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HIGH EXPLOSIVE FILLER OF ARTILLERY SHELLS

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AUTOMATED DETECTION OF CAVITIES PRESENT
IN THE HIGH EXPLOSIVE FILLER OF ARTILLERY SHELLS

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ABSTRACT

Initial research has been conducted into the use of digital image analysis techniques for automated detection and characterization of piping cavities present in the high explosive (HE) filler region of 105-mm artillery shells. Experimental work utilizing scene segmentation techniques followed by a sequential similarity detection algorithm for cavitation detection have yielded promising initial results. A description of this work is shown with examples of computer-detected defects.

INTRODUCTION

The U. S. Army's Production Base Modernization Program for ammunition plants includes requirements for high through-put inspection of 105-mm HE projectiles to detect critical cavitation defects and other flaws. Such a projectile is shown in Fig. 1. At present this inspection paradigm is shown in Fig. 2. With this approach each group of four projectiles are radiographed with a Linatron 4-MeV source and recorded on Kodak AA 35.6- by 42.8-cm sheet film or its equivalent. The film is both automatically loaded and subsequently developed and then presented to one of several film readers for the acceptance

or rejection decision. This approach is both costly because of film costs and of doubtful reliability because of reader variability caused in part by fatigue. Reading experience of recent years at these installations has generated considerable skepticism over the validity of qualitative visual analysis and has indicated that the human element is undoubtedly the weakest link in the radiographic inspection process. In view of the fact that defects in the HE filler of artillery shells can cause premature detonations with the accompanying catastrophic results, technology to improve the detection of defects is of utmost importance.

A modern, automated HE melt-pour system currently under development will be designed to load at least 800,000 projectiles per month. Initially 10 percent of these will be radiographed for inspection. Eventually 100 percent inspection will be required when the process goes off the controlled phase. Two automation goals should be considered: 1) elimination of film as a storage medium, 2) elimination of the humanly derived accept/reject decision. This report will deal specifically with defect detection from already existing film-recorded imagery. However, references to alternative forms of image acquisition and storage will be referred to when it is felt appropriate.

CRITICAL HE FILLER DEFECTS

There are four major categories of defects defined as present in the HE filler. These include a crack, cavity, porosity, and base separation. A crack is a feature appearing as a dark irregular line whose length to width ratio equals or exceeds 20 to 1 and whose width does not exceed .16 cm. Porosity refers to multiple areas caused by a multitude of small overlapping or interconnected cavities such that no individual cavity within the area of involvement is clearly discerned. Base separation occurs at filler-casement boundary

and is characterized by a narrow dark band. The results reported will concentrate on cavity detection. However, it is felt that the paradigm will be extendable to the other defect classes as this research continues.

The HE filler has been divided into four discrete segments as shown in Fig. 3. There exist segment-specific criteria related to maximum permissible defect sizes for each previously defined defect type. The criteria are expressed in either linear or projected area units. The maximum permissible defect is generally larger as one proceeds from Segment A to Segment D. These maximums are bounded by 0 - 1.9 cm for linear measures, and by 0 - 3.25 sq cm for projected area measures. It should, therefore, be pointed out that while detection of all defects is always necessary, there exist segment-specific upper bounds which define acceptability. Failure to fall below this bound in any segment is sufficient to reject the projectile. Our current research effort can be divided into four sequential phases:

- 1) Detection of shell macrostructure for the purpose of scene segmentation.
- 2) Detection of regions within the segmented shell scene containing cavitations.
- 3) Measurement of detected anomalies.
- 4) Classification of shells into an accept or reject category.

A brief discussion of the first two phases follows:

SHELL SCENE SEGMENTATION

When the human interpreter views a shell to detect and estimate defects, he first mentally segments the scene into its components. That is, he notes the regions containing HE filler, casement, and fuse-well. He may also mentally divide the scene into the four specified segments A, B, C, and D

in order to apply the individual inspection criteria with respect to each of these segments. Thus, if one is looking for a pipe cavitation, for example, one must first isolate the HE filler from the shell's casement. On the other hand, if one wishes to detect cracks in the shell casement or base region separation, the detection of the region between the filler and the shell boundary is necessary.

