Automatic X-ray Crack Inspection for Aircraft Wing Fastener Holes


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Abstract. This paper presents an automatic X-ray image processing system for fastener hole radial and circular crack detection. A robot guided X-ray imaging system equipped with a digital detector is employed to take high resolution reference images of fastener holes of various shapes, thicknesses and in different locations of an aircraft wing. Learning module of the system is activated to train the system with knowledge of hole shapes, segmentation thresholds, grey level distributions of holes and backgrounds as well as hole pitches. Based on this knowledge, the system is able to segment fastener holes of unknown incoming images with localized thresholds, maximizing the shape similarity of the detected holes. Blob analysis is then applied to derive hole gravity and boundary chain code. From the gravity point of each hole, radial and circular scanning lines (arcs) are calculated to find subpixel transitions (edges, which are potentially crack pixels) in the neighborhood of the hole. Transition (edge) polarity and width are used to filter out unwanted disturbances. Finally crack filtering helps removing noise and highlighting the genuine cracks. The effectiveness of the system is demonstrated by processing real aircraft wing images. We are able to achieve a processing speed of 300ms per 1024 x 1024 X-ray image (Intel Dual Core PC 2.0GHz).

1. Introduction

Aircrafts are fabricated from a lightweight aluminum alloy that allows for an optimum balance of flight properties and cargo capacity. Aircraft wings, when subjected to the stresses of normal operation, fatigue damage can occur in high stress locations around fasteners. Crack growth, if left undetected, can lead to catastrophic failure. The inspection of aging aircraft for fastener hole cracks has been a time-consuming but essential task for the military services and commercial airlines alike.

In order to identify the presence of cracks before they reach critical lengths, aircraft operators have updated their inspection techniques. While visual inspection is an important part of the detection process, many cracks in their initiation are too small to see visually, may be hidden beneath the head of the rivet, or may initiate in the inner layer of the lap joint and cannot be seen from outside of the aircraft. To assist with the detection of these small and hidden cracks, non-destructive inspection (NDI) methods are used. Some of the more common NDI methods used in aircraft crack detection are eddy current, ultrasound and digital radiography.

Recent advances in magnetic sensor technology made the electromagnetic non-destructive evaluation method able to address crack detection issue. To detect deeply buried flaws, a low frequency electromagnetic field must be induced in the specimen under test. Traditional eddy current testing methods based on excitation-detection coils is
fundamentally limited by the poor sensitivity of the detection coils at low frequencies. Both anisotropic magnetoresistive sensors (AMR) and giant magnetoresistive sensors (GMR) have been successfully used in prior work for detecting deep cracks under installed fasteners [1][2].

The use of phased array ultrasonic [3][4] crack detection is another option. Ultrasonic phased array transducers are made of multiple crystals that are electronically pulsed in a sequence using a specified delay between pulses to create electronic scanning, beam steering, and focusing capability. Ultrasonic phased array inspection is gaining wide acceptance and has many advantages over conventional A-scan inspection. These advantages include the ability to perform scanning with no mechanical movement, the ability to perform angular (sectorial) scans and dynamic focusing without setup alteration, two-dimensional visualization of results, and similar portability to A-scan equipment. Ultrasonic phased array inspection results can be difficult to understand due to the complexity of angular ultrasound compounded by multiple transducer element excitation. Computational simulation can be used to predict the feasibility [5].

Digital radiography has emerged as a leading technology for aircraft crack inspection. It offers many advantages over conventional film-based radiography [6][7]. Digital Radiography enhances productivity as it records a ready to process image in short time and eliminates the need for any chemical processing required as in the case of using a film. In our previous work [8], we proposed methods and procedures to identify suitable x-ray sources and digital detectors to meet the high sensitivity required to inspect an aircraft. Different sensors and x-ray tubes were evaluated by using a set of a wire IQI penetrimeter, aluminium specimens with 6mm thickness and a 2T hole penetrimeter. We recommended amorphous silicon flat panels to be the most suitable detector for the aircraft inspection applications.

In this paper we propose an automatic X-ray image processing system for fastener hole radial and circular crack detection. Learning is performed to acquire from multiple aircraft wing X-ray images a sequence of fastener hole segmentation thresholds, hole sizes and shapes. Then, a so called “smart threshold” is applied based on learnt knowledge to optimize the finding of fasteners for any incoming wing image. Radial and circular scanning around fastener holes is performed to find subpixel crack locations. For post processing, three crack filters are applied to remove noise in crack images.

The rest of the paper is organized as follows: in section 2, the hardware used for the on-wing X-ray inspection, a robot guided X-ray imaging system equipped with a digital detector, is described. In section 3, the proposed fastener hole crack detection software is described in detail. Experimental results with real field trial images are given in section 4. Finally in section 5 conclusions and future work are provided.

