Spatial and Temporal Reasoning for Ambient Intelligence Systems

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Mehul Bhatt, Hans W. Guesgen (Eds.)

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Preface

Welcome to the Workshop on Spatial and Temporal Reasoning for Ambient Intelligence Systems at the International Conference on Spatial Information Theory 2009 in France. The workshop is a first in line of what promises to be a successful series of events focusing on both theoretical as well application-centered questions pertaining to spatial and temporal reasoning in the domain of intelligent and smart environments, or ambient intelligence in general.

A wide-range of application domains within the fields of ambient intelligence and ubiquitous computing environments require the ability to represent and reason about dynamic spatial and temporal phenomena. Real world ambient intelligence systems that monitor and interact with an environment populated by humans and other artefacts require a formal means for representing and reasoning with spatio-temporal, event and action based phenomena that are grounded to real aspects of the environment being modelled. A fundamental requirement within such application domains is the representation of dynamic knowledge pertaining to the spatial aspects of the environment within which an agent, system or robot is functional. At a very basic level, this translates to the need to explicitly represent and reason about dynamic spatial configurations or scenes and desirably, integrated reasoning about space, actions and change. With these modelling primitives, primarily the ability to perform predictive and explanatory analyzes on the basis of available sensory data is crucial toward serving a useful intelligent function within such environments.

The emerging fields of ambient intelligence and ubiquitous computing will benefit immensely from the vast body of representation and reasoning tools that have been developed in Artificial Intelligence in general, and the sub-field of Spatial and Temporal Reasoning in specific. There have already been proposals to explicitly utilise qualitative spatial calculi pertaining to different spatial domains for modelling the spatial aspect of an ambient environment (e.g., smart homes and offices) and also to utilize a formal basis for representing and reasoning about space, change and occurrences within such environments. Through this workshop, and its successor events in the future, we aim to bring together academic and industrial perspectives on the application of artificial intelligence in general, and reasoning about space, time and action in specific, for the domain of smart and intelligent environments.

Mehul Bhatt
Hans Guesgen
(Workshop Co-Chairs)

Invited Talk

Designing Information, Communication, and Experiences in Ubiquitous Hybrid Worlds

"It seems like a paradox but it will soon become reality: The rate at which computers disappear will be matched by the rate at which information technology will increasingly permeate our environment and our lives". This statement by Streitz & Nixon illustrates that new challenges for designing the interaction of humans with computers embedded in everyday objects will arise. While disappearance is a major aspect, "smart" artefacts are also characterized by sensors collecting data about the environment, the devices and humans acting in this context in order to provide ambient intelligence-based support. The resulting issues are discussed based on the distinction between "system-oriented, importunate smartness", implying more or less automatic behaviour of smart environments, and "people-oriented, empowering smartness", where the empowering function is in the foreground. The latter approach can be summarized as "smart spaces make people smarter" which is achieved by keeping "the human in the loop" and empowering people to be in control, making informed decisions and taking actions. Whatever type of smartness will be employed, representations of people, content and contexts play a central role. Last but not least, privacy issues in sensor-based smart environments are being discussed ranging from being a legal and moral right to becoming a commodity and privilege. The approaches and concepts will be illustrated with examples taken from different research projects ranging from smart rooms over cooperative buildings to hybrid cities.

Norbert Streitz
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Smart Future Initiative (previously Fraunhofer-IPSI)
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Invited Talk

Spatial and Temporal Modeling for AmI Systems: Industrial Applications

The talk presents two ongoing research projects at Siemens Corporate Research and Technology in the domain of Ambient Assisted Living (AAL) and Public Surveillance. One key feature in both domains is the ability to detect and identify specific behavioral patterns of persons. While AAL applications mainly focus on providing assistance functionalty to the user, Public Surveillance applications aim at detecting (and possibly preventing) potentially dangerous situations. To this end adequate models (e.g. of human behavior or processes) have to be constructed, taking into account spatial context and temporal dependencies. These models can be evaluated using standard approaches such as DL-reasoning, whereas alternative methods (e.g. graph-based spatial reasoning, or abductive reasoning) may turn out to be more flexible and performant.

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Corporate Technology
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Spatio-Temporal Outlier Detection in Environmental Data

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Abstract. Spatio-temporal outliers are occurrences that can reveal significant information about the phenomena under investigation. They are detected after comparing their non-spatial attributes with their spatio-temporal neighbours. One of the important definitions that need to be made is the spatio-temporal neighbourhood of an instance. There can be no universally applicable definition of the spatio-temporal neighbourhood (STN), but rather the definition should be based on empirical results in order to improve the quality of the decision making related to the spatial phenomena. Here we address this issue by defining STNs using Space-Time Autoregressive Integrated Moving Average (STARIMA). The method is illustrated using spatio-temporal outlier detection in Chinese annual temperature data.

Keywords: Spatio-temporal outlier, spatio-temporal neighorhood, STARIMA

1 Introduction

Massive data with both spatial and temporal dimensions are collected with increasing use of sensors so that data mining on this complex data structure is gaining popularity. Spatio-temporal outlier (STO) is an instance whose non-spatial attribute is significantly different from its spatio-temporal neighbourhood (STN). Their occurrences can reveal significant information about the phenomena under investigation. For example, all distinct natural events can be regarded as STOs such as big forest fires, earthquakes and volcanic activities, traffic accidents, hurricanes and floods. To have a better understanding or for better modelling of the spatial phenomena, STOs should be detected.

Most of the general outlier detection algorithms can be adapted to spatio-temporal domain but bearing one thing in mind: STOs are not global but local, in terms of their spatio-temporal neighbourhoods (STNs). This locality arises because of the spatial and temporal correlation, which need to be taken into account to when dealing with spatio-temporal phenomena.

STO detection can be examined under distance, wavelet analysis, clustering, visualization and graph based approaches.

Distance based outlier detection find outliers based on distances between instances. Adam et. al. [1] constructed spatial neighbourhood using Voronoi polygons and semantic neighbourhood using similarity coefficients, which were considered as STNs of an instance. However, temporal neighbourhood of an instance had not been involved in the definition of STN. Furthermore, predefined parameters as threshold values to define semantic similarity are intuitive. Similarly, Yuxiang et. al. [3] used descriptive statistics to detect spatial and temporal outliers separately. They also defined spatial neighbourhood intuitively and spatial and temporal dimensions were not considered as a whole.

Wavelet analysis based methods use wavelet transformation to detect STOs, which are considered as instances having high wavelet power. If the wavelet value of an instance exceeds a threshold, then that instance is regarded as a suspicious outlier. Barua and Alhajj [2] used wavelet transformation to detect outliers in sea surface temperature. However, it was not mentioned on choosing the threshold value. Since temporal dimension was not considered, only spatial outliers were found. Lu and Liang [4] detected spatial outliers in meteorological streaming data by using wavelet transform to latitudes of the data so that suspicious spatial outliers could be detected. Then, competitive fuzzy edge detector was used to find the boundary of the outlier region. Finally, center of the outlier region was found by fuzzy weighted average and tracked in the streaming data. They found spatial outlier trend rather than combining space-time to detect STOs.

Clustering approach detects STOs as instances which are not lying in any cluster. Birant and Kut [5] detected STOs by a three step procedure. First a clustering algorithm is applied (i.e. DBSCAN [12]) to detect possible spatial outliers as the instances which are not clustered. Second, possible spatial outliers are validated using statistical measures. Third, verified spatial outliers were checked in time. If the spatial outlier is different from its temporal neighbourhood, which is defined as consecutive time units, it is validated as STO. However, how to construct the spatial neighbourhood for statistical analysis in step two is not very clear in their approach. Cheng and Li [6] proposed a four step method for detecting STOs which is very similar but classification was conducted to form regions that have semantic meaning at different resolutions. In their approach, last step was achieved (i.e. comparison of the height values of possible outliers in consecutive time frames) based upon visual checking and simple calculation. In addition, both spatial and temporal neighbourhood definitions are made intuitively.

Visualization based methods mostly rely on visualization and also statistical analysis. Jin et. al. [8] detected real time traffic incidents using incrementally learning ability which considers user feedbacks. They generated spatial-temporal traffic models for each day-of-week using historical data based on occupancy of road. STOs were detected by comparing real time traffic data and with the models and if the difference was greater than a threshold an alarm was triggered. Alarm triggering in consecutive time frames indicates a high possibility of an incident. However, more generic approach for spatial neighbourhood should be derived, since in their case study all sensors are lined up along one freeway.

Graph based STO detection methods rely on graph theory and mostly represents the data in a graph. Li et. al. [7] detected temporal outliers in traffic data where spatial adjacencies were not taken into account. Road network was represented as a directed graph where vertices represent street intersections and edges represent road segments. Updating the temporal neighbourhood vector was based on the idea that: if two edges are historically similar in terms of feature values then current dissimilarity will be noted much and vice versa. In other words, big rewards and penalties come from previously stable trends. Main limitation of their research is that it did not consider the spatial nature of the data. Also, selecting the required parameters was done intuitively without giving any description on how to choose them. Kou et. al [9] proposed two graph-based spatial outlier detection algorithms. Edges represent the distance between two instances and nodes represent the instances. First algorithm detects point outliers by cutting the highest value edges (i.e. most distant instances) of the graph until user defined *m* outliers were found, where an outlier is defined as an node which has no edges connected to it. Proposed approach identifies outliers in order so that outliers were ranked. Most probable outlier will be detected first. Second algorithm detects region outliers by investigating the similarity between the possible outlier region and in its neighbours and also similarity in the region itself. But in many cases it cannot be known how many outliers the population have and also forcing each object to have “k neighbours” may mislead.

Most of the researches discussed above either did not consider spatial or temporal dimension of the data or did not use experimental findings when defining STN. This paper is motivated from this common judgment about defining the STNs. In order to capture the real information and to make more reliable decisions, STNs of an instance should be defined based on explanatory analysis. In this research, STN is defined by STARIMA and outliers are detected using statistical analysis.

Outline of the paper is as follows: next section explains how to derive the STN based on STARIMA. Third section discusses the proposed methodology for detecting STOs and explains the case study and fourth section concludes the paper with future work.

2 Deriving Space-Time Neighbourhoods (STN)

2.1 Definition of STO

STO is an instance whose non-spatio-temporal attribute value is significantly different from than its spatio-temporal neighbourhood (STN). This section will discuss on STN derivation, next section will discuss what is meant by “significantly different”.

Figure 1 shows an example of grid data, where attribute values of each grid square can be either ‘x’ or ‘o’. Centre grid is detected as spatial outlier in both Figure 1a and 1b. However, spatial outlier is validated as a STO only in Figure 1a, since it is also different from its temporal neighbours. In Figure 1b there is a spatial outlier trend which may be caused by a faulty sensor device or something special is happening at that grid all the time.

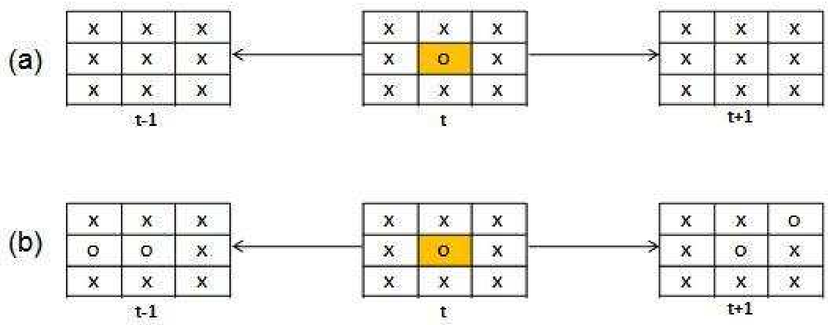


Fig. 1. STN of the colored instance

Choosing STN of a population intuitively will lead a wrong understanding about the data as well as detecting wrong STOs. As discussed in Section 1 previous papers defined STN institutively – a more precise or empirical approach is needed, which should reflect the correlation among space and time in the population. In the next subsection, we will introduce the principle of STARIMA which is able to define the STN based on the space-time correlation in the population.

2.2 Principle of STARIMA

STARIMA is a space-time dynamic model, and it expresses each observation at time t and location i as a weighted linear combination of previous observations and their neighbouring observations lagged in both space and time. STARIMA is defined as in equation 1:

$$z_i(t) = \sum_{k=1}^{p}\sum_{h=0}^{m_k}\phi_{kh}W^{(h)}z_i(t-k) - \sum_{l=1}^{q}\sum_{h=0}^{n_l}\theta_{lh}W^{(h)}z_i(t-l) + \varepsilon_i(t) \quad (1)$$

Where p is the autoregressive order, q is the moving average order, m_k is the spatial order of the k^{th} autoregressive term, n_l is the spatial order of the l^{th} moving average term, Φ_{kh} is the autoregressive parameter at temporal lag k and spatial lag h, θ_{lh} is the moving average parameter at temporal lag l and spatial lag h, $W^{(h)}$ is the $N \times N$ matrix of weights for spatial order h, and $\varepsilon_i(t)$ is a normally distributed random error at time t and location i.

STARIMA modelling is a procedure that captures the linear space-time autocorrelation structure from space-time series data. Moreover, in the STARIMA model, the space-time lag operator is the representation of space-time dependence, which indicates that each observation $z_i(t)$ at current time t and location i is not only influenced by the previous time series at the location, but also impacted by the previous time series of its spatial neighbours [14].

The space-time dependence is measured by the space-time autocorrelation function (ST-ACF) and space-time partial autocorrelation function (ST-PACF). From the calculation of ST-ACF and ST-PACF, we are able to define the time lag (temporal neighbour) and the space lag (spatial neighbour at particular time lag).

2.3 Defining STN based upon space-time lags

The autoregressive order p and the moving average order q of the STARIMA model are chosen provisionally after an examination of the space-time autocorrelation (ST-ACF) and space-time partial autocorrelation functions (ST-PACF)

In the conventional STARIMA model, the spatial hierarchical orders are defined in discrete-space data, and equal weights are assumed for the h^{th} order neighbours in the spatial weight matrix [10, 13]. However, the space-time series of environmental data usually have three special features: 1) nonlinear and nonstationary spatial trends, 2) stronger spatial correlation, and 3) anisotropic spatial distributions of the raw data sets. Definition of the spatial hierarchical orders and equal weights will result in 1) the computational costs of ST-ACF and ST-PACF becoming enormous; and 2) space-lag order m_k or n_l at each time-lag of the STARIMA model being difficult to decide. To simplify the calculation of the ST-ACF and ST-PACF, semivariogram scaled weights are chosen to measure the spatial variance in the space-time series of environmental data. Semivariogram-based analysis is able to evaluate spatial and temporal variations, and it can determine the magnitude of spatial dependence and the range of spatial autocorrelation among data. The instances within the range are spatially autocorrelated, whereas instances outside the range are considered independent. In other words, the instances within the range can be considered as spatial neighbours.

3 STO Detection for Space-Time Series

Three steps are proposed in order to detect STOs. First step is to define the time-lag based upon ST-ACF and ST-PACF, and space-lag based upon semivariogram, which define the range of STN. Then possible STOs are identified based on time series analysis of observations at individual instances. The third step is to define the STNs of the possible outliers and validate them based on statistical analysis. We illustrate these three steps in Chinese annual temperature data.

3.1 Data

Data used is the annual average temperature (degree/year) of China. Data is gathered from 193 stations which have 52 year observations from 1951 to 2002. The stations which have more missing than observed values are not considered in the following analysis. There were still missing values in the remaining 137 stations and are not interpolated to have more realistic results. More detailed explanation about the data may be found in [11].