With this necessity clearly in mind, an algorithm has been developed for macrostructure segmentation of the shell into its component parts on a laboratory computer. Figure 4 shows the results of an automatic detection of the HE filler boundary, casement boundary, rotation band, shell midline, and the four previously referred-to segments. The algorithm was written and run without modification on all shells examined. The digital spatial resolution across a 4-shell region is equivalent to that of a 500-line vidicon. Thus, each projectile is represented by a digital matrix with 444 rows and 128 columns. The boundary detection techniques involved rather straightforward threshold detection and boundary following techniques. Figure 5 shows a typical scan line across one projectile. The encircled area represents a typical density depression when a cavitation is encountered. It also appears that the least dense portion of the scan line (labeled 1 and 2) occurs at the left and right casement-filler boundaries. A simple peak detector was therefore sufficient to find these boundaries on each scan line. Since it is known *a priori*, that the background-casement boundaries must lie outside their respective casement filler-boundaries, only these portions of each scan line need be searched. The boundary value criteria in this latter case were the detection of the onset of either a negative (viewer's left), or a positive (viewer's right) first derivative. These points (labeled 3 and 4) are also shown for the scan line in Fig. 5. Identical detection criteria were applied

to each scan line beginning at the projectile's base and extending to a point above the fuse-well. Once these boundaries were successfully detected, the four segment boundaries were determined by the known dimensions of the projectile. All processing at this level was undertaken in a raster scan (single line at a time) manner. Thus, no large digital image arrays need be stored in memory. It appears that this macrostructure scene segmentation algorithm will be sufficient to isolate the major shell components.

CAVITY AND CRACK DETECTION

Our method for defect detection involves the use of a class of algorithms commonly referred to as Sequential Similarity Detection Algorithms (SSDA).^{1,2} These algorithms have as their major attribute the potential to examine sequentially and efficiently, large regions of a scene and rapidly discard all those regions except those containing a point of interest, i.e., a crack or cavitation. Thus, they are ideally suited for a detection task where all but a small percent of the scene is not suspect. We shall describe SSDA within the context of cavitation detection. It should be pointed out that, while our initial efforts are confined to a specific defect, the SSDA concept is easily extended to the other defect categories. All SSDA are based on the premise that there exists a finite number of prototypes (templates) which adequately describe regions of a scene of interest, in this case cavitations. These templates can be denoted by a set of vectors C defined

$$C \equiv [\underline{t}^1, \dots, \underline{t}^K] \quad (1)$$

where $K = 10$ is the number of prototype templates and each $\underline{t}^k$ is a vector of length $m = 16$.

In our initial research we are treating cavitations as characterized by profiles of one dependent variable. Several such cavitations are shown in Fig. 6. We are assuming that a cavitation profile will be detectable as a small (.02-.06 density unit) depression in a raster line scan occurring perpendicular to its long axis. (Such a depression is shown in Fig. 5.) Thus, if one detects indications of such a depression on successive raster scans of the HE filler region of a shell, this defines a suspect region for this class of defect. In this case each $\underline{t}^k$ represents a vector of length $m = 16$ comprising a prototype cavitation profile. Two such profiles are shown in Fig. 7. These one-dimensional profiles are found by digital integration of representative cavitations in a direction parallel to their long axes. Let us now segment each raster line across the shell into 3 parts. Part 1 represents that portion of the line representing a segment to the viewer's left of the HE filler. Part 2 is the filler segment itself, and Part 3 is the line segment to the viewer's right of the HE filler. Segment 2 for each horizontal raster scan across the shell's filler is detected from the macrostructure analysis phase discussed earlier. Denote the filler segment on each scan line by a vector $\underline{x}$ of length n where $n \geq m$, and $n < 128$. The vector $\underline{x}$ is likewise divided into overlapping subvectors $\underline{x}^l$ of length m . There are $l = n - m + 1$ such subvectors, denoted $\underline{x}^l$, possible across each $\underline{x}$ when a template window of length m is slid in unit increments across $\underline{x}$. The detection task is conceptually simple. Given subimage $\underline{x}^l$, does there exist a template $\underline{t}^k$ such that $\underline{x}^l$ matches $\underline{t}^k$? Since a perfect match is not expected, an error criterion between each $\underline{x}^l$ and all members of C must be established. We will define this normalized error measure as

