INFRARED PYROMETRY FOR WASTE CHARACTERIZATION

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ABSTRACT The objective of this research is the development of two methodologies by which heat sources contained in underground storage tanks (USTs) can be remotely characterized. A problem statement is established based upon the restrictions of UST robotic capabilities and basic infrared (IR) pyrometer operation. The first analysis is designed to provide real time information to a robot operator about the UST interior. The other analysis is designed to calculate an estimated temperature distribution using a least-squares solution after a data survey. A mock UST designed by Sandia National Laboratories and New Mexico State University was build to provide a test bed for data collection. Two data sets are graphically presented to show the positions of known heat sources and their thermal responses. The results of the two analyses on the data sets are graphically presented to illustrate the correlation between known heat sources and estimated thermal targets. In conclusion, the estimated temperature distribution provides a higher resolution image of the UST surface, as compared to the measured temperature distribution, such that individual heat sources may be located.

KEYWORDS: infrared, pyrometer, Hanford, tanks, characterization

INTRODUCTION

Throughout the Department of Energy (DOE) complex, production and research sites have become concerned with environmental restoration (ER) of their facilities. In March 1995, DOE published a report, Estimating the Cold War Mortgage vol. 2 [1], which stated that the U.S. Government prepared a cost estimate for the Environmental Management (EM) Program of 230 billion dollars for the next five years. Twenty-one percent of the EM funding is allocated for the Hanford site located in Washington State [1]. Of the 332 Underground Storage Tanks (USTs) in the DOE complex, which contain a total of approximately 100 million gallons of radioactive and hazardous waste [2], Hanford possesses 177 USTs. For Hanford, environmental restoration and waste management (ER&WM), especially of the USTs, is a primary focal point.

Of the 177 USTs at Hanford, there are 149 single-shell tanks. Between 1944 and 1980, approximately 93 million gallons of radioactive and hazardous wastes were placed in the single-shelled USTs [1]. No additional wastes have been added to the tanks since the 1980s, while some of the liquid wastes have been pumped into the new double-shelled tanks. Currently, the single-shelled USTs at Hanford contain 61 million gallons (230 million liters) of nuclear and hazardous wastes. Sixty-seven of the single-shelled tanks have leaked as much as 1.0 million gallons (3.78 million liters) of radioactive and hazardous waste, contaminating the surrounding soil and ground water [1, 3].

The highest percentage of waste types found in the tanks are salt cake, liquid, and sludges. All types contain radioactive and hazardous components [1]. Also contained in the USTs are non-standard wastes, such as laboratory wastes (gloves, tools, etc.), shroud tubes, ceramic balls, experimental fuel elements, soil, cement, and relatively small amounts of raw nuclear material [1]. All of these must be remediated from the tanks and safely stored.

OBJECTIVES

Due to the number of USTs in the U.S. and the amount and types of waste contained in them, many methods for the characterization of the tanks are needed [2, 6]. Heat is generated within the USTs by radioactive decay of the nuclear material and the chemical reactions of the hazardous wastes in the tanks. The temperatures can vary from room temperature to the boiling point temperature of water. The heat generated by the wastes jeopardizes the integrity of the tanks, which could eventually lead to the discharge of hazardous and radioactive wastes into the environment. The objective of this research is the development of a methodology that will locate heat sources within USTs.

Historically, the characterization of waste has been a time-consuming and expensive task. The Multi-Sensor Analysis Program for Environmental Restoration, MAPER [4], project provides a method of characterizing waste objects using data fusion. Data collected by many different sensors and analyzed in a hybrid fashion [5] provides a more comprehensive image of the site. By utilizing data from all available sensor types, MAPER analysis can provide an estimate of the surface and subsurface of an underground storage tank to aid in tank characterization.

ASSUMPTIONS

To design the mathematical models, some basic assumptions were made:

- The surface to be measured was assumed to be a blackbody.
- The atmosphere surrounding the pyrometer is non-participating such that the atmosphere will not affect the heat flux measured by the pyrometer.
- The motion of the pyrometer passing over the site would be horizontal and planar.
- The temperature measured by the pyrometer is the average temperature of the surfaces viewed by the pyrometer.