First spatial neighbourhood was determined as 1550km by using isotropic semivariogram model. Second by using space-time autocorrelation and partial autocorrelation functions of STARIMA, space lag is determined as 1 and temporal lag is determined as 2. Thus, STN of an instance covers two previous year observations of the instances whose distance with other instances' distance is less than 1550km.

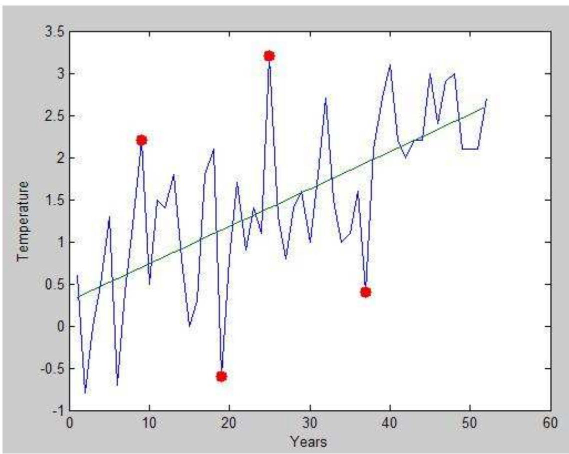
3.2 Time Series Analysis

For each of the station, year-temperature relation is investigated. Linear regression is employed to fit the data. If the residual (difference between the real value and output of linear regression model) for a specific year exceeds three standard deviations of the residuals, it is detected as possible outlier. 463 possible outliers were detected. Figure 2 shows this step and possible outliers are marked in red. Green line shows the linear regression model of the station. Years are shown starting from 1 to 52 which are the representatives of the years from 1951 to 2002.

3.3 Validation of Possible Outliers

After detecting possible outliers, their STNs are constructed including two previous year observations of the stations whose distance with the possible outlier's station is less than 1550 km. After constructing the STN of each possible outlier, temperature value of the possible outlier is compared with the $\mu + k\sigma$ and $\mu - k\sigma$ of its STN's temperature values. μ is the mean and σ is the standard deviation of the temperature values of the STN. *k* determines the belief in the outlier. As *k* increases, detected outliers should be more distant from their STN compared to lower *k* values which decreases the number of outliers detected. Possible outlier is validated as a STO if its temperature value is higher than $\mu + k\sigma$ or lower than $\mu - k\sigma$.

When *k* is set to 2, 24 STOs were found and when *k* is set to 3, 7 STOs were found. Figure 3 shows a verified STO, when k is 2. Horizontal blue line is the mean of the STN of the possible outlier (shown by red point) and black lines shows the upper and lower limits when k times standard deviation is added and subtracted from the mean.



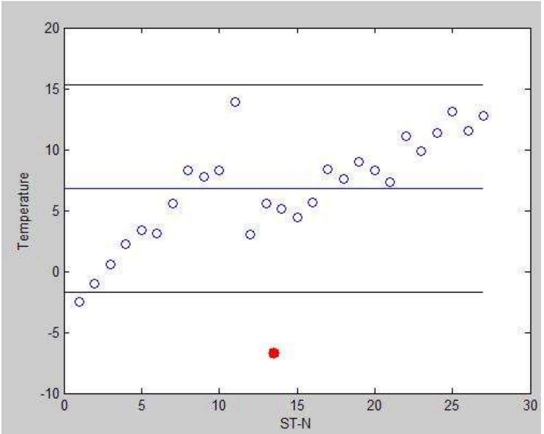


Fig. 3. STN of an STO instance

4 Discussion and Future Work

Main innovation in this research is that STN definition was based on empirical results instead of intuitive feelings. STARIMA and semivariogram analysis were used to define the STN of an instance.

Common characteristic of the detected STOs is that they all lie below the μ - $k\sigma$ limit. There is only one STO that exceeds μ + $k\sigma$ limit when k is 2. In other words almost all of the detected STOs are colder instances than their STN. This may arise density problems in the data. Different density regions may bias the standard deviation and mean of the data. Biased mean and standard deviation will consequently result in misleading STOs. Future work will be concentrated on handling density problems in the data.

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Spatio-Temporal and Context Reasoning in Smart Homes

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Abstract. Ambient intelligence has a wide range of applications, including smart homes. Smart homes can support their inhabitants in a variety of ways: monitoring for potential security risks, adapting the home to environmental conditions, reminding the inhabitant of tasks to be performed (e.g. taking medication), and many more. This often requires the ambient intelligence to recognise the behaviour of the inhabitants, which can be done more effectively if spatial, temporal, and contextual knowledge is taken into consideration. For example, cooking in the evening is pretty normal, but it is unusual if somebody has been cooking only an hour previously. However, if we know the context of the current situation, we may be able to explain this anomaly: having a party in the house may require several dishes to be cooked over a short interval. In this paper, we discuss spatio-temporal and context-based reasoning in smart homes and some methods by which it may be achieved.

Key words: Spatio-temporal reasoning, context-awareness, smart home, behaviour recognition, activity segmentation

1 Motivation

It is well-known that we are facing a demographic change towards an aging population. In Europe, for instance, it was reported that the number of people aged 65 and over is projected to increase from 10% of the total population in 1950 to more than 25% in 2050. In New Zealand, the number of people over 65 has doubled between 1970 and 2005 [2]. Furthermore, the global life expectancy at birth is projected to increase from 58 years in 1970–1975 to 75 years in 2045–2050 [3]. The group of elderly (aged 65 years and above) is the fastest growing segment of the world population.

Aging often results in some degree of physical disability, and even when the elderly are physically healthy, the aging process can be accompanied by cognitive impairment such as diminished sense and touch, slower ability to react, physical weakness, and memory problems. It is impossible to rely solely on increasing the number of caregivers, since even now it is difficult and expensive to find care. Additionally, many people are choosing to stay in their own homes as long as possible, and hope to remain independent. In order for them to remain autonomous, they need to perform the basic self-help tasks also known as the 'Activities of Daily Living (ADLs)' that include bathing, dressing, toileting, eating, and so on [1]. This has lead to a large number of monitoring systems also known as 'smart homes', or 'ambient intelligence systems' that consist of a network of sensors connected to household appliances, with the aim of assisting in the activities of daily living, either directly through involvement with the person, or by alerting carers when a problem arises. Examples of such smart home projects include the Adaptive Home [5], iDorm [6], MavHome [7], PlaceLab [4], Georgia Tech Aware Home [8], and Gator Tech Smart House [9].

For a smart home to react intelligently to its inhabitant's needs, the system needs to recognise their behaviour and to use spatio-temporal information, such as where (in which room?) and when (at what time) did a particular event occur? Additionally, and possibly more importantly, the contextual information (how was the current situation reached? what else is happening? what is the state of the environment?) needs to be considered.

Although, to some extent, the location of the sensors is known *a priori* from the sequence of sensor observations, it is not enough to allow effective reasoning. Using the example from [12], it would be unusual for somebody to walk around in a triangle repeatedly in the living room from the sofa to the window and then to the television. But it makes sense if that person is walking around a triangle repeatedly between fridge, cabinet and stove in the kitchen. And even in the kitchen, this behaviour would be unusual if it occurs in the middle of the night. One issue with both spatial and temporal resolution is that the scale on which it is measured can change the analysis. For example, an event can happen once a year (birthday, Christmas, etc.), weekly (visit from a health worker), daily (showering), or repeatedly during the day (phone calls). If the birthday was being celebrated every day then this would be something that the smart home should recognise as unusual. However, the temporal resolution may have to be even finer to recognise many potentially dangerous events (e.g., microwave oven used for too long).

Besides spatio-temporal information, context awareness also play an important role in interpreting behaviour, and should not be treated independently. For example, it is normal for a person to take an afternoon tea in the garden (spatial) if it is summer and it occurs during the day (temporal). The context information could include details such as whether the cup is filled with tea, or whether the person is standing, squatting, or sitting in the garden, as well as what they were doing earlier in the day and who else is around. For example, it may be normal for a person to boil water in the middle of the night if the weather is cold, and the person has just finished watching a movie. If we know the context of the situation, we can reason that the person was in the living room and then goes to the kitchen (spatial), and since it is Saturday (temporal), the person stays up longer.

The above examples clearly show that space, time and context all play an important role in behaviour recognition. Representing all of this information in the smart environment is a significant challenge. This paper discusses the importance of spatio-temporal and context awareness, and how to represent them in behaviour recognition, the first part of the smart home problem.

2 Behaviour Recognition

The smart home uses sensors to collect information about the inhabitant's activities. These could be from a wide variety of sensors, including video cameras, microphones, on-body sensors, or Radio Frequency Identification (RFID) tags. However, we are not directly interested in the types of sensors used, but rather how the sensory signals are being processed independent of the sensor type. We assume that the sensor output arrives in the form of 'tokens' in a sequence over time. The tokens could be the direct representation of the current sensor states being triggered (i.e., kitchen light is turned off, heater is switched on, bedroom door closed, etc.), but they do not have to be. Table 1 shows an example of a sequence of tokens from the sensors.

Date Activation	*Time Activation*	*Room*	*Object Type*	*Sensor State*
16/6/2008	18:05:23	living room	television	off
16/6/2008	18:08:19	living room	curtain	closed
16/6/2008	18:09:48	kitchen	light	on
16/6/2008	18:10:35	kitchen	cabinet	open
16/6/2008	18:25:06	kitchen	fridge door	open
16/6/2008	19:00:02	laundry	washing machine	on
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Table 1. Example of a sequence of tokens from the sensors where the sensor states are in the form of on/off or open/closed. A representation of actual tokens may contain more attributes such as sensor identification, the source of sensor, types of sensor (reed switch, leak detector, motion), etc.

Since human behaviours periodically change and the exact activities are not directly observed, it is certainly hard to model using a deterministic approach, which relies on some known properties of the behaviours, which is difficult to determine beforehand. One way to deal with these is to use a stochastic approach where the variable states (activities) are determined using a probability distribution. Given that we have this sequence of tokens obtained from the sensors, the question is then how to recognise behaviours. The challenges in this task are that behaviours are rarely identical on each use; the order in which the individual components happen can change, the length of time each piece takes can change, and components can be present or absent at different times (for example, making a cup of tea may involve milk, or may not, the milk could be added before or after the water, and the length of time the teabag is left in the cup can vary). Adding in the fact that the exact activities are not directly observed and that sensor observations are themselves intrinsically noisy, it is no surprise that Hidden Markov Models (HMMs), and variants of them, have been the most popular method of recognising behaviours [17–19].

The HMM is a probabilistic graphical model that uses a set of hidden (unknown) states to classify a sequence of observations over time. For example, the sensor observations could be that the bathroom fan is on and the water is running where the possible state could be that someone is taking a shower. By linking all these sequences of sensor observations over time into activities, it can help to recognise behaviours. Fig. 1 shows a simple representation of a HMM where the nodes represent the variables and the edges represent the conditional dependencies between the nodes. Further details on HMMs can be found in [10, 11].

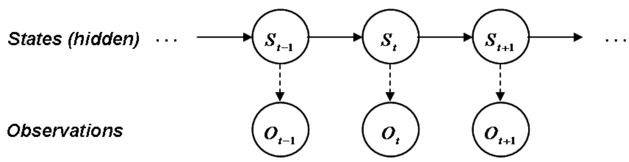

Fig. 1. The graphical representation of a Hidden Markov Model. The nodes represent the variables (top line is the hidden states, and bottom line is the observations). The edges (arrows) represent the conditional dependencies: solid lines represent the conditional dependencies between states, $P(S_t|S_{t-1})$ i.e. the probability of transition to a state S_t, which depends only on the current state S_{t-1}, and dashed lines represent the conditional dependencies of the observation on the hidden states, $P(O_t|S_t)$ i.e. the observation at O_t depends only on the hidden state S_t at that time slice.

In order to use HMMs, there are a few problems that have to be solved. One is to break the token sequence into appropriate pieces that represent individual behaviours (i.e., segmentation), and another is to classify the behaviours using the HMM. In previous work [16] we have proposed a method of automatic segmentation of the token stream, based on competition between a set of trained HMMs. In this paper, we propose methods by which this can be augmented with spatial, temporal, and contextual information in order to improve the classification accuracy. We do not cover the problem of training the individual HMMs; at present we use hand-labelled data to do this, although we plan to identify a better approach in future work.

Although many methods have been proposed to label inhabitant's activities, these approaches relied heavily on hand-labelled and manual segmentation, both which are time-consuming and error-prone. Some works even progressed towards using the sliding window technique to partition the input sensory stream but they do rely on a fixed window length, which results the segmentation being biased towards the size of window used [13, 14]. To address this, an initial study has been conducted that uses a set of Hidden Markov Models (HMMs) with each HMM recognises different behaviours and compete among themselves to explain the current sensor observations. We will discuss how we can further incorporate the spatio-temporal and context information to the existing model. Before discussing this further, we demonstrate that such a system is capable of identifying human behaviours from a real smart home.

2.1 Experiment: Behaviour Recognition using HMMs

This experiment was conducted to perform behaviour recognition and segmentation so that behaviours can be individually segmented based on competition between trained HMMs. Given a set of HMMs trained on different behaviours, we present data from the sensory stream to all of the HMMs, which each computes the likelihood of the sequence of activities according to the model of each behaviour. We posit that a typical behaviour is a sequence of activities that occur close to one another in time, in one location. While this is not always true, for now we are focussing on these types of behaviour, which includes activities such as cooking and preparing beverages. It is interesting to note that it would not necessarily include common activities such as laundry, which may well be separated in time (while waiting for the washer to finish) and in space (for example, if clothes are hung outside rather than using a dryer).

In order to demonstrate our algorithm, we took a dataset from the MIT PlaceLab [4]. They designed a system based on a set of simply installed state-change sensors that were placed in two different apartments with real people living in them. The subjects kept a record of their activities that form a set of annotations for the data, meaning that there is a 'ground-truth' segmentation of the dataset. We trained the HMMs using this hand-segmented and labelled data. While this is a simplification of the overall aims of the project, it enables us to evaluate the method properly.

We assume for now that activities take place in one room, and that the location of the sensors is known *a priori*. For this reason, we concentrated on just one room, namely the kitchen, which contained more behaviours than any other room. The behaviours that were originally labelled in the kitchen were (i) prepare breakfast, (ii) prepare beverage, (iii) prepare lunch, and (iv) do the laundry. We split behaviour (i) into two different ones: prepare toast and prepare cereal. This made two relatively similar behaviours.

We partitioned the data into a training set consisting of the first few days, followed by a test set consisting of the remainder. The HMMs were each trained on the relevant labelled data in the training set using the standard Expectation-Maximization (EM) algorithm [10]. The data that is presented to the five trained HMMs is chosen from the sensor stream using a Parzen window that moves over the sequence. The choice of the size of this window is important, because it is unlikely that all of the activities in the sequence belong to one behaviour, and so the HMM chosen to represent it will, at best, represent only some of the activities in the sequence. Rather than using a fixed window length, we proposed a variable window length that moves over the sequence of observations. We do not discuss the details on how our algorithm self-determines the Parzen window size (see [16] for further details), but focus on how effective our algorithm is at recognising behaviours based on the competition among HMMs in that particular room in the house. To simplify this experiment, we use a Parzen window of size 10.