$$e(x_i^{\ell}, t_i^k) \equiv \left| (x_i^{\ell} - \bar{x}^{\ell}) / \sum_{j=1}^m |x_j^{\ell} - \bar{x}^{\ell}| - (t_i^k - \bar{t}^k) / \sum_{j=1}^m |t_j^k - \bar{t}^k| \right| \quad (2)$$

| | denotes magnitude

where $\bar{x}^{\ell}$ is the mean value of subvector $\underline{x}^{\ell}$ and $\bar{t}^k$ is the mean of template k . The cumulative error function E , and threshold function T_k , defined over all elements of $\underline{x}^{\ell}$ and $\underline{t}^k$ for each template $k = 1, \dots, K$, is defined

$$E_i^k(\underline{x}^{\ell}, \underline{t}^k) \equiv \sum_{i=1}^M e(x_i^{\ell}, t_i^k) \quad (3)$$

for $i = 1, \dots, M \quad 1 \leq M \leq m$.

A representative cumulative error function E and threshold function T_k for an $\underline{x}^{\ell}$ window containing a cavitation is shown in Fig. 8. Also shown are E functions for several $\underline{x}^{\ell}$ windows which do not contain cavitations. Note the more rapid error build-up in the latter case. It should also be noted that the error function E_i is accumulated with a random index i . This has the effect of maximizing the amount of new information considered at each step. Clearly, if an $\underline{x}^{\ell}$ matches $\underline{t}^k$ perfectly, then $e(x_i^{\ell}, t_i^k)$ is zero for each i and the monotonic nondecreasing function defined by E_i^k is a horizontal line of zero slope and intercept. Any degree of mismatch will increase the slope and intercept of E_i^k . If one bounds E_i^k from above by threshold function T_k , then the template $\underline{t}^k$ for which M is maximized (slope of E minimized) for each $\underline{x}^{\ell}$ is the best candidate for a match. Expressed mathematically this maximum is

$$I^k(\underline{x}^{\ell}) \equiv \left[i \leq m / \sum_{r=1}^R e(x_i^{\ell} t_i^k) \leq T_k \quad \forall r \leq m \right] \quad (4)$$

$k = 1, \dots, K$ / denotes "such that"
 $\forall$ denotes "for each"

If one has K such relative maxima for each window $\underline{x}^{\ell}$, then choose the I^k for which $i \leq m$ is maximized. That is

$$I \equiv \max [I^1, \dots, I^K] \quad (5)$$

As each $\underline{x}^{\ell}$ for each raster line is examined in succession, a surface of these I maxima defining the filler region will be formed. Regions of high relative I will define regions of high cavity probability. Only these local regions need be examined in the subsequent measurement and classification phases.

Figure 9 shows the output of the SSDA previously described for four shells containing a total of ten pipe cavitations. The lightest region is all the scene area outside the HE filler region. The medium gray region is the HE filler region which extends from the base of the HE filler to the end of shell segment C at the base of the fuse well. The darkest regions define the most probable regions for the occurrence of pipe cavitations and represent less than one percent of the area over a representative HE filler region. Also note that over 95 percent of the picture elements are eliminated before $I = 3$. This represents at least a factor of 10 improvement in computer time over classical correlation measures for $K = 10$. In this example $I \geq 12$ was chosen as constituting these most probable regions. All of the cavitations have been found along with several false positive regions which do not contain obvious voids.

