

Mobile Post-Emergency Monitoring System for Nuclear Power Plants

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Abstract. In this paper, a concept of designing the post-emergency system for monitoring the equipment and territory of nuclear power plant after a severe accident was developed. Power and communications network lines are found out as the most vulnerable ones during the accident monitoring, and self-descriptiveness and survivability and veracity are recognized as system basic parameters. To ensure the self-descriptiveness it's proposed to equip measurement and control modules with backup wireless communication channels and deploy the repeaters network based on drones. To provide the survivability modules possess the backup power battery, and repeaters appear in the appropriate places after the accident. Moreover an optimization of drone's location is proposed according to the minimum energy consumption criterion. To ensure the veracity it's expected to design the noise-immune protocol for message exchange and archiving and self-diagnostics of all system components. Formulas for estimating the reliability level of the post-emergency monitoring system were obtained.

Keywords. Infrastructure, Network, Controller, NPP, Reliability Model

Key Terms. Data, Integration, Infrastructure, Object, Technology

1 Introduction

Nowadays nuclear power is one of the most powerful and clean energy sources [1]. Constant control and monitoring of the power unit equipment parameters and components within premises and adjacent areas is held to ensure its stable work. The number of sensors reached up to several thousand per power unit [1, 2]. Requirements for reliability and survivability of monitoring tools increased in post-Fukushima period [3]. Paradigm of systems and services providing localization, minimization and crash recovery is changing. Proper information support is needed for successful and critical management during and after the accident. It is impossible to provide optimal decisions before and after the accident without timely and reliable information about the current state and change dynamics.

Almost all power unit sensors and associated equipment are combined into several networks using measurement modules [1, 4, 5]. Often these networks are based on the widespread wired serial interfaces [1, 4]. It should be noted that data flow in measuring channels of Nuclear Power Plant (NPP) is relatively small and sufficient to control and make decisions during normal operation. However, the data flow increases dramatically in pre-emergency and post-emergency conditions. It is caused by a significant increase of sensor data acquisition frequency in obtaining information about the dynamics of the situation. Furthermore, additional data acquisition systems are activated, the ones that are not involved in NPP regular operation. Therefore, emergency mode channel capacity is used to design such kind of networks that have duplication and mechanical protection of data channels to improve the communication reliability.

During the accident a part of data channels will inevitably fail. The probability of the total communication loss (with all data acquisition systems) is low, even in case of a serious accident. However during the damage of a part of communication channels the information flows should be redirected to not damage one. Thus the frequency of collisions increases and the probability of the local networks overload is high [4, 6]. It creates a lack of information when it is most needed. To overcome this situation, the additional wireless channels may be used [5, 7]. It will provide a necessary bandwidth and restore the connection with the data acquisition modules that are damaged.

The aim of this work is to design a concept of NPP integrated system for both post-emergency monitoring and decision support. It is expected that such integrated system (infrastructure as a system of systems), despite the injury during the accident, can ensure a high reliability of data exchange with measurement (and under certain conditions - control) channels to make correct decisions. Within this study we believe that such system can monitor the appropriate equipment as well as buildings and territories nearby.

2 Basic Requirements for Communication Systems of Post-Emergency Monitoring

The main characteristics of the post-emergency NPP monitoring system have to be self-descriptiveness, survivability and veracity [8]. Thus self-descriptiveness means that the data flow from data channels and control channels must be timely, sufficient and stable. The system has to provide necessary bandwidth in the post-emergency

conditions. It is obviously that a high survivability can only provide the required self-descriptiveness. Obtained data must be reliable. So in the post-emergency conditions, when a part of measurement and control modules are damaged, a required veracity can be provided by self-testing the data acquisition modules. A last one will define the current metrological characteristics of measurement and control channels.

To ensure the mentioned characteristics above in post-emergency conditions using wireless communication channels is a difficult problem, because measurement and control modules can be located indoors or under the rubble, which significantly reduces the signal level. Thus, the level of electromagnetic interference in post-emergency conditions increases dramatically at NPP. At the same time the emergency service for localization and minimization of the consequences after the accidents, should be located in a distance which excludes the emergency service from damage during the accident. Thus, providing a direct wireless connection between the measurement and control modules and control center requires significant power transmitters. However, a probability of the supplying network lines for measurement and control modules damage is very high in the accident, as well, so those modules and wireless communication components should be able to use additional emergency battery. In this case, the usage of powerful transmitters can reduce survivability of the post-emergency monitoring system by limiting its working time without battery recovery.

