A swarm of Mini-MEs: reasoning and information aggregation in ubiquitous multi-agent contexts

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4th OWL Reasoner Evaluation Workshop
Athens, Greece
June 6th, 2015
1. Information aggregation in ubiquitous multi-agent contexts

2. Proposed approach and tools

3. Information dissemination and fusion

4. Experiments

5. Conclusion
The Semantic Web of Things

- Interoperability and intelligence from Semantic Web technologies
- Pervasiveness from the Internet of Things (connected micro devices)
- Flexibility and scalability from the Multi-Agent System (MAS) architectural paradigm
- Applications:
  - Ubiquitous commerce, learning, healthcare
  - Home and building automation
  - Smart mobility
  - Environmental monitoring
  - ...

Scioscia, Ruta, Di Sciascio
ORE, Athens, 2015-06-06
Issues

- **Performance constraints** of mobile and pervasive devices: processing, memory, energy

- **Software platform limitations** for porting existing Semantic Web tools to pervasive contexts

- **Effective and efficient approaches for information management:**
  - Distributed architectures for data exchange and processing
  - Multi-agent information fusion
  - Achieving local and global situation awareness
Proposed approach and tools

Proposed approach

Objectives

- Decentralized information dissemination in a ubiquitous MAS
- Non-monotoning reasoning services for information fusion
- Swarm intelligence: emergent situation awareness from many local interactions
- Thrifty, efficient reasoning engine
Proposed approach and tools

Mini-ME: a mini history

2012: Version 1.0 [Ruta et. al., ORE 2012]
- Matchmaker optimized for mobile and ubiquitous contexts
- Support for standard Semantic Web languages (OWL) through the OWL API [Horridge and Bechhofer, OWLED 2009]
- Expressiveness-complexity trade-off (target: $\mathcal{ALN}$ with acyclic TBoxes)
- Reasoning services: Concept Satisfiability, Subsumption, Contraction, Abduction; Ontology Coherence, Classification

2014: Version 2.0 [Ruta et. al., ORE 2014]
- Re-engineering for improved efficiency and maintainability
- OWLlink protocol support for standard inferences
- Concept Covering reasoning service

2015: Version 2.1
- Concept Difference and Compute Bonus reasoning services
Proposed approach and tools

Exploited reasoning services 1/2

- Be $S$ and $R$ two (universally quantified) concept expressions, both formalized in a Description Logic according to a common ontology $T$
  - **Concept contraction:** [Colucci et. al., IJEC 12(2), 2007]
    - If $S \sqcap R \sqsubseteq \bot$, $Contract(S, R, T)$ finds the part $G$ of $R$ causing the inconsistency and the part $K$ which can be kept
    - Explanation for (un)satisfiability
  - **Concept abduction:** [Colucci et. al., IJEC 12(2), 2007]
    - If $S \sqcap R \not\sqsubseteq \bot$ but $S \not\sqsubset R$, $Abduce(S, R, T)$ finds the hypothesis $H$ which should be made on $S$ in order to reach a full match $S \sqcap H \sqsubseteq R$
    - Explanation for (missed) subsumption
- **Minimality** criterion for solution selection in both services
Proposed approach and tools

Exploited reasoning services 2/2

• **Bonus:** [Colucci *et. al.*, IJEC 12(2), 2007]
  - $\text{ComputeBonus}(S, R, T)$ finds what is missing in $R$ from $S$
  - Equivalent to abduction of mutually contracted versions of $R$ and $S$

• **Concept difference:** [Teege, KR 1994]
  - $S - R$ (i.e. $\text{Difference}(S, R, T)$) finds all the information which is part of $S$ but not of $R$
  - **Maximality** criterion for solution selection
(Pervasive) multi-agent system

Mobile agents are not synchronized

Each agent produces annotated descriptions from its sensing organs, runs a reasoner and exchanges messages

