Segmentation of Objects from Volumetric CT Data - Final Report

Version 12/14/11

Awareness and Localization of Security-Related Threats (ALERT)
A DHS Center of Excellence at Northeastern University
Boston, Massachusetts

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1 Executive Summary
The DHS Northeastern University Center of Excellence (COE) for explosives detection, mitigation and response entitled Awareness and Localization of Explosives-Related Threats (ALERT), was tasked by DHS to run a series of workshops to involve third parties in algorithm development. These workshops, of which there have been six since spring 2009, are known by their acronym, ADSA (algorithm development for security applications). The participants at the first ADSA workshop agreed that CT-based explosives detection equipment could be improved if the segmentation step of automated threat recognition (ATR) yielded features of explosives with improved precision. The improvements would be based on methods to overcome artifacts in CT images such as blurring, streaking and low-frequency shading. The participants also indicated that improved segmentation algorithms for aviation security could be developed using scans of non-threats on medical CT scanners.

ALERT, with funding from DHS, created in 2010 the segmentation initiative in which five research groups were provided scans of non-threats on medical scanners. The researchers developed segmentation algorithms and presented their algorithms at a recent symposium. The symposium also addressed the applicability of the segmentation algorithms to existing explosives detection equipment and reviewed steps for continuing their research. The purpose of this document is to report on all aspects of the segmentation initiative. The key findings and recommendations from the workshop are as follows.

Findings: The program has achieved its goals: Third parties developed segmentation algorithms that are useful. ALERT succeeded in engaging third parties. Third parties learned about CT-based EDS and items in bags. The program was efficient, provided five research groups in CT segmentation for minimal resources.

Recommendations: Provide additional funding to ALERT so that third parties can continue their work. Execute initiatives for reconstruction and other detection modalities.
2 Disclaimers

This report was prepared to document work sponsored by an agency of the United States government. Neither the United States government nor Northeastern University nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation or favoring by the United States government or Northeastern University. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Northeastern University, and shall not be used for advertising or product endorsement purposes.

This report summarizes an initiative during which a number of people participated. The views in this report are those of ALERT and do not necessarily reflect the views of all the participants. All errors and omissions are the sole responsibility of ALERT.

The material in this report is based upon work supported by the U.S. Department of Homeland Security under Order Number HSHQDC-10-J-00396. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

This final report is intended to meet the final contract deliverable. A Segmentation Monograph will be published in the near future. The technical monograph will be published by ALERT and distributed to a broader “Algorithm Development for Security Applications” (ADSA) community in the familiar ADSA monograph format. The monograph will contain the following additional information.

a. Additional details on the generation of the image database including:
   i. Description of objects scanned
   ii. Packing manifests
   iii. Project plan for packing luggage

b. Final reports from the researchers

c. Quantitative evaluation of the algorithms supplied by the researchers

d. Additional findings and recommendations

e. Material from the symposium
   i. Invitation letter
   ii. Agenda
   iii. Instructions for researchers
   iv. Attendee list
   v. Minutes
   vi. Questionnaires

f. Additional supplement materials including the following material
   i. Request for proposal
   ii. Communications with researchers
   iii. Technical reports describing tools
iv. Non-disclosure agreement (blank)
v. Specification for log files
g. Miscellaneous communications and errata
3 Introduction

The Department of Homeland Security (DHS) has requirements for future scanners that include a larger number of threat categories, higher probability of detection per category, lower false alarm rates and lower operating costs. One tactic that DHS is pursuing to achieve these requirements is to create an environment where the capabilities of the traditional vendors of security systems could be augmented by the development of algorithms by third parties. A third party in this context means people and organizations other than the traditional vendors. Examples of third parties include academics, national laboratories and companies other than the traditional vendors. DHS is particularly interested in following the model used by the medical imaging industry, in which university researchers have developed numerous algorithms that have eventually been deployed in commercial medical imaging equipment.

This project, “Segmentation of Objects from Volumetric CT Data,” is the first phase of a multi-year strategy to stimulate research and development of advanced algorithms from volumetric CT data for the purpose of enhancing automated object of interest detection algorithms for Explosives Detection Systems (EDS) and for CT-based checked baggage scanners for the check-point. The task order awarded to Northeastern (HSHQDC-10-J-00396 dated 9/21/2010) includes the management, engineering and technical coordination of the project in accordance with the Program Statement of Work.

DHS funded ALERT and LLNL (through a separate funding vehicle) to execute the segmentation initiative. As an integral part of this initiative, five research groups were selected and subsequently funded by ALERT to develop or refine existing advanced segmentation algorithms using datasets supplied to them by ALERT. The groups were closely monitored and mentored by the ALERT/LLNL team. They presented the results of their research at a symposium held on December 8th 2011.

The purpose of this final report is to present the following aspects of the segmentation initiative.

1. Program definition
2. Dataset creation
3. Participant\(^B\) identification
4. Algorithm development
5. Independent evaluation of the algorithms
6. Recommendations for additional work

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\(^A\) When we speak of an algorithm, we are talking about the mathematical steps. The actual implementation, usually in a general purpose computer, is beyond the scope of this work.

\(^B\) We use the terms participant and researchers to mean the 3rd party who develops an algorithm.
4  Program Description

4.1  Overview

The purpose of the program is to provide security-like data to academic researchers and third party developers, to enhance the present segmentation state-of-the-art, and to stimulate additional communication and research in the segmentation algorithm research community.

The following steps outline the process that was used to identify project participants, fund them to develop improved segmentation algorithms and evaluate the resulting algorithms. Unless otherwise noted, the task is complete. Only the researchers final report and the program published monograph are incomplete.

1. Individuals were identified through their attendance at the ALERT Algorithm Development for Security Applications (ADSA) workshop series as likely to participate in this segmentation exercise. They received a letter with a project description soliciting their participation in the Segmentation Initiative, as well as a non-disclosure agreement (NDA).

2. The recipients of the letter may request to participate via a proposal including a completed NDA. Each of the program’s three Domain Experts will select 10 Candidates\(^C\) for a total of 30 Candidates. 12 Candidates requested participation.

3. All of these Candidates received the Qualification Dataset Group\(^D\).

4. These 12 Candidates were told to use the project description, Qualification Dataset Group and their segmentation algorithms to segment objects (>500 Modified Hounsfield units (mHU) and ≥50mL, minimum) in the Qualification Dataset Group.

5. Those Candidates desiring to obtain the Training\(^E\) and Validation\(^F\) Dataset Groups and be funded for additional segmentation efforts were asked to submit to ALERT both their segmentation performance on the Qualification Dataset Group and a proposal. Funding was available to support 5 final Candidates.

6. Five final Candidates were chosen to receive segmentation research subcontracts. These five, now designated as Researchers\(^G\), were selected based on their submitted proposals.

7. The five Researchers were given the Training and Validation Dataset Groups. The Training Dataset Group would be used to train the Researchers’ segmentation algorithms. The objects in the Training Dataset Group were identified and characterized. The five researchers were then required to segment objects (again, >500 Hounsfield units (HU) and ≥50mL, minimum) in the Validation Dataset Group.

8. Researchers were required to develop segmentation algorithms and demonstrate their performance using the Training and Validation Dataset Groups to the program’s three Domain Experts, who monitored progress, provided in depth mentoring and assessed performance.

\(^C\) Candidates
\(^D\) Qualification Data
\(^E\) Training Data
\(^F\) Validation Data
\(^G\) Researchers
9. Each Researcher was asked to segment the objects in the Evaluation Dataset Group, under the supervision of the three Domain Experts to enable them to view the Researcher’s process. This exercise was meant to demonstrate the ease-of-use, robustness and amount of tweaking required to obtain the segmentation results.

10. Each Researcher is required to deliver a final written report of their results from their perspective and an assessment of what could be done better performance and other improvements. **IN PROCESS**

11. The five Researchers were required to present their segmentation performance on the Training and Validation Dataset Groups to DHS and security system companies at a meeting called the segmentation symposium. At this symposium, the three Domain Experts also reviewed the five Researchers’ segmentation approaches including the ease-of-use, robustness, tweaking required and performance on the Evaluation Dataset Group.

12. ALERT is required to produce a written final report on the project outcomes. This report will include the final Researcher reports as well. **IN PROCESS**

### 4.2 Program Gantt Chart (Schedule)

A project Gantt chart is presented in Section 4.2. It shows the program tasks, people assigned to each task, the linkages between tasks and the percent complete.

The program is on schedule with the above adjustments.

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**Evaluation Data**
4.3 Program Expenditures
During the last two quarters of the program expenditures have accelerated. Seven invoices have been issued. They were associated with the research, data procurement, management, administration and domain expert efforts. To date, $828,131 has been charged. Most of the funds for the program have been obligated (>98%). The remaining funds will be invoiced and submitted within 90 days.
5 Program Elements and Processes

5.1 Project Definition
The following steps were taken to define the project.
1. A preliminary definition was provided by the participants at ADSA01.
2. The first version of a complete project plan was written and refined by the participants at ADSA02.
3. The project plan was revised and published as part of the final report for ADSA02.
4. A classified meeting was held with three incumbent EDS vendors to identify problem cases.
5. The project plan was converted into a task order white paper.
6. The white paper was submitted to DHS and an ALERT task order rfp was generated.
7. ALERT submitted a task order proposal to DHS which was subsequently funded. (In concert with this action LLNL made a proposal to DHS S&T and received funds to support to help implement the effort.)

5.2 Funding
The following organizations were funded as a result of the proposals that were submitted to DHS.
1. ALERT – Michael Silevitch, & John Beaty PI
2. LLNL – Harry Martz, PI

The funding for ALERT included funding for the dataset creation ($50K) and funding for five research teams ($70K each)

5.3 Database
A "Vendor" was identified and a database of CT scans of baggage and ground truth data was generated using the following steps. Page 38, provides more detail of the definition, procurement and maintenance of the four datasets.
1. A plan was written to pack suitcases with items commonly found in stream of commerce baggage. The items did not include explosives or explosive simulants.
2. Contractual arrangements were made to scan luggage on a state-of-the-art medical CT scanner at the manufacturer’s factory.
3. ALERT personnel performed the following steps.
   a. Procured luggage and items to pack in them.
   b. Labeled, photographed and cataloged the items.
   c. Packed the suitcases
   d. Created a database of items as packed into suitcases
   e. Scanned the luggage at the vendor’s factory
   f. Created video tapes of unpacking the luggage
4. The Vendor performed the following steps.
a. Reconstructed the projection data corresponding to the scans of the luggage. The reconstructions were performed with offline reconstruction. The resulting resolution was approximately 3 mm FWHM.
b. Converted the images to DICOM format.
5. ALERT then performed the following additional steps.
   a. Converted the DICOM images to TIFF files.
   b. Used a network in Mevislab to semi-automatically outline the items in the scans. The resulting data was known as ground truth data, label images and AO images.
   c. Divided the scans into four sets denoted: qualification, training, validation and evaluation.
   d. Distributed the data to the Researchers with instructions from the leadership team.
   e. Revised the data based on feedback from various stakeholders.
   f. Distributed revised data and/or offset values on a highest-priority basis to the Researchers

5.4 Researcher Proposal solicitation and selection
The following process was used to solicit proposals from prospective research groups.
1. A request for proposal was written and distributed to prospective researchers.
2. Prospective researchers were asked to submit a formal letter to receive the qualification data. An NDA had to be executed to obtain the data.
3. ALERT distributed the qualification database.
4. Prospective researchers submitted a proposal and their initial segmentation results from the qualification database.
5. The domain experts selected five research groups. These research teams (the Researchers) are listed in the following subsections.

5.4.1 Marquette University, Milwaukee, WI
Xin Feng
Taly Gilat-Schmidt
Wenjing Zhang
Jun Zhang

5.4.2 Siemens Corporate Research, Princeton, NJ
Leo Grady
Timo Kohlberger
Vivek Singh
Claus Bahlmann
Dorin Comaniciu

5.4.3 Stratovan Corp., Sacramento, CA
David Wiley
Jim Olson
Bernd Hamann
5.4.4 Telesecurity Sciences Corp., Las Vegas, NV
Brandon J. Kwon
Samuel M. Song
Jason J. Lee
Douglas P. Boyd

5.4.5 University of East Anglia, UK
Paul Southam
Graham Tattersall

5.5 Algorithm Development
The five research teams developed their segmentation algorithms over a period of approximately seven months. The research teams were mentored by the domain experts during this period of time.

5.6 Symposium
A symposium was held on December 8th, 2011. The following is a list of the topics discussed during the symposium.

1. Project overview
2. Expectation management
3. Presentations from the five research groups
4. Evaluation by the domain experts
5. Recommendations for next steps

The presentations corresponding to these topics can be found in the appendices in Section 9 of this final report.

5.7 Final reports
The researchers are scheduled to deliver final reports based on their work on December 19th, 2011. A Segmentation Monograph will be created which will include the researcher’s final report.

Findings and Recommendations

5.8 Researcher Performance

5.8.1 Findings
1. The Project has achieved its goals:
   a. The Five research teams:
      i. Developed and applied novel segmentation algorithms
      ii. Learned about CT-based EDS and items in bags
      iii. Learned SSI behaviors and practices
   b. ALERT learned how to:
i. Involve third parties
ii. Transform a classified problem into a public domain version
iii. Learned to deal with SSI behaviors and practices

2. All of the Researchers were able to segment the objects in the dataset bags. The domain experts could quantify the specific performance results because of the following reasons:
   a. Segmentation is part of ATR, which is an integrated system geared to pass TSA EDS certification at TSL in Atlantic City by demonstrating a specific PD and PFA performance on TSA data
   b. Segmentation can also be separated from ATR to determine prevalence and features of non-threats
   c. The project Objective was only segmentation, not feature extraction and training with scans of explosives and stream of commerce data
   d. Incumbent vendors have proprietary segmentation/ATR approaches so it was impossible to compare performance against them.

3. Based on the patent literature, the Researchers created novel methods.

4. Common strengths of the five research groups:
   a. Understood problems caused by CT artifacts such as finite resolution and streaks, leading to merging and splitting of objects
   b. Implemented methods to compensate for splitting and merging
   c. Created separate algorithmic paths for some objects (e.g., sheets)
   d. Developed methods to score/evaluate results
   e. Dealt with object philosophies
   f. Have potential to solve real security problems
   g. Patents were filed or are in the process of being filed

5. Specific strengths of the research groups:
   a. Telesecurity Sciences
      i. Sequential segmentation and carving
      ii. Bilateral filtering
      iii. Recursive k-Means clustering for splitting
   b. University of East Anglia
      i. "Sieves" algorithm
      ii. Classifier strategy
   c. Stratovan
      i. Tumbler – kernel based segmentation
      ii. Automatic seed generation
   d. Marquette University
      i. Synthetic sinogram processing
      ii. Multi-path
      iii. Seed generation
      iv. Adaptive threshold
   e. Siemens Corporate Research
i. Synthetic sinogram processing
ii. Confidence measure
iii. 3D display

6. Areas for improvement
   a. Feature extraction
   b. Artifact reduction in projection space

7. Areas of concern:
   a. Use of shape
   b. Turning the segmentation initiative into a classification problem
   c. Over-training on objects in the bag dataset

8. Future potential:
   a. Researchers working with vendors, DHS and TSA to enhance their algorithms and transition to fielded systems
   b. More involvement of third parties
   c. Application to AIT, AT2, and other modalities

5.8.2 Recommendations for Future Work

1. Split initiative into two projects:
   a. Segment all objects, no regard for minima
      i. Prevalence studies can be performed
      ii. Classification based on object-types

2. Support for the research community
   a. Funding
   b. Forums & conferences
   c. Databases into public domain
   d. Evaluation methodology

3. Vendors should be encouraged to compare their segmentation methods to the results of this segmentation initiative.

5.9 Database Future Development

5.9.1 Findings

1. Some of the values of the tags in the TIFF files were incorrect. (Wrong byte order used when saving some of the TIFF Images resulted in incorrect tag values)
2. The A.O. TIFF files were not directly readable by imagej, and matlab.
3. Ground truth was difficult to establish on some textured items and all items scanned in the presence of CT artifacts.
4. Difficult cases were present but not emphasized.
5. The scans were too oversampled leading to large data files.
6. Insufficient quality control was performed on the distributed databases.
7. DHS did not review datasets at time of receipt to detect QC issues
8. Scans of objects in isolation were purposely not made available to the Researchers due to template-matching concerns of Domain Experts.
5.9.2 Recommendations

1. Use an image format without headers and footers. This is known as a raw format.
2. Resample the images so that the pixel size matches the resolution of the images.
3. Use gzip or zip to compress files.
4. Perform additional quality control on the databases.
5. Use shorter filenames.
6. Retain the images of the phantom before each scan for QC and measurement validation.
7. Scan additional difficult cases.
8. Scan more homogeneous objects in different containers and levels of clutter and concealment.
9. Establish ground truth for all objects.
10. Revise or replace the Mevislab network used to develop the ground truth data.
11. Reduce manual intervention when developing the ground truth data.

5.10 Process Findings and Recommendations

5.10.1 Findings

1. Different object philosophies were used by program management, domain experts, database developers and researchers.
2. Acceptance (evaluation) criteria were not made clear at any point in the program and may have turned the segmentation project into a classification project.
3. The need for feature extraction was not sufficiently emphasized.
4. The duration of and funding for the project may not have been sufficient.
5. Communication with the researchers may have been insufficient, late and inconsistent.
6. Schedule for and definition of deliverables may not have been clear to the researchers.

5.10.2 Recommendations

1. Better specifications for acceptance criteria, databases and deliverables
2. Sample segmentation code and simple examples to understand inputs and outputs
3. Kickoff meeting for process and technical aspects
4. More group meetings: mentors and researchers
5. Develop evaluation criteria and distribute code
6. More time to evaluate results
6 Acknowledgements

The program management team would like to thank the following people and organizations for their involvement in the segmentation initiative.

