FORMALIZED METHOD OF INTER-MACHINE INTERACTION OF INTELLIGENT PARTICLES WITH A SERIES OF BEHAVIORAL SCENARIOS OF PARTICLES AND THE SWARM AS A WHOLE

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Abstract: The article is devoted to the development of a formalized method of inter-machine interaction of intelligent particles, which includes a series of scenarios for the behaviour of individual particles and the swarm as a whole. The main emphasis is placed on the formation of model and algorithmic support for a promising multi-agent technology based on the principles of communication between particles. Various behaviour scenarios of particles during their life cycle are considered, from emission to deposition through propagation, with the application of functions of data collection, transmission, and reception within the swarm. Graph theory and methods of pulse-width modulation are applied for modelling the interaction. Algorithms for controlling the operating modes of particles are presented, optimized for specific stages of experimental research. The results of efficiency analysis of the proposed approaches are provided, as well as recommendations for the design of communication technologies for swarm systems..

Key words: Inter-machine interaction, smart particles, communication technologies, information visibility, control modes.

1. INTRODUCTION

The study of anthropogenic impact on the environment is associated with the enhancement of the reliability of technical systems and the development of cyber-physical systems with multiloop control. To improve the accuracy of data on technological processes, the use of the Smart Dust technology is proposed. Smart Dust is a novel technology that does not yet have an established definition, while its scope of application remains open and versatile.

The research tasks are related to the development of model and algorithmic support for a promising multi-agent technology. The scientific novelty of the study consists in the elaboration of methodological approaches to management based on the exchange of

information among swarm particles according to the principles of machine-to-machine interaction, as well as in the substantiation of solutions to particular theoretical and model-practical problems associated with the formation of a multiloop cyber-physical system. At the current stage of technological development, the model abstraction of the swarm is represented by a group of particles without active controlling capability, meaning that swarm propagation is considered in conjunction with physical processes. With regard to these model limitations, the study is aimed at designing communication technologies for swarm particles in formats one-to-one, one-to-many, and many-to-many, as well as at formalizing methods and algorithms of machine-to-machine interaction of particles with the development of behavioural scenarios for individual particles and for the swarm as a whole.

2. RELATED WORK

A common feature across all areas of application is that the term "Smart Dust" refers to miniature autonomous electronic devices equipped with their own power supply, data exchange interfaces, computational resources, and memory [1,2,3]. These particles are capable of communicating both with each other and with an external system. The review [4] provides an overview of the current state of technology development in the field of Smart Dust. It is noted that miniature digital circuits, wireless communication, and microelectromechanical systems constitute the three fundamental technologies that largely enabled the creation of compact autonomous elements (intelligent Smart Dust particles) possessing sensing, computational, and communication capabilities, as well as embedded power sources.

Competing researchers are those working in adjacent areas who develop intelligent systems for industrial and environmental monitoring by employing methods of IoT and machine learning [5]. Despite the active development of Smart Dust-related research, there are currently no ready-made algorithms and models that would allow the use of a swarm of Smart Dust particles to solve model problems of environmental monitoring aimed at assessing anthropogenic impacts on the environment. Moreover, the behavioural aspects of the particle swarm under various boundary conditions have not yet been studied, including the effects of swarm regression.

3. DESCRIPTION OF THE PROBLEM AND PROPOSED SOLUTION

The subject of the study is the technology of transmitting collected data under conditions of degradation of the carrier objects of information. The data exchange task is reduced to one-way transmission of information, that is, replication. The interaction of objects is considered on the principles of one-to-one (point-to-point) communication, one-to-many communication under conditions of divergence, and many-to-many communication under conditions of data convergence.

The object of the study is a group of particles lacking active control capability, which perform the collection of technological data and possess a limited time-to-live (TTL) parameter. As a whole, the swarm of functional particles is capable of implementing a multi-agent technology that serves as the basis for a multi-loop cyber-physical system provided that interaction with the external environment takes place.

