0,0) * diag(R,G,0) = diag(R,0,0)$
IV	$diag(R,0,0) * diag(0,G,B) = diag(0,0,0)$
V	$diag(0,0,B) * diag(R,G,0) = diag(0,0,0)$
VI	$diag(0,0,B) * diag(0,G,B) = diag(0,0,B)$

It can be noted that two-color quantum $\{W\}$ and $\{M\}$ at the output has both non-empty quantum, and the rest $\{R\}$, $\{Yel\}$, $\{B\}$, $\{C\}$ have one non-empty and one empty quantum. Then it is quite easy, using the scheme of two normally closed and two normally open contacts, as well as measuring the presence or absence of illumination in the corresponding optical channel, to implement the following logical procedure. The further passage of the light quantum at the output of the summing coloroid is blocked with the visualization of the obtained solutions if only one light channel at the output of the evaluation unit has illumination. If there is an empty set at the output of the first light filter $\{M\}$ in the evaluation block or there is illumination simultaneously in two channels of the secondary filters $\{Yel\}$, $\{C\}$, then the output signal of the summing coloroid is not blocked and follows for further evaluation. A similar architecture can be designed with a more stringent requirement of non-compliance with condition (14), using a system of filters $\{R\}$, $\{G\}$, $\{B\}$ and a three-channel switching contact block to select only information color quantum $\{R\}$ and $\{B\}$.

3.2. Implementation of a basic coloroid of optical logic for decision systems

Let us consider an expanded optical scheme of a basic logical coloroid (Fig. 5, ***level*** - evaluation; S - a white light emitter) with three levels of evaluation of the decision support process for the conclusion "Is the situation safe?".

The first ordinary level of decision is considered in the previous section and we will take, for example, output value – $\{W\}$ or $\{YYNN\}$.

After the secondary evaluation (by Level 2) by the system of light filters, it is proposed to introduce a third group of experts who control the third level of the system of light filters, which, for example, with a tertiary evaluation Level 3 of form $\{Yel\}$, $\{C\}$, $\{M\}$ will give $\{Blc\}$ at the output, i.e. "*no decision*" (see Table 5).

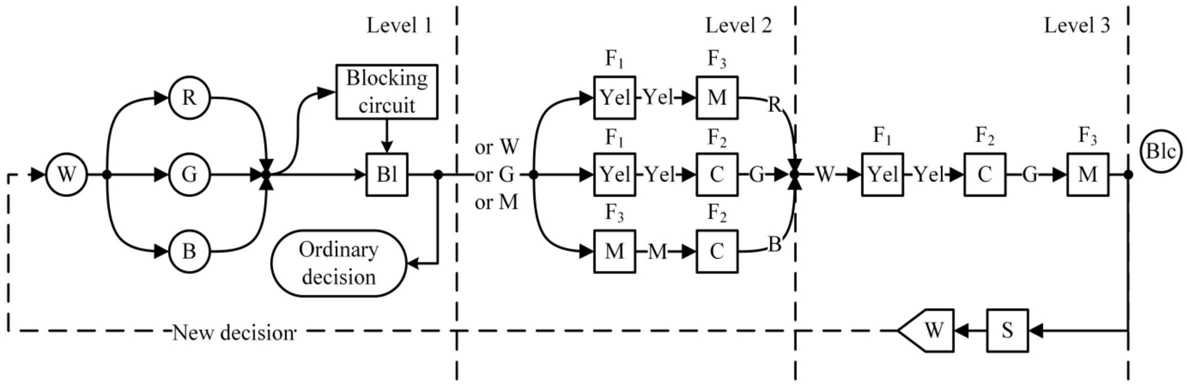

Figure 5: Optical schemes of basic logical coloroid

For example, for the primary evaluation $\{G\}$, $\{G\}$, $\{G\}$ the Level 1 output produces a green light emitter $\{G\}$ that passes through the filters $\{Yel\}$, $\{C\}$ in each branch (by Level 2) and provides a secondary estimate as an estimate $\{YN\}$. Further, at the 3rd level with filters, for example, $\{Yel\}$, $\{C\}$, $\{C\}$ we obtain the final estimate at the output of the base coloroid – $\{YN\}$.

