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Two-cycle information model in LED bar graph displays on microcontrollers

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Abstract. The article considers the principles of designing and implementing software for microcontrollers used in discrete-analog display devices. The main attention is paid to the development of a two-cyclic information model, which allows minimizing energy consumption and increasing the reliability of data presentation in ergatic systems. An analytical representation of the dynamic information model, its technical implementation using a matrix connection of LEDs, and a generalized display control algorithm are proposed. The presented methods include optimizing the program code, reducing the load on the microprocessor, and ensuring the stability of the data visualization system. The presented generalized approach to software implementation is universal and adaptable to displays of any dimension, making them promising for use in automated control systems. The results of the work can be used to improve the technical and economic efficiency of serial and specialized data visualization devices.

Keywords: LED, bar graph display, two-cycle excitation, LED degradation, electromagnetic interference, information model, algorithm, microcontroller, software, embedded system.

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1. Introduction

Design parameters of modern automation and control of technological processes determine the reliability of ergatic systems. The use of optoelectronics allows significant simplification of the technical side of achieving a high level of the complex operational characteristics of the system. At the same time, one of the most important tasks facing the developer is to create and support the visual channel of the operator's interaction with hardware, because a significant part of the information is received by a person *via* the visual channel. Therefore, means for displaying visual information represent an important component of most control devices, where the operator provides system operation management [1]. Nowadays, there are many different types of displays for information-measuring systems, which differ in their principle of operation, electrical characteristics, design features, and areas of application. Scale (bar graph) display devices based on light-emitting diodes (LEDs) are of considerable practical interest due to their high level of ergonomic characteristics, which is extremely relevant for the construction of ergatic systems [2]. The analogue method of information display on the scale, as well as its digital discrete-analogue implementation, consists of comparing a certain signal value with the spatial location of the corresponding pointer relative to the measuring scale. This method has a lower accuracy of reference compared to the digital symbol method, but provides several significant advantages. This approach allows us to present the measured value in the form of a corresponding visual image and operatively control its change in time. The figurative analogue form of data representation has high information redundancy and allows for a significant reduction in the number of operator errors in complex operating conditions. The combination of analogue information display with the digitally oriented principles of optoelectronic systems construction led to the creation of LED bar graph display devices. Further development of mass production of semiconductor display elements and an increase in the level of their operational parameters with simultaneous significant price reduction caused a wide spread of multi-element scales based on LEDs [3]. Practical applications of LED bar graph displays showed that they have a unique set of technical characteristics that make them indispensable in most industrial products, automation and control equipment, as well as in special-purpose systems. Herewith, the scales consisting of 30–150 LEDs are considered optimal from the ergonomic and practical point of view for the equipment of individual use [4]. These displays are in great demand in industry, measuring equipment, monitoring systems and other wide areas [5–10]. Control of these displays in modern systems, devices, and technological equipment is impossible without the wide introduction of microprocessor technology and microcontrollers (MCUs).

Reducing the cost of MCUs allowed us to create visualization devices with the cost of hard logic systems level. As a result, indication means based on MCUs consist of two parts: hardware and software, which provides a high level of flexibility for systems and devices. These technical solutions can be quickly adapted to any task, can be easily modified without changing the hardware part, because the implementation of additional functions causes only reworking of the MCU software [5].

However, despite the high level of technical parameters and efficiency of bar graph displays on MCUs, little attention has been paid to the optimization of this group of devices, leaving significant reserves for improving technical and economic characteristics, as well as reducing the level of necessary system resources [1–3, 8, 9, 11].

The work aims to form the principles of MCU software construction in bar graph displays for embedded systems, minimized by the necessary resources, and practical software support implementation of a reliable information model (IM) on a multi-element LED scale with matrix connection of elements.

2. The role of information models and microcontrollers in ergatic systems

The reliability of any human-machine (ergatic) system is determined, on the one hand, by the reliability of hardware and software, and, on the other hand, by the reliability of information interaction between the operator and the information display device. The latter is based on IM, which allows for evaluating the state of the controlled object or system using the visual image formed on the information field (IF). Reliability improvement is achieved by ensuring the adequacy of IM to the controlled process. This can be realized by fulfilling several requirements. IM should represent only essential properties, relations, and connections in the controlled system, and be a simplified reflection of reality. The obligatory property of IM is visibility; it is necessary for the quick perception of data by the operator, without additional analysis. At the same time, it is essential to select the optimal way of information coding, for which the IM is responsible [12].

Often IM includes many elements, which are determined by the degree of detailed representation of states and conditions of functioning of the control object. Usually, an IM element is associated with some parameter of the control object. Any image consists of a certain set of graphical primitives, which are the appropriate visualization symbols with geometric properties. Alphanumeric and any other symbols can also act as primitives [12, 13].