2. A Robot Guided X-Ray System for Aircraft Wing Imaging

Currently, the detection of deeply buried flaws is carried out by using either eddy current techniques or ultrasound methods. The drawback of ultrasound and Eddy current methods is that they are difficult to apply to areas hidden within aircraft wing structure. For automatic fastener hole crack detection, we proposed a robot guided digital X-ray imaging system (Fig. 1). A large raster scanning manipulator system has been developed to automatically move an x-ray tube and a digital sensor along the wing of the aircraft. Radiographs are taken as the system moves and a large montage of the whole wing area can be built up gradually. The movement is programmed from a database drawing of the wing.
3. **Automatic Image Processing for Fastener Hole Crack Detection**

Fig. 2 illustrates the process flow of the proposed automatic image processing for fastener hole crack detection system. To equip the system with learning capability for various fasteners and imaging contrasts, the system has a learning module which allows user to learn manually a sequence of X-ray images. Knowledge about the segmentation thresholds, hole sizes and shapes are acquired and stored. For any unknown incoming wing image, fastener hole segmentation module will apply a localized “smart threshold” for each individual hole to determine its location and boundary. After that, radial and circular scanning lines (arcs) are calculated to find subpixel transitions (edges, which are potentially crack pixels) in the neighborhood of the hole. Transition polarity and width are used to filter out unwanted disturbances. Finally crack filtering helps removing noise and highlighting the genuine cracks.

![Image of process flow diagram](image)

Fig. 2 Process flow of the proposed automatic image processing for fastener hole crack detection
3.1 Knowledge Acquisition for Different Fastener Holes

As shown in Fig. 3, X-ray 2D scanning of an aircraft wing can generate images containing various objects in the background, such as wires, piping, screws and other structures. It is essential for an automatic algorithm to distinguish fastener holes and locate them from background disturbances. To do this, a learning module is incorporated to train the software with knowledge of what a fastener hole is and what is not.

The learning module allows user to load multiple images with different types of fasteners. User can either select manually a number of thresholds to evaluate the binarization results and identify the best one, or activate a semi-automatic process which uses Otzu’s auto-threshold within a predefined adjustment percentage, say +/-25% to perform auto binarization. Note that the global threshold selected for each image is for a rough search of fastener holes. A localized threshold will be determined in segmentation module to fine tune the binarization result for each hole.

The following knowledge about fastener holes will be acquired for segmentation module:

- A set of possible thresholds $t_i, i = 1..N$
- Max hole number which is used to reject binarizations with too many objects
- Hole shape in Fourier Descriptor for shape matching later on
- Background pixel grey-level distribution outside holes; this will be used for filtering out the false alarm pixels. The distribution is represented by an average value of all pixels surrounding the hole and a statistical deviation.
- Max and min hole areas and max and min hole extends in X and Y directions

A learning data structure is used to record up to 100 different thresholds, 100 fastener shapes, and other attributes.

3.2 Localized Smart Threshold for Fastener Hole Localization

Let $g(x,y)$ be an X-ray image pixel at location $(x,y)$ with intensity within $[0, 255]$, binarization using a learnt threshold $t_i$ can be formulated as

$$b_i(x,y) = \begin{cases} 1 & g(x,y) > t_i \\ 0 & \text{otherwise} \end{cases}$$

where $i = 1,2, \ldots N$.

Applying object analysis algorithm to a binary image, a number of blobs $\omega_i$ can be detected

$$O_i(\Omega) = \sum_{j=1}^{M_i} \omega_j$$

whereby blob $\omega_j$ meets the following requirements.
• Its shape has been defined in learning result, e.g. there exists a learnt shape \( a_k \) such that \( \sum_{k=1}^{6} |a_k - b_k| < T \) where \( b_k \) represents Fourier descriptor of the first 5 coefficients of the to be inspected shape and \( T \) is a predefined threshold, and
• Its X and Y extends are within the max X and Y extends, and
• Its area is between min and the max learnt areas, and
• \( M_l \) is within the max learnt hole number

The aim of the smart threshold based fastener hole detection is to find a best global \( t_i \) such that from the binary image \( b_i(x,y) \) a max number of fastener hole like blobs can be found, or \( M_l \) is maximized. After determination of the preferred global threshold \( t_i \) and \( M_l \) blobs \( \sum_{j=1}^{M_l} \omega_j \), a localized threshold can be found for each blob \( \omega_j \) by calculating Otzu's dynamic threshold within a small neighborhood of the blob. Blob gravity points and boundary chain codes are derived for crack scanning explained in the next section. Fig. 4 illustrates the process of the “smart threshold” detection of fastener holes.