Table 5
Operations by the basic logical coloroid

Number	Equation	Quantum
I		$\{N\} + \{YN\} + \{Y\} = \{YYNN\}$
II *a*	light filters {*Yel*}, {*M*}	$\{YYNN\} - \{Y\} - \{YN\} = \{N\}$
II *b*	light filters {*Yel*}, {*C*}	$\{YYNN\} - \{Y\} - \{N\} = \{YN\} \approx \{NNY\}$
II *c*	light filters {*M*},{*C*}	$\{YYNN\} - \{Y\} - \{N\} = \{YN\}$
III		$\{N\} + \{YN\} + \{Y\} = \{YYNN\}$
IV	light filter {*Yel*}, {*M*}, {*C*}	$\{YYNN\} - \{Y\} - \{YN\} - \{N\} = \{0\}$
V	Switching on the light emitter	$\{YYNN\}$

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 $\{Yel\}$, $\{M\}$ of Level 2, where the magenta light emitter will be blocked $\{B\}$ by a yellow filter $\{B\}$ (remains $\{R\}$), and through the filters $\{M\}$, $\{C\}$ of the secondary evaluation Level 2, where magenta light emission is blocked $\{R\}$ by a cyan filter (remains $\{B\}$) $\{NY\} - \{Y\} = \{N\}$; $\{NY\} - \{N\} = \{Y\}$.

When passing through a $\{Yel\}$, $\{C\}$ filter, will be blocked $\{R\}$ and $\{B\}$. At the output of optical devices of Level 2, the sum of red and blue light $\{M\}$ is formed, i.e. we get magenta light as the score for this case – $\{NY\}$.

At the output of the 3rd level, the magenta light $\{M\}$ is converted by the filters, for example, $\{Yel\}$, $\{M\}$, $\{M\}$, and the final output is will give – $\{N\}$.

The above equations do not cover all possible combinations of filters but allow us to consider the basics of the formation of logical coloroid and algorithmic inference procedures (Fig. 6).

Similarly, solutions are formed for various options for expert assessments. A logical coloroid can be an integral part of a system (network) of series-parallel, hierarchically organized elements, where the optical signal at the output of a certain coloroid will be one of the input signals for the next coloroid, and so on.

4. Summary and conclusion

The article considers the principles of constructing the computational architecture of an optical logical coloroid for the problem of extracting relatively simple solutions from various types of fuzzy estimates of the general decision support process.

The architecture is based on the use of simple color filters that perform the logical operations of conjunction and disjunction and ensure the required inference procedure. It is shown that when forming a filtering mechanism for simple solutions, there are admissible deviations from input estimates that do not exceed 7%.

An algorithmic inference procedure based on the proposed optical scheme for filtering simple solutions as part of the basic coloroid structure with 12 input fuzzy sets is presented.

The scientific novelty of the article lies in the development of fundamentally new hardware (allows us to separate simple solutions from the general array of solutions) and software (using a logical scheme of estimates and conclusions based on the fuzzy information ranking basis proposed in the article).

This approach is built on a strict mathematical apparatus and using proven and known physical optical methods.

The proposed logical optical structure allows, at the initial stage, with a coordinated (equal) assessment (for example, of three experts) on the given logical task, to draw a logical conclusion about the final solution.

This simplifies the hardware implementation of the coloroid and reduces the computation time while maintaining the required accuracy of estimates.

The experimental substantiation of the proposed approach in the future will consist in the technical implementation of the developed optical logic devices as elements of the architecture of computing systems and coloroid inference networks.

The evaluation of the approach is based on the following advantages:

– the high speed of information processing;

– the number of operations in fuzzy color in logic comparison with binary logic is reduced by at least 1-2 orders of magnitude;

– the robust stability of the calculation is provided by the use of basic rather simple transformations of the light, widely used in television and showing high reliability;

– optical designs are simply implemented for parallel computing;

– presentation of output information for an operator in the form of a certain color, increases the efficiency of interaction between the operator and the decision-making system.