- DHS S&T Explosives Directorate for funding ALERT and LLNL to implement this segmentation initiative.
- DHS S&T Office of University Program for providing the core funding for ALERT which includes the ADSA workshops which led to this segmentation initiative.
- Doug Bauer and Laura Parker, DHS S&T, and George Zarur, DHS & TSA (retired), for their vision to involve third parties in the development of technologies for security applications.
- Greg Struba and Earl Smith, DHS-Booz Allen support staff, for coordinating the participation of DHS and TSA.
- Rick Moore and Alyssa White (Massachusetts General Hospital) for dataset design, procurement, and management.
- The Domain Experts:
  - Carl Crawford, Csuptwo, LLC
  - Harry Martz, Lawrence Livermore National Laboratory
  - Homer Pien, Massachusetts General Hospital
- Mariah Nobrega for handling logistics for the project.
- Brian Loughlin, Mariah Nobrega and Rachel Parkin for providing logistical support for the symposium.
- Brian Loughlin and Rachel Parkin for taking the minutes during the symposium.
- The "Vendor" for working with ALERT to scan the luggage for the initiative's datasets on their medical scanner.

The segmentation initiative would not have been a success without the five research groups. The technical content of this report is due mostly to their contributions. We extend our heartfelt thanks to them for their participation.
7 Project Team

Principal Investigators and Program Management:

Michael Silevitch, Northeastern University
John Beaty, Northeastern University

Domain experts:

Carl Crawford, Cuptwo, LLC
Harry Martz, Lawrence Livermore National Laboratory
Homer Pien, Massachusetts General Hospital

Data Acquisition and Procurement

Rick Moore, Massachusetts General Hospital
Alyssa White, Massachusetts General Hospital

Unnamed Vendor

Database creation:

Rick Moore, Massachusetts General Hospital
Alyssa White, Massachusetts General Hospital

Tool developers:

Karina Bond, Lawrence Livermore National Laboratory
Carl Crawford, Cuptwo, LLC
Jeff Kallman, Lawrence Livermore National Laboratory
Seemeen Karimi, University of California, San Diego
Rick Moore, Massachusetts General Hospital
Harry Martz, Lawrence Livermore National Laboratory

Preparation of final report:

Carl Crawford, Cuptwo, LLC
Rick Moore, Massachusetts General Hospital
Alyssa White, Massachusetts General Hospital

John Beaty, Northeastern University
Rachel Parkin, Northeastern University
Mariah Nobrega, Northeastern University

Symposium logistics:

Rachel Parkin, Northeastern University
Mariah Nobrega, Northeastern University

SSI review:

Horst Wittmann, Northeastern University
8 Definitions

8.1 Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ADSA</td>
<td>Algorithm Development for Security Applications (name of workshops at ALERT)</td>
</tr>
<tr>
<td>ADSA01</td>
<td>First ADSA workshop held in April 2009 on the check-point application</td>
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<tr>
<td>ADSA02</td>
<td>Second ADSA workshop held in October 2009 on the grand challenge for CT segmentation</td>
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<tr>
<td>ADSA03</td>
<td>Third ADSA workshop held in April 2010 on AIT</td>
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<tr>
<td>ADSA04</td>
<td>Fourth ADSA workshop held in October 2010 on advanced reconstruction algorithms for CT-based scanners.</td>
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<tr>
<td>ADSA05</td>
<td>Fifth ADSA workshop held in May 2011 on fusing orthogonal technologies</td>
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<tr>
<td>ADSA06</td>
<td>Sixth ADSA workshop to be held in November 2011 on the development of fused explosive detection equipment with specific application to advanced imaging technology</td>
</tr>
<tr>
<td>AIT</td>
<td>Advanced imaging technology. Technology for find objects of interest on passengers. WBI is a deprecated synonym.</td>
</tr>
<tr>
<td>ALERT</td>
<td>Awareness and Localization of Explosives-Related Threats, A Department of Homeland Security Center of Excellence at NEU</td>
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<tr>
<td>AT</td>
<td>Advanced technology</td>
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<tr>
<td>ATD</td>
<td>Automated threat detection</td>
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<tr>
<td>ATR</td>
<td>Automated threat resolution; a synonym of ATD.</td>
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<tr>
<td>BAA</td>
<td>Broad agency announcement</td>
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<tr>
<td>BLS</td>
<td>Bottle Liquids Scanners</td>
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<tr>
<td>CERT</td>
<td>Certification testing at the TSL</td>
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<tr>
<td>COE</td>
<td>Center of excellence, a DHS designation</td>
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<tr>
<td>COP</td>
<td>Concept of Operation</td>
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<tr>
<td>CPU</td>
<td>Central processing unit (a general purpose computer)</td>
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<tr>
<td>CRT</td>
<td>Certification readiness testing</td>
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<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>DHS</td>
<td>Department of Homeland Security</td>
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<tr>
<td>DHS S&amp;T</td>
<td>DHS Science &amp; Technology division</td>
</tr>
<tr>
<td>DICOM</td>
<td>Digital Imaging and Communications in Medicine; <a href="http://medical.nema.org">http://medical.nema.org</a></td>
</tr>
<tr>
<td>DICOS</td>
<td>Digital Imaging and Communications in Security. NEMA standard for image format for security; NEMA IIIC Industrial Imaging and Communications Technical Committee.</td>
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<tr>
<td>DoD</td>
<td>Department of Defense</td>
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<tr>
<td>EDS</td>
<td>Explosive detection scanner that passes TSL’s CERT.</td>
</tr>
<tr>
<td>ETD</td>
<td>Explosive trace detection</td>
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<tr>
<td>EXD</td>
<td>Explosive detection directorate of DHS</td>
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<tr>
<td>FA</td>
<td>False alarm</td>
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<tr>
<td>FBP</td>
<td>Filtered back-projection</td>
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<tr>
<td>FOUO</td>
<td>For official use only</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
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<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>GC</td>
<td>Grand challenge</td>
</tr>
<tr>
<td>Gordon-CENSIS</td>
<td>Center for Subsurface Sensing and Imaging Systems, a National Science Foundation Engineering Research Center at NEU</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphical processing unit</td>
</tr>
<tr>
<td>HME</td>
<td>Homemade explosive</td>
</tr>
<tr>
<td>HVPS</td>
<td>High voltage power supply</td>
</tr>
<tr>
<td>IED</td>
<td>Improvised explosive device</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of electrical and electronic engineers</td>
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<tr>
<td>IHE</td>
<td>Integrating the Healthcare Enterprise</td>
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<tr>
<td>IMS</td>
<td>Ion mobility spectrometry</td>
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<tr>
<td>IQ</td>
<td>Image quality</td>
</tr>
<tr>
<td>IRT</td>
<td>Iterative reconstruction technique</td>
</tr>
<tr>
<td>LAC</td>
<td>Linear Attenuation Coefficient</td>
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<tr>
<td>LLNL</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>Manhattan II</td>
<td>TSA procurement program for next-generation EDS. This term has been supplanted with the term Checked Baggage Inspection System (CBIS)</td>
</tr>
<tr>
<td>MBIR</td>
<td>Model based iterative reconstruction</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo [modeling]</td>
</tr>
<tr>
<td>MMW</td>
<td>Millimeter wave</td>
</tr>
<tr>
<td>MU</td>
<td>Marquette University</td>
</tr>
<tr>
<td>MV</td>
<td>Multiple view</td>
</tr>
<tr>
<td>NDA</td>
<td>Non-disclosure agreement</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-destructive evaluation</td>
</tr>
<tr>
<td>NEMA</td>
<td>National Electrical Manufacturers Association</td>
</tr>
<tr>
<td>NEU</td>
<td>Northeastern University</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>NQR</td>
<td>Nuclear Quadrupole Resonance</td>
</tr>
<tr>
<td>OOI</td>
<td>Object of interest</td>
</tr>
<tr>
<td>OSARP</td>
<td>On screen alarm resolution protocol/process</td>
</tr>
<tr>
<td>OSR</td>
<td>On screen resolution</td>
</tr>
<tr>
<td>OUO</td>
<td>Official use only</td>
</tr>
<tr>
<td>PD</td>
<td>Probability of detection</td>
</tr>
<tr>
<td>PFA</td>
<td>Probability of false alarm</td>
</tr>
<tr>
<td>PI</td>
<td>Principle Investigator</td>
</tr>
<tr>
<td>PPV</td>
<td>Positive predictive value</td>
</tr>
<tr>
<td>QR</td>
<td>Quadruple resonance</td>
</tr>
<tr>
<td>RFI</td>
<td>Request for information</td>
</tr>
<tr>
<td>ROC</td>
<td>Receiver operator characteristic</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on investment or region of interest</td>
</tr>
<tr>
<td>RSNA</td>
<td>Radiology Society of North America</td>
</tr>
<tr>
<td>SAT</td>
<td>Site acceptance testing</td>
</tr>
<tr>
<td>SBIR</td>
<td>Small business innovation research</td>
</tr>
<tr>
<td>SCR</td>
<td>Siemens Corporate Research</td>
</tr>
<tr>
<td>SI</td>
<td>Segmentation Initiative</td>
</tr>
<tr>
<td>SIRT</td>
<td>Simultaneous iterative reconstruction technique</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>SOC</td>
<td>Stream of commerce</td>
</tr>
<tr>
<td>SOP</td>
<td>Standard operating procedure</td>
</tr>
<tr>
<td>SPIE</td>
<td>International society for optics and photonics</td>
</tr>
<tr>
<td>SR</td>
<td>Statistical reconstruction</td>
</tr>
<tr>
<td>SSI</td>
<td>Sensitive security information</td>
</tr>
<tr>
<td>STIP</td>
<td>Security Technology Integrated Program</td>
</tr>
<tr>
<td>TBD</td>
<td>To be determined</td>
</tr>
<tr>
<td>THZ</td>
<td>Tera-Hertz imaging</td>
</tr>
<tr>
<td>TIP</td>
<td>Threat image projection</td>
</tr>
<tr>
<td>TQ</td>
<td>Threat quantity; minimum mass required for detection. Value(s) is classified.</td>
</tr>
<tr>
<td>TRX</td>
<td>TIP-ready x-ray line scanners</td>
</tr>
<tr>
<td>TSA</td>
<td>Transportation Security Administration</td>
</tr>
<tr>
<td>TSL</td>
<td>Transportation Security Lab, Atlantic City, NJ</td>
</tr>
<tr>
<td>TSO</td>
<td>Transportation security officer; scanner operator</td>
</tr>
<tr>
<td>TSS</td>
<td>Telesecurity Sciences</td>
</tr>
<tr>
<td>UEA</td>
<td>University of East Anglia</td>
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<tr>
<td>WBI</td>
<td>Whole body imaging; a deprecated term for AIT</td>
</tr>
<tr>
<td>XBS</td>
<td>X-ray back scatter</td>
</tr>
<tr>
<td>XDI</td>
<td>X-ray diffraction imaging</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
</tr>
<tr>
<td>Z</td>
<td>Atomic number</td>
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<tr>
<td>Zeff</td>
<td>Effective atomic number</td>
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### 8.2 Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Classification</td>
<td>The processing a indicating which type of object in which category is present in a scan.</td>
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<tr>
<td>Detection</td>
<td>The process of creating a binary decision of the presence of absence of a specific type of object in a scan.</td>
</tr>
<tr>
<td>Feature extraction</td>
<td>The process of determining features of objects from their scans.</td>
</tr>
<tr>
<td>Features</td>
<td>Characteristics of objects such as mass, density and volume.</td>
</tr>
<tr>
<td>Identification</td>
<td>The process of cataloging items in scans in categories.</td>
</tr>
<tr>
<td>Scan</td>
<td>The set of images that results from scanning a piece of luggage on a CT scanner.</td>
</tr>
<tr>
<td>Segmentation</td>
<td>The process of associating voxels in scans to specific objects.</td>
</tr>
<tr>
<td>Ground Truth</td>
<td>A semi-automatic delineation of the segmented objects</td>
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9 Supplemental Material in the Appendices

The supplemental material listed in the following subsections is available in this interim final report.

All of the images shown in the supplemental material were obtained from scans on a commercial medical scanner. Explosives and explosive simulants were not scanned. Scans were not obtained on security scanners.

9.1 Symposium presentations
9.1.1 “Research Challenge Project Overview,” Harry Martz, Carl Crawford and Homer Pien
Research Challenge
Project Overview

Harry Martz, Lawrence Livermore National Laboratory
Carl Crawford, Csuptwo
Homer Pien, Massachusetts General Hospital

Executive Summary

- Objective: Bring new people (third parties) and ideas to segmentation of items in bags
- Do not expect third parties to solve the problem in a few months
- Five research groups (third parties) have applied/developed segmentation algorithms for volumetric CT scans of bags
  - Marquette University, Milwaukee
  - Siemens Corporate Research, Princeton
  - Stratovan Corp., Sacramento
  - Telesecurity Sciences Corp., Las Vegas
  - University of East Anglia, UK
- Developed quantitative scoring metrics
- Potential outcomes
  - Algorithms transition to fielded EDS
  - Researchers continue working on algorithms with TSA, ALERT and vendors
  - People trained to work in field
- Lessons learned by ALERT and researchers
  - Execution of initiative
  - Communication of specs and results
  - Novel algorithms
  - Process for engaging 3rd parties
Expectation Management

- Learning process for
  - DHS
  - ALERT
  - Researchers
- Lessons learned along the way
- Be patient!

Agenda

- History
- Objectives
- Process
- *Mea culpa*
- Futures
- Miscellaneous

- Details will be in final report
- Want to get the researchers on stage ASAP
**DHS Goals**

- Vendors doing an excellent job
- But, need
  - Increase probability of detection (PD)
  - Decreased probability of false alarm (PFA)
  - Detect more threats including wide-variation of home-made explosives (HMEs)
  - Reduced mass
  - Reduced labor costs
    - Eliminate human in the loop if possible
  - New algorithm ideas
  - New people
  - Development risk mitigation
DHS Tactics

- Augment abilities of vendors with 3rd parties
  - Academia
  - National labs
  - Industry other than the vendors
- Create centers of excellence (COE) at universities
- Hold workshops to educate 3rd parties and discuss issues with involvement of 3rd parties
  - Algorithm Development for Security Applications (ADSA)

Vision created by George Zarur and Doug Bauer

ADSA01 - Recommendations

- Organize research challenges
  - CT first
    - Segmentation first
      - Easiest task to do first
      - Better features from segmentation will improve classifier
      - Classifier crown-jewels of vendors, especially features
    - Reconstruction second
      - Difficult to get projection data and parameters
  - Then other modalities
  - Then other aspects of generalized model
    - Sensor modeling and design
    - Human factors
Refinement

- “Grand challenge” cannot be used
  - Instead: research challenge, segmentation initiative, project or program
- ADSA02 discussed project details
- Classified meeting conducted with vendors
  - Mapped problem to public domain problem
  - Difficult configurations ≠ cannot detect

OBJECTIVES
Objectives

- Develop or apply *better* segmentation methods
  - Better precision on features such as mass, density
  - "Better" is difficult to define and assess
- Problem is that state-of-the-art is proprietary to vendors
- Success measures
  - Engagement of third parties
  - Researchers in same room as vendors and DHS/TSA
  - Transition from third parties to vendors
  - Researchers receive funding from vendors and DHS
  - ALERT learns to work with 3rd parties and vice versa

Object Philosophy

- From the RFP: "Candidates will use the project description, Qualification Dataset Group and their segmentation algorithms to segment objects (>500 [modified] Hounsfield units (MHU) and ≥50 mL, minimum) in the Qualification Dataset Group."
- Definitions purposely left open (denoted "object philosophy")
  - Physical objects v. components
  - Homogeneity of objects
- Want segment-all instead of segment threat-like objects
  - Threats will change over time
- Object classification and identification are out of scope
Object Philosophies

One physical object or N components?

EDS Diagram

Sensor → Recon → ATR → Display → Decision

Threat

Operator
Example ATR Diagram

Volumetric CT slices → Segmentation → Feature Extraction → Detect → Decision

ATR Overview - Literature

Segmentation → Feature Extraction → CT Correction → Detect

Sheet filter/path
Bulk filter/path
Weapons filter/path

Mass Density Z-effective Texture Volume
Orientation Resolution
Non-linear thresholds

Researchers to concentrate on yellow tasks
Cluttered Cross Sections

- Artifacts types
  - Shading
  - Streaks
  - Noise
  - Blurring
  - Rings

- Artifacts lead to
  - Merging of objects
  - Splitting of objects
  - Imprecise density, volume, mass, shape

Reduce Cluster Size
PROCESS

Steps

- DHS funding supplied to ALERT and LLNL
- Project plan written
- Proposals solicited
- Researchers chosen
- CT scans supplied
- Researchers develop algorithms
  - Mentorship provided by “Domain Experts”
- This symposium
- Final reports
  - Researchers
  - ALERT
Databases

- Packed suitcases with normal objects
- No threats, simulants or threat-like objects
- Scan on medical CT scanner
- Outline objects using semi-automated method
  - Denoted ground truth data
- Database packaged with packing videos and packing lists

Sample Images
Team

- Program management (ALERT)
  - Michael Silevitch
  - John Beatty
- Database (Massachusetts General Hospital)
  - Rick Moore
  - Alyssa White
- Tool developers
  - Seemeen Karimi, University of California, San Diego
  - Jeff Kallman, Karina Bond, LLNL
- Domain experts (mentors)
  - Carl Crawford, Csuptwo
  - Harry Martz, LLNL
  - Homer Pien, Massachusetts General Hospital

MEA CULPA
**Mea culpa (1)**

- Object definition (or lack thereof)
  - Different object philosophies used by program management, domain experts, database developers and researchers
- Acceptance (evaluation) criteria
  - Not clearly defined
- May have turned into detection problem (not intended)
- Database
  - DICOM and TIFF files: Non-standard headers led to loading errors
  - Not enough scans of homogeneous objects in different configurations
  - Difficult cases not emphasized
  - Semi-automated method for generating ground truth had limitations, especially low-density and textured objects, and with CT artifacts: ground truth not ground truth
  - Quality control insufficient

**Mea culpa (2)**

- Not clear that segmentation included feature extraction (mass, density)
- Duration (~10 months) and funding ($70k) may not be sufficient
- Should have had more and earlier face time between researchers and mentors
  - More group communication
MISCELLANEOUS

EDS (CT) Vendors

- L-3 Communications
- Analogic
- Reveal/SAIC
- Morpho Detection (GE, Invision)
- Surescan
- Rapiscan
Researcher Presentations

- Speak for ~30’
- Discussion for ~30’
- Want real-time discussion
- Moderator to keep on time/track

Quiz

- What is the one sport in which neither the spectators nor the participants know the score or the leader until the contest ends?
- Today is not a contest and whatever it is will not end today!
9.1.2 “Report From The Evaluation Committee & Additional Discussion,” Harry Martz, Carl Crawford and Homer Pien
Report From The Evaluation Committee & Additional Discussion

Carl Crawford, CsupTwo
Harry Martz, Lawrence Livermore National Laboratory
Homer Pien, Massachusetts General Hospital

Executive Summary

- Project has achieved its goals
  - Five research teams
    - Developed and applied novel segmentation algorithms
    - Learned about CT-based EDS and items in bags
  - ALERT
    - Learned how to involve third parties
    - Transform classified problem into public domain
- Future potential
  - Researches working with vendors, DHS and TSA to enhance their algorithms and transition to fielded systems
  - More involvement of third parties
  - Application to AIT, AT2, and other modalities
How Good Did They Do?

