The control algorithm of a programmable tandem detonator

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Abstract. The article describes the results of laboratory tests of the algorithm of control of programmable detonators designed for tandem systems. Control elements were made on the basis of microcontrollers using RISC architecture. The detonator has a system to quickly excite the precursor charge and can be programmed at any time to delay the detonation of the main charge. The lack of delay in excitation of the precursor charge was realized using a comparator. The article presents the results of preliminary laboratory tests of the control algorithm of the executed system. The flexibility of the solution to program any delay time for the excitation of the main load provides a wide range of practical applications.

1. Introduction
In order to ensure the safety of system operation, research was undertaken into the control algorithm of the programmable tandem detonator. The aim of the research was defined as a research question: does the algorithm of fuse control ensure safe operation during normal operation and in the event of an error? The research of the algorithm of control of the cumulative missile detonator with precursors in the tandem system [1] was carried out on the example of the developed programmable tandem detonator module. A simplified block diagram of the detonator system is shown in figure 1. It was built on the basis of microcontrollers with RISC architecture. Since all the microprocessors in this system are synchronized from a single clock source, the study adopted one algorithm implemented on several cores simultaneously. Additionally, an algorithm for resuming the stopped process in case of error detection has been developed.

With multiple processors, we can increase the reliability of the algorithm by mutually controlling the most important parameters or states. The parallel algorithm executed on several microcontrollers synchronized with the clock can be described by means of the machine of parallel states [2].

Independent state machines can monitor each other as long as they can communicate and transmit information or states. Sometimes this may result in some consistency problems, which the algorithm has to solve, for example, using hierarchical modelling [3] or fuzzy logic [4], [5]. The article presents the algorithm of control and supervision and the results of research of the algorithm realized on several microcontrollers synchronized with the clock at the same time.

2. System design and operation
A simplified block diagram of tandem detonator control is shown in figure 1. The system uses three independent microcontrollers using RISC architecture. In order to enable parallel operation of the system and synchronization of the algorithm (software) running on these processors it was necessary to use a common clock source.
Independent processors working together, where one of them has the highest priority, resemble a client-server network architecture. In this case, there are two slave processors as client. Microcontroller number 3 (figure 1) takes on the role of a server (host processor). The replication of commands between all processors ensures high consistency [2], each processor receives an undamaged replica of the command and the results of the commands executed. In this way, a change in the state of any of the machines in the system states is visible on the remaining machines. The execution of commands must be deterministic, changes of state depend only on the own function of the transition and the command.

The host processor must agree on the sequence of replicated commands and executed commands. It also maintains communication through the RS data bus with the external system. The slave processor state machines can be treated as independent, but in the whole system, together with the slave processor, they form a mutually controlling whole. By replicating commands and states, each processor can detect a malfunction of another microcontroller. In case of an error, the higher-level processor decides about the state change using hierarchical modeling [3] or fuzzy logic [4], [5]. In this way, the state of failure of one of the processors forces the superior processor to operate, whose task is to restore the balance of the system. This is particularly important in the case of fire-fighting systems. Such agreements must not allow the system to fail to revert to a failure state.

The operating algorithm of the tandem programmable detonator is presented in the form of a state machine in figure 2. As described above, three microcontrollers are used in the programmable detonator. Therefore, the algorithm is executed on three processors in parallel mode.

Figure 2 shows two auxiliary processors in the form of TH-1 and TH-2 sub processes (internal algorithms). Both of these algorithms are constructed identically to the algorithm shown in figure 2. The TH-1,2 microcontroller state machines, which are responsible for the sub-processes of arming and detonating the precursor and main charge, look the same. This means that the operating diagrams (excluding the TH-1 and TH-2 sub processes) in figure 2 apply to all processors in the detonator circuit. Explaining this, it can be assumed that we have three identical algorithms running here on three processors synchronized with a common clock from POWER/Reset to ARMED states.

Until no error occurs in the operation of one of the algorithms, i.e. until none of the state machines is in state ERROR, the algorithms remain consistent.

As described above, the mutual correlation of algorithms is ensured by a common clock signal and an identical state machine diagram (figure 2). The system uses an internal data bus for communication between processors, which is used to compare states.
Figure 2. State machine algorithm of the programmable tandem detonator.

Each processor has access to it and knows the status of the others. If one of the machines is in the ERROR state, the whole system loses its consistency. Until proper operation is restored, the system remains in the locked state. The author of the algorithm conducted multiple experiments, during which the algorithm was introduced into the error state by purposefully forcing the damage. Each time, the system immediately went into ERROR state.
The problem was to construct an algorithm that would be able to restore the system to proper operation after the failure has subsided. The problem was to construct an algorithm that would be able to restore the system to proper operation after the failure has subsided. Leaving the system in a locked state when the damage has disappeared is not an optimal solution. This is particularly important for the security of the system. An external system can transmit the ‘disarm’ command via an RS connection (figure 1). This makes it possible to protect the system. If the system is operational, the algorithm (figure 2) should be in ready state. In this state, the system remains protected (disarmed).

Two algorithms are proposed to restore the proper functioning of the detonator system after the damage has subsided. The first one is based on hierarchical modeling [3] and the second one uses fuzzy state machine, fuzzy edge identification [4,5,6]. For security reasons, both algorithms work independently. The resumption of operation of the stopped state machine algorithm is the result of a number of individual tasks. Usually, each one of them requires a specific time and energy e.g. to check the value of the security mechanism position sensor.

The functionality of the algorithm can be defined as a set of measurement tasks performed in a specific order. The entire control cycles can be arranged as a hierarchical tree [3]. In this way we will obtain the weighting coefficients of the individual functions. The task of resuming the algorithm can be defined as an optimal solution described by the vector of tested parameters and the target function. Optimization is therefore a search for a minimum of target functions. In this case, we are looking for a vector of many parameters:

\[
x = [x_1, x_2, \ldots, x_k]
\]

which optimizes the function vector, whose elements represent the function of the target:

\[
f(x) = (f_1(x), f_2(x), \ldots, f_N(x))
\]  

One of the classic approaches to solving this problem is to minimize the scalar function that combines the partial functions of the target:

\[
\min_{x \in \mathbb{R}} f(x) = \sum_{i=1}^{K} w_i f_i(x)
\]

where \( w = [w_1, w_2, \ldots, w_N] \geq 0 \) is a vector of weighting factors adopted \( a \text{ priori} \) before the start of the minimization process based on the hierarchical model. Therefore, if there is a non-empty set of optimal solutions, then minimizing the weight function of the target (3) will lead to this solution regardless of the adopted weighting coefficients \( w \). Errors resulting from the incorrect sequence of the verification functions (wrongly adopted hierarchical model) do not have a significant impact on finding an optimal solution.

The second approach to solving this problem is based on fuzzy reasoning [4,5,6]. Based on the verbal description (language model), fuzzy relations between the measured values and the decision (restoring the correct functioning of the detonator system) are created:

\[
R = \frac{N}{I} \quad (X I \rightarrow Y I)
\]

Depending on (4) \( \rightarrow \) is a symbol of the operation by which fuzzy implications are defined, the symbol * means \( N \) of fuzzy relations. The fuzzy RN relation represents the \( N \) fuzzy implication in the verbal description (e.g. danger, security sensor is open). Other relations R1, R2, ..., RN are created analogously using the same definition of fuzzy implication.

The result is a relationship matrix \( R \), which contains a set of possible solutions in \( X \) columns and \( Y \) rows. The change of value with the direction is a gradient, which is measured by the discrepancy between the values of the adjacent values. We represent all possible resultant relationships in the form of matrix and the gradient of changes as a change of value along with the direction of movement in the matrix. Using the modified Fuzzy Edge Identification algorithm [6], we obtain a closed set of
solutions in the form of ‘contours’, which we calculate from the dependencies of gradient determination as the difference in adjacent columns and rows [6]:

\[ dY(j, k) = X(j, k+1) - X(j, k-1) \]  \hspace{1cm} (5)

\[ dX(j, k) = X(j+1, k) - X(j-1, k) \]  \hspace{1cm} (6)

The task of resuming the algorithm described above as an optimal solution described by the vector of tested parameters x and the target function is located inside this set. Using fuzzy state machine [4,5] and fuzzy edge identification [6], the inference based on the search for an optimal solution was applied. Both algorithms, working independently and together, decide to resume the algorithm. If one of them sustains a state of failure of the programmable tandem detonator, the system will remain locked. The strategy of this algorithm inside the Blocking sub process (figure 2) guarantees the safety of the control algorithm of the programmable tandem detonator.

3. Laboratory tests

![Laboratory test rig for the algorithm of detonator control.](image)

The aim of the research, defined in the introduction, was a research question: does the ignition control algorithm ensure safe operation during normal operation and in the event of an error? In order to carry out the research program, a measurement stand was prepared, shown in figure 3. The algorithms described above and the algorithm of the main processor (figure 2) are implemented in c++ language on the microcontrollers (figure 1). This article discusses only a narrow scope of research, concerning the thesis contained in the above question. The methodology of testing the effectiveness of algorithm has been formulated in the form of a classic multi-stage optimization. The most important indicator of the algorithm's effectiveness is the safety of the ignition system control.

The two algorithms used together to restore the correct functioning of the detonator system after the defect had disappeared were tested. In a hierarchical model, the corresponding function representing the above indicator is placed highest. In the fuzzy model it had the highest weight. The remaining partial functions of the target (3) were optimized in subsequent steps.

Many tests were performed, during which all possible system failures and algorithm malfunctions were simulated. The results were collected and analyzed in a spreadsheet. The observations consisted in testing the operation of the system by measuring signals on an oscilloscope. In accordance with the
principle of detonator operation, any unintentional triggering of an excitation pulse shall constitute a system malfunction. This was the primary criterion in the research of the algorithm.

The next step was to observe the remaining Blocking state of the system (figure 1) after ERROR signal. After each series of tests, the algorithm was corrected, which resulted from the minimization of operating errors described above by the vector of tested parameters and the function of the target (2).

4. Conclusions
The ignition control algorithm has been shown to be safe during normal operation and in the event of an error or failure. The research did not reveal any case of algorithm malfunction.

The applied research method (multistage optimization) proved to be effective, the aim of the research was achieved, the positive answer to the initial question and the results of the tests confirm the correct functioning of the detonator system. The issue is difficult in terms of formalizing a set of measurement tasks performed in a specific order.

The implementation of verbal rules in the form of a digital algorithm was possible with the use of the algorithms discussed here. I would like to thank the authors of the publications [3,5,6] that helped us to develop functional software algorithms. Both algorithms tested together (hierarchical and fuzzy logic) proved to be fully effective. The high level of operational safety of the algorithm was achieved due to the fact that the most important indicator of the effectiveness of the algorithm is the safety of the control of the detonator system.

In the next stage, climate tests and shooting tests will be conducted.

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