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Modeling and Analysis of Soft-Test/Repair for CCD-Based Digital X-Ray Systems

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***Abstract*—Modern X-ray imaging systems evolve toward digitization for reduced cost, faster time-to-diagnosis, and improved diagnostic confidence. For the digital X-ray systems, charge coupled device (CCD) technology is commonly used to detect and digitize optical X-ray image. This paper presents a novel soft-test/repair approach to overcome the defective pixel problem in CCD-based digital X-ray systems through theoretical modeling and analysis of the test/repair process. There are two possible solutions to cope with the defective pixel problem in CCDs: one is the hard-repair approach and another is the proposed soft-test/repair approach. Hard-repair approach employs a high-yield, expensive reparable CCD to minimize the impact of hard defects on the CCD, which occur in the form of noise propagated through A/D converter to the frame memory. Therefore, less work is needed to filter and correct the image at the end-user level while it maybe exceedingly expensive to practice. On the other hand, the proposed soft-test/repair approach is to detect and tolerate defective pixels at the digitized image level; thereby, it is inexpensive to practice and on-line repair can be done for noninterrupted service. It tests the images to detect the detective pixels and filter noise at the frame memory level and caches them in a flash memory in the controller for future repair. The controller cache keeps accumulating all the noise coordinates and preprocesses the incoming image data from the A/D converter by repairing them. The proposed soft-test/repair approach is particularly devised to facilitate hardware level implementation ultimately for real-time telediagnosis. Parametric simulation results demonstrate the speed and virtual yield enhancement by using the proposed approach; thereby highly reliable, yet inexpensive, soft-test/repair of CCD-based digital X-ray systems can be ultimately realized.**

***Index Terms*—Charge coupled device (CCD), defective pixels, diagnostic confidence, digital X-ray, repair, telediagnosis, teleradiology, testing, virtual yield, yield.**

I. Introduction

Modern X-ray imaging systems evolve toward digitization for reduced imaging cost and higher diagnostic confidence [15]. To provide faster and efficient processing and manipulation of image data, digitization of image data is emerging as a promising alternative technology over conventional analog data-based image processing technology [14]; examples include digital X-ray-based systems such as flat panel, computed radiography (CR), and digital radiography (DR). Digital X-ray technology is rapidly replacing conventional film-based X-ray techniques. Today's *filmless digital imaging technology* is emerging as a standard in medical applications such as *telemedicine and teleradiology* due to its promising perspectives such as cost-effectiveness, improved lifetime, reliability, and maintainability [10]. For example, military medical systems require convenient, real-time and efficient medical imaging solutions for their stringent mission-critical purposes [10]. Conventional X-ray films require huge amount of storage, which is very sensitive and vulnerable to temperature and humidity, and hazardous chemical processing for X-ray film development, which may also result in toxic environmental contamination. Furthermore, exposure of patients to X-ray is limited to certain angular setups, which further limits the effectiveness of conventional film-based X-ray medical imaging. Therefore, migration to digital X-ray technology is highly desired.

One of the most critical issues in CCD-based imaging system such as digital X-ray system is how to detect and repair *dark current* (or so-called *black noise*) to assure quality of service [7], [6]. Generally, digital X-ray system operates an electric or mechanical shutter for about 1000 ms and sometimes even for longer than 1 s. During that time period, the dark current could accumulate in CCD pixels without flushing; the phosphor cannot properly emit enough light so that the corresponding analog signal becomes too weak to sensor. As a result, the black noise can appear on the resulting X-ray image. Therefore, the dark current should be kept as low as possible by cooling or choosing a better quality and more expensive CCDs with low dark current characteristics.

Timely X-ray film read/processing is also one of the most critical requirements to provide high quality service. Under certain harsh environments, such as geographical isolation and tactical emergency, X-ray films should be remotely sent to radiologist for timely diagnosis. Filmless digital X-ray system can solve this problem by efficiently transmitting digital X-ray image data over the network to radiologist virtually in real time. Hence, filmless digital X-ray systems provide a promising solution, especially for processing and delivery of time-sensitive medical cases; still, a few problems have yet to be resolved, such as hardware reliability and slow software level calibration.

Besides the speed factor of X-ray processing, another critical factor is the *reliability* of the image for higher diagnostic confidence. Excessive X-ray exposure possibly damages CCD pixels and make them defective [5], [13]. Hence, it is required for digital X-ray systems to be maintained regularly by using costly and time-consuming software-based image calibration

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and tuning. Once a defective pixel hit by all means, the pixel creates a salt-and-pepper noise on target image, since it cannot receive and sense any photon; therefore, a noticeable darker noise point than any other image pixels becomes visible [8], [19]. The reliability is determined either by software or hardware factor. In reality, most CCDs suffer from defective pixels; therefore performance degradation is also experienced consequentially [19]. High-yield CCDs with less defects help resolve this problem at excessive cost in conjunction with complex calibration procedure [2]. The calibration procedure is generally practiced on software level and off-line for detecting/correcting defective pixels and performing optical corrections such as barrel correction. The approach proposed in [19] removes defective pixels on CCDs of a digital camera by periodically executing new off-line calibrations to update old calibration results under a new exposure. However, conventional off-line software-level calibration may create an excessive delay on digital X-ray image processing, which may not be acceptable under stringent processing constraints of today's digital X-ray applications.