- All researchers were able to segment objects in bags.
- Can’t answer that question quantitatively for the following reasons.
  - Segmentation is part of ATR, which is trained to pass TSA EDS certification at TSL in Atlantic City at specific PD and PFA.
    - Segmentation can also be separated from ATR to determine prevalence and features of non-threats.
  - Objective was only segmentation.
    - Not feature extraction and training with scans of explosives and stream of commerce data.
  - Incumbent vendors’ segmentation is proprietary.
    - May be possible that all work presented today has been implemented by the vendors.

How Far Did They Go?

- ADSA02 contained review of patent literature related to ATR for EDS.
- Based on patents, researchers created novel methods.
- Would need to implement patents to perform comparison.
80-20 Rule May Apply

- Probably got 80% of the way to segmentation. However, five times as much effort is required to get last 20%.
  - Per Merzbacher (Morpho Detection), multiplier could be much greater … maybe 99-1 rule.

Common Strengths

- Understood problems caused by CT artifacts such as finite resolution and streaks, leading to merging and splitting of objects
- Implemented methods to compensate for splitting and merging
- Separate paths for some objects (e.g., sheets)
- Developed methods to score/evaluate results
- Dealt with object philosophies
- Potential to solve real security problems
- Patents filed
Specific Strengths

- Telesecurity
  - Sequential segmentation and carving
  - Bilateral filtering
  - Recursive k-Means clustering for splitting
- East Anglia
  - Sieves
  - Classifier
- Stratovox
  - Tumbler – kernel based segmentation
  - Automatic seed generation

- Marquette
  - Synthetic sinogram processing
  - Multi-path
  - Seed generation
  - Adaptive threshold
- Siemens
  - Synthetic sinogram processing
  - Confidence measure
  - 3D display

Time for Disclaimer

- Researchers and ALERT have done excellent work.
- Domain experts applaud all their efforts
- Next slides discuss opportunities for improvements
  - Should not be considered to be criticism of their work
- We bear some responsibility for weaknesses
  - Corollary of Heisenberg’s Uncertainty Principle is that we could not observe without affecting
  - Did convince ALERT to overcome lessons learned with liquid threat detection project conducted by LLNL
**Improvement Areas**

- Some difficult cases not sufficiently addressed
  - Easy to segment bulks in isolation
  - Difficult to segment bulks in presence of clutter and sheets artfully concealed
- Artifact reduction performed in projection space
- Feature extraction not sufficiently addressed
  - Precision and accuracy of mass, density
  - Means and higher order statistics

---

**Reduce Cluster Size**

Diagram showing the transition from ATR today to ATR Future, highlighting features 1 and 2, with labels for "Bare" HME, Effects of Containers, Effects of Concealment, and Non-threats.
Areas of Concern

- Use of shape
- Turning into classification problem
- Over-training on objects in the bag set

Specific Comments

- All great teams!
- Look forward to seeing them staying involved with the security industry
- Thank you for listening to the domain experts
9.1.3 “Next Steps,” Harry Martz, Carl Crawford and Homer Pien
Next Steps

Carl Crawford, Csuptwo
Harry Martz, Lawrence Livermore National Laboratory
Homer Pien, Massachusetts General Hospital

Recommendations

- Split into two projects
  - “Segment-all”
    - Prevalence studies can be performed
    - Classification based on object-types
  - Detect threats
    - Ultimate goal: pass TSA EDS Certification with better PD and PFA
Recommendations (2)

- Support research community
  - Funding
  - Forums & conferences
  - Databases into public domain
  - Evaluation methodology
- TSA purchases based on performance

Recommendation (3)

- Process changes for grand challenges
  - Better specifications for acceptance criteria, databases and deliverables
  - Sample segmentation code and simple examples to understand inputs and outputs
  - Kickoff meeting for process and technical aspects
  - More group meetings: mentors and researchers
  - Develop evaluation criteria and distribute code
  - More time to evaluate results
Researchers

- Derive quantitative evaluation metrics
- Revise presentations
- Complete final reports
- Publish
- Seek additional funding from
  - Vendors, DHS, TSA, ALERT
- Release code
- Revise algorithms
  - Artifact reduction
  - Feature extraction
  - Textured objects and sheets
- Develop ATR and try to certify

Program Management

- Complete final report
- Database and problem statements into public domain
- Facilitate community and networking
DHS

- Fund additional research by researchers, national labs and vendors
- Encourage vendors to engage third parties
- Choose more representative unclassified problems
  - AIT, AT2, cargo
- Provide access to image database at LLNL

Domain Experts

- Continue development of quantitative evaluation tools
- Better understanding of segmentation results
- Evaluate use of “evaluation database”
National Labs

- Execute segmentation algorithms on scans of threats and stream of commerce data
  - Use DHS image database at LLNL
- Compare with vendor ATRs

Vendors

- Compare proprietary segmentation to researcher segmentation
- Engage/hire researchers
- Provide more unclassified problems
Beyond Segmentation Challenge

- Additional grand challenges
  - ATR for CT and AIT
  - Reconstruction for CT, AIT, AT2

- Develop metrics for sub-systems
  - Reconstruction
  - Segmentation

- Advanced hardware development

The Structure of Scientific Revolutions
Thomas Kuhn

Kuhn has made several notable claims concerning the progress of scientific knowledge: that scientific fields undergo periodic "paradigm shifts" rather than solely progressing in a linear and continuous way; that these paradigm shifts open up new approaches to understanding that scientists would never have considered valid before; and that the notion of scientific truth, at any given moment, cannot be established solely by objective criteria but is defined by a consensus of a scientific community. Competing paradigms are frequently incommensurable; that is, they are competing accounts of reality which cannot be coherently reconciled. Thus, our comprehension of science can never rely on full "objectivity"; we must account for subjective perspectives as well.
Automatic Object Delineation from Checked Airport Baggage CT Scans

David F. Wiley, PhD  President and CTO

Summary

- Robust and automatic delineation of objects irrespective of:
  - Topology
  - Shape
  - Orientation
  - Density
  - CT artifacts
  - Touching objects
  - Thin objects
- Novel segmentation technology: two patents filed
- Portable to the GPGPU*
- Integrated visualization and analysis of extracted objects
- Platform for automatic object detection

*GPGPU: General Purpose Graphics Processing Unit
STRATOVAN Background

• Founded in 2005.

• Startup from the Institute for Data Analysis and Visualization (IDAV) at University of California, Davis.

• 3D medical imaging, surgical planning, and treatment planning software.

• Products in orthopedic, craniofacial, neuroimaging, etc.

• Proprietary imaging platform called Encircle.

STRATOVAN Management and R&D

• **David F. Wiley, PhD**  
  *President and CTO*  
  • 20+ years in software  
  • Medical imaging, user interfaces, software platforms, image processing  
  • 25+ publications

• **Jim Olson, MBA**  
  *CEO*  
  • 30+ years in the Silicon Valley  
  • Former CEO of SkyStream

• **Bernd Hamann, PhD**  
  *Director*  
  • Leading visualization scientist in the world  
  • UC Davis Assoc. Vice Chancellor  
  • 400 peer-reviewed papers over the last 20+ years

• **Deb Ghosh, PhD**  
  *Software Engineer*  
  • Geometric modeling, deformation, and feature detection,

• **Christian Woodhouse, BS**  
  *Application Developer*  
  • Imaging software and user interfaces
Problem Statement

- Automatic segmentation of objects from CT baggage scans
- No assumption of object types in bag
- Extract object features: mass, volume, and density
- Robust handling of:
  - CT artifacts
  - Streaking
  - Noise
  - Scattering
  - Ill-defined boundaries
  - New and unknown objects

Tumbler: Kernel-based Image Segmentation

- Define a 3D kernel
  - Multi-voxel, usually a sphere (4mm, 3mm, 2mm, or 1mm radius)
- Choose a start location
  - Automatically find “good” start locations
  - Add the neighboring voxels to a queue
- Define movement criteria (min, max, mean, std dev)
  - Determine thresholds that need to be satisfied to move kernel
- Iterative flood-fill process
  - Remove voxel position from queue and determine if the movement criteria is satisfied
  - If acceptable, move, add new neighbors to the queue and repeat
Slide 6

**D1**

determined from a trained function
1. voxel properties at start location
2. smaller than object, bigger than holes
3. "thickness" of the object

Deb, 11/29/2011

**D2**

1. Start in the center of homogeneous regions
2. avoid edges

Deb, 11/29/2011
**Tumbler: 2D Examples**

Demonstration video of Stratovan Decorum’s automatic segmentation process.
Current Performance 1: Great

Bag 3
- Toothpaste
- CDs
- Soaps
- Jacket zipper
- Clay
- Rubber sheet

Bag 6
- 8 pack soda
- Candle
- Umbrella (in purse)
- Shaving cream
- Honey
- Batteries

Bag 15
- Toothpaste
- Duct tape
- Water
- Clay
- Batteries
- Rubbing alcohol
- Urethane foam

Bag 17
- 2 liter soda
- 8 pack soda
- Petroleum jelly
- Bracelets
- Honey
- Acetone
- Motor oil
- Nylon

Bag Verification 12
- Skin cream
- Phantoms

Current Performance 2: Good

Bag 3
- Flat iron
- Skip-bo box

Bag 6
- Large flashlight
- Blow dryer
- Tripod
- Rubber
- Cereal

Bag 15
- Crayons
- Aerosol
- Cell phone
- Toy truck
- Baby doll
- Nylon
- Skip-bo box

Bag 17
- Pot w/ lid
- Aerosol
- Candles
- Glass candle
- Large flashlight
- Laptop

Bag Verification 12
- Hard drive
- Aerosol paint
- Cell phone
- Steel bottle
- Steel bottle w/ liquid (axial view)
Current Performance 3: Ok

Bag 3
- Tennis shoes
- Toothbrushes
- Rubber sheet

Bag 6
- Toy truck
- Rubber boot
- Baby doll
- Bottle w/ water
- Bottle w/ castor oil

Bag 15
- Neoprene (thin)

Bag 17
- Water
- Gel pad
- Small electronic
- Rubber
- Scotch tape
- Bag Verification 12

Current Performance 4: Challenging

Bag 3
- Candles
- Bag 6
- Rubber boot
- Bag 15
- Neoprene (thick)

Bag 17
- Large flashlight
- Merged rubber sheet, books
- Tea candles w/ bag handle
- Rubber w/ cards and crayons
- Neoprene
- Flashlight w/ nail
### Current Performance 5: Liquids

<table>
<thead>
<tr>
<th>MHU</th>
<th>Rubbing Alcohol</th>
<th>Motor Oil</th>
<th>Water</th>
<th>2L Soda</th>
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MHU = Modified Hounsfield Unit (water is 1000 MHU)

Volume is the sum of all segmented object voxels.

Variation in object metrics implies higher likelihood of detection discrimination.

### Performance Summary

**Easily segmented:**
- High-intensity and high-gradient boundary objects
- Homogenous objects
- Heterogeneous objects can be “aggregated” based on overlapping voxels

**Challenging:**
- Low-intensity and low-gradient boundary objects
- Very thin/sheet-like objects (low contrast)
- Some heterogeneous objects do not have overlapping regions
- Clamped high-intensity objects that are touching
Splitting

Improve object splitting by optimizing:
• Kernel size
• Guiding threshold parameters

Kernel Radius: 2mm
Min: 750 MHU
Max: 1300 MHU

Kernel Radius: 4mm
Min: 750 MHU
Max: 1055 MHU

Merging

Automatic merging based on overlapping voxels.

Overlapping voxels imply connectedness.
Bag 15 Results

Demonstration video of Stratovian Decorum’s object hierarchy and organization.

Capabilities and Challenges

**Capabilities:**
- No topological, size, shape, density, or mass constraints.
- No specific limitations on type of object.
- Smallest/thinnest object depends on CT resolution and contrast.

**Challenges:**
Low-intensity objects (<800 MHU):
- Have low contrast which poorly defines boundaries with other low-intensity objects.
- Are subject to noise, CT artifacts, etc.

CT spacing should be somewhat uniform: ideal is an aspect ratio better than 3:4.
Artifacts: Streaking and Shading

Low-frequency shading and streaking result in more parts and widens an object's intensity histogram.

Artifacts: Streaking and Shading

Absolute Min: 427.1
Dynamic Min: 587.9
Dynamic Max: 974.8
Absolute Max: 1004.0

Absolute Min: 730
Dynamic Min: 740
Dynamic Max: 974.8
Absolute Max: 1004.0
Ground Truth Comparison: **Toothpaste**

![Image of Toothpaste]

<table>
<thead>
<tr>
<th>Color Key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>Matched to ground truth</td>
</tr>
<tr>
<td>Red</td>
<td>In ground truth, but not in our segmentation</td>
</tr>
<tr>
<td>Green</td>
<td>In our segmentation, but not in ground truth</td>
</tr>
<tr>
<td>Blue</td>
<td>In our segmentation, but part of another object</td>
</tr>
</tbody>
</table>

Bag T 15

---

Ground Truth Comparison: **Steel Bottle w/ Water**

![Image of Steel Bottle w/ Water]

<table>
<thead>
<tr>
<th>Color Key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>Matched to ground truth</td>
</tr>
<tr>
<td>Red</td>
<td>In ground truth, but not in our segmentation</td>
</tr>
<tr>
<td>Green</td>
<td>In our segmentation, but not in ground truth</td>
</tr>
<tr>
<td>Blue</td>
<td>In our segmentation, but part of another object</td>
</tr>
</tbody>
</table>

Bag V 12
Ground Truth Comparison: Rubber Sheet

No boundary delineation exists between the stacked rubber sheets.

Strengths and Weaknesses

**Strengths:**
- No topological constraints
- Easy to tune: seed, size, guiding criteria
- Tolerates noise and CT reconstruction artifacts
- Finds ill-defined boundaries
- Consistent results
- Easy to train
- Hardware agnostic
- Can be adapted to dual-energy scans (and fused data)
- Intuitive user interface
- Portable to GPGPU
- Platform for detection

**Weaknesses:**
- Low intensity objects (<800 MHU) due to low contrast
- Flat objects layered on top of each other (low CT resolution)
- Touching thin objects
- Relatively uniform voxel spacing
- CT reconstruction artifacts do change results
Risks and Mitigation

Inherent imaging issues (in order of importance):
- **Resolution**: uniform and small spacing (< 1mm) is ideal.
- **Low contrast**: filtering, improve bit representation, use floats.
- **CT artifacts**: improve reconstruction methods.
- **Calibration**: is water really 1000 MHU? Add phantoms to CT bed so they are captured in every scan.

Software segmentation:
- **Topology**: spherical kernel can handle most shapes and topologies well.
- **Touching objects**: modify kernel shape and/or decrease pixel/slice spacing.
- **Never before seen objects**: cover our parameter space.

---

**Risks and Mitigation: Training Parameter Space**

87 Training points

Bag 6 – 1447 Objects/parts

We are able to extract objects substantially different from our training objects.
Comments on Images, Reference Labels, Communications, and Acceptance Criteria

- **Images (minor issues):**
  - Pixel/slice spacing in DICOM incorrect
  - Slice order reversed
  - Incorrect DICOM tags in some bags
  - Bag numbering in packing reference offset (unpacking videos are crucial)

- **Reference labels (minor issues):**
  - Some incorrect label numbers in ground truth
  - Voxel shifting in ground truth

- **Acceptance criteria:**
  - Difficult to ascertain “success,” “failure,” or “quality” quantitatively
  - Only focused on certain objects: water, book, cell phone, etc.
  - Does not adequately deal with the heterogeneous problem: laptop

- **Communication:** excellent, mentors were excellent, timely response, very supportive.

Future Work

- Improve training to cover parameter space
- Improve aggregation to group object parts reliably
- Improve matching/detection system to perform “bottom-up” matching reliably
- Evaluate on scans from multiple equipment vendors
- Port to GPGPU
- Detection knowledge-base

**Contact:**

David F. Wiley  
[www.stratovan.com](http://www.stratovan.com)  
wiley@stratovan.com  
916-813-7233

Jim Olson  
[www.stratovan.com](http://www.stratovan.com)  
olson@stratovan.com  
650-400-4046
Mean Kernel Intensity:

Guiding Criteria:
Mean < 5

Mean Kernel Intensity:
(0+0+0)/3=0

Guiding Criteria:
Mean < 5
Mean Kernel Intensity: 
\[(0+10+0)/3=3.33\]

Guiding Criteria: 
**Mean < 5**

---

Mean Kernel Intensity: 
\[(10+10+10)/3=10\]

Guiding Criteria: 
**Mean < 5**
2D Example: Noise, Streaks, Shadows, etc.

Intensity Values

Mean Kernel Intensity: 0

Guiding Criteria: Mean $< 5$

---

Mean Kernel Intensity: $(0+0+0)/3=0$

Guiding Criteria: Mean $< 5$
Intensity Values

Mean Kernel Intensity:
\[
\frac{(0+10+0)}{3} = 3.33
\]

Guiding Criteria:
Mean < 5

Intensity Values

Mean Kernel Intensity:
\[
\frac{(0+10+0)}{3} = 0
\]

Guiding Criteria:
Mean < 5
Tumbler Parameters: Choose a Start Location

- Start in the center of homogeneous regions
- Avoid edges

Seed Sorting

- Do large kernel sizes first, small last (4, 3, 2, 1mm)
- Do high intensity first, low intensity last (4096 to 0)
- Weigh “edges” less so we prefer to start in the middle of objects
- Take care to not penalize “thin” objects
For many objects, intensity histograms provide reasonable discrimination.