Effective use of high-speed optical logic systems is possible in various areas that require the use of intelligent decision support systems: military, medicine and production of medical products; technical and infrastructure; sociological; ecological; emergency prevention, etc.

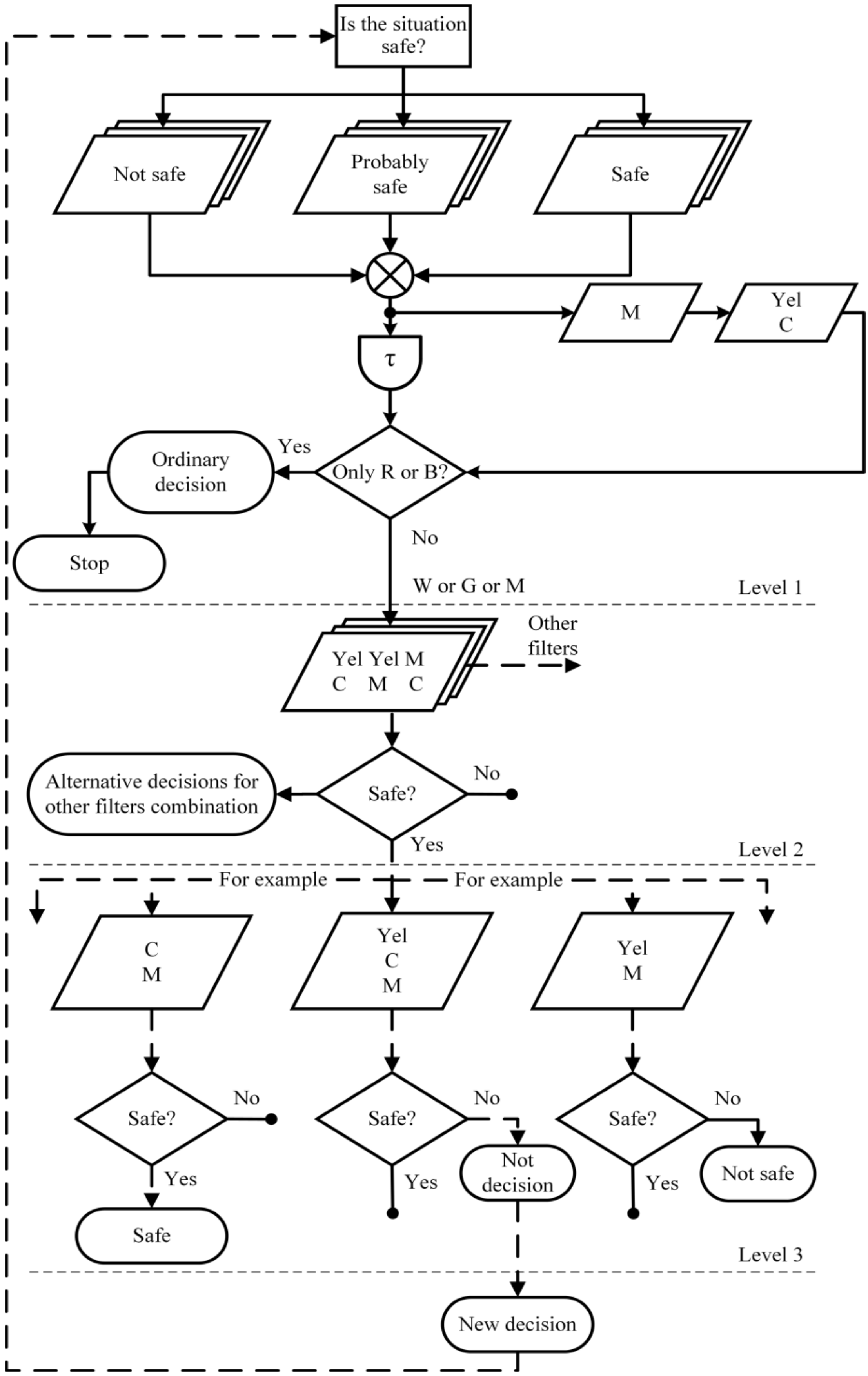

Figure 6: Block diagram of logical inference

The proposed color optical devices can be successfully used to improve the efficiency of intelligent automation systems for complex objects and processes in various industries to increase productivity and quality indicators of technological and infrastructure complexes, for example, when managing the movement of heavy ships in sea channels and in large seaports [27].

These devices will improve speed, and reliability, expand functionality and simplify the hardware and software implementation of fuzzy control and decision systems.

The proposed increase in efficiency is based on the general justified and proven advantages of using optical elements (including the logic elements proposed in this article to build a general computational structure for processing and decision making).

Additional advantages of the proposed approach are the simplicity and manufacturability of the optical devices, the use directly, without digital conversion, of input fuzzy information in the form of an appropriate set of colors, the possibility of constructing coloroid inference networks.

5. References

[1] A. Kotb, Simulation of high quality factor all-optical logic gates based on quantum-dot semiconductor optical amplifier at 1 Tb/s, Optik (2016) 127 (1): 320-325.

[2] Y. Wang, X. Wu, et al. Fuzzy logic based feedback control systems for the frequency stabilization of external-cavity semiconductors lasers, International Journal of Optomechatronics (2020) 14(1): 44-51. DOI:10.1080/15599612.2020.1828516.

[3] A. Deb , R. Wille, O. Keszocze, S. Shirinzadeh, R. Drechsler, Synthesis of optical circuits using binary decision diagrams, Integration, the VLSI Journal (2017) 59: 42-51.