The key feature of IM is its shape, as it is the basis of the visual image that is formed in IF. Two groups of IMs can be distinguished – positional and additive. In the first case, the reference is determined by the position of the optical heterogeneity on IF. In the second one – by the length and position of the reference end of the optical heterogeneity. In the LED bar graph displays, a heterogeneity is a mark or a line shining on a measuring scale. In the absence of strict limitations on power consumption, it is more appropriate to use the additive model of scale representation of information, due to its reliability and greater trustworthiness in case of failure of individual LEDs [14].

Improving the reliability of information transfer from technical means to humans is a cornerstone in any automation system, and many experimental studies have been carried out on the perception of personalized information display reference devices [15]. With decreasing the cost of production of various information systems, the human-machine interface used in embedded systems is developing at an ever-increasing rate. This can be achieved due to the decreasing cost of MCUs and their widespread use. At a lower cost than hard logic solutions, MCUs extend the range of applications by increasing the degree of integration. They allow us to reduce the total cost of the system due to cheaper components and lower production and development expenses. On the other hand, the increasing complexity of software can extend the development time and impose higher requirements on communication with ergatic system elements. For efficient use of MCU, the main program should function as some analogue of a real-time operating system, when establishing the correct sequence and handling periodicity of each subroutine. In devices with shared hardware resources, non-destructive information control and appropriate independent data registers must also be organized, and access priorities set. The ability to program logical data processing decreases the need for external components, minimizing printed circuit board footprint and material costs. Built-in Analog-to-Digital Converters allow measurement of small amplitude signals in noisy environments, making the MCU suitable for harsh operating conditions [5].

3. Analytical representation of a dynamic information model

The implementation of additive discrete-analog (bar graph) data representation with high resolution and a long alphabet is based on dynamic principles of IF control signals forming. Its elements can be connected in a matrix, increasing the overall reliability of the system due to a significant reduction in interconnections. However, such device construction imposes restrictions on the algorithm for generating control signals for the bar graph display due to the impossibility of an independent excitation of individual elements. This problem is usually solved by scanning the element matrix along one of its coordinates. As a result, multi-cycle IMs are used for discrete-analog data representation, offering a relatively simple technical implementation. A significant disadvantage of this bar graph display construction is the impulse overload of certain groups of active elements, particularly in LED matrices. This issue can be resolved by reducing the number of clock cycles required for information display. For devices with many IF elements, a two-coordinated matrix connection of LEDs is advisable. This approach is well-suited for dynamic IM image generation and ensures high reliability of the entire system [4, 16].

The visual representation of IM messages intended for the operator is displayed in the bar graph IF, which is generally composed of a set **A** of elements a_i in the form $A=\left\{a_1, a_2, ..., a_i, ..., a_{p-1}, a_p\right\}$, where p is the total number of IF elements $i=\overline{1, p}$. Set **A** is perfectly ordered. This method of information coding relies on the values of the weight function of the IF elements, which are defined relative to the spatial multichannel measure. Message representation in the IF is implemented using the IM and a finite set of l symbols $S_{\nu BG}$, where $\nu=\overline{1, l}$, which form the alphabet of the additive model $\mathbf{\Omega}_{BG}=\left\{S_{1BG}, S_{2BG}, ..., S_{\nu BG}, ..., S_{(l-1)BG}, S_{lBG}\right\}$.

In the considered approach, IF is implemented in the form of a two-dimensional matrix consisting of n groups of m elements, where $p = n\times m$. The matrix connection is achieved by m groups with the same common electrode, where LEDs are located next to each other in IF. The outputs of these common group electrodes form one coordinate of the matrix. The second coordinate is realized by the other n identical electrodes with equal numbers in each group.

So, the electrical realization of an IF $m\times n$ matrix can be represented as

$$\mathbf{A}_{\mathrm{M}}=\begin{Vmatrix} a_{11} & a_{12} & \cdots & a_{1(y-1)} & a_{1y} & a_{1(y+1)} & \cdots & a_{1(m-1)} & a_{1m} \\ a_{21} & \tilde{a}_{22} & \cdots & a_{2(y-1)} & a_{2y} & a_{2(y+1)} & \cdots & a_{2(m-1)} & a_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{(x-1)1} & a_{(x-1)2} & \cdots & a_{(x-1)(y-1)} & a_{(x-1)y} & a_{(x-1)(y+1)} & \cdots & a_{(x-1)(m-1)} & a_{(x-1)m} \\ a_{x1} & a_{x2} & \cdots & a_{x(y-1)} & a_{xy} & a_{x(y+1)} & \cdots & a_{x(m-1)} & a_{xm} \\ a_{(x+1)1} & a_{(x+1)2} & \cdots & a_{(x+1)(y-1)} & a_{(x+1)y} & a_{(x+1)(y+1)} & \cdots & a_{(x+1)(m-1)} & a_{(x+1)m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{(n-1)1} & a_{(n-1)2} & \cdots & a_{(n-1)(y-1)} & a_{(n-1)y} & a_{(n-1)(y+1)} & \cdots & a_{(n-1)(m-1)} & a_{(n-1)m} \\ a_{n1} & a_{n2} & \cdots & a_{n(y-1)} & a_{ny} & a_{n(y+1)} & \cdots & a_{n(m-1)} & a_{nm} \end{Vmatrix}.$$

