Integrating Ontologies with Three-Dimensional Models of Anatomy

Daniel L. Rubin
Yasser Bashir
David Grossman
Parvati Dev
Mark A. Musen

Stanford Medical Informatics
Stanford University
Projectile Injury

- Penetrating trauma responsible for many civilian deaths; major cause of battlefield fatalities
- Survivability after projectile injury depends on rapid acquisition & interpretation of knowledge
  - Need to know anatomic structures injured and extent of organ damage
  - Need to know physiological consequences
  - Need to make triage decision (immediate surgery, medi-vac, observe, etc.)
Objectives

● Build computable model of human anatomy
  ▪ Predict direct anatomic injuries
  ▪ Predict propagation of injuries
● Develop intelligent applications
  ▪ On-scene diagnosis
  ▪ Assist triage decisions
● Provide graphical display of anatomy, bullet trajectory, and tissue damage
3-D Geometric Models

- Many prior applications
  - Surgical simulation, planning
  - Medical visualization
  - Teaching
- Encode spatial geometric information
- Contain no knowledge about contents of these models
  - Identity of anatomic structures
  - Tissue properties
  - Physiological status of organs
Requirements

- Intelligent applications for injury:
  - 3-D geometric data
  - Knowledge pertinent to injuries
  - Reasoning services
    Use geometric data and knowledge to predict consequences of injuries
Need Variety of Knowledge

● Anatomic knowledge
  ▪ Where do organs lie in the body?
  ▪ What organs are fed by different arteries?
  ▪ What are the subparts of an organ?

● Biomechanical knowledge
  ▪ What are the tissue material properties of an organ?

● Tissue injury knowledge
  ▪ How do different organs respond to injury?
Need Variety of Reasoning Services

- Which organs were directly injured?
- What additional tissue damage will occur as the primary injury propagates?
- How will physiological parameters be altered by the injury?
- How should the subject be treated?
The Virtual Soldier Project

Data Collection in the Field

Vital Signs and Physiological Data

PTag containing CT image data

Data Interpretation and Triage

Triage Physician/Nurse

Data Interpretation and Triage

Holomer Capabilities at Remote Location

Visualization

User Queries

Create "Holomer" Instance

Tissue biomechanics/ Bullet path model

Integrate anatomic knowledge

Holomer with predicted wound track

FMA

Medic Functions and Capabilities

Data collection

Visualization

iPaq Handheld

Radio Link

Injured subject with estimated wound path
Approaches

- Make knowledge explicit and computable
  1. Use *ontologies* for knowledge representation
     - Useful in rich and complex domains
     - Can reuse existing knowledge sources

- Integrate patient data and canonical knowledge
  2. Create patient-specific models
  3. Develop reasoning services
1. Ontologies for knowledge representation
Knowledge Sources

● Geometric Knowledge
  ▪ Geometry ontology constructed to describe computer graphics principles
  ▪ Specifies data structures used to represent geometric models

● Anatomic Knowledge
  ▪ Foundational Model of Anatomy (FMA) ontology
  ▪ Specifies anatomical entities and relationships (e.g., partonomies, continuities, adjacencies)
  ▪ Logical as opposed to spatial model
Ontology Views

FMA

Head
Musculo-skeletal
Abdomen
Female Pelvis
Thorax
Neck
Back
Lung
Heart

Non-Eng Eqv
Synonym
Definition
Adjacency
Attributed part
Part-Of
Member of
Constituational part
Constituional part

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Ontology Views for Reasoning

- Catalog of organs; controlled vocabulary of names
- Organ parts and compositionality
- Adjacencies for organs and organ parts
- Connectivity
- Containment
- Arterial supply & regional organ perfusion
Organ Sub-Parts: Artery Segments

Right Coronary Artery
- Segment 1
- Segment 2
- Segment 3
- Segment 4 (Posterior Interventricular branch)
- Conus artery
- Right Diagonal artery
- Right Marginal artery
- Atrioventricular artery

Left Coronary Artery
- Segment 1
- Segment 2
- Segment 3
- Conus artery
- Right Diagonal artery
- Right Marginal artery
- Atrioventricular artery
- Circumflex artery
- Ramus intermedius
- Diagonal branch
Subdivision of Myocardial Regions Based on FMA Knowledge

Regions of Left Ventricle

- LAD
- LCX
- RCA
- Great Cardiac
- Middle Cardiac
- Coronary Sinus
- Anterior
- Septal
- Inferior
- Lateral

* Left Marginal

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Other Knowledge Sources

- Biomechanics ontology
  - Tissue material properties
  - Useful for predicting trajectory of projectiles
- Tissue injury ontology
  - Taxonomy of types of injuries
- Physiology ontology
  - Knowledge of how injuries affects circulatory dynamics