THEORY

This section focuses on the development of the numerical model, fastIR [4], used to estimate a surface temperature distribution. The temperature distribution of a surface from a non-contact temperature sensor can be approximated using radiation heat transfer theory, focusing on infrared radiation thermometry.

INFRARED PYROMETERS

The sensor chosen for temperature collection in the mock UST is the Exergen IRt/c.2-K-60C pyrometer [7]. It is an infrared pyrometer that measures the emitted flux from a surface and outputs a voltage in millivolts. The pyrometer uses type K thermocouple wires to create the voltage differential in the circuit. Since it utilizes the properties of a type K thermocouple it is linear from 25ºC to 80ºC (298 to 353 K) and requires either an ice junction or a normalization to correct for ambient environmental temperature. The pyrometer has a FOV ratio of 2:1. This means that the FOV spot diameter is one half the distance between the pyrometer and the waste surface.

RADIATION THERMOMETRY

Radiation thermometry is a method for calculating surface temperature given the emitted flux from the surface. An infrared pyrometer is a specialized radiation thermometry sensor that measures the emitted flux from a surface which occurs in the infrared region of the electromagnetic spectrum, approximately 0.5 to 20 μm. The calculation of surface temperature from emitted flux is performed by applying Planck's and Wein's Displacement Laws [8].

$$e = \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T_b} - 1)} \tag{1}$$

where

$$C_1 = 0.59552197 * 10^{-16} \quad \left[\frac{W \cdot m^2}{Sr}\right],$$

$$C_2 = 0.1438769 \quad [m \cdot K], \tag{2}$$

$$\lambda = \text{ Wavelength} \quad [\mu m],$$

$$\mathrm{T_b} = \text{ Blackbody Temperature} \quad [K].$$

Wein's Displacement Law is simply the derivative of Planck's Spectral Distribution (Equation 1) set to zero and solved for $\lambda_{\max} T$. The result of the derivation is shown below [8]:

$$\lambda_{\max} T = \frac{C_2}{5} \frac{1}{1 - e^{-C_2/\lambda_{\max} T}}. \tag{3}$$

Equation 3 can be solved for $\lambda_{\max} T$. Such that the equation becomes

$$\lambda_{\max} T = C_3, \tag{4}$$

where C_3 is a constant equal to 2.8978 x 10^{-3} $m \cdot K$.

THE DEVELOPMENT OF THE NUMERICAL MODELS

The stated objective is the characterization of thermal sources within underground storage tanks. To accomplish this, two numerical models were developed. The first model is a "picker" routine which locates areas, called targets, of elevated temperature. The targets are used to define areas where closer examination maybe required or bounding boxes for thermal sources. The second model is a temperature distribution estimator. This model is used to calculate a higher resolution temperature distribution, as compared to the raw measured temperature distribution, for a survey site. The higher resolution allows for the separation of a thermal response into its individual responses of separate heat sources which are in proximity to each other.

PICKER MODEL DEVELOPMENT

The pickIR routine is designed to find "areas of interest" within the larger site domain. This routine finds the measured temperatures that exceed a maximum threshold value specified by the user. The subroutine assigns an area to the temperature, creating a target. Those targets found within a site can then be consolidated by MAPER utility routines, to yield one or more targets in a list. The subdomains help the operator decide where more data should be collected, which, in turn, reduces the survey time, since a denser scan would not have to cover the entire site. The pickIR routine is also used to find specific thermal targets within the data survey. Engineering judgment is required to determine weather the routine has located a specific target or weather it has bound an area for further examination.

FASTIR DEVELOPMENT

The numerical model, fastIR, for determining surface temperature uses the measured temperature distribution to calculate an estimated temperature distribution. The measured temperature values are subject to blurring due to the averaging of the surface temperatures that are contained in the FOV. The estimated temperature distribution is the focused result of a weighted least-squares solution applied to the measured data.

SITE DISCRETIZATION

The nature of the problem stems from the fact that the pyrometer finds the average temperature over the FOV. This causes the blurring of the measured temperature distribution, since the FOV could cover a large area with many heat sources at different temperatures. A focused temperature distribution would show the individual responses of the many heat sources that were obscured by the large FOV. This is similar to taking a data survey at a lower altitude with a higher scan density, but that may put the robot at risk of running into an unknown obstacle near the waste surface. To find the focused temperature distribution without taking a lower scan, the site must be divided up into units that are smaller than the FOV, so the average temperature can be calculated over smaller areas, cells, rather than the larger FOV. With the cell areas defined, it is a matter of determining how each cell with its unknown temperature affects the measured temperature distribution.