During the simultaneous excitation of elements within a set $\mathbf{A}_{\nu BG}^{\mathrm{M}}$ that forms the image of an $S_{\nu BG}$ symbol, only elements with arbitrarily chosen but identical numbers in any set of groups can be excited simultaneously. Therefore, to perform two-cyclic image synthesis, the elements of the set $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{M}}$ are divided into two non-overlapping subsets, which are excited in different clock cycles during formation of the symbol $S_{\nu BG}$ [17]. One possible way to divide the image into two independent subsets can be expressed as follows: $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{M}}=\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{D}}=\left\{\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM12}}+\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM22}}\right\}$, where $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{M}}$, $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM}xx}$ are the subsets whose elements synthesize the $S_{\nu BG}$ symbol and $x = 1\vee 2$

$$\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{M}}=\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM}}=\begin{Vmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1(y_\nu-1)} & \tilde{a}_{1y_\nu} & \tilde{a}_{1(y_\nu+1)} & \cdots & \tilde{a}_{1(m-1)} & \tilde{a}_{1m} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2(y_\nu-1)} & \tilde{a}_{2y_\nu} & \tilde{a}_{2(y_\nu+1)} & \cdots & \tilde{a}_{2(m-1)} & \tilde{a}_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{(x_\nu-1)1} & \tilde{a}_{(x_\nu-1)2} & \cdots & \tilde{a}_{(x_\nu-1)(y_\nu-1)} & \tilde{a}_{(x_\nu-1)y_\nu} & \tilde{a}_{(x_\nu-1)(y_\nu+1)} & \cdots & \tilde{a}_{(x_\nu-1)(m-1)} & \tilde{a}_{(x_\nu-1)m} \\ \tilde{a}_{x_\nu 1} & \tilde{a}_{x_\nu 2} & \cdots & \tilde{a}_{x_\nu(y_\nu-1)} & \tilde{a}_{x_\nu y_\nu} & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \end{Vmatrix}, \quad (1)$$

where $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{D12}}$, $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{D22}}$ act as disjoint subsets of $\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM}}$ and in matrix representation of dimension $m\times n$ have the form:

$$\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{D12}}=\begin{Vmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1(y_\nu-1)} & \tilde{a}_{1y_\nu} & 0 & \cdots & 0 \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2(y_\nu-1)} & \tilde{a}_{2y_\nu} & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{(x_\nu-1)1} & \tilde{a}_{(x_\nu-1)2} & \cdots & \tilde{a}_{(x_\nu-1)(y_\nu-1)} & \tilde{a}_{(x_\nu-1)y_\nu} & 0 & \cdots & 0 \\ \tilde{a}_{x_\nu 1} & \tilde{a}_{x_\nu 2} & \cdots & \tilde{a}_{x_\nu(y_\nu-1)} & \tilde{a}_{x_\nu y_\nu} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \end{Vmatrix} \quad (2)$$

$$\tilde{\mathbf{A}}_{\nu BG}^{\mathrm{DM22}}=\begin{Vmatrix} 0 & \cdots & 0 & \tilde{a}_{1(y_\nu+1)} & \cdots & \tilde{a}_{1(m-1)} & \tilde{a}_{1m} \\ 0 & \cdots & 0 & \tilde{a}_{2(y_\nu+1)} & \cdots & \tilde{a}_{2(m-1)} & \tilde{a}_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & \tilde{a}_{(x_\nu-1)(y_\nu+1)} & \cdots & \tilde{a}_{(x_\nu-1)(m-1)} & \tilde{a}_{(x_\nu-1)m} \\ 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \end{Vmatrix} \quad (3)$$

As a result, we can express the corresponding sum of matrices $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM12}}$, $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM22}}$, which are used for the two-cyclic image formation of the symbol $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{M}} = \tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM}} = \tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM12}} + \tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM22}}$ on the LED bar graph matrix.

Considering the analyzed IMs, the optimal approach for constructing long-alphabet display devices involves the use of linear additive-dynamic IMs with a small number of clock cycles. These IMs significantly increase the reliability of data display for operator processing and enable rapid identification of trends in controlled parameter changes. Research in this direction has shown that the minimum possible number of clock cycles achievable in a dynamic mode is two [16].

