The 3-D Complete Body Screening (3D-CBS) Features and Implementation

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Abstract--: **An innovative, low-radiation 3-D Complete-Body-Screening (3D-CBS) medical imaging device is presented, combining benefits of the functional imaging capability of PET with those of the anatomical imaging capability of CT. Although PET technology has existed for 50 years, its benefits have never been fully realized. In addition to the radiation problem, the problem of how to increase the narrow viewing field in a cost-effective manner so that full-body examination can be done quickly has always been a stumbling block – until now. The technological innovations, set forth in this article, are in the electronics that enables a different detector assembly, and together they enable execution of more complex algorithms measuring more accurately the information obtained from the collision of the photon with the detector. This improvement permits a cost-effective extension of the FOV to over one meter in length and captures more accurately about 1 in 10 pairs of photons emitted instead of the 1 in 10,000 pairs of photons captured by current PET. The innovations lie partly in the way existing components (available off the shelf) are assembled and partly in the innovative electronics (digital signal processing on each electronic channel). A hardware prototype implementing the innovative functions of the 3D-Flow^{TM} architecture shows the feasibility of the entire system. This hardware construction is the basic element of the project. Several sections of the 3D-CBS have been simulated and built. The benefit of this research lies not only in improving the PET/CT efficiency by a factor of several hundred, but this technology creates competition and lowers examination cost.**

I. INTRODUCTION

Steve Webb, author of a book [1] on the history of PET, remarked during the last plenary talk at the IEEE-NSS-MIC conference on Friday October 24, 2003, that CT was rapidly improved to find commercialization in about 15,000 units in the U.S since 1976, while PET, which was invented [2] half a century ago, is still not at a stage of development of efficient detection of annihilation radiation that would lend itself to a commercialization similar to that of the CT (PET has only about 1,000 units in the U.S.). In addition to this observation by Webb, another statement was made by Roderic Pettigrew, the director of the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health (NIH), during his talk at the plenary meeting on Wednesday, October 22, 2003 at the IEEE-NSS-MIC conference, when he expressed the wish that the efficiency of PET could be increased 100 to 1000 times. (Current PET captures, with not very accurate measurements of energy and spatial resolution, only about 1 pair of photons per 10,000 emitted in the patient's body).

The answer to both statements is finally here with my innovative technology, summarized in this paper, which I presented for the first time at the IEEE conference in Lyon in October 2000, in the book [3] (which was distributed to the major players in this field), and now also by having overcome the hurdles in implementing the main components, showing the feasibility of the blue print detailed in [3].

My mission is to make available at an affordable cost to a large population a life-saving technology, with safe, low radiation requirements, which has a) the potential to diagnose cancer and other diseases at an early enough stage when they can still be treated successfully and b) to follow up treatment of patients suffering from recurrent cancer with more efficacy. (See Figure 1).

Until a few years ago (and still now, according to some) there was the belief that the only way to improve PET efficiency was to improve the efficiency of the crystal detector and not the electronics. I have heard statements from many people who are working intensively in the PET field to this effect. The proof that my discovery is valuable and that finally it will allow a big step in the field is that PET efficiency can be improved by using a special massively parallel-processing system with digital signal processing on each electronic channel, which in turn enables a series of other improvements and simplifications in the detector assembly and enables the execution of complex real-time algorithms . The publication of my study in my documents [3], [4], [5] has already changed the trends in improving the electronics and its benefits. The role of the electronics in PET has been acknowledged by Ed Hoffman during his plenary talk on Wednesday, October 22, 2003 at the IEEE-NSS-MIC conference when he stated that PET efficiency has improved about five times by improving its electronics. None of the new PET components (crystals, PMT, APD, or the new Flat Panel Sensors that replace the PMT) can improve PET efficiency by more than a factor of two or so. However, if we use components (PMTs, economical crystals) which were available three years ago (or even older), with my innovative technology in electronics and detector assembly, which allows execution of more complex and more accurate algorithms, we can achieve the two to three orders of magnitude improvement in efficiency that Roderic Pettigrew called for. After more than 50 years, PET can finally realize its full potential in detecting diseases in asymptomatic people, studying physiological processes, and other applications yet to be conceived.