WEIGHTING THE CELLS IN THE FIELD OF VIEW

Since the pyrometer is at a constant standoff height as it passes over the site, the FOV does not change size. This means that the FOV contains the same number of cells for each observation. Knowing the diameter of the FOV and the dimensions of the cells, the number of cells contained in the FOV can be calculated, which will be constant for a given survey height.

Each time a cell is included in the FOV, it contributes to the measured temperature. The influence of the individual cells on the measured temperature depends on geometry. The cells completely within the FOV contribute the most to the average temperature measured by the pyrometer, while the cells partially within the FOV contribute less to the measured temperature. For a circular FOV, only one quadrant of weights need to be calculated. By applying symmetry, the weights of the other cells in FOV can be assigned. The method for weighting the individual cell is ratio of individual cell area contained in the FOV over the area of the FOV (Equation 5).

$$W_i = \frac{A_{cell_i}}{A_{FOV}} \qquad i = 1,2,3,\ldots N_{cells}, \tag{5}$$

Where N_{cells} is the total number of cells with in the site, W_i is the weight for each cell, A_{cell_i} is the area of a single cell contained within the FOV, and A_{FOV} is the area of the FOV.

BUILDING THE SYSTEM OF EQUATIONS

As the sensor passes over the site, temperature observations are recorded at discrete locations. For each observation, the FOV encompasses particular cells within the site. For any one cell there could be a number of observations in which it affects the measured temperature, so it may have many temperatures associated with it. However, there is only one true temperature for each cell, so a least-squares method is

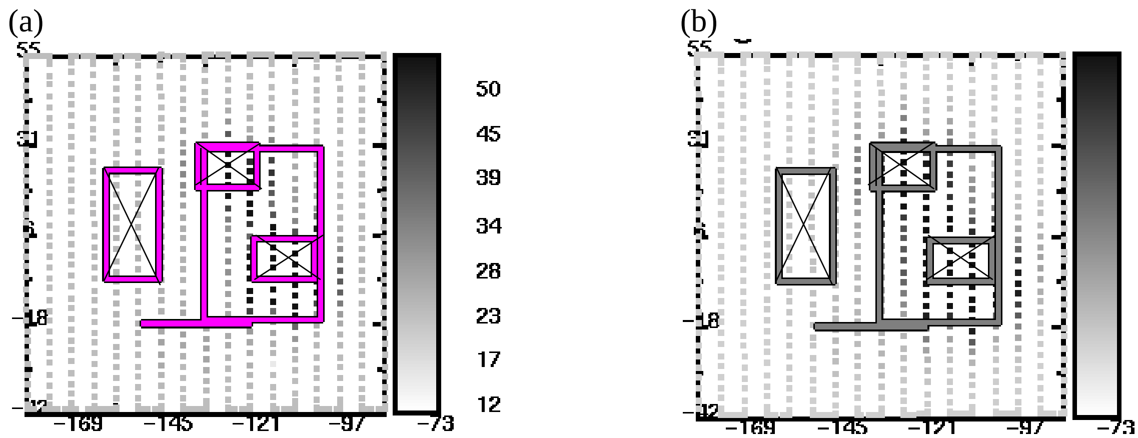

FIGURE 1. RESULTS OF THE PICKIR ANALYSIS ON THE MEASURED TEMPERATURE DISTRIBUTIONS.

used to find the best temperature estimate for each cell.

For all sensor observations, the temperature measurements are expressed as

$$T_{m_j} = \sum_{i=1}^{N_{cells}} W_i T_i \qquad j = 1,2,3,\ldots N_{obs}, \tag{6}$$

where T_{m_j} is the measured temperature, T_i is the actual temperature of the cell, W_i is the weight applied to the cell, and N_{obs} is the total number of observations in the site.

Equation 6 can be represented in vector form as

$$\{T_m\} = [W]\{T_{cell}\}, \tag{7}$$

Where the $\{T_m\}$ vector is N_{obs} x 1 long, the T_{cells} vector is N_{cells} x 1 long, and the matrix [W] is N_{obs} x N_{cells} long and wide.