Thus, a technological stack is formalized as a set of objects and functions that requires a transition towards methodological substantiation, the search for and application of an appropriate theory, methodology, model abstraction, mathematical framework, and software implementation in the form of a simulation model.

3.1. A group of particles without active control capability

Let us consider the following model conditions under which particle emission occurs within a technological process, namely the discharge of flue gases and suspended particles from a thermal power facility. Under the influence of forced-draft fans and the energy of convective flows, the flue gases move upward through the exhaust stack. The particle swarm, driven by physical processes, propagates within a confined space and maintains a high particle density along the entire length of the exhaust stack.

The model abstraction of a particle includes a number of characteristics, in particular the lifetime parameter (TTL), which characterizes the rate of degradation of the swarm as a whole and its ability to maintain communication among particles for the purpose of exchanging information regarding the implementation of the technological process. The primary function of a particle is to ensure continuous exchange of technological information, that is, to transmit collected data and to receive data from other particles.

Thus, taking into account the model constraints, a set of judgments can be formulated:

- Within the field of informational visibility, the particles engage in continuous exchange of collected information, including competitive information (many-to-one).
- Within the boundaries of the flue ducts, the particles maintain high informational visibility, considering the low degradation of the swarm at the initial stage of the experiment.
- Outside the flue ducts, the particles are exposed to the influence of atmospheric air masses, dispersion in the air, and their natural deposition on surfaces and the ground. At this stage of the experiment, the informational visibility of the particles decreases, and the swarm undergoes degradation.
- Research value is represented by swarm particles that have engaged in informational exchange with other swarm particles during their movement from emission to deposition.

According to the modelled experimental conditions, the scenario for the first control group of particles is formulated as follows:

- at the emission stage, there is collection of technological information with a high polling frequency of sensors, intensive transmission of data to other particles, and low reception of data from other particles.
- at the dispersion stage, there is collection of technological information with a moderate polling frequency of sensors, moderate transmission of data to other particles, and moderate reception of data from other particles.
- at the deposition stage, there is collection of technological information with a low polling frequency of sensors, moderate transmission of data to other particles, and high reception of data from other particles.

The scenario for the second control group of particles involves inverted actions (functions) in relation to data reception and transmission across all three stages of the experiment, with the aim of ensuring convergence of the control modes of particle functioning.

4. PRESENTATION OF THE EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Graphical representation and design of a particle swarm controller model

Let us consider the methodology of graph theory, specifically the section concerning finite automata, in the context of applying the methodological basis for the formalization and representation of a group of particles whose primary principle of interaction is communication.

In accordance with the adopted model conditions of the experiment, the implementation of the scenario for the first control group of particles can be represented by a control unit governing the operating modes of a swarm particle (Figure 1). This controller is represented by a Mealy finite automaton and performs three control modes: emission (inner loop of the node), propagation (middle loop of the node), and deposition (outer loop of the node).

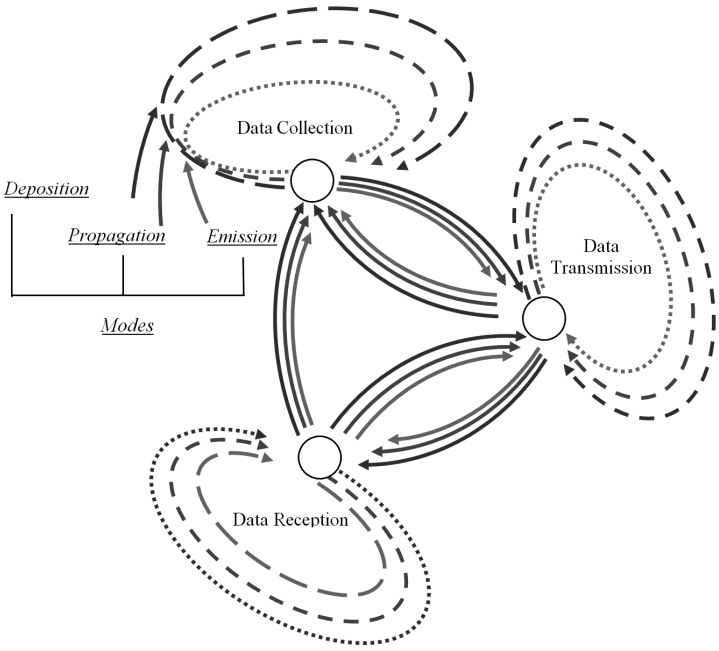

Figure 1. State machine graph (diagram) of actions of the model conditions characterizing each stage of the experiment