There also have been a few works proposed to build a reliable CCD-based digital signal processing system from hardware's standpoint in [1], [4], [8], [9]. Digital camera uses high resolution color CCDs. In [8], it was proposed that defects on color CCDs can be detected and repaired such that a defective CCD pixel can be detected by checking which color has been corrupted among the three colors (i.e., red, green, and blue) and repair the pixel by replacing with a spare CCD pixel provided. The approaches relying on spare rows and columns of CCD pixels and, hence, are impractical to implement since it imposes additional cost to the already expensive CCDs [9], [8]. In [1], [4], a self correcting hardware design was presented, in which, unlike the global replacement of defective CCD pixels, spare pixels can replace defective or dead pixels located only on locally neighboring rows or columns. Since each CCD pixel is a sensing device with its predetermined image position to receive a photon from, replacement of a CCD pixel with a spare pixel will result in an irrelevant image data reception afterall; thus, serious post image reconstruction must be done.

Cost- and performance-effective testing and repair of CCD pixel defects are critical and essential requirements to realize high quality digital X-ray systems. Currently, the capacity of black and white CCDs for a digital X-ray has reached larger than 6 megapixels resulting in geometric increase in processing speed requirement, even with a simple filtering algorithm. For effective and efficient processing of huge amount of digital X-ray image pixel data, digital X-ray systems require ultra-high speed data processing with low noise rate.

The main objective of this paper is to propose a new cost and performance-effective approach to detect and repair CCD hardware pixel defects by proposing a novel yet effective theoretical model for yield and repair rate. Unlike the legacy hard-repair approaches, the proposed repair approach mainly depends on post-processing of the digitized X-ray image data in a real-time processing environment implemented on a field programmable gate array (FPGA). Performance characteristics of the proposed CCD soft-repair approach and benefits from implementation of the proposed hardware-oriented approach will be also investigated through extensive parametric simulations. Note that the proposed work is not to develop new filtering or calibration algorithms, but to propose a hardware-oriented image quality enhancement approach with respect to speed and hardware reliability-driven quality of service. For implementation purpose, any off-the-shelf image processing algorithms can be employed and realized on hardware level. An ultimate implementation plan would be on single chip-level fabrication [i.e., system-on-chip (SoC)] to utilize the performance benefits of SoC technology. Fast run-time dynamic filtering of digital image data on SoC-level is the ultimate goal of the proposed approach.

This paper is organized as follows. In Section II, previous works are reviewed, and basic principles of the proposed approach are introduced. In Section III, the proposed soft-testing and repair process is evaluated. In Section IV, a parametric analysis with respect to CCDs yield and soft-repair rate is provided. Conclusions and discussions are presented in Section V.

II. Review and Preliminaries

A typical digital X-ray system is shown in Fig. 1. The optical block captures the light generated by phosphor which emits light when it receives X-ray. The CCD image sensor contains numerous pixels and each of which senses photons using electronic well. CCDs convert accumulated photons in the electronic well to a corresponding voltage. Then, an analog amplifier, such as OP-amp, amplifies the signals before it directs the signals to A/D converter for digitization. Thereafter, the sensed image data is propagated all the way to the frame memory through the A/D converter under the coordination of the controller. The size of the frame memory is determined by the required digital image quality. For example, if a 1-Mega pixel CCD is used, 2-Mbyte RAM is needed for the frame memory when gray-scale color depth of 16 bits is required (i.e., $1024 \times 1024 = 1$ M pixel, each pixel needs 16 bit (2 Byte), therefore, 2-Mbytes needs for 1 M pixel).

Unfortunately, CCDs are not free from hardware defects. Imperfect fabrication and improper processing may induce defects (referred to as *hard defects*) on the photo-sensitive pixels and supporting system components in CCDs. In [4], the main causes of CCD hard defects are categorized as follows:

1) failure of row/column pixels (either line or readout/control transistors/circuit);
2) failure of row select/reset shift register;
3) failure of column sense amplifiers;
4) failure of A/D converter;
5) failure of buffers;
6) failure of read-out/reset transistors on each photo-diode.

In practice, all the defects of the above mentioned types affect the quality of the raw image data on the frame memory, since the hard defects that propagated all the way from the CCD to the frame memory through the A/D converter as shown in Fig. 1. The effect of a hard-defect observed on the frame memory is referred to as *soft defect*. Notably, a soft defective pixel on the frame memory usually shows an abnormal value compared to its neighboring pixel values. Without loss of generality, one-on-one correspondence between a hard-defect on the CCD and a soft

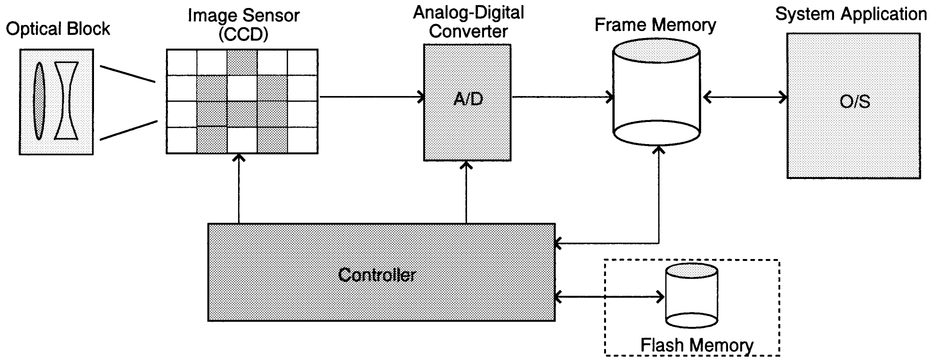

Fig. 1. Block diagram of a digital X-ray CCD system.

defect on the frame memory can be assumed, unless other component failures than CCD failures are taken into account. In this context, it is feasible to test and repair (i.e., soft-testing/repair) CCD hard defects on soft memory-mapped level in the form of soft defects on the frame memory. This paper only deals with *permanent* CCD hard defects.

