

Relation-Centric Development of Spatially-Aware Applications

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Abstract

With an increasing density of computationally enhanced objects that are distributed in physical space, it becomes important that they operate autonomously and allow for a more implicit interaction with humans. Spatial properties and relations are important in this regard, as an awareness about such context information builds up the basis for autonomously adapting to spatial changes in the environment. In this paper, we propose a relation-centric approach for the development of spatially-aware applications for autonomous embedded systems, which builds upon qualitative abstractions of spatial relations and the rule-based inference of conclusions from them. We implemented a service-oriented software framework for this purpose and demonstrate our approach by means of two application scenarios.

1 Introduction

With the embedding of sensors, actuators as well as processing and wireless communication capabilities into everyday objects, to which we refer to as “digital artefacts”, *spatially-aware behaviour* becomes increasingly relevant for the interaction with and among them. To allow for contextual interaction, they have to be able to collect information from sensor data, represent and reason about their perceptions of the environment, and share these perceptions and collaboratively adjust with other digital artefacts.

As digital artefacts are situated in physical space, especially the acquisition of (i) *spatial properties* like their position or direction through sensors, and (ii) *spatial relationships* between them like distance and orientation, provide valuable context information. The consideration of spatial relationships provides digital artefacts with an understanding of their relative spatial situation or context with respect to other artefacts, and enables automatic adaptation to changing

spatial contexts at runtime in a semantically meaningful way. Thus, more *autonomous* behaviour and a more *implicit* (i.e. at the periphery of human attention) rather than explicit interaction with humans becomes possible. Autonomous operation of artefacts refers to their coordination of activities in a self-managed style; in this regard, spatial abstractions have been identified to be valuable for supporting mechanisms of self-organization in [1], among others.

An important issue is the *abstraction of spatial context*, which is about separating from details that are not relevant for the application. For example, abstractions of *locations* using high-level information like rooms and buildings instead of geographical coordinates [2], or relations between locations which are represented with semantically meaningful names [3], have been used by researchers with the aim to provide spatial information in a sensor-independent and more natural way that is closer to human concepts of space.

In our work we not only utilize location information, but additionally consider the direction and spatial extension of artefacts with respect to a global reference system and with respect to each other. We aim at facilitating the development of spatially-aware applications for autonomous digital artefacts by using non-numerical *qualitative abstractions of spatial relations* (cf. [4]), which abstract from low-level details and have clear advantages whenever the spatial cognition of humans is involved. We propose a novel concept for developing spatially-aware applications for autonomous artefacts, which comprises the maintenance of a spatial model of their environment and the provision of a programming model that is based on qualitative spatial relations.

The works closest to ours are the Relate system [3], the Cooperative Artefacts [5] concept and the Mediacup [6], which all utilize spatial relations for the interaction between mobile devices. However, our work is distinct with regard to the consideration of explicitly defined spatial areas, the recognition of spatial rela-

tions therefrom, their flexible and domain-specific abstractions (i.e. with application-dependent semantics and granularity) as well as the proposed concept for inferring conclusions from the recognized relations by using logical rules.

This paper is structured as follows. First, Section 2 presents our concepts for spatial awareness that have been implemented in a service-oriented software framework. In Section 3, a relation-centric approach for developing spatially-aware applications on top of our framework is proposed. It has been evaluated by means of two application scenarios presented in Section 4: (i) a belt which provides humans with a tactile perception of their environment, and (ii) an application which serves as a fundament for focus-nimbus based spatial interaction. Finally, Section 5 summarizes the paper.

2 Spatial Awareness

The aim of our work is to provide *spatial awareness* – i.e. knowledge about spatial properties (e.g. position) and relations (e.g. distance) – to physical real-world objects with embedded digital technology to which we refer to as “digital artefacts”. They utilize XML-based *self-descriptions* for autonomously *exchanging* their spatial properties with other artefacts in range by using our Zones-of-Influence approach which has first been published in [7].

A *Zone-of-Influence (ZoI)* is an explicitly defined geographical area which is relevant for an artefact’s behaviour, whereas a single artefact can be associated with multiple ZoIs. A ZoI is characterised by its name, position, direction and geometric extension in space. These spatial properties can either be static (i.e. not changing over time) or dynamic (i.e. dependent on sensor values). The position of a ZoI is referred to as *anchor point*, and its shape and size are specified relative to the anchor point. ZoIs can be used for representing the physical extension of an artefact (referred to as physical ZoI) or any other application-relevant geographic region (e.g. its interaction range).

Digital artefacts acquire *spatial relations* by comparing two ZoIs with respect to certain spatial properties. A spatial relation $R(p, r)$ is defined by a primary ZoI p and a reference ZoI r , meaning that p is in relation R to r . We basically distinguish between quantitative and qualitative relations, where the former are represented with numerical and the latter with symbolic values. Qualitative spatial relations abstract continuous properties by discrete symbols, making only as many distinctions as necessary and thus hiding details which are not relevant for a certain application.

Each artefact maintains a repository (i.e. a

database) of current and past relations, which are characterised by a name defining the relation type (e.g. **StaticDistance**), a value (e.g. **far**), an identification of the primary and reference ZoI as well as a *time interval* in which it is valid. An interval is represented by a start and an end point in time, and it defines methods for (i) acquiring qualitative temporal relations such as **before** and **overlaps** to other intervals, (ii) combining intervals using set-operations such as **intersect** and (iii) determining if the time interval contains the current point in time. However, temporal relations are not considered in the following, more about that can be found in [8].

Figure 1 illustrates some common *qualitative abstractions of spatial relations*. For topological relations, five relations according to the RCC-5 calculus presented in [4] can be distinguished. For orientation relations, a cone-based representation which partitions the 360° range in four equally sized sectors can be used, describing where the primary ZoI p is placed relative to the reference ZoI r and the direction of r . Distance relations are calculated using the Euclidean distance and partitioned such that a qualitative distance conforms to an interval of quantitative ones (cf. [9]). However, these qualitative relations are just examples; as will be seen in Section 4, any other application-specific relations and relation semantics are possible. Besides static relations as discussed by now, *dynamic* relations considering temporal aspects like **moving away** or **rotating counterclockwise** can also be defined, but are not considered in this paper.

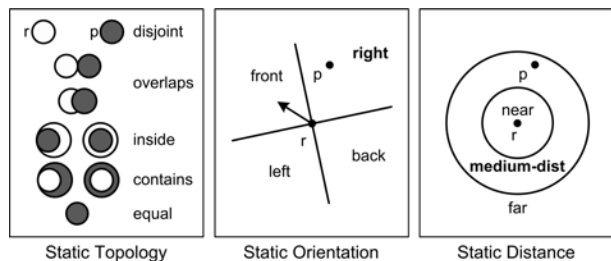


Figure 1. Qualitative spatial relations.

In order to achieve spatially-aware behaviour, we propose a *rule-based approach* for inferring conclusions from the stored history of spatial relations, namely to combine relations in the repository (*condition* of the rule) in order to (i) infer new relations or (ii) trigger respective application-level actions (*consequence* of the rule). Using rules can facilitate the development of spatially-aware applications as they allow for *declarative programming* at a higher level of abstraction.

We have implemented a *service-oriented framework*

[8] which is based on the above concepts, and developed several applications for evaluation purposes on top of it. It is split into components for (i) discovering artefacts and exchanging self-descriptions with them, (ii) providing an up-to-date ZoI model of the spatial situations of discovered artefacts, (iii) visualising the currently maintained ZoI objects, (iv) recognizing spatial relations by a pairwise comparison of ZoIs using pluggable relation recognizers and (v) inferring conclusions with logical rules. Relation recognizers and rules depend on the application requirements and can be adapted at runtime (i.e. dynamically changed by the respective application) to support context-aware behaviour. The insertion of recognized relations into the repository as well as the matching of rules with the relations therein is conducted periodically. The framework is based on the Equinox OSGi framework¹ and uses the JBoss Drools 4.0² rule engine for reasoning about qualitative relations.

3 Application Development

As emphasized in the introduction, we particularly consider spatial relations between artefacts (e.g. their position with respect to each other) important for the development of spatially-aware applications. As a consequence, we propose a *relation-centric approach* for describing the behaviour of artefacts, which corresponds to the design process for building context-aware applications presented in [10] but is focused on spatial contexts on the one hand and is specific to our software framework on the other hand. It consists of the following five steps:

1. *Identification of spatial relations* between objects which are relevant for the application. A spatial relation is characterised by its type (e.g. qualitative orientation), the possible values (e.g. **left**, **front**, **right** and **back**), their semantics – i.e. how they are interpreted, which depends on the respective application (e.g. the meaning of **front** may be different in automotive and human-computer-interaction scenarios) – and the dimensionality, among others.
2. *Definition of Zones-of-Influence* needed for the recognition of the relations identified in step 1. Therefore, the artefacts which are to be related, as well as their corresponding Zones-of-Influence (i.e. represented by one or more possibly different spatial regions), have to be identified.

¹<http://www.eclipse.org/equinox>

²<http://labs.jboss.com>

3. *Selection or integration of sensors* which can be used for determining the spatial properties position, direction or the spatial extension of the artefacts' dynamic Zones-of-Influence. For example, the ZoI of a moving car's breaking distance can be modelled by its changing position and direction, as well as the velocity defining shape and size of the ZoI. These dynamic properties can be specified in the self-descriptions of artefacts by including references to the respective sensors (cf. [8]).
4. *Selection or implementation of relation recognizers* according to the identified relations and ZoIs in the steps 1 and 2. Similar to the use of spatial sensors, suitable recognizers can be either selected if available or have to be implemented otherwise.
5. *Rule-based modelling of the application behaviour* by mapping spatial relations or combinations of them to application-level actions or inferring new relations therefrom.

4 Application Scenarios

In this section we demonstrate how the relation-centric approach described above has been applied to the development of two different spatially-aware applications. The first one addresses the perception of spatial situations by means of tactile feedback, and the second one deals with providing an awareness about the focus- and nimbus-relations between artefacts. In both scenarios, just 2D-relations are used, which is however not a restriction of our framework. These two applications have been chosen to show the framework's feasibility, and in particular the value of qualitative relations for spatially-aware applications involving spontaneously interacting artifacts.

4.1 Tactile Space Awareness

The first scenario aims at providing a person with a tactile perception of surrounding artefacts. Similar to [11], we use a belt with eight vibrator elements for the indication of spatial relations. As one can imagine, tactile space awareness is useful for scenarios like blind people guidance or notifications in environments where auditive and visual feedback are not feasible.

We have developed this application according to the five steps proposed in Section 3. First, we observed that we require topological, orientation and distance relations. We define a geometric area around the belt for which it is responsive to artefacts, which requires the topological relations **overlaps** and **inside**. According

to the eight vibrator elements of our tactile belt, we decided for using the eight qualitative orientation relations *front*, *front-right*, *right*, *back-right*, *back*, *back-left*, *left* and *front-left* in order to indicate orientations to surrounding artefacts. To provide more comprehensive awareness about relative positions, we additionally distinguish ten qualitative distance relations *distance_0* to *distance_9* to be represented by different vibration intensities. However, other relations or combinations of them could be used for tactile space awareness, as for example to represent the velocity of approaching artefacts with according vibration intensities or to encode different situations by respective vibration patterns.

In the second step, we define two types of ZoIs. First, the person’s awareness zone representing the responsive geometric area of the belt is modelled as a dynamic ellipse-shaped ZoI, whose extension in the direction of movement may depend on the person’s velocity. Second, all other artefacts relevant for the application are modelled by their physical extensions in space (i.e. their physical shapes). Every artefact, which contains a representation of its physical extension in the self-description, can thus be displayed by the tactile belt.

In order to determine position and direction of the dynamic Zones-of-Influence – i.e. those of the user (who wears the belt) and of the mobile artefacts – we use the Intersense IS-900³ ultrasonic tracking system. Position and direction of stationary artefacts are represented with static ZoIs. Moreover, the user’s velocity is acquired from a virtual sensor which is based on an analysis of position trajectories.

For each type of qualitative spatial relation, a respective recognizer has been implemented. In this regard, orientation relations are calculated by relating the anchor points of two ZoIs at a time, and distance relations are defined by the minimum distance between the shapes of the respective two ZoIs. The implemented orientation and distance recognizers are parameterized by defining a mapping of quantitative relation values (e.g. 11, 4°) to qualitative symbols (e.g. *front*). Topological relations are recognized according to the RCC-5 calculus mentioned in Section 2.

In the last step, the actual application behaviour is modelled with the single logical rule depicted below. It checks for the simultaneous existence of a topological *overlaps* or *inside* relation as well as an orientation and distance relation between the primary ZoI (i.e. a certain artefact’s physical shape) and the reference ZoI (i.e. the user’s awareness shape) at the current point in time (method *isCur()* which is invoked for the relation intervals). For each combination of primary and

reference ZoI in the relations repository, for which the rule condition is fulfilled, the application-level method *TactileBelt.vibrate()* is invoked with the primary ZoI *\$pZ* (i.e. an artefact) and its distance *\$d* and orientation *\$o* relations to the reference ZoI *\$rZ* (i.e. the user’s zone) as parameters. This method simply activates the vibration element as defined by the orientation relation, with the vibration intensity given by the distance relation.

```
rule "TactileSpaceAwareness"
  when // condition
    Relation(name=="StaticTopology", value==
      "overlaps" || value=="inside", $pZ:pZoI,
      $rZ:rZoI, $i1:interval)
    Relation(name=="StaticOrientation", $o:value,
      pZoI==$pZ, rZoI==$rZ, $i2:interval)
    Relation(name=="StaticDistance", $d:value,
      pZoI==$pZ, rZoI==$rZ, $i3:interval)
    eval($i1.isCur() && $i2.isCur() && $i3.isCur())
    eval($rZ.equals("Person:AwarenessShape"))
  then // consequence
    TactileBelt.vibrate($pZ, $o, $d);
end
```

The hardware of our tactile belt can be seen in Figure 2. Figure 2a) shows the belt with its eight vibrator elements, which are connected to the belt controller shown in Figure 2b). It consist of an Atmega32-based microcontroller board for controlling the vibrator switches according to commands received via Bluetooth from a notebook computer running our framework. Figure 2c) shows a user wearing the tactile belt together with a batter pack and the wireless IS900 tracker for acquiring the user’s position and direction.

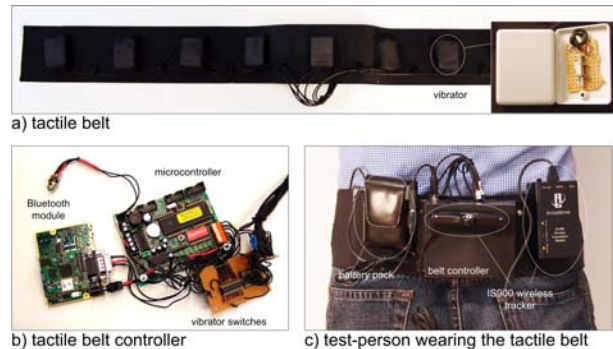


Figure 2. Hardware of the tactile belt.

The output of our framework’s visualisation component is shown in Figure 4. The ellipse represents the user’s awareness zone and the arrow his direction in space. Four artefacts – i.e. their physical Zones-of-Influence – are visualised with corresponding green shapes. Two of them are in a topological *overlaps* relation with the user’s awareness zone, resulting in a *front-right* relation to the table and a *back* relation to an obstacle behind the user. Hence, the rule de-

³<http://www.isense.com>

pictured above is executed for each of them, resulting in a vibration of the corresponding vibrator elements (cf. the visualisation in Figure 4).

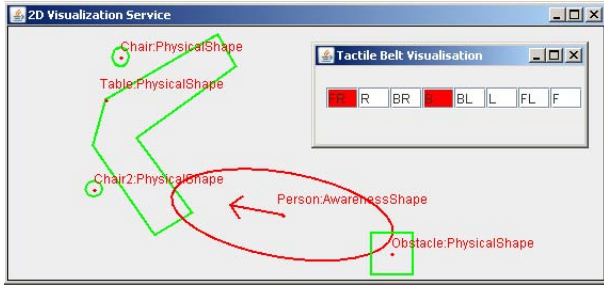


Figure 3. 2-D visual. of the spatial situation.

4.2 Focus-Nimbus Awareness

In our second scenario we have developed an application which provides a fundament for focus-nimbus based interaction similar to [12], defining that an object p is in the focus of another object r if r is aware of p ; in this case, r is said to be in the nimbus of p . Our implementation determines the focus of an artefact r both by its field-of-view (FoV) and the view area from which the other artefact p – more precisely, a certain point of interest on its physical shape – can be observed. The view area is an arbitrarily shaped geographic region defined by p , which however might be influenced by the ZoIs of obstacles around p .

As for the previous scenario, we developed the focus-nimbus awareness application along the five steps of Section 3. First, we identified the need for the FoV relations **within** ($\pm 45^\circ$ with respect to the person’s viewing direction) and **outof**, as well as for a topological relation in order to determine if the person is within the view area of a certain point of interest (i.e. from where it can be seen). Second, we observed the following ZoIs to be relevant for this application: (i) the view area of a certain point of interest is modelled as a static or dynamic freeform-shaped ZoI with the point of interest itself as its anchor point, and (ii) a dynamic point-shaped ZoI representing the person (i.e. his physical extension is disregarded).

The acquisition of the person’s position and direction is again achieved by using our IS-900 tracking system, position and direction of the points of interest are either stationary or again determined by the tracking system. Two types of relation recognizers are distinguished. First, the application-specific FoV relation recognizer builds upon a quantitative orientation recognizer, which provides a numeric angle for the orientation of a primary ZoI’s anchor point to that of the

reference ZoI, and results in a qualitative **within** relation for orientations in the range of $[-45^\circ, 45^\circ]$ and an **outof** relation otherwise. Second, the topological recognizer is again defined according to the RCC-5 calculus mentioned in Section 2.

The application behaviour is defined with the rule depicted below. Its condition part checks for the simultaneous existence of a FoV relation of a primary ZoI $\$pZ$ from a point of interest to the reference ZoI $\$rZ$ of the person, as well as a topological **contains** or **overlaps** relation from $\$pZ$ to $\$rZ$. As a consequence of a fulfilled rule condition, two relations are inserted in the repository: a relation **within** of type **Focus** from the primary ZoI $\$pZ$ to the reference ZoI $\$rZ$ and a relation **within** of type **Nimbus** from $\$rZ$ to $\$pZ$ (i.e. $\$pZ$ and $\$rZ$ are switched). Applications building on top of this Focus-Nimbus Awareness can simply query for relations of type **Focus** or **Nimbus** and conduct according behaviour.

```

rule "FocusNimbusAwareness"
  when
    Relation(name=="FoV", value=="within",
      $pZ:pZoI, $rZ:rZoI, $i1:interval)
    Relation(name=="StaticTopology",
      value=="contains" || value=="overlaps",
      pZoI==$pZ, rZoI==$rZ, $i2:interval)
    eval($i1.isCur() && $i2.isCur())
    eval($rZ.equals("Person:FoV"))
  then
    Relation $focus = new Relation("Focus",
      "within", $pZ, $rZ, $i1.getIntersect($i2));
    Relation $nimbus = new Relation("Nimbus",
      "within", $rZ, $pZ, $i1.getIntersect($i2));
    insert($focus); insert($nimbus);
  end

```

Figure 4 shows the 2D visualisation of a spatial situation involving a person and a single point of interest, together with the corresponding relations in the repository. The green freeform shape represents the view area from which the point of interest can be seen, and the grey lines annotate the 90° view angle of the person. The content of the relations repository at the bottom of Figure 4 shows the recognized and inferred relations together with the time intervals in which they hold.

5 Conclusions

We have presented a novel approach for the relation-centric development of spatially-aware applications for spontaneously interacting autonomous digital artefacts. It is based on the representation of spatial regions to which we refer to as Zones-of-Influence, and the recognition of spatial relations between them. Fundamental is the qualitative abstraction of these relations, which are specific to an application and separate from details that are not relevant for it. Digital artefacts become aware about this spatial context

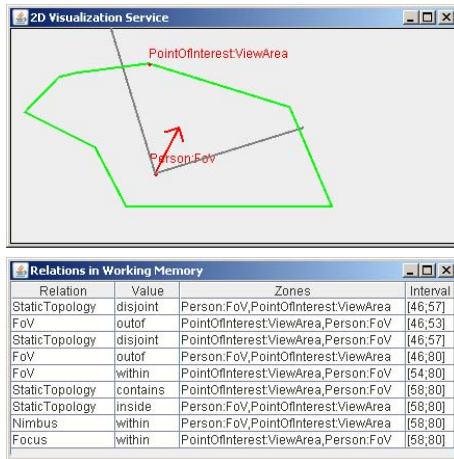


Figure 4. Visualisation and spatial relations.

information by exchanging it with other artefacts via so-called self-descriptions. Rules are used for inferring conclusions from qualitative spatial relations and thus provide a declarative approach for achieving spatially-aware behaviour. With our software framework, which enables the use of qualitative spatial relations, we demonstrated the development of spatially-aware applications by means of two different application scenarios. They showed the feasibility of our approach, as well as the value of using qualitative relationship abstractions which separate from low-level sensor details and allow for a more natural programming.

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