Improving the reliability in bio-nanosensor modules using hardware redundancy techniques

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ABSTRACT

A nano-robot is a controlled robotic system at the nanoscale. Nowadays, nanorobotics has become of particular interest in medicine and pharmacy. The accurate diagnosis of the diseases as well as their rapid treatment will make everyone surprised and will significantly reduce the associated risks. The modeling of reliability in biosensors is studied for the first time in this paper. The use of practical hardware redundancy has turned into the most cost-effective to improve the reliability of a system. Additionally, the Markov model is used to design fault-tolerant systems in nanotechnology. The proposed method is compared with some existing methods, such as triple modular redundancy and non-fault-tolerant systems; it is shown that using this method, a larger number of faults between 3-5 can be tolerated. Using the proposed method, the number of modules can be increased to nine. However, a larger number than 9MR is not recommended because of an increased delay and requiring more hardware. As the scale of components used in digital systems has gotten smaller, the use of hardware redundancy has become cost-effective. But there is a trade-off between the amount of used hardware and fault tolerance, which can also be investigated.

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1. INTRODUCTION

One of the most important technologies in the world is nanotechnology. It allows us to interact with living systems on a molecular scale [1]. From the nanotechnology perspective, constructing and designing mechanical machines at the nano or micro scale is called nanorobotics [2], which is considered as one of the branches of nanotechnology [3]. Nanorobotics technology has caught the attention of many scholars and industries because of its wide range of applications in various fields such as medicine [4], biotechnology, mechanics [5], electronics, studying physical systems, and communication systems. Nowadays, nanorobotics is of particular interest in medicine, healthcare, and pharmacy [6]. A major challenge in nanoscience is designing synthetic molecular devices that automatically work and are programmable [7]. Much progress has been made in the past 10 years, so that accurate and early diagnosis of the disease, as well as the rapid and convenient treatment of the diseases, will surprise people in the future and will significantly reduce the associated risks and costs [8]. But creating such micro-robots in a way that they can move in arteries to detect and identify diseases requires more research because of the complexity of the human body [9].

The main components of nanorobots that exist in any nanorobot regardless of their application are 1-nano-sensors, 2-nano-motors, and 3-nano-manipulator. One of the most important parts of a nanorobot is its sensor. Therefore, making more accurate, smaller, and more capable sensors is needed. Nano-sensors are sensors at the nanometric scale that are more accurate and responsive due to their small and nanometric size. Nowadays, biosensors are used in various fields such as medicine, chemical industry, food industry, environmental monitoring, and production of pharmaceutical and healthcare products. Biosensors are powerful tools to identify biological molecules and are made by combining a biological sensor with a convertor. A biosensor consists of three components [10], [11], which are bio-receptor, converter or detector, and processor.

Over the past decade, major advances in microsystems technology to make small [12], integrated, and reliable devices in combination with biological elements have made considerable changes to biosensors. Cancer can now be diagnosed by monitoring the density of some antibodies of the existing genes in the bloodstream or other body fluids, or by doing tissue tests. Diabetes can also be diagnosed by determining blood glucose density [13]. However, despite their widespread usage in medicine, these techniques have some potential limitations. For example, the response time of some diagnostic devices is somewhat long, and they are expensive. So, there is a need for the development of efficient and reliable diagnosis and measurement technologies. Nanotechnology advancements have resulted in the development of nano-scale biosensors that are highly sensitive and versatile. Since 2004, this technology has been developing rapidly [14]. Biosensors are devices with nanometric structures that measure changes in various biological parameters and convert them into measurable signals [15]. Nano-sensors have shown a great deal of potential in many areas and, most importantly, in precise and early diagnosis of diseases, and this has attracted researchers and even artisans to this field. However, the practical realization of bio-nanosensors and using the full potential of this new technology are subject to many obstacles. One of the major obstacles that should be resolved in bio-nanosensors is fault tolerance.

Because of the more complexity associated with computer systems, uncertainties existing in many parts of a system, and the impact of multiple factors on the output, it is necessary to design a system that does not fail despite failure in different parts of the system, continues performing properly, and fulfills the system's ultimate goal. Such a system is called a fault tolerance system. A fault tolerance system is a system that can continue to operate normally despite hardware failures or software errors and makes no faults or errors. The concept of redundancy is utilized to design fault tolerance systems. Redundancy refers to adding information, resources, or time beyond the system's normal operation. Different forms of redundancy include hardware redundancy, software redundancy, information redundancy, and time redundancy.