The A/D converter reads analog image data (i.e., voltage) and convert it to corresponding digital values onto the frame memory storage. In reality, CCDs may contain the mega-scale number of pixels, and they may be either bad or defective (e.g., dead) pixels. In safety-, mission-, and deadline-critical applications, defective pixels may result in devastating consequences. However, defective CCD pixels cannot be effectively replaced by using traditional approach which relies on redundant defect-free pixels, because each CCD pixel can sense only the image pixel on its exact and unique physical position. Therefore, reliability and quality enhancement efforts should be practiced on some other level such as A/D converter or frame memory [19]. Once the raw image data is stored in the frame memory, it is more efficient to manipulate the image data in digital form since post data processing techniques such as calibration, filtering, and image processing algorithms can be applied. A few image processing algorithms have been proposed for the digitized images with defective pixels. In the proposed soft-repair process of the pixels with soft-test, 3×3 *average filter* (or 3×3 *mean filter*) is considered. A nonvolatile flash memory is employed in the proposed approach to cache and cumulate defect locations, referred to as *noise history data map*. By using the noise history data map stored in the flash memory, the repair process for soft-defect pixels hit on the frame memory can be implemented in a few different ways such as hardware, software, or firmware-level. In the proposed system, SoC-based hardware implementation is considered for the performance benefits of the SoC technology. the proposed approach can be effectively extended.

The main idea of the proposed approach is to capture and detect noises (i.e., soft defects) hit on the frame memory in digital X-ray system, which have been propagated all the way from CCDs (i.e., hard defects) through A/D converter to frame memory as shown in Fig. 1. A run-time writable flash memory is also used to store and keep track of up-to-date and cumulative *noise history data map*, which is used to pre-process incoming image data to enable skipping testing and repairing previously identified noise pixel positions. The proposed soft-testing and repair approach can be performed in a dynamic manner, since the proposed approach dynamically updates the pixel noise map on flash memory cache, while conventional software-level calibration or filtering approaches can be categorized as static. Thus, the dynamic pixel noise map in the flash memory can be constructed in an acceptable amount of execution time referred to as *pixel noise saturation time*. Having the proposed approach implemented on hardware, especially the whole system implemented on a single chip, the critical issues, such as processing speed and yield of CCDs as a measure of the reliability of the hardware structure of digital X-ray system as addressed before, can be effectively circumvented. The improvements due to the proposed hardware implemented soft-repair approach is referred to as *virtual CCD yield enhancement* and it can be implemented at a minimal hardware cost of flash memory caching without costly extra calibration procedures.

III. Proposed Soft-Test/Repair Process

Notations:

D_n	Number of defective pixels at the nth test/repair cycle.
D_T	Total number of soft defects hit on the frame memory.
F_h	Number of stuck high pixels.
F_l	Number of stuck low pixels.
F_s	Number of insensitive pixels.
F_{fault}	Number of defective pixels.
F_{repair}	Number of repaired pixels.
F_{test}	Number of tested pixels.
p	Insensitivity ratio.
$P(n)$	nth pixel under test and repair.
r_{defect}	Decrease ratio of the number of defects after each repair cycle.
R_n	Number of repaired pixels during the nth repair cycle.
r_{repair}	Repair ratio.
T_{test}	Test time.
T_{repair}	Repair time.
$T_{\mathrm{net\ repair}}$	Time for repairing a defective pixel.
W_T	Window (i.e., time for test and repair).
Y_H	Hard yield.
Y_V	Virtual yield.

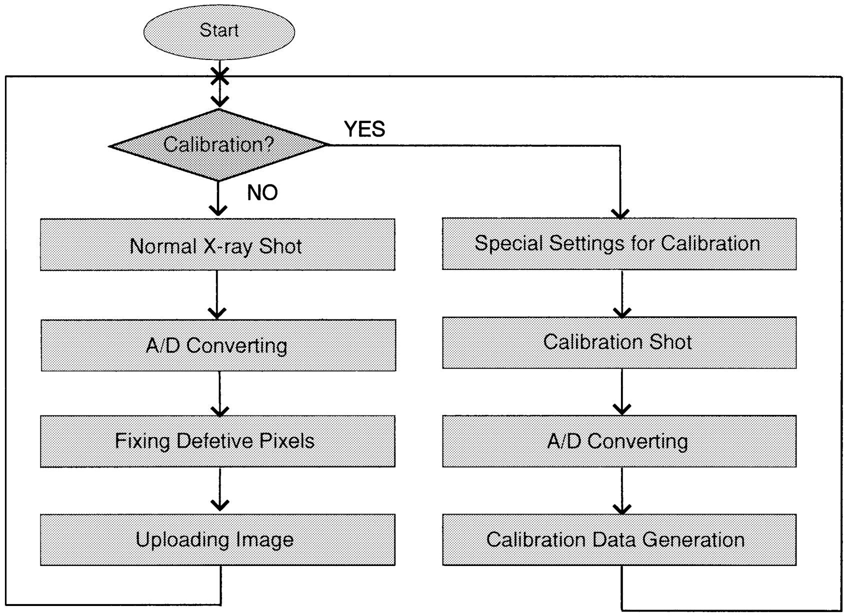

Fig. 2. Flowchart of the calibration CCD system.

