Short Paper: Semantic Sensor Composition

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Abstract. This paper describes an application of semantics to sensors to automatically create sensor compositions. Two main contributions of this paper are a sensor ontology and a composition system. The OWL ontology describes user goals, functional and non-functional properties of sensors and sensor composition, while the Region Connection Calculus and Allen's Interval Algebra are used for describing the spatial and temporal properties of sensors. The composition system composes sensors and sensor processes to satisfy a user specified goal. Through experiments, this paper demonstrates the feasibility of semantics for specifying sensor compositions with low reasoning times, and the composition approaches with low composition times in most cases. Some scalability issues with semantic sensor networks are resolved with reasoning, but new composition approaches are needed for large scale use requiring large compositions.

1 Introduction

Sensors are becoming more prevalent and diverse [1], requiring methods of managing this diversity to ensure interoperability. This paper describes the application of semantics to sensors for composition, which provides some semantic interoperability. The definition of a sensor in this paper is "an entity capable of observing a phenomenon and returning an observed value" [2]. Semantic sensor composition allows data flow between sensors to be specified based on semantic constraints of sensors and user goals. Semantics allow users to interact with sensor networks without needing to know specifics of the sensor networks. Abstracting these low level details is a way of dealing with the diversity of sensors. This paper describes two contributions: a sensor ontology describing semantic constraints of sensors and goals, and a composition system that uses these constraints and reasoning to build sensor compositions satisfying user goals.

The sensor ontology describes semantics for composition such as types, processes, spatial and temporal properties, user goals, and sensor specific semantics. The Web Ontology Language (OWL) (specifically OWL 1.1 [3]) is used to specify these semantics. To improve the expressivity of spatial and temporal properties, semantics from the Region Connection Calculus (RCC) [4] and Allen's Interval

Algebra (AIA) [5], respectively, are used in addition to OWL. This semantic diversity is advantageous [6] by expressing relations of regions for sensing and communication, and of time intervals for operation time. These relations simplify the quantitative descriptions of regions and intervals, and allow reasoning in their respective logics, which are not covered by OWL.

The composition system, in the initialisation phase, takes syntactic sensor specifications, extracts the semantics, and asserts them into the sensor ontology. The derivation of RCC and AIA relations are performed by the composition system. In the composition phase, a matchmaking algorithm then analyses a set of sensors and sensor processes to create a set of possible matches based on the sensor and user goal constraints. A composition algorithm then creates composite sensors by building a binary tree of source to target sensors using the matches. The new composite sensors are then added to the current set of sensors. The process repeats until the goals are satisfied or there are no more compositions to be created. Every composition must end at data collecting sensors or base stations.

This paper discusses experiments that evaluate the capabilities of the composition system through three aspects of sensor networks: the number of neighbouring sensors, the number of sensors in the network, and the length of composition. The first aspect looks at wide composition trees, which translates to many short compositions at each sensor. The second aspect tests the filtering of relevant sensors and processes by the matchmaking algorithm. The third aspect looks at deep composition trees, or long sensor compositions. Favourable results are seen with the first two experiments with low execution and reasoning time. The third experiment shows some scalability issues with the matchmaking approach adopted by other sensor composition systems.

An evaluation of the sensor ontology and composition system is given to identify and discuss strengths and weaknesses of the system. The novel addition of RCC and AIA semantics in addition to OWL allows relations about spatial and temporal properties be asserted in the ontology. These additions are exploited in the composition system through the fast reasoning to find spatially and temporally collocated sensors. The composition system allows composition to be created automatically based on user specified goals. While short compositions can be found quickly, long and large sensor compositions are still problematic because of the matchmaking approach. However, the application of semantics to sensors shows feasibility for composition, which provides semantic interoperability of sensor resources, and automation of many tasks, allowing users to interact with sensor networks on a higher level by expressing queries and goals.

The rest of this paper is organized as follows. Section 2 summarises related work. Section 3 describes the semantic constructs of the sensor ontology with visualisations. Section 4 describes the composition system. Section 5 shows a few experiments with the system. Section 6 gives an evaluation of the ontology and the system. Section 7 provides concluding remarks. The sensor ontology and other artefacts from this paper, including the original thesis [7], are available from `http://cs.anu.edu.au/people/Nguyen.Tran/SemanticSensorComposition/`.

2 Related Work

This section looks at the related research fields of semantic Web service composition (SWSC), sensor ontologies and sensor composition.