For each agent, a cache stores the most recent received message

Time-to-live: when messages become too old, they are discarded
Message structure

- **t**: timestamp
- **Four conjunctive concept expressions**
  - **C (Confirmed)**: terms observed by both the sender and other agents
  - **X (Clash)**: terms observed by the sender, inconsistent with observations by other agents
  - **M (My)**: terms observed by the sender, but not by other agents
  - **E (External)**: terms observed by other agents, but not by the sender
Agent behavior

Each agent loops in data gathering and annotation rounds, then looks at its cache and prepares its outgoing message. Three cases:

1. **Generate**, when there is a new annotation $N$ but no message in cache

   ![Diagram showing Generate case]

   $N \rightarrow P'$

   $C' = T \quad X' = T \quad M' \quad E' = T$

2. **Relay**, when there is a message $P$ in cache but no new annotation

   ![Diagram showing Relay case]

   $P \rightarrow P'$

   $C \quad X \quad M \quad E \rightarrow C' = T \quad X' = T \quad M' = T \quad E' = C \cap X \cap M \cap E$

3. **Integration and relay**, when both $N$ and $P$ exist and must be integrated
Integration reasoning service

Information dissemination and fusion

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Information integration always preserves consistency as long as any integrated annotation $N$ is consistent.

Integration reaches a steady state in two steps after every variation in observations:
- Two consecutive observations of a concept $S$ make $C \sqsubseteq S$ even when starting from $C \sqsubseteq \neg S$.

Computational complexity entirely depends on that of the exploited reasoning services.
Example scenario

Note: not reported in the submitted version of the paper due to lack of space.

- **VANETs** (Vehicular Ad-hoc NETworks) for collaborative monitoring of road and traffic conditions
- **Agents:** vehicles equipped with a smartphone running Mini-ME and connected to the OBD-II (On-Board Diagnostics) port
- **Data sources:** OBD-II readings, smartphone sensors (accelerometer, gyroscope, magnetometer)
- Reference **$\mathcal{ALN}$ ontology** modeling road, traffic, weather and driving style
- Data $\rightarrow$ concepts transformation via **machine learning**
- Parameters joined in conjunctive concept expressions
- Communications via **IEEE 802.11p ad-hoc wireless protocol**
Experimental setup

- Scenario simulations in NCTuns network simulator [Wang and Chou, SMPT Journal, 17(7), 2009]
- Maps with pre-defined data, different for each map zone

![Map Image]

- Agents
  - moving according to the Manhattan mobility model
  - running Mini-ME 2.1
  - communicating through simulated IEEE 802.11p interfaces

- Experiment materials available on
Simulation parameters

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of agents</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Sense &amp; process period (sec)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max agent speed (m/sec)</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td>Map size (km)</td>
<td>$5 \times 2$</td>
<td>$10 \times 2$</td>
</tr>
<tr>
<td>No. of map zones</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Duration (sec)</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
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</thead>
<tbody>
<tr>
<td>CIP resolutions</td>
<td>9330</td>
<td>16444</td>
</tr>
<tr>
<td>Avg. CIP time (msec)</td>
<td>9.8</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Preliminary indication of node-level performance-wise feasibility of the proposed approach
Conclusions

Contributions

- Multi-agent framework for information fusion and dissemination in ubiquitous contexts
  - Exchange of semantically annotated information
  - Swarm intelligence: emergent collective situation awareness from local interactions
  - Ability to follow rapidly changing data
  - Quick recovery from detection mistakes

- A novel reasoning service for concept expression integration
  - Fusion of local (detected) and external (received) information
  - Preservation of agents’ “perspective”
  - Combination of existing non-monotonic reasoning services

- Efficient implementation in the Mini-ME reasoner for mobile and pervasive devices

- Early performance results
Future work

- Comprehensive **experimental evaluations**
  - Reasoning performance on real, very constrained devices (*e.g.* sensor motes)
  - Scalability
    - Size and complexity of managed ontology and expressions
    - Number and topology of agents
    - Number and type of monitored parameters
  - Communication performance of the information exchange protocol
  - Quality of the disseminated information with respect to application goals
- **Implementation** in a message-oriented mobile middleware
- **Comparison** with the state of the art
- Extension of the approach toward **multi-item fusion**