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As described by Steve Webb during his talk, with reference to [1] and [2], the first Positron imaging device was built in 1950 [6]; the first clinical Positron Imaging device was built in 1952; the Positron Imaging device with multiple detectors was built in 1962; results were published in 1968 [7], the first Tomographic Imaging Device and the first Computed Tomographic Imaging Device (PET) was built in 1968-1971 [8] and its commercial version in 1971-1976. The major step in PET development, that of enabling PET to become a device that can be used on asymptomatic people requiring low radiation and providing more accurate measurements of incident photon energy and spatial resolution, is now possible with my innovative technology as described in [3], [4], [5].

The local committee of an open review [10] of my innovative technology, which was extended via web to a worldwide participation on July 1st, 2003 summarized: “Crosetto’s novel technique provides better images in a shorter time with less radiation to the patient. A primary means of accomplishing this is the use of more detectors to cover a larger solid angle. However, this requires a new electronic technique capable of handling the increased data rate and allowing a more efficient use of economical crystals in the detector. A novel electronic technique combined with an improved and simplified detector assembly are the principal features of Crosetto’s invention.”

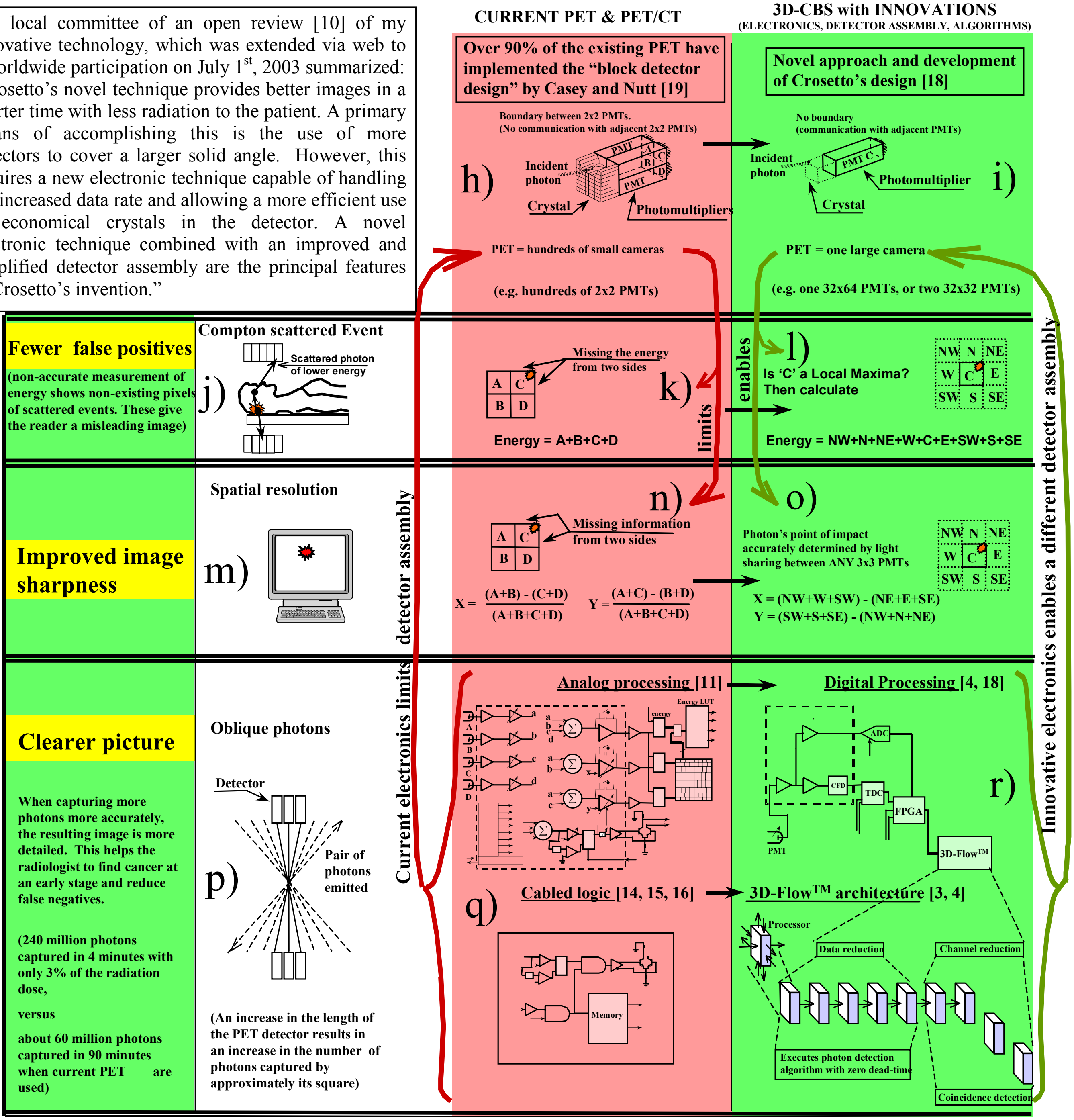

Figure 1. The three statements on yellow banners on green on the left summarize the advantages important to the doctor/radiologist compared to current medical imaging devices. Each statement is illustrated in the next column, limitations of current technology is shown next in the red column, and the improvement achievable with 3D-CBS is illustrated in the green (right) column. See Sections j, k, and l for energy resolution; m, n, and o for spatial resolution; and p, q, and r for sensitivity. The key innovations start from the feature in Section "r," which enables the innovation in Section "i," which in turn enables the innovations in Sections "l" and "o." Additional innovations are achieved as a result of the combination of these.