A general calibration process in digital X-ray systems considered in this paper is shown in Fig. 2.

Based on the reference calibration process shown in Fig. 2, the main characteristics of the proposed soft-repair process are summarized as follows.

1) The hard defects on the pixels on CCDs is assumed to follow the Poisson distribution (i.e., $e^{-\lambda t}$). Note that clustered defects are not considered in this paper.
2) It is assumed that only CCDs contain defective pixels (i.e., dead pixels or hard defects), and all other components (i.e., the A/D converter, the frame memory and the flash memory), are assumed to be defect-free.
3) Without loss of generality, it is also assumed that the defective pixels are propagated from the CCD to the frame memory (i.e., soft defects) through the A/D converter.

In this paper, a simple mean filter as a criterion is used as shown in Fig. 3.

The proposed soft-test equation is given as follows:

$$\left| \frac{\sum_{k=1}^{N} P(k)}{N} - P(0) \right| \leq C \tag{1}$$

where $P(1) \cdots P(N)$ are the surrounding pixels of the tested pixel $P(0)$. The constant C is the threshold for determining whether it is defective or not in testing (e.g., 10%). This means the average value and the tested pixel value have almost same value. If (1) holds, then the tested pixel is diagnosed as normal, otherwise it is a defective pixel. It indicates that the tested pixel is too bright or too dark compared to its neighboring pixels. Actually, only a defective pixel cannot be too much bright or dark than their neighboring pixels because of the Gaussian effect (i.e., each nine pixel contains each other's shading information).

After testing and repair process completed, the controller updates the noise history data map in the cache (i.e., nonvolatile memory such as flash memory or E^2PROM). The proposed noise history data map caching technique allows for at-speed repair with minimal overhead as shown in soft-test/repair cycles in Fig. 4.

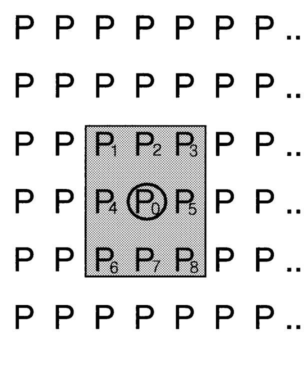

Fig. 3. Example of 3 × 3 Filter.

Equation (1) may not effectively take into account some defective pixels if they are adjacent to pixels of similar gray-scale colors. Since different input images are to be stored and processed in the frame memory at each test cycle successively, the defective pixels, in general, can be detected within a certain finite number of test/repair cycles.

There are generally three possible failure modes such as low sensitivity, stuck low, and stuck high [9]. On the frame memory, defective pixels are relatively brighter or darker to result in relatively larger or smaller digitized data words compared to its neighboring pixels, which can be used for testing purpose.

Each pixel on the frame memory can be cached in two bits of flash memory. The states of caching a pixel on the flash memory can be defined as follows.

1) 00 state: low sensitivity (i.e., F_s).

   Something covered part on photodiode, leakage in the photodiode, poor transfer characteristic of the transistor, etc.

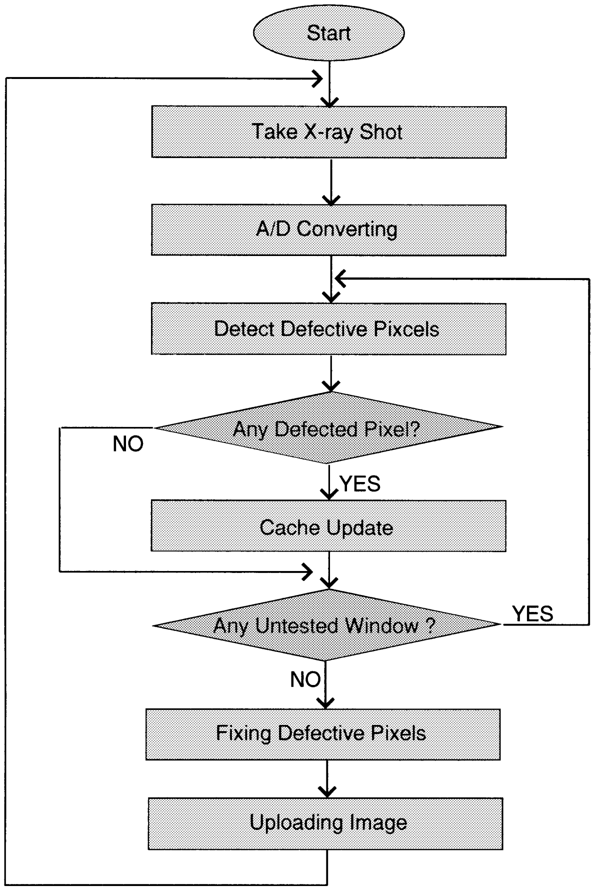

Fig. 4. Flowchart of the proposed caching CCD system.