3 The Basic Principles of Self-Descriptiveness, Survivability and Veracity

To support the uninterrupted long functioning of the post-emergency monitoring system on in base of the wireless network within the noise high level environment we are required to reduce significantly a distance of the wireless communication as well as increase essentially the noise resistance of such communication. The first requirement can be satisfied through the usage of intermediate repeater modules. These modules have to be mobile in order to: (i) be located in the distance before the accident, such distance practically excludes them from the damage during the accident; (ii) fairly quickly (within minutes) occupy a proper place according to the accident's nature, as well as, noise level and the distance to the serviced measurement and control modules; (iii) move (change the dislocation place) according to the environment changes, specified in point (ii).

The mentioned above requirements can be easily implemented, when repeater modules are moved by air. Recently drones became to be used widely [9-11]. Nowadays, they are the most profitable platform where repeater modules can be placed. Such solution provides the maximum access to the required location as well as high-speed movement. Network of repeaters based on drones, which are located at the considerable distance from NPP and fly to locations after the accident, is able to provide the necessary data flow in minutes after the accident occurred.

To increase the wireless communication resistibility to noises, it is necessary to implement error correction and detection codes [12, 13]. However, for such environments it is required to provide noise immunity for data and instructions, as well as, for all communication systems. Existing protocols are designed for the normal noise level [14] only, and they may not function properly during the accident at NPP. It is neces-

sary therefore to develop a communication protocol able to function at the allowable noise level that corresponds to the most severe post-emergency conditions in NPP. On other hand, the high noise immunity requires using the redundant codes, therefore it is necessary to archive essentially the sensor data before coding that enables to reduce a traffic [15].

To ensure the sufficient bandwidth of communication channels it should be possible to provide a parallelization of data streams [16] i.e. a distribution of measurement and control modules between different repeater modules. However, to maintain the self-descriptiveness of the post-emergency monitoring system at a sufficient level it's necessary to provide the dynamic adaptation of repeater modules and the software-technical reconfiguration of the structure according to system functioning conditions. Some repeaters may be damaged in the post-emergency conditions or may return to the place of deployment for the battery recharging. In such cases their traffic must be taken by other repeaters.

Survivability of the post-emergency monitoring system is ensured, firstly, by providing the additional battery for a consumption of measurement and control channels. Thus, it is necessary to save the battery charge for the longer system operation. For this purpose, besides of using the energy-efficient hardware, the wireless transmitter's power should be reduced as much as possible. This can be achieved by reducing the distance between repeaters from one side, and served by them measurement and control modules from other side. It is possible to do that by optimizing the distribution of the serviced measurement and control modules between different repeaters. However, to minimize the energy consumption, it is possible to use a dynamic evaluation of errors level during the data exchange as well as adaptation of transmitter's capacity to such level.

Secondly, a high survivability of the post-emergency monitoring system is provided by different features of network repeaters. They appear on the place of accident after its occurrence (they cannot be damaged during the accident) and must be able to reallocate data streams dynamically, and optimize the own position regarding the serviced measurement and control modules, as well as a configuration of the territory and occurrence of mechanical obstacles. Drone-repeaters have to restore the battery charge during the temporary return to the service base. It should be possible to have additional drones replacing the damaged ones.

The high veracity of the data flow should be ensured by the constant self-testing of channel repeaters. Thus, it is not necessary to provide by default a frequent self-testing procedure. The usage of noise immunity codes with errors correction will allow running a current control of communication channels for errors level. At the same time, the errors level reflects the level of noise and generates information for a subsystem of drones' optimal placement. Thus, it is possible to choose the location and transmitting power within the high level of errors. However, such level has to be acceptable for a given system of noise-immune coding.

Ensuring the self-testing procedure for the measurement and control modules should be considered as a separate problem. Those modules can be damaged during the accident or after it, for example, due to the penetrating radiation. Hence data reliability can be achieved by introducing the metrological support autonomous subsystems for the measurement and control modules [17-19]. These subsystems must be

resistant to errors of its components which can increase rapidly in the post-emergency conditions, for example, due to the penetrating radiation.