DATA COLLECTION

The data sets were collected by passing the sensor head, at the end of a CIMCORP robotic arm, over the mock UST site. The pyrometer views the site through the hole in the bottom plate of the sensor head. There is not a window between the pyrometer and the site. This means the only medium between the pyrometer and the radiant surface is the atmosphere, which is assumed to be non-participating. This is not true for a vast majority of the Hanford USTs, but it simplifies the problem in this case. The data is collected from the pyrometer and stored on disk using the Sandia Supervisory Data Acquisition System, SDAS, software. The data was converted to a MAPER-formatted curvilinear data set. Then the MAPER curvilinear data set was triangulated onto a uniform grid for analysis.

UST CONFIGURATION

The UST configuration contains one 55 gallon drum, two 15” x 12” (0.4 x 0.3 m) aluminum pancake griddles, and one heated steel pipe. The two griddles are set to 120ºC (393 K) and 205ºC (478 K). They are colored black, and are assumed to be blackbodies with emissivities of one. The steel pipe is wrapped in plumber’s heat tape with an approximate temperature of 38ºC (311 K); both are reflective, but are assumed to be black within the IR portion of the spectrum. Figures 1(a) and 1(b) graphically present the curvilinear measured data sets and the locations of the true targets, the hatched rectangles, and the large pickIR consolidated targets at the standoff height of 33.25 in. (0.84 m) and 45.25 in. (1.15 m), respectively.

RESULTS

The temperature distributions estimated by the fastIR routine were examined. The picker routine was applied to the estimated temperature distributions for two different scan heights to locate targets in the data sets. These targets were compared to the known heat sources to find a correlation between the known objects and the targets located within the estimated temperature distributions.

FASTIR ANALYSIS

When the fastIR analysis was first developed, a linear least-squares method was used to calculate the estimated temperature distributions. This method did not work. The resulting temperature distributions contained large oscillations between positive and negative temperatures. Upon closer inspection, the system of equations was found to be very ill-conditioned. The condition number for the lower scan, H = 33.25 in. (0.84 m), is 1.273306 x 10^5 and the condition number of the higher scan, H = 45.25 in. (1.15 m), is 2.693932 x 10^8.

WEIGHTED LEAST-SQUARES METHOD

By weighting the coefficient matrix of the least-squares system, intuition may be used to modify the system to obtain expected results. This is also called regularization. It is a method used to smooth the results of the LSQRs system. There are three types of regularizer that can be applied to a system. They are: zeroth order which reduces the solution to its minimum values, first order which minimizes the slope of the solution, and second order which smoothes the curvature of the solution [9]. A zeroth order regularizer is used in this analysis, since it is desirable to reduce the oscillations of the temperature distributions.

WEIGHTED LEAST-SQUARES RESULTS

The regularizer value for the lower scan, H = 33.25 in. (0.84 m), is $\alpha_0 = 0.20$ and the regularizer value for the higher scan, H = 45.25 in. (1.15 m), is $\alpha_0 = 0.15$. The estimated temperature distribution, estimated target locations, and true target locations for the lower scan at H = 33.25 in. (0.84 m) are shown in Figure 2(a). The estimated temperature distribution, estimated target locations, and true target locations for the higher scan at H = 45.25 in. (1.15 m) are shown in Figure 2(b).

CONCLUSIONS

There are five general conclusions from this research. They are:

1. *By using regularization, the measured temperature distributions from the mock UST can be used in the presented methodology to obtain focused estimated temperature distributions.* The most reliable results from the fastIR analysis were produced by the regularized system of equations. Without regularization, the estimated temperature distributions had large oscillations between positive and negative temperatures. This estimated temperature distribution was unacceptable for any type of application. With the application of a regularizer to the system of equations, the estimated temperature distribution became more reliable. But without the correct regularizer value, the estimated