Each mode is characterized by the same set of functions, which include data collection, data transmission, and data reception. The distinguishing feature of each

mode is the frequency of repetitive actions (steps) within a function and the conditions of transition from one function to another.

Considering the limited computational potential of the particle, pulse-width modulation (PWM) can be applied as a principle for regulating the frequency of repetitive actions (Figure 2). The duty cycle of the control signal ensures the periodicity of functional actions for each mode (1).

$$S = T/t, \quad (1)$$

where, T is the pulse period, t is the pulse duration.

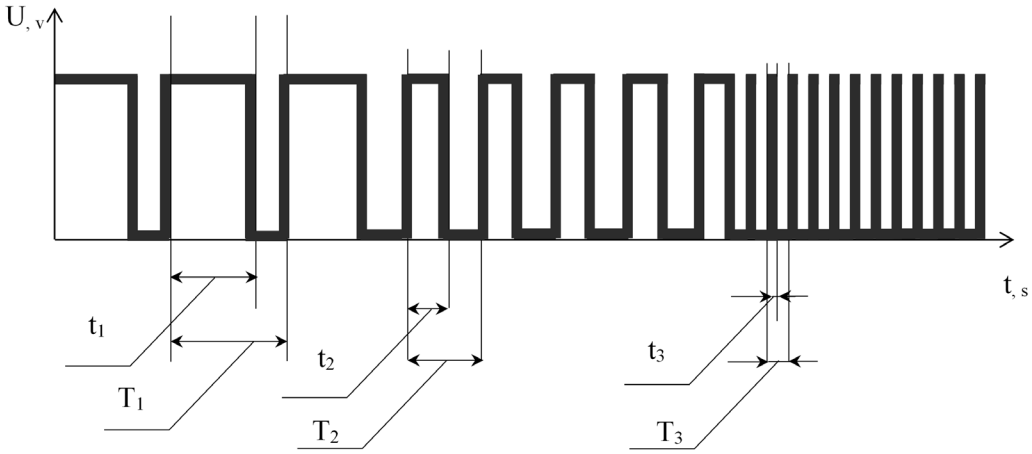

Figure 2. Model diagram of the control signal of the particle swarm mode controller "Deposition" using the pulse width modulation method

In accordance with the model diagram, each mode is characterized by the frequency responses of the particle functions (Table 1).

Table 1. Frequency characteristic of particle functions in various modes

	"Data Collection" Function	***"Data Transmission" Function***	***"Data Reception" Function***
"Emission" Mode	$S_1 = 10/3$ (3,33)	$S_2 = 10/3$ (3,33)	$S_3 = 10/6$ (1,5)
"Propagation" Mode	$S_1 = 10/5$ (2)	$S_2 = 10/5$ (2)	$S_3 = 10/5$ (2)
"Deposition" Mode	$S_1 = 10/6$ (1,5)	$S_2 = 10/5$ (2)	$S_3 = 10/3$ (3,33)

Thus, the characteristics of the data collection, transmission, and reception functions are defined for each mode of the model study of swarm particles by the parameter S, the duty cycle of the pulse-width modulation method, which, in turn, can be applied as a control signal for regulating the frequency of repeated actions (steps).

For the purpose of designing and subsequently algorithmizing the model scenario implemented by the first control group of swarm particles, the graphical language of sequential schemes Sequential Function Chart (SFC) of the IEC 61131-3 (GOST R) standard is considered.

Figure 3 presents the SFC scheme of a swarm particle function with a detailed representation of the "Propagation" mode of the swarm particle scenario. The initial step is sensor polling. In the "Propagation" mode, the primary priority logic remains the collection of parameter data concerning the technological process (temperature, flow velocity, and the concentration of gases and suspended particles). At this step, the action of "technological data acquisition" is carried out until an interrupt occurs under a specified condition.

