A Semantic Situation Awareness Framework for Indoor Cyber-Physical Systems

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Ph.D. in Engineering Dissertation Defense

A Semantic Situation Awareness Framework for Indoor Cyber-Physical Systems

Pratikkumar Desai
Monday, 4/29/2013

<table>
<thead>
<tr>
<th>Dissertation Committee</th>
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<tr>
<td>Director</td>
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<td>Co-Director</td>
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Embedded systems
  e.g. thermostat

Networked embedded system
  e.g. wireless sensor networks

Cyber-physical system
  e.g. Intelligent traffic management systems
Cyber-Physical Systems

Cyber: Computation, communication, and control that are discrete, logical, and switched.

Physical: Natural and human-made systems governed by the laws of physics and operating in continuous time.

Cyber-Physical Systems (CPS): Systems in which the cyber and physical systems are tightly integrated at all scales and levels.
Motivation & Challenges
(Situation awareness)
Mobile sensing platform

Situation: Actual fire at chair
Motivation

Mobile sensing platform

Event: Fire from temperature and CO₂ data
Uncertainty: Sensor data
e.g. Due to resolution, calibration or robustness of sensors

Mobile sensing platform
Incomplete domain knowledge
e.g. Unknown sources in the environment

Mobile sensing platform
Indoor location awareness

Complex system

Interoperability

Internet
Context
“is a physical phenomenon, measured using sensors, and product of an event”

Contextual situation awareness:
“is a process of comprehending meaning of environmental context in terms of events or entities”

Location awareness:
“is a process of identifying objects from raw spatial information and their relationship with the ongoing events”
Contextual situation awareness + Location awareness

Raw environmental sensor data → Entities (High level abstractions) → Situation

Raw spatial information → Object-Entity relationships → Situation

Situation

- Raw Sensor Data (Environmental context)
- Low-level abstractions (Qualities) e.g. High temperature, Low CO₂
- High-level abstractions (Entities) e.g. Fire, Dry-ice
- PointOfInterest (Indoor objects) e.g. Fireplace, Chair
- Indoor location Coordinate e.g. (300,200,100)
- Relative distance estimation

Contextual Situation Awareness

Location Awareness
Contextual Situation Awareness
Abductive reasoning
Crisp abstractions

Domain Knowledge Base

Quality-type
- temperature
- CO₂

Quality
- LowTemp
- HighTemp
- LowCO₂
- HighCO₂

Entity
- Fire
- DryIce
- RoomHeater
- NormalCondition

Observation process
- Raw sensor data
- Qualities
- Entities

Perception process

http://wiki.knoesis.org/index.php/Intellego
Temperature: 500°C
CO2: 1010 ppm

Fire

DryIce
RoomHeater

\[
\text{io:entity} \equiv \exists \text{io:inheresIn.}\{\text{HighTemp}\} \\
\wedge \exists \text{io:inheresIn.}\{\text{HighCO}_2\}
\]

\equiv \{\text{Fire, RoomHeater}\} \wedge \{\text{Fire, DryIce}\}

\equiv \{\text{Fire}\}

Temperature: 500°C
CO2: 999 ppm

RoomHeater
Motivation

Mobile sensing platform

Uncertainty: Sensor data
e.g. Due to limitation, calibration or robustness of sensors

Incomplete domain knowledge
e.g. Unknown sources in the environment
Fuzzy abstractions

\[ \mu_{\text{LowCO}_2}(a) = \frac{1200 - 1160}{400} = 0.1 \]

Membership function \( \mu \)

\[ \mu_{\text{HighCO}_2}(a) = \frac{1160 - 800}{400} = 0.9 \]
Fuzzy abductive reasoning

\[ \mu_{Fire}(a) = \mu_{High\,Temp}(a) \land \mu_{High\,CO_2}(a) \]
io: entity
≡ \{ \exists \text{io: inhereIn. \{HighCO}_2\}} \sqcup \exists \text{io: inhereIn. \{LowCO}_2\}}
\sqcap \exists \text{io: inhereIn. \{HighTemp\}}
\equiv \{\{\text{Fire, DryIce}\} \sqcup \{\text{NormalCondition, RoomHeater}\}}
\sqcap \{\text{Fire, RoomHeater}\}
≡ \{\text{Fire, RoomHeater}\}

\mu_{\text{Fire}}(a) = \mu_{\text{HighTemp}}(a) \land \mu_{\text{HighCO}_2}(a)
= \min(1, 0.9)
= 0.9

\mu_{\text{RoomHeater}}(a) = \mu_{\text{HighTemp}}(a) \land \mu_{\text{LowCO}_2}(a)
= \min(1, 0.1)
= 0.1
Evaluation – Contextual Situation Awareness

<table>
<thead>
<tr>
<th>Reasoning approach</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Recall</th>
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</thead>
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<tr>
<td>Crisp abductive reasoning</td>
<td>86 %</td>
<td>78.57 %</td>
<td>73.33 %</td>
</tr>
<tr>
<td>Fuzzy abductive reasoning</td>
<td>94 %</td>
<td>92.85 %</td>
<td>86.66 %</td>
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</table>
Interoperability
Semantic Web

• Semantic web:
  • Formally define the meaning of information on web.
  • Provide expressive representation, formal analysis of resources.