As technology has advanced and the scale of components used in digital systems has got smaller, the use of practical hardware redundancy has turned into the most cost-effective and appropriate way to improve the reliability of a system [16]. Reliability is the conditional probability of the system working properly at the range of $[t_0, t]$, provided that it has been working properly at the beginning (t_0). In other words, reliability is the probability of the system properly producing output during a particular period of time [17]. Fault tolerance is a technique to improve the reliability of a system. In addition to cost and efficiency, reliability is the third critical criterion for designing fault tolerance systems. For estimating the time of systems failure, we can use reliability modeling. In the present paper, section two explains the methods and materials, section three presents the results, and section four discusses the results.

2. METHODS AND MATERIALS

2.1. Reliability modeling

Reliability modeling is one of the most important techniques for evaluating fault-tolerant systems. Two important analytical techniques used for evaluating the reliability of a system are hybrid modeling and Markov modeling [18]. The two most common hybrid models are series and parallel systems. In practice, real systems are a combination of series and parallel subsystems in which it is assumed that the failure rates of the components are independent of each other. One of the significant features of the Markov modeling is considering fault coverage in systems, meaning that if a system fails, there is no need to notice it 100%; the system itself can notice this failure at a percentage (a probability between 0 and 1) and apply replacing or repairing mechanisms [19].

2.2. Sensor, nanosensor, and biosensor

The main parameters used for robot architecture and controlling them are sensors, actuators, power supply, and data transmission [20]. The most important part of a robot is its sensor. A sensor is a tool that can detect a stimulus or its changes and react to it. This reaction shows the changes. Nano-sensors are sensors at the nanometric scale [21] that are highly accurate and responsive because of their small and nanometric size. Sensors whose detector sections are biological are known as biosensors. They can make the measurement easier, more sensitive, and faster in biological environments due to their nanometric size. Various nanostructures are used in bio-nanosensors, including nano-particles, quantum dots, nanotubes, nano-fibers, and nano-wires [22].

2.3. Main components of biosensors module

A biosensor module is a type of tracking tool made by combining a bio-receptor with a converter [21]. Table 1 demonstrates various combinations of bio-receptors and converters. The role of the bio-receptor is to detect the analyte and its changes, and the role of the converter is to convert the response into a measurable signal [23]. In general, each biosensor module includes some components [13], [24], which are analyte, biological elements (bio-receptor), converter, processor, and monitor.

Table 1. Different combinations of bio-receptors and converters in bio-nanosensor module [25]–[28]

Bio-receptor	Converter
Enzyme: Analyze the analyte or restricts the catalyst with analyte	Electrochemical: Empirometric, potentiometric
Micro-organism: Feeds on analyte or analyte inhibits the growth of it.	Optical: Fluorescence
Antibody: Detects the specific analyte and binds to it.	Weight: Quaternary micro balance, thermal, thermometric
Other materials that can be used here: Cell genetic material, tissue samples, organs	

3. RESULTS AND DISCUSSION

There are many challenges for using nanorobots in the healthcare industry [29]. Nanorobots are still not common in the industry, despite the optimistic accounts of pioneers in this field. Actually, the human body is significantly more complex than any human-made robot, so the fabrication of nanorobots that can make their way through the body and perfectly accomplish their missions is of great importance.

Bio-nanorobots are still unknown. Modeling, designing, and evaluating reliability require the use of theoretical estimation and the virtual environment. A biosensor includes a bio-receptor, a converter, and a processor. The system will not work properly if any of these three elements do not work properly, so it is a series system. The simplest way of calculating the reliability of a series system is by using the non-failure probability function of all the system's components. Suppose that $C_i(t)$ shows the event in which C_i works properly at time t. $R_i(t)$ is the reliability of element C_i at time t, and $R_s(t)$ is the reliability of the whole system in mathematical terms.

$$R_s(t) = P(C_1(t) \cap C_2(t) \cap C_3(t) \cap C_4(t) \cap C_5(t)) \tag{1}$$

Supposing that $Ci(t)$ is independent, then (2).