“VSKB” = all pertinent ontologies in VS Project
2. Creating patient-specific models
A “Patient-Specific Model (PSM)”

- Contains data specific to the patient at a point in time
  - Patient-specific geometry
  - Description of projectile path of damage
  - Vital signs
- Links to canonical ontologies
- Provides API for queries, reasoning services, and visualization routines
Building Geometric/Knowledge Models

Segmented CT Volume Data of the Chest (or Visible Human Image set)

3-D Geometric Model

Biomechanical Knowledge

FMA

Reasoning

Display and User Queries
Visible Human Raw Data
3. Developing reasoning services
Reasoning Tasks

- Predict organ injury
- Predict physiological consequences of organ injury
- Classify injuries (trauma score; ICD-10)
- Predict survival
- Decision support
  - Diagnosis and triage
  - Recommend additional tests
Predicting Organ Injury

- Direct organ injury
  1. Organs visible on CT: injury predicted by intersection with “cone of damage”
  2. Organs not visible on CT: inferred from adjacency knowledge in FMA

- Propagation of organ injury
  3. Use knowledge of arterial anatomy to infer downstream consequences of arterial damage
Injury Caused by “Cone of Damage”

We infer injured tissues using FMA:
- names of injured tissues
- knowledge of organ adjacencies
Reasoning about injuries and their consequences
Reasoning using Classification

- Some reasoning tasks are classification tasks
  - Diagnosis
  - Extent of injury
  - Consequences of injury (e.g., vascular damage)
  - Triage and associated actions

- Representation of VSKB in Description Logic enables efficient classification
  - Represent knowledge conducive to classification
  - Infer non-obvious relationships among concepts (e.g., ischemia)

- This approach builds on current standards for knowledge interoperability (OWL)
OWL model relates anatomic structures to vascular supply

This organ is defined here
OWL automatically infers where distal blood flow is lost

If we assert that the RCA is occluded between conus a. and diagonal a., we can infer the ischemic consequences.
OWL automatically infers what structures are damaged.

Types of ischemic organs of heart that will be ischemic.
Implementation

- VSKB ontologies in Protégé
- PSM
  - Geometric data objects in ITK (C++)
  - API to read patient data; visualize output
  - C++/Java interface to link PSM to ontologies
- OWL-based reasoning deployed as a Web service
- Outputs of reasoning updates PSM
C++/Protégé Interface

- Geometric modeling code in C++; Protégé API in Java
- C++/Protégé interface developed using JACE
- Proxy C++ classes created for core Java classes (KnowledgeBase, etc.)
- JVM invoked in C++; direct Protégé API calls via JACE interface
DEMO
Conclusions

- Benefits of integrating geometric models with ontologies
  - Makes anatomic knowledge and relationships explicit and computer-accessible
  - Useful for reasoning (e.g., propagation of vascular injury)

- Benefits of integrating additional information in Patient Specific Model
  - Biomechanical and other data for simulation
  - Extensibility to accommodate future data
Acknowledgements

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Contact info:
rubin@smi.stanford.edu
Pre-processing of link between {geometry (image+mesh), biomechanics, etc} and FMA.
How? Spatial objects (abstract geometry objects)
Working with the PSM: Reasoning and Visualization

- Patient-Specific Model (PSM)
- Visualization
- Indirect effects
- Tissue damage
- Physiological effects

Reasoning
Architecture for Integrating Image Data and Knowledge

- Provide reasoning services for current and anticipated requirements
- Use blackboard architecture where all reasoners relate to data available in a Patient-Specific Model (PSM)
- Enable all modules in VSP to read and write to PSM at runtime
Ontologic approach to geometric models of anatomy

- Input: segmented CT data (pre-injury)
- Build an integrated 3-d model of anatomy:
  - Represent 3-d geometry of anatomic structures
  - Integrate tissue physical properties, biomechanics, physiology, and clinical parameters (vital signs)
  - Simulate geometric effects of penetrating injury
- Geometric model links to knowledge sources (e.g., anatomy in FMA ontology)
- (Use physiologic models to predict consequence of the injury)
- Display predicted organ injury
Geometric Model Building

- Organ parts derived from segmented CT data
- Construct mesh models from segmented organ parts using VTK and ITK (added to PSM)
- Biomechanical and other information added to PSM
  - Tissue physical properties; density
- Knowledge in VSKB is cached in PSM for efficient computation
  - E.g., Heart $\rightarrow$ pericardium; LA; LV; RA; RV
- This model is extensible; can include other info
VSKB Knowledge
Cached in PSM

Geometry
Tissue Density
Elasticity
Surface area...

Cached knowledge

Rendering of geometric data associated with cached geometric knowledge
What Is An Ontology?