The results of sliding a Parzen window of size 10 over the data consisting of 727 sensor observations is shown in Fig. 2, which displays the outputs of the algorithm, with the winning behaviour at each time being clearly visible. The winning behaviour is classified when the $\alpha = 1$. As the figure shows, we can determine that the subject is doing laundry at observation 150 since $\alpha = 1$ at that observation (see first graph in Fig. 2). The classification accuracy of this experiment was high enough (over 90% accuracy) to encourage us to look further.

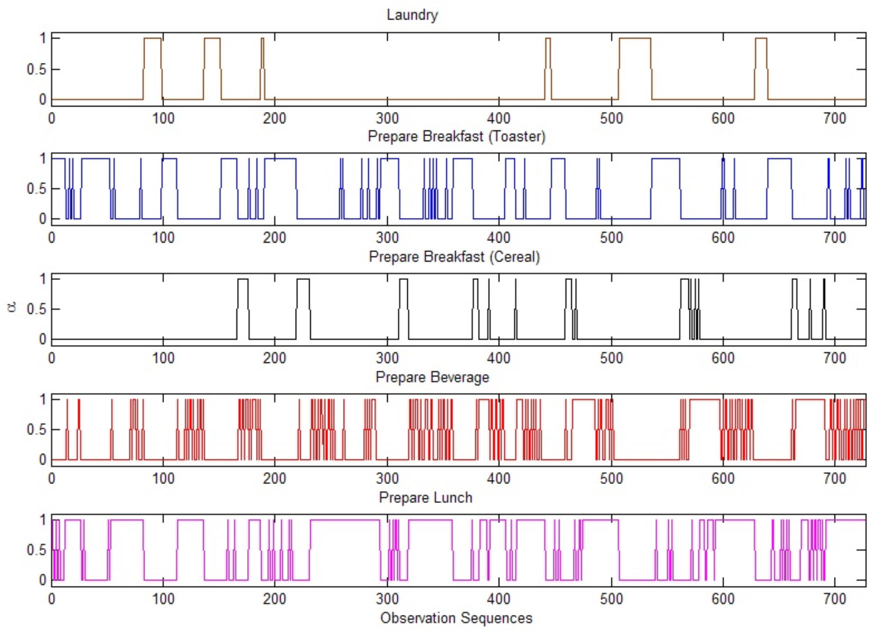

Fig. 2. Illustration of competition between HMMs based on a testing set of 727 observations

2.2 Results

The experimental results show that the method works effectively to detect changes of activities based on relatively small amount of training data. As the model is relatively simple and based on recursive computation, the computational costs are significantly lower than many other methods.

One of the limitations found in the study is that the method misclassified the behaviour in situations where the end of one behaviour contains observations that could be at the start of the next. For example, the last activity for preparing lunch could be to put the leftover food in the fridge. After preparing lunch, the inhabitant proceeds to make a cup of coffee, and the first activity to make a cup of coffee is to take the milk from the fridge (see observation O_5 in Fig. 3). This will not pose a problem if the second behaviour happens immediately after the first. However, if the second behaviour happened two hours after the first, that would be a totally different unrelated behaviours.

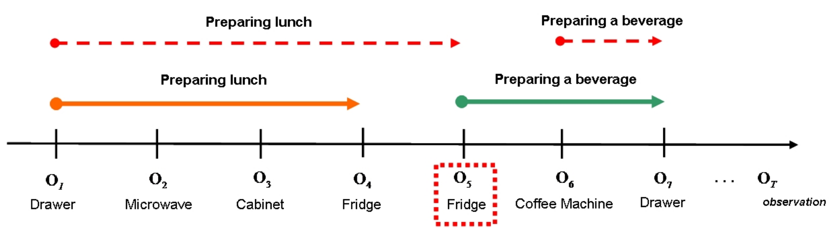

Fig. 3. Misclassification (shown in dashed arrow) occurs when the end of one behaviour contains the observations that could be in the start of the next behaviour

One way to reduce the misclassification is by adding extra information. If temporal information is included, then places where two behaviours abut one another can be reduced (see Fig. 4). If spatial information is included, then places where the two different unrelated behaviours occur can be reduced, since now the room location will change before the second behaviour occurs.

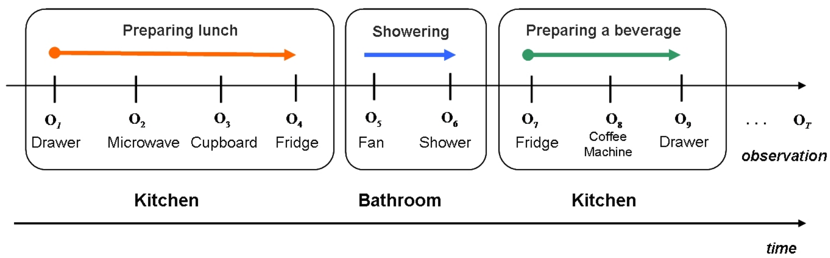

Fig. 4. Illustration of how spatio-temporal information can be included to classify behaviours.

The current study assumes that actions in a behaviour are contiguous, and that all of the separate parts of the behaviour as different instances of that behaviour. This may not be the case in the real environment, as behaviours are normally interleaved: a person may well make a beverage at the same time as preparing lunch, which could be done while the laundry was running. Where a behaviour is split into relatively short pieces (e.g., a visit to the toilet), it should be possible to recognise this. However, care needs to be taken to ensure the fact that somebody cooks 3 times a day (breakfast, lunch, and dinner) does not get bunched into one behaviour interspersed with breaks.

3 Spatio-Temporal and Context Reasoning

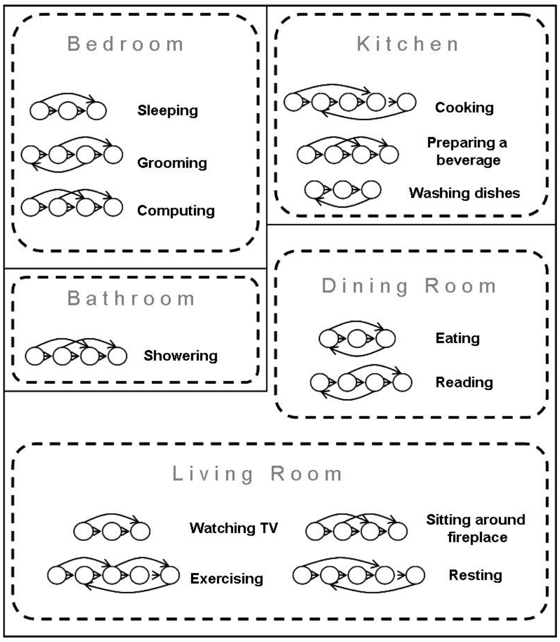

Fig. 5. Illustration of how each behaviour is defined using separate HMMs in different locations in the home (e.g. sleeping, grooming, and computing are the representation of separate behaviours in the bedroom)

We have presented a simple system that performs behaviour recognition and segmentation, and our results suggest that the method works effectively. In the experiment presented here we used very basic spatial information by concentrating on just the kitchen. To extend the method to other rooms such as bedroom, dining room, living room, and bathroom, we will need a better spatial model. We have also shown that by not using temporal information, the system makes errors that could be avoided. Fig. 5 summarises how the possible behaviours to be recognised can be identified based on the different locations (rooms) that the inhabitant is in. As the figure shows, if the behaviour takes place in the living room, the possible activities are 'watching TV', 'exercising', 'sitting around fireplace' or 'resting'. Assuming that the system is based on data of what the person does in their house (for example, during some training phase), it is reasonable to assume that these behaviours cover the possible actions. Note that we are not interested in the exact coordinates of the activity, but rather in the room where the activity occurs; it may be that for other activities, a finer spatial resolution is needed.

Spatial information is not enough to classify whether a person's behaviour is typical or not, however. Without temporal information, the system cannot differentiate between a person showering in the bathroom at 3am and at 8am. Referring to the example shown in Fig. 6, when 'watching TV' is chosen as the winner behaviour, the system may know that this behaviour can occur throughout the day, but is mostly seen during the night, and when 'sitting around fireplace' is chosen as the winner, the system might recognise that this behaviour only occurs in the winter. Thus, time gives us another way in which we can segment the activities that should be recognised. This is shown in Fig. 6. Of course, once we have both spatial and temporal data, we need to fuse them in some way. This can be relatively simple in this case, since we can merge our two partitions.

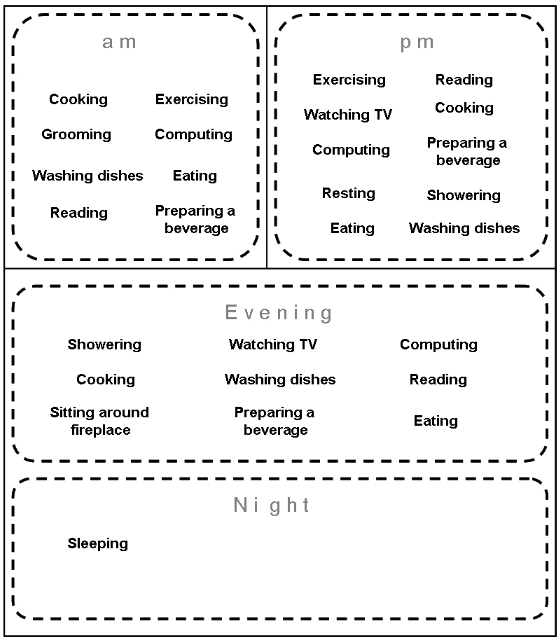

Fig. 6. Illustration of how each behaviour is defined in different time of a day

The second place where temporal information can be useful is when we form a pattern of how the smart home inhabitant spends their days. The output of the original system is a list of behaviours and the time they occur, and another system can therefore be used to learn a model of the behaviour sequence. This could be another HMM, for example. By adding in knowledge of the length of time that people spend on particular activities, a meta-level description of behaviours can be achieved. Fig. 7 shows an interpretation of this.

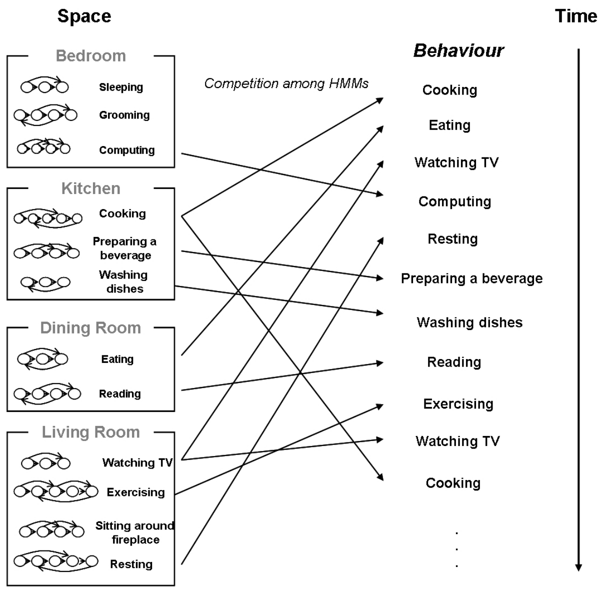

Fig. 7. Illustration on how temporal information can be useful to generate a sequence of behavioural patterns

In this case, we are starting to use information about previous activities that the person has been performing to classify their current behaviour. However, even here, we are missing relevant data. There is a host of other information that could be useful, either about the state of the environment (temperature, whether the heater is on, etc.) or how the current situation was reached. A person who reaches home from work in the middle of the night and proceeds to the kitchen to make some snack is considered normal, while a person that has been soundly asleep throughout the night and suddenly wakes up to cook may not be.

Having shown that context awareness and spatio-temporal information are useful in the recognition process, we need to decide how to include them. One option is implicit in Figs. 5 and 6, since we can use the current time and place data from the sensor stream to limit the number of HMMs that are allowed to compete. However, this may make mistakes, particularly with time, if the person is late one day and makes lunch at 3pm. Rather, some form of weighting system could be used to suggest how relevant each behaviour is based on the time and spatial data. This could be implemented in the form of a fuzzy logic system, for example.

4 Conclusion

We have shown that competition between HMMs is a possible mechanism for behaviour recognition and segmentation in a smart home. In this paper, we have discussed how context awareness and spatio-temporal information can improve the accuracy of this system, and how it can be used to better recognise when behaviours are not typical.

Algorithms for behaviour recognition generally fall into two categories: those that are based on an explicit representation of behaviours together with the events that characterise them, and those that mine them from sensor streams. The second has the advantage that we don't need to know what events constitute a behaviour, and therefore they are the preferred approach by many researchers. However, most approaches do not fully exploit the data but mainly focus on which sensors are triggered, and use these sensor sequences for learning. We are using the extra information in the stream (based on implicit information to represent behaviours where we use a set of hidden states to classify a sequence of observations over time), which falls into three categories: spatial, temporal, contextual.

For a smart home to support inhabitant's daily activities, the system should not only recognise behaviours, but also to monitor potential abnormality. A system could learn whether a novel input presented to it is a completely new behaviour, additional information to describe the current learned behaviours (which may be due to newly added sensors), or an abnormal behaviour. We are particularly interested in the use of novelty detection methods to address this, although there may be other suitable machine learning methods. The idea behind novelty detection is to train on a set of normal behaviours consisting of spatial, temporal and contextual information and then using the learned 'normal' behavioural models to identify inputs that do not fit into the pattern of the training set [15]. Applying these ideas to behaviour recognition in smart homes is the future direction of this research.

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An Ontology for Qualitative Description of Images

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Abstract. Our approach describes any image qualitatively by detecting regions/objects in the image and describing its visual characteristics (shape and colour) and its spatial characteristics (orientation and topology) by means of qualitative models. The description obtained is translated into a Description Logic (DL) based ontology which provides a formal and explicit meaning to the qualitative tags which represents the visual features of the objects in the image and the spatial relations between them. As a result, for any image, our approach obtains a set of individuals which are classified, using a DL reasoner, according to the descriptions of our ontology.

1 Introduction

Visual knowledge about space is qualitative in nature. The retinal image of a visual object is a quantitative image in the sense that specific locations on the retina are stimulated by light of a specific spectrum of wavelengths and intensity. However, the knowledge about a retinal image that can be retrieved from memory is qualitative. Absolute locations, wavelengths and intensities cannot be retrieved from memory. Only certain qualitative relations between features within the image or between image features and memory features can be recovered. Qualitative representations of this kind share a variety of properties with "mental images" which people report about when they describe from memory what they have seen or when they attempt to answer questions on the basis of visual memories [1].

Psycho-linguistic researchers have studied which language human beings use to describe from memory what they have seen: usually nouns are used to refer to objects, adjectives to express properties of these objects and prepositions to express relations between them [2]. These nouns, adjectives and prepositions are qualitative labels which extract knowledge from images which can be used to communicate and compare image content.

However, describing any image qualitatively and interpreting it in a meaningful way as human beings can do remains a challenge. The association of meaning to the representations obtained by robotic systems, also known as *symbol grounding problem*, is still a prominent issue within the Artificial Intelligence (AI) domain [3]. In this paper, we present a little step forward in that direction.

The approach presented in this paper describes any image qualitatively and stores the results of the description as facts according to an ontology. The main regions that characterize each image are extracted by using a graph-based image segmentation method [4] and then the visual and spatial features of these regions are computed. The visual features of each region are described by qualitative models of shape and colour [5], while the spatial features of each region are described by qualitative models of topology [6] and orientation [7, 8]. We propose to use an ontology to give a formal and explicit meaning to the qualitative labels used to describe each image. Thus, ontologies will provide an explicit representation of knowledge inside the robot.