$$R_s(t) = R_1(t)R_2(t)R_3(t)R_4(t)R_5(t) = \prod_{i=1}^{5} R_i(t) \tag{2}$$

Supposing that the lifetime of components changes exponentially over the course of time, the reliability of each component equals (3):

$$R_i(t) = e^{-\lambda_i t} \tag{3}$$

in which t is the time and λ_i is the failure rate of each component and it is a time-dependent variable but λ_i is considered a constant value in the calculations of this paper. The reliability of the whole system is calculated by (4) or (5):

$$R_s(t) = e^{-\lambda_1 t}. e^{-\lambda_2 t}. e^{-\lambda_3 t}. e^{-\lambda_4 t}. e^{-\lambda_5 t} \tag{4}$$

$$R_s(t) = e^{-\sum_{i=1}^{5} \lambda_i t} = e^{-\lambda_{sys}} \tag{5}$$

in which $\lambda_{sys} = \sum_{i=1}^{5} \lambda_i$ is related to the failure rate of the system. The failure rate of a bio-nanosensor system can be calculated by summing up the failure rates of all the elements in the system, because the failure rate is considered at the component level and is not available for the whole system.

3.1. Markov model for biosensors

The nuclear magnetic resonance (NMR) technique is the most common way to increase the system's reliability, which is shown in Figure 1. In this technique, there are N repetitive modules that all do the same thing parallelly. Then, their results go to a majority vote. N must be an odd number bigger than 3 to be eligible for voting. The NMR system can detect [N/2] modules having faults.

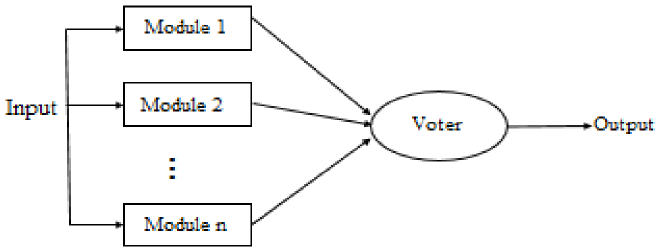

Figure 1. NMR structure [30]

To achieve a reliable bio-nanosensor, we evaluate the development of the Markov model with an NMR structure that depends on a fault coverage factor and can repair it. The advantage of using the NMR structure is that it can tolerate more faults. For example, if N is 5, it can tolerate 2 faults. The majority vote method allows the 5MR system to offer correct results when facing binary faults. In many critical computing applications, two faults should be tolerated to achieve the desired reliability in the system.

Figure 2 shows the reliability of the NMR system for modules 1, 3, 5, and 7. The x-axis shows the time interval between 0 and 1. This time interval is usually appropriate for analyzing the system's reliability. As expected, the system reliability increases by increasing the number of modules. It can be understood from Figure 3 that NMR is appropriate for short-time applications similar to triple modular redundancy (TMR).