This IM, using only two clock cycles for image formation, ensures high reliability across various equipment. Additionally, it reduces the level and narrows the spectrum of electromagnetic interference generated in control circuits and the matrix of active emitters. Simultaneously, LEDs exhibit a lower degradation rate. Furthermore, this IM is hardware-invariant, making it suitable as a foundation for developing a family of highly efficient two-cyclic bar graph displays [8–11]. For a bar graph display with a matrix IF with dimension $m \times n$, it can be represented as $\mathbf{A}_{\nu\mathrm{BG}}^{\mathrm{M}}$

$$\mathbf{A}_{\nu}^{D} = \left\{ \bigcup_{y=1}^{\nu-mq} \left[\bigcup_{x=1}^{q+1} a_{xy} \left| \begin{matrix} t = t_s + t_g - 0 \\ t = t_s + 0 \end{matrix} \right. \right] \right\} \bigcup \bigcup \left\{ \bigcup_{y=\nu-mq+1}^{m} \left[\bigcup_{x=1}^{q} a_{xy} \left| \begin{matrix} t = t_s + 2t_g - 0 \\ t = t_s + t_g + 0 \end{matrix} \right. \right] \right\}, \tag{4}$$

where, $q = E(\nu/\mathrm{m})$ is the integer part of (ν/m), m is the number of excited low-order elements in matrix groups in the image, ν is the total number of excited IF elements, a_{xy} is the element that has the number y in the group with the number x, t is the current time, t_s is the time of the beginning of the symbol regeneration period, τ_g is duration of the cycle, $2\tau_g$ is symbol regeneration period. In the time description, "0" indicates that the adjacent time intervals are non-intersecting, meaning they represent open intervals. According to this description of the formation of the symbol $\mathbf{A}_{\nu}^{D}$ in dynamic two-cyclic mode, two subsets $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM12}}$ and $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM22}}$ of bar graph display elements are defined, which represent two time intervals from $t = t_S + \tau_g - 0$ to $t = t_S + \tau_g + 0$. During the first of them, the elements of the subset $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM12}}$ are excited. It includes elements with numbers from 1 to $b_1 = \nu - mE(\nu/m)$ in all high-order bits of the matrix from the first to $E(\nu/m)+1$. In the second time interval, elements of the subset $\tilde{\mathbf{A}}_{\nu\mathrm{BG}}^{\mathrm{DM22}}$ are excited. It includes elements with numbers from (b_1+1) to m in all high-order bits of the matrix from the first to $E(\nu/m)$.

Switching the excitation of the current subset of elements to the next one occurs constantly with a sufficiently high frequency. Due to the inertia of human vision, cyclic repetition of excitation of these two subsets of elements with a frequency above 50 Hz will forms a complete visual image that corresponds to the symbol, described by (1) [2]. For example, one can form the symbol, which includes 46 elements on the IF of a bar graph display whose elements are connected as a 10×10 matrix. The required symbol is formed in two-time intervals (cycles). During the first of them, 30 IF elements are excited. This subset includes 6 low-order elements of the first 5 groups of high-order bits of the matrix according to (2). During the second interval, the remaining 16 IF elements from 46 ones corresponding to the generated symbol are excited. This subset includes 4 high-order elements of the first 4 groups of high-order bits of the matrix according to (3). Alternate excitation of these two subsets of IF elements with a frequency of more than 50 Hz creates for the operator a continuous visual image of the generated symbol.

5. Technical approach to the implementation of the two-cycle information model

For the implementation of a two-cyclic dynamic IM, we selected the MCS-51 platform. This platform, being simple and cost-effective, satisfies all the requirements for these display devices. An analysis of the current state of the MCS-51 family, based on the Intel 8051 core, convincingly demonstrates that these MCUs continue to be dynamically developed by various manufacturers. Currently, the primary manufacturers of 8051-based MCUs are Atmel/Microchip Technology and Silicon Labs, which continue to maintain and develop this legacy architecture for modern embedded applications. Philips produces several dozen of a wide variety of MCUs with increased performance. Dallas Semiconductor offers versions with an equivalent clock frequency of 99 MHz, which is significantly higher than the standard Intel 8051. Standard Micro (SMC) has integrated the 8051 core and a complete Arcnet network controller into a single chip for industrial use. MCUs from Cypress and Atmel support the USB interface. Triscend developed MCUs with a built-in programmable logic matrix. Analog Devices has extended the 8051's functionality to the level of a digital signal processor. Considering the relatively low price, these developments make the MCS-51 platform one of the best digital hardware for a wide range of industrial and specialized applications [18–26].

Software tools are an integral part of digital solutions based on MCUs. The required program can be implemented in Assembly language or generated by a translator from a high-level programming language. Despite the higher level of labor intensity of the MCU software creation, this solution is in demand for critical components of the system software. Obviously, support for information visualization, which requires constant expenditure of MCU resources, should be classified as part of this group of system software components. Using the Assembly language, one can reduce the number of program commands and the quantity of memory accesses, which enables one to increase the execution speed and reduce its size. This approach ensures a decrease in the use of MCU resources for data display, freeing them up to expand the system functionality [19, 14, 26].