3.3 Radial and Circular Crack Detection and Filtering

Radial and Circular Cracks: there are two kinds of cracks near a fastener hole to be detected: radial cracks which developed themselves from hole boundary and stretching outwards in the radial direction, and circular cracks which propagate outside the hole along the circular direction (Fig. 5, the 1st and the 2nd pictures). Subpixel edge detection algorithm is used to detect these two cracks by inspecting an abrupt changes in grey level values. For a radial crack, as shown in the 3rd picture of Fig. 5, multiple scan lines perpendicular to the radial direction are employed for edge detection. User is able to define the length of a scan line and the scan depth in radial direction. For circular cracks, radial scan (as shown in the
4th picture of Fig. 5) can be used. Again, the scan line length and incremental angle can be defined by users.

Fig. 5 Radial (1st picture from the left) and circular cracks (2nd picture) and their detection using scan lines perpendicular to the radial direction (3rd picture) and using radial scans (4th picture)

**Subpixel Crack Detection Algorithm**: When a crack detection scan line cuts across a crack perpendicular to the crack propagation direction, its grey level profile typically has the form displayed in Fig. 6a. Subpixel edge detection algorithm can be deployed to determine the crack position and width. We use an energy balanced approach to calculate subpixel edge location in a digital curve, a proprietary high speed subpixel edge detection method. As shown in Fig. 6a, for a rising edge, edge start and end points can be determined from each scan line using a minimum contrast constraint. Then, a model based double resolution is performed to interpolate edge region (Fig. 6b) before an energy balanced subpixel edge detection function is applied to derive subpixel edge position (Fig. 6c):

$$t = s + \frac{A_1^2}{A_1^2 + A_2^2}$$  \hspace{1cm} (3)

where $A_3, A_2$ are areas of edge profile defined in Fig. 6c. For rising edge, we define the edge polarity as minus. Similarly we can calculate a descending edge (plus edge).

Fig. 6 Subpixel crack detection by determining transitions in a rising and falling edge: (a) edge start and end point and subpixel transition $t$; (b) double resolution to gain more accuracy; (c) calculate $A_1$ and $A_2$ for subpixel position $t$ calculation

**Filtering for Noise Reduction**: Many a time, when X-ray images are noisy, not only the cracks, but also noise are detected by the edge detection algorithm mentioned earlier. To reduce the noise, a few constraints are introduced:

- Edge pair polarity check: crack should process a edge polarity from plus to minus (e.g. profile transitions are from black pixels to white and then back to black)
- Background consistency check: this option allows user to compare the background grey level deviation with the learnt background. Only backgrounds with similar grey level distributions are potential cracks
- Max crack width check: crack width detected should be less than a predefined value derived during learning

Another technique used in increasing the SNR of edge profile is a so called adaptive linesum function which traces the edge propagation and performs edge directional
integration to enhance SNR before applying subpixel edge detection algorithm. In this way an improvement in SNR by a factor of 10 or above can be achieved.

4. Experimental Results

We now describe the details of our method used in real X-ray images to verify the validity of the proposed approach. We use two groups of images: the first group is on-wing acquired images. Since there are no cracks detected even with human eyes for the images in the first group, we use a second group of real crack images from aluminum samples. Fig. 7 shows two smart threshold processing results using different learnt knowledge. The result in Fig. 7a is achieved by learning three hole patterns while Fig. 7b is achieved by learning only two patterns.

![Fig. 7](image)

Fig. 7 (a) Fastener hole detection by learning three fastener patterns; (b) Fastener hole detection by learning two fastener patterns. The red circle covering each hole indicates the crack search area, which can be defined by user.

Fig. 8 shows the crack detection results with and without noise filtering. As can be seen from Fig. 8a, noise pixels are falsely detected as cracks around hole boundary and other areas, especially when user selects a big crack search area. After applying background consistency and edge polarity check, the noise is removed (Fig. 8b).

![Fig. 8](image)

Fig. 8 (a) Crack detection without filtering: some red dots indicating detected cracks are found near hole boundary; (b) Crack detection with edge polarity and background grey level consistency filters
In Fig. 9, we apply the crack detection to a low SNR crack image. Linesum function with 35 integrations is used to reduce the noise level. As can be seen from the image, one real crack is detected, but there are some noise displayed in the crack map.

![Fig. 9](a) original crack image;  (b) Crack detection with only one crack detected; Using a lower contrast constraint to get the other two cracks will produce very noisy result

5. Conclusions and Future Works

A crack detection software system developed for aircraft wing fastener hole inspection from digitized radiographic image has been presented. We used a learning module to train the system on fastener shapes and segmentation threshold and then used a smart threshold to locate the fastener holes. Subpixel edge detection algorithm is applied subsequently to detect all potential cracks both in radial direction as well as in circular direction. Finally a few crack filtering mechanisms are implemented to remove the noise and output the crack map. The future works include the enhancement of crack detection sensitivity and the development of a crack model based detection algorithm.

References