II. INNOVATIONS ALLOWING IMPROVING OF PET EFFICIENCY BY A FACTOR GREATER THAN 400

A. Key innovation of the electronics

Concept: The concept of the 3D-Flow^{TM} parallel-processing architecture that enables execution of a complex real-time algorithm, calculating different types of depth of interaction with zero dead time, and with data exchange with neighboring processors for a time longer than the time interval between two consecutive input data, is explained in several documents [4], [9], [5] (see also U.S. patent No. 5,937,202). This provides better energy measurement (Figure 1-l), helps to reject scatter events more efficiently (Figure 1-j), and provides a way to improve spatial resolution by measuring more accurately the location where the incident photon hits the detector (Figure 1-o). It also increases sensitivity in accepting oblique photons by eliminating the parallax error in accurately measuring the depth of interaction (Figure 1-r). One of the key algorithms that can be changed for different detector types having crystals with different decay times is described in figure 34 at page 53 of reference [5].

This concept was simulated and its hardware implementation was shown working in hardware FPGA at the IEEE-NSS-MIC-2001 industrial exhibition, and at the July 1st open review [10]. The concept of digital processing versus analog processing [11] is shown in Figure 33 of [5]. Another aspect of the invention is the way these concepts are implemented in hardware; the way the North, East, West, and South (NEWS) connections are implemented on IBM PC boards or designed to be implemented in VME boards. This practical implementation is not only a concept, but now the IBM PC implementation with the NEWS information exchanged via flexible printed circuits is a reality that shows feasibility and cost-effectiveness.

Advantages compared to current technology:

The limitations of current technology are shown in the performance of the features and measurements reported by third parties at http://www.itnonline.net/, by the PET manufacturers, and in articles [12], [13], [14], [15], [16]. The key measurements made by the PET manufacturer CTI, that show the limitation of current electronics in detecting photons at the edges and corners of a 2x2 PMT, are shown in [17].