[4] D. Azhigulov, B. Nakami, I.A. Ukaegbu, High-speed thermally tuned electro-optical logic gates based on micro-ring resonators, Optical and Quantum Electronics (2020) 52: Article 412.

[5] Y. Wang, X. Wu, et al. Fuzzy logic based feedback control systems for the frequency stabilization of external-cavity semiconductors lasers, International Journal of Optomechatronics (2020) 14(1): 44-51. doi:10.1080/15599612.2020.1828516.

[6] P. Singh, D. Tripathi, S. Jaiswal, and N. Dixit, All-Optical Logic Gates: Designs, Classification, and Comparison, Advances in Optical Technologies (2014) 19. doi:10.1155/2014/275083.

[7] V. Jandieri, R. Khomeriki, T. Onoprishvili, D. H. Werner, J. Berakdar, and D. Erni, Functional all-optical logic gates for true time-domain signal processing in nonlinear photonic crystal waveguides, Optics Express (2020) 28(12): 18317-18331. doi:10.1364/OE.395015.

[8] X. Wang, H. Fei, H. Lin, M. Wu, L. Kang, M. Zhang, X. Liu, Y. Yang, L. Xiao, High-performance spiral all-optical logic gate based on topological edge states of valley photonic crystal (2022). https://doi.org/10.48550/arXiv.2209.08358.

[9] L. Caballero, M. Povinelli, J. Ramirez, P. Guimaraes, and O. Neto, Photonic crystalintegrated logic gates and circuits, Optics Express (2022) 30(2): 1976-1993. doi:10.1364/OE.444714.

[10] O. Yoosefi, A. Rodriguez, Improved design of all-optical half subtractor based 2-dimensional photonic crystal, International Journal of Advance Engineering and Research Development (2019) 20196 (3).

[11] Z. Zhu, J. Yuan, L. Jiang, Multifunctional and multichannels all-optical logic gates based on the in-plane coherent control of localized surface plasmons, Optics letters (2020) 45(23): 6362-6365.

[12] C. Qian, X. Lin, J. Xu and others, Performing optical operators by a diffractive neural network, Light Sciences (2020): www.nature.com/Lsa Open Access.