In SWSC, semantic interoperability of Web services provides additional capabilities that can be automated: (semantic) searching, invocation, composition, interoperation, execution monitoring and recovery [8]. Syntactic interoperability of Web services is the syntax and the established communication protocols of the Web. To gain additional functionalities that are meaningful to humans, Web Services are marked up semantically using ontologies. For example, searching for the desired output of Web services based on ambiguous terms, and composing multiple Web services to create a new Web service that satisfies some user goals [9]. The semantics for Web services and their composition are adapted to this work for sensor processes in a similar way to Lécué et al. [10].

The research on sensor ontologies has produced many ontologies for modelling of sensors and their capabilities, but they are domain specific for each research community [11], such as focusing on marine or geospatial use. The design of the sensor ontology makes extensions or integration simpler to perform. For example, the CSIRO sensor ontology is a generic sensor ontology that describes sensor capabilities and operation [12]. The ontology provides some of the basic semantics for describing sensors in the sensor ontology. The sensor ontology could be integrated into the CSIRO sensor ontology to provide diverse semantics that have been evaluated with a sensor composition system.

There are two sensor composition systems that relates to this paper by focusing on the data flow in sensor networks: a Semi-Automatic Sensor Composer and Semantic Streams. The Semi-Automatic Sensor Composer is an extension of the Semi-Automatic Web services Composer [13]. The composer uses a matchmaking algorithm to compose the Web services [14]. The extension adds non-functional sensor attributes to the Web Services on the sensor. The composition system aids a user in matching sensors by their processes, a reinterpretation of Web services, and non-functional attributes such as location and types. This approach is clearly not scalable as there can be many sensors of many types in a sensor network.

Semantic Streams offers a fully automated semantic sensor composition system based on Constraint Logic Programming Reals (CLP-R) [15]. The functional and non-functional properties of sensors are described semantically in CLP-R. The non-functional properties are hard-coded such as the numeric boundaries of the sensing region. These boundaries are computed quantitatively for each query to build the semantic streams of data flowing through the network. The sensor compositions are deduced automatically from the inference engine with backtracking capabilities. The Semantic Streams research shows the composition of sensors being performed automatically. However the logic used is very restrictive in its expressiveness and so limits the capabilities of the composition system.

These two sensor composition systems have a similar composition approach of identifying the user goals and build sensor composition trees towards that goal. Composing sensors mainly differs from composing Web services by the additional sensor, spatial and temporal properties. These properties add additional complexities to the composition problem, which are not addressed by Web services composition. This paper follows the composition approach of the two sensor systems above.

3 Sensor Ontology

This section describes the construction of the sensor ontology. Each of the semantics used for composition can exist independently, but each is required in the composition system.

3.1 Type Semantics

The top level of the COMETMAN energy classification scheme of sensors is used in the sensor ontology: Chemical, Optical, Mechanical, Electrical, Thermal, Magnetic, Acoustic, and Nuclear [16]. These can be extended to be more or less descriptive of a sensor or a family of sensors.

3.2 Process Semantics

The semantics for sensor processes are modelled after the CSIRO Sensor Ontology [12] with some differences and an explicit modelling of the data types, inputs and outputs. Each process has a set of inputs and outputs. The data flow between two processes is a match of an output to an input, which is recorded as a binding. Figure 1 shows the ontology fragment of the *Process* concept. Figure 2 shows the *Binding* concept, where the *bindingDistance* property records the distance between the composed processes. The advantage with this form of composition is the coordination or micro-management of sensors through their inputs and outputs.

The matching of outputs to inputs on the semantic level allows analysis beyond precise or identical definitions required on the syntactic level. The added semantics allows determining the degree of match of outputs to inputs, which is exploited with the *DataType* concept. The *hasDataType* property maps to a string representing the *DataType* concept. The composition system takes the strings and interprets them as concepts[3].

3.3 Spatial Semantics

Sensors have spatial information required in forming networks that can benefit from a semantic interpretation, Figure 3. The sensing/communication regions of sensors can be approximated with polygons [17]. Polygons have the advantage of storage of points of the polygon, and variability of region and number of

[3] The Semantic Web Best Practice Description discusses this issue further: `http://www.w3.org/TR/swbp-classes-as-values/`.