Thus, the following principles of the system functioning are proposed:

- A communication network of the system for the NPP post-emergency condition monitoring is put in the drones group (fleet), that located permanently at a considerable distance from the NPP. The communication network is deployed after the accident, when drones are flying into the accident zone.
- Drones fleet is divided by the role and equipment into: repeaters, observers (equipped with a TV camera) and additional sensors (they can be located in drones or be dropped down in certain places). Drones should be able to change their role by upgrading equipment at the location base.
- Drone-repeaters work together on a principle of “one leader”. This principle ensures a maximum reliability of the wireless communication system (a minimum of collisions). If the “leading drone-repeater” (Master) is damaged then other drone-repeater takes Master functions, for example, drone with the smallest working time (among all involved ones) at the accident place.
- The Master drone-repeater determines the location zone per each drone-repeater and measurement modules which will interact with Master, or some other task.
- Each drone-repeater independently selects a location with the minimum noise (as given areas by Master), and the necessary transmitter power for measurement modules (in terms of errors in transmitted data), and the possibility of landing (with the permission of the Accident Liquidation Centre, according to the accident assessment using drones observers).
- Drone-observers enable to run the continuous visual monitoring of the accident location for: actions assessing the drones of other purpose, selecting the safe places for drone-repeater landing, assessing the trajectory of drone-sensors and their location.
- Measurement and control modules are equipped with backup batteries, blocks of wireless communication, as well as, self-testing and self-diagnostic systems.
- To meet the system requirements the self-adaptability, self-testing and self-healing procedures are used.

4 Structure of the System

The constantly active wire network of the measurement and control modules and its wireless extension [20] includes sensors and actuators from 1 to n which are connected to m traditional measurement and control modules (Fig. 1). Each of them includes the multichannel analog to digital converter ADC or digital to analog converter DAC, microcontroller of the traditional data processing and an adapter of the wired interface. Through this interface the measurement and control modules interact with the control and decision making center receiving commands and sending measurement results. To provide the work of those modules within the system of post-emergency monitoring each module is equipped with an additional wireless microcontroller which receives data from the wireless network, or prepares data for the transmission through wireless network. This microcontroller operates only in pre-

emergency and post-emergency modes. It receives measurement results (from the measuring module microcontroller or adapter of wired interface), then compresses, encodes and transmits it through the wireless interface. Measurement and control modules, with the absence of network power, are charged from the independent accumulator unit (it is not presented on Fig 1).

In the normal exploitation mode the data and commands exchange is running through the wired network. If it is damaged during an accident, another wireless network is created on the basis of drones. Due to “Master’s” commands drones are situated in the air in a way to run following functions: to cover all measuring modules which are equipped with the wireless connection; to distribute data streams through drones as evenly as possible; to secure the highest possible veracity of the transmission for sensor data and controlling commands; to avoid obstacles and making no obstacles per each other.

In the independent power supply of the measurement and control modules (from the backup accumulators only) it is very important to minimize their power consumption. For this purpose all possibilities have to be explored including a limitation of the wireless interface power, and drones must be placed in the appropriate zones close enough to the signal sources. Error level during the message exchange can be considered as one of the important criteria for the effective energy-saving. If the error level is acceptable for the selected coding method then it is enabled to try decreasing the transmitter’s power of the wireless interface both as a part of measuring modules and a part of drones.

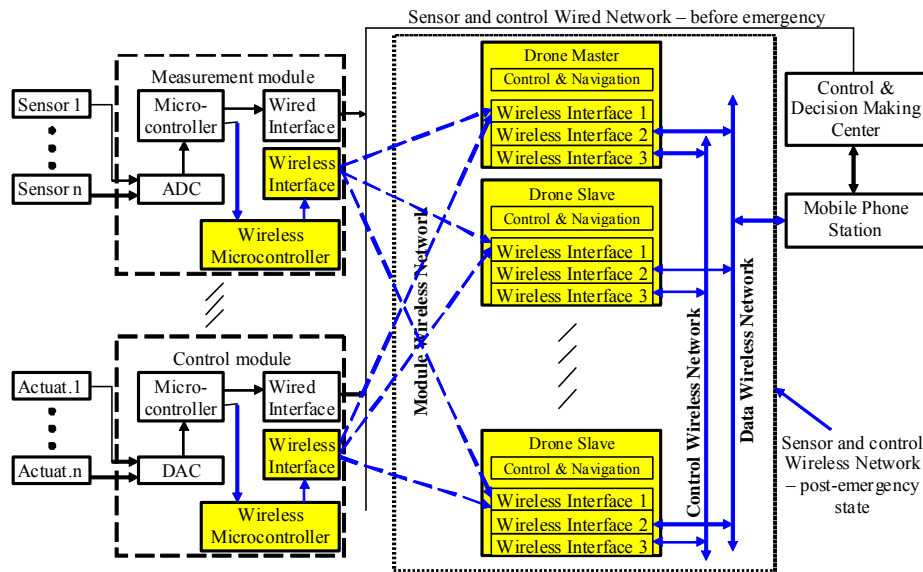


Fig. 1. Structural scheme of wired network for measurement and control modules and its wireless extension