[13] J. Kacprzyk, W. Pedrycz (Eds), Springer Handbook of Computational Intelligence, Springer, 2015.

[14] V. Timchenko, Yu. Kondratenko, V. Kreinovich, Why color optical computing, In: N. H. Phuong and V. Kreinovich (eds.), Deep Learning and Other Soft Computing Techniques: Biomedical and Related Applications, Springer, Cham, Switzerland, 2023, to appear.

[15] A. Sanjeev, Y. Kapellner, N. Shbero, E. Gur, Z. Zalevsky, Non-contact optical wave front shaping for focusing light and high-resolution imaging inside and behind biological scattering medium, Proc. SPIE 10932, Emerging Digital Micromirror Device Based Systems and Applications XI (2019) 1093204. doi: 10.1117/12.2507797.

[16] M. Alles, S.V. Sokolov, S.M. Kovalev, Fuzzy Logical Control Based on Optical Information, Automatic Control and Computer Sciences (2014) 48 (3): 123–128.

[17] N. Sugano, Fuzzy Set Theoretical Approach to the Tone Triangle System, International Journal of Software Science and Computational Intelligence (2015) 5(3):33-54 doi:10.4018/ijssci.2013070103.
[18] C. Qian, X. Lin, et al. Performing optical logic operations by a diffractive neural network, Light Sci Appl (2020) 9, 59. doi:10.1038/s41377-020-0303-2.
[19] K. Moritaka, T. Kawano, Spectroscopic analysis of the model color filters used for computation of CIELAB-based optical logic gates, ICIC Express Letters, Part B: Applications (2014) 5(6): 1715-1720.
[20] P.L Gentili, Establishing a New Link between Fuzzy Logic, Neuroscience and Quantum Mechanics through Bayesian Probability: Perspectives in Artificial Intelligence and Unconventional Computing, Molecules, 2021, 26, 5987. https:10.3390/molecules26195987.
[21] E. Kim, J. Park, J. Kim, S. Kim, Color Decision System based on Deep Learning and Fuzzy Inference System, 2018 Joint 10th International Conference on Soft Computing and Intelligent Systems and 19th International Symposium on Advanced Intelligent Systems, 2018, pp. 236-239. doi:10.1109/SCIS-ISIS.2018.00049.
[22] 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 (2022) 52(4): 89-105. doi: 10.34229/2786-6505-2022-4-7.
[23] J. Kacprzyk, , S. Zadrożny, G.D. Tré, Fuzziness in database management systems: half a century of developments and future prospects, Fuzzy Sets and Systems, North-Holland (2015), 281: 300-307. https://doi.org/10.1016/j.fss.2015.06.011.
[24] J.M. Solesvik, et al., Fuzzy decision support systems in marine practice, in: Proceedings of the Fuzzy Systems (FUZZ-IEEE), 2017 IEEE International Conference. doi: 10.1109/FUZZ-IEEE.2017.8015471.
[25] B. Werners, et al., Alternative Fuzzy Approaches for Efficiently Solving the Capacitated Vehicle Routing Problem in Conditions of Uncertain Demands. In: C. Berger-Vachon, et al. (Eds.), Complex Systems: Solutions and Challenges in Economics, Management and Engineering. Book Series: Studies in Systems, Decision and Control, Vol. 125, Berlin, Heidelberg: Springer International Publishing, 2018, pp. 521-543. doi:10.1007/978-3-319-69989-9_31.
[26] T. Wang, Q. Wu, J. Zhang, B. Wu & Y. Wang, Autonomous decision-making scheme for multi-ship collision avoidance with iterative observation and inference, Ocean Engineering (2020) 197, 106873.
[27] V. Timchenko, Yu. Kondratenko, V. Kreinovich, Decision support system for the safety of ship navigation based on optical color logic gates, Selected Papers of the IX International Scientific Conference "Information Technology and Implementation" (IT&I-2022), Conference Proceedings, Kyiv, Ukraine, 2022, pp. 42-52.