PCA Shape Profiling

Roll of Tape  Aerosol Canister  Bar of Soap

For many objects, intensity histograms provide reasonable discrimination.
Detection Knowledge-base
Extraction of Objects from CT Bag Images by Sequential Segmentation and Carving

Brandon J. Kwon, Samuel M. Song, Jason J. Lee, and Douglas P. Boyd

TeleSecurity Sciences, Inc.
7391 Prairie Falcon Road, 150-B
Las Vegas, NV 89128

December 8, 2011

Executive Summary

- Algorithm components
  - Pre-processing (edge preserving smoothing)
  - Parameterized Segmentation and Carving (SC)
    - Sequential SC using different sets of parameters for different objects
    - Carving out of segmented objects for next SC step
  - Post-processing
    - Splitting merged objects
    - Merging split objects
- Results
  - All homogeneous bulk objects in five focus cases are successfully segmented.
  - All merged objects are split and split objects are merged.
  - All sheets are detected (with some fragmentation)
  - Subject to definitions of object and homogeneity
- Future Work
  - Better segmentation of sheet objects
Our Definition of Object

- **Object**
  - Composed of physically contiguous *homogeneous* material
    - Homogeneity: difference in HU of contiguous voxels ≤ 50 (or thereabouts)
- **Segmented regions should be:**
  - Homogeneous so that “features” can be estimated from MHU values
  - Large enough so that estimates can be determined with high confidence
- **Ramifications**
  - Cell phone
    - Three objects: plastic case, circuit board, battery
  - Two touching bottles
    - Of same liquid: 1 or 2 objects
    - Of different liquids, e.g., water & alcohol: 2 objects
  - Candle (wax) in candle holder (glass)
    - 2 objects: candle and holder
  - Three soap bars in a paper container (not touching)
    - 3 objects

---

TeleSecurity Sciences, Inc.

- Start-up in Jan, 2006 by three founding members
  - Douglas P. Boyd, Ph.D., Hui Hu, Ph.D. and Samuel M. Song, Ph.D.
- Current Scientific Staff
  - Nine full-time and four part-time/consultants (most with advanced degrees)
- Development of Software Solutions for Security Imaging Systems
  - Automatic Target Recognition
    - EDS, AIT, AT/AT2, Cargo
  - CT Systems
    - Security and Medical
    - No-motion scanner design, reconstruction sub-system
- TSS has a working relationship with most security imaging system vendors
- Primary source of funding are contracts from DHS and industry
  - TSA contract related to CT segmentation project:
    - *Development of GUI for EDS* (Prime Contractor: TASC)
Researchers

- Samuel M. Song, Ph.D.
  - Former professor (1995-2005), Ph.D. in Electrical Engineering
  - Experience in medical image processing, 3-D imaging and visualization, analysis of images, video applications, etc.
- Brandon J. Kwon, Ph.D.
  - Computer vision, analysis of video sequence for navigation applications, 3-D discrete reconstruction with few views, CT reconstruction, 3-D segmentation
- Jason J. Lee, M.S.
  - Image processing, dual-energy image analysis, ATR algorithms
- Douglas P. Boyd, Ph.D.
  - Founder/Founding Member of Imatron, InVision (now Morpho Detection), TeraRecon, Acculmage, TeleSecurity Sciences
  - Inventor of many novel CT applications, e.g., EBCT

Problem Statement

- Perform automatic object segmentation of 3-D CT data of checked bags.
  - Requirements for objects to be segmented (from SOW)

  … has an average linear attenuation coefficient of $\geq 500$ Modified Hounsfield Units (MHU), and aggregate pixel volume $\geq 50$ mL.

- Our interpretation
  - Object be *homogeneous* as defined by region growing criteria,
    $$|f(p) - f(q)| \leq c \quad \text{with} \quad c \approx 50 \text{ MHU}$$
  - Voxel size of $(\Delta x, \Delta y, \Delta z) = (0.98 \text{ mm}, 0.98 \text{ mm}, 1.29 \text{ mm})$
    $$\Rightarrow 50 \text{ cc} = 40358 \text{ voxels imply virtually all objects except clothes.}$$
Overview of Our Approach

- Unsupervised Segmentation
  - Many advanced segmentation algorithms such as graph cut and many region growing approaches require seed points (user input).

- Our Tool Set and Contributions
  - **Bilateral Filter**, C. Tomasi and R. Manduchi (1998), Proc. ICCV.
    - Edge preserving smoothing filter (non-linear)
    - Finds all regions satisfying the symmetric region growing criteria
    - Invariant to voxel processing order and fast implementation exists: $O(N)$
  - **Segmentation and Carving (SC)**
    - Repeated SC using different sets of parameters for different objects
    - Carving out of segmented objects for next SC step
  - **Split and Merge**
    - Split merged heterogeneous objects
      - RANSAC, recursive k-means
    - Merge homogeneous objects

TSS Algorithm

- Preprocessing: Bilateral filter
- SC1: Homogeneous bulk objects
- SC2: Homogeneous medium thickness objects
- SC3: Homogeneous sheet objects
- SC4: Homogeneous metallic objects
- SC5: Remaining objects (heterogeneous)
- Post-processing: Split and Merge (histogram-based object splitting and merging)
Bilateral filtering for gray and color images (1998), R. Tomasi and R. Manduchi, in Proc. ICCV.


Bilateral filtering: a smoothing filter that preserves edges

\[ g(r) = K \int_{\omega} f(\omega) h_d(\omega - r) h_r(\omega) d\omega, \]

where \( h_d(r) \) and \( h_r(r) \) are Gaussians, and \( K \) is a scale factor so that DC gain is unity.
Symmetric Region Growing

- SRG with \( g(p, q) \equiv |f(p) - f(q)| \leq c, c = 4 \)
  - 1D segmentation by sequential scan
    - Check neighbors sequentially
      
      | 2 | 3 | 5 | 2 | 10 | 17 | 22 | 20 | 16 | 8 | 2 | 1 |
      | 2 | 3 | 5 | 2 | 10 | 17 | 22 | 20 | 16 | 8 | 2 | 1 |
    
    \( k \)-th row
    
  - 2D segmentation by merging 1D segmentation results
    - Check neighbors across rows
      
      | 8 | 7 | 10 | 8 | 6 | 1 | 8 | 12 | 15 | 13 | 5 | 3 |
      | 2 | 3 | 5 | 2 | 10 | 17 | 22 | 20 | 16 | 8 | 2 | 1 |
      | 8 | 7 | 10 | 8 | 6 | 1 | 8 | 12 | 15 | 13 | 5 | 3 |
      | (k+1)-th row |
    
    \( k \)-th row
    
  - If any two pixels satisfy \( g(p, q) \), their labels are merged.
  - 3D segmentation by merging 2D segmentation results
    - Check neighbors across slices

Segmentation and Carving—Overview

- In SRG, different \( c \) results in characteristically different objects by selectively processing voxels within a window of MHUs, \( l_1 \leq f \leq l_2 \).
  - Segmentation and Carving: SC\((l_1, l_2, c)\)
    - Threshold: mask = 1, if \( l_1 \leq f \leq l_2 \)
    - Perform object dependent processing of the binary mask
    - Perform SRG\((c)\): \( g(p, q) \equiv |f(p) - f(q)| \leq c \)
    - Carve out the segmented result for the next SC step
  - Sequential application of SC
    - SC1: SC\((600,2000,50)\) for homogeneous bulk objects
    - SC2: SC\((600,2000,50)\) for homogeneous medium thickness objects
    - SC3: SC\((400,1500,50)\) for homogeneous sheet objects
    - SC4: SC\((3700, MAX, 30)\) for homogeneous metallic objects
    - SC5: SC\((1200, MAX, 300)\) for all remaining objects (heterogeneous)
Segmentation and Carving—Specifics

- Processing of the segmented binary mask
  - SC1 and SC2
    - Includes opening (erosion + dilation) with structuring element, \( SE = N \times N \times N \) cube
      - Removes regions whose thickness is less than \( N \)
      - \( N = 11 \) for SC1 (bulk objects)
      - \( N = 5 \) for SC2 (medium thickness objects)
  - SC3, SC4, and SC5
    - Includes Weak Connection Removal (also clean up small remaining regions)
      - Convolve the 3-D mask with a \( 7 \times 7 \times 7 \) kernel of 1’s
      - Remove voxels whose count < threshold (80)

Sequential Application of SC
Volume Compensation
– Active Contour using Level Set

• The boundaries as determined by SC are inaccurate. We adjust the boundaries by the level set technique.

  Level set curve minimizing Mumford-Shah energy functional

  \[ E(C, c_1, c_2) = \mu \cdot \text{Length}(C) + \lambda_1 \int_{\partial(C)} |u_0(x, y) - c_1|^2 \, dxdy \]

  \[ + \lambda_2 \int_{\omega \cap (C)} |u_0(x, y) - c_2|^2 \, dxdy \]

• Used for volume compensation for objects from SC1

Object Splitting & Merging—
Flow Chart

Objects from SC1  Objects from SC2  Objects from SC3  Objects from SC4  Objects from SC5

Split by RANSAC  Split by Recursive k-means  Split by Recursive k-means  Split by Recursive k-means  Split by Opening

Large Small

Rule-based Split and Merge
Object Splitting—Overview

- Histogram analysis for segmented objects
  - If there are multiple peaks in a histogram of an object, we split it.

- We apply this histogram analysis for objects segmented from SC1, SC2, and SC3.
  - SC4: All segmented objects are virtually homogeneous → No need for histogram analysis
  - SC5: Heterogeneous objects → No need for histogram analysis

Object Splitting for Bulk (SC1)

Objects—Step 1

- Merged object cases from SC1 found by histogram analysis

- These “large” merged objects are split as follows

- Step 1. Merged point detection
  - At each boundary voxel, calculate the number of object voxels within a 11 × 11 × 11 window surrounding the voxel.
  - At the point where objects are merged, such numbers are usually much greater than those at other boundary points.
Object Splitting for Bulk (SC1) Objects—Step 2

- Step 2. Splitting using a plane fitted by RANSAC
  - RANSAC (Random Sample Consensus)
    - An iterative method to estimate parameters of a model from a set of observed data robust against outliers
    - We fit a 3-D plane for the detected merged points by RANSAC
      - The plane can be found accurately in spite of outliers.
      - The objects are split by the fitted plane.

- Outliers

\[
p_1 = 0.920 \quad p_2 = 0.901 \quad p_3 = 1.02
\]

- from T15 (70% Isopropyl Alcohol and Water)

\[
p_4 = 1.09 \quad p_5 = 1.14
\]

- from V12 (Organic Stack and Aerosol Metallic Paint)

\[
p_6 = 0.832 \quad p_7 = 0.894
\]

- from T17 (Mountain Dew and Motor Oil)

Object Splitting for Small SC1 Objects and SC2/SC3 Objects

- Small SC1 Objects and SC2/SC3 Objects
  - Utilize recursive k-means clustering not relying on the shape property because shapes are usually irregular.
  - Recursive k-means with \( k = 2 \) until all objects pass the histogram analysis test.
Recursive k-Means Clustering

- Splitting results by recursive $k$-means clustering

![Image of clustering results with $\rho$ values: 0.992, 0.913, 1.18, 1.22, 0.889, 0.873, 0.633, 1.03, 1.21, 0.832]

Object Splitting by Opening

- SC2 and SC5 Merged Object Splitting

- We finally split these objects by morphological opening
  - Objects removed by opening are thin objects.
Object Merging

We merge objects based on the following three criteria

- Spatial proximity
  - Objects within some distance from the boundary
- Mean MHU values
- Type of objects (bulk, medium thickness, sheet)
  - Represented by a mean of distance transform of binary masks
Result for T3

Object Name | # of detected objects | (Volume(cc), Density(MHU/1000/cc))
--- | --- | ---
Toothpaste | SC1 (179.42, 1.37)
Magazine | SC3 (412.95, 0.85)
Candies | SC3 (88.03, 1.18)
CD's | SC3 (105.25, 0.61)
Sneaker L | SC2 (103.7, 1.03)
Sneaker R | SC2 (103.8, 1.04)
Bar Soap | SC1 (179.92, 1.37)

Green: Volume < 50 cc
Result for T3

Objects:
- Flat Iron [3]
  - SC3 (11.83, 0.83)
  - SC3 (13.83, 2)
- Leather Jacket (zipper)
  - SC1 (14.48, 4.09)
- Butyl Rubber Sheet
  - SC2 (201.48, 1.18)
- Clay Block
  - SC1 (201.48, 1.18)
- Clay Block
  - SC1 (201.48, 1.18)
- Skip Bo [6]
  - SC3 (101.91, 1.94)
  - SC2 (72.18, 1.60)
  - SC5 (72.18, 1.60)
  - SC1 (72.18, 1.60)

Additional Note:
- < Missing Objects >
Dataset T6

Result for T6

Object Name | # of detected objects | (Volume(cc), Density(MHU/1000/cc))
--- | --- | ---
Honey | 1 | SC1 (1697.7, 1.37)
8pk Coke | 1 | SC1 (1862.95, 1.01)
Stainless Steel | 1 | SC1 (131.1, 1.3)
Candle with Lid | 2 | SC1 (261.34, 0.97)
1/2 Full Castor Oil | 2 | SC3 (12.39, 0.77)
48pk Batteries | 2 | SC4 (146.75, 4.07)
RC Car | 6 | SC3 (15.01, 4.01)
Doll Baby | 1 | SC3 (237.42, 1.07)
Shaving Cream | 4 | SC1 (186.45, 1.07)
Flash Light | 3 | SC3 (20.01, 3.47)
Neoprene Rubber Sheet | 1 | SC2 (135.9, 1.11)
Result for T6

Dataset T15
Dataset T17

Result for T17

<table>
<thead>
<tr>
<th>Object Name</th>
<th># of detected objects</th>
<th>Volume (cc)</th>
<th>Density (MHU/1000/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain Dew</td>
<td>1</td>
<td>1021.26</td>
<td>0.88</td>
</tr>
<tr>
<td>8pk Coke</td>
<td>1</td>
<td>322.5</td>
<td>0.91</td>
</tr>
<tr>
<td>Candle Glass</td>
<td>4</td>
<td>172.56</td>
<td>2.3</td>
</tr>
<tr>
<td>Honey</td>
<td>2</td>
<td>1992.37</td>
<td>1.38</td>
</tr>
<tr>
<td>Petroleum Jelly</td>
<td>2</td>
<td>21.13</td>
<td>0.68</td>
</tr>
<tr>
<td>Water Bottle</td>
<td>2</td>
<td>474.34</td>
<td>0.86</td>
</tr>
<tr>
<td>Aerosol Metallic Paint</td>
<td>2</td>
<td>371.76</td>
<td>0.89</td>
</tr>
<tr>
<td>Flash Light</td>
<td>4</td>
<td>72.94</td>
<td>1.78</td>
</tr>
<tr>
<td>Pot With Lid</td>
<td>4</td>
<td>1202.26</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Overall Performance

• Performs well for homogeneous objects such as
  – Bulk objects
    • Bottles of liquid
      – Water, beverage, honey, oil, aerosol, etc
      – Steel bottles are segmented separately.
    • Clay block, nylon, candle, piece of steel, battery, etc
      – Medium thickness objects (5-10 voxels thick)
    • Magazine, thick rubber sheet, etc
  – Ex) Cell phone → leather case + inner metallic part + remaining heterogeneous part

• Performs well for heterogeneous objects
  – All sheet objects are segmented but
    – Usually segmented in several smaller pieces for thin rubber sheets
    – Misses very small metallic objects.

Limitations

• Thin rubber sheets are segmented as several smaller pieces.
  – MHU values of thin rubber sheets are spread over from 0 to 600-800 across 7-10 voxels
  – In SC3, by thresholding with $I_1 = 400, I_2 = 1500$, the binary mask for thin rubber sheets are 2-3 voxel wide.
  – In some cases, the mask becomes 1 or 0 pixel width because of streaking CT artifacts → Objects are split into several smaller pieces
  – Partial volume compensation processing is needed
    • The scanner appears to have the PSF with FWHM of about 3-4 mm
    • A 3mm sheet shows up as a sheet of about 6 voxels FWHM with MHU of ~600
• Fails to segment the stack of sheet objects in V12 correctly.
  – We segmented it as a single large bulk object as all sheets have similar MHU.
• We have conceptual solutions to solve these limitations. Additional effort will be required to implement the solutions with additional funding.
Feature Extraction

- **Mass-CT**
  - Mass of object (Units: MHU / 1000 x voxel size)
    \[ \text{Mass-CT} = \text{Sum of Object CT value} \times 0.98 \times 0.98 \times 1.29 \times 0.001 \]

- **Volume**
  - Volume of object (Units: cc)
    \[ \text{Volume} = \text{Number of voxels in object} \times 0.98 \times 0.98 \times 1.29 \times 0.001 \]

- **Density-CT**
  - \[ \text{Density-CT} = \frac{\text{Mass-CT}}{\text{Volume}} \]

- **Std-CT**
  - Standard deviation of Object CT values

**Alarm Decision:**

- Density, Volume, Confidence (Std-CT, Number of Voxels, etc.)