B. Key innovation of the detector assembly

The key innovation of the detector assembly is the construction of one or a few large cameras (Figure 1-i) versus hundreds (or thousands) of small cameras, such as are used in current PET [19] (Figure 1-h).

Advantages compared to current technology:

More details of the assembly of the detector, such as making equal length cuts (or no cuts) with reflecting material between crystals versus cuts of different lengths as implemented in current PET, are (described in [4], [5]). This simplifies assembly, lowers the cost, and increases the efficiency of the detector when used with the new 3D-Flow^{TM} electronic architecture.

C. Key innovation of the synergistic combination of A and B

1. The 3D-Flow^{TM} parallel-processing architecture allows the execution of complex algorithms with neighboring signals correlation in real time and provides the capability to extract more accurate information from the signal generated by the interaction between the incident photon and any type of crystal detector. This allows a more efficient use of economical crystals.
2. The coupling of the detector with the electronics is made in such way that there are no boundaries or fixed detector segmentations; rather, each sensor of the detector (PMT, APD, etc.) is an element of a large array with the capability to act as the center of a cluster of elements, all providing information.

Advantages compared to current technology:

1. A more sophisticated, powerful, digitally programmable electronics, implemented in a way made simple by an optimized placement of the components (such as some 20,000 pins routed in only eight layers of signals), and by the assignment of the signal to the pins of the components, permits more efficient use of economical crystals.
2. The one-to-one mapping of the detector array with a single array of electronic processing channels remedies the inefficiency of current PET in capturing fewer photons, less accurately at the edge and corner of each of the hundreds (or thousands) of small cameras or at the edge of detectors with fixed segmentation.
3. The simplified architecture of the electronics and detector assembly allows expansion of the length of the PET detector (FOV) without an exponential increase in the complexity of the electronics, as the architecture of current PET would require. This new architecture also allows the capture of more oblique photons with a simple, cost-effective electronics and results in greater uniformity of the image across the FOV.

III. IMPACT AND BENEFITS DERIVED FROM THE ABOVE INVENTIONS

The breakthroughs of the 3D-CBS allow for improvements in six areas: (a) quality and quantity of detection; (b) uniformity of image across the FOV; (c) improved examination time; (d) lower radiation dosage requirements; (e) unique three-dimensional dynamic imaging; and (f) lower costs. (See details at pp. 20-23 of reference [5]).

Figure 2 shows the area of improvement needed in current PET devices in order to reach the theoretical limit of efficiency. The "coincidences" include "true" (image forming events), "scatter" (non-image forming, Compton scattered events, most of which are later rejected during image reconstruction), and "randoms" (non-image-forming events which are emitted within the required time difference but belong to two different positron-electron annihilations.)

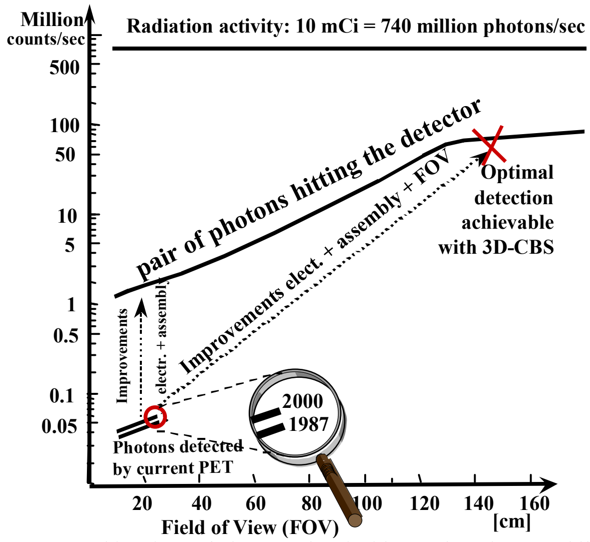

Figure 2. Graphic view of the actual coincidence detection capability of current PET vs. the theoretical limit that new PET/CT detectors should attempt to achieve. The 3D-CBS aims to approach the theoretical limits in one giant step instead of providing small incremental improvements every few years (two to three times every five years), as has occurred during the past decades. The areas of improvement are the electronics (see vertical arrow, left on figure) and the combination of the improvement of the electronics, a different detector assembly, the execution of a complex real-time algorithm, and the increased FOV (see inclined arrow to the right).