The remainder of this paper is organized as follows. Section 2 describes the related work. Section 3 details what our approach consists of. Section 4 describes the ontology schema and facts provided by our approach. Section 5 presents the results of our approach applied to the description of digital images which describe our robot environment. Finally, in Section 6, our conclusions and future work are explained.

2 Related Work

Related works have been published that describe images qualitatively [9, 10, 11]. In [9], landscape images are divided by a grid for its description so that semantic categories (grass, water, etc.) are identified and qualitative relations of relative size, time and topology are used for image description and retrieval in data bases. In [10], a qualitative description for sketch image recognition is proposed, which describes lines, arcs and ellipses as basic elements and also the relative position, length and orientation of their edges. In [11], a verbal description of an image is provided to a robotic manipulator system so it can identify and pick an object up that has been previously described qualitatively using predefined categories of type, colour, size, shape and spatial relationships.

We believe that all the works described above provide evidence for the effectiveness of using qualitative information to describe images. However, to the best of our knowledge, none of these works can describe any image from the robot environment in a general way, that is, by describing visually and spatially only the main important regions without adding to the system any previous learning process.

Moreover, in the literature, related works which use ontologies to store and structure the knowledge extracted from an image can be found [12, 13, 14]. In [12], images containing objects of a specific domain are described by an ontology which contains qualitative features of shape, colour, texture, size and topology for object classification purposes. In [13], an ontology based object categorization approach is presented for the recognition and communication of the ball and the goal in the RoboCup tournament by Sony AIBO robots. Finally, in [14] the possible use of Description Logic (DL) as a knowledge representation and reasoning system for high-level scene interpretation is examined.

Despite all these works, the application of ontologies in robotics and in other automatic systems is still novel, since ontology-like techniques are still under maturation (OWL is still evolving and reasoners are being improved to be more scalable). Ontology benefits are theoretically proved but not always practically tested. Nevertheless, there is a growing tendency to introduce high-level semantic knowledge into robotic systems [15], and our approach is a small contribution to this.

3 Our Approach for Qualitative Description of Images

The approach presented in this paper describes qualitatively any image by describing the visual and spatial features of the objects/regions within it. These objects/regions are obtained by applying the graph-based image segmentation method presented in [4] and other image processing algorithms developed to extract the boundaries of the segmented regions. The visual features of each region in the image are described by qualitative models of shape and colour [5], while the spatial features of each region in the image are described by qualitative models of topology [6] and orientation [7, 8].

The structure of the qualitative description obtained by our approach is shown in Figure 1. For each region in the image, its visual and spatial features are described qualitatively. We consider as visual features the shape and colour of the region, which are absolute properties which only depend on the region itself. As spatial features, we consider the topology and orientation of the regions, which are properties defined with respect to other regions (i.e. containers and neighbours of the regions).

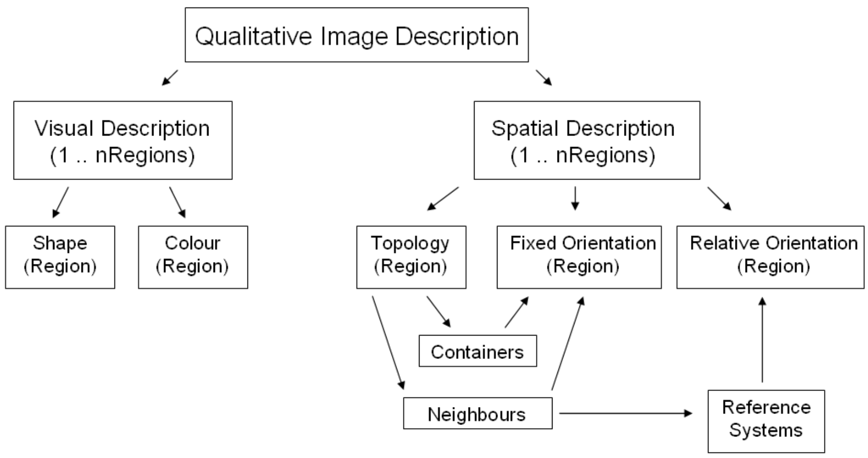


Fig. 1. Structure of the qualitative image description obtained by our approach.

3.1 Describing Spatial Features of the Regions in the Image

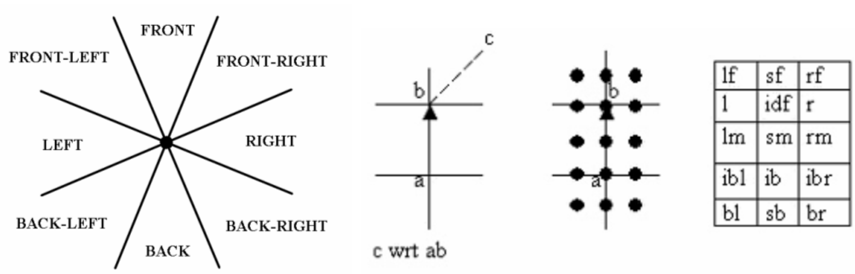
As spatial features of any region in the image, we describe its topology and its fixed and relative orientation.

Topological Description. The relations of topology described by our approach are a subset of those defined in [6]: *disjoint, touching, completely_inside, container_of*.

Our approach determines if an object is *completely_inside* or if it is the *container_of* another object. It also defines as *neighbours* of an object, all those objects with the same container, which can be other objects or the image itself. The neighbours of an object can be (i) *disjoint* from the object, if they do not have any edge or vertex in common; (ii) or *touching* the object, if they have at least one vertex or edge in common. As digital images are two-dimensional, no information on depth is obtained; therefore the topological relations of *meeting, overlapping, touching_inside* and *equal* defined in [6] cannot be distinguished and are all substituted by *touching* in our approach.

Fixed and Relative Orientation Description. Orientation relations between the objects in the image are structured in levels of containment.

We define the fixed orientation of a region with respect to its *container neighbours*. Relations of fixed orientation are described by the qualitative model defined by Hernandez [7] which divides the space into eight regions (Figure 2(a)) named as: *front (f), back (b), left (l), right (r), left-front (lf), right-front (rf), left-back (lb), right-back (rb),* and *centre (c)*.



(a) (b)

Fig. 2. (a) Hernandez's orientation model. (b) Freksa's orientation model and its iconical representation: *l is left, r is right, f is front, s is straight, m is middle, b is back and i is identical.*

In order to obtain the relative orientation of a region, we use the Freksa's double cross orientation model [8], which divides the space into 15 qualitative zones by means of a Reference System (RS), as it is shown in Figure 2(b). These zones are named as: *left-front (lf), straight-front (sf), right-front (rf), left (l), identical-front (idf), right (r), left-middle (lm), same-middle (sm), right-middle (rm), identical-back-left (ibl), identical-back (ib), identical-back-right (ibr), back-front (bf), same-back (sb), back-right (br)*, as defined in Figure 2(b). Our approach obtains the relative orientation of a region with respect to the reference systems built by all the pairs of neighbours of a region. The points a and b of the RS are the centroids of the neighbour regions composing the RS.

The advantage of providing a description structured in levels of containment is that the level of detail to be extracted from the image can be selected. For example, we can extract all the information in the image or only that information dealing with the objects immediately contained in the image, which could be considered as a more general or abstract description of that image.

As the spatial features described are relative to other objects/regions in the image, the amount of spatial relations that can be described depends on the amount of neighbours the object/region has, as it is explained in Table 1.

Table 1. Spatial features described depending on the amount of objects in each level

Spatial Features Described		***Objects within the same container***		
		1	**2**	$>$ **2**
Wrt its Container	Topology	x	x	x
	Fixed Orientation	x	x	x
Wrt its Neighbours	Topology	-	x	x
	Fixed Orientation	-	x	x
	Relative Orientation	-	-	x

3.2 Describing Visual Features of the Regions in the Image

In order to describe the visual features of the objects/regions in an image, we use the qualitative models of shape and colour formally defined in [5].

Qualitative Shape Description. Our approach extracts automatically the boundary of any object by applying a graph-based image segmentation and the relevant points of each boundary by analysing the slope defined by groups of points contained in that boundary. Each relevant point is described by a set of four features <KEC$_j$, A$_j$ or TC$_j$, L$_j$, C$_j$> :

– Kind of Edges Connected (KEC) by the relevant point *j*, described as: {*line-line, line-curve, curve-line, curve-curve, curvature-point*};
– Angle (A) in the relevant point *j*, described as: {*very_acute, acute, right, obtuse, very_obtuse*};
– Type of Curvature (TC) in the relevant point *j*, described as: {*very-acute, acute, semicircular, plane, very_plane*};

– Compared Length (L) of the two edges connected by j, described as: {*much-shorter (msh), half-lenght (hl), quite-shorter (qsh), similar-lenght (sl), quite-longer (ql), double-lenght (dl), much-longer (ml)*};
– Convexiy (C) in the relevant point j, described as: {*convex, concave*}.

Qualitative Colour Description. Our approach translates the Red, Green and Blue (RGB) colour channels into Hue, Saturation and Value (HSV) coordinates which are more suitable to be divided into intervals of values corresponding to colour names. The qualitative tags used by our approach to represent colours are the following: *black, dark-grey, grey, light-grey, white, red, yellow, green, turquoise, blue, violet.*

4 Giving Meaning to Qualitative Descriptions

Our approach describes any image by using qualitative information, both visual (e.g. shape, colour) and spatial (e.g. topology, orientation). We propose to use ontologies to give a formal meaning to the qualitative labels associated to each object. Thus, ontologies will provide an explicit representation of the knowledge inside the robot system.

An *ontology* is an *explicit specification of a conceptualization* [16] providing a non-ambiguous and formal representation of a domain. Ontologies usually have specific purposes and their intended consumers are computer applications rather than humans. Therefore, ontologies should provide a common vocabulary and meaning to allow these applications to communicate among themselves [17].

The use of an ontology-based representation is intended to enhance tasks such as reasoning, communication or collaboration. Next we emphasize the main motivations of using ontologies within our system:

– **Symbol Grounding**. As commented previously, ontologies can provide a formal and explicit meaning to the qualitative labels which describe an image and are stored inside the robot system.
– **Knowledge sharing**. The adoption of ontologies provides us with a standard way to publish our representations in order to be shared and reused by other systems. Thus, the use of a common conceptualization will ease the communication between systems if necessary.
– **Reasoning**. New knowledge may be inferred from the explicit representations using reasoners. This gives some freedom and flexibility when inserting new descriptions or new facts, and this new knowledge can be automatically classified (e.g. a captured object is a door) without providing explicit axioms. Thus, ontologies may support decision making tasks depending on the obtained classifications.

As a proof of concept, we have developed an ontology to represent qualitative description of images. We have adopted the revision 2 of OWL[3] [18, 19] as ontology language and we have used the OWL ontology editor Protégé 4[4],

[3]Ontology Web Language: `http://www.w3.org/2007/OWL/wiki/Syntax`
[4]Protégé: `http://protege.stanford.edu`

together with the DL reasoners Pellet[5] and FacT++[6]. Table 2 gives a subset of the main OWL 2.0 axioms and concept constructors. Note that the description logic $\mathcal{SROIQ}$ [20] provides the logical underpinning for OWL 2.0.

Table 2. Some OWL 2 Axioms and Concept Descriptions. Where C, D are complex concepts, R denotes an *atomic role*, A represents an *atomic concept* and a, b *individuals*.

OWL Axioms		
Global Concept Inclusion	$C \sqsubseteq D$	$Right\_Triangle \sqsubseteq Triangle$
Equivalence	$C \equiv D$	$WhiteObject \equiv Object \sqcap$ $\ni hasColour.\{white\}$
Class Assertion	$C(a)$	$Length(much\_shorter)$
Property Assertion	$R(a, b)$	$isContainerOf(image1, object1)$
Disjointness	$C \sqsubseteq \neg D$	$Circle \sqsubseteq \neg Triangle$
Negative Property Assertion	$\neg R(a, b)$	$\neg isContainerOf(image2, object1)$
Limiting a class	$C \sqsubseteq \{a, b, c\}$	$Colours \sqsubseteq \{red, black, white\}$
Different Individuals	$a \neq b$	$white \neq red$

OWL Concept Constructors		
Top Concept	$\top$	$Thing$
Atomic Class	A	$Circle, Colour$
Negation	$\neg C$	$\neg Triangle$
Intersection	$C \sqcap D$	$Triangle \sqcap \forall hasAngle.RightAngle$
Union	$C \sqcup D$	$Obtuse \sqcup Very\_Obtuse$
Universal	$\exists R.C$	$\exists isContainerOf.Object$
Value Restriction	$\ni R.\{a\}$	$\ni hasColour.\{white\}$
Existential	$\forall R.C$	$\forall isLeft.Object$
Min Cardinality	$\geqslant n\, R.C$	$\geqslant 3\, hasPoint.Point$
Max Cardinality	$\leqslant n\, R.C$	$\leqslant 2\, hasAngle.Angle$
Exact Cardinality	$= n\, R.C$	$= 4\, hasPoint.Line\_Line$

The developed ontology have been split into three knowledge layers: (1) a *reference conceptualization*, which is intended to represent knowledge (e.g. the description of a *Triangle*) that is supposed to be valid in any concrete application. This layer is also known as *top level knowledge* by the community; (2) the *contextualized knowledge*, which is application oriented and it is mainly focused on the concrete representation of the domain (e.g. characterization of doors at Jaume I University) and could be in conflict with other context-based representations; and (3) the *set of facts*, which represents the assertions or individuals extracted from the image analysis, that is, the set of concrete qualitative descriptions. The first two elements compose the *terminological knowledge* (T-BOX) and the latter the *assertional knowledge* (A-Box). Both the T-Box and the A-Box are available on-line at `http://krono.act.uji.es/people/Ernesto/qimage-ontology/`.

Currently one of the main problems that users face when developing ontologies is the confusion between Open World Assumptions (OWA) and Close World

[5]Pellet: `http://clarkparsia.com/pellet/`

[6]FacT++: `http://code.google.com/p/factplusplus/`

Assumptions (CWA) [21]. Closed world systems such as databases or logic programing (e.g. PROLOG) considers that anything that cannot be found is false (negation as failure). However, Description Logics (and therefore OWL) assume an open world, that is, anything is true unless it can be proven the contrary (i.e. two concepts overlap unless they are declared as disjoint).

In our use case, we have faced that problem when characterizing concepts such as "Quadrilateral", where individuals belonging to that set should have exactly four sides (i.e. four connected points). Minimum cardinalities are easy to manage by just declaring the inidividuals (in that case the sides of the quadrilateral) to be different among themselves. However, stating maximum (and therefore exact) cardinalities is not straightforward. For these cases closure axioms are the key to limit the domain of interpretation. It is not only necessary to say that an individual has four sides to be classified as a "Quadrilateral", but also it is required to say explicitely that it has not more sides with the negative property assertion axioms. Moreover, it is also necessary to declare the size of a class by means of nominals, that is, to explicitely say that a class is composed by a concrete set of individuals (e.g. possible sides or points for quadrilaterals) and not any other.

5 Results

Our approach obtains a qualitative image description and an instance of an ontology for any digital image, including those which describe our robot environment.