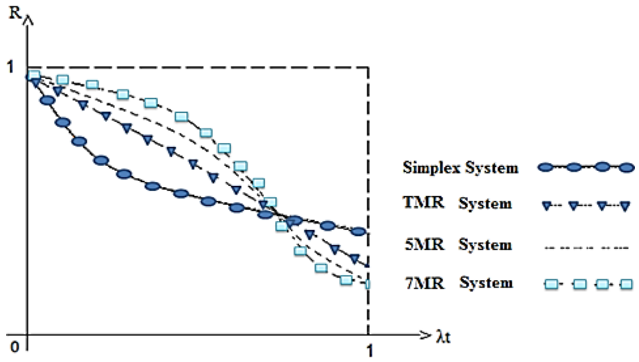

Figure 2. reliability in an NMR system with different modules

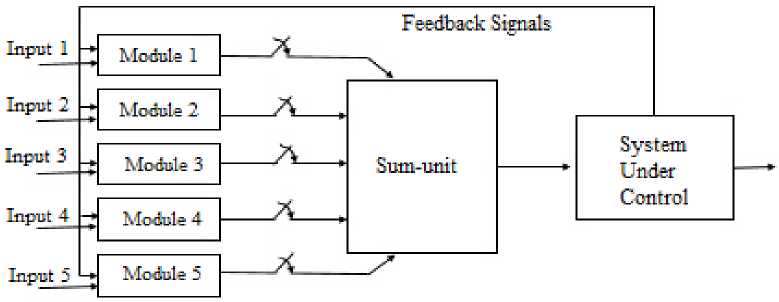

Figure 3. The basic structure of a Markov model for biosensors

The bio-nanosensor we want to model is a 5-module redundancy system that uses fault detection techniques to detect errors in one of the 5 independent modules. Modules submit their output to the sum unit, and it is enough that only one of the 5 modules does its job properly. As a result, the system would tolerate faults of 4 modules provided that the fault is handled properly. To do this, the fault module should be removed from the sum unit operation by opening a switch. As long as the switch is closed, the associated module provides the current to the sum unit. However, when the switch is opened, the module is completely separated from the sum unit and does not affect the system’s operation anymore.

Measuring the ability of the system to succeed after a fault is called fault coverage, so it can tolerate the faults and is named with C. In addition, it is supposed that the system has the fault rate λ and the repair rate μ and the main structure of the system is shown in Figure 3.

The Markov modeling of biosensors is shown in Figure 4. It is supposed that the system begins in a faultless state, which is named state 5. There are two ways through which the system can see state 5. First, as a transit to state 4 and related to faults of one of the five modules and the proper management of these faults. Second, as a transit to state 6, which is related to the faults of one of five modules that are not successful, known, or controlled. When the system transits to state 7, it equals the 5MR system in a majority vote. It cannot tolerate the third fault if one or two faults are not handled properly.

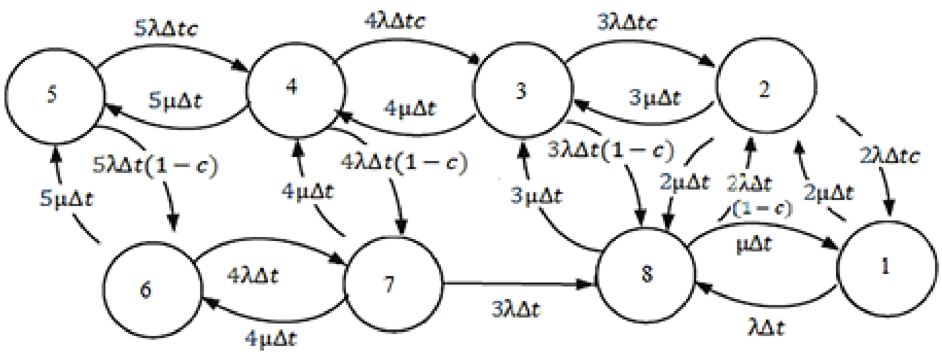

Figure 4. The Markov model of the system shown in Figure 3

Regarding the transition from state 3 to 2 and the failed state or 8, state 3 is related to a system in which two modules have a fault and have properly managed these faults. At state 3, the system can tolerate another fault and transition to state 2, provided that the fault is detected and repaired and transmit any unknown faults from state 3 to the failed state. Finally, any faults which occur in state 1 cause the system to transmit to the failed state rapidly, while in each state, the probability of remaining at the same state at the end of the time interval *Δt* as that of the beginning of that time interval is calculated by 1-p_e (*Δt*), in which p_e *(Δt)* is the probability of the state at the time interval *Δt*.

The equations of the Markov model in Figure 3 are improved based on the NMR system. The probability that it remains at state *i* at the time *t+Δt* depends on i) the probability of remaining in one state at the time *t* by which the system can be transmitted to state *i*, and ii) the probability of transition.