For instance, the right-most shell contains a long region of dark on the right HE filler boundary. This false positive region is due to the absence of HE filler in the shell. It should be pointed out, however, that such a shell would have been previously eliminated from the process in a production algorithm because of inordinately large high densities caused by the missing HE filler. It was included only because it contained a cavitation.

The goal of the detection phase was to find all cavitations possible at a cost of several false positive regions. These suspected regions would then be examined in the subsequent measurement phase. It is expected that the absence of a detectable boundary of the proper shape will eliminate these false positive regions at that time. The detection phase just described is critical to the success of the total process because it must isolate all potential "needles in the haystack," i.e., small suspect regions.

CONCLUSIONS

We have chosen to concentrate initial feasibility efforts on Phase 2, the detection phase. If reliable detection is possible, regions with cracks or cavitations can be measured with already existing texture or boundary tracking techniques. Since the major defect classification criteria are based on permissible area involvement as a function of shell segment, the summed area of boundary enclosed regions in specific segments should offer little, if any, difficulty.

It should be noted that SSDAs are easily generalized to characterize two-dimensional space if some defect classes require this. These SSDAs offer the best hope for a rapid sequential large region search technique designed to detect the relatively small subregions containing cracks or cavitations. In this application, $K = 10$ templates were checked against each

subvector $\underline{x}^l$ in about the same amount of time necessary to perform one classical correlation over the same population of subvectors. It also appears probable that an intensified 500- or 1000-line vidicon may possess enough sensitivity and resolution to replace film. At the very worst, this would then involve the real time capture and storage of an entire four-shell scene in digital mass memory. Such is completely possible with current technology. The SSDA algorithms could then either be hardwired or programmed using existing microprogrammable devices.

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FIGURE CAPTIONS

- Fig. 1. 105-mm HE cartridge
- Fig. 2. Present quality control procedure
- Fig. 3. Delineated segments of HE filler
- Fig. 4. Results of automatic scene segmentation designed to isolate shell macrostructure. Encircled regions contain cavitations.
- Fig. 5. Representative single scan across a pipe cavitation. (Note filler-casement boundary appears as points of maximum relative depression on either side of the shell midline.)
- Fig. 6. Magnified regions containing cavitations
- Fig. 7. Two representative pipe cavity profiles used as templates for pipe cavity detection. (These templates constitute 16-line averages across the center portion of a cavitation.)
- Fig. 8. Cumulative error function and threshold function for representative template
- Fig. 9. Output from the SSDA. HE filler is shown as medium gray with cavitations shown as black areas. Fully 90 percent of the image area is eliminated from examination before $I^k = 3$. Encircled regions contain detected cavitations.

NOTE: Figures 6a and 6b should be paired with Figs. 7a and 7b.

105MM, HE, CARTRIDGE, M1

ORD D1681

Fig. 1. 105-mm HE cartridge

SCHEMATIC OF
PLANNED SYSTEM

Fig. 2. Present quality control procedure

SEGMENTED PROJECTILE - 105MM

Fig. 3. Delineated segments of
HE filler

Fig. 4. Results of automated scene segmentation designed to isolate shell macrostructure. Encircled regions contain

SCAN NO. 100

Fig. 5. Representative single scan across a pipe cavitation. (Note filler-casement boundary appears as points of maximum relative depression on either side of the shell midline.)

Fig. 6a. Magnified regions containing cavitations.

Fig. 6b. Magnified regions containing cavitations.

cavity profiles used as templates
for pipe cavity detection. (These
templates constitute 16-line
averages across the center portion
of a cavitation.)

Fig. 7b. Two representative pipe cavity profiles used as templates for pipe cavity detection. (These templates constitute 16-line averages across the center portion of a cavitation.)

HE filler is shown as medium gray
with cavitations shown as black
areas. Fully 90 percent of the
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