As it is outlined in Figure 3, for each image, our approach obtains the main regions which characterize it, describe them visually and spatially by using qualitative models of shape, colour, topology and orientation and obtains a qualitative description of the image in a flat format (see Table 3) and also as a set of ontology facts stored in an .owl file. This .owl file, which represents the *assertional knowledge* (A-Box), is imported by Protégé and, according to the *terminological knowledge* (T-BOX) defined on our ontology schema, new knowledge is inferred by the reasoners (FaCT++ or Pellet) which can be used by the robot.

Table 3 presents an excerpt of the qualitative description which describes region 4 in the image. Its spatial description can be intuitively read as: region 4 is *completedly inside* region 0 and exactly located at *front, front right, back, back right* with respect to the centre of region 0. The *neighbours* of region 4 are regions 6 and 7, which are both *disjoint* and located *front left, left, back left* with respect to region 4. Moreover, region 4 is *back right (br), back left (bl)* with respect to the reference system built by its two neighbours (region 6 and 7). The visual description of region 4 shows that its colour is *blue* and that the shape of its boundary is qualitatively described as composed of four *line-line* segments whose angles are two *acute* and *convex* and two *obtuse* and *convex* and whose compared distances are respectively *much shorter, much longer, much shorter, much longer*. Finally, the orientation of its vertices with respect the centroid of the region is clockwise: *front, back, back, front.*

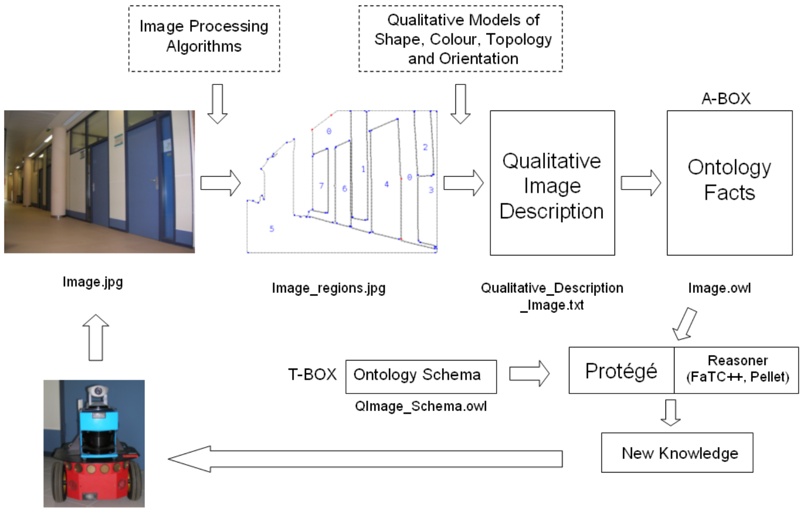


Fig. 3. Architecture of our approach, which obtains a qualitative description and an instance of an ontology for any image.

Table 3. An excerpt of the qualitative description obtained for the image in Figure 3.

[**SpatialDescription**,
(...)
[4, [0, Completedly_inside, front_right, back_right, back, front],
[[neighbours, 6, 7], [disjoint, 6, 7],]
[[6, front_left, left, back_left], [7, front_left, left, back_left]],
[[[6, 7], br, bl]]
(...)]
[**VisualDescription**,
[4, blue,
[Boundary_Shape,
[line-line,acute,much_shorter,convex],
[line-line,acute,much_longer,convex],
[line-line,obtuse,much_shorter,convex],
[line-line,obtuse,much_longer,convex]],
[Vertices_Orientation, front, back, back, front]],
],
(...)]

In Table 4 an excerpt of our ontology is presented. In this table, we can differenciate the already mentioned three layers of knowledge (see Section 4). As examples of *reference conceptualizations*, Table 4 shows the properties of an Object in our ontology, the definition of a Shape as a set of at least 3 relevant points, the definition of a Quadrilateral as a Shape with 4 points connecting two lines and so on. As examples of *contextualized knowledge*, Table 4 shows (1) the definition of the wall of our lab (UJI_Lab_Wall) as a light-grey or yellow object and (2) the definition of a door of our lab (UJI_Lab_Door) as a blue or dark-grey quadrilateral object which is completedly inside or touching an object classified as a wall of our lab (UJI_Lab_Wall). Note that the contextualized descriptions are rather preliminary and they should be refined in order to avoid ambiguous categorizations. Table 4 also shows some *ontology facts* corresponding to the image in Figure 3 and the qualitative description in Table 3, as for example: Object 0 is *light-grey* and is *completedly_inside* the image, then it is classified as a UJI_Lab_Wall by the reasoners and Object 4 is a *blue quadrilateral* and is *completedly_inside* a UJI_Lab_Wall (Object 0), then it is classified as a UJI_Lab_Door by the reasoners.

Table 4. Excerpt from the Ontology for Qualitative Descriptions

	Reference Conceptualization
α_1	Image_type $\sqsubseteq$ $\exists$is_container_of.Object_type
α_2	Object_type $\sqsubseteq$ $\exists$has_colour.Colour_type
α_3	Object_type $\sqsubseteq$ $\exists$has_fixed_orientation.Object_type
α_4	Object_type $\sqsubseteq$ $\exists$has_relative_orientation.Object_type
α_5	Object_type $\sqsubseteq$ $\exists$is_touching.Object_type
α_6	Object_type $\sqsubseteq$ $\exists$has_shape.Shape_type
α_7	Shape_type $\sqsubseteq$ $\geqslant 3$ has_point.Point_type
α_8	Quadrilateral $\sqsubseteq$ Shape_type $\sqcap = 4$ has_point.line_line
α_9	is_bl $\sqsubseteq$ has_relative_orientation
α_{10}	is_left $\sqsubseteq$ has_fixed_orientation

	Contextualized Descriptions		
β_1	UJI_Lab_Wall	$\equiv$	Object_type $\sqcap$ ($\ni$ has_colour.{yellow} $\sqcup$ $\ni$ has_colour.{light_grey})
β_2	UJI_Lab_Door	$\equiv$	Object_type $\sqcap$ ($\ni$ has_colour.{blue} $\sqcup$ $\ni$ has_colour.{dark_grey}) $\sqcap$ $\exists$has_shape.Quadrilateral $\sqcap$ ($\exists$is_touching.UJI_Lab_Wall $\sqcup$ $\exists$is_completely_inside.UJI_Lab_Wall)

	Ontology Facts
γ_1	Image_type : image_1
γ_2	Object_type : object_0
γ_3	Object_type : object_4
γ_8	is_completely_inside(object_0, image_1)
γ_6	has_colour(object_0, light_grey)
γ_7	has_colour(object_4, blue)
γ_8	is_completely_inside(object_4, object_0)

Finally, we have evaluated the proper classification of the obtained ontology facts (A-Box) according to our ontology schema (T-Box). For this purpose, Protégé has been used as front-end to visualize the explicit knowledge represented in the T-Box and A-Box, and the knowledge inferred using the reasoners.

6 Conclusions and Future Work

This paper has presented a new approach for qualitative description of any image by means of an ontology. Our approach obtains a visual and a spatial description of all the characteristic regions/objects contained in an image. In order to obtain this description, qualitative models of shape, colour, topology, fixed and relative orientation are applied. As the final result, our approach obtains a set of qualitative concepts and relations stored as instances of an ontology. The main aim of this ontology is to describe and classify visual landmarks in the robot world.

As future work, we intend to (1) extend our approach in order to integrate a reasoner inside the robot system, so that we could avoid the use of Protégé front-end and the new knowledge obtained could be provided to the robot in real time; (2) extend our ontology in order to characterize and classify more landmarks in the robot environment.

Acknowledgments

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Qualitative Spatial and Terminological Reasoning for Ambient Environments

Recent Trends and Future Directions

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Abstract. In this paper, we provide an overview how approaches for spatial and terminological representation and reasoning can be applied to ambient environments and smart places. We introduce formal modeling of scene descriptions that are based on qualitative spatial and ontological aspects. Given this formalization, reasoning techniques related to spatial calculi can directly be applied and operationalized for identifying ambient conditions and verifying situation-specific requirements. Furthermore, we point out future challenges on ambient intelligence benefiting from spatial and ontological reasoning.

1 Introduction

Ambient Intelligence (AmI) has started to become a mainstream and economically viable venture for a larger consumer base. In particular, it is expected that AmI projects related to smart environments such as smart homes and offices will adopt a radically different approach as soon as formal knowledge representation and reasoning techniques are involved [1, 4]. Such techniques can support not only early design stages in order to aid and complement ambient requirements but also smart environments in dynamic situations in order to provide their intended functionalities. Indeed, since AmI systems primarily pertain to a spatial environment, formal representation and reasoning along the ontological (i.e., semantic make-up of the space) and spatial (i.e., configurations and constraints) dimensions can be a useful way to ensure that the designed model satisfies key functional requirements that enable and facilitate its required *smartness*.

In this paper, we provide an overview of state-of-the-art spatial representation and reasoning techniques that are beneficial to spatial aspects of AmI. We further provide latest approaches of formal ontological modeling and its contribution to specifying ambient environments. We indicate how the different formalisms interact and how they are operationalized for AmI-specific representation and reasoning. Furthermore, a use case of an intelligent apartment for the elderly is illustrated. Finally, future challenges in the field of spatial, temporal, and terminological reasoning for AmI are discussed.

2 Qualitative Scene Descriptions

Qualitative Reasoning (QR) is concerned with capturing everyday commonsense knowledge of the physical world with a limited set of symbols and relationships and manipulating it in a non-numerical manner [9]. The subfield of qualitative reasoning that is concerned with representations of space is called Qualitative

Spatial Reasoning (QSR) which includes the underlying representation. We introduce essence of qualitative representations in general, and a topological as well as an orientation representations in the following paragraphs. How such representations are derived and applied to reason about spatial configurations within a spatial environment is shown in Section 4.

2.1 Qualitative Spatial Calculi

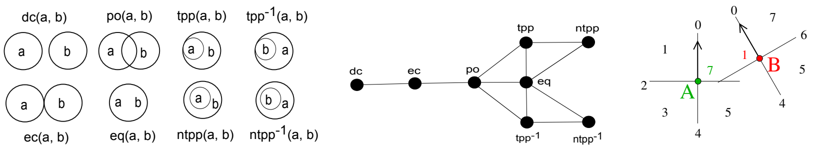
The main aim of research in qualitative methods in spatial representation and reasoning is to develop powerful representation formalisms that account for the multi-modality of space in a cognitively acceptable way [9, 15]. A qualitative spatial description captures distinctions between objects that make an important qualitative difference but ignores others. In general, objects are abstracted to geometric primitives, e.g., points, lines, or regions in the Euclidian plane and discrete systems of symbols, i.e., finite vocabularies, are used to describe the relationships between objects in a specific domain. A complete model for a certain domain is called a *qualitative calculus.* It consists of the set of relations between objects from this domain and the operations defined on these relations. How reasoning can be performed based on these operations is shown in Section 4. In general, spatial calculi can be classified into two groups: topological and positional calculi [17]. Topological calculi are, for instance, the region-based calculi RCC-5 or RCC-8 [31] and positional calculi, i.e., calculi dealing with orientation and/or distance information, are for example the DoubleCross Calculus [16] or $\mathcal{OPRA}_m$ [29].

2.2 Topology and the Region Connection Calculus (RCC)

Topological distinctions are inherently qualitative in nature and they also represent one of the most general and cognitively adequate ways for the representation of spatial information [21, 32]. The prevalent axiomatic approach to building topological theories of space in the QSR domain has its roots in the philosophical logic community, most notably [7, 8]. Following this work, the class of axiomatic topological theories referred to as *Region Connection Calculus* (RCC) have been developed [31]. The work by Egenhofer and Franzosa adopts a point-set theoretic approach and is based on conventional mathematical topology [13].

The RCC-8 Fragment RCC is a modification and extension of the Clarke's original region-based theory. The basic part of the formal theory assumes a dyadic relation of *connection*, namely $\mathsf{C}(a,\ b)$, denoting that region a is connected to region b. Topologically, this has the interpretation that the topological closures of a and b share at least one point. From the primitive of *connection*, the mereological relation of *parthood* is defined which is, in turn, used to define *proper-part* (PP), *overlap* (O) and *disjoint* (DR). Further, the relations *disconnected* (DC), externally connected (EC), partial overlap (PO), equal (EQ), *tangential proper-part* (TPP) and *non-tangential proper-part* (NTPP) are defined. These relations, along with the inverses of the last two, namely TPP^{-1} and NTPP^{-1} constitute a *jointly exhaustive and pairwise disjoint* (JEPD)[1] set of base relationships, commonly referred to as the RCC-8 fragment of the region

[1] In the case of binary relations, JEPD means that for any pair of entities exactly one base relation holds. For arbitrary n-ary calculi this must hold for any n-tuple.



(a) RCC-8 Primitives (b) RCC-8 Continuity Structure (c) The $\mathcal{OPRA}_2$ relation $\boldsymbol{A}\ {}_2\angle^1_7\ \boldsymbol{B}$

Fig. 1: Topological and orientation primitives.

connection calculus. Figure 1(a) is a 2D illustration of the topological relationships that constitute the RCC-8 fragment.

2.3 Orientation and the $\mathcal{OPRA}_m$ Calculus

Orientation information is essential for describing and navigating in spatial configurations. For representing relative orientation in recent years many different calculi have been presented, e.g., the DoubleCross Calculus[16] and the Dipole Calculus [34]. Here, we apply the $\mathcal{OPRA}_m$ approach [29] because of its expressiveness [10]. The calculi in this family are designed for reasoning about relative orientation relations between *oriented points* (points in the plane with an additional direction parameter) and are well-suited for dealing with objects that have an intrinsic front or move in a particular direction. An oriented point $\boldsymbol{O}$ can be described by its Cartesian coordinates $x_O, y_O \in \mathbb{R}$ and a direction $\phi_{\boldsymbol{O}} \in [0, 2\pi)$ with respect to an absolute frame of reference. With the parameter m the angular resolution can be influenced, i.e., the number of base relations is determined.

In the case of $\mathcal{OPRA}_2$, the orientation calculus we apply in our examples, for each pair of oriented points, 2 lines are used to partition the plane into 4 planar and 4 linear regions (see Fig. 1(c)). The orientation of the two points is depicted by the arrows starting at $\boldsymbol{A}$ and $\boldsymbol{B}$, respectively. The regions are numbered from 0 to 7, where region 0 always coincides with the orientation of the point. An $\mathcal{OPRA}_2$ base relation is a pair (i, j), where i is the number of the region, seen from $\boldsymbol{A}$, that contains $\boldsymbol{B}$ and j vice versa. These relations are written as $\boldsymbol{A}\ {}_2\angle^j_i\ \boldsymbol{B}$. Additional base relations describe situations in which both oriented points are at the same position but may have different orientations (${}_m\angle i$).

3 Ontological Formalization for Scene Descriptions

We present a modular specification of ontologies for incorporating the multi-dimensional perspectives in smart environment design. In particular, the different thematic aspects of the domain are reflected by connected modules. We briefly introduce ontological formalization aspects followed by the specification of an ontological scene description for smart environments.

3.1 Ontological Specification and Reasoning

Although ontologies can be defined in any logic, we focus here on ontologies as theories formulated in DL [2], supported by the web ontology language $\mathcal{OWL}$ DL 2 [30]. DL distinguishes between TBox and ABox. The TBox comprises all class and relation definitions, while the ABox comprises all instantiations of these classes and relations. Even though ontologies may be formulated in more or less expressive logics, DL ontologies have the following benefits: they are widely used and a common standard for ontology specifications, they provide constructions that are general enough for specifying complex ontologies, and they provide a balance between expressive power and computational complexity in terms of reasoning practicability [20].