6. Principles of constructing software for MCUs used in bar graph displays

Analysis of the software approach for excitation of the IF based on a two-cyclic IM in the form (1) showed that to reduce resource consumption in the solutions being developed, it is necessary to focus on optimizing the program blocks executed during interrupts that serve the I/O subsystem of MCU. The interrupt mechanism is particularly well-suited for handling events that occur asynchronously during program execution. The use of this principle fully corresponds to the tasks solved by the visualization subsystem. Also, the use of dynamic indication for IF based on an electrical matrix of elements has its advantages due to the reduction of the necessary equipment, in contrast to the implementation of static indication, where each element requires a separate control channel. In this case, the decrease in the brightness of IF seen by the operator due to pulsed excitation of the LED is compensated by an increase in the excitation current of the elements. Using a two-cyclic IM, the current increase will be minimal and will not exceed two times. This also ensures a low level of electromagnetic interference generated by the display and minimal LEDs' degradation due to the low amplitude of the excitation currents of the IF elements.

At the same time, one of the main tasks of optimizing the MCU software is to reduce the computing resources required to service the display subsystem. In this case, the required processor time is critical. The use of a two-cyclic IM reduces the number of interrupts for servicing the display subsystem per unit of time, which provides significant savings in this system resource. Additionally, the use of a generalized linear algorithm for data obtaining, their mathematical processing, and the use of the results obtained to control the IF enables block-by-block optimization of the software, with account of characteristics of a specific hardware platform. The relative independence of software blocks in this linear algorithm structure creates conditions for minimizing the amount of required memory and reducing the quantity of processor time spent on interblock transitions.

Based on the considered principles, an algorithm was proposed and tested that implements a generalized approach to creating a software component of the visualization subsystem in bar graph displays. The developed algorithm is shown in Fig. 1. This approach is invariant relatively to the used mathematical data processing and the characteristics of the hardware platform. The developed template enables us to create program code, but does not provide the ability to directly optimize specific blocks and the program. Next, the functional blocks of the template are realized with account of specific hardware parameters and possible options for mathematical data processing. As a result, several practical implementations of the code will be obtained, which differ in technical characteristics. These programs can be analyzed according to selected optimization criteria, and the developer can choose the most suitable option.

The interrupt handler program corresponding to the generalized algorithm for servicing the visualization subsystem shown in Fig. 1 is executed continuously at a frequency that is higher than the critical flicker fusion

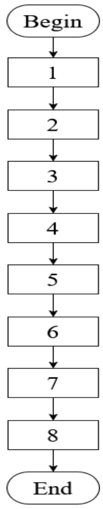

Fig. 1. Generalized algorithm of the interrupt handler.

frequency. It should be noted that full initialization of the subsystem occurs once the display starts, which is not represented in this algorithm and includes general settings of the interrupt handler, as well as setting the necessary variables. The first block of the program provides initialization of variables for the current moment in time. Block 2 acts as a clock selector, ensuring that the current interrupt corresponds to the clock number to prevent information overlaps and false data output. Block 3 provides receiving and storage in RAM of the current value of the input data, which should be visualized and comes from the external subsystem of the device.

Next, control codes (CC) for the buses of the IF element matrix are generated. CC is a binary code, where logical levels correspond to the excitation or non-excitation signals of a specific matrix bus. Based on the implementation of a two-cyclic IM (4), logical signals for excitation of a two-dimensional matrix of elements are represented in the form of four sets, which are formed by blocks 4 and 5.

Block 4 produces CC for the high-order buses of the IF element matrix during the first

$$\mathbf{A}_{\mathrm{H1}} = \left\{ \bigcup_{x=1}^{q+1} a_{xy} \left| \begin{matrix} t = t_s + t_g - 0 \\ t = t_s + 0 \end{matrix} \right. \right\} \tag{5}$$

and second cycle

$$\mathbf{A}_{\mathrm{H2}} = \left\{ \bigcup_{x=1}^{q} a_{xy} \left| \begin{matrix} t = t_s + 2t_g - 0 \\ t = t_s + t_g + 0 \end{matrix} \right. \right\}. \tag{6}$$

Block 5 generates CC for the low-order buses of the IF element matrix in the first and second cycles

$$\mathbf{A}_{\mathrm{L1}} = \left\{ \bigcup_{y=1}^{\nu-mq} a_{xy} \left| \begin{matrix} t = t_s + t_g - 0 \\ t = t_s + 0 \end{matrix} \right. \right\} \tag{7}$$

and

$$\mathbf{A}_{\mathrm{L2}} = \left\{ \bigcup_{y=\nu-mq+1}^{m} a_{xy} \left| \begin{matrix} t = t_s + 2t_g - 0 \\ t = t_s + t_g + 0 \end{matrix} \right. \right\}, \tag{8}$$

respectively.

Block 6 is responsible for blocking IF excitation. It is necessary to ensure the correct formation of the image in the IF when the cycle number changes or new data is received. This eliminates uncontrolled display glare, which can be a problem in dynamically generating images. Block 6 function is implemented by applying CC with blocking potentials to all low-order or high-order buses of the IF matrix. Their value is determined by the specific parameters of the LED elements.