In its turn the request to draw closer to the signal sources is connected closely with the running the principles 4 and 5 above. Hence all drones have to be equipped with

rather the high quality navigation system. Such system must provide different types of navigation below:

- Using the existing system of the global navigation (GPS) [21]. Note the level of noises is increasing rapidly in post-emergency conditions at the NPP. At the same time the signal from the GPS satellite is rather weak. So a probability is very high that such signal cannot be able for a reliable navigation;
- Using the local system of beacons similar to the GPS [22 – 25]. A distance to the local beacons (sources of the individual signals which location is tied to the local terrain map) may be even thousand times smaller. Ensuring the required signal level, even if it being powered from the accumulators, won't be a problem;
- Protection from collisions with the local obstacles is better performed using the ultrasound location [25, 26]. But the ultrasound probing impulses must have the unique individual coding. Otherwise the impulses from the other drones will be accepted as native ones, hence the defense system against the collision with the obstacles will be out of an order;
- The previous analysis showed the ultrasound locating system is extremely inaccurate, and it is too slow in dynamic conditions. It will not be able therefore to prevent a collision of the drones between each other. The assessment of the protection variants against such collisions showed that the better variant would be considered when positions of all drones are taking into account by the “leading” one (Master) with its following delivering commands about the positions and movement vectors per each subordinate (Master –Slave principle). However, when the Master is damaged, the system becomes inoperable. Hence it is necessary to try predicting a possibility with commands absence from the Master when its function may be replaced by each (or assigned one) drone [27, 28]. To avoid the collisions, such kind of replacement should be organised according to the hierarchical principle.

Note that sensor data collection and actuators control (exchange in the network of measurement and control modules), and retransmitting of these data (message exchange with the center of decision making and control), and drones control (following the “Master’s” commands) are different tasks which have very little in common. Except while running the exchange task in the network of the measurement and control modules, the errors level may be defined and this information should be included when selecting the place for drone’s dislocation. That’s why to increase the reliability of the post-emergency monitoring system’s functioning it is reasonable to divide the solution of these tasks above on the hardware level. Those tasks must be run by different microcontrollers equipped with their own peripheral devices. During this it is expedient to form the three independent wireless networks of data exchange (measurement and control modules, retransmitted data and drones control networks) with will not conflict with each other, create queues, and etc.

5 Reliability Models

According to the proposed concept the three systems of post-emergency monitoring systems (S1, S2, S3) and reliability block diagrams (correspondingly: RBD1 (Fig. 2), RBD2 (Fig. 3) and RBD3 (Fig. 4)) have been developed.

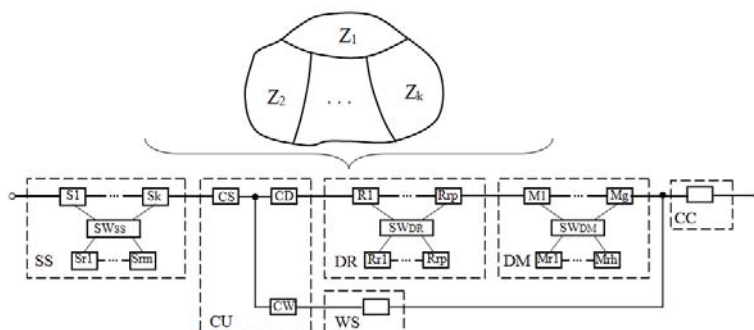


Fig. 2. Reliability block diagram of the system with general sensors, where S_i (S_{rv}) – sensors (redundant sensors), SS – sensor system, SW – switching units, CS – sensor controller, CD – drone system interface controller, CW – wire system interface controller, CU – controller unit, DR – drone transmission system, DM – drone monitoring system, R_j - transmission drones, M_b – monitoring drones, WS - wired system, CC – crisis centre