Reasoning over the TBox, which defines the categorization and axiomatization of the domain, allows, for instance, to check the consistency of the ontology and to determine additional constraints or axioms that are not directly specified in the ontology. Reasoning over the ABox, which defines instances and their relations in a specific model of the TBox, allows, for instance, to classify instances or to determine additional relations among instances. In case of architectural design, the domain of buildings and their characteristics and constraints have to be defined. The requirements for classes and instances of concrete buildings can then be axiomatized. In addition to reasoning over ontologies (TBox) and their instances (ABox), however, spatial reasoning is of particular interest, as spatial positions of entities and their spatial relations between each other are highly important to describe the environment. Here, we apply a specific feature of the reasoning engine RacerPro [19] that supports region-based spatial reasoning directly by the so-called SBox [18], which provides reasoning based on the RCC-8 fragment, as described in Section 4.3.

3.2 Ontological Scene Description

The specification of smart environments can be seen from different perspectives, and ontologies are a method to formalize these perspectives. In order to support representations and reasoning of ambient aspects, requirement constraints of architectural and ambient entities have to be defined primarily from terminological and spatial perspectives. The environment is therefore defined from a *conceptual*, *qualitative*, and *quantitative* (spatial) perspective, illustrated in Fig. 2.

The representation of the scene description consists of different *thematic modules*. A *thematic module* for a domain is an ontology that covers a particular aspect of (i.e., a perspective on) the domain. Here, thematically different modules are interpreted by disjoint domains, i.e., the theories they reflect are not overlapping. In detail, the scene descriptions combines aspects about (1) physical entities specifically for the ambient domain (the conceptual module), (2) qualitative spatial relations, such as region-based relations given by RCC (the qualitative module), and (3) metrical information of a particular scene (the quantitative module). While here the conceptual module is based on DOLCE-Lite, an OWL version of DOLCE [28], the qualitative module inherits axiomatizations form different qualitative spatial calculi (here: RCC-8), and the quantitative module is closely connected to an architectural format for metrical data (here: IFC [27]).

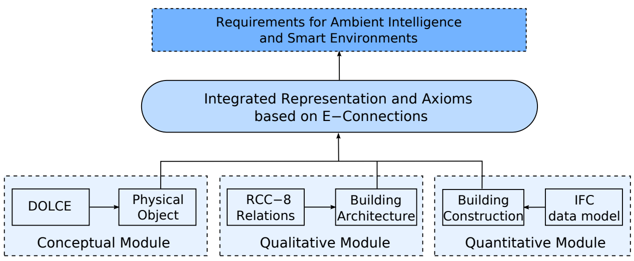


Fig. 2: Multi-Dimensional Representation for Ambient Scene Description

All the different modules are linked together by alignments that are given by human experts. Such link relations identify connections between thematically different modules. Logically, these link relations are specified by formalizing $\mathcal{E}$-connections [25]. The resulting theory, that combines the disjoint modules by applying $\mathcal{E}$-connections to them, is given by the *Integrated Representation* (cf. Fig. 2). Here, additional constraints over link relations may be defined. However, particular ambient constraints that determine certain conditions for a concrete smart environment, are defined in the *Requirements* module. This ontology extends the integrated representation by introducing restrictions and axioms over the entities given by the thematically different modules.

Such an ontological scene descriptions provides several benefits. Thematic modules are kept separately, such that their terminology and perspectives are clearly distinct. Local changes are easy to maintain. The integrated representation is logically grounded in the theory of $\mathcal{E}$-connections. It is general and flexible enough to be adapted to particular constraints on certain ambient aspects. These aspects are defined in an additional requirements module. It is possible to define various requirements modules, that provide additional extensions to the general scene description. These may allow particular requirements of a specific ambient environment. Whether they are satisfied can be proven. For instance, it can be analyzed by ontological reasoning (as described in Section 4.3) whether requirements of a particular *access requirement module* or *accessibility requirement module* or *comfort requirement module* hold or not.

4 Reasoning about Space, Change and Terminologies

In general, we identify three different aspects of reasoning: (a) scene modeling, knowledge integration respectively, (b) reasoning about changing configurations, and (c) spatio-terminological reasoning, i.e., spatial relations and additional properties of the objects at hand are ontologically combined to provide more powerful reasoning.

4.1 Qualitative Spatial Reasoning

Classical qualitative spatial reasoning (QSR) deals with static knowledge about spatial configurations. Reasoning is based on compositions and constraint satisfaction. Relations of a spatial calculus are used to formulate constraints about the spatial configuration of objects from the domain of the calculus. This results in the specification of a spatial *constraint satisfaction problem* (CSP) which can be solved with specific reasoning techniques, e.g., by applying composition and intersection operations on the incorporated relations. A prerequisite for applying constraint-based reasoning (CBR) techniques is a set of *base relations* $\mathcal{BR}$, also called primitive relations, which are jointly exhaustive and pairwise disjoint (JEPD). In Section 2.1 we introduced the calculi RCC-8 and $\mathcal{OPRA}_m$ which fulfill these prerequisites.

Reasoning about static spatial descriptions within such calculi is performed by way of *converse* ($R^{\smile} = \{\ (y,x) \mid (x,y) \in R\ \}$), *intersection* ($R_1 \cap R_2 = \{\ r \mid r \in R_1 \wedge r \in R_2\ \}$), and *composition* ($R \circ S = \{\ (x,z) \mid \exists y \in D : ((x,y) \in R \wedge (y,z) \in S)\ \}$). For instance regarding RCC-8, if it is known that a and b are *disconnected* and that c is *tangential part* of b, then, by composition, it is also known that a and c are *disconnected*. From an axiomatic viewpoint, each entry of such a composition table is in actuality a (composition) theorem of the form: $(\forall a,\ b,\ c).\ R_1(a,\ b)\ \wedge\ R_2(b,\ c)\ \rightarrow\ R_3(a,\ c)$. The composition results can be precomputed and stored in so-called *composition tables* (CT). It is on the basis of such composition theorems that the composition table is constructed or pre-defined in order to exploit it for constraint-based reasoning. CBR can be applied for refining incomplete descriptions of configurations as well as for consistency checking, e.g., if the relations are derived by hand or the data is provided from multiple sources.

4.2 Reasoning About Changing Configurations

Spatial neighborhoods are highly natural perceptual and cognitive entities [14]. These extend static qualitative representations by interrelating the discrete set of base relations by the temporal aspect of transformation of the basic entities. Two spatial relations of a qualitative spatial calculus are conceptually neighbored, if they can be continuously transformed, by motion and/or continuous deformation, into each other without resulting in a third relation in between. However, the term *continuous* with regard to transformations needs a grounding in spatial change over time. Different kinds of transformations, such as locomotion, growing or shrinking, or deformation, result in different neighborhood structures, called conceptual neighborhood graphs (*CNG*). These *CNG*s can be utilized for modeling changing spatial descriptions. For example, the continuity structure of RCC-8 is depicted in Fig. 1(b). In [12] the general neighborhood structure of $\mathcal{OPRA}_m$ is derived. For example, regarding the specific granularity $m = 2$ and neglecting coinciding o-points the neighborhood structure is given by:

$$\mathtt{cn}_g({}_2\angle_i^j) = \{{}_2\angle_{i-1}^{j-1}, {}_2\angle_{i-1}^{j}, {}_2\angle_{i-1}^{j+1}, {}_2\angle_{i}^{j-1}, {}_2\angle_{i}^{j+1}, {}_2\angle_{i+1}^{j-1}, {}_2\angle_{i+1}^{j}, {}_2\angle_{i+1}^{j+1}\}$$

If one wants to know how to really get from one configuration into another, i.e., a sequence of actions is required, the general neighborhood structure is not sufficient. Based on such considerations the concept was extended to *action-augmented conceptual neighborhood graphs* (*ACNG*) [10]. In these graphs edges are annotated with additional information on specific actions which lead to the change of the relation between the objects, e.g., turning left/right or moving forward to change orientation. For example, based on the *ACNG* it can be described how to get from your desk to the kitchen in your appartment.

4.3 Spatio-Terminological Reasoning

Spatio-terminological reasoning can be used to ensure that particular AmI requirements specified for smart environments are satisfied. It connects information about general entities of the domain from the terminology with spatial abstract representations from spatial calculi. This is given by the integrated representation of the different ontological modules, as described in Section 3. Terminological information is represented by the conceptual module. It specifies primitive entities of the domain, e.g., living room, entrance, refrigerator, sofa, curtain, telephone, light switch, etc. Combined with information from the qualitative module on spatial relations, specific spatial constraints about such terminological entities can be specified in the requirements module. Reasoning over this integrated representation provides spatio-terminological inferences.

While the qualitative module specifies primitive spatial entities, such as points, regions, or directions, the conceptual module specifies domain-specific AmI entities. One of these terminological aspects defined by the conceptual model are *spatial artifacts*. Spatial artifacts are properties of certain (terminological) entities and they are related to certain functional (agent-dependent)

Fig. 3: BAALL floorplan

aspects of entities. Explicit characterizations of spatial artifacts are necessary to enforce structural and functional constraints for AmI environments, especially when the environment is intended to consist of a wide-range of sensory apparatus (cameras, motion sensors, etc.).

Technically, the reasoning engine RacerPro [19] is used for proving the consistency of the ABox (terminological instances) according to definitions of the TBox and the consistency of the SBox (qualitative spatial instances) consisting of topological relationships (i.e., RCC-8; cf. Section 3.1) between *spatial entities* and *spatial artifacts*. An actual ambient environment representation can then be analyzed in order to determine whether it satisfies the requirements that are defined by the *Task-Specific Requirements* module (cf. Fig. 2).

5 BAALL: A Case Study in Representation and Reasoning

The Bremen Ambient Assisted Living Lab (BAALL) is an *intelligent apartment*, suitable for the elderly and people with physical or cognitive impairments [23]. With a size of 60 sqm, it comprises all necessary conditions for trial living, intended for two persons. It is situated at the Bremen site of the German Research Center for Artificial Intelligence (DFKI) and it has been developed in cooperation with the university of Bremen in the EU project SHARE-it and the SFB/TR8 Spatial Cognition Research Center of the Deutsche Forschungsgemeinschaft.

BAALL provides building automation, in particular control of lighting, air conditioning, appliances, doors, access restriction, and user-based profiles. Standard technologies, such as EiB/KNX, LON, Powerline, UPNP, and RFID are used. Furthermore the apartment is equipped with *intelligent furniture* that can be automatically customized to the user. The cupboards in the kitchen, for instance, can flexibly change their position so that they can also be reached easily by wheelchair users. As such, the apartment is intended to provide an adaptive assistance system, that learns and creates user profiles in order to be as comfortable and non-intrusive as possible. As BAALL has been developed, in particular, for the elderly, it also provides health-critical components, such as bio-sensors measuring heart rate, temperature, skin resistance, and general body activities.

5.1 Qualitative World Model of BAALL

Given a metric representation of the environment, e.g., by polylines (a sequence of points) from floor plans or CAD data, the derivation of a qualitative world model (QWM) is rather simple. Regarding calculi founded on the geometric primitives points and/or lines the relations between the entities can be calculated straightforward wrt. the geometric definitions of the relations. The objects represented need to be abstracted to points, e.g., the center of gravity. If a specific orientation of an object, e.g., the intrinsic front of a TV or shelf, should be represented, such information must be added manually as such information is in general not automatically derivable from floor plans or CAD models.

As geometric definitions are more abstract wrt. regions the derivation of corresponding relations is not so straightforward as regions may have arbitrary shape. To lower complexity, in many cases, objects are approximated by simpler geometric shapes like maximum bounding retangles or circles. Additionally, concerning our indoor environment example mainly, three relations are of main interest. For representing the connectivity between rooms in our environment we need DC and EC reflecting whether they are directly reachable from one another or not. The doors connecting those rooms are regarded as regions as well and and are externally connected to both rooms they connect. For describing which objects are located in which room, we apply the NTPP relation. Each polyline is given a unique identifier, such that with additional ontological information the relational structure between real world objects can be inferred. We derived the qualitative world model of BAALL semi automatically by means of the SparQ toolbox, which will be introduced in more detail in Section 5.2. We do not need to describe the relational structure between all pairs of objects. With respect to regions it is sufficient to derive a) the connectivity structure of rooms and doors (cf. Table 1), b) the containment of objects in a room (object is NTPP of room), e.g., bed and bookshelf are proper parts of the bedroom or that couch, sideboard and table are proper part of the living room, and c) additional relations between objects in the same room (in general: EC or DC) (cf. Table 2) to generate a complete world model with unambiguous RCC relations between any region, i.e., room or object, represented. Regarding relative orientation it may not be sufficient to only derive relations between pairs of objects situated in the same room to globally derive object relations unambiguously. Nevertheless, relations between arbitrary objects may be determined unambiguously. For example, with the model at hand we can determine that $Door_2$ is left ahead of the bed and the bed is right behind the door. Making finer orientation distinctions or using ternary relations, i.e., reflecting information like 'if looking from the couch at the table, $Door_2$ is left front', these ambiguities can be resolved to a certain extent.

5.2 Qualitative Spatial Reasoning with SparQ

SparQ[2] [35] is a toolbox for representing and reasoning about space based on qualitative spatial relations. SparQ aims at making a broad variety of qualitative

[2] `www.sfbtr8.spatial-cognition.de/project/r3/sparq/`

	bedroom	$hall_1$	$hall_2$	closet	bath	liv. room	kitchen	$door_1$	$door_2$	$door_3$	$door_4$	$door_5$
bedroom	EQ	EC	EC	DC	DC	DC	DC	EC	DC	EC	DC	DC
$hall_1$		EQ	DC	EC	EC	EC	DC	EC	EC	DC	DC	EC
$hall_2$			EQ	EC	DC	EC	DC	DC	DC	EC	EC	DC
closet				EQ	DC	DC	DC	DC	DC	DC	DC	DC
bath					EQ	DC	DC	DC	DC	DC	DC	EC
liv. room						EQ	EC	DC	EC	DC	EC	DC
kitchen							EQ	DC	DC	DC	DC	DC
$door_1$								EQ	DC	DC	DC	DC
$door_2$									EQ	DC	DC	DC
$door_3$										EQ	DC	DC
$door_4$											EQ	DC
$door_5$												EQ

Table 1: The topological structure of rooms in BAALL.

	bed	bshelf	bst_1	bst_2	couch	sb	table	$door_1$	$door_2$
bed	$EQ,_2\angle 0$	$DC,_2\angle_7^1$	$EC,_2\angle_3^7$	$EC,_2\angle_5^1$				$DC,_2\angle_7^7$	
bshelf		$EQ,_2\angle 0$	$DC,_2\angle_1^7$	$DC,_2\angle_1^7$					
bst_1			$EQ,_2\angle 0$	$DC,_2\angle_6^2$					
bst_2				$EQ,_2\angle 0$					
couch					$EQ,_2\angle 0$	$DC,_2\angle_1^7$	$DC,_2\angle_7^1$		$DC,_2\angle_5^1$
sb						$EQ,_2\angle 0$	$DC,_2\angle_1^7$		$DC,_2\angle_1^1$
table							$EQ,_2\angle 0$		$DC,_2\angle_1^7$
$door_1$								$EQ,_2\angle 0$	$DC,_2\angle_4^4$
$door_2$									$EQ,_2\angle 0$

Table 2: Topological and relative orientation ($\mathcal{OPRA}_m$) relations between objects in the same room.

spatial calculi and the developed reasoning techniques available in a single homogeneous framework. SparQ is designed for application designers or researchers not familiar with qualitative reasoning, as well as QSR researchers. For the first group SparQ offers access to reasoning techniques without further effort in an easy-to-use manner. For the second group SparQ provides an implementation toolbox of key techniques in QSR, making experimental analysis easier. Furthermore, SparQ offers an easy format to specify new calculi. The toolbox is released under the GPL license for freely available software and can easily be included into applications.