IV. IMPLEMENTATION: SYSTEM DESCRIPTION

Figure 3 shows the main hardware components of the 3D-CBS which are:

- **a)** **detector (crystal + PMT),**
- **b)** **photon detection board,**
- **c)** **coincidence detection board, and**
- **d)** **software.**

The detector can be purchased off the shelf. A prototype of the photon detection board for 16 channels (see Figure 7) was built. The coincidence detection board (center in the figure), is designed and under construction. The real-time software for trouble-shooting during operation has been developed.

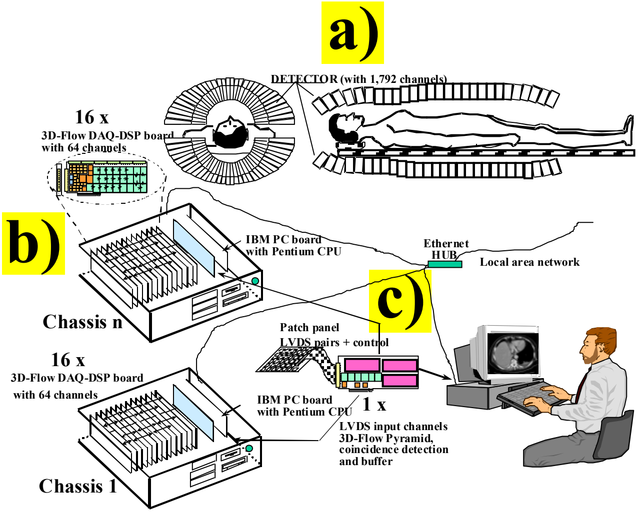

Figure 3. Layout of the hardware assembly of the 3D-CBS

Figure 4. Gantry for the 3D-CBS that can accommodate detectors of different types, different shapes and different lengths (or FOV, from 16 cm to 180 cm in length. It allows construction of a circular detector for head and torso or any elliptical geometry for any section of the body. The possibility of lifting the upper half solves the problem for claustrophobic people when the FOV is increased.

Figure 5. Chassis for several 3D-Flow^{TM} DAQ IBM PC boards, one 3D-Flow^{TM} routing/coincidence board, and one SBC-CPU board. The power supply, power distribution and power cooling has been calculated for the full load of the 17 PCI boards and one SBC-CPU board for the final implementation of the electronics for the 3D-CBS.