---

**Comparison with Reference – Minimum Volume: 50 cc**

Percent Overlap Between Detected Objects and Ground Truth

<table>
<thead>
<tr>
<th>Dataset T3</th>
<th>Dataset T6</th>
<th>Dataset T16</th>
<th>Dataset T17</th>
<th>Dataset V12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toothpaste tube</td>
<td>93.83</td>
<td>Honey</td>
<td>95.16</td>
<td>Toothpaste Tube</td>
</tr>
<tr>
<td>Sneaker – R</td>
<td>16.31</td>
<td>Toothpaste</td>
<td>23.78</td>
<td>Toothpaste</td>
</tr>
<tr>
<td>Sneaker – L</td>
<td>17.24</td>
<td>Toothpaste</td>
<td>7.61</td>
<td>Toothpaste</td>
</tr>
<tr>
<td>Flue</td>
<td>0.00</td>
<td>Toothpaste</td>
<td>21.86</td>
<td>Armored Flt</td>
</tr>
<tr>
<td>CDs</td>
<td>78.38</td>
<td>Books</td>
<td>51.61</td>
<td>Cell phone</td>
</tr>
<tr>
<td>Reta Soaps</td>
<td>68.39</td>
<td>Books</td>
<td>50.75</td>
<td>Water bottle</td>
</tr>
<tr>
<td>Candles</td>
<td>76.81</td>
<td>Camera Tripod</td>
<td>36.66</td>
<td>Black Clay</td>
</tr>
<tr>
<td>Toothbrushes</td>
<td>3.16</td>
<td>Rubber (soft)</td>
<td>65.14</td>
<td>RC Car</td>
</tr>
<tr>
<td>Earthen Jacket</td>
<td>1.80</td>
<td>RC Car</td>
<td>14.80</td>
<td>Toy</td>
</tr>
<tr>
<td>Rubber (hard)</td>
<td>87.84</td>
<td>Shoes</td>
<td>89.38</td>
<td>Bat</td>
</tr>
<tr>
<td>Magazine - GIL</td>
<td>89.05</td>
<td>Books with lid</td>
<td>89.38</td>
<td>Rubbing Alcohol</td>
</tr>
<tr>
<td>Skip Bo</td>
<td>95.42</td>
<td>Stainless Steel 1.2 Full water</td>
<td>85.92</td>
<td>Playing cards - 2</td>
</tr>
<tr>
<td>Coat</td>
<td>69.52</td>
<td>Large Nylon</td>
<td>95.85</td>
<td>Nonpice (black)</td>
</tr>
<tr>
<td>Doll</td>
<td>46.60</td>
<td>Comfort masks</td>
<td>91.83</td>
<td>Armored</td>
</tr>
<tr>
<td>Bat</td>
<td>79.67</td>
<td>Nonpice (black)</td>
<td>34.06</td>
<td>Armored</td>
</tr>
<tr>
<td>Edge cutting tools</td>
<td>68.31</td>
<td>Nonpice (black)</td>
<td>63.63</td>
<td>NC cylinders - Green</td>
</tr>
<tr>
<td>Large Flashlight</td>
<td>63.51</td>
<td>Skip (no)</td>
<td>41.53</td>
<td>Large</td>
</tr>
<tr>
<td>Large Nylon</td>
<td>93.98</td>
<td>Stainless Steel 1/2 Full water</td>
<td>85.92</td>
<td>Nonpice (black)</td>
</tr>
</tbody>
</table>
Comparison with Reference—Minimum Volume: 10 cc

Percent Overlap Between Detected Objects and Ground Truth

<table>
<thead>
<tr>
<th>Dataset T3</th>
<th>Dataset T6</th>
<th>Dataset T15</th>
<th>Dataset T17</th>
<th>Dataset V12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toothpaste tube</td>
<td>93.83</td>
<td>Honey</td>
<td>95.16</td>
<td>Toothpaste tube</td>
</tr>
<tr>
<td>Smoker - R</td>
<td>25.36</td>
<td>Check with red</td>
<td>25.49</td>
<td>Check with red</td>
</tr>
<tr>
<td>Smoker - L</td>
<td>17.24</td>
<td>Red paint</td>
<td>8.58</td>
<td>Cyan</td>
</tr>
<tr>
<td>Flat iron</td>
<td>26.48</td>
<td>Hard drive</td>
<td>29.46</td>
<td>Customer</td>
</tr>
<tr>
<td>GIFs</td>
<td>78.50</td>
<td>Book</td>
<td>51.63</td>
<td>Cell phone</td>
</tr>
<tr>
<td>Bar Soap</td>
<td>60.39</td>
<td>Toilet</td>
<td>50.95</td>
<td>Water bottle</td>
</tr>
<tr>
<td>Candles</td>
<td>76.81</td>
<td>Carter</td>
<td>38.68</td>
<td>Block of clay</td>
</tr>
<tr>
<td>Toothbrush</td>
<td>3.16</td>
<td>Rubber tube</td>
<td>65.14</td>
<td>BC Car</td>
</tr>
<tr>
<td>Earphones</td>
<td>2.45</td>
<td>Car</td>
<td>21.53</td>
<td>Toy</td>
</tr>
<tr>
<td>Rubber (hard)</td>
<td>87.84</td>
<td>Dirt coat</td>
<td>89.38</td>
<td>Dirt</td>
</tr>
<tr>
<td>Magazine</td>
<td>90.16</td>
<td>Cookie with lid</td>
<td>89.38</td>
<td>Rubbing alcohol</td>
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<tr>
<td>Skip Box</td>
<td>61.87</td>
<td>Stainless steel 1/2 Full</td>
<td>85.52</td>
<td>Playing cards - 3</td>
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<tr>
<td>Dell</td>
<td>46.60</td>
<td>Concrete</td>
<td>92.53</td>
<td>Assorted</td>
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<tr>
<td>Bottles</td>
<td>87.84</td>
<td>Nonporous (black)</td>
<td>35.38</td>
<td>Water oil - 2</td>
</tr>
<tr>
<td>Edge shaving cream</td>
<td>71.33</td>
<td>Nonporous (black)</td>
<td>65.16</td>
<td>Nail</td>
</tr>
<tr>
<td>Large flashlight</td>
<td>71.33</td>
<td>Large nylon</td>
<td>95.85</td>
<td>Nonporous (black)</td>
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<tr>
<td>Large blue</td>
<td>73.84</td>
<td>Large nylon</td>
<td>95.85</td>
<td>Nonporous (black)</td>
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<tr>
<td>Small nylon</td>
<td>45.70</td>
<td>Large nylon</td>
<td>93.98</td>
<td></td>
</tr>
<tr>
<td>Neoprene (thin)</td>
<td>87.84</td>
<td>Large nylon</td>
<td>93.98</td>
<td></td>
</tr>
<tr>
<td>Neoprene (thick)</td>
<td>87.84</td>
<td>Large nylon</td>
<td>93.98</td>
<td></td>
</tr>
</tbody>
</table>

Detection Performance

Number of Detected Objects

<table>
<thead>
<tr>
<th>Total Number of Objects</th>
<th>Dataset T3</th>
<th>Dataset T6</th>
<th>Dataset T15</th>
<th>Dataset T17</th>
<th>Dataset V12</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12</td>
<td>17</td>
<td>17</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
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<td>19</td>
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</tr>
<tr>
<td>50</td>
<td>10</td>
<td>17</td>
<td>17</td>
<td>19</td>
<td>13</td>
</tr>
</tbody>
</table>

Intersection (%)

<table>
<thead>
<tr>
<th>Volume (cc)</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>10</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>7</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>17</td>
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<td>12</td>
<td>19</td>
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<tr>
<td>30</td>
<td>10</td>
<td>7</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>17</td>
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<td>13</td>
<td>11</td>
<td>17</td>
<td>15</td>
<td>12</td>
<td>19</td>
</tr>
</tbody>
</table>

PD = \frac{\text{Number of Detected Objects}}{\text{Total Number of Objects}}
Work-in-Progress: Deconvolution for Sheets

- Deblurring by Wiener filtering using estimated blur kernels
  - Neoprene rubber sheet from T15
    
    ![](image)
    
    Display window: [0 1500]
    
    - Density of segmented sheet from original image: 0.662
    - Density of segmented sheet from deblurred image: 0.811
    - After the "maximum filtering": 1.05
      - Density of Neoprene: ~1.23 g/cc

Work-in-Progress: Deconvolution Kernel

- Blur kernels estimated from CT images

![](image)

\[ h(x, y, z) = h(x)h(y)h(z) \]
Strengths and Weaknesses

- **Strengths:** entire segmentation process consists of five sequential SCs focusing on objects with different characteristics
  - Fast implementation: each SC takes about 10 secs with current GPU implementation. Further optimization should result in sub-second processing.
  - The algorithm can adapt to emerging threats by tuning the SC parameters
  - Upon detection of all objects, advanced high-level processing (AI) can be added
    - For instance, bulk/sheet $\rightarrow$ detonator $\rightarrow$ conductor $\rightarrow$ power source $\rightarrow$ THREAT

- **Weaknesses**
  - Fails to segment the stack of sheet objects in V12 correctly.
  - Misses very small metallic objects that are inner parts of heterogeneous objects (volume constraint)

Risks and Mitigation

- **Risks**
  - The proposed approach has only been tested on a limited set of data. It may perform poorly on other data.
  - As in all other detection systems, the system will never achieve PD = 100%.

- **Mitigation**
  - Collect and process more data, develop more specific algorithms, perform additional testing.
  - Tightly integrate ATD output with the Level 2 workstation and OSARP (HR-OSARP).
    - Provide exquisite 3-D renderings (Electronic Unpacking) of objects in bags.
    - Allow screeners to flag regions not flagged by the ATD.
Comments

- Reference labels (ground truths) should respect homogeneity.
  - The reference label for the stainless steel bottle with water includes both the bottle and water.
  - Cell phone …, Notebook Computer …
- The thickness measurements for sheets.
  - Would have allowed checking of partial volume compensation processing, e.g., deconvolution processing
- Further work towards ATD for EDS
  - Need good luggage detector (external casing)
  - Need to recognize metal, wire, circuit boards, and batteries
    - Artificial intelligence, heuristics, etc.

Recommendation

- To ALERT
  - Evolve the challenge: CT Segmentation ➔ ATD for EDS
    - More data from real EDS with real threats (IEDS, sheets, etc.)
    - The funding should match the budget required
- To DHS S&T and TSA
  - The results warrant further funding to develop the ideas further
    - Perhaps a RFP?
  - EDS Certification Process to deploy best-of-the-best system
    - DICOS Standard will support the separation of EDS Scanner and ATD Algorithm
    - Separate certification of EDS Scanner and ATD algorithm?
      - EDS Scanner: IQ, resolution, noise statistics, penetration, etc.
      - ATD Algorithm: ROC curve
    - TSS is a key partner of TASC for a recent TSA contract
      - Development of GUI for EDS (deliverable: Next Generation EDS Workstation)
      - The Workstation may serve as a platform for all future ATD development
9.1.6 “SIEVESECT,” Richard Harvey, Paul Southam and Graham Tattersall, University of East Anglia
SIEVESECT

Richard Harvey, Paul Southam, Graham Tattersall
School of Computing Sciences
University of East Anglia,
Norwich, NR4 7TJ, UK

Executive summary

**Novel scale-based technique**
*Sieve* identifies potential objects (or segments) by region-growing from intensity extrema. Produced dense set of regions

**Regions merged**
Via density histogram comparison

**Resulting regions are suited to further classification**

December 14, 2011
University of East Anglia
School of Computing Sciences

About UEA
+ Well ranked
  + Guardian UK 18th
  + THES World rank 145

+ Strong international brand
  + Sites in Norwich and London
  + Around 15000 students

+ Lots of science
  + Europe’s largest collection of bioscientists
  + New Scientist science rank – fourth in UK

University of East Anglia
School of Computing Sciences

About Computing Sciences
+ Research intensive department

+ Strong computer vision and signal processing presence

+ Commercial activity via our consulting computing SYS Consulting Ltd

+ Spin-out and IP-exploitation routes well established

+ Access to our own venture funds (Iceni and LCIF)
Problem Statement

To identify malignant objects in baggage:

Objects are connected sets…

that contain other connected sets.

Idea: decompose image into hierarchies of connected sets and extract features
Overview of algorithm
2D image (max decomposition)

Sieve example
As a scale tree
Logarithmically Increasing Scale (Volume)

Sieved Volumes

Channel Volumes

Merged Channels

BAG T03
Channels and merged volumes

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BAG T06
Channels and merged volumes

Merged Channel Volume

CH1

CH2

CH3

CH4

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Segmentation Movies

Bag 03

Bag 06

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Kolmogorov Smirnov
Splitting/Merging

D = 0   D = 60   D = 200

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CT artifacts

December 14, 2011
CT artifacts

December 14, 2011

Bag V12 Slice 462

Bag V12 Channel 2

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Limitations on types, densities, sizes, masses of objects that can be segmented

- We are using density histograms to differentiate objects can be a problem if data are clipped.
- We could use shape/geometry.
- Subsequent to sieving we eliminate small-scale (50 ml) and large scale (2000 ml) objects.
- D not optimised via training.

Feature Extraction for log files

- Our method returns regions that are statistically different from their parents – potential objects
- Density, volume and hence mass can be read directly from those regions – there is no post-processing of regions.
Strength and Weaknesses

Strengths
- Very general image transform.
- Covered by patents.
- Computationally efficient.
- Well proven scale-space robustness properties.
- Can be generalised to classification without segments (MSERs).

Weaknesses
- A transform is not the same as a classifier.
- Works on connected sets in the density domain.
  - Iso-density touching objects are not separable.
  - Non-cubic voxels need care.

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Risks and Mitigation

Technical Risks:
- Have we been working with representative data?
- Have we been solving a task that is representative of reality?
- Have we been solving a useful task?

Logistical Risks:
- Requires US-UK collaboration.
- Project is resourced out of the University.

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Comments

- Much iteration on the ground truth data
- Huge commercial potential for supervised learning
- Sieves can be used in combination other with cool ideas
- For the future, it may be worth adopting more sophisticated methods for comparing segmentations
- Can avoid merging channels
  - Build classifier on channel data
  - Extend MSERs to 3D.

---

Recommended architecture
sieve-based classifier

Classifier

Training data

- Classifier features derived from MEAN of all examples in the training set of 30 bags.
- Test every segment in channel-merged objects in BAG03, BAG06, BAG12 and BAG15.
- Scores are logarithmic distances between feature vector of unknown objects and target object.

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**Recommended architecture**

**sieve-based classifier**

---

**Training data**

<table>
<thead>
<tr>
<th>Target Object</th>
<th>Features used by classifier</th>
<th>Objects ranked by classifier score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bottle</td>
<td>histogram, mean density, volume</td>
<td>Object, Bag, Score</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

---

**Sieve classifier results**

**Testing on training data**

<table>
<thead>
<tr>
<th>Target Object</th>
<th>Features used by classifier</th>
<th>Objects ranked by classifier score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Drive</td>
<td>histogram, mean density, volume</td>
<td>Object, Score</td>
</tr>
<tr>
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<td>Yes</td>
<td>No</td>
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<table>
<thead>
<tr>
<th>Target Object</th>
<th>Features used by classifier</th>
<th>Objects ranked by classifier score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bottle 1</td>
<td>histogram, mean density, volume</td>
<td>Object, Score</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
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</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
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<td>Yes</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

---

*December 14, 2011*
Overview of algorithm
2D image (max decomposition)

Simplified

Removed

December 14, 2011

Sieve example
As a scale tree

December 14, 2011
Results comparison to AO Ground Truth

Bag 03
December 14, 2011

Bag 06

Results comparison to AO Ground Truth

Bag 12
December 14, 2011

Bag 15
CT artifacts

Bag V12 Slice 538

Bag V12 Channel 3

December 14, 2011
9.1.7 “ALERT Segmentation Initiative Presentation,” Xin Feng, Taly Gilat-Schmidt, Wenjing Zhang, and Jun Zhang, Marquette University
ALERT
Segmentation Initiative
Presentation

Presented by
Dr. Xin Feng, Principal Investigator
Department of Electrical and Computer Engineering
Marquette University

December 8, 2011

1. Who are we and why are we here?
The segmentation research team:

- Marquette University
  - PI: Dr. Xin Feng, Electrical and Computer Engineering
  - Co-PI: Dr. Taly Gilat-Schmidt, Biomedical Engineering
  - RA: Wenjing Zhang, Ph.D. Candidate, EECE Department

- University of Wisconsin-Milwaukee
  - Co-PI: Dr. Jun Zhang, EECS Department

- Domain Expert/Mentor: Carl Crawford
2. Executive Summary

- What we developed:
  - a fully-automated, true 3D segmentation algorithm

- What we accomplished:
  A three-stage merging-splitting strategy
  - Stage One: split image into more homogeneous regions by gradient generate seeds map
  - Stage Two: grow each regions with adaptive thresholding
  - Stage Three: merge fragmented objects extract texture as new feature for clustering and merging
  - New heuristic method to merge objects fragmented by metal streaks

Sample Result

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of voxels</td>
<td>175,675</td>
</tr>
<tr>
<td>Mass-CT</td>
<td>270.51g</td>
</tr>
<tr>
<td>Volume</td>
<td>216.77cm³</td>
</tr>
<tr>
<td>Density-CT</td>
<td>1.248g/cc</td>
</tr>
</tbody>
</table>
3. Problem Statements and Challenges

- **Problem Statement:**
  - Given a set of CT-scanned luggage image files, deliver an automatic 3D segmentation algorithm to segment and label all objects with (HU>500) and (volume > 50mm³)

- **Problem Challenges:**
  - Homogenous and heterogeneous objects
  - Massive metal streaks all over
  - Potential threats with various shapes and density
  - Limited feature (intensity only)

- **Algorithmic Challenges**
  - No one-size-fit-all; needs integrated methods
  - Streak identification/removal without raw data: how?
  - Needs innovative methods for slitting/merging
4. The Algorithm

- Three specific challenges
  - Splitting/Merging: always a “contradictory pair”
  - Region grow: how to determine the homogeneous area
  - Adding features: an effective way to improve overall accuracy
The three-stage strategy for splitting/merging/feature extraction

- **Stage one**: splitting objects using gradient histogram; generating seeds map
- **Stage two**: region growing by adaptive thresholding
- **Stage three**: merge with extra features: (intensity, texture)
  Merge fragmented objects caused by streaks

**Algorithm Details**

- **Splitting/Generating Seeds Map**
- **Adaptive Region Growing**
- **Merging**
Stage 1: Splitting/Generating Seeds Map

- Splitting the 3D image into more homogenous sub-regions
- Homogeneity
  - Low gradient voxels
  - Each sub-region has near-uniform density
  - Will be used as seeds map for Stage Two (region growing)
- 3D Gradient of image
  \[ \nabla f = \left( G_x, G_y, G_z \right) = \left( \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right) \]
  \[ |\nabla f| = \left( G_x^2 + G_y^2 + G_z^2 \right)^{1/2} \]
  Gradient operator: Sobel
- Generating seeds map using low gradient voxels

\[ \lambda: \text{cut-off threshold} \]

Stage 1: Splitting/Generating Seeds Map

- Only homogenous regions are chosen as seeds map
- The cut-off threshold \( \lambda = 70\% \)
Stage 1 Example

Intensity based CCL segmentation

Gradient based seeds map

Stage 2: Region Grow by Adaptive Thresholding

- Goal: fully grow the initial seeds map
- Challenges in region grow:
  - Intensity variation within objects
  - Fixed threshold will cause over/under segmentation
  - Percentage threshold $\sigma_\mu$ with respect to intensity is inappropriate (because of nonlinear variation of intensity levels)
Stage 2: Region Grow by Adaptive Thresholding

- Study found the variation of intensities within the objects may be caused by scattering effects of the x-ray.
- Proposed solution: model the region growing threshold $\sigma_\mu$ as nonlinear function of intensity level of the object:

$$s_m = f(m) = m e^{b/m}$$

Stage 2 Example of Nonlinear Threshold

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Voxels</td>
<td>38,259</td>
</tr>
<tr>
<td>Mass-CT</td>
<td>110.59g</td>
</tr>
<tr>
<td>Volume</td>
<td>47.21cm$^3$</td>
</tr>
<tr>
<td>Density-CT</td>
<td>2.34g/cc</td>
</tr>
</tbody>
</table>

Segmented Region grow result with nonlinear threshold

Segmented image provided by label file
Stage 3: Merging Objects

- Challenges:
  - The single feature measure of intensity is inadequate for merging fragmented objects
  - Streak artifacts caused by high-density metal objects severely fragmented neighborhood objects

Merging Fragmented Objects

- Proposed solution 1: Apply heuristic rules
  - Observation: fragmented object caused by streaks may still be weakly connected by a few voxels
  - Identify regions with adjacent edges
  - Caution: irrelevant objects may also share borders with other objects

- Proposed solution 2:
  - Extract texture as new feature by texture analysis
  - Consider mean texture and intensity as 2D feature
  - Perform the recursive clustering analysis to merge two closest objects according to:

\[ D(\text{object}[i], \text{object}[j]) < d \]
Stage 3: Merging Method

- Merging heuristic:
  - If two “separated” objects have small distance in feature space,
  - and they share adjacent edge with quite a few touching voxels
  - Then they are considered as one object and should be merged.