Currently, three main features are available: qualification, fundamental relation transformations, and constraint-based reasoning. The integration of conceptual neighborhood-based reasoning is currently in progress. We applied the qualification feature for deriving the qualitative world model of BAALL (cf. Section 5.1). To qualify metrical data by SparQ with respect to a given calculus, e.g., $\mathcal{OPRA}_2$, the positions as well as the orientations must be provided. In the example below we relate the bed, the bookshelf, and the door to the room represented by their centres of gravity. The result from SparQ represents the relations $_2\angle_1^7$, $_2\angle_1^1$, and $_2\angle_1^7$.

```
$> sparq qualify opra-2 all "((BED 255 210 1 0)(BSHELF 319 462 0 -1 )(DOOR 420 270 -1 0))"
((BED 1_7 BSHELF) (BED 1_1 DOOR) (BSHELF 1_7 DOOR) )
```

Constraint-based reasoning can be applied to check consitsency of qualitative world models or to complete partially defined models, e.g., the missing topological relations between bed, couch, living room, and bedroom:

```
$> sparq constraint-reasoning rcc-8 algebraic-closure "((BEDROOM DC LIVROOM)(BED
NTPP BEDROOM)(COUCH NTPP LIVROOM)"
((BED (dc) COUCH)(LIVROOM (ntppi) COUCH)(LIVROOM (dc) BED)(BEDROOM (dc)
COUCH)(BEDROOM (ntppi) BED)(BEDROOM (dc) LIVROOM))
```

5.3 Spatio-Terminological Reasoning with RacerPro

The environment of BAALL is instantiated by the ontological scene description according to Section 3. The different entities are formalized in the conceptual module ABox, such as Kitchen, LivingRoom, Sofa, and Camera. The conceptual module also indicates, whether an entity has to define spatial artifacts. The sofa, for instance, defines a *functional space*, i.e., the space an agent has to be located in, in order to interact with it for a specific function (e.g., sitting). The camera, for instance, defines a *range space*, i.e., the area it can monitor.

Corresponding spatial regions of the conceptual module are mirrored in the qualitative module SBox, and spatial dependencies based on RCC-8 relations are specified. RacerPro not only proves the formal consistency of the BAALL model. It also allows to verify that certain pre-defined AmI requirements are satisfied. They are formalized in the requirements module as an extension to the integrated representation. For an AmI environment, for instance, it is necessary that the entrance door is monitored by some camera, in order to ensure that visitors are tracked, i.e., no unauthorized person may enter the apartment:

```
Class:       FrontDoor_FunctionalSpace
SubClassOf:  FunctionalSpace, rcc:properPartOf some (MotionSensor_RangeSpace), ...
```

Whether BAALL satisfies this constraint is automatically proven with analyzing ABox and SBox consistency by applying RacerPro for spatio-terminological reasoning. It can also be illustrated by the following query, which indicates the combination of the SBox (?*X) and ABox (?X):

```
? (retrieve (?*X ?*Y) (and (?X FrontDoor_FunctionalSpace)
                           (?Y MotionSensor_RangeSpace) not (?*X ?*Y :NTPP)))
> NIL
```

6 Summary and Challenges

We have presented an overview of different approaches from the field of qualitative spatial reasoning and formal ontology and the manner in which they may be applied for representation and reasoning purposes in ambient intelligence systems. Qualitative spatial descriptions can assist in formalizing essential spatial relations and their compositions. Ontological descriptions can assist in formalizing essential AmI entities and artifacts. Reasoning with both descriptions can prove spatial consistency and domain-specific requirements. In particular, qualitative spatial and terminological reasoning can be applied to specific AmI use cases, such as the ones resembling the BAALL environment discussed in this paper. There are, however, different challenging research questions left for future work, as we point out in the sections to follow.

6.1 Ontologies and AmI

The AmI-related ontology aspects, pointed out in Sections 3 and 4.3, have to be investigated in more detail. It will be up to future work, whether the theory of $\mathcal{E}$-connections is expressive enough to define integrations of all different modules, that will be necessary to describe scenes of any kind in AmI. General modularity aspects [22] from the field of ontological engineering may have to be investigated, given domain-specific modeling issues with respect to smart environments. On a more fine-grained level, specific (domain-dependent) ontologies have to be developed to cover a wide range of different aspects necessary to formalize AmI aspects. For instance, a thorough specification of different sensors and their properties have to be analyzed together with their link relations to other ontologies from the integrated representation. This will also result in a more thorough scene description ontology to model ambient environments.

One of the general ontological challenges, which affect AmI ontologies, is the specification of processes in ontologies. Bridging the gap between highly expressive ontological definitions of actions and activities, such as the Process Specification Language [33], and computational complexity in terms of reasoning practicability will be a challenging task here. Moreover, particular processes in smart environments will be of interest. Strongly connected to these activity formalizations is the ontological integration of the temporal dimension in general. Furthermore, the combination of spatial and ontological reasoning in general is an important next step. It is up to future research, how a flexible and loose coupling of the different reasoning techniques, similar to the one supported by $\mathcal{E}$-connections (Section 3.2), will be specified. And, more importantly, its impact on the design of smart environments and its conformity with existing industrial / architectural standards and design tools then has to be analyzed.

6.2 Space, Interaction and Change

One fundamental research question pertains to the integration of spatial calculi for scene modelling. Presently, it is not possible to reason over different aspects of space, i.e., , for example, either in the domain of oriented points or in the domain of regions, or even over different granularities within the same spatial aspect. Although, there is already effort in the QSR community to overcome such limitations and extend calculus expressivity, the research in this direction needs to be strengthened. For example, in [11] transformations between point-based, o-point-based, and line-based calculi dealing with relative information were defined and investigated. A unified approach of representing points, lines and regions is presented in [24]. An approach by [6] combines regions and orientations in a *ternary projective calculus for regions*. The position of one region is described with respect to two other regions, and this position is given by five collinearity regions, which result in five projective relations.

At an application level, the simulation of the spatial interaction betweeen subjects and smart artefacts within an ambient environment is a topic that directly benefits by the formal modelling of spatial and terminological knowledge, and the spatio-terminological reasoning tasks that it facilitates. For instance, spatial, terminological and spatio-terminological reasoning, in the manner as suggested in Section 4.3 (and elaborated in [5]) may be used to model functional requirements at the design stage, whereupon a design may be actually simulated within a virtual reality setup (e.g., [26]) to visualize and simulate the impact of the spatio-terminological (functional) constraints on the work-in-progress design. Closely related to the topic of such simulation is the task of motion pattern abstraction for activitiy analysis and interpretation. In recent years different quantitative approaches to derive motion patterns from sensor data were presented, e.g., an approach based on expectation maximization and Hidden Markov Models [3]. From our perspective such models are helpful for machine-machine interaction, but not very helpful for human-machine interaction and action analysis, behavior interpretation respectively. With action-augmented conceptual neighborhoods (Section 4.2), motion evaluation is possible at a high-level of abstraction, if data in a suitable form is available. We believe that the combination of both methods will improve systems on behavior monitoring and interpretation in specific, and ambient intelligence systems is parrticular.

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A Continuous-based Model for the Analysis of Indoor Spaces

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Abstract. Recent years have witnessed development of GIS research to ambient and indoor environments. Preliminary studies have been particularly active in the fields of urban planning and architectural design, particularly with the development of space syntax and ubiquitous computing, and where indoor spaces are often considered as structural and graph-based representations. However, it has been demonstrated that a structural model cannot integrate all the properties of space, and particularly the way a given space is continuously distributed. The objective of the preliminary research presented in this paper is to consider a built environment as a continuous frame of reference, and where an analysis of such continuity is realized using a combination of grid-based and structural-based representations, thus favoring integration of geometrical and topological properties within a homogeneous framework.

Keywords. Indoor spaces, continuous-based modeling

1 Introduction

Over the past few years the range of applications of Geographical Information Science has been progressively extended from large to small scale environments, and for many disciplines beyond the usual scope of environmental and urban sciences. Amongst many factors that have favored this evolution, recent developments of ubiquitous computing such as ambient systems have largely favored the application of GIS to indoor spaces (Li, 2008). An indoor space can be informally defined as a large-scale built environment where people are likely to behave, whereas an ambient system or device utilize pre-attentive processing to display information without any apparent human interaction. Several recent applications have illustrated the potential of GIS in indoor spaces. Raubal and Worboys (1999) discussed the elements affecting the process of human way finding in built environments using the notions of image schemata and affordance. Kwan and Lee (2005) applied GIS to find evacuation routes for people stuck in a building during an emergency. Li *et al*. (2007) modeled an accessible space within a building using a GIS model and video sensors in order to track suspicious moving objects in a simple and quick fashion.

Behind these applications, a methodological issue that still requires particular attention is the way these indoor spaces should be spatially represented. This implies to define an appropriate reference model of an indoor space, together with an integration of the ambient devices that are part of the represented environment. This modeling issue is not completely new as the representation of indoor spaces has been long the object of considerable attention in several domains such as architectural and urban planning with early developments of space syntax (Hillier and Hanson, 1984), and navigation knowledge as considered by cognitive studies (Golledge, 1993). One of the main principles of space syntax is to assume a functional relationship between human behavior and the structure of the environment where these human behave. Such structural properties of indoor environments have been largely studied, using graph-based approaches and measures where usually nodes model rooms and edges connections between these rooms. The idea behind these modeling approaches is to favor emergence of structural patterns that might explain or predict human behaviors, and thus helping urban planners and architects to design and organize built environments. Space syntax is intrinsically related to the architectural and design domains, and has been rarely directly applied to other application areas as its basic assumptions cannot be always and directly translated to other domains. This is the case for cognitive studies oriented to the modeling of navigation knowledge, agent-based or other closely related simulation domains, where the main modeling issue relies in the identification of an appropriate spatial representation with respect to the phenomenon or behavior considered. When considering the displacement of an agent or robot acting and perceiving an environment, or when simulating the spread of a fire within an indoor environment, the question that arises concerns the identification of the appropriate modeling paradigm, either continuous or discrete, graph-based and if so under which spatial structure.

The preliminary research presented in this paper addresses this specific modeling issue and introduce a continuous-based representation of space whose objective is to consider an indoor space at a finer level of abstraction, using a continuous-based model of space that that will constrain the represented environment. The reminder of the paper is organized as follows. Section 2 briefly introduces related work while Section 3 develops the main principles of our modeling approach. Section 4 illustrates the potential of our framework using an illustrative case study while Section 5 concludes the paper.

2 Modeling background

It is until relatively recently that spatial quantitative approaches have been oriented to the structural modeling of the built environment. The analysis of spatial configurations has been studied as a tentative measure of the interaction between human beings and the built environment. The spatial layout of an indoor space is approximated by a graph-based representation where a built environment is decomposed into connected rooms (or alternatively convex or vista spaces) (Benedikt, 1979). This generates a basic node-edge representation where nodes represent rooms, and edges connections, such as corridors and doors, between rooms. The assumption of this modeling approach is that there might be a correlation between the structural patterns that emerge from a building layout and the way people occupy and move through space, and social interactions (Hillier and Hanson, 1984). This approach is structural and assumes a close relationship between the structure of a built environment and human behaviors within it.

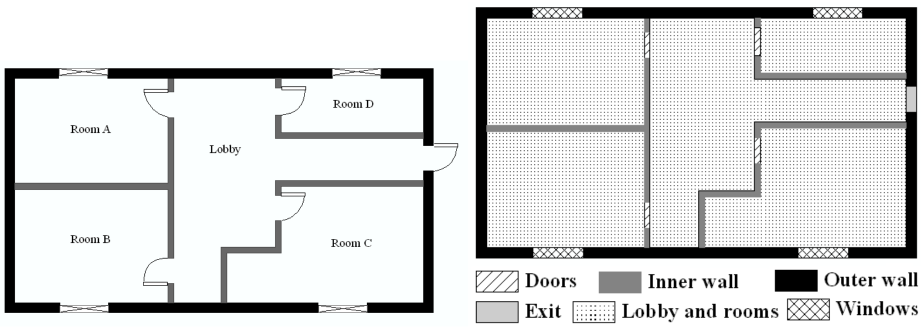
There is no formal theory behind space syntax although many experimental studies have long proven its interest for architectural design and urban planning (Hillier, 1999). The main advantage of space syntax is that it has been easily computationally experimented with basic principles and operations long identified by graph theories. Many operators have been applied: local operators that evaluate the connectivity of a given room (e.g., degree) in the emerging network or degrees of clustering, global operators that measure the role played by a given room in the whole network (e.g., centrality and betweenness values). Despite its successful diffusion within the urban planning and architectural design communities, the structural and computational principles of space syntax have been recently criticized with respect to its lack of integration of geometrical properties (Ratti, 2004). On the modeling dimension, this indirectly raises an interesting issue, that is, the old duality of space, in between feature- and continuous-based perceptions of space. In other words, although a structural representation of space is likely to reveal the main layout and some emerging properties of space, it lacks the continuity and geometrical measures of space that encompass another dimensional range of properties. Space as a continuum is inherent to many phenomena such as the diffusion of physical processes or cognitive perception of the environment, or agent and robotics navigation where the environment is quantitatively measured. Also people's behaviors are often non deterministic processes that cannot always be approximated by a structural representation of space.

Alternative solutions have been proposed to consider indoor spaces at a lower level of granularity. Ray *et al.* (2009) intoduced a fine cell-based modeling for real-time indoor positioning. Each cell is associated with an evolution law (height directions) that represents displacement opportunities. Li *et al.* (2007) considered an indoor space as a continuous space represented as a graph at a lower level of granularity through filling a cellular unit with additional edges and nodes. Although there is lack of procedure to formalize the filling operation, this provides a sort of compromise, where structural properties might be still encapsulated within the graph-based representation, and where the geometrical properties are implicitly represented by the continuous layout of the graph. The basic idea is of this modeling approach is derived from an occupancy grid which was initially proposed in the communities of mobile robotics and artificial intelligence (Moravec and Elfes 1985; Thrun *et al.* 2005). An occupancy grid is a regular matrix consisting of equally-sized cells, and each cell can be connected to its eight neighboring cells. The surrounding environment of a mobile robot is covered by such kind of grid. Then the movement probability of a robot could be estimated and recorded. A high probability is assigned to cells within accessible space, while a low probability to cells occupied by obstacles. Simplicity and metric embeddedness are two advantages of the occupancy grid approach (Franz, 2005).