Block 7 transmits the previously generated CCs in blocks 4 and 5 to the external ports of the MCU. This forms the signals for excitation of the corresponding LED array during the first and second cycles of data output to the IF and re-enables the information display. So, the new IF image based on the existing CCs stored in the MCU ports is formed. Minimizing the execution time of the blocks 6 and 7 functions enhances the display brightness. The formed CCs are saved in the MCU ports and provide continuous excitation of the matrix elements between successive interrupts. Block 8 updates and stores in memory all program variables for further formation of new CCs during subsequent cycles and concludes the display interrupt handler routine.

Having presented a generalized approach to the implementation of software support for bar graph information display, we can proceed to the second stage – practical software development.

7. Software implementation of two-cycle information model

The generalized approach to software implementation for dynamic two-cyclic IM, presented in the form of the algorithm in Fig. 1, provides a basic platform for developing program code for display control that is optimized with respect to MCU resources. This code also considers the architecture and operating principles of a specific MCU [18].

Based on the stated principles, a detailed functional software support algorithm for controlling the display on a bar graph indicator built on the LED matrix is shown in Fig. 2. Excitation of bar graph display elements during the two-cyclic dynamic synthesis of the IM using a double-digit code “YX” on the LED matrix is performed *via* the MCU ports. Here, X and Y represent the corresponding binary code in the MCU ports (latch registers) used to excite either the low and high digits of the matrix or its rows and columns, respectively, according to (1).

The interrupt program begins with block 1, which is responsible for coordinating the timing of the element matrix excitation with the system time through a programmable 16-bit MCU timer-counter T/C0. Timing parameters, accuracy, and stability of the entire system are maintained using a MCU clock generator on a quartz resonator, which in the standard 8051 version operates at a frequency of 12 MHz [18, 27].

Block 2 of the program loads current data intended for visualization into the MCU port. The data is generated by the external subsystem of the device at the necessary intervals. Loading into the display subsystem of external data to visualize the input signal is performed when the regeneration period of the current symbol begins.

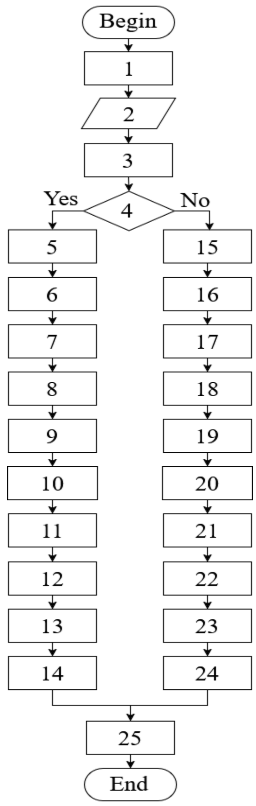

Fig. 2. Detailed algorithm for controlling the bar graph display.

Block 3 temporarily blocks the reading of new input data and prevents new data from being sent to the bar graph display until the whole regeneration cycle of the IM is completed a specified number of times. This is necessary to avoid information overlapping and invalid data being displayed on the scale.

Block 4 controls the current cycle number and ensures the division of the program into two independent branches. Each of them generates the IF control signals for the corresponding cycle of a two-cyclic IM. The processing of the first cycle data begins with block 5, and the second one with block 15.

For each cycle, the corresponding sets of matrix bus control signals are formed, presented in (5)–(8). As a result, the high-order buses are excited by the CC based on $\mathbf{A}_{\mathrm{H}i}$, and for the low-order ones $\mathbf{A}_{\mathrm{L}i}$ is used, where $i = \overline{1, 2}$ and corresponds to the cycle number.

In the first cycle, the values of the set $\mathbf{A}_{\mathrm{H1}}$ (block 5) and set $\mathbf{A}_{\mathrm{L1}}$ (block 6) are defined according to (5) and (7). Next, based on $\mathbf{A}_{\mathrm{H1}}$, the variable $\mathbf{A}_{\mathrm{DH1}}$ is formed (block 7), and on $\mathbf{A}_{\mathrm{L1}}$ – the $\mathbf{A}_{\mathrm{DL1}}$ one (block 8). The resulting variables are stored in MCU RAM. They are necessary to form a subset $\tilde{\mathbf{A}}_{\mathrm{vBG}}^{\mathrm{DM12}}$ of IF elements according to (2), which will then be excited to implement the first cycle of symbol S_{vBG} synthesis. These variables are stored unchanged in the RAM until new data is received.

Using the variable $\mathbf{A}_{\mathrm{DH1}}$ block 9 generates CC $\tilde{\mathbf{A}}_{\mathrm{DH1}}$ for the high-order buses of the matrix, and block 10 forms CC $\tilde{\mathbf{A}}_{\mathrm{DL1}}$ for the low-order buses based on $\mathbf{A}_{\mathrm{DL1}}$.

Block 11 turns off the power to the matrix of IF elements, blocking the indication. This is necessary to complete transient processes that occur when switching matrix buses, as well as to avoid parasitic illumination of IF when changing a cycle. As a result, the quality of the generated image improves and thereby increases the accuracy of information reading by the operator from the display.