2) 01 state: stuck low (i.e., F_l).
 Photodiode shorted, gate to photodiode path cut, transistor stuck off.
3) 10 state: stuck high (i.e., F_h).
 Photodiode always charged because of the malfunction of flushing circuit, transistor stuck on.
4) 11 state: normal pixel.

The corelation between each type of defective pixels and the total number of defective pixels, i.e., F_{fault}, can be defined as follows:

$$F_{\text{fault}} = F_s + F_h + F_l \tag{2}$$

The detection approaches and threshold equations for different type of defective pixel can be shown as follows:

1) 00 state: low sensitive pixels can be detected by the following equation:

$$\left| \frac{\sum_{k=1}^{N} P(k)}{N} - P(0) \right| \geq C \tag{3}$$

where $C = 10\%$. 10% means 10% of the maximum digital value converted from A/D converter (e.g., in the case of the 16-bit A/D converter, the 10% is $65\,535/10$). This means that a low sensitive pixel displays out of the range of the average value over 10% tolerance. This constant value depends on the characteristic of system. If (3) holds, then the pixel can be categorized as a low sensitive pixel.

2) 01 state: the stuck low pixels can be detected by the following two equations:

$$\left| \frac{\sum_{k=1}^{N} P(k)}{N} \right| \geq C_{011} \tag{4}$$

$$P(0) \leq C_{012} \tag{5}$$

where C_{011} and C_{012} are 50% and 10%, respectively. This means that the stuck low pixels displays near zero range yet the average value displays more than 50% of the range. The constant value could be changed smaller value for tight detection. Basically, this constant value depends on the characteristic of system. If both (4) and (5) hold, the pixel can be categorized as a stuck low pixel.

3) 10 state: the stuck high pixels can be detected by the following equation:

$$\left| \frac{\sum_{k=1}^{N} P(k)}{N} \right| \leq C_{101} \tag{6}$$

$$P(0) \geq C_{102} \tag{7}$$

where the reference C_{101} and C_{102} are 50% and 90%, respectively. The constant value can be varied from the give value depending on the system and quality level. If both (6) and (7) hold, then the pixel can be tested as a stuck high pixel.

Stuck low and stuck high pixels (i.e., State 01 and 10) can be repaired by replacing the defective pixel values by using the following equation. Since a defective pixel does not have any repair information, the defective pixel value is to be replaced by the average value of its neighboring pixel values

$$P(0) = \frac{\sum_{k=1}^{N} P(k)}{N}. \tag{8}$$

Note that the repair for a defective pixel defect of the state 00 depends on how much the pixel is insensitive. Thus, the following equation can be used to take into account the insensitivity

$$P(0) = (1 - p) \cdot \frac{\sum_{k=1}^{N} P(k)}{N} + P(0) \tag{9}$$

where p $(0 \leq p \leq 1)$ is the insensitivity ratio of the defective pixel under test. The insensitivity ratio p can be defined as following equation:

$$p = \frac{P(0)}{\frac{\sum_{k=1}^{N} P(k)}{N}}$$

where the denominator $(\sum_{k=1}^{N} P(k))/N$ is the reference value.

The proposed CCD soft-testing/repair process scans for the soft defects on the frame memory for a certain amount of time (i.e., referred to as T_{test}). The proposed soft-test/repair process repeats as many times as the total number of pixels within a temporal window of the process [i.e., within time T_{test} in (10)]. The pixels on the frame memory detected as soft defects are repaired, and then the locations are cached and accumulated in the flash memory. The time for each test/repair process cycle is referred to as *window* (W_T) and can be expressed as follows:

$$W_T = T_{\text{test}} + T_{\text{repair}} \tag{10}$$

where T_{test} is the time for testing and detecting the defective pixels and T_{repair} is the time for repairing defective pixels. Within a certain number of test/repair cycles, all pixels will be tested (and repaired, if needed). If the system capacity allows, it can test and repair all pixels in one cycle (i.e., if W_T is long enough to test and repair all pixels captured and stored on the frame memory).

The image data is stored in the frame memory, pixel by pixel. D_n is the number of defective pixels propagated from the CCD at the nth test/repair cycle, and can be calculated as follows:

$$D_n = D_T \cdot {r_{\text{defect}}}^{n-1} \tag{11}$$

where D_T is the total number of soft defects hit on the frame memory and r_{defect} is the decrease rate of D_n after each repair cycle. Since D_T is the total number of defective pixels, the following equation can be derived as well:

$$D_T = D_n + R_n \tag{12}$$

where R_n is the number of repaired pixels which are detected by the soft-test and D_T is a constant assumed to be a known characteristic of the CCD. On the other hand, F_{test} is the number of pixels that can be tested within the test time T_{test}, and W_T is the window size (i.e., $T_{\text{repair}} + T_{\text{test}}$). Also, the number of defective pixels (i.e., F_{fault}) can be expressed as follows:

$$F_{\text{fault}} = F_{\text{test}} \cdot (1 - Y_H). \tag{13}$$

Therefore, the F_{repair} can be expressed by dividing T_{repair} by $T_{\text{net repair}}$, as follows:

$$F_{\text{repair}} = \frac{W_T - T_{\text{test}}}{T_{\text{net repair}}} \tag{14}$$

where $T_{\text{net repair}}$ is the repair time for a defective pixel and F_{repair} is the number of repaired pixels that can be repaired within $W_T - T_{\text{test}}$. From (13) and (14), the repair ratio [i.e., $r_{\text{repair}}(n)$] can be expressed as follows:

$$r_{\text{repair}}(n) = \frac{\min(F_{\text{repair}}, F_{\text{fault}})}{F_{\text{fault}}} \tag{15}$$

$$= \frac{\min(F_{\text{repair}}, F_{\text{fault}})}{F_{\text{test}} \cdot (1 - Y_H)}. \tag{16}$$