The specified condition affecting the switching process of SFC step activity is the information visibility of the particle, under which a communication session can be established (data transmission request). On fulfillment of this condition, the transition to the "data transmission session" step takes place. At this step, the action of "technological data transmission" is carried out until an interrupt occurs under the specified condition.

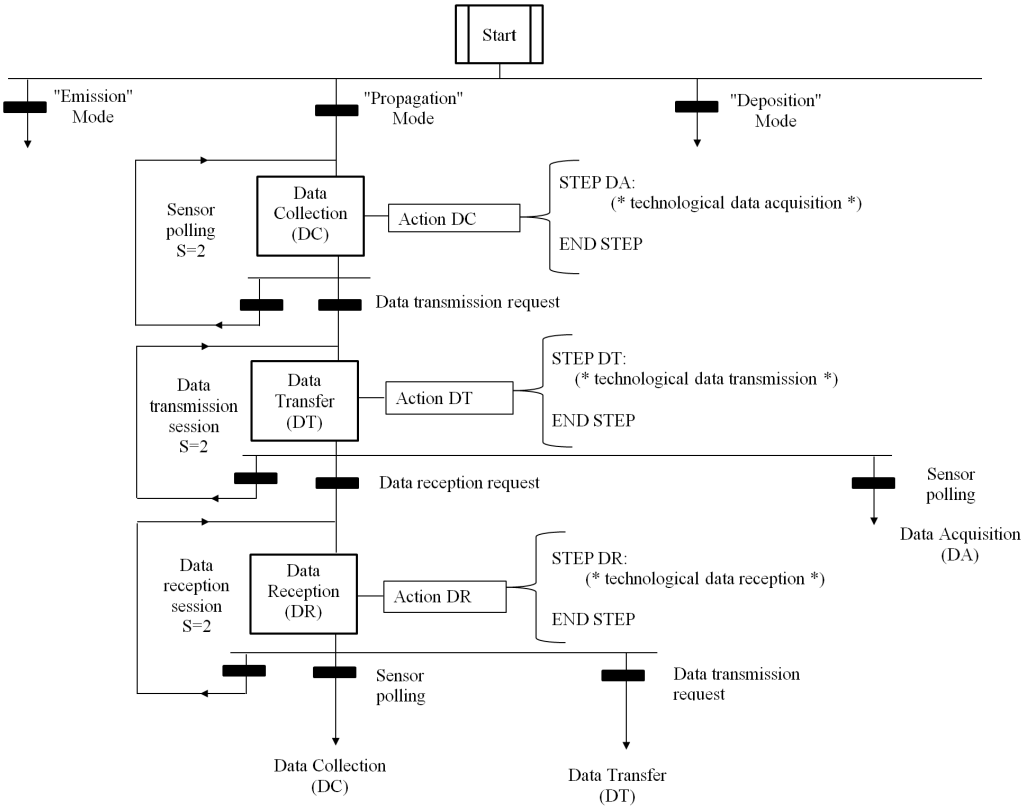

Figure 3. SFC scheme of particle swarm function implementation with detailed representation of the "Propagation" mode in the particle swarm scenario

The specified condition in this case is also the information visibility of the particle, under which a communication session can be established (data reception request). On fulfillment of this condition, the transition to the "data reception session" step occurs. At

this step, the action of "technological data reception" is executed until an interrupt occurs under the specified condition.

The specified condition here is the absence of information visibility of the particle, under which a communication session can be established. On fulfillment of this condition, the transition to the "sensor polling" step occurs.

It should be noted that in the "Propagation" mode, the characteristics of the functions of data collection, transmission, and reception in the model study of swarm particles are defined by the value "2" of the parameter S, the duty cycle of the pulse-width modulation method.