Recursive Implementation
Segmentation of Heterogeneous Objects by Iteration

Example: from Stage 1 to Stage 2

Stage One: Splitting and Seeds map

Object 3001 Snow white doll

Stage Two Region grow
Example: from Stage 2 to Stage 3

Stage Two
Region Grow

Stage Three
Merging

More Merging Examples

➢ Problem: single object is fragmented by metal streaks
More Merging Examples

Segmentation Initiative Final Report, Page 140
More Merging Examples

Performance Comparison with Standard CCL

Split a robber sheet from the group of cans

Existing CCL: split failed    New algorithm: split succeeded
Performance Comparison with Standard CCL

**Existing CCL:**
Unable to merge fragmented object caused by streak artifacts

**New Algorithm:**
Successfully merged fragmented objects

---

**Performance Comparison with Standard CCL**

**Number of False Split Objects**

<table>
<thead>
<tr>
<th></th>
<th>CCL Algorithm</th>
<th>Proposed Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>T5</td>
<td>2</td>
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</tr>
<tr>
<td>T15</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>T17</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>V12</td>
<td>1</td>
<td>1</td>
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</tbody>
</table>
Comparison Between CCL and New Algorithm

Number of False Merged Objects

<table>
<thead>
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<th>Number of False Merged Objects</th>
<th>CCL Algorithm</th>
<th>Proposed Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>T5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>T15</td>
<td>6</td>
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<tr>
<td>T17</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>V12</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

CCL vs. New Algorithm on T15

CCL results

New Algorithm
Summary of Strengths and Weaknesses

**Strengths:**
- A three-stage splitting-segmentation-merging approach
- Unique heuristic merging of fragmented object caused by streaks
- Added feature for better merging results
- Completely automatic; Robust performance

**Weakness:**
- Streak removal: “work-around it” instead of “removing it” due to lacking of raw CT data (sinogram data)
- Physical measurement results in 15% less than actual, probably due to “dark” streaks
- Tuning of two parameters ($\lambda$ and $\sigma_\mu$) affects splitting and merging results, needs fine tuning

---

Comparison of Physical Features

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Calculated from Label</th>
<th>Segmented Results</th>
<th>Errors</th>
<th>Ground Truth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 Water Bottle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of voxels</td>
<td>405,510</td>
<td>355,824</td>
<td>-12%</td>
<td></td>
</tr>
<tr>
<td>Volume(ml)</td>
<td>502.39</td>
<td>440.84</td>
<td>-12%</td>
<td>500</td>
</tr>
<tr>
<td>Mass(g)</td>
<td>477.59</td>
<td>449.69</td>
<td>-5.8%</td>
<td>510</td>
</tr>
<tr>
<td>Density(g/cc³)</td>
<td>0.95</td>
<td>1.02</td>
<td>+2%</td>
<td>1.00</td>
</tr>
<tr>
<td>4003 Robbing Alcohol Bottle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of voxels</td>
<td>916,592</td>
<td>826,379</td>
<td>-9.8%</td>
<td>N/A</td>
</tr>
<tr>
<td>Volume(ml)</td>
<td>1135.58</td>
<td>1023.81</td>
<td>-9.8%</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass(g)</td>
<td>953.90</td>
<td>919.51</td>
<td>-3.6%</td>
<td>N/A</td>
</tr>
<tr>
<td>Density(g/cc³)</td>
<td>0.84</td>
<td>0.89</td>
<td>+5.6%</td>
<td>N/A</td>
</tr>
</tbody>
</table>
### Comparison of Physical Features

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Calculated from Label</th>
<th>Segmented Results</th>
<th>Differences</th>
<th>Ground Truth</th>
</tr>
</thead>
<tbody>
<tr>
<td>3001</td>
<td>Snow White Doll</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of voxels</td>
<td>210,063</td>
<td>175,675</td>
<td>-16.1%</td>
<td>N/A</td>
</tr>
<tr>
<td>Volume(ml)</td>
<td>260.25</td>
<td>270.51</td>
<td>+3.0%</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass(g)</td>
<td>166.71</td>
<td>216.77</td>
<td>+23.0%</td>
<td>N/A</td>
</tr>
<tr>
<td>Density(g/cc³)</td>
<td>0.64</td>
<td>1.25</td>
<td>+48.8%</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Toothpaste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of voxels</td>
<td>158,260</td>
<td>114,974</td>
<td>-27.3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Volume(ml)</td>
<td>196.07</td>
<td>142.44</td>
<td>-27.3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Mass(g)</td>
<td>279.75</td>
<td>208.02</td>
<td>-25.6%</td>
<td>N/A</td>
</tr>
<tr>
<td>Density(g/cc³)</td>
<td>1.43</td>
<td>1.46</td>
<td>+2.1%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Comparisons of “ground truth”

<table>
<thead>
<tr>
<th>Object 70: OFF repellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment image</td>
</tr>
<tr>
<td>Label image</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

| Volume (ml) | 158.63 | 346.49 |
| Mass(g)     | 136.47 | 307.98 |
| Density(g/cc³) | 0.86 | 0.88 |
Risks and Mitigation

- Risk: tuning of two parameters ($\lambda$ and $\sigma$) affects splitting/merging results
  - Always a pair of “contradictive actions”
  - Cutoff parameter $\lambda$ of the gradient histogram is critical in selecting homogeneous areas thus affects splitting
  - Adaptive threshold $\sigma$ needs to be fine tuned, affecting merging.

- Mitigation:
  - Split more aggressively with lower $\lambda$ in the gradient histogram
  - Grow more generously with higher threshold $\sigma$

Parameter Tuning: $\lambda$ (gradient cut-off threshold)

$\lambda = 0.70$  

$\lambda = 0.65$
Examples Our Algorithm Did Not Work Well

Bad example from V12

Object 12

Marquette University Department of Electrical and Computer Engineering

Examples Our Algorithm Did Not Work Well

Bad example from V12

Object 1

Marquette University Department of Electrical and Computer Engineering
**Presentation Outline**

1. The Research Team
2. Executive Summary
3. Problem Statements/Challenges
4. The Algorithm
5. Image Examples
6. Splitting/Merging
7. Summary of Strengths and Weaknesses

**8. Future Work**

---

**Future Work (1): Evaluation and Detection**

- Establish the evaluation criteria
- Establish the evaluation method
- Intelligent Detection
**Future Work (2): Metal Streak Identification**

1. Segment metal in image volume based on HU number

2. Forward project metal image to create metal sinogram

3. Simulate beam hardening by taking square root of metal sinogram

4. Create streak image by thresholding image reconstructed from square root sinogram
References


- Final Report, 2nd Algorithm Development for Security Applications Workshop (ADSA02), ALERT Center of Excellence, Northeastern University, October 2009.


THANK YOU!

xin.feng@mu.edu
**Examples of Results**

**Segmented image**  **Label image**  **Object 3: toothpaste**

<table>
<thead>
<tr>
<th></th>
<th>196.07</th>
<th>142.44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>279.75</td>
<td>208.02</td>
</tr>
<tr>
<td>Density</td>
<td>1.43</td>
<td>1.46</td>
</tr>
</tbody>
</table>

**Examples of Results**

**Segmented image**  **Label image**  **Object 59: duct tape**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Examples of Results

Segmented image  Label image  Object 60: Crayons

Segmented image  Label image  Object 3005: battery pack

Marquette University Department of Electrical and Computer Engineering
Examples of Results

Segmented image  Label image  Object 8028: Neoprene (thick)

Comparison with Label Object 4003

The New Algorithm  Label Results
Comparison with Label Object 8018

The New Algorithm

Label Result

Comparison with Label Object 9995

Proposed Algorithm

Label Result
9.1.8 “Security Screening Segmentation Challenge,” Leo Grady, Timo Kohlberger, Vivek Singh, Claus Bahlmann and Dorin Comaniciu, Siemens Corporate Research
Security Screening Segmentation Challenge

Leo Grady, Timo Kohlberger, Vivek Singh, Claus Bahlmann, Dorin Comaniciu

Image Analytics and Informatics
Siemens Corporate Research, Princeton NJ

Executive Summary

<table>
<thead>
<tr>
<th>System</th>
<th>Siemens Technology</th>
<th>Successes</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Metal artifact reduction</td>
<td>1) Fast Markov Random Field optimization</td>
<td>1) Artifact reduction able to mitigate effects of metal</td>
<td>1) Not capturing object parts below 500MHUs</td>
</tr>
<tr>
<td>2) Bag isolation</td>
<td>2) Recursive Isoperimetric Algorithm</td>
<td>2) Able to separate touching objects</td>
<td>2) Not separating objects with a relatively large area surface contact</td>
</tr>
<tr>
<td>3) Segmentation</td>
<td>3) Statistical learning of segmentation confidence measure</td>
<td>3) Able to group large numbers of small above-threshold objects</td>
<td>3) More data/testing needed</td>
</tr>
<tr>
<td>4) Automated confidence measure</td>
<td></td>
<td>4) Provide an accurate confidence level of segmentation quality</td>
<td>4) Not taking advantage of semantic content to guide segmentation</td>
</tr>
</tbody>
</table>
Siemens Corporate Research

- Experts in medical imaging software and algorithms
- ~100 PhD-level people working on medical imaging
- Basic research ↔ clinical products

Internationally recognized team

Winner of segmentation challenge in 2009 and 2011

Researchers

Dr. Leo Grady
- Principal Research Scientist
- PhD from Boston University in 2003
- Expertise: Image segmentation, graph theory, optimization
- ~50 papers, ~1,200 total citations, h-index: 16
- 26 granted patents, ~40 additional patents pending
- Software for 15 Siemens products and 4 products for Siemens partners
- New book: Discrete Calculus, 2010 Springer

Dr. Timo Kohlberger
- Research Scientist
- PhD from University of Mannheim, 2005
- Expertise: Model-based segmentation, parallel computing
- Best paper award by the Pattern Recognition Society in 2003

Dr. Vivek Singh
- Research Scientist
- PhD from University of Southern California in 2011
- Expertise: Computer vision, machine learning
- Best paper at SMiCV

Dr. Claus Bahlmann
- Project manager
- PhD from University of Freiburg in 2004
- Focus on projects in safety, security, mobility, energy, and healthcare
- Expertise: Pattern recognition, computer vision, machine learning
- Best paper award in 2002 IWFHR
- PhD thesis won Wolfgang-Gentner-Nachwuchsforbien award

Dr. Dorin Comaniciu
- Global Technology Leader for Image Analytics and Informatics
- PhD from Rutgers University in 1999
- Expertise: Machine learning, informatics
- 200 papers, 12,000 citations, h-index: 35
- 82 patents
- Won best paper award at CVPR and MICCAI. Won Top Inventor award at Siemens. Won Longuet-Higgins award for fundamental contributions to computer vision
Problem statement:

Enable threat detection with image segmentation

Physical composition
- Artifact reduction for accuracy
- Association of quantities that comprise a critical mass

Object recognition
- Appearance/density characteristics
- Shape characteristics
- Important not to under/over segment

Overview of algorithm

1. Used to evaluate segmentation hypotheses of isoperimetric segmentation algorithm and end recursion
2. Used to evaluate end segmentation for segments of poor confidence for a second round of segmentation
Example Segmentation – Train 03

Performance for Different Object Characteristics

Homogeneous

Less challenging
Algorithm can reliably separate objects of this type

Challenging
Algorithm can separate objects of this type when the interface between the objects is relatively small

Heterogeneous

Challenging
Algorithm can separate objects of this type when the inhomogeneity is also incoherent

Most challenging
Algorithm can sometimes separate objects of this type
Risk of oversegmentation
Objects less than 50mL at any stage were discarded.

**Segmentation – Merging & Splitting**

- **Merging:** Markov Random Field
- **Splitting:** Recursive isoperimetric algorithm

**Automated confidence measure**

- **Why a confidence measure?**
  - Our segmentation method suggests principled splits and merges, but the value of these splits/merges need to be evaluated to determine which split/merge hypotheses should be accepted.
  - After segmentation system is finished, the confidence measure can be used to determine if there are any segments of low confidence. For these segments, we can apply a “Plan B” segmentation with different parameters to mitigate risk.

- **Features based on the surface and volumetric properties of a segment**
  - 42 features - average density, gradient, curvature, etc.

- **Density approximation using Mixture of Gaussians**
  - Trained on ground truth segmentations
  - Compute feature vectors for Ground Truth segments
  - Reduce dimensionality using PCA
  - Fit a Mixture of Gaussians \( f(x) \) over the feature vectors projected on PCA subspace
  - Determine optimal mixture size using a validation dataset
**Limitations**

**Types**
- Sheet-like objects with a substantial connection to a nearby object
- Objects with multiple distinct parts

**Densities**
- Massive metal artifacts
- Densities near threshold

**Sizes**
- Large objects connected by a small connection may be oversegmented

**Masses**
- Object contains areas of above-threshold density connected by areas of below-threshold density

---

**Artifact reduction for reducing streaks**

1. Identify metal (threshold HUs)
2. Metal image → Radon transform
3. Non-metal image → Radon transform
4. Interpolate → Inverse Radon transform
Feature Extraction

**Merging:**
Markov Random Field

Mumford-Shah: Central model for image segmentation and denoising

\[
E(f, g, R) = \alpha \left( \int_R (f - p)^2 + \int_{\partial R} (g - p)^2 \right) + \mu \left( \int_R \| \nabla f \|^2 + \int_{\partial R} \| \nabla g \|^2 \right) + \beta(R)
\]

Data term Smoothness term Boundary term

**Splitting:**
Recursive isoperimetric algorithm

Physical property estimation

Volume = (#Segmented Voxels) \times (Voxel size)
Mean density = (Mean Hounsfield Unit of Segmented Voxels)/1000

**Quantitative – Physical estimation**

- Comparison of intensity statistics between ground truth and correctly separated cans & bottles after streak-artifact reduction:

![Graph showing MHUs of ground truth segments and MHUs of computed segments.](graph.png)

- Estimating the density of bar soap from 8 separate soap segments:
  
  measure mean: 0.982 g/ml = 982 MHU  
  min: 975 MHU / max: 985 MHU  
  real-world soap: 0.932 g/ml = 932 MHU
Segmentation Initiative Final Report, Page 165

Quantitative - Overlap

- Segmentation labels are matched to ground truth labels in order to maximize the relative overlap between segments.
- Over-segmented labels are assigned to one ground truth label, intersections with other ground truth labels don't count.
- In case of over-splits, only one sub-segment is assigned to a ground truth segment, all others don't count.

Quantitative - Automated confidence measure

- Automated confidence measure values for different objects in the image.