All offered equations for bio-nanosensor system's Markov model can be as (6):

$$P'(\mathrm{t}) = P(t).Q \tag{6}$$

where

$$Q = \begin{bmatrix} -5\lambda\Delta t & 5\lambda\Delta tc & 0 & 0 & 0 & 5\lambda\Delta t(1-c) & 0 & 0 \\ 5\mu\Delta t & -5\mu\Delta t - 4\lambda\Delta t & 4\lambda\Delta t & 0 & 0 & 0 & 4\lambda\Delta t(1-c) & 0 \\ 0 & 4\mu\Delta t & -4\mu\Delta t - 3\lambda\Delta t & 3\lambda\Delta tc & 0 & 0 & 0 & 3\lambda\Delta t(1-c) \\ 0 & 0 & 3\mu\Delta t & -3\mu\Delta t - 2\lambda\Delta t & 2\lambda\Delta tc & 0 & 0 & 2\lambda\Delta t(1-c) \\ 0 & 0 & 0 & 2\mu\Delta t & -2\mu\Delta t - \lambda\Delta t & 0 & 0 & \lambda\Delta t \\ 5\mu\Delta t & 0 & 0 & 0 & 0 & -5\mu\Delta t - 4\lambda\Delta t & 4\lambda\Delta t & 0 \\ 0 & 4\mu\Delta t & 0 & 0 & 0 & 4\mu\Delta t & -8\mu\Delta t - 3\lambda\Delta t & 3\lambda\Delta t \\ 0 & 0 & 3\mu\Delta t & 2\mu\Delta t & \mu\Delta t & 0 & 0 & -6\mu\Delta t \end{bmatrix} \tag{7}$$

$$P'(t) = [P_5'(t) \quad P_4'(t) \quad P_3'(t) \quad P_2'(t) \quad P_1'(t) \quad P_6'(t) \quad P_7'(t) \quad P_8'(t)] \tag{8}$$

$$P(t) = [P_5(t) \quad P_4(t) \quad P_3(t) \quad P_2(t) \quad P_1(t) \quad P_6(t) \quad P_7(t) \quad P_8(t)] \tag{9}$$

$$P(0) = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] \tag{10}$$

$$[P_5' \quad P_4' \quad P_3' \quad P_2' \quad P_1' \quad P_6' \quad P_7' \quad P_8'] = [P_5 \quad P_4 \quad P_3 \quad P_2 \quad P_1 \quad P_6 \quad P_7 \quad P_8].Q \tag{11}$$

Matrix equations for the Markov model can be calculated by means of the differential equation or the Laplace transform. To simplify the equation, the *Δt* parameter is ignored. Hence, the differential (12) to (20).

$$P_5'(t) = -5\lambda P_5(t) + 5\mu P_4(t) + 5\mu P_6(t) \quad (12)$$

$$P_4'(t) = 5\lambda C P_5(t) - (5\mu{+}4\lambda)P_4(t) + 4\mu P_3(t) + 4\mu P_6(t) \quad (13)$$

$$P_3'(t) = 4\lambda C P_4(t) - (4\mu{+}3\lambda)P_3(t) + 3\mu P_2(t) + 3\mu P_8(t) \quad (14)$$

$$P_2'(t) = 3\lambda C P_3(t) - (3\mu{+}2\lambda)P_2(t) + 2\mu P_1(t) + 2\mu P_8(t) \quad (15)$$

$$P_1'(t) = 2\lambda C P_2(t) - (2\mu{+}\lambda)P_1(t) + \mu P_8(t) \quad (16)$$

$$P_6'(t) = 5\lambda(1-C)P_5(t) - (5\mu{+}4\lambda)P_6(t) + 4\mu P_7(t) \quad (17)$$

$$P_7'(t) = 4\lambda(1-C)P_4(t) + 4\lambda P_6(t) - (8\mu + 3\lambda)P_7(t) \quad (18)$$

$$P_8'(t) = 3\lambda(1-C)P_3(t) + 2\lambda(1-C)P_2(t) + \lambda P_1(t) + 3\lambda P_7(t) - 6\mu P_8(t) \quad (19)$$

$$P_5(t) + P_4(t) + P_3(t) + P_2(t) + P_1(t) + P_6(t) + P_7(t) + P_8(t) = 1 \quad (20)$$

Using the Laplace transform, we have (21) to (29).