4.2. Results of simulation of particle swarm behaviour scenarios

To study the behaviour of a smart dust particle array, a simulation environment was implemented. The implementation was carried out in the C# programming language within the VSCode environment. The ScottPlot library was employed for graph plotting.

The simulation consists of 1000 iterations, where each iteration represents a time interval sufficient for measuring the current parameters, recording them, transmitting, receiving, and storing information from neighbouring particles.

A total of 1000 particles participate in the simulation. Each particle is equipped with three sensors (temperature, flow velocity, and concentration of gases and suspended particles) for environmental parameter measurement, as well as a memory capacity sufficient to store six complete sets of measured data. It is assumed that each particle can store not only its own measurement results but also the data of five other particles.

Each particle possesses a unique identifier ID (0–999) that is transmitted and recorded together with the corresponding measurement values. The memory stores information about which particle is associated with the recorded values at each iteration.

The simulation considers three main stages of smart dust particle operation: the emission stage (iterations 0–199), the propagation stage (iterations 200–499), and the deposition stage (iterations 500–999).

In the first stage, the particles remain at a stable distance from each other. Therefore, the probability of connection establishment is constant and equals $P_{connection} = 0.7$. Since the conditions inside the chimney are extreme (temperature, pressure, and flow velocity), the probability of failure of each particle at this stage is $P_{failure} = 0.0018$.

In the following stages, after leaving the chimney, the environmental conditions become significantly more favourable. Consequently, the probability of particle failure per iteration decreases to $P_{failure} = 0.0006$. The probability of establishing a connection between particles depends on the spatial distance between them. In this simulation, the probability of information visibility is calculated using (2):

$$P_{connection} = P_{base} * \sqrt{1 - \frac{i-200}{N-200}} \quad (2)$$

where P_{base} is the base probability of establishing a connection equal to 0.7, i is the index of the current iteration, N is the total number of iterations equal to 1000.

An additional verification has been introduced into the program: if particle N establishes a connection with particle M at iteration i, then it is assumed that particle M has also established a connection with particle N in the same iteration. In other words, all communication sessions are considered bidirectional. If a communication session is

established, all data measured in the given iteration are assumed to be transmitted in both directions, whereas if a session is not established, no data are transmitted.

In the first pass, the program calculates which particles fail at each iteration. In this simulation, the possibility of particle recovery is not taken into account, that is, a particle that has failed is regarded as non-functional in all subsequent iterations. The result of the simulation for the number of functioning particles is presented in Figure 4.

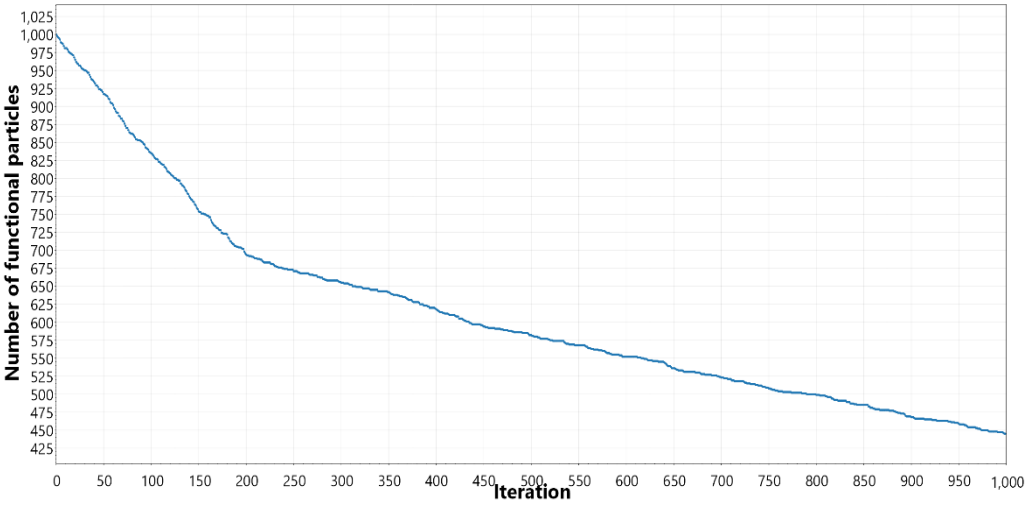

Figure 4 - Number of functional particles at each iteration

As shown in Figure 4, at the first stage failures occur more actively due to unfavourable conditions in the tube. Subsequently, in the atmosphere, the probability of failure decreases.

