A Semantic Situation Awareness Framework for Indoor Cyber-Physical Systems

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A Semantic Situation Awareness Framework for Indoor Cyber-Physical Systems

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</table>
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

http://www.cs.binghamton.edu/~tzhu/
CPS Examples

- Disaster Management
- Military Drones
- Air Traffic Control
- Traffic Management

- Smart Grid
- Smart Home
- Remote Patient Monitoring
Motivation & Challenges
(Situation awareness)
Motivation

Mobile sensing platform

Situation: Actual fire at chair
Event: Fire from temperature and CO₂ data

Mobile sensing platform
Motivation

Mobile sensing platform

Uncertainty: Sensor data
e.g. Due to resolution, calibration or robustness of sensors
Incomplete domain knowledge

e.g. Unknown sources in the environment

Mobile sensing platform
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”

Context
Environmental context
e.g. temperature, CO₂, heart rate

Location
e.g. coordinates

Contextual situation awareness

Location awareness
Contextual situation awareness + Location awareness

- Raw environmental sensor data
- Raw spatial information
- Entities (High level abstractions)
- Object-Entity relationships
- Situation

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

Observation process
- Raw sensor data
- Qualities
- Entities

Perception process

- Abductive reasoning
- Crisp abstractions

Domain Knowledge Base

- Temperature
  - LowTemp
  - HighTemp

- CO₂
  - LowCO₂
  - HighCO₂

- Quality-types
  - LowTemp
  - HighTemp
  - LowCO₂
  - HighCO₂

- Entities
  - Fire
  - DryIce
  - RoomHeater
  - NormalCondition

http://wiki.knoesis.org/index.php/Intellego
Temperature: 500°C HighTemp
CO2: 1010 ppm HighCO₂

\[ io:entity \equiv \exists io:inheresIn. \{HighTemp\} \]
\[ \land \exists io:inheresIn. \{HighCO₂\} \]
\[ \equiv \{Fire, RoomHeater\} \land \{Fire, DryIce\} \]
\[ \equiv \{Fire\} \]

Temperature: 500°C HighTemp
CO2: 999 ppm LowCO₂

\[ \equiv \{Fire\} \]
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

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

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

\[ \mu_{Fire}(a) = \mu_{HighTemp}(a) \land \mu_{HighCO_2}(a) \]
\textbf{io: entity}
\[ \equiv \{\exists \text{io: inheresIn.}\{\text{HighCO}_2\}\sqcup \exists \text{io: inheresIn.}\{\text{LowCO}_2\}\} \]
\[ \sqcap \{\exists \text{io: inheresIn.}\{\text{HighTemp}\}\} \]
\[ \equiv \{\{\text{Fire, DryIce}\}\sqcup \{\text{NormalCondition, RoomHeater}\}\} \]
\[ \sqcap \{\text{Fire, RoomHeater}\} \]
\[ \equiv \{\text{Fire, RoomHeater}\} \]

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

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

<table>
<thead>
<tr>
<th>Reasoning approach</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Recall</th>
</tr>
</thead>
<tbody>
<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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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
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.

\[ d_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \] 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 B₁ Transmit Data

RSSI Link
TDoA Link

B₁

R₁₁
T₁₁

B₂

R₁₂

B₃

R₁₃

B₄

R₁₄
Beacon $B_2$ Transmit Data

RSSI Link

TDoA Link

B_1

B_2

B_3

B_4
Beacon B₃ Transmit Data

RSSI Link

TDoA Link

B₁

B₂

B₃

B₄

L

0 R₂₁ R₃₁ ?
R₁₂ 0 ? ?
R₁₃ R₂₃ 0 ?
? ? ? 0

0 ? ? ?
R₁₂ 0 R₃₂ ?
R₁₃ R₂₃ 0 ?
? ? ? 0

0 ? ? ?
R₁₂ 0 ? ?
R₁₃ R₂₃ 0 ?
? ? ? 0

0 ? ? ? R₁₁ T₁₁
R₁₂ 0 ? ? R₂₂ T₂₂
R₁₃ R₂₃ 0 ? R₃₃ T₃₃
? ? ? 0 ? ?