• Ontology
  • Formally represents knowledge as a set of concepts within a domain and the relationships between pairs of concepts.

• RDF (Resource Description Framework)
  • Graph-based language for modeling of information.
  • Allows linking of data through named properties.

Contextual situation awareness (Semantic modeling)

Observation process

- Raw Sensor Data
- SSN annotated Observations
- Low-level fuzzy abstractions (qualities)

Perception process

- Fuzzy reasoning
- High-level Abstractions (entity)

- SSN Ontology
- Domain Ontology
- Fuzzification Rules
- Fuzzy Inference rules ontology
Indoor Localization
Indoor location awareness
Traditional Indoor Localization Techniques

• Active Badge and Active Bat system.
• RADAR: An In-building RF-based user location and tracking system.
• RFID radar
• Object tracking with multiple cameras
• Computer vision based localization

• Wireless Sensor Network
TDoA (Time Difference of Arrival)

Stage 1: Beacon transmits RF and Us signals together

Stage 2: Listener receives RF signal first at $T_{rf}$ and starts the clock

Stage 3: At $T_{us}$ time US signals is received by Listener

Stage 3: Distance is calculated using $\Delta T$ and speed of signals
Trilateration

Number of nodes = 3.

\[ d_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \text{ for } i = 1, 2, 3 \]

Outlier rejection and Multilateration
The Proposed Algorithm

• Utilizes fusion of RSS (received signal strength) of RF signal and TDoA data for accurate distance estimation.

• The algorithm stages:-
  • RSSI data training
  • Distance estimation
  • Localization

• Uses TDoA as a primary distance estimation technique.
• RSSI data is trained and converted into appropriate distance measurements.
• The proposed algorithm can be used in absence of one or many TDoA links.
Initial Conditions

- Distances between all beacons are known and fixed
Beacon $B_1$ Transmit Data

RSSI Link
TDoA Link

$B_1$

$B_2$

$B_3$

$B_4$

$L$

$R_{1L}$ $T_{1L}$

$R_{12}$ $0$ $?$ $?$

$R_{13}$ $?$ $0$ $?$

$R_{14}$ $?$ $?$ $0$
Beacon $B_2$ Transmit Data

RSSI Link

TDoA Link
Beacon B₃ Transmit Data

RSSI Link

TDoA Link

B₁

B₂

B₃

B₄
Beacon $B_4$ Transmit Data
Evaluation–Proposed Algorithm
Location Awareness
Indoor Environment

Bedroom-1
- Bed-1
- Chair-2

Bedroom-2
- Desk-1

Drawingroom-1
- Fireplace-1
- Sofa-1
- Chair-1
- Plant-1

Kitchen-1
- Treadmill-1
- Stove-1

Gym-1
Hierarchical mapping of the indoor environment
POI is-a ChairPOI
ChairPOI has individual Chair-1
Chair-1 has individual Drawingroom-1
Drawingroom-1 has individual Drawingroom
Drawingroom is-a StructuralComponent
Chair-1 inLo:isLocatedIn Drawingroom
Chair-1 inLo:hasPOI Drawingroom
Chair-1 inLo:hasUnit Drawingroom
Chair-1 inLo:hasXmin Drawingroom
Chair-1 inLo:hasXmax Drawingroom
Chair-1 inLo:hasYmin Drawingroom
Chair-1 inLo:hasYmax Drawingroom
Chair-1 inLo:hasZmin Drawingroom
Chair-1 inLo:hasZmax Drawingroom
Chair-1 xsd:string
Chair-1 xsd:float
IdentifiedPOI

\[\equiv \{\exists inLO: \text{PointOfInterest}. \{\text{inLo}: \text{hasXmax} \geq 190\}\} \]
\[\land \{\exists inLO: \text{PointOfInterest}. \{\text{inLo}: \text{hasXmin} \leq 190\}\} \]
\[\land \{\exists inLO: \text{PointOfInterest}. \{\text{inLo}: \text{hasYmax} \geq 570\}\} \]
\[\land \{\exists inLO: \text{PointOfInterest}. \{\text{inLo}: \text{hasYmin} \leq 570\}\}\]