At the second stage, the program calculates the number of established communication sessions between the particles that remain operational in the given iteration. When a connection is established, particle *M* records the data of particle *N* in the given iteration, including its *ID*, and vice versa. The graph of the number of communication sessions between particles is presented in Figure 5.

Figure 5 shows that the number of communication sessions decreases more rapidly than the number of functioning particles, since at stages 2 and 3 the particles move apart from each other, thereby reducing the probability of a successful communication session under conditions of informational visibility. The program then calculates the amount of information preserved in the particles that remain functional at the current iteration, including both their own data and duplicated data received from other particles, both those still functional at this moment and those that have failed but managed to transmit data before failure.

Figure 6 demonstrates that the amount of information in the final iterations of the simulation begins to decrease despite the fact that new data are obtained at each iteration. This is due to the failure of particles that have accumulated a large amount of data, which are no longer taken into account since access to them is lost together with the particle failure [6].

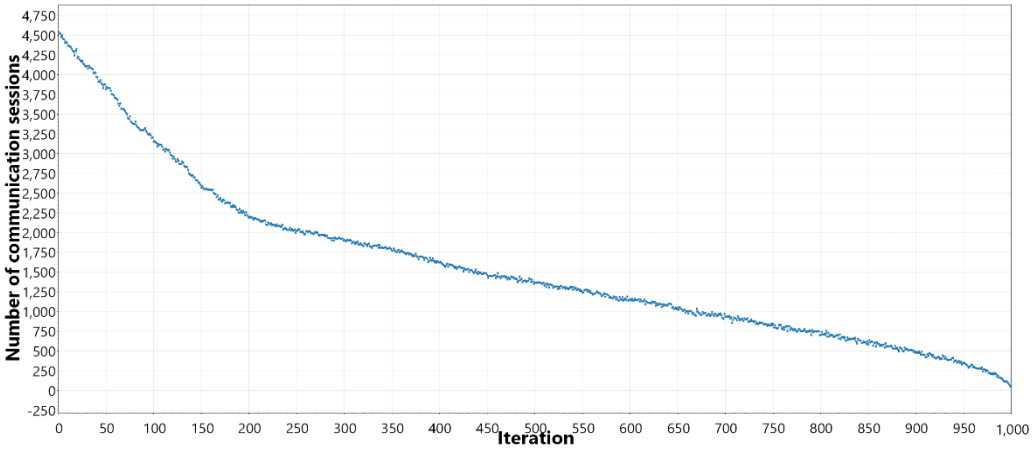

Figure 5. Number of communication sessions at each iteration

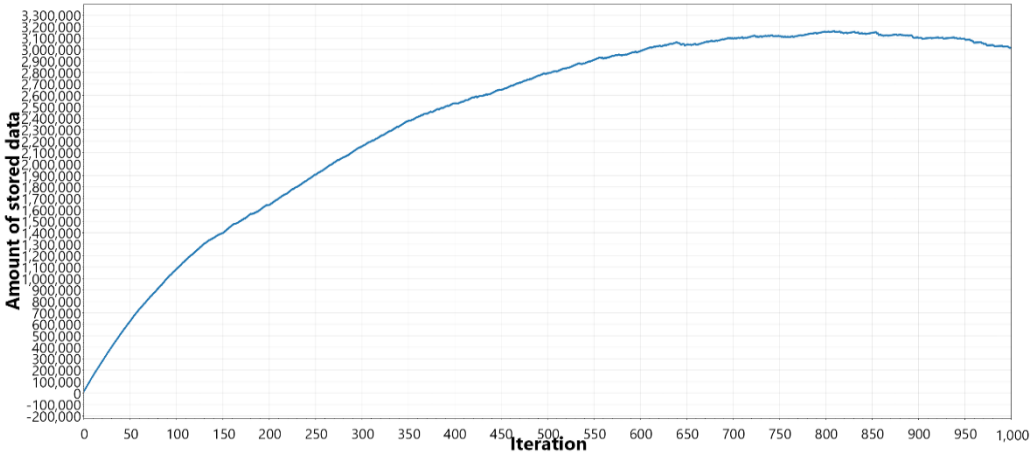

Figure 6. Amount of stored data at each iteration

A plot of the number of stored records with data for each particle is also presented in Figure 7.

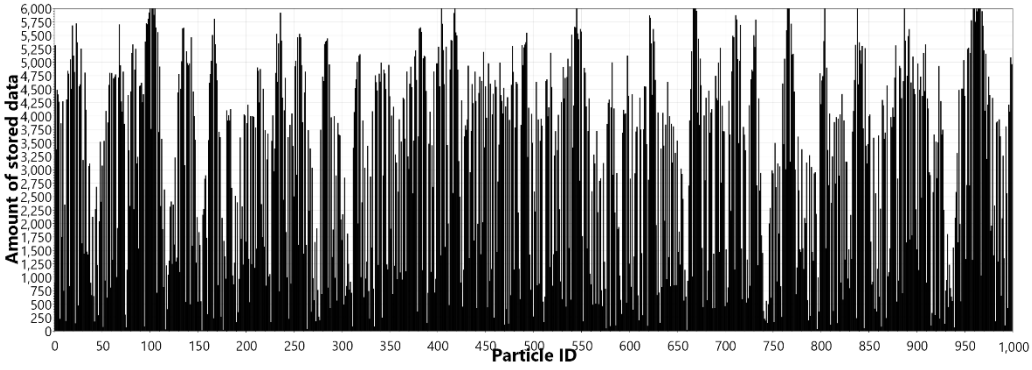

Figure. 7 – The amount of stored data by each particle

Figure 7 presents all cells, regardless of the iteration at which the particles failed. It is important to note that not all of these data will be possible to read. The numerical values of the number of functioning smart dust particles and communication sessions every 50 iterations are presented in Table 2.

Table 2. Simulation results

Iteration number	***Functional***	***Visible pairs***
0	*1000*	*4546*
50	*917*	*3815*
100	*835*	*3149*
150	*754*	*2565*
200	*694*	*2187*
250	*671*	*2023*
300	*655*	*1908*
350	*642*	*1771*
400	*618*	*1621*
450	*894*	*1462*
500	*582*	*1365*
550	*568*	*1240*
600	*552*	*1156*
650	*536*	*1051*
700	*523*	*933*
750	*508*	*846*
800	*499*	*702*
850	*485*	*577*
900	*468*	*477*
950	*459*	*353*
999	*445*	*52*

The obtained simulation results demonstrate that data exchange between smart dust particles makes it possible to preserve a substantial volume of measurement data despite significant swarm degradation, with fewer than half of the particles remaining operational by the end of the simulation.

The use of data exchange enables the implementation of cheaper and therefore less reliable smart dust particles [7], while still maintaining a large volume of collected data.

5. CONCLUSION

Within the framework of the conducted study, a method of inter-machine interaction of smart particles ("smart dust") within a multi-agent system is presented. A model of a

swarm control controller is proposed, based on the use of pulse-width modulation technology to regulate the periodicity of functional actions in each mode. The main focus is placed on the development of effective model and algorithmic support for communication between individual particle pairs and the system as a whole. The results of simulation modelling include the communication characteristics of particle pairs under conditions of information visibility, the parameters of swarm degradation over the entire duration of the experiment, as well as the statistics of data exchange and accumulation concerning the implementation of the technological process.

The developed methodology of inter-machine interaction opens new prospects for the practical application of smart dust technology in environmental monitoring and in the assessment of the impact of industrial enterprises on the environment.

The proposed solutions significantly expand the areas of application of smart particles and contribute to the advancement of cutting-edge information interaction technologies in cyber-engineering and industrial automation.

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