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

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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
  - ...

Issues

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- 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

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Proposed approach

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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

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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

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 $\mathcal{T}$
- Concept contraction: [Colucci *et. al.*, IJEC 12(2), 2007]
  - If $S \sqcap R \sqsubseteq \bot$, $Contract(S, R, \mathcal{T})$ 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 $S \not\sqsubseteq R$, $Abduce(S, R, \mathcal{T})$ 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

Exploited reasoning services 2/2

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- Bonus: [Colucci *et. al.*, IJEC 12(2), 2007]
  - $ComputeBonus(S, R, \mathcal{T})$ 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.* $Difference(S, R, \mathcal{T})$) finds all the information which is part of S but not of R
  - Maximality criterion for solution selection

Message-based MAS

- (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

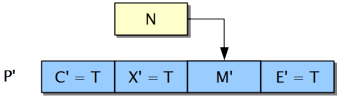
Message structure

- *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

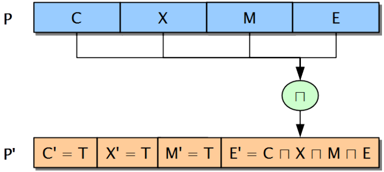
t	C	X	M	E

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

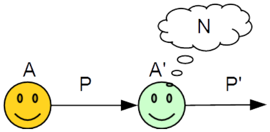


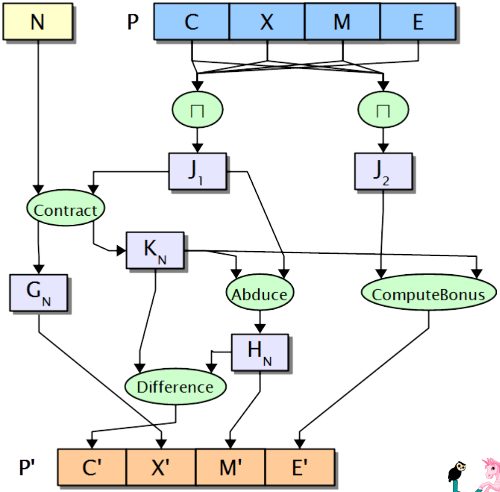
  2. Relay, when there is a message P in cache but no new annotation



  3. Integration and relay, when both N and P exist and must be integrated

Integration reasoning service





Relevant properties

- 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

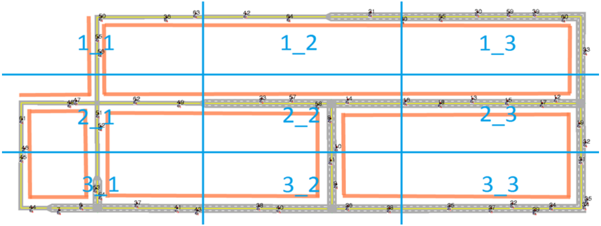
Example scenario

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



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

`http://sisinflab.poliba.it/swottools/minime/download/ore2015exp.zip`

Results

Simulation parameters

Scenario	**1**	**2**
No. of agents	60	80
Sense & process period (sec)	2	2
Max agent speed (m/sec)	36	50
Map size (km)	5 × 2	10 × 2
No. of map zones	9	10
Duration (sec)	300	300

Results

Scenario	**1**	**2**
CIP resolutions	9330	16444
Avg. CIP time (msec)	9.8	8.1

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

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

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- 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

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