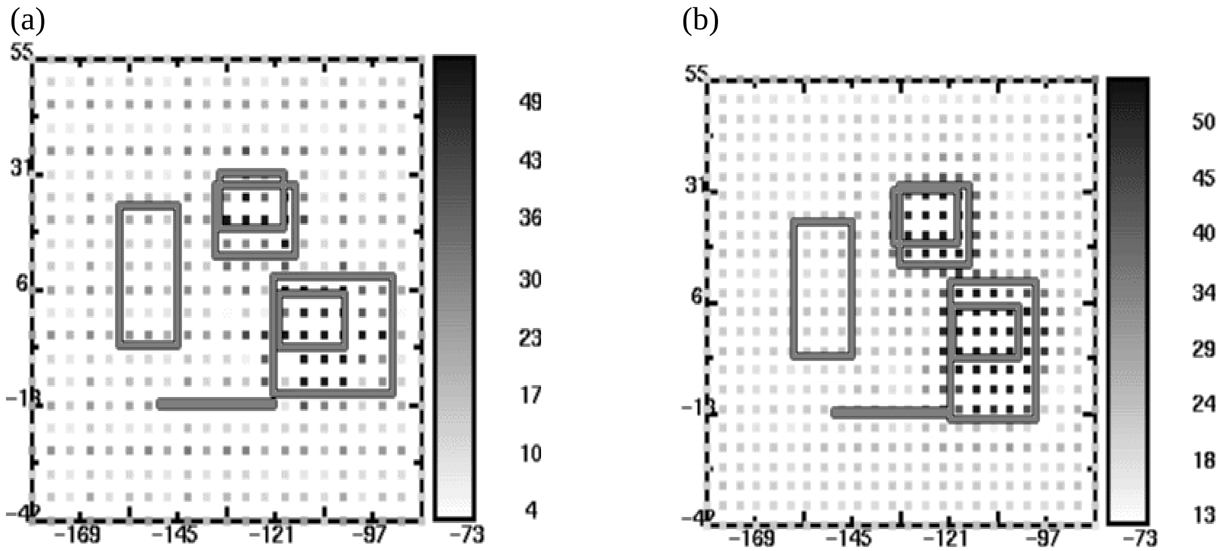

FIGURE 2. RESULTS OF THE WEIGHTED LEAST SQUARES SOLUTION WITH ESTIMATED TARGETS AND KNOWN OBJECTS.

temperature distribution was still not optimal, as shown in Figure 2(a). An optimal regularized system would produce a reliable temperature distribution at the lowest regularizer value, such that the condition number and variance ratio have acceptable values. This means that there is not one “true” solution to the system of equations, but engineering judgment is required to decide when the estimated temperature distribution is optimized for the given application.

2. *The regularized higher altitude system of equations resolved the blurred response from the measured data into two individual responses from the known heat sources in the mock UST.* This allows the robot to scan at higher altitudes, but produces nearly the same results as a lower altitude scan—refer to Figures 2(b) and 1(a) which show the estimated temperature distribution with regularization and the measured data set with estimated target location, respectively. This keeps the robot further away from the obstructions located near the waste surface. It is undesirable to have the robot collide with an object, so keeping a set distance between the robot and the surface is better than scanning down close to the waste surface.

3. *The methodology presented creates an ill-conditioned system of equations.* Dividing the mock UST site into smaller cells and assigning temperatures to the cells creates an ill-conditioned system of equations. This is common in many inverse analyses, but error propagation can be minimized [9]. By minimizing the error in the measured data, the error in the solution can be decreased. One way this may be done is by using correct data collection techniques which reduce the uncertainty of the measured data.

4. *An estimated temperature distribution with better resolution than the measured data could not be obtained without regularization.* The results from the fastIR analysis without regularization

were unacceptable. The estimated temperature distribution could not be improved without changing the methodology all together. Even then, there would be no guarantee that the conditioning of the system of equations from the new method would be any better.

5. *The speed of the robot as it surveys the site is an important aspect in the analysis.* The speed at which the robot scans the mock UST site is important. The blurring and skewing of the data, due to the robot's speed, greatly affect the results of the analyses. Recall that small changes in the measured data cause large changes in the results due to the ill-conditioning of the system. If the blurring and skewing are thought of as errors in the measured data, then those errors would be amplified in the results. So, it makes sense to minimize the error in data collection. This can be done by determining the optimum survey speed for the pyrometer. The blurring and skewing of the measured data due to scan speed also affect the results of the pickIR analysis. The estimates of the targets are enlarged, compared to the known heat sources, due to the measured data sets. This is acceptable, so long as the heat sources are contained within the targets' bounding boxes.

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- DOE NMSU Waste-management Education and Research Consortium (WERC).

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