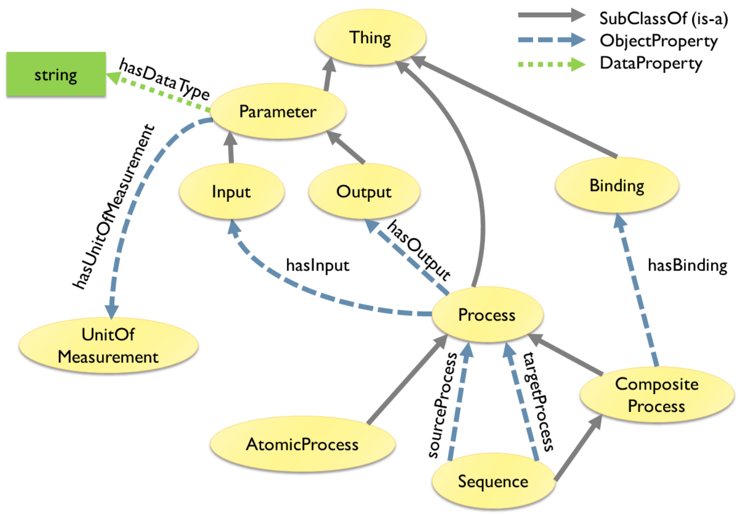

Fig. 1. The process semantics in the sensor ontology.

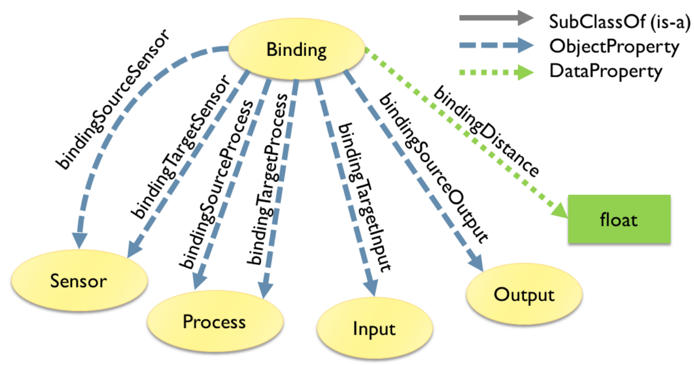

Fig. 2. The binding semantics in the sensor ontology.

points. An OWL mapping of the Region Connection Calculus (RCC) relations describes the relationships between the regions. The RCC relations are externally determined by analysing the polygons, and then asserted into the ontology. The combined use of RCC and OWL provides semantic diversity and capabilities beyond OWL.

Some advantages of using RCC relations are that the RCC relations only change when necessary, whereas numeric descriptions require frequent computation. The view of the spatial and temporal world as relations is more natural to users. The RCC relations can simplify the creation of sensor compositions through RCC reasoning, but this is not explored in this paper. The complexity of RCC can be varied by using more or fewer relations to describe spatial

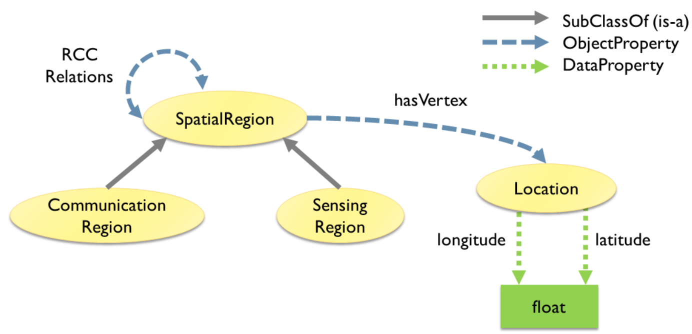

Fig. 3. The spatial semantics in the sensor ontology.

properties [17]. These advantages and the OWL integration makes RCC ideal to describe spatial properties of sensors.

3.4 Temporal Semantics

Sensors operate over one or more time intervals that can be described qualitatively using the thirteen exhaustive relations of Allen's Interval Algebra (AIA) [18]. The temporal semantics, Figure 4, are modelled after the AIA relations in the OWL-Time ontology [5] with some minor differences. The AIA relations are also determined externally and then asserted into the ontology. The advantages of using AIA are similar to the RCC advantages.

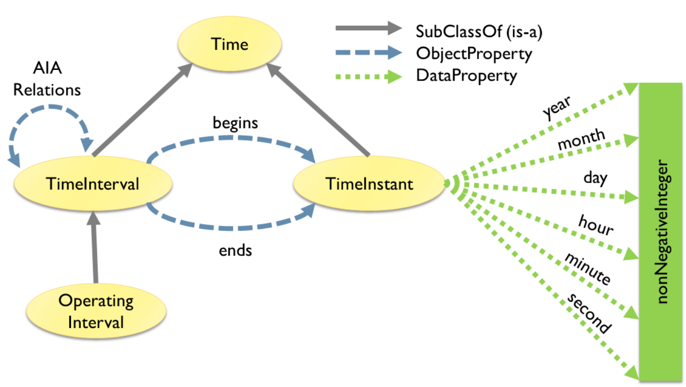

Fig. 4. The temporal semantics in the sensor ontology.