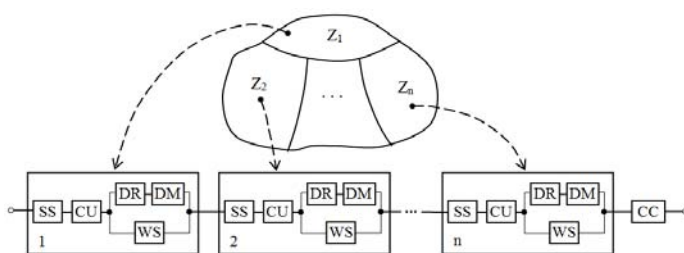


Fig. 3. Reliability block diagram of the system with separated zones of sensors and drones

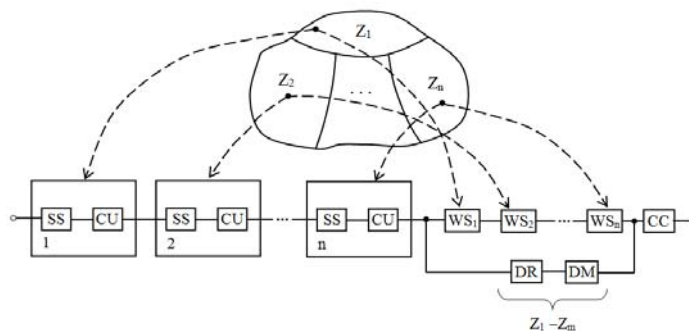


Fig. 4. Reliability block diagram of the system with separated zones of sensors and general drone fleet

Each system has a general way for increasing the system reliability, which includes sliding redundancy in SS, DR and DM – any failed element of the main chain ((S_1 - S_2 -...- S_k) for SS, (R_1 - R_2 -...- R_q) for DR and (M_1 - M_2 -...- M_g) for DM) can be replaced by means of any element of the redundancy chain ((S_{r1} - S_{r2} -...- S_{r_m}) for SS, (R_{r1} - R_{r2} -...- R_{rp}) for DR and (M_{r1} - M_{r2} -...- M_{rp}) for DM). Moreover, each system

has a possibility to replace the failed main chain by means of the redundancy chain: (DR-DM) by means of (CW-WS) for S1, (CD-DR-DM) by means of (CW-WS) for S2, (WS₁-WS₂-...-WS_n) by means of ((DR-DM)₁-(DR-DM)₂-...-(DR-DM)_m) for S3.

Based on the proposed reliability block diagrams we can obtain the following formulas for calculating the reliability function (RF) per each of these systems:

$$P_{S1}(t) = P_{SS}(t) \cdot P_{CS}(t) \cdot [1 - (1 - P_{CD}(t) \cdot P_{DR}(t) \cdot P_{DM}(t)) \cdot (1 - P_{CW}(t) \cdot P_{WS}(t))]; P_{CC}(t), \quad (1)$$

where $P_{SS}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^m \frac{k \cdot \lambda_S \cdot t}{i!}$; $P_{CS}(t) = e^{-\lambda_{CS} \cdot t}$; $P_{CD}(t) = e^{-\lambda_{CD} \cdot t}$;

$$P_{DR}(t) = e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^p \frac{q \cdot \lambda_R \cdot t}{j!}$$
; $P_{DM}(t) = e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^h \frac{g \cdot \lambda_M \cdot t}{l!}$; $P_{CW}(t) = e^{-\lambda_{CW} \cdot t}$;
$$P_{WS}(t) = e^{-\lambda_{WS} \cdot t}$$
; $P_{CC}(t) = e^{-\lambda_{CC} \cdot t}$.

$$P_{S2}(t) = \{P_{SS}(t) \cdot P_{CU}(t) \cdot [1 - (1 - P_{DR}(t) \cdot P_{DM}(t)) \cdot (1 - P_{WS}(t))]\}^n \cdot P_{CC}(t), \quad (2)$$

where $P_{CU}(t) = e^{-\lambda_{CU} \cdot t}$.

$$P_{S3}(t) = (P_{SS}(t) \cdot P_{CU}(t))^n \cdot \left[1 - (1 - \prod_{i=1}^n P_{WS_i}(t)) \cdot (1 - (P_{DR}(t) \cdot P_{DM}(t)))^m \right] \cdot P_{CC}(t) \quad (3)$$

The fact, that each of the systems has devices with redundancy elements, enables to consider both those devices separately as well as systems with a multi-level degradation [29, 30]. For example, in the Table 1-3 the degradation levels with corresponding characteristics for the systems SS, DR, DM are shown