\[\equiv \{\text{Sofa} - 1, \text{Chair} - 1, \text{Fireplace} - 1\} \]
\[\land \{\text{Sofa} - 1, \text{Chair} - 1, \text{Fireplace} - 1\} \]
\[\land \{\text{Chair} - 1\} \]
\[\land \{\text{Sofa} - 1, \text{Plant} - 1, \text{Fireplace} - 1, \text{Chair} - 1\}\]

\[\equiv \{\text{Chair} - 1\}\]
Object-entity relationship

Structural Components
- DrawingRoom-1
- Chair-1
- DrawingRoom

Point of Interests
- FireplacePOI
- Fireplace-1
- ChairPOI
- Sofa-1

Entities
- DryIce
- Fire
- PresenceOfRoomHeater
- NormalCondition
- HighHeartRate

Relationships:
- hasIndividual
- isLocatedIn
- hasApplicableEntity
Evaluation – Location Awareness

Mobile-robot route
### Reasoning approach

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<th>Precision</th>
<th>Recall</th>
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</thead>
<tbody>
<tr>
<td>Crisp abductive reasoning</td>
<td>87.5 %</td>
<td>43.75 %</td>
</tr>
<tr>
<td>Fuzzy abductive reasoning</td>
<td>100 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Location aided fuzzy abductive reasoning</td>
<td>100 %</td>
<td>88.89 %</td>
</tr>
</tbody>
</table>

### Location independent reasoning

- **Crisp abductive reasoning**: 87.5% Precision, 43.75% Recall
- **Fuzzy abductive reasoning**: 100% Precision, 50% Recall
- **Location aided fuzzy abductive reasoning**: 100% Precision, 88.89% Recall

---

**Diagram Description**

- **Location independent reasoning**
  - Crisp abductive reasoning
  - Fuzzy abductive reasoning
  - Location aided fuzzy abductive reasoning

- **Location aided reasoning**

- **Fireplace**

- **Location points**

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**DEPARTMENT OF ELECTRICAL ENGINEERING**

**WRIGHT STATE UNIVERSITY**
Comprehensive Framework
Comprehensive Framework (System level)

- Indoor Positioning System
  - Semantic Object Identifier
    - Spatial Reasoning
      - Location Awareness
      - Domain Knowledge
        - Fuzzy Abstraction Rules
          - Qualities
            - Fuzzy Abductive Reasoning
              - Entities
                - Contextual Situation Awareness
      - Situation
  - Environment Sensors
Comprehensive Framework (Semantic modeling)

- **Raw Physical Context Data**
- **SSN annotated Observations**
- **Low-level Fuzzy Abstractions (Qualities)**
- **High-level Abstractions (Entities)**
- **Optimized Situation**

**Ontology Domain**
- **SSN Ontology**
- **Domain Ontology**
- **Fuzzy Abductive Reasoning Rules**

**Semantic Context**
- **Indoor Location Ontology**
- **Semantic Location Identifier**
- **Raw Location Data**
Location (a): (200,250,20)

Location (b): (400,150,30)

Temp: 150 °C
CO₂:1120 ppm

Temp: 180 °C
CO₂:1160 ppm

Object coverage area
Mobile robot path
Fire: 0.80
Heater: 0.20

Location (a):
(200,250,20)

Fire: 0.90
Heater: 0.10

Location (b):
(400,150,30)
Fire: 0.90
Heater: 0.10

Location (a): Fireplace

Location (b): Chair

Object coverage area

Mobile robot path
Key Contributions

- Developed a fusion based indoor localization algorithm to achieve accurate spatial information of the sensing platform.
  - Accurate indoor localization algorithm.
  - Surveillance and tracking of mobile robots in indoor environments.
  - Integration of indoor positioning results with virtual world environment.

Related papers:
- An invited journal paper in preparation.
Key Contributions

• Introduced fuzzy abstraction and inference technique to comprehend events via handling the uncertainty in the context information & the ambiguity in the domain knowledge.
  
  • A journal paper in preparation.

• Developed semantic mapping technique for indoor objects to aid the situational context awareness results via further discriminating not applicable events.
  
• Developed and deployed a comprehensive situation awareness framework for cyber-physical system.
  • A journal paper in preparation.
Future work

• Richer spatio-temporal relation modeling between indoor objects and entities

• Efficient coverage space for the indoor objects

• Accurate indoor localization via smartphones
Questions?