The decrease ratio r_{defect} can be defined as follows:

$$r_{\text{defect}} = 1 - r_{\text{repair}}(n). \tag{17}$$

Then, the number of repaired pixels after n cycles, R_n of the CCD system can be given as follows:

$$R_n = \sum_{k=1}^{n} (D_{k-1} - D_k) \tag{18}$$

$$= (D_T - D_T \cdot r_{\text{defect}}) + \left(D_T \cdot r_{\text{defect}} - D_T \cdot {r_{\text{defect}}}^2\right) + \left(D_T \cdot {r_{\text{defect}}}^2 - D_T \cdot {r_{\text{defect}}}^3\right) + \cdots + \left(D_T \cdot {r_{\text{defect}}}^n - D_T \cdot {r_{\text{defect}}}^{n-1}\right) \tag{19}$$

$$= D_T \left(1 - {r_{\text{defect}}}^{n-1}\right). \tag{20}$$

Also, (20) can be derived from (11) and (12). By definition of normalization, $\bar{R}_n$ can be formulated as follows:

$$\bar{R}_n = \frac{\text{Number of Repaired Pixel}}{\text{Total Number of defective Pixel}} \tag{21}$$

$$= \frac{D_T \left(1 - {r_{\text{defect}}}^{n-1}\right)}{D_T} \tag{22}$$

$$= 1 - {r_{\text{defect}}}^{n-1}. \tag{23}$$

From (17) and (16), the repair rate can be calculated as follows:

$$\bar{R}_n = 1 - \left[1 - \frac{\min(F_{\text{repair}}, F_{\text{fault}})}{F_{\text{test}} \cdot (1 - Y_H)}\right]^{n-1} \tag{24}$$

$$= 1 - \left[1 - \frac{\min(F_{\text{repair}}, F_s + F_l + F_h)}{F_{\text{test}} \cdot (1 - Y_H)}\right]^{n-1}. \tag{25}$$

Therefore, the virtual yield Y_V is given by

$$Y_V(n) = Y_H + (1 - Y_H) \cdot C_{\text{st}} \cdot \overline{R_n} \tag{26}$$

$$= Y_H + (1 - Y_H) \cdot C_{\text{st}} \cdot \left(1 - {r_{\text{defect}}}^{n-1}\right) \tag{27}$$

where Y_H is the CCD hard yeld, and C_{st} is the soft-test coverage (i.e., the rate of detecting defective pixels out of the total number of actual defective pixels). Therefore, from (16) and (17), the overall virtual yield can be re-expressed as follows:

$$Y_V(n) = Y_H + (1 - Y_H) \cdot C_{\text{st}} \cdot \left[1 - \left(1 - \frac{\min(F_{\text{repair}}, F_{\text{fault}})}{F_{\text{test}} \cdot (1 - Y_H)}\right)^{n-1}\right] \tag{28}$$

$$= Y_H + (1 - Y_H) \cdot C_{\text{st}} \cdot \left[1 - \left(1 - \frac{\min(F_{\text{repair}}, F_s + F_l + F_h)}{F_{\text{test}} \cdot (1 - Y_H)}\right)^{n-1}\right]. \tag{29}$$

IV. Parametric Analysis

In this section, the effect of the proposed soft-test/repair process on the virtual yield of CCDs will be evaluated through numerical simulations based on Y_V derived in the previous section.

CCDs of 6 Mega pixels ($2\text{ K} \times 3\text{ K}$) are assumed in this simulation. Three CCDs containing 10%, 7%, and 3% defected pixels are considered, respectively (i.e., 10% is $(2048 \times 3072)/10$). From (23), the repair rates are calculated as shown in Figs. 5, 7, and 9. $Y_H = 90\%, Y_H = 93\%$, and $Y_H = 97\%$ CCDs are used for Figs. 5, 7, and 9, respectively. Also, the CCDs of $Y_H = 90\%, Y_H = 93\%$, and $Y_H = 97\%$ are used for Figs. 6, 8, and 10, respectively, based on (27). Note that three CCDs with 90%, 93%, and 97% hard yields are also considered for the purpose of comparison.

For the simulation, we assumed that the large window size is given by the time to scan and fix defective pixels for 30% of total pixel (i.e., 2048×3072). In the same way, the medium window size is given for 20% and the small window size is given for 10%.