Table 1. Degradation levels characteristics of sensor system

Number of the degradation level	Condition that determines the degradation level	Formula for calculating the RF
m+1	All elements of the main chain (S1- S2-...-Sk) are functioning, all elements of the redundancy chain (Sr1- Sr2-...-Srm) are functioning	$P_{SS}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^m \frac{k \cdot \lambda_S \cdot t}{i!}$
m	All elements of the main chain (S1- S2-...-Sk) are functioning, one element of the redundancy chain (Sr1- Sr2-...-Srm) is failed, or it is functioning instead of a failed element for the main chain	$P_{SS}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^{m-1} \frac{k \cdot \lambda_S \cdot t}{i!}$
...

Number of the degradation level	Condition that determines the degradation level	Formula for calculating the RF
1	All elements of the main chain (S1- S2-...-Sk) are functioning, m elements of the redundancy chain (Sr1- Sr2-...-Srm) are failed, or they are functioning instead of failed elements for the main chain	$P_{SS}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^{m-m} \frac{k \cdot \lambda_S \cdot t}{i!} =$ $e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^0 \frac{k \cdot \lambda_S \cdot t}{i!} = e^{-k \cdot \lambda_S \cdot t}$
0	At least one of the elements of the main chain (S1- S2-...-Sk) is failed, m elements of the redundancy chain (Sr1- Sr2-...-Srm) are failed or they are functioning instead of failed elements for the main chain	0

Table 2. Degradation levels characteristics of drone transmission system

Number of the degradation level	Condition that determines the degradation level	Formula for calculating the RF
p+1	All elements of the main chain (R1- R2-...-Rq) are functioning, all elements of the redundancy chain (Rr1- Rr2-...-Rrp) are functioning	$P_{DR(d=p+1)}(t) = e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^p \frac{q \cdot \lambda_R \cdot t}{j!}$
p	All elements of the main chain (R1- R2-...-Rq) are functioning, one element of the redundancy chain (Rr1- Rr2-...-Rrp) is failed or it's functioning instead of a failed element for the main chain	$P_{DR(d=p)}(t) = e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^{p-1} \frac{q \cdot \lambda_R \cdot t}{j!}$
...
1	All elements of the main chain (R1- R2-...-Rq) are functioning, p elements of the redundancy chain (Rr1- Rr2-...-Rrp) are failed or they are functioning instead of failed elements for the main chain	$P_{DR(d=1)}(t) = e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^{p-p} \frac{q \cdot \lambda_R \cdot t}{j!} =$ $e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^0 \frac{q \cdot \lambda_R \cdot t}{j!} = e^{-q \cdot \lambda_R \cdot t}$
0	At least one of the elements for the main chain (R1- R2-...-Rq) is failed, p elements of the redundancy chain (Rr1- Rr2-...-Rrp) are failed, or they are functioning instead of failed elements for the main chain	$P_{DR(d=0)}(t) = 0$

Table 3. Degradation levels characteristics of drone monitoring system

Number of the degradation level	Condition that determines the degradation level	Formula for calculating the RF
h+1	All elements of the main chain (M1- M2-...-Mg) are functioning, all elements of the redundancy chain (Mr1- Mr2-...-Mrp) are functioning	$P_{DM(d=h+1)}(t) = e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^h \frac{g \cdot \lambda_M \cdot t}{l!}$
h	All elements of the main chain (M1- M2-...-Mg) are functioning, one element of the redundancy chain (Mr1- Mr2-...-Mrp) is failed, or it's functioning instead of a failed element for the main chain	$P_{DM(d=h)}(t) = e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^{h-1} \frac{g \cdot \lambda_M \cdot t}{l!}$
...
1	All elements of the main chain (M1- M2-...-Mg) are functioning, h elements of the redundancy chain (Mr1- Mr2-...-Mrp) are failed, or they are functioning instead of failed elements for the main chain	$P_{DM(d=1)}(t) = e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^{h-h} \frac{g \cdot \lambda_M \cdot t}{l!} = e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^0 \frac{g \cdot \lambda_M \cdot t}{l!} = e^{-g \cdot \lambda_M \cdot t}$
0	At least one of the elements of the main chain (M1- M2-...-Mg) is failed, h elements of the redundancy chain (Mr1- Mr2-...-Mrp) are failed, or they are functioning instead of failed elements for the main chain	$P_{DM(d=0)}(t) = 0$

Using the data from Tables 1-3 and assuming that devices CS, CD, CW, WS, CC are characterized by a two-level degradation (these devices have only 1 and 0 degradation level), we can determine levels and provide characteristics per each of them per each of the systems S1, S2, S3 correspondingly.