$$P_5(s) = \frac{1}{s+5\lambda} + \frac{5\mu}{s+5\lambda}P_4(s) + \frac{5\mu}{s+5\lambda}P_6(s) \quad (21)$$

$$P_4(s) = \frac{5\lambda C}{s+5\mu+4\lambda}P_5(S) - \frac{4\mu}{s+5\mu+4\lambda}P_3(s) + \frac{4\mu}{s+5\mu+4\lambda}P_6(s) \quad (22)$$

$$P_3(s) = \frac{4\lambda C}{s+4\mu+3\lambda}P_4(S) - \frac{3\mu}{s+4\mu+3\lambda}P_2(s) + \frac{3\mu}{s+4\mu+3\lambda}P_8(s) \quad (23)$$

$$P_2(s) = \frac{3\lambda C}{s+3\mu+2\lambda}P_3(S) - \frac{2\mu}{s+3\mu+2\lambda}P_1(s) + \frac{2\mu}{s+3\mu+2\lambda}P_8(s) \quad (24)$$

$$P_2(s) = \frac{2\lambda C}{s+2\mu+\lambda}P_2(S) - \frac{\mu}{s+2\mu+\lambda}P_8(s) \quad (25)$$

$$P_6(s) = \frac{5\lambda(1-C)}{s+5\mu+4\lambda}P_5(S) - \frac{4\mu}{s+5\mu+4\lambda}P_7(s) \quad (26)$$

$$P_7(s) = \frac{4\lambda(1-C)}{s+8\mu+3\lambda}P_4(S) - \frac{4\lambda(1-C)}{s+8\mu+3\lambda}P_6(s) \quad (27)$$

$$P_8(s) = \frac{3\lambda(1-C)}{s+6\mu}P_3(S) - \frac{2\lambda(1-C)}{s+6\mu}P_2(s) + \frac{\lambda}{s+6\mu}P_1(s) + \frac{3\lambda}{s+5\mu+4\lambda}P_6(s) \quad (28)$$

$$P_5(s) + P_4(s) + P_3(s) + P_2(s) + P_1(s) + P_6(s) + P_7(s) + P_8(s) = 1 \quad (29)$$

Using the Laplace transform and the system reliability provided, the probability of being at state 1, 2, 3, 4, 5, 6, and 7 is achieved. In other words, reliability can be written as (30) or (31),

$$R(t) = P_5(t) + P_4(t) + P_3(t) + P_2(t) + P_1(t) + P_6(t) + P_7(t) \quad (30)$$

$$R(t) = A + Be^{-(3\mu+2\lambda)t} + De^{-(3\mu+\lambda)t} + Ee^{-(\mu+2/3\lambda)t} + Fe^{-\lambda t} \quad (31)$$

in which A, B, D, E, and F are parameters based on λ, μ, and C. It can be seen that reliability depends on several key parameters, such as the failure rate, fault coverage, repair rate, and time period. The results demonstrate that the Markov model can be used for reliable bio-nanosensors. Moreover, using the NMR-based structure in the Markov model will result in more reliability in bio-nanosensors.

As shown in Table 2, although more hardware is used, the system can tolerate more faults and errors; note that there is always a trade-off between the amount of used hardware and fault tolerance based on application. Accordingly, using the proposed method, the number of modules can be increased to nine. However, a larger number than 9MR is not recommended because of an increased delay and requiring more hardware.

Table 2. Results comparison of the proposed method with other methods

Method	Redundancy hardware	fault	Delay
non-fault-tolerant systems	-	0	-
TMR	2	2	Low
5MR	4	3	Medium
7MR	6	4	Much
9MR	8	5	Much
>9MR	>8 and Even	> 5	unacceptable

4. CONCLUSION

Nanotechnology allows us to interact with living systems on a molecular scale. The occurrence of errors in computational systems is inevitable, so if there is no technique to tolerate faults and errors, erroneous results are obtained. Consequently, a method with the capability of tolerating faults and errors is required. Our proposed method employs nanorobotics, which is a novel and prominent technology with medical applications. A more perfect nanorobot has a higher fault tolerance. For this purpose, hardware redundancy techniques are used in carbon nanotube-based bio-nanosensors for reliability evaluation. It can be seen that reliability depends on several key parameters, such as the failure rate, fault coverage, repair rate, and time period. The results demonstrate that the Markov model can be used for reliable bio-nanosensors. Moreover, using the NMR-based structure in the Markov model will result in more reliability in bio-nanosensors. although more hardware is used, the system can tolerate more faults and errors between 3 to 5. Besides reliability, other parameters, such as security and availability, can also be investigated.

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