3.5 Sensor Semantics

Sensors are the focus, which is reflected in Figure 5 showing the sensor semantics in the sensor ontology. The *AtomicSensor* concept is described by the semantics above. The *CompositeSensor* concept connects the sensors and defines the order of execution and data flow.

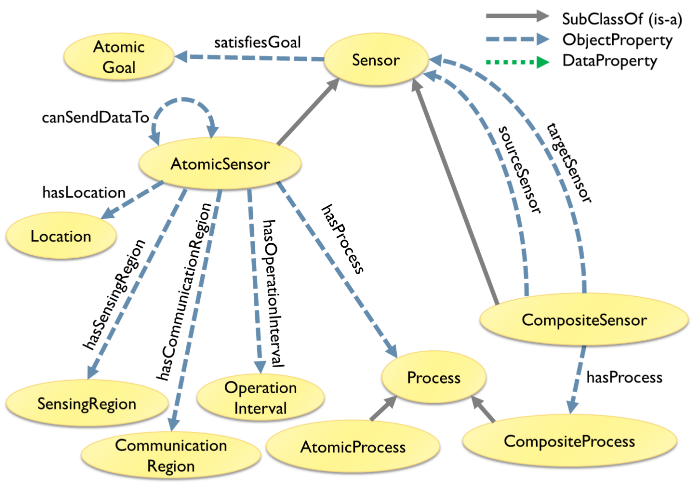

Fig. 5. The sensor semantics in the sensor ontology.

3.6 Goal Semantics

Goals specify the desired results and constraints that the composition system must try to satisfy. The semantics shown in Figure 6 are modelled after the *Sensor* concept in a similar way that Lin et al. [19] specifies the goal ontology for OWL-S. Only atomic goals are discussed in this paper, but composite goals can be extended to specify the order goals need to be satisfied.

The *changeStream* data property is used in the composition system to determine if the most general data type of *Stream* should be instantiated. Instantiating *Stream* to a more specific type allows sensors that can forward data to forward it directly to sensors that can take that specific type. This allows for sensors not required in the goal to be used and so extend the length of compositions. The *sensingRegionOverlap* data property indicates whether the sensing regions of the sensors must overlap.

4 Semantic Sensor Composition System

A conceptual model of the composition system, with the flow of information, is given in Figure 7. This section covers the parts of the system surrounding the

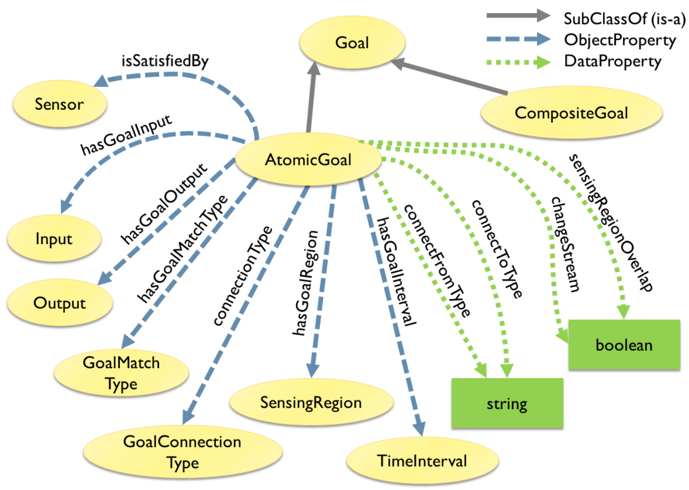

Fig. 6. The goal semantics in the sensor ontology.

sensor ontology. Syntactic descriptions of sensors and goals can be easily created or generated. The composition system extracts semantics from these syntactic descriptions and populates the sensor ontology. The following tools used are not discussed: OWL 1.1[4], Pellet 2.0.0 RC7[5], and OWL API[6].