In practice, the indication is switched off by applying all blocking potentials to one of the groups of the element matrix buses. These can be either low-order buses or high-order buses. The selection of a specific group determines only the sequence of loading new CC into the MCU ports to unblock the data display. Therefore, the CC of the bus group with which the indication was blocked is the last to be loaded into the MCU port. In our case, these will be the CC low-order matrix buses, which are controlled through port “X”.

After disabling the indication, which is implemented in block 11 by loading the blocking potentials into port “X”, the obtained values of the CC $\tilde{\mathbf{A}}_{\mathrm{DH1}}$ for the high-order buses of the matrix are transmitted and stored in the “Y” MCU port (block 12), and the low-order buses CC $\tilde{\mathbf{A}}_{\mathrm{DL1}}$ are transmitted and stored in the “X” port (block 13). The last operation unblocks the information display. As a result, a new image is formed in the IF, corresponding to the first data display cycle.

It should be noted that the low power level provided by the outputs of the MCU ports “X” and “Y” does not allow the IF matrix buses to be directly connected to them. This is especially true for multi-element LED displays, where bus switching current in dynamic mode is typically within the range of 200...500 mA. To solve this technical problem, bus drivers based on transistors or specialized chips are usually used. These system components do not perform logical processing, and the signal phase is formed in blocks 9 and 10, depending on the parameters of the specific IF. Therefore, the presence of this hardware is not reflected in the data processing algorithm.

As a result, excitation signals are applied to the buses of the IF element matrix according to (2), which in matrix form can be represented as

- for the high-order buses (port “Y”)

$$\mathbf{A}_{\mathrm{DH1}} = \begin{vmatrix} \tilde{a}_{h1} & \tilde{a}_{h1} & \ldots & \tilde{a}_{h(x_\mathrm{v}-1)} & \tilde{a}_{hx_\mathrm{v}} & 0 & \ldots & 0 \end{vmatrix},$$

- for the low-order buses (port “X”)

$$\tilde{\mathbf{A}}_{\mathrm{DL1}} = \begin{vmatrix} \tilde{a}_{l1} \\ \tilde{a}_{l2} \\ \vdots \\ \tilde{a}_{l(y_\mathrm{v}-1)} \\ \tilde{a}_{l y_\mathrm{v}} \\ 0 \\ \vdots \\ 0 \end{vmatrix},$$

where $\tilde{a}_{hi}$, $\tilde{a}_{li}$ are the i-th binary code bits for excitation of the high-order and low-order IF matrix buses, respectively.

Subsequently, after the indication is unblocked by storing CC $\tilde{\mathbf{A}}_{\mathrm{DL1}}$ to “X” port, this makes it possible to excite the necessary elements of IF in the first cycle accordingly to (2). Block 14 changes the cycle number variable and ends the execution of the specific branch of the first cycle routine, transferring control to block 25.

In the case of an image formation corresponding to the second cycle of IM synthesis (3), block 4 transfers control to the program branch, which begins from block 15. Here, in the second cycle, the values of the set $\mathbf{A}_{\mathrm{H2}}$ (block 15) and set $\mathbf{A}_{\mathrm{L2}}$ (block 16) are defined according to (6) and (8). Then, in blocks 17 and 18 the variables $\mathbf{A}_{\mathrm{DH2}}$ and $\mathbf{A}_{\mathrm{DL2}}$ are formed based on sets $\mathbf{A}_{\mathrm{H2}}$ and $\mathbf{A}_{\mathrm{L2}}$, respectively. Both variables are stored unchanged in the MCU RAM until new data is received and are used to form the subset $\tilde{\mathbf{A}}_{\mathrm{vBG}}^{\mathrm{DM22}}$ of IF elements according to (3). The subset $\tilde{\mathbf{A}}_{\mathrm{vBG}}^{\mathrm{DM22}}$ will then be excited at the second cycle of symbol S_{vBG} synthesis. Using the variable $\mathbf{A}_{\mathrm{DH2}}$ block 19 generates the CC $\tilde{\mathbf{A}}_{\mathrm{DH2}}$ for the high-order buses of the matrix, and block 20 forms the CC $\tilde{\mathbf{A}}_{\mathrm{DL2}}$ for the low-order buses based on $\mathbf{A}_{\mathrm{DL2}}$. Further block 21 switches off the indication, similar to the function of block 11 in the first cycle routine.

The next two blocks 22 and 23 transmit and store the previously formed CCs $\tilde{\mathbf{A}}_{\mathrm{DH2}}$ and $\tilde{\mathbf{A}}_{\mathrm{DL2}}$ in the “Y” and “X” MCU ports, respectively. Loading the low-order buses CC $\tilde{\mathbf{A}}_{\mathrm{DL2}}$ to the port “X” unblocks the information display. So, a new image is formed in IF, corresponding to the second data display cycle.