Page 165
**Strengths**

Artifact reduction
- Reasonable correction of challenging artifacts
- Operates as postprocessing instead of reconstruction

Merging
- Hierarchical and MRF based method is able to group together a collection of small objects

Splitting
- Accurately splits touching objects
- Oversegmentation rare
- Performed well on some challenging objects that are inhomogeneous or sheetlike

Confidence measure
- Accurate confidence measure using a statistical estimation
- Used to evaluate hypothesis splits
- Used as postprocessing to determine if “Plan B” segmentation is needed
- Gives overall confidence in the segmentation quality

**Weaknesses**

Artifact reduction
- Very strong artifacts may still impact performance

Merging
- Above-threshold regions of an object will not be merged with above-threshold objects far away if connected by below-threshold region

Splitting
- Sheetlike objects with large surface contact may be unsplit
- Inhomogeneous sheetlike objects can be inappropriately split
- Objects containing many distinct parts may be split – Ambiguous

Confidence measure
- Sometimes does not distinguish between an object and its parts

---

**Risks**

Metal artifacts

Merging – Missed merging

Splitting – Missed splitting, oversplitting

Confidence measure - Inaccuracy

**Mitigation**

1) Two stages of correction – Explicit correction and MRF
2) Future will be based on reconstruction

1) Two stages of correction – Multiscale and MRF
2) Add below-threshold joining

1) Two stages of correction – Multiscale and isoperimetric
2) Confidence measure judges appropriate splits
3) Confidence measure permits “Plan B” postprocessing
4) Train explicit classes for common objects, especially sheetlike objects

1) More training data
Images
- Dataset was great
- Not clear about similarities between these images and real security screening CT

Reference labels
- Any undefined segmentation problem will have some ambiguity about segments
- TIFF was unexpected
- Problems with shifts that took some time to identify and remedy
- Would have been helpful to get the quantitative evaluation software at an early stage

Communications
- Communication was great
- Having a mentor PoC was very helpful
- Appreciated the reminders

Acceptance criteria
- Appropriate for the task
- Fundamentally ambiguous to define – Needed to make some decisions
- Some aspects of threat detection were not communicated for security purposes

Comments

Future Projects
- Reconstruction
  - Much better way of handling metal artifacts
  - Can also be used to improve image quality of non-metal objects
  - Iterative reconstruction techniques are becoming feasible and give better results than filtered backprojection
- Target recognition
  - Use training set of common objects to extract
  - Keep a miscellaneous category
- Visualization/navigation
  - Efficient workflows for visualizing 3D data and performing visual inspection
  - Analytics to prioritize visual inspection
- Threat detection
  - Use the results of all these challenges to perform real automated threat detection
  - Use recognition, segmentation, physical composition to make determination
  - User study with and without visualization/navigation workflow
Thank you for your attention!
Baggage screening – Bag isolation

Objects less than 50mL at any stage were discarded

Coarse

Middle

Fine

Merging: Markov Random Field

Splitting: Recursive isoperimetric algorithm

Splitting: Recursive isoperimetric algorithm

Splitting: Recursive isoperimetric algorithm
Baggage screening – Segmentation

Merging: Markov Random Field

Mumford-Shah: Central model for image segmentation and filtering

\[ F(f, g, R) = \alpha \left( \int_R (f - p)^2 + \int_{\partial R} (g - p)^2 \right) + \mu \left( \int_R \|\nabla f\| + \int_{\partial R} \|\nabla g\| \right) + x(R) \]

Many variants proposed in literature:
1) Different data terms (total variation, histogram based)
2) Different smoothness terms (piecewise constant, L_1 gradient norm)
3) Different boundary terms (inclusion as anisotropic diffusion constants in gradient term)

Optimization dominated by level set methods. However, these methods are
1) Slow
2) Sensitive to initialization and parameters
3) Likely to get stuck in local minima
4) Cumbersome to implement, with many tricks and parameters

Graph formulation and combinatorial optimization of Mumford-Shah

1) Strongly outperforms traditional level set implementations in speed, robustness to initial contour, robustness to parameters and produces lower energy solutions
2) Allows nonlocal movement and application to problems defined on arbitrary graphs
3) No implementation parameters

- Patent pending: L. Grady and C. Alvino, "Piecewise Smooth Mumford-Shah on an Arbitrary Graph", #20090190833
Merging: Markov Random Field

Baggage screening – Segmentation

Technology used in multiple projects/products

Modified for baggage screening by initializing solution at 500MHU and limiting the deviation of the “corrected” data term
Motivated from the classical isoperimetric problem: For a given volume, what is the shape with minimum perimeter?

Enclosing a volume with a boundary may be considered as a separation of the space.

Baggage screening – Segmentation

The isoperimetric constant quantifies the separability of the space.

How to define the problem for a discrete geometry (graph)?

Instead of points, $S$ is a set of nodes.

$$S = \{4, 5\}$$

$$\overline{S} = \{1, 2, 3\}$$

$$\partial S = \{d, e\}$$
Baggage screening – Segmentation

Problem NP-Hard, so indicator vector relaxed and made into a free variation

Specification of boundary condition still required – equivalent to *grounding* circuit

Baggage screening – Segmentation

Electrical potentials thresholded at value that minimizes isoperimetric ratio
Problems with watersheds:

1. Small perturbations cause many basins:

2. Two objects may lead to same basin: Not handled by watershed algorithm

Robust to: Seed placement Perturbations Same basin
Baggage screening – Segmentation

Splitting: Recursive isoperimetric algorithm
**Baggage screening – Segmentation**

**Splitting:** Recursive isoperimetric algorithm

- Isoperimetric splitting
- Evaluate isoperimetric ratio
- Isoperimetric splitting
- Evaluate isoperimetric ratio

**Merging:** Markov Random Field

**Coarse**

**Middle**

**Fine**

**Splitting:** Recursive isoperimetric algorithm

**Splitting:** Recursive isoperimetric algorithm

**Splitting:** Recursive isoperimetric algorithm
**Confidence Measure**

**Baggage screening – Confidence Measure Evaluation**

- **Input:** Candidate segment
- **Input:** Image data within and surrounding candidate segment
- **Calculate 42 geometric and appearance characteristics**
- **Project descriptors into PCA space**
- **Evaluate the probability that PCA coefficients belong to Gaussian Mixture Model**
- **Output probability as confidence measure**

---

**Case analysis of Confidence Measure vs. IsoRatio:**

**Test 12**

- **Under-segmentation**
  - Confidence Measure helps split the bottles from the base
- **Over-segmentation**
  - Confidence Measure avoids splitting of "good" segments

Confidence Measure + IsoRatio

<table>
<thead>
<tr>
<th>IsoRatio</th>
<th>1.5</th>
<th>8.0</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>IsoRatio</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Case analysis of Confidence Measure vs. IsoRatio:
Train17

- **Under-segmentation**
  - Confidence Measure helps split the bottle from the base

- **Over-segmentation**
  - Confidence Measure avoids splitting of "good" segments

Baggage screening – Advanced 3D rendering
Baggage screening – Virtual unpacking
9.2 Other Appendix Material

9.2.1 Appendix: “Data acquisition and segmentation for final report,” Alyssa White and Rick Moore.

9.2.1.1 Dataset design
About 75 million international and 650 million domestic enplanements occur annually (FAA website, March, 2010), many with checked baggage. Selecting a representative set of luggage across the parameters of size, material, age, frame, aspect-ratio, etc. to scan for (task order1) is required. The range of legally packable items is similarly broad over parameters of material, size, geometry, density, phase, aspect-ratio, among others. The ALERT center procured the following luggage for this project:

Bag 7001 – Red Hard Shell Case

Bag 7002 - Backpack

Bag 7003 – Medium Black Roller

Bag 7004 - Blue Duffle
Bag 7005 – Water-Proof Backpack

Bag 7006 – Large Black Roller

Bag 7007 – Laptop case

Bag 7008 - Cardboard Box
To pack the luggage ALERT procured the following items

<table>
<thead>
<tr>
<th>Code</th>
<th>Desc</th>
<th>Code</th>
<th>Desc</th>
<th>Code</th>
<th>Desc</th>
<th>Code</th>
<th>Desc</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>clothes Iron</td>
<td>64</td>
<td>candle - glass</td>
<td>2081</td>
<td>small electronic</td>
<td>4057</td>
<td>laptop</td>
</tr>
<tr>
<td>3</td>
<td>toothpaste tube</td>
<td>65</td>
<td>Candle with lid</td>
<td>2082</td>
<td>Camera Tripod</td>
<td>5001</td>
<td>StainlessSteel containing water</td>
</tr>
<tr>
<td>4</td>
<td>Wooden frame</td>
<td>66</td>
<td>Shampoo</td>
<td>2083</td>
<td>Ruppenware - 3 pk</td>
<td>5002</td>
<td>Nalgene with Rice</td>
</tr>
<tr>
<td>5</td>
<td>Metal frame</td>
<td>67</td>
<td>conditioner</td>
<td>2084</td>
<td>Leather Jacket</td>
<td>5003</td>
<td>StainlessSteel containing Castor oil</td>
</tr>
<tr>
<td>6</td>
<td>Chocolate Bar 1</td>
<td>68</td>
<td>Rubber Sealant</td>
<td>2085</td>
<td>Clay block 1</td>
<td>5004</td>
<td>StainlessSteel containing Water</td>
</tr>
<tr>
<td>7</td>
<td>Chocolate Bar 2</td>
<td>69</td>
<td>Aerosol - Off!</td>
<td>2086</td>
<td>Clay block 2</td>
<td>5005</td>
<td>Nalgene containing water</td>
</tr>
<tr>
<td>8</td>
<td>RedHeelShoeL</td>
<td>70</td>
<td>Jewelry-earrings</td>
<td>2087</td>
<td>Butyl rubber sheet</td>
<td>5006</td>
<td>Rectangular Glass containing castor oil</td>
</tr>
<tr>
<td>9</td>
<td>RedHeelShoeR</td>
<td>71</td>
<td>butyl rubber sheet 2</td>
<td>2088</td>
<td>StainlessSteel Vacuum bottle with Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Mens shoe-R</td>
<td>72</td>
<td>Jeans-4-fold</td>
<td>2089</td>
<td>Ceramic containing water</td>
<td>5007</td>
<td>Large Nylon Disc 1</td>
</tr>
<tr>
<td>11</td>
<td>Mens shoe- L</td>
<td>1001</td>
<td>Palm680inLeatherCase</td>
<td>2090</td>
<td>Pocket Knife</td>
<td>5008</td>
<td>Large Nylon Disc 2</td>
</tr>
<tr>
<td>12</td>
<td>Mens Sneaker - R</td>
<td>1002</td>
<td>LCD-Clock-Cord</td>
<td>2091</td>
<td>Remote control car</td>
<td>5009</td>
<td>Pocket Knife</td>
</tr>
<tr>
<td>13</td>
<td>Mens Sneaker - L</td>
<td>1003</td>
<td>Large Flashlight</td>
<td>2092</td>
<td>Digital Camera</td>
<td>5010</td>
<td>Pocket Knife</td>
</tr>
<tr>
<td>14</td>
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<td>1004</td>
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<td>jewelry earnings</td>
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<td>2080</td>
<td>Radio with cord</td>
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<td>4pk scotch tape</td>
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</tbody>
</table>

*Figure 1: List of objects contained within the CT datasets.*

**9.2.1.2 Creation of datasets**

ALERT characterized all of the objects that went into the datasets. Each bag and each object in each bag were identified (labeled with a vector and serial number), measured (length, width, height), and density-characterized. Each object was also scanned in isolation following the acquisition of the datasets. The bag was introduced into the CT scanner in multiple orientations (upright, sidewise, skew, invert). It was also disrupted and rescanned in multiple orientations. Known reference phantoms composed of reference materials were scanned with each dataset, to serve as a calibration and to monitor image quality throughout the scanning process. At the Vendor, unpacking of the bags was videotaped after
imaging. The Dataset Groups contained images of luggage that present a range of difficult segmentation issues (varying kinds and number of objects, proximity (relative position), and purposeful obfuscation).

We acquired datasets over a 7 month span beginning in September of 2010 and extending to March of 2011. These datasets were put together using a combination of 8 bags and approximately 145 items to create a variety of luggage combinations which represent a range of difficulties. The datasets were all acquired at the same vendor using a medical CT scanner at a resolution of 1mm.

Any suitcase contains 8-25 of these objects, plus filler objects such as clothing (e.g. sweaters). Some bags are packed randomly, while others were packed to create certain situations. All objects have been measured (x, y, z) weighed, physically labeled with a code number, and photographed. An example of the labeling is demonstrated in the image below:

![Example of labeling](image)

**Figure 2: Photo of large flashlight, object #1003 with yellow physical label.**

The process to collect the datasets at the vendor is as follows:

1. Researcher packs objects into bags at ALERT.
2. Researcher documents which objects are packed into which bags as they are being packed.
3. Researcher loads bags and travels to the vendor location.
4. At the vendor, researcher images first bag in orientation #1-n, taking photo of orientation before each scan.
5. After all images of bag 1 are acquired, researcher removes bag from scanner and takes video of the unpacking of the bag, careful to capture position of objects within the bag.
6. If session involves repacking of the bag with same objects in more challenging positions, researcher repacks bag and repeats steps 4-5.
7. Repeat steps 4-5 (6 If necessary) for all bags brought to the Vendor.
8. Researcher brings bags back to ALERT, unpacks and returns objects to storage location.

**9.2.1.3 Details of data acquisition**

On October 14, 2010, Rick Moore (affiliated with MGH, subcontractor responsible for data collection) collected a number of test datasets at the vendor. He used 2 different bags to collect these sets – the
Red Hard Shell bag 7001 and the Backpack 7002. There were 15 items in each bag; none of these were the geometric objects. Of these test datasets, 9 were segmented and prepared for use in the Qualification Dataset to be sent out to all researchers who would sign our NDA. Only 2 of these 9 resulted in the Qualification dataset.

- CT_15.28.8 – RedHardShell, Packed, (0,0) orientation.
- CT_17.37.5 – Backpack, Packed, (0,0) orientation.

On January 6, 2011, Alyssa White (affiliated with MGH, subcontractor responsible for data collection) collected 28 datasets at the vendor. She used 7 different bags (bag numbers 7001-7007) and collected four datasets on each bag. There were 10-21 items in each bag; 2 geometric objects were incorporated into these sets. Bag 7003 and bag 7006 each contained one geometric object, therefore 8 of the 28 datasets contains a geometric object. Of these 28, 24 have been segmented and sent to the chosen participants. Twelve were included in the Training Set, another 6 in the Validation set, and 6 others in the Evaluation set. Four of the Datasets acquired are not being used at this time. Table n shows the details of the 28 datasets collected, while table n+1 shows how the 24 datasets used were separated between the Training, Validation and Evaluation sets. Notice that we chose to incorporate similar bags in each of the 3 sets. I.e. The 4 RedHardShell scans, packed and repacked with the same objects, were separated 2:1:1 between the Training, validation and evaluations sets. This allows researchers to train on datasets similar to those they may be evaluated with later on in the program.

**Images Acquired on 1/6/2011**

<table>
<thead>
<tr>
<th>Bags</th>
<th>Desc</th>
<th>Condition</th>
<th>Orientation</th>
<th>CT file</th>
</tr>
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Distribution of Images from 1/6/2011

Training Datasets

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<th>CT file</th>
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Evaluation Datasets

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On February 3, 2011, Alyssa collected 18 Datasets at the vendor. She used 6 bags to obtain these sets, bag numbers 7001-7006. There were 10-29 objects in each bag. All 24 geometric objects were spread out among these bags. Seventeen of the 17 sets have been segmented and sent to our participants. Eight were included in the Training set, 5 in the Validation set, and 4 in the evaluation set. One dataset was missing slices, and therefore not used.

Images Acquired on 2/3/2011

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On March 15, 2011, Alyssa collected 18 Datasets at the vendor. She used 7 bags to collect these sets, bag numbers 7001 - 7006, and 7008. There were 10-17 objects in each bag. All 24 geometric objects were initially spread out between the 7 bags. Two bags, 7001 and 7008, were then re-packed with only geometric objects and clothing and re-imaged. Ten of the 24 geometric objects were contained in the re-packs of these bags. All 18 datasets were segmented and distributed to our participants. 10 were included in the Training set, 4 in the Validation set, and 4 in the Evaluation set.
### Images Acquired on 3/15/2011

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<td>(0,0)</td>
<td>9.31.4</td>
</tr>
<tr>
<td>7008</td>
<td>Cardboard Box</td>
<td>re-packed</td>
<td>(0,0)</td>
<td>12.53.8</td>
</tr>
</tbody>
</table>

### Distribution of Images from 3/15/2011

#### Training Set

<table>
<thead>
<tr>
<th>Image Code</th>
<th>Object Type</th>
<th>Condition</th>
<th>Width</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>7001</td>
<td>RedHardShell</td>
<td>Packed</td>
<td>(0,0)</td>
<td>8.47.45</td>
</tr>
<tr>
<td>7001</td>
<td>RedHardShell</td>
<td>re-Packed</td>
<td>(0,0)</td>
<td>12.44.16</td>
</tr>
<tr>
<td>7002</td>
<td>Backpack</td>
<td>Packed</td>
<td>(0,0)</td>
<td>9.1.36</td>
</tr>
<tr>
<td>7003</td>
<td>MedBlkRoller</td>
<td>Packed</td>
<td>(0,0)</td>
<td>10.27.4</td>
</tr>
<tr>
<td>7004</td>
<td>Blue Duffle</td>
<td>Packed</td>
<td>(0,0)</td>
<td>9.49.23</td>
</tr>
<tr>
<td>7005</td>
<td>WtrPrfBackpack</td>
<td>Packed</td>
<td>(0,0)</td>
<td>9.19.38</td>
</tr>
<tr>
<td>7006</td>
<td>LrgBlkRoller</td>
<td>Packed</td>
<td>(0,0)</td>
<td>11.18.1</td>
</tr>
<tr>
<td>7008</td>
<td>Cardboard Box</td>
<td>Packed</td>
<td>(0,0)</td>
<td>11.27.55</td>
</tr>
<tr>
<td>7008</td>
<td>Cardboard Box</td>
<td>re-packed</td>
<td>(0,0)</td>
<td>12.53.8</td>
</tr>
</tbody>
</table>

#### Validation Set

<table>
<thead>
<tr>
<th>Image Code</th>
<th>Object Type</th>
<th>Condition</th>
<th>Width</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>7001</td>
<td>RedHardShell</td>
<td>Packed</td>
<td>(0,15)</td>
<td>8.53.11</td>
</tr>
<tr>
<td>7002</td>
<td>Backpack</td>
<td>Packed</td>
<td>(0,15)</td>
<td>9.9.13</td>
</tr>
<tr>
<td>7008</td>
<td>Cardboard Box</td>
<td>Packed</td>
<td>(0,0)</td>
<td>11.27.55</td>
</tr>
<tr>
<td>7006</td>
<td>LrgBlkRoller</td>
<td>Packed</td>
<td>(0,0)</td>
<td>11.11.10</td>
</tr>
</tbody>
</table>

#### Evaluation Set

<table>
<thead>
<tr>
<th>Image Code</th>
<th>Object Type</th>
<th>Condition</th>
<th>Width</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>7001</td>
<td>RedHardShell</td>
<td>re-Packed</td>
<td>(0,0)</td>
<td>12.34.27</td>
</tr>
<tr>
<td>7003</td>
<td>MedBlkRoller</td>
<td>Packed</td>
<td>(0,0)</td>
<td>10.18.7</td>
</tr>
<tr>
<td>7005</td>
<td>WtrPrfBackpack</td>
<td>Packed</td>
<td>(0,15)</td>
<td>9.31.4</td>
</tr>
<tr>
<td>7008</td>
<td>Cardboard Box</td>
<td>Packed</td>
<td>(0,10)</td>
<td>11.37.7</td>
</tr>
</tbody>
</table>
To provide an understanding of how the bags and objects are packed, a couple of packing lists (with associated CT images showing placement) are shown. Filler objects are denoted by "x"