A very *high yield* (i.e., 99.5%) CCD is adopted for the purpose of comparison in Fig. 6, 8, and 10. Note that the conventional method uses a defective pixel map on PC or workstation

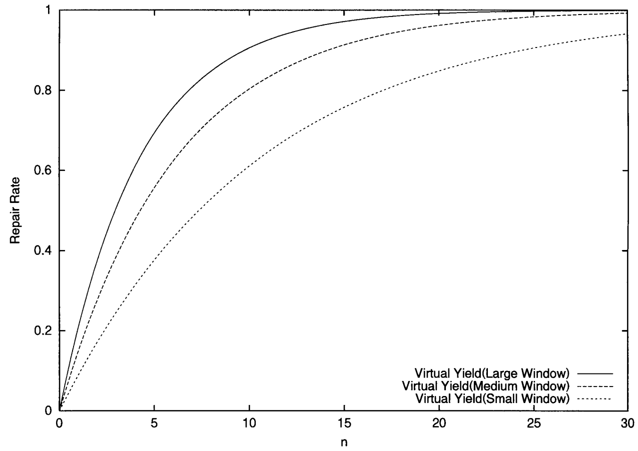

Fig. 5. Repair rate (hard-yield 90%).

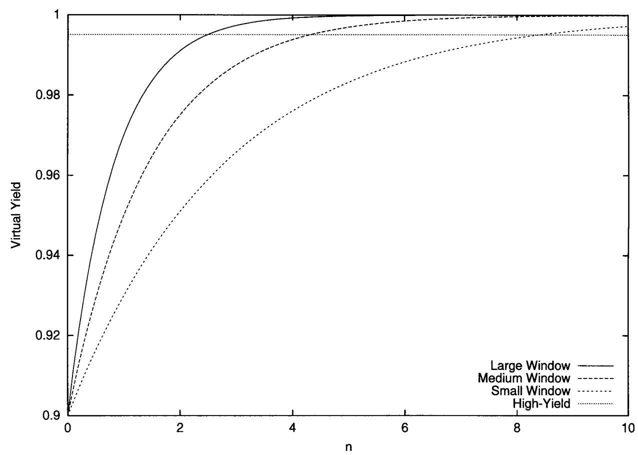

Fig. 6. Virtual yield (hard-yield 90%).

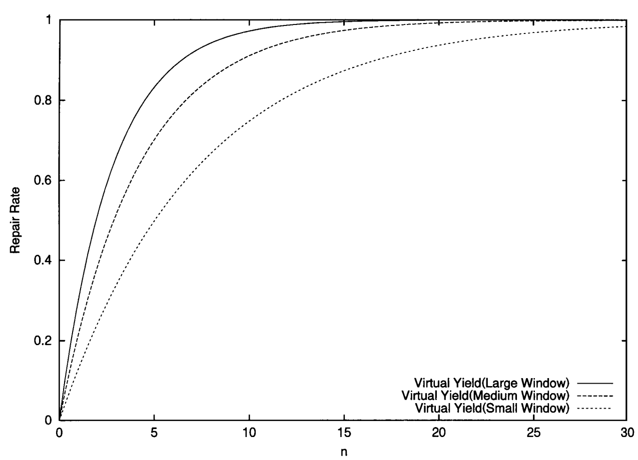

Fig. 7. Repair rate (hard-yield 93%).

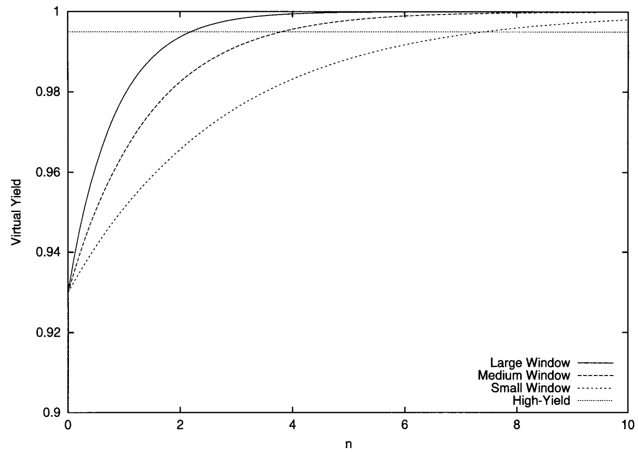

Fig. 8. Virtual yield (hard-yield 93%).

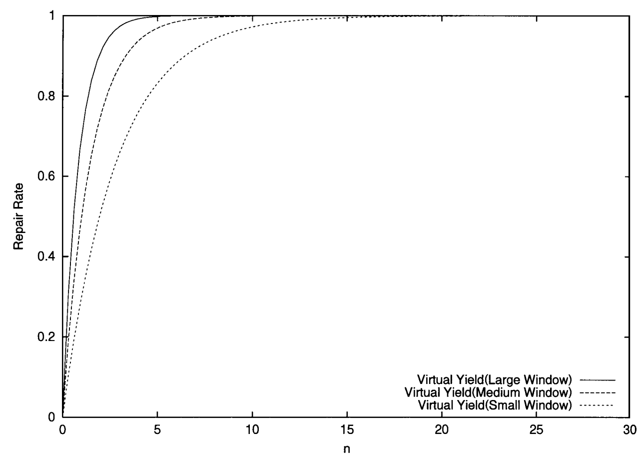

Fig. 9. Repair rate (hard-yield 97%).