0 ? ? ?
R₁₂ 0 ? ?
R₁₃ R₂₃ 0 ?
? ? ? 0
Beacon $B_4$ Transmit Data

0 $R_{21}$ $R_{31}$ $R_{41}$
$R_{12}$ 0 ? ?
$R_{13}$ $R_{23}$ 0 ?
$R_{14}$ $R_{24}$ $R_{34}$ 0

0 $R_{12}$ $R_{32}$ $R_{42}$
$R_{13}$ $R_{23}$ 0 ?
$R_{14}$ $R_{24}$ $R_{34}$ 0

$B_1$

$B_2$

$B_4$

0 $R_{1L}$ $T_{1L}$
$R_{12}$ 0 ? ?
$R_{13}$ $R_{23}$ 0 ?
$R_{14}$ $R_{24}$ $R_{34}$ 0

0 $R_{1L}$ $T_{1L}$
$R_{12}$ 0 ? ?
$R_{13}$ $R_{23}$ 0 ?
$R_{14}$ $R_{24}$ $R_{34}$ 0

$T_{DoA}$ Link

$RSSI$ Link

$L$

$B_3$
Evaluation–Proposed Algorithm

![Graph showing RMS error in position estimation vs. # of Monte Carlo simulations for different methods: TDoA, A= fixed, and A= Trained. The graph illustrates the comparison of these methods across multiple simulations.](image)
Location Awareness
Hierarchical mapping of the indoor environment
Identified POI

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

\[ \equiv \{ Sofa \_ 1, Chair \_ 1, Fireplace \_ 1 \} \]
\[ \cap \{ Sofa \_ 1, Chair \_ 1, Fireplace \_ 1 \} \]
\[ \cap \{ Chair \_ 1 \} \]
\[ \cap \{ Sofa \_ 1, Plant \_ 1, Fireplace \_ 1, Chair \_ 1 \} \]

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

Structural Components

Point of Interests

Entities

DrawingRoom-1

Sofa-1

Fireplace-1

Fire

PresenceOfRoomHeater

NormalCondition

HighHeartRate

DrawingRoom

FireplacePOI

Chair-1

ChairPOI

isLocatedIn

hasIndividual

hasApplicableEntity
Evaluation – Location Awareness

Mobile-robot route

Location (a) (190,570)

Location (b) (630,325)

Mobile-robot route

Drawingroom-1

Fireplace-1

Sofa-1

Chair-1

Plant-1
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<tr>
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<td>87.5 %</td>
<td>43.75 %</td>
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<tr>
<td>Fuzzy abductive reasoning</td>
<td>100 %</td>
<td>50 %</td>
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<tr>
<td>Location aided fuzzy abductive reasoning</td>
<td>100 %</td>
<td>88.89 %</td>
</tr>
</tbody>
</table>

Location independent reasoning

Location aided reasoning

Fireplace
Comprehensive Framework
Comprehensive Framework (System level)

- Indoor Positioning System
  - Semantic Object Identifier
  - Spatial Reasoning
  - Location Awareness

- Contextual Situation Awareness
  - Domain Knowledge
  - Environment Sensors
    - Qualities
      - Fuzzy Abductive Reasoning
        - Fuzzy Abstraction Rules
          - Entities
            - Situation
Comprehensive Framework (Semantic modeling)

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

- Raw Location Data
- Semantic Location Identifier
- Indoor Location Ontology

- SSN Ontology
- Domain Ontology
- Fuzzy Abductive Reasoning Rules

Department of Electrical Engineering
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
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: 0.80
Heater: 0.20

Location (a): Fireplace

Fire: 0.90
Heater: 0.10

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
Acknowledgements
Questions?