- Enumerates concepts, attributes of concepts, and relationships among concepts
  - Defines a structure ("model") for the application area
  - Encodes knowledge
  - A "knowledge source"
- Can be comprehended by people and processed by machines
- Provides a "domain of discourse" for characterizing some application area; a common vocabulary (shared understanding)
Protégé-2000

- Ontology editor
  - Model concepts, attributes, and relationships
- Tools
  - Visualize ontologies and knowledge bases
- Storage
  - Archive ontologies and knowledge bases in a variety of formats
- Java API
  - Link knowledge bases to other applications
- A world-wide community of active users
Challenges

- Making knowledge explicit and computable
  - Geometric knowledge: implicitly represented in 3-d models
  - Anatomic/physiologic knowledge: usually in head of observer
  - This separation makes automated reasoning difficult

- Integrating and computing with patient data and canonical knowledge
  - **Data**: geometry, biomechanics, vital signs
  - **Knowledge**: anatomy, tissue strain ↔ injury
  - Combining and using these in reasoning tasks
The Foundational Model of Anatomy (FMA) Ontology

Material Physical Anatomical Entity

- Anatomical Spatial Entity
- Body Substance

Anatomical Structure

- Cell
- Organ
- Organ Part
- Body Part
- Organ System
- Organism
- Tissue
- Organ Component
- Organ Subdivision
Integrating Knowledge and Data

- Geometry
- Biomechanics
- Patient-Specific Model (PSM)
- Vital Signs
- Knowledge
- Injury data
Cached knowledge in PSM derived from anatomy ontology

Each node above is an object containing patient-specific knowledge: anatomy, geometry, biomechanics, tissue damage, physiology
Knowledge about Vascular Supply

- Right coronary artery
  - Trunk of right coronary artery
  - Right conus artery
  - Atrial branch of right coronary artery
  - Ventricular branch of right coronary artery
  - Posterior interventricular branch of right coronary artery
  - Atroventricular node branch of right coronary artery
  - Recurrent atroventricular branch of right coronary artery
  - Intermediate atrial branch of right coronary artery
  - Right posterolateral branch of right coronary artery
  - Variant branch of right coronary arterial tree
  - Unnamed branch of right coronary artery
  - Proximal portion of right coronary artery
  - Distal portion of right coronary artery
  - Wall of right coronary artery
  - Lumen of right coronary artery

- Left coronary artery

**BRANCH:**
- First septal branch of posterior interventricular artery
- Second septal branch of posterior interventricular artery
- Third septal branch of posterior interventricular artery

**ARTERIAL SUPPLY OF:**
- Right ventricle
- Atroventricular bundle
- Right branch of atroventricular bundle
- Left branch of atroventricular bundle
Knowledge for Injury Reasoning

Part-of knowledge

Other useful knowledge

**Heart**
- Wall of heart
- Right atrium
  - Wall of right atrium
  - Cavity of right atrium
  - Interatrial septum
  - Inflow part of right atrium
  - Outflow part of right atrium
  - Right auricle
- Right side of interatrial septum
- Left atrium
- Right ventricle
- Left ventricle
- Right side of heart
- Left side of heart
- Fibrous skeleton of heart
  - Papillary muscle
  - Cardiac valve
  - Tricuspid valve
  - Mitral valve
  - Aortic valve
  - Pulmonary valve
- Interatrial septum
- Interventricular septum
- Cavity of right atrium
- Cavity of left atrium
- Right coronary artery
  - Right coronary artery
  - Left coronary artery
- Left coronary artery
  - Coronary sinus
  - Great cardiac vein
  - Right marginal vein
  - Left marginal vein

**ADJACENCY:**

<table>
<thead>
<tr>
<th>related object</th>
<th>coordinate</th>
<th>laterality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right lung</td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>Left lung</td>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>Esophagus</td>
<td></td>
<td>Posterior</td>
</tr>
<tr>
<td>Right main bronchus</td>
<td>Superior</td>
<td>Right</td>
</tr>
<tr>
<td>Left main bronchus</td>
<td>Superior</td>
<td>Left</td>
</tr>
<tr>
<td>Diaphragm</td>
<td></td>
<td>Inferior</td>
</tr>
</tbody>
</table>

**ORIENTATION:**

<table>
<thead>
<tr>
<th>related object</th>
<th>coordinate</th>
<th>laterality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apex of heart</td>
<td>Inferior</td>
<td>Left</td>
</tr>
<tr>
<td>Base of heart (anatomical)</td>
<td>Posterior</td>
<td>Right</td>
</tr>
</tbody>
</table>

**CONTAINED IN:**
- Middle mediastinum

**ARTERIAL SUPPLY:**
- Right coronary artery
- Left coronary artery

**VENOUS DRAINAGE:**
- Coronary sinus
- Great cardiac vein
Key knowledge used in reasoning