<table>
<thead>
<tr>
<th>Example List 1</th>
<th>2 Clothes Iron</th>
<th>69 Rubber Sealant</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Metal Frame</td>
<td>2011 Jewelry - Bracelets</td>
<td></td>
</tr>
<tr>
<td>14 Toy - Robot</td>
<td>2080 Radio</td>
<td></td>
</tr>
<tr>
<td>21 Aerosol - Metallic Paint</td>
<td>2097 Electrical Tape</td>
<td></td>
</tr>
<tr>
<td>31 Socks</td>
<td>3002 Digital Camera</td>
<td></td>
</tr>
<tr>
<td>66 Shampoo</td>
<td>3006 Hard Drive</td>
<td></td>
</tr>
<tr>
<td>67 Conditioner</td>
<td>4003 Rubbing Alcohol</td>
<td></td>
</tr>
<tr>
<td>X Sweater</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Packing list and CT Images for corresponding dataset. Note: CT images shown were acquired using a Medical CT scanner, not a commercial luggage scanner.
Figure 2: Continued
Figure 2: Continued

<table>
<thead>
<tr>
<th>Example List 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>17 Pot With Lid</td>
<td>2083 Tupperware - 3 Pk</td>
<td></td>
</tr>
<tr>
<td>21 Aerosol -Metallic Paint</td>
<td>2090 Butyl Rubber</td>
<td></td>
</tr>
<tr>
<td>30 Socks</td>
<td>2093 Neoprene (Thick)</td>
<td></td>
</tr>
<tr>
<td>50 Yoga Mat</td>
<td>4004 Acetone</td>
<td></td>
</tr>
<tr>
<td>51 2Liter Soda</td>
<td>4006 Motor Oil -2</td>
<td></td>
</tr>
<tr>
<td>56 8pk Soda</td>
<td>4055 Ac Adapter - Grey</td>
<td></td>
</tr>
<tr>
<td>61 Petroleum Jelly</td>
<td>4056 4pk Scotch Tape</td>
<td></td>
</tr>
<tr>
<td>63 Tealite Candles</td>
<td>4057 Laptop</td>
<td></td>
</tr>
<tr>
<td>64 Candle-Glass</td>
<td>8015 Large Nylon</td>
<td></td>
</tr>
<tr>
<td>1003 Flashlight-Large</td>
<td>8020 Butyl Rubber (Mid)</td>
<td></td>
</tr>
<tr>
<td>2004 Water Bottle</td>
<td>X Sweatpants-Rolled</td>
<td></td>
</tr>
<tr>
<td>2008 Gel Pad</td>
<td>X Shirt</td>
<td></td>
</tr>
<tr>
<td>2011 Jewelry-Bracelets</td>
<td>X Sweater</td>
<td></td>
</tr>
<tr>
<td>2051 Honey</td>
<td>X Sweater</td>
<td></td>
</tr>
<tr>
<td>2081 Small Electronic</td>
<td>X Cami</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Packing list and CT image for corresponding dataset. Note: CT images shown were acquired using a Medical CT scanner, not a commercial luggage scanner.
Segmentation difficulty = 3
Figure 3: Continued
Reference segmentation maps were created for each dataset of packed luggage using the segmentation criteria of >500 Modified Hounsfield units (mHU) and ≥50mL. The segmentation maps were created using an ALERT manual or semi-automated segmentation algorithm running on MeVislab, a publicly available image processing software.

The Qualification and Training Dataset Groups were provided with information about the baggage, contents and reference segmentation map. The Validation Dataset Group will be provided to Researchers without the reference segmentation map. The Evaluation Dataset Group was reserved for use by the Domain Experts for evaluation purposes.

**CT Segmentation Project Luggage Segmentation Process**
Throughout the process of segmentation of luggage, we have observed a few main factors that greatly contribute to the difficulty of the task. These main factors include *artifacts* from metal objects, *thinness*...
of objects, and a number of issues that are caused by the shape of the object. Also the issue of adjacent objects is a main factor.

We used about 140 objects to pack the suitcases used for these datasets. They include clothing, jewelry, electronics, food, liquids, lotions and soaps, games, toys, books, and objects of interest that we strategically placed throughout the bags. The Objects of Interest, or OIs, include sheets of various thicknesses of Neoprene and Butyl rubber, as well as cylinders of Nylon, PVC, urethane foam, clay and aluminum. We tried different ways to mask or hide the sheet rubber OIs.

The method we used to segment objects involved two steps; manually placing an envelope around the OI, and thresholding the OI apart from anything else that may be contained within that envelope. The task of drawing this envelope has proven to be as difficult as expected. The main factors that cause difficulty in this area are: thinness of the object, shape and changing of shape between slices, and the human factor involved. It took the segmentor anywhere from 1-4 hours to segment a dataset, depending on the complexity, using this semi-automatic method.

The image is opened in a viewer that allows for semi-automatic or manual contouring of an object. The user may either allow the contour to attach itself automatically to changes in intensity gradients, or draw the contour freehanded. The number of slices needed to do this depends on how many slices the object is present in, and how much the shape of the object changes between slices. If the shape of the object, and thus the shape of the contour, changes greatly from slice to slice, the individual performing contouring will need to produce a lot more slices that have the object enveloped. There is an interpolation step which joins together all of the contours in order to envelope the entire object of interest in every slice it is present in. In order for this step to produce an accurate result, there must be good guidelines to follow.

The figure below is a screenshot of the network used for segmentation of objects. The orange colored modules are viewers used to show your image produced at each stage in the process. The green modules are not usually used directly by the person performing the segmentation, they are on the sidelines, processing data that is fed through. The blue modules, generally, are the interactive modules used by the segmentor to perform actions.
Figure 11: Screen shot of the network used to segment objects from a CT dataset.

1.) Start by Loading the CT image into the program.
2.) Draw contours around the object of interest in multiple slices.
3.) Save contours in case the interpolation step is not successful and the program crashes. Once saved, contours can be loaded back in via CSIOload module.
4.) Interpolation step combines these contours to produce an area of interest in every slice between the first and last slice selected.
5.) Converts all voxels within interpolated envelope to one label number, all voxels outside envelope are zero.
6.) Viewer shows original CT image. Segmentor plants seeds within the object to be segmented.
7.) Region growing allows application of thresholds. Beginning at voxels where seeds were planted, all voxels in contact that have a mHU value within specified thresholds will be considered ‘object’.
8.) Arithmetic joins result of step 5 with result of step 7 together to produce one labeled object.
9.) Save the label image and move onto the next object in the dataset.

If the dataset being segmented contained 12 objects in the bag, this segmentation process would need to be repeated 12 times, once for each object. The product is 12 TIFF image files. We had to create a network for Mevislab that would join these 12 images together to produce the reference segmentation map. We call the reference segmentation map file the ‘Aggregate Object file’ or A.O. file. The network used to make these A.O. files is the Aggregator network.
There were several problems we faced through the duration of this program that had to do with segmentation and the resulting A.O. files. These errors were found predominantly by the researchers within the Training and Validation data that was sent out by ALERT, as it was during these stages that the researchers were using the Aggregate Objet Reference Map images. ALERT created and dispersed multiple versions of the A.O. files as errors were found and corrected. It was discovered over the duration of the program that the main source of error was the inclusion of DICOM image headers into the Tiff image files that were created from the original DICOM CT data from the vendor. ALERT was unaware that these 8 byte headers were written into the CT TIFF image files. Another factor that contributed to the errors seen in the A.O. files was the nature of the software used to perform segmentation. MeVisLab proved to have an unordinary method of handling TIFF image files, which resulted in shifting of the segmentation images during the loading and saving process of the MeVisLab network.

The following is an excerpt from the document ‘info for researchers’ sent on September 6, 2011

“It was also brought to our attention by one of the researchers that the Aggregate Object files we provided were shifted in comparison to the CT data images. After initial inspection of this shift it was clear that the shift was not universal for the whole file, and could not be fixed by simply applying an offset to the data. It appeared that each individual object in the image was shifted by a different amount relative to the CT data. Upon further inspection it became clear that the MeVisLab image save module used by our segmentation and aggregation program was flawed. Our semi-automatic segmentation method involves a network on the program MeVislab, which allows us to segment and label one object at a time from the original CT data and save each object as its own individual file. We then take each individual file and add them into an aggregation network with the same program, using the same MeVisLab image save module. We save the developing A.O. file each time a new object is added in, until all objects have been added and there is a final save. By experimentation, we found that the MeVisLab
image save module shifts the data by 8 bytes every time it is used. Since each A.O file was saved a different number of times, depending on which order objects were added into the A.O. file, each object is shifted a different amount relative to its position on the original CT data image and the other objects in the A.O. file.

To compensate this error we remade all of the A.O. files for all 30 training data sets, by applying an 8 byte shift in the opposite direction each time we added in another object in order to compensate for the shift that happened the previous time it was saved. There is however one final save that must be done, so the whole A.O. image will be shifted 8 bytes to the right compared to the original CT data image.”

We now know the reason for this 8 byte shift applied to each dataset each time the MeVisLab ImageSave module was used. At the time, when we corrected this shift and sent the new files, we were still not aware that the DICOM header had gotten carried over to the TIFF image files. We knew a shift was resulting but we were unclear about the source. We were simply trying to supply the researchers with more accurate A.O. reference map images. At the present time, the files have been fixed properly and there is no shifting of the images.

The following is another excerpt from the same document:

“Another issue that has been brought to our attention is that the TIFF files resulting from MeVislab are not readable by Matlab; however they are readable using ImageJ, and of course, MeVislab. The explanation is as follows: Mevislab saved the TIFF files as a non-standard 3D file structure. In general, 3D images are saved as multi-page TIFFs, i.e. multiple 2D images indexed and contained in one file. Apparently, MeVisLab saved the 3D image exactly as a 3D image with depth stored with a non-standard process. We think that the third dimension might be encoded in channels. ImageJ was able to read the TIFF without any problem; it issued an error but it was still able to load the data. On the other hand, Matlab’s “imread” was not able to interpret MeVisLab’s non-standard TIFF format. Our solution to this problem is to load the A.O. TIFF files into ImageJ, and save them as a TIFF that can be read by Matlab. We will send these files to any researchers who request them.“

The Subsequently, the same researcher group who reported these issues, also found that even with the adjustments made to the A.O. files, there remained small differences of 1-3 pixels in both the x and y direction when overlaying the A.O. files to the CT data. We evaluated this claim and also reproduced those differences. The errors were a result of the way that the segmenters had to load the CT Tiff image files into MeVisLab. The Mevislab ImageLoad module we used in the segmentation network could not simply load in Tiff files and align them correctly within the field of view. An offset had to be manually entered into the network in order to correctly center the image set. This offset was configured by the segmentor using a method that was reliant on visualization of the edges of the dataset field-of-view (FOV). It is for this reason that many of the A.O. files which resulted from segmentation of these datasets were shifted by 1-3 pixels in relation to the original CT DICOM data. ALERT determined that these small errors were within the acceptable % error which is expected from semi-automatic segmentation, and no action was taken to disperse new A.O. images to all of the researchers. Responsive to this data shift problem, Domain Expert Carl Crawford, wrote a code to correct all shifting errors in the A.O. image files. The new images output from his program had no shifting in relation to the
CT data from the Vendor, and since these files were not produced with Mevislab, they were able to be read in with Matlab software.

The following table highlights the data issues throughout the segmentation program:

<table>
<thead>
<tr>
<th>Question or problem</th>
<th>Explanation</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of slices is different for DICOM and TIFF version of A.O. file for CT_15.28.8 in the Qualification set.</td>
<td>A.O. files (Aggregate Object files) are the ground truth files supplied to researchers from ALERT. The data comes to us from the Vendor in DICOM format. We must convert these DICOM files to Tif format ourselves. In Multiple datasets, we may have cut off slices at the end of the CT dataset in the Tiff files.</td>
<td>The slices at the end of the image that are cut off from the Tiff version do not contain any data, they are slices containing only air. Slice #1 of the DICOM does directly correspond to slice #1 of the Tiff file, so this can be ignored.</td>
</tr>
<tr>
<td>Researcher reported that He could not see some of the label images in the A.O. files</td>
<td>Our label numbers for objects vary from 2-9999, so the objects with low label numbers may not appear in the image with normal contrast and baseline settings.</td>
<td>Adjusting these settings will allow objects with lower label numbers to be viewed.</td>
</tr>
<tr>
<td>The DICOM version of the CT data for one of the Training datasets was missing from the drives sent out to the researchers.</td>
<td>Training.Dataset7.CT_14.30.20 was missing a DICOM file</td>
<td>Distribute missing file out to all researchers</td>
</tr>
<tr>
<td>Objects in A.O. files seem to be shifted by varying amounts compared to position on CT data from vendor.</td>
<td>The Aggregator network used to make the A.O. files involved loading each individual segmented object file into the network, one by one, to produce a file containing all objects in that Dataset. The ImageSave module of that network applied an 8 byte offset to the data with each object that was saved. This resulted in each individual segmented object file being shifted by different amounts in the A.O. file compared to its original position.</td>
<td>Re-make all A.O. files with the aggregator network, compensating ahead of time for the 8 byte shift. This will produce an A.O. file that is shifted as a whole by 8 bytes in relation to the CT data, (rather than each object being shifted around by a different number of bytes). Send these new A.O. files to researchers, with instruction to shift the image by 8 bytes.</td>
</tr>
<tr>
<td>A.O. tiff files cannot be read into matlab</td>
<td>The Tiff files that are saved and output from MeVisLab are not compatible with Matlab.</td>
<td>Load the A.O. Tiff file that was saved in Mevislab into ImageJ, save as Tiff. This file will be compatible with Matlab.</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-----------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>A.O. files, when overlaid onto original CT data, do not line up perfectly. There is some amount of shift in the X and/or Y direction.</td>
<td>When loading the CT data Tiff file into MevisLab, an offset needs to be applied in order to center the image in the field of view. This offset was determined manually (visually). Some (about half) of these visually determined offsets were off by anywhere from 1-5 pixels in the X and/or Y direction. This results in the A.O. files that are made from this image to be shifted the same way. When these files are compared to the CT data, there is some offset.</td>
<td>Offset errors were found to be on the same order of magnitude that could be expected from semi-automatic segmentation, therefore will not greatly affect the researchers work.</td>
</tr>
</tbody>
</table>

### 9.2.1.4 Distribution of Data

Between January and March of 2011, ALERT distributed the Qualification datasets to all researchers who submitted a proposal, and signed an NDA for the segmentation challenge. The data was sent to 12 researchers and the 3 Domain Experts.

In May, after the phase 2 proposals were reviewed, we sent Training and Validation data to the 5 participants chosen to go forward. We prepared 30 Training datasets, and 15 Validation datasets. The training datasets we provided were complete with the A.O. reference map files, while the validation sets did not include these files.

The following shows the file structure of the Training and Validation datasets as they were on the drive given to the researchers:
One of the researchers noticed that a DICOM file was missing from one of the training datasets, and we promptly sent the missing file out to all the researchers.

As previously discussed, there was an 8-byte shifting error in the A.O. files which was corrected and ALERT distributed new A.O. files for the Training data on July 19, 2011.

In September of 2011, wALERT distributed the 15 Validation A.O. files, along with the Evaluation data which did not include A.O. files on September 5, 2011.

The Evaluation A.O. files, and some individual object CT images for the OIs were sent to the Domain Experts only on September 16, 2011.

ALERT was made aware that there were still minor shifting errors of 1-3 voxels in 54% of the cases, between the A.O. images and the CT images. These shifts were in both the X and Y direction, and were corrected by an automatic program written by Carl Crawford. These new A.O. files that were run through his program do not have any shifting in relation to the CT data, and they are compatible with Matlab software. The files were distributed only to the research group that identified the error and requested the new files.

The table below details the distribution of ALERT segmentation data. All data distributed was encrypted using TrueCrypt at the media level.
<table>
<thead>
<tr>
<th>Date - 2011</th>
<th>Name of data</th>
<th>Media Type</th>
<th>Description</th>
<th>Sent to</th>
</tr>
</thead>
<tbody>
<tr>
<td>January - March</td>
<td>Qualification (Phase 1) Data</td>
<td>DVD</td>
<td>2 Datasets, complete with ground truth files</td>
<td>DEs and all researchers who submitted Proposal and signed NDA</td>
</tr>
<tr>
<td>May – June</td>
<td>Training and Validation datasets</td>
<td>1TB USB external hard drive</td>
<td>30 Training datasets, complete with A.O., and 15 Validation datasets, not including A.O. files</td>
<td>5 chosen researchers and DEs</td>
</tr>
<tr>
<td>(Varies between researchers)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 22</td>
<td>Training Dataset 7 -DICOM file</td>
<td>DVD</td>
<td>DICOM version of Training Dataset 7 was missing from Hard drives</td>
<td>5 chosen researchers and DEs</td>
</tr>
<tr>
<td>July 19</td>
<td>New A.O. files for Training Datasets.</td>
<td>16GB flash drive</td>
<td>Error in module creating A.O. files, all 30 A.O. files for Training Dataset corrected and redistributed.</td>
<td>5 chosen researchers and DEs</td>
</tr>
<tr>
<td>September 5</td>
<td>Validation A.O. files and Evaluation CT Datasets</td>
<td>160GB USB external hard drive</td>
<td>A.O. files for 15 Validation Datasets, as well as 14 Evaluation datasets, without A.O. files</td>
<td>5 chosen researchers and DEs</td>
</tr>
<tr>
<td>September 16</td>
<td>Evaluation A.O. files and individual object scans for OOIs</td>
<td>16GB flash drive</td>
<td>14 A.O. files for Evaluation dataset, as well as individual object CT datasets for OOIs</td>
<td>Domain Experts Only</td>
</tr>
<tr>
<td>November 16</td>
<td>Final, corrected A.O. files for Training and Validation datasets</td>
<td>16GB flash drive</td>
<td>30 A.O. files for Training Set, 15 A.O. files for Validation Set</td>
<td>UEA only</td>
</tr>
</tbody>
</table>

### 9.2.1.5 Creation of Datasets

- Packing of bags
- Scanning of bags
- Photos/videos
- All documentation (spreadsheets)
- Splitting 4 dates of acquisitions into T.V and E.

Segmentation
  - Process, software
Lessons learned and problems

Dispersal of data
- When sent and to whom
- Re-sending data
- Documentation of all data
- Media and encryption

Archive data – prepared to send to Harry

9.2.2 Appendix: CT Segmentation – Lessons Learned,” Alyssa White and Rick Moore
This document has been deemed SSI and as such will only be referenced here rather than included.