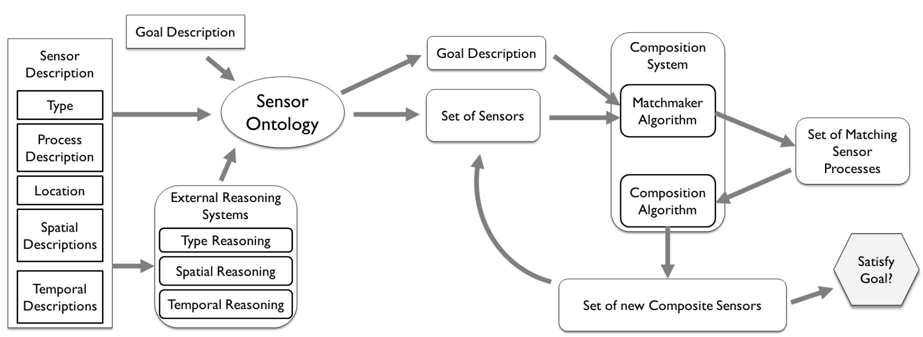

Fig. 7. Overview of the composition system.

[4] `http://www.w3.org/Submission/owl11-overview/`
[5] `http://clarkparsia.com/pellet/`
[6] Version that came with Pellet 2.0 RC7 was used. `http://owlapi.sourceforge.net/`

4.1 Matching Sensors

Matching sensors is filtering the required sensors based on user goals and then filtering on sensor properties as compositions are created. Filtering sensor types matching the goal is a simple query. Filtering on spatial and temporal properties is made simpler by the asserted RCC and AIA relations. The *canSendDataTo* relation in the sensor ontology is derived from the RCC and AIA relations to suggest sensors in range and that operate in the same time frames of each other.

For sensor processes, the matching is based on their inputs and outputs. The ontology allows determining the degree of match of the concept(s) of the outputs to the concept(s) of the inputs. There are four degrees of matches: exact ($outputClass \equiv inputClass$), subsumed by ($outputClass \sqsubseteq inputClass$), subsumes ($outputClass \sqsupseteq inputClass$) and fail [10,14]. The sensors with processes with inputs and outputs matching goal are filtered and the OWL reasoner is invoked to determine the degree of match in the composition process.

Creating new matches is performed by a matchmaking algorithm. The algorithm creates a set of possible matches from the current working set of sensors for the composition algorithm. The matches are recorded based on the *Binding* concept with the structure of the properties of the concept. The composition algorithm creates a new set of composite sensors on each iteration and the matchmaking process is repeated on these new composite sensors.

4.2 Composing Sensors

The composition algorithm takes the bindings created by the matchmaking algorithm and builds a binary tree of processes and sensors to create new composite sensors. Base stations are defined as sensors having a process marked to be a data collector. Composition is directed towards these sensors and all compositions end with a base station.

New composite sensors are checked against the goal requirements. If the new composite sensors satisfy the goal, the system stops and adds the new sensors into the sensor ontology; otherwise, the composite sensors are added to the set of working sensors and the process repeats. The new composite sensors are compared to the old sensors to reduce the number of comparisons. Circular compositions resulting from composite processes on the same sensors or in a chain of compositions are checked against the current composition trees.

For experiments, the composition system is split into the "Initialisation Phase", encapsulating the creation and extraction of semantics from syntactic descriptions (left half of Figure 7), and "Composition Phase" (right half of Figure 7), encapsulating the composition system. Data collection and ontology consistency checks of the ontology are performed at the start, middle, and end of the two phases of the system. The data collected are summarised in next section.

5 Experiments

Experiments were conducted to evaluate the system for performance based on automatically generated random syntactic sensor descriptions. The evaluation uses randomly generated location, sensing and communication regions, and operation intervals. The same properties are also randomised in the goal descriptions. Data points were recorded after three data points had been generated to "warm-up" the Just-In-Time compiler [20]. Three experiments are presented: the first two compare the effects of density of sensors, and the last looks at the combinatorial problem when a message forwarding process is introduced with freedom of input and output.

5.1 Experiment Scenario

A scenario was created and varied according to the experiments. Let $n \in \{10, 15, 20, 25\}$, then the scenario conditions for Experiment 1 are:

- 1000×1000 two dimensional grid
- For Experiment 2 only: change the above grid to a $50n \times 50n$ two dimensional grid
- n Wind Sensors with
  - Wind Speed Process
    - Outputs wind speed
  - For Experiment 3 only: additional Message Forwarding Process
    - Input is a generic stream of data and output is also a stream
- n Temperature Sensors with
  - Temperature Process (outputs the ambient temperature)
  - Wind Chill Temperature Process
    - Inputs of wind speed and temperature
    - Output of wind chill temperature
  - For Experiment 3 only: additional Message Forwarding Process
    - Input is a generic stream of data and output is also a stream
- $2 \times n/5$ Base Stations with
  - Capture Messages Process
- Randomising
  - Location
  - Sensing Region
    - Maximum size: 100×100
  - Communication
    - Maximum size: 200×200
  - Operation Interval
    - Operation times varies over the same day

The number of wind and temperature sensors remains the same, and the number of base stations is in proportion to the other sensors in a ratio of $(number\ of\ windsensors + number\ of\ temperature\ sensors) : 1\ basestation$. The ratio ensures that satisfiable compositions are likely to be found. The results for the three experiments are summarised in Figures 8 and 9 for the average time over 50 iterations of the algorithm, and Figures 10 and 11 for the number of individuals created for each part of the algorithm. The key of the results figures means *windSensors_temperatureSensors_baseStations* (e.g. 10_10_4 means 10 Wind Sensors, 10 Temperature Sensors, and 4 Base Stations were used in the experiment).

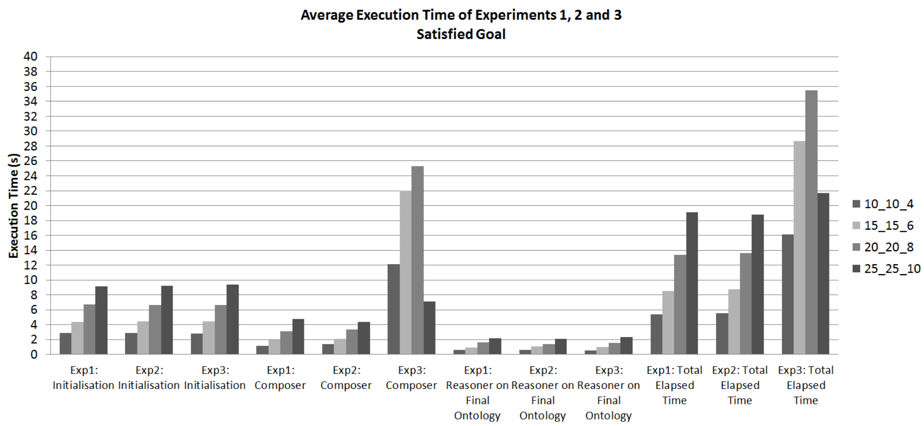

Fig. 8. Average execution times of experiments 1, 2 and 3 for compositions satisfying the goal.

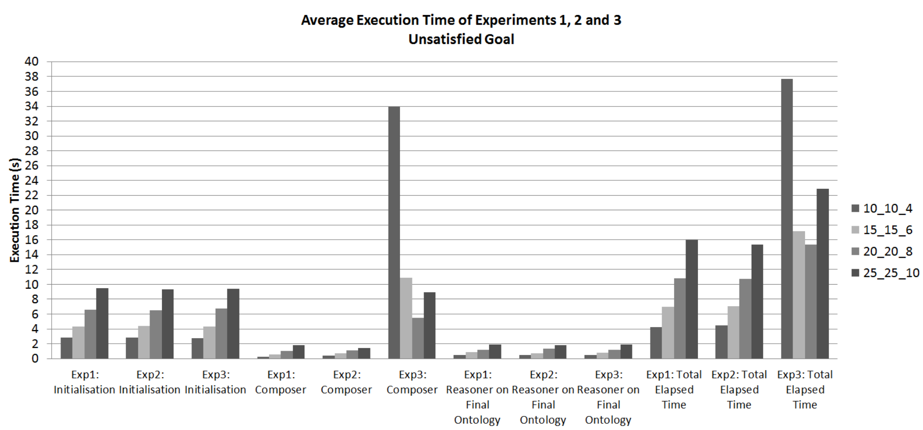

Fig. 9. Average execution times of experiments 1, 2 and 3 for compositions not satisfying the goal.

5.2 Experiment 1: Increasing Density

This experiment looks at the performance of the composition system as more sensors are added to a fixed region. As the density increases, it is expected that the likelihood of compositions satisfying the goal is higher, but more sensors may need to be checked in a targeted region. This experiment tests the composition system as the breadth of the composition trees increases.

