Uncertainty Management in Context-Aware Applications

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Abstract. The objective of context-aware computing is to develop applications which perceive and analyze the user's activities and behavior to provide him with relevant information and services. However, the mechanisms used for perception or context analysis could provide uