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Synthesis of an electronic system for controlling the conveyor line of rolling elements in the production of roller bearings

Adam Szcześniak[1*], Zbigniew Szcześniak[2]

[1] Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

[2] Faculty of Electrical Engineering, Automation and Computer Science, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

* Corresponding author's e-mail: adam_szczesniak@o2.pl

ABSTRACT

The electronic sequential control system is a key element in the efficient and precise process of delivering rolling elements to spiral storages. The application of properly designed control systems enables effective monitoring of the filling status of storage and adjustment of the flow of parts in interoperative transport. The electronic control system was developed based on a sequence graph of storage filling, which defines the sequence of actions and distributor settings. In the present work, memory blocks and single or two points sensors were used for effective real-time monitoring of the filling status of storage. Another key element of the system is the two-level control of the storage filling status, allowing for precise adjustment of storage emptying depending on the technological time of receiving elements. Verification and optimization of the electronic control system were carried out using the computer program FluidSim by Festo. The use of modern electronic and software-based solutions makes the production of roller bearings more efficient and optimal.

Keywords: electronic delay execution systems, synthesis and verification of sequential circuits.

INTRODUCTION

In serial production of rolling elements, automation of the transport route between individual stages is essential. Special machine tools used for processing elements have a high degree of automation. Activities such as delivering elements to workstations, applying elements for processing, etc., increase worker utilization, but can be more efficiently performed by a team of devices configured in a mass handling system. Automation of transport between production stages increases the efficiency of machine tools and reduces transport costs. The transport system must be flexible to be able to adjust to the production of different elements. In design, the analysis and synthesis of the conceptual diagram of the device play a crucial role [1, 2]. In sequential circuits, the output state depends on the current input state and the sequence of previous input states, whereas in combinational circuits, it depends only on the current input [3, 4]. Asynchronous sequential circuits do not have a clock signal, changes in inputs have an immediate impact on the internal state of the system [5].

The lack of a clock signal makes the design of asynchronous circuits more difficult than synchronous circuits [6]. With more inputs and internal states, using traditional transition tables becomes more cumbersome, and synthesis algorithms become more complicated [7]. To simplify the analysis of sequential circuits, an algorithmic approach to synthesis has been proposed [8]. The most popular programming language among PLC programmers is ladder diagram language, which facilitates understanding and executing more complex logical and arithmetic operations [9, 10]. Control schemes in this language consist of symbols placed in circuits resembling a relay ladder, allowing for the construction of control systems based on logical dependencies derived from Boolean algebra [7]. The article presents a continuation of research discussed in previous articles concerning the synthesis of electropneumatic sequential circuits with logic elements [11–13]. Control of transport routes is achieved using distributors consisting of actuators and two-state valves [14]. In the case of position control systems for actuators, proportional valves are used [15,16], and digital position transducers are employed to measure actuator position [17]. Lin, Zhang et al. and Lynnyk et al. presented examples of control system design using pneumatic elements and devices [20, 21]. The accuracy of positioning of executive elements plays a significant role in control systems, and analysis of accuracy in signal processing can be found in the literature [22–26].

An analysis of a conveyor line system delivering rolling elements to storages is described in the literature [14]. The conveyor line can be configured in any way by connecting distributors R. Rolling elements are transported from the reservoir to a specified height using a vertical lift PP, and then directed to spiral storage units M using distributors R, utilizing gravity and the specific properties of rolling elements. In general, the number of storages M is one greater than the number of distributors R, i.e., M=X+1 for R=X. This article presents a method of designing an automatic control system for the distribution of rolling elements using a fragment of a conveyor line with 8 storages M and 7 distributors R as an example. The configuration shown in Figure 1 is a fragment of a generalized configuration of a section of the conveyor line [14]. The article deals with solving the problem of automatic delivery of bearing rings to machining stations using a control system based on electronic circuits. The ring feeder places the elements on rail buses. Signals from storage filling sensors determine the choice of transport route.

The availability of the bus in which the selected storage at the machining station connects to the feeder is determined by controlling the distributors according to the adopted transport configuration. By using two-point measurement of storage filling, it is possible to establish a rotational stock by positioning the lower level sensor for rolling elements D and the upper level sensor for rolling elements G, as shown in Figure 2. On the basis of the findings regarding the configuration of the analyzed transport line, appropriate settings for individual distributors can be determined depending on the signals received from the sensors detecting the level of storage filling. The decision to choose the transport route is determined by the information from these sensors. Required settings for distributors R to ensure the continuity of the flow of parts to the respective spiral storage units are presented in Figure 1. For the analyzed configuration of the transport line, the flow to the storage is unobstructed with the distributor settings (Table 1).

For example to insure flow to, the selected storage M31, it is necessary for distributors R2, R3, and R31 to be activated (state 1), and distributors R32 and R4 to be deactivated (state 0). The remaining distributors can be in any state. Storage filling control can be achieved using single-point or two-point sensors, which must cooperate with delay circuits responding to the movement of rolling elements. Measurement and control systems based on electronic circuits have been created to monitor interoperative

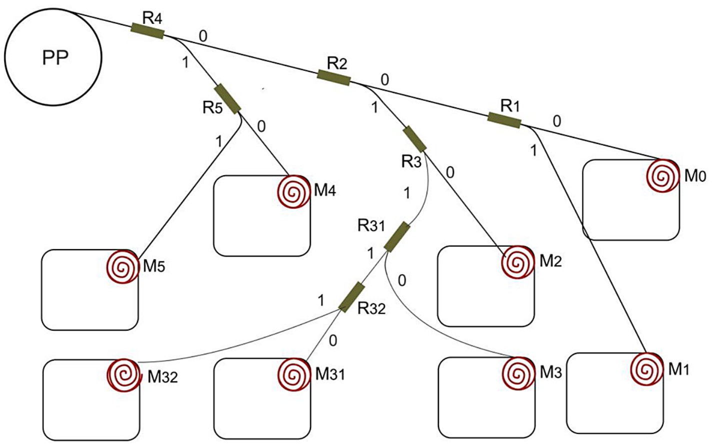

Figure 1. Configuration of the analyzed transport line: PP – vertical lift, R – transport route distributors, M – spiral storage units; M=8, R=7

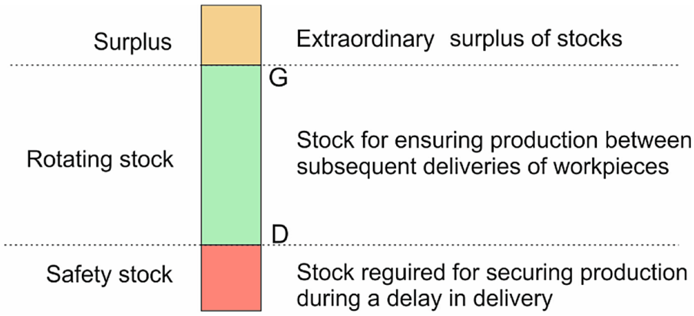

Figure 2. Stock of parts for the spiral storage unit of the machine tool and the position of the storage filling status control sensors

Table 1. State of R manifolds to provide a flow stream of workpieces to corresponding spiral storages M

	R1	R2	R3	R31	R32	R4	R5
M0	0	0	-	-	-	0	-
M1	1	0	-	-	-	0	-
M2	-	1	0	-	-	0	-
M3	-	1	1	0	-	0	-
M31	-	1	1	1	0	0	-
M32	-	1	1	1	1	0	-
M4	-	-	-	-	-	1	0
M5	-	-	-	-	-	1	1

transport of rolling elements. The methods delaying input signals of rising and falling edges, which cooperate with sensors monitoring the movement of elements, have also been developed. Inductive or capacitive proximity sensors are used to detect the presence of rolling elements [27]. Adopting to using the two-level control of storage status, it is possible to monitor the process of emptying storages depending on the time required to receive elements from the storage between checkpoints. The proposed method of control system design allows for the rapid creation of an electronic control circuit.

To characterize a mass handling system, three basic parameters must be determined: the intensity of the request stream, the service process intensity, and the queue discipline [28].

The success of an application directly depends on its stability, reliability, and security, which makes the proper implementation of control mechanisms critical [29, 30].

ELECTRONIC SPIRAL STORAGE CONTROL SYSTEM FOR ROLLING ELEMENTS

Moving rolling elements (bearing rings) in the area of the level control sensor of the spiral storage unit generate short pulses at its output, as shown in Figure 3. A short-term change in the sensor signal state generates a pulse or a signal dropout depending on whether it is a pulse generated by a moving ring in the filling phase of the storage (range A) or by a moving ring in the emptying phase of the storage (range B). To eliminate these unwanted signals, it is necessary to use an appropriate delay circuit cooperating with the storage level sensor. Figure 3 shows the general principle of operation of the delay circuit.

Delay signal leading edge implementation circuit

On the basis of the requirements presented in Figure 3, a circuit for implementing the delay of the input signal leading edge, as shown in Figure 4, was developed. The timing of t_p is achieved using capacitor C1 charged by resistor R1. A high state at the input of the circuit causes transistor T1 to enter saturation, resulting in current flow through resistor R1 and charging capacitor C1. A low state at the input of the circuit blocks transistor T1 and opens transistor T2, resulting in the discharge of capacitor C1 through resistor R2.

When transistor T2 is activated, the collector-emitter voltage U_{CE} is approximately 0.6 V, so

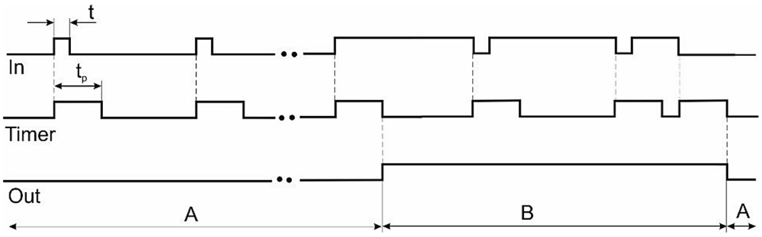

Figure 3. General principle of operation of the delay circuit

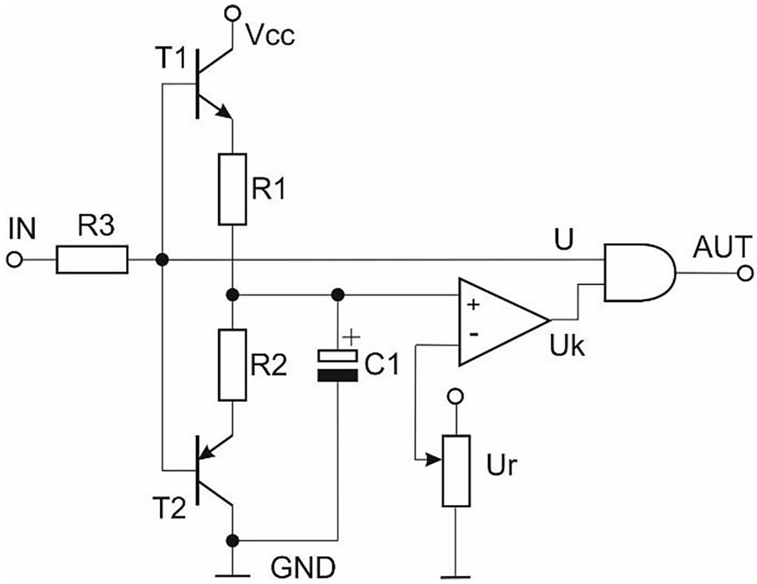

Figure 4. Schematic of the developed electronic circuit that implements the delay of the input signal leading edge

only up to this voltage can capacitor C1 be discharged. The essence of this circuit is the use of comparator Uk, at the output of which a high state (logical 1) is achieved when the condition Uc – Ur > 0 is met (i.e., when the voltage on capacitor C1 is greater than the reference voltage Ur). This allows for an increase in the voltage charging range of the capacitor, and thus the switching of the AND gate with a time close to the time constant τ = R1 C1, defined as the comparison time tp. In the case of the input signal IN in a high state (U = 1) and with a duration t greater than the comparison time tp (with the comparator signal Uk in a high state), then a high signal is present at the output of the AND gate. This state reflects the presence of a workpiece in the sensor's operating zone. The operation principle is depicted in Figure 5.

Circuit for implementing the leading and trailing edge delay of the input signal

Utilizing the schematic of the implementation circuit for delaying the leading edge of the input signal of the sensor, a module schematic for delaying both the leading and trailing edges of the input signal was developed, as depicted in Figure6. It consists of two leading edge delay circuits, with the input of the second circuit connected to the input of the first circuit through a NAND gate. Additionally, the output of the first circuit AUT1 is connected to the Set (S) input of an RS flip-flop built with NOR gates, while the output of the second leading edge delay circuit AUT2 is connected to the Reset (R) input of this flip-flop. The operation principle of the circuit is presented in Figute 7.

Electronic circuit for two-point control of the spiral storage filling state

Taking into account the requirements of the technological process of producing rolling elements, a circuit for two-point control of the spiral storage unit filling state was developed. The circuit was designed based on

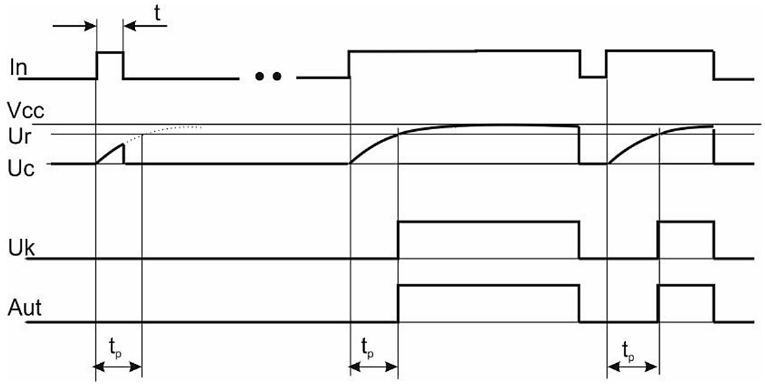

Figure 5. Voltage diagram in the leading edge delay pulse circuit

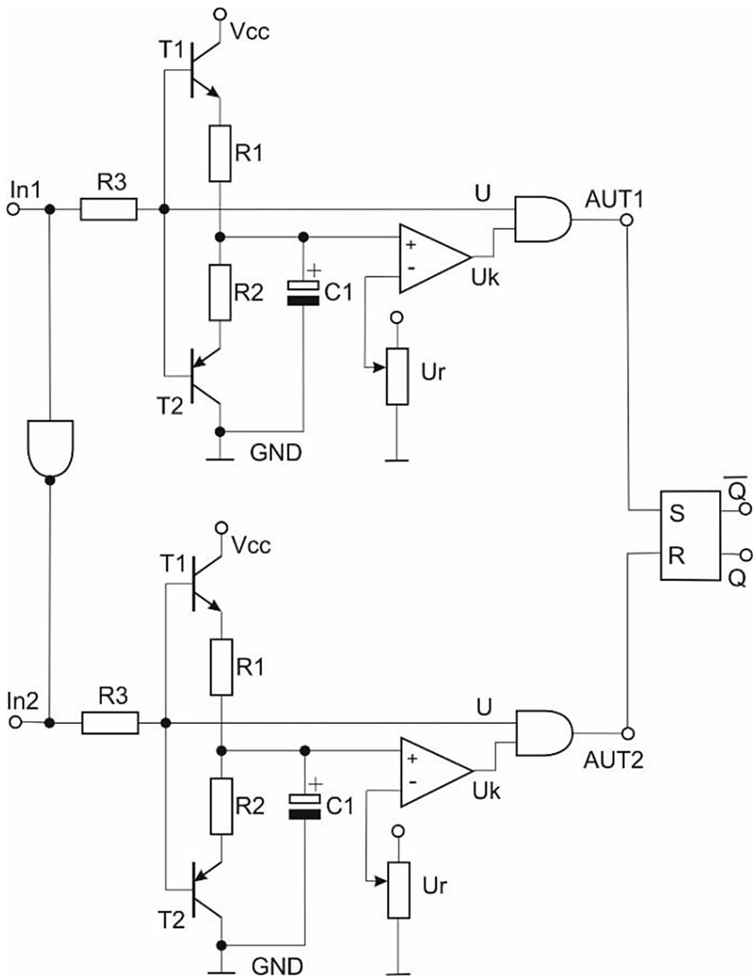

Figure 6. Schematic of the developed electronic module implementing the delay of both the leading and trailing edges of the input signal

the developed schematic of the module implementing the delay of both the leading and trailing edges of the input signal. In the designed circuit, the signal performing the function ¬(¬D + ¬Q) + G was applied to input In1, as depicted in Figure 8.

In Figure 9, ranges of the spiral storage unit state are marked: a – filling range of the storage unit, b – range of the filled storage unit state, c – range of the empty storage unit state, t – range of the technological emptying of the storage unit (rotational stock).

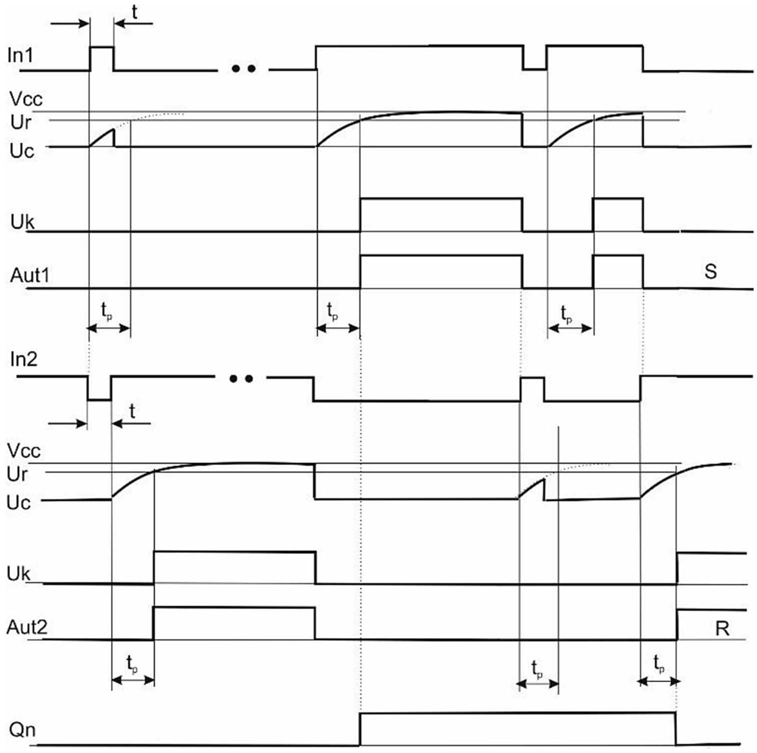

Figure 7. Voltage diagram in the leading and trailing edge delay pulse circuit

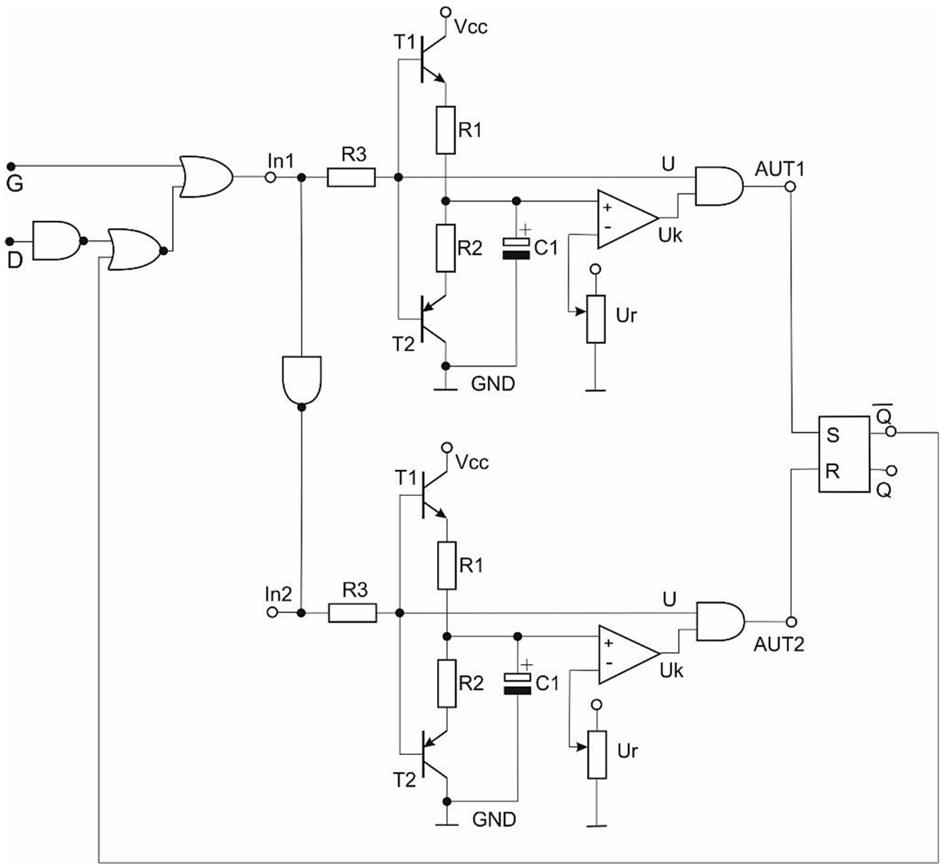

Figure 8. Schematic of the adopted electronic module for two-point control of the spiral storage unit filling state

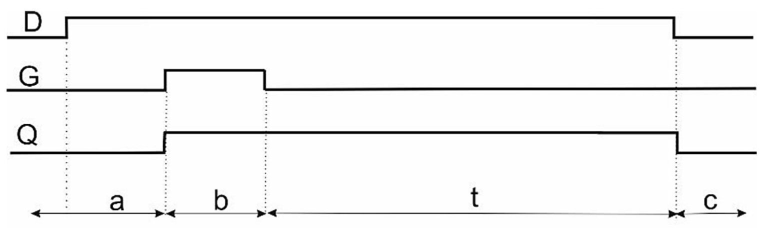

Figure 9. Input-output voltage chart of the module for two-point control of the spiral storage unit filling state

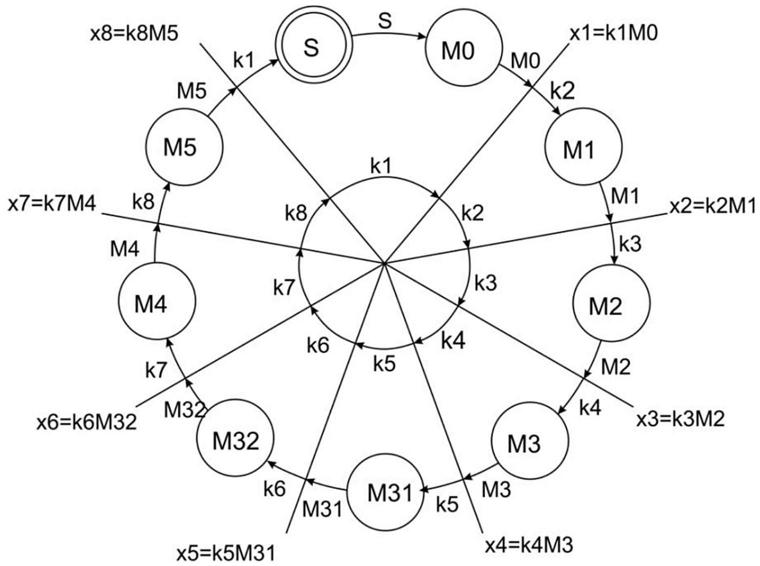

Figure 10. Sequence graph of filling the spiral storage units

DEVELOPMENT OF A CONTROL SYSTEM FOR TRANSPORTING ROLLING ELEMENTS TO THE SPIRAL STORAGE UNIT

The primary component of the control system is the memory block, which is designed based on the sequence diagram for filling the storage units. The sequence for filling the storage units from M0 to M5 is followed in the diagram, as shown in Figure 10. The graph is radially divided, with memory state k assigned to each storage unit M. Signal xn is placed along the division line to indicate the transition to the next state kn (filling the storage unit in state kn allows the system to move on to the next unfilled storage unit). The graph shows the memory state of the sequential filling control system during the storage unit filling process. The memory is in a high state for the storage unit being filled. The selection of the next storage unit occurs in the subsequent high memory state (logical state 1), i.e., during the transitioning high memory state. The sequence of filling the storage units depends on the memory state, and is as follows: k1 → M0, k2 →M1, k3 →M2, k4 →M3, k5 → M31, k6 →M32, k7→M4, k8 → M5.

From the graph (Figure 10) and the state of the distributors to manage the flow of items to the corresponding storage units M, a sequential control system for filling the storage units was created, as illustrated in Figure 11. The electronic system for sequential filling of spiral storage units of rolling elements consists of three main blocks:
- block of control systems for filling the single-point;
- two-point storage units M0 – M5, in accordance with Figure 6 or Figure 8;
- memory control system block and memory k1 – k8;
- control system block for output elements, i.e., flow distributors;
- R1-R5 to storage units M0-M5.

The system memory is built using RS flip-flops, controlled by signals x1 through x8, with each new memory state resetting the previous one. The storage unit states are represented by signals M0 to M5, which correspond to the status of control sensors interacting with delay

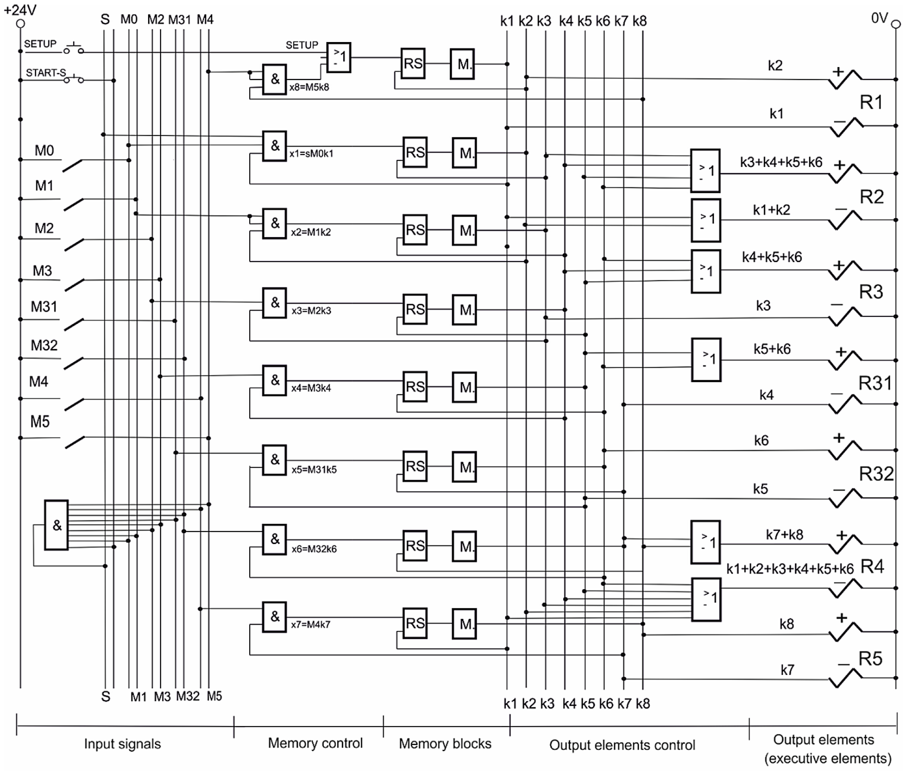

Figure 11. Electronic system for sequential filling of spiral storage units of rolling elements

circuits. The states of distributors, which control the flow of items to the respective spiral storage units M, are managed by summing elements. The distributors not involved in directing the flow to fill the currently chosen storage unit maintain their previous positions, as resetting them to zero positions is inefficient; they can be set to any position. It should be emphasized that the vertical feeder is controlled according to the following relation:

$$S = (START\text{-}S)\,[(M0)+(M1)+(M2)+(M3)+q +(M31)+(M32)+(M4)+(M5)] \quad (1)$$

Figures 12, 13, and 14 illustrate selected simulation flowcharts of the sequential control system for filling spiral storage units with rolling elements in the analyzed transport line configuration. In Fig. 12, the system depicted is in memory state k6. Spiral storage unit M32 is being filled. In this case, distributors R2, R3, R31, and R32 are activated (set to state 1), while distributor R4 is deactivated (logical state 0). This corresponds to the state of the distributors, ensuring the flow of details to spiral storage unit M32. In Figure 13, the system depicted is in memory state k5. Spiral storage unit M31 is being filled. In this case, distributors R2, R3, and R31 are activated (set to state 1), while distributors R32 and R4 are deactivated (logical state 0). This corresponds to the state of the distributors, ensuring the flow of details to spiral storage unit M3. The presented simulation distinguishes the following phases of the system:

1. Initial state: all storage units M0, M1, M2, M3, M31, M32, M4, M5 are unfilled.
2. Upon activating the control system (START-S), rolling elements are delivered to storage unit M0. Distributors R1, R2, and R4 are in the off state (logical state 0), whereas the vertical feeder is activated.
3. After filling storage unit M0 (logical state 1), storage unit M1 is filled with distributor R1 activated (set to state 1) and distributors R2, R4 deactivated (logical state 0).
4. After filling storage unit M1 (logical state 1), storage unit M2 is filled with distributor R2 activated (set to state 1) as well as distributors R3 and R4 deactivated (logical state 0).
5. After filling storage unit M2 (logical state 1), storage unit M3 is filled with distributors R2 and R3 activated (set to state 1) as well as distributors R31 and R4 deactivated (logical state 0).
6. After filling storage unit M3 (logical state 1), storage unit M31 is filled with distributors R2,

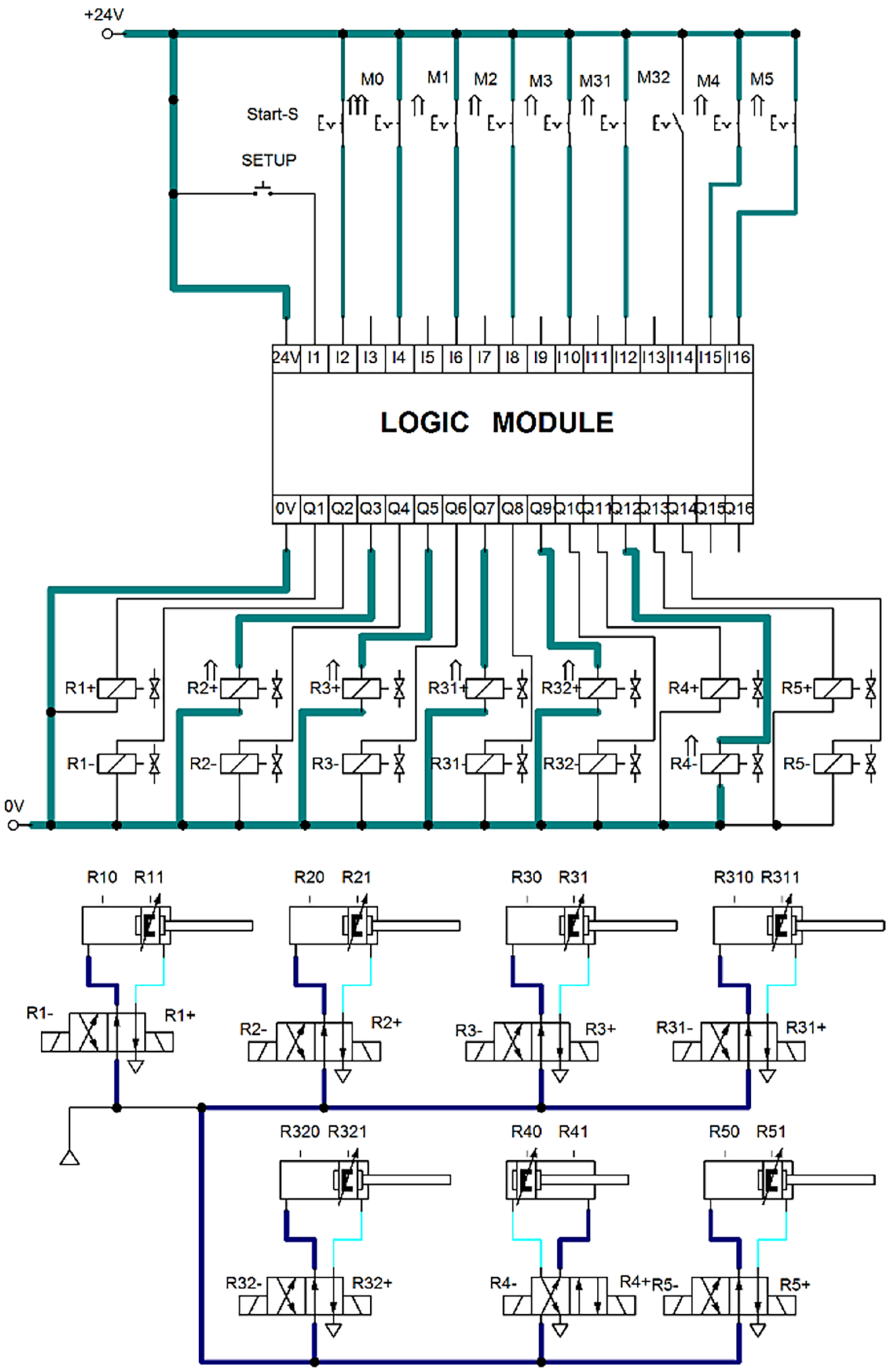

Figure 12. General diagram of the electronic sequential system in the selected state of filling spiral storage units

R3, and R31 activated (set to state 1) as well as distributors R32 and R4 deactivated (logical state 0), and so on.

7. After filling storage unit M31, the remaining storage units are filled in the sequence M32, M4, and M5. Upon filling them, the system turns off the vertical feeder of rolling elements (S=0) and halts the cycle in state k1 (distributors R1, R2, and R4 are in the off state), awaiting notification of a storage unit to be filled.
8. Next, storage unit M1 is signaled for filling, which is filled with distributor R1 activated (set to state 1) as well as distributors R2 and R4 deactivated (logical state 0), with the vertical feeder of rolling elements activated.

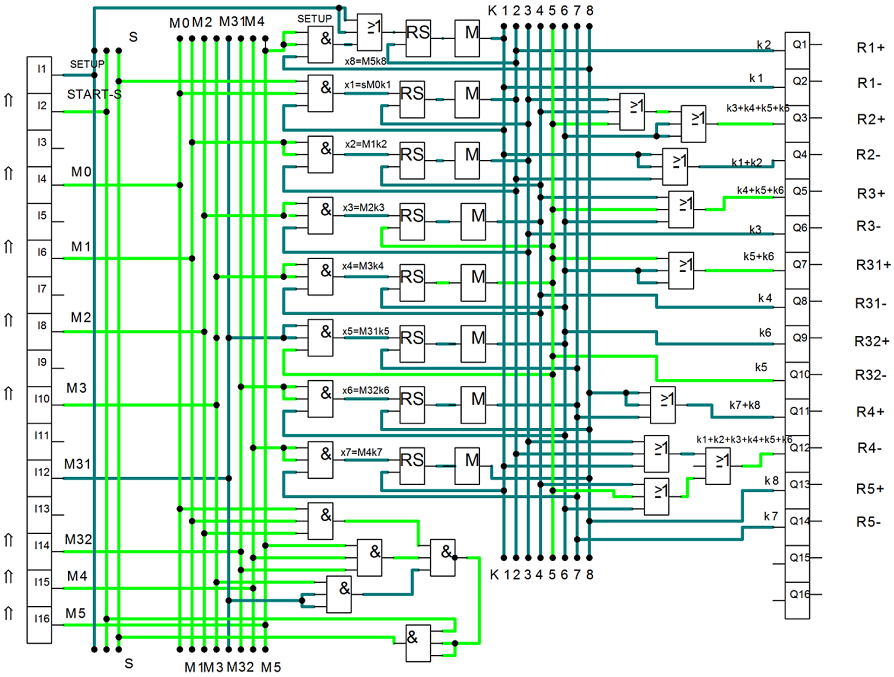

Figure 13. Logical module of the electronic sequential system in the selected state of filling spiral storage units

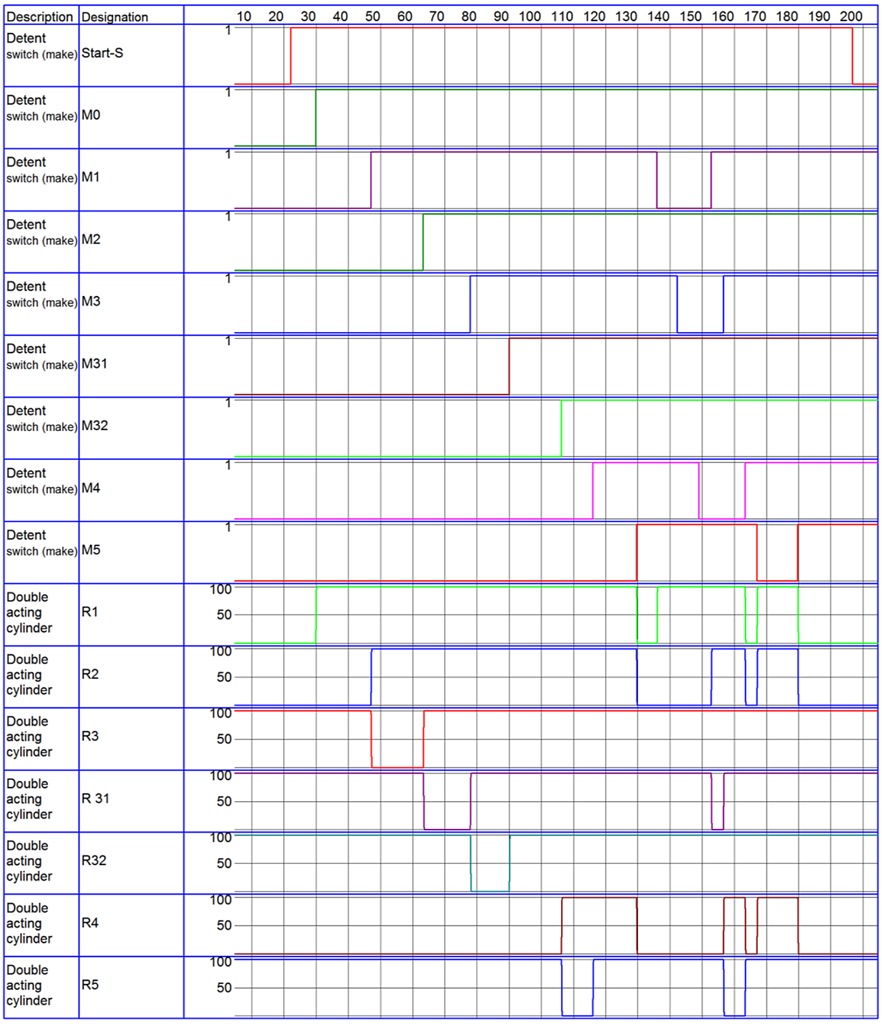

Figure 14. Flowchart of the sequential control system for filling spiral storage units of rolling elements

9. After filling storage unit M1 (logical state 1), the next unit signaled for filling is storage unit M3, which is filled with distributors R2 and R3 activated (set to state 1) as well as distributors R31 and R4 deactivated (logical state 0).
10. Following the filling of storage unit M3 (logical state 1), the next unit signaled for filling is storage unit M4, which is filled with distributor R4 activated (set to state 1) and distributor R5 deactivated (logical state 0).
11. Upon filling storage unit M4 (logical state 1) and all remaining units, the vertical feeder of rolling elements is turned off, and the cycle of the automaton halts in state k1 (distributors R1, R2, and R4 are in the off state), awaiting notification of an empty storage unit for filling.
12. The handling of filling an empty storage unit occurs sequentially, selecting from M0 to M5.
13. The control system algorithm concludes operation by turning off START-S.

CONCLUSIONS

The article was inspired by designers of transport route control used in the production of rolling bearings. Taking into account the difficulties and inconveniences of using transition and output tables in the synthesis of sequential asynchronous systems, an algorithmic approach was present to develop the synthesis of asynchronous sequential systems in interpretational transport.

The developed method of creating a control scheme is universal and can be used for any configuration of a transport line with N warehouses and N-1 distributors. The transport system must also the adopted algorithmic method present a guarantee to retooling the production process that required the use of universal modules from control devices independent of the transport route configuration and quick program change.

It should be emphasized that a two-point control method is an innovative solution for the filling level of spiral magazines for machine tools, implemented in the form of electronic diagrams, which allows the implementation of a comprehensive control system using electronic diagrams.

Further research will aim to develop methods and principles for creating control modules for transport routes delivering elements to storage units in interoperative transport using queuing algorithms for queueing storage requests for service.

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