Results The results show an increase in the execution time of all parts of the algorithm as more sensors are added. The Initialisation Phase dominates

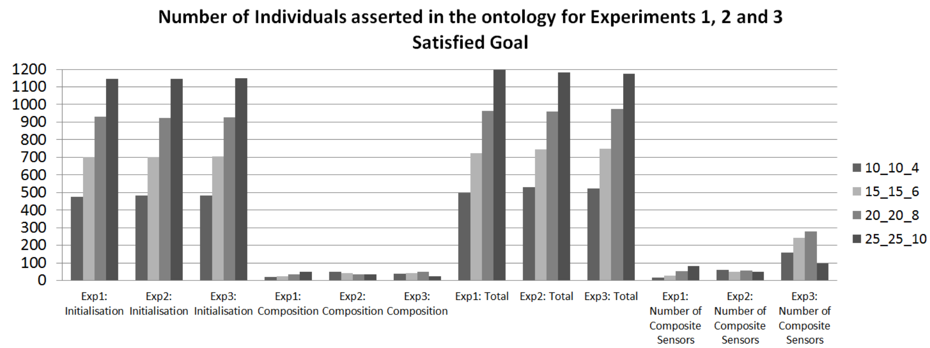

Fig. 10. Number of Individuals generated in the ontology for experiments 1, 2 and 3 for compositions satisfying the goal. The rightmost set of results is not the number of individuals.

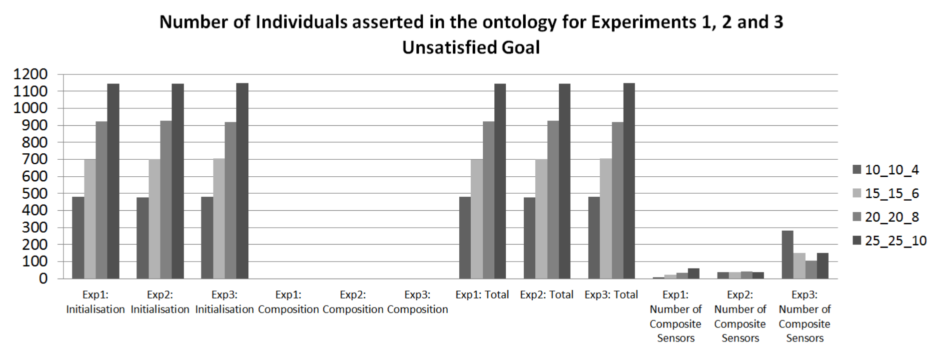

Fig. 11. Number of Individuals generated in the ontology for experiments 1, 2 and 3 for compositions not satisfying the goal. The rightmost set of results is not the number of individuals. No individuals are created for an unsatisfied goal.

the execution time and the reasoner takes the least time. Comparing the two cases for the goal, the composer takes less time in the unsatisfiable case, the Initialisation Phase remains about the same, and the reasoner takes less time. For the unsatisfiable case, the composer does not add more individuals to the ontology as there are no suitable sensors, hence the reasoner takes less time.

The increasing number of individuals with the increasing number of sensors is observed. The size of the ontology and the number of individuals naturally affects the reasoner's capabilities to check for consistency and answering queries [21]. The reasoner remains efficient when the number of individuals is around a thousand. The number of individuals required for the composite sensors are comparatively small compared to the initialisation.

The small number of individuals for composite sensors is ideal as more compositions are likely to be added, but initialisation only needs to be performed once (or partially when new sensors are added). This experiment shows composite sensors do not make the ontology unreasonable complex and that most of the time taken is in the initialisation and composition phase. The number of composite sensors increases, suggesting more sensors evaluated in the composition phase and the likelihood of finding a satisfying composite sensor decreases.

5.3 Experiment 2: Constant Density

This experiment looks at the performance of the system as more sensors are added to a region of space that increases in ratio with the number of sensors. Since the density remains constant, it is expected that the likelihood of compositions satisfying the goals in any region remains the same and similarly with the running time. This experiment tests the filtering capabilities of the composition system to remove irrelevant sensors.

Results The execution times have no significant difference to Experiment 1 for both cases (paired 2-tailed student's t-test value is between 0.45 and 1.00 for each time component). The composition part has some differences in the execution time, performing slightly better with more sensors (i.e. less time) and slightly worst with fewer sensors (i.e. more time). The number of individuals created by composition reflects the changes in execution time.

The area where the sensors are placed seems to have an effect on the number of sensors created. Smaller areas means sensors are likely to be closer, so there more sensors for the composition system to check. The time taken by the composition system seems to be dependent on the number of sensors instead of the sensors required to measure the goal sensing region. Another possibility is the goal region covers an area common to many sensors. The density of sensors does not seem to have a significant difference in the performance of the composition system.