As a result, excitation signals are applied to the buses of the IF element matrix in accordance with (3), which in matrix form can be represented as

- for the high-order buses (port “Y”)

$$\mathbf{A}_{\mathrm{DH2}} = \begin{vmatrix} 0 & \ldots & 0 & \tilde{a}_{h(x_\mathrm{v}+1)} & \tilde{a}_{h(x_\mathrm{v}+2)} & \ldots & \tilde{a}_{h(m-1)} & \tilde{a}_{hm} \end{vmatrix},$$

- for the low-order buses (port “X”)

$$\tilde{\mathbf{A}}_{\mathrm{DL2}} = \begin{vmatrix} \tilde{a}_{l1} \\ \tilde{a}_{l2} \\ \vdots \\ \tilde{a}_{l(x_\mathrm{v}-1)} \\ \tilde{a}_{l(x_\mathrm{v}-1)} \\ 0 \\ \vdots \\ 0 \end{vmatrix}.$$

Further block 24 changes the cycle number variable and ends the execution of the specific branch of the second cycle routine, transferring control to block 25. This block combines both branches of the interrupt handler. As a result, an image of one of the two S_{vBG} symbol parts will be formed, according to the cycle number. This image will remain unchanged until the next interrupt occurs, which will cause the synthesis of the image of another part of the S_{vBG} symbol. After this, in block 25, internal program variables are updated and stored in MCU RAM for subsequent use when generating new CCs and the routine exits the interrupt handler.

The proposed principles for constructing the MCU software for the bar graph display were implemented in the MCS-51 Assembly language based on the algorithm presented in Fig. 2. The program was designed for an embedded system hardware platform based on the 8051 MCU, which controlled a bar graph indicator based on a 10×10 LED matrix. The indicator was built on ten modules HDSP-4850 (10-element LED bar graph array [28]). The minimization of the interrupt handler code volume enables achieving a value of 814 bytes. When using the standard 12 MHz version of 8051, this display interrupt is accomplished in 85 µs. Accordingly, at an image regeneration frequency of 50 Hz, the information display using the proposed algorithm will require 0.85% of the processor time. These parameters of the display subsystem have an insignificant effect on the overall performance of the embedded system on the MCU.

8. Conclusions

The high level of technical and economic characteristics and the ease integration of hardware and software solutions into digital information and analytical systems for information display have increased interest in digital data visualization with a high ergonomic parameters level. In this area, bar graph means of the information displays are irreplaceable. The proposed integrated approach to the creation of appropriate solutions based on MCU provides a high level of complex technical, economic, and ergonomic characteristics of the system in which it is used. Such system implements a two-coordinate matrix electrical connection of indicator elements arranged in a histogram form, together with two-cycle image synthesis in the IF.

In this approach, the main attention is paid to software support for generating a readout on the display histogram. Based on the analysis of the logical-temporal visualization IM on the IF of the display, a generalized representation of the software support of the bar graph scale, which is controlled by the MCU program, was formed. As a result, unified functional platform for developing a display control program has been proposed and implemented as a cyclic indication interrupt. This allows us to minimize the required volume of system resources when using a specific hardware platform, for the selected type of MCU and technical solution of IF as the next stage of program development.

On this basis, an algorithm for two-cyclic formation of a bar graph data display on a scale of LED elements connected to a 10×10 matrix was developed and implemented in the form of the 8051 MCU machine code. The use of the presented principles for developing display device software enables us to minimize the MCU resources required for bar graph data visualization to a level of only 814 bytes of system memory and 0.85% of processor time.

The proposed approach to building data visualization subsystems in information-measurement and automated control systems can greatly enhance ergonomics and minimize operator errors.

The presented MCU software template makes it possible to simplify the development of specialized information visualization devices and increase the level of technical and economic characteristics of serial products of measuring equipment and display tools for various purposes.

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Двотактна інформаційна модель у світлодіодних шкальних індикаторах на мікроконтролерах

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Анотація. У статті розглянуто принципи створення та реалізації програмного забезпечення для мікроконтролерів, що використовуються в дискретно-аналогових пристроях індикації. Основна увага приділяється розробці двотактної інформаційної моделі, яка дозволяє мінімізувати енергоспоживання та підвищити надійність відображення даних в ергатичних системах. Запропоновано аналітичне представлення динамічної інформаційної моделі, її технічну реалізацію з використанням матричного з'єднання світлодіодів та узагальнений алгоритм керування індикатором. Наведені методи охоплюють оптимізацію програмного коду, зменшення навантаження на мікропроцесор та забезпечення стабільності системи візуалізації даних. Такий узагальнений підхід до реалізації програмного забезпечення є універсальним та адаптивним для індикаторів будь-якої розмірності, що робить його перспективними для використання в автоматизованих системах керування. Результати роботи можуть бути використані для підвищення техніко-економічної ефективності серійних та спеціалізованих пристроїв візуалізації даних.

Ключові слова: світлодіод, шкальний індикатор, двотактне збудження, деградація світлодіодів, електромагнітні завади, інформаційна модель, алгоритм, мікроконтролер, програмне забезпечення, вбудована система.