3 Methodology

The modeling approach is based on the principles of a node-edge graph that represents an indoor space. Unlike the aforementioned principles of space syntax discussed in previous sections, nodes do not represent cellular units such as rooms but represent cells within an occupancy grid, and connections between cells are materialized by edges. More formally a built environment is modeled as a two dimensional space of extent *S* materialized as a continuous space of cellular units. The continuous representation covering *S* is parameterized by a level of granularity *g* that generates a grid graph of step *g* with additional diagonal edges so that each node is connected to 8 neighbors (apart from the ones located in the boundary of the extent *S*). *N* models the set of nodes, and *E* the set of edges. In order to reflect the spatial distribution of the built environment, nodes and edges are labeled according to their memberships to a given cellular unit such as a room or a connecting space (every cellular unit in the built environment is identified). Therefore, each node has one and only one membership value as a node is contained by one and only one cellular unit, while the membership value of an edge is multi-valued when this edge intersects several cellular units.

The above procedure is illustrated in Figures 1 and 2. The floor plan of a typical indoor space is shown in Figure 1a. Its cellular units are defined and identified as shown in Figure 1b. These units are identified and categorized (e.g., Doors), and individually identified (e.g., Door A, Window C). These cellular units are covered by a grid graph (Figure 2), thus allowing the node and edge membership values to be derived from the intersections between cellular units and the grid graph.



(a) (b)

Figure 1: A floor plan (a) with its corresponding grid graph (b)

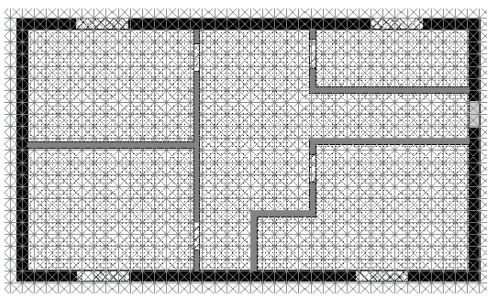
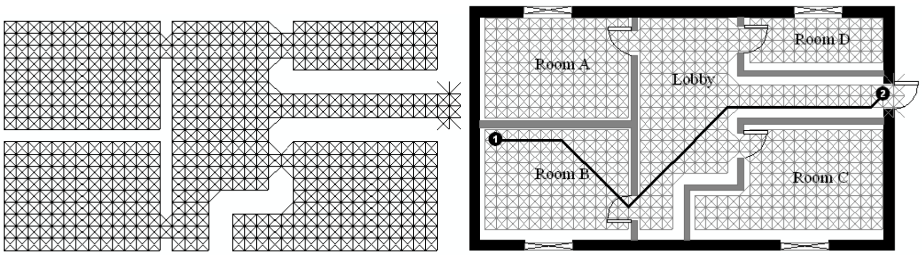


Figure 2: The overlap of the grid graph, cellular units (a) and resulting labels (b)

Impedance values are assigned to each edge of E. Edges reflect impedance values necessary for network analysis, even in the scarce case where a node is located in a non-free space. When this happens, incoming and outcoming edges to this node are labeled accordingly. Impedance values of course depend on the nature of the phenomenon represented (e.g., planning evacuation or fire diffusion). An evacuation route is for example modeled by the shortest walking path between a given location and the nearest exit in a given indoor environment. In the case shown in Figure 1, let us suppose that doors and the exit are open, the impedance of an edge reflects its degree of occupancy (i.e., free space or occupied space) and is defined in the following way. If the single or multi-valued membership of the edge includes one element referring to a cellular unit of inner wall, outer wall, or window, then its impedance value is equal to infinity, and otherwise, it equals the length of the edge, i.e., g or $g\sqrt{2}$. Figure 3a illustrates all edges excluding those with infinity impedance, which indeed represents all free space in the indoor environment. Finally, the application of a shortest path algorithm between a location and an exit gives the route shown in Figure 3b.



(a) (b)

Figure 3: Free space represented by a grid graph (a), and example of shortest path between a location and the closest exit (b)

4 Case study: Mapping gas leak in an indoor space

The objective is to map the spatial extent of a gas leak with time in the indoor space illustrated in Figure 1a (in fact we retain the illustrative case of phenomenon that is likely to continuously spread over space). Suppose the source of the gas leak is located in a given room of an indoor space. Let us assume that the impedance of each edge equals the time it takes gas to diffuse along the edge. Supposing that the diffusing speed is denoted as v in the free space considered, let T be g/v. Then, the impedance values of edges could be defined according to Table 1.

Table 1: Example edge impedance values for gas diffusion in an indoor space.

Description	Edge length	Impedance
Edges are completely within free space: room, lobby, opened door, opened window, or opened exit.	g	T
	$\sqrt{2}g$	$\sqrt{2}T$
Edges are completely within or intersect less occu-	g	$40T$

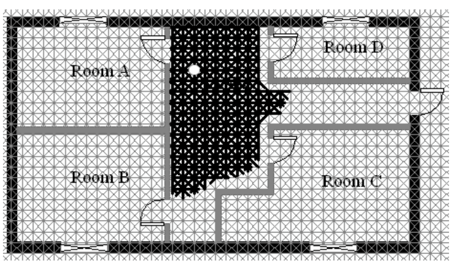
pied space: closed door, closed window, closed exit, or inner wall.	$\sqrt{2}g$	$40\sqrt{2}T$
Edges are completely within or intersect more occupied space: outer wall.	g	*Infinity*
	$\sqrt{2}g$	*Infinity*

Let n_0 denote the node representing the source of gas leak, and t_0 the starting time of leak. For a given time instant $t_0 + mT$, where m is a real number, Algorithm 1 figures out the evolution of the nodes and edges covered by the gas diffusion. First, the algorithm finds all nodes whose shortest paths to n_0 are less than mT in terms of cost (i.e., diffusing time) and save them into S_n. Then, check each edge through examining its two associated nodes and figure out those covered by gas during the interval from t_0 to $t_0 + mT$. Especially, if not the whole but part of an edge is covered by gas then only the covered part will be saved into S_e as described in step 4c.

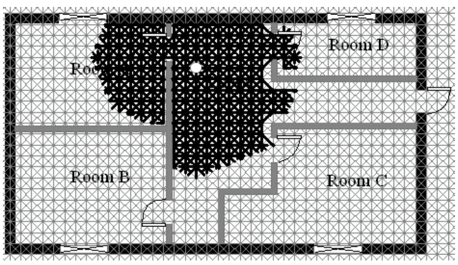
Algorithm 1: Nodes and edges diffusion of gas over time

1. Let *NC* denote an array saving the cost of the shortest path from a given node to n_0. Let *infinity* denote a large enough number. Initialize for each node n of N, $NC(n)$ to *infinity* and $NC(n_0) = 0$
2. Let S_n and S_e be two empty sets saving the resulting nodes and edges, respectively.
3. Repeat the following procedure
   a) Let n_x be the node having the shortest value in *NC* and n_x does not belong to S_n
   b) If $NC(n_x) > mT$ then go to step 4
   c) Save n_x into S_n
   d) For each neighbor n_e of n_x let $NC(n_e) = \min(NC(n_e), NC(n_x) + d_{ex})$, where d_{ex} denote the impedance of the edge (n_e, n_x), that is, its two associated nodes
4. For each edge e, repeat the following procedure.
   a) Let e denote an edge (n_1, n_2) and t denote the impedance of e.
   b) Let $d_1 = NC(n_1)$, if n_1 belongs to S_n, or *infinity* otherwise. Let $d_2 = NC(n_2)$, if n_2 belongs to S_n, or *infinity*, otherwise.
   c) If $\min(d_1+t, d_2+t)<mT$ then save e into S_e, else if $\min(d_1, d_2)<mT$, then part of e, i.e., mT-$\min(d_1, d_2)$ is saved into S_e.

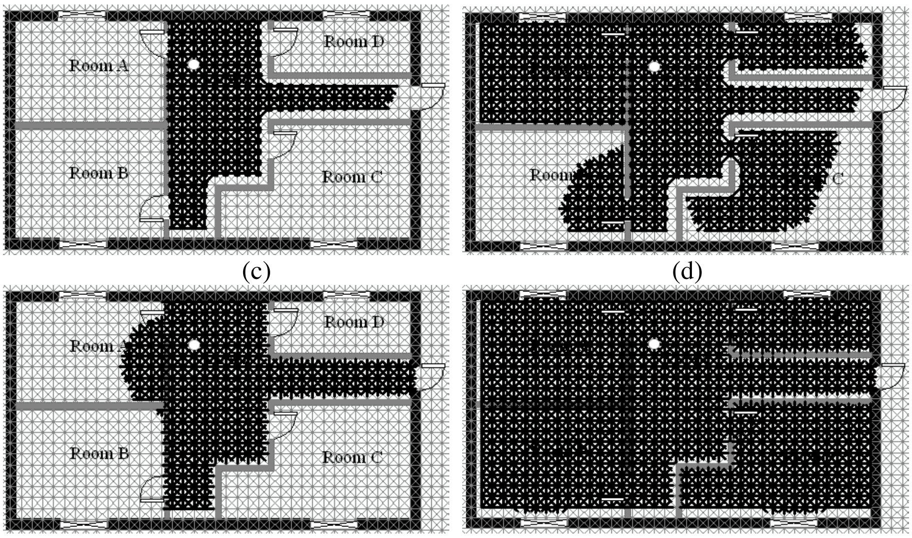
The approach is illustrated by the following scenarios. In scenario 1 (Figure 4, a, c, e), windows, doors, and the exit are closed. In scenario 2 (Figure 4, b, d, f), windows and the exit are still closed, while all doors are open. The source of gas leak is located in the lobby. Figure 4 illustrates the snapshots of the spatial extents of gas leak at time instants t_0+10T, t_0+20T, and t_0+45T under these two scenarios, respectively.



(a)



(b)

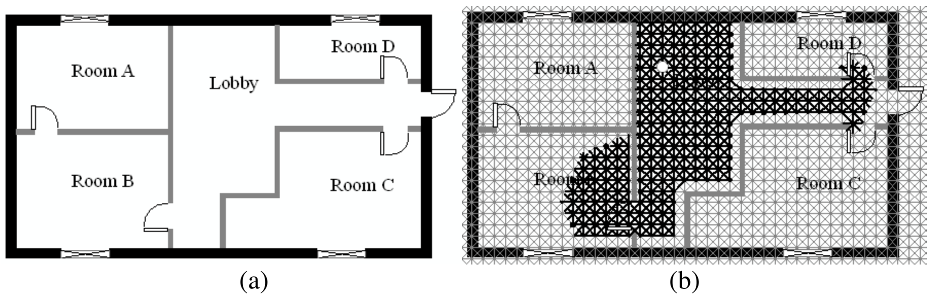


(c) (d)

(e) (f)

Figure 4: Snapshots of spatial extents of gas leak at time instants t_0+10T (a and b), t_0+20T (c and d), and t_0+45T (e and f) under scenario 1 (a, c, and e) and scenario 2 (b, d, and f), respectively. The white circle represents the location of leak source.

Figure 4 shows that, as expected, the simulated gas leak always diffuses in "free space" first, and then passes through less occupied space such as doors when the diffusion lasts long enough. Let us assume the case of scenario 2, where to avoid a fast gas diffusion, different room designs might be investigated. For example, the locations of doors can be moved further from the gas source (as shown in Figure 5a), and thus different spatial extents of gas leak are generated (one snapshot at time instant t_0+20T is displayed in Figure 5b). The influence of the changed floor plan on gas diffusion can be clearly figured out through comparing Figure 5b with Figure 4d.



(a) (b)

Figure 5: A new floor plan (a) and a snapshot of the spatial extent of gas leak at time instant t_0+20T scenario 2 (b). The white circle represents the location of leak source.

The diffusion process reveals the behavior of a given phenomenon with respect to a given location in the built environment. A complementary and global evaluation of the properties that emerge from the grid-based occupancy should be derived from a measure of the centrality versus peripheries of the spatial layout of the floor plan. As initiated and applied in space syntax studies at the structural level, several centrality measures have been applied to room distributions in built environment. We retain such principles but by applying such a measure to the continuous representation. The betweenness is a representative centrality measure applied to graphs (Bonacich, 1987). The principle of this node-based measure denotes the number of time a given node appears in shortest paths between the other nodes of the graph. The most central a node is, the most important its centrality role in the structure of the whole graph, and often its accessibility depending on the phenomenon represented. More formally, the betweenness $C_B(n_a)$ of a node n_a is given as follows, where σ_{ij} is the number of the shortest paths between nodes n_i and n_j, and $\sigma_{ij}(n_a)$ the number of the shortest paths between nodes n_i and n_j that n_a lies on.

$$C_B(n_a) = \sum_{a \neq j \neq i} \frac{\sigma_{ij}(n_a)}{\sigma_{ij}} \tag{1}$$

Figure 6 illustrates the betweenness values of nodes in free space under scenarios 1 and 2. Values of betweenness are classified and magnified per order of betweenness values into 5 categories and represented by black circles. This figure shows the distribution trends of betweenness values. For instance, and under scenario 1, nodes with high betweenness values are located in the central area, while under scenario 2 nodes located in the lobby or around doors play a specific role in the spatial layout. Central nodes as identified here play a crucial role in the diffusion of any continuous phenomenon such as in the one of the example and scenarios considered for gas diffusion.

One of the interests of the approach is to study the impact of different distribution layouts with respect to a given phenomenon of interest, thus providing architectural designers in the considered case a complementary view on their projects. The approach is flexible enough to be applied to different cases end environments as far as edge impedances are parameterized appropriately.

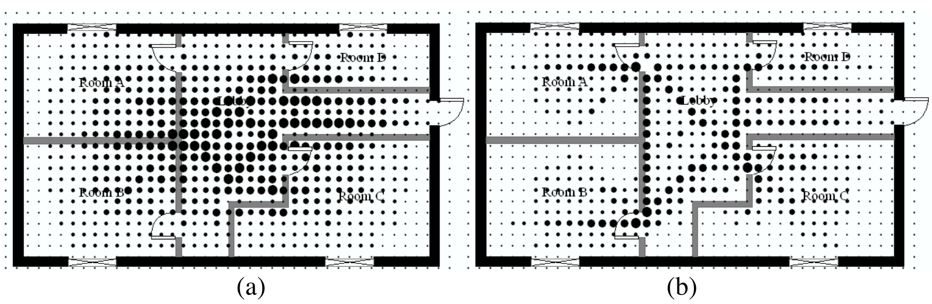


Figure 6: Betweenness values of nodes under scenarios 1(a) and 2(b). Black circle magnitudes reflect betweenness values of the nodes.

5 Conclusion

Built environment and indoor spaces represent a novel domain of application for the development of spatial information models, at the crossroad of many disciplines from design to engineering sciences. Early developments have been often successful in defining spatial representations of built environments such as structural-based models, cognitive and quantitative models. However, the concept of space as considered in indoor environments deserves complementary spatial modeling approaches adapted to the specific continuous properties of built environments. The research presented in this paper provides a continuous-based representation of a built environment, and where an occupancy grid is considered as the reference modeling concept. An indoor space is covered by a grid graph, where labeled edges retain the semantics of the distribution of the built environment and of a given phenomenon of interest (i.e., the distribution of a variable of interest). The interest of this approach is that the coverage of the emerging graph allows a study of the spatial diffusion of a given phenomenon of interest, and the application of structural measures that reveal the emerging structural properties of the represented space. The approach thus keeps a continuous representation of space, while still embedding structural properties at a lower level of granularity. The potential of the approach is illustrated by a representative case study. The research is still preliminary, and we plan to extend the modeling approach to 3D environments and to apply these modeling concepts to experimental setups in built environments.

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