5.4 Experiment 3: Message Forwarding Sensors

This experiment investigates the complexity of the compositions by adding a simple message forwarding process to each sensor type. The process has one input and one output, where both has the most general type *Stream* and unit of measurement *measureAny*. This process simply takes any input and forwards the message to another sensor (not at the same sensor). This experiment tests the composition system as the sensor network becomes more complex, requiring longer chains of compositions.

Some problems were encountered in this experiment, which revealed limitations of the system for future work. The problems come from the vast number of composite sensors created in the composition algorithm. An upper limit on the time taken is placed at 400 composite sensors. The results presented in this section are only for compositions not satisfying the goal and when the algorithm terminates because of a large set of composite sensors.

Results The number of compositions is low compared to the number of composite sensors created as seen in Table 1. When the algorithm creates more than 400 composite sensors the average size of the set of sensors is shown in the last column of Table 1, which can be very large. The large set of sensors in the last column for a small starting set of atomic sensors results from the composition system check for many more possible composite sensors, resulting in complex compositions.

Table 1. Message Forwarding Sensors – Results: Satisfied Goal, Number of Individuals ±1 standard deviation

Sensors	Initialisation	Composition	Total	Number of Composite Sensors	Average Number of Composite Sensors (stop when > 400)
10_10_4	484 ± 14	37 ± 34	522 ± 36	160 ± 109	3730 ± 5200
15_15_6	705 ± 15	43 ± 35	748 ± 39	243 ± 136	2711 ± 5088
20_20_8	928 ± 17	48 ± 41	976 ± 50	280 ± 159	1224 ± 1065
25_25_10	1151 ± 18	23 ± 11	1174 ± 20	98 ± 87	1955 ± 1346

6 Evaluation

The experiments show the feasibility of applying semantics to sensors and of automatically creating compositions. From the execution times for experiments 1 and 2, the reasoner performed efficiently and showing only small increases with more sensors and many more individuals in the ontology. Comparing to the initialisation phase, in the composition phase few number of individuals for composite sensors are created when the goal can be satisfied. Experiment 3 shows a wide variation of execution times over 50 iterations, which is only partially seen in the figures. However, the number of composite sensors and individuals are also low, but higher than experiments 1 and 2 in some cases.

Table 1 shows the crippling number of sensors created in the last column for experiment 3. The creation of long compositions required many sensors to be created, which vary greatly on each iteration, similarly with the time taken in the composition phase. However, checking consistency and reasoning on the ontology are performed quickly, similar to experiments 1 and 2. So, the semantic overhead in searching for composition do not contribute greatly to the overall execution times.

Experiments 1 and 2 have very similar execution times and resulting number of individuals. This suggests the number of surrounding sensors and number of sensors does not affect the composition system significantly. The composition system stops early when the goals cannot be satisfied, suggesting the system can quickly determine unsatisfiable goals. The execution time of the initialisation phase and checking of consistency by the reasoner are similar across all three experiments.

The number of individuals created in the initialisation phase is numerous because the quantitative values for the regions and intervals. The values do not affect the reasoner, but can be removed to reduce the size of the ontology. Despite the large number of composite sensors created in experiment 3, the number of individuals representing compositions remains low (in the case of satisfied goal). This suggests the composite sensors have many common constituent sensors.

These experiments show that the composition system works well on wide composition trees, but struggles on deep composition trees. The number of individuals in the ontology do not affect the reasoning time. Comparatively few individuals are created in the composition phase than the initialisation phase. Semantic sensor composition is achieved with a sensor ontology and a composition system, but some weaknesses are apparent that limits the application of composition system to large and complex sensor networks.

7 Conclusion

This paper describes two contributions: a sensor ontology and a composition system. The ontology covers semantics of the sensor types, process semantics, spatial semantics, temporal semantics, sensor semantics, and goal semantics. The spatial and temporal semantics are a novel addition, providing semantic diversity and capabilities beyond OWL. The composition system provides automated and goal directed composition of sensors using the ontology. Experiments show the feasibility of the sensor ontology in describing sensors and sensor compositions, and the limitations of the composition approach. From the experiments, future work includes looking at pruning methods and AI search approaches that exploits semantic information. The sensor ontology and composition system provide semantic interoperability, semantic diversity, and automation, which allows users to query, interact, and extract knowledge directly from any sensor network.

Acknowledgements This work was conducted as part of an Honours research project with a scholarship from the CSIRO ICT Centre.

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