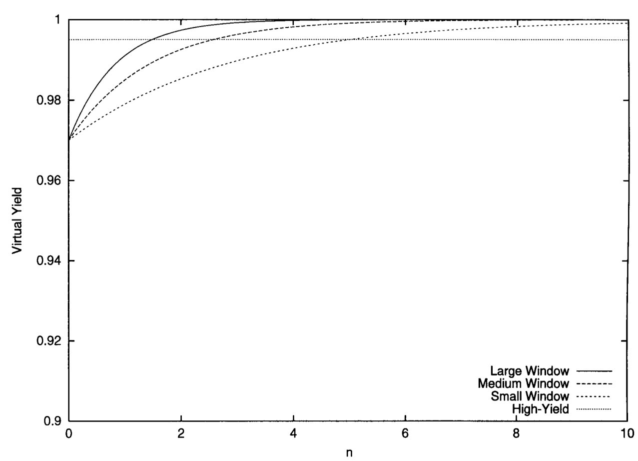

Fig. 10. Virtual yield (hard-yield 97%).

not in hardware level. So, we compare proposed soft-test repair approach with very high yield (99.5%) without repair.

By comparing the results of Figs. 5–10, the following observations can be drawn.

1) The proposed soft-test/repair approach is beginning to outperform the conventional calibration approach after a certain number of test/repair cycles in terms of virtual yield. In Fig. 9, the repair rate approaches 100% at $n = 5$ with large window size. Therefore, just a a certain number of initial image shots are needed to repair the defective pixels building a complete noise history data map on the cache. Thereafter, it will be just a matter of preprocessing incoming image data with reference to the complete noise history data map on the cache. In Fig. 5, the convergence to 100% is delayed to $n = 20$ with large window size.

The increase rate of the repair rate is determined by r_{defect} based on (23).

2) The proposed approach achieves high virtual yield after a certain point compared to the conventional approach regardless of the hard-yield and expensive CCDs being used in the conventional approach, as shown in Figs. 6, 8, and 10 in which the CCDs have $Y_H = 90\%, Y_H = 93\%$, and $Y_H = 97\%$, respectively. In Fig. 6, the virtual yield of the proposed repair process with small window size is starting to exceed the repair rate of high yield with large window at $\mathrm{n} = 8$. After the number of repair cycles exceeds $\mathrm{n} = 8$, the virtual yield converges to 100%. It is higher than the high yield CCD (i.e., 99.5%) and improved by 10%. This is very significant virtual yield enhancement by all means, which is very desirable in high resolution digital X-ray systems.
3) In Figs. 5, 7, and 9, the hard yield Y_H affects the repair rate. All the yields approach up to 100% regardless of the low initial hard yields. However, this does not mean that any low hard yield such as $Y_H = 30\%$ can virtually be enhanced to 100%. CCDs may or may not have reparable defects (i.e., not clustered defects). Actually, the criterion of acceptable image depends on the requirement of the system such as the resolution of system [i.e., line per millimeter (lpm) or dot per inch (dpi)], since some systems cannot tolerate clustered defective pixels. However, most medical systems use the binning mode (i.e., combining the pixel by hardware or software) for gathering more photons and increasing the image quality.
4) In Figs. 5, 7, and 9, the increase rate of the repair rate is shown and it depends on the window size. The higher hard-yield CCD quickly approaches 100% repair rate. However, even the small window size can achieve 100% repair rate just in a few more repair cycles. From this result, even if new defective pixels hit, the repair rate can achieve 100% by using the proposed soft-test/repair process. In practice, a CCD price depends on its grade which is determined by the number of defective pixels. Therefore, this approach can reduce the cost of products while increasing the image quality.
5) The resulting virtual yields are shown in Figs. 6, 8, and 10, based on (27). The hard yields determine the initial virtual yields. After a certain number of repair cycles, all the virtual yields converge to 100%.

From the results and findings shown so far, it can be concluded that the hard defects which mapped on the frame memory can be effectively repaired by the proposed soft-test/repair approach. Also, the repair rates and the virtual yields approach 100% in a small number of repair cycles. Furthermore, the proposed approach can enhance the repair rate as high as up to 100%, even though new defective pixels hit due to physical shocks or exposing to excessive X-ray.

V. Conclusion

This paper has presented a soft-test/repair approach for CCD-based digital X-ray systems through sound establishment of a novel theoretical modeling and analysis of the proposed test/repair procedure. It has been revealed that the yield of the CCD is one of the most critical components affecting the quality of service (QoS) of a digital X-ray system. There are two possible solutions to cope with the defective pixel problem in CCDs; one is the hard-repair approach and another is the proposed soft-repair approach. The proposed soft-repair approach is to circumvent defective pixels at the digitized image level; thereby, it is inexpensive to practice and on-line repair can be done for noninterrupted service. It tests the images to find the defective pixels and filter the defects at the frame memory level, and caches them in a flash memory in the controller for future use. The controller cache keeps accumulating all the noise coordinates, and preprocesses the incoming image data from the A/D converter by repairing them. The algorithms can be implemented on hardware level (i.e., on the controller) to speed up the process. Unlike the calibration approaches shown in [8], [19], the proposed approach stores the noise history map dynamically on hardware level and always keeps the up-to-date data within proper window size. Numerical simulations have revealed that the proposed soft/hard approach using the proposed soft-testing and repair process will outperform the conventional hard approach after a certain break-even point in terms of virtual yield, thereby, ultimately realizing high QoS of digital X-ray systems.

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