A. Detectors

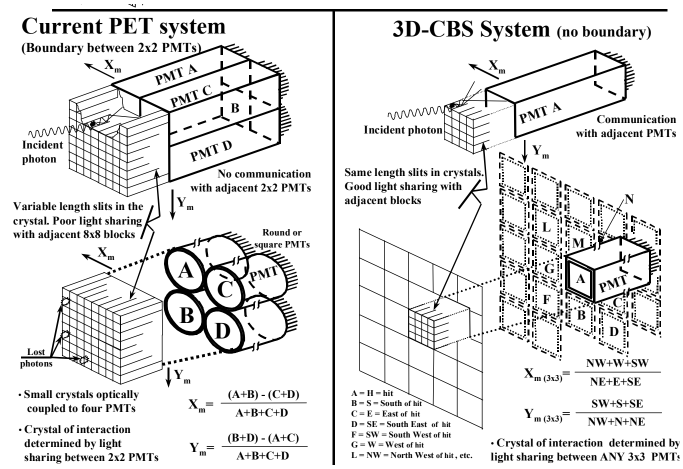

Figure 6. Comparison of the assembly of the 3D-CBS crystals coupled to the PMT (or APD) sensors allowing centroid calculation with no detector boundary limitation [18] (right) vs. the detector assembly of current PET which has a 2x2 PMT (or module) detector boundary limitation [19]. The identification of the crystal of interaction in the 2x2 PMT block is made through the Anger Logic shown at the bottom left of the figure. The crystals at the edges and corners of the 8x8 crystal block contributes a smaller signal compared to the inner crystals, making their identification more difficult (see measurements on Figure 3 of [17]). The 3D-CBS assembly (right) solves these problems by permitting all crystals to have the same degree of light sharing with adjacent crystals with slits of equal length (or no slits), allowing sharing the light with adjacent PMTs in all four directions with no boundaries. The interconnections in the North, East, West and South directions of the electronic channels of the 3D-Flow^{TM} system, allow any PMT receiving the highest signal to be identified as the center of a 3x3 (or 5x5) cluster.

B. Electronics: Photon Detection board

The photon detection board (see Figure 7) performs digital processing on each electronic channel using a scalable architecture suitable to be implemented on the most cost-effective technology (also in FPGA). This architecture takes the parallelization process one step further than DSP, and its software tools allows to create in a few hours a new application with different algorithms executed on thousands of processors. (See detail in an article presented at the same conference [20]).

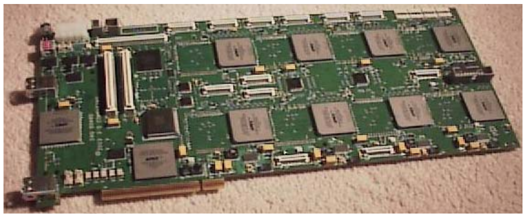

Figure 7. 3D-Flow^{TM} DAQ IBM PC board for photon detection.

C. Electronics: Coincidence detection Board

The coincidence detection board is designed and under construction. It uses a coincidence detection technique related to the radiation activity, which requires about 120 million comparisons per second, rather than using the coincidence-detection technique used by current PET which is related to the number of electronic channels. The current technique would require about 16 trillion comparisons per second for a detection on a full granularity PET with 1800 electronic channels. (See details in [21] presented at the same conference).

D. Software

Simulation of the real-time algorithms on experimental data has been performed and reported in [22], [23]). The entire simulation of the electronics has been performed with the Design Real Time tools [4]. Figure 8 is separated into three sections. On the left is shown the flow of the software design and simulation process to create and simulate a 3D-Flow^{TM} system; on the right is shown the System-On-a-Chip for High-speed Real-time Applications and TESting (SOC-HRATES) hardware design process.

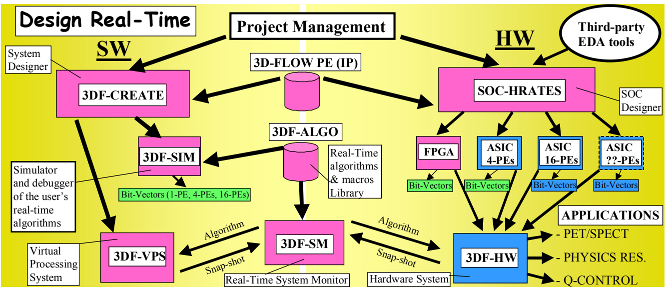

Figure 8. Interrelation between entities in the Real-Time Design Process.

The common entities of the system are shown at the center:

1. The IP 3D-Flow^{TM} processing element, which is the basic circuit to which the functionality required by different applications has been constrained;
2. A set of 3D-Flow^{TM} real-time algorithms and macros organized into a library;
3. The System Monitor software package that allows the user to monitor each 3D-Flow^{TM} processor of the 3D-Flow^{TM} system (hardware or VPS –Virtual Processing System), via RS-232 lines. The System Monitor (SM):

a) performs the function of a system-supervising host that loads different real-time algorithms into each processor during the initialization phase;
b) detects malfunctioning components during run-time;
c) excludes malfunctioning processors with software repair by downloading into all neighbors a modified version of the standard algorithm, instructing them to ignore the offending processor.

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