For example, in the table 4 the characteristics of the given degradation level *a* for the system with common sensors S1 are shown, and in Table 5 the characteristics of the lowest degradation level for the system S1 are shown too.

Table 4. Characteristics of the given degradation level a for system S1 according to degradation levels of devices, which this system includes

Degradation level of the system		Shorthand names for the devices							
		SS	DR	DM	CS	CD	SW	WS	CC
a	Degradation level of the device	m (Tab.1)	$p+1$ (Tab.2)	$h+1$ (Tab.3)	1	1	0	0	1
	Formula for calculating the RF	$P_{SI(d=a)}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot \sum_{i=0}^{m-1} \frac{k \cdot \lambda_S \cdot t}{i!} \cdot e^{-q \cdot \lambda_R \cdot t} \cdot \sum_{j=0}^p \frac{q \cdot \lambda_R \cdot t}{j!} \cdot e^{-g \cdot \lambda_M \cdot t} \cdot \sum_{l=0}^h \frac{g \cdot \lambda_M \cdot t}{l!} \cdot e^{-\lambda_{CS} \cdot t} \cdot e^{-\lambda_{CD} \cdot t} \cdot e^{-\lambda_{CC} \cdot t}$							

Table 5. Characteristics of the lowest degradation level for the system S1

Degradation level of the system		Shorthand names for the devices							
		SS	DR	DM	CS	CD	SW	WS	CC
1	Degradation level of the device	1 (Tab.1)	0 (Tab.2)	0 (Tab.3)	1	1	1	1	1
	Formula for calculating the RF	$P_{SI(d=1)}(t) = e^{-k \cdot \lambda_S \cdot t} \cdot e^{-\lambda_{CS} \cdot t} \cdot e^{-\lambda_{CD} \cdot t} \cdot e^{-\lambda_{SW} \cdot t} \cdot e^{-\lambda_{WS} \cdot t} \cdot e^{-\lambda_{CC} \cdot t}$							

Similar tables are available for systems S2 and S3 too. For example, the characteristics of their lowest degradation levels are given in Tables 6 and 7 correspondingly.

Table 6. Characteristics of the lowest degradation level for the system S2

Degradation level of the system		Shorthand names for the devices					
		SSi	DRi	DMi	CUi	WSi	CC
1	Degradation level of the device	1 (Tab.1)	0 (Tab.2)	0 (Tab.3)	1	1	1
	Formula for calculating the RF	$P_{S2(d=1)}(t) = (e^{-k \cdot \lambda_S \cdot t} \cdot e^{-\lambda_{CU} \cdot t} \cdot e^{-\lambda_{WS} \cdot t})^n \cdot e^{-\lambda_{CC} \cdot t}$					

Table 7. Characteristics of the lowest degradation level for the system S3

Degradation level of the system		Shorthand names for the devices					
		SSi	CUi	WSi	DRj	DMj	CC
1	Degradation level of the device	1 (Tab.1)	1 (Tab.2)	0 (Tab.3)	1	1	1
	Formula for calculating the RF	$PS3(d=1)(t) = (e^{-k \cdot \lambda_S \cdot t} \cdot e^{-\lambda_{CU} \cdot t})^n \cdot (e^{-q \cdot \lambda_S \cdot t} \cdot e^{-g \cdot \lambda_S \cdot t})^m \cdot e^{-\lambda_{CC} \cdot t}$					

6 Conclusions

A proposed concept of NPP post-emergency monitoring based on drones satisfies requirements to self-descriptiveness and survivability and veracity. Such approach enables: (i) to avoid the unacceptable damage and fatal failure of post-emergency monitoring system during the accident (ii) to ensure the minimal time of system deployment (iii) to provide the sufficient bandwidth of communication channels with possible (if needed) extension (iv) to employ the recovery operation if components are damaged(v) to ensure the ability of flexible usage for other problems solving (delivery of sensors and other needed equipment to the certain location).

Proposed framework models of assessing the reliability and survivability enable to compare the output options for its further selection. Future studies should be related to the specification of output parameters as well as detailed analysis of their values for fixed solutions of systems design. Moreover it is necessary to specify the models of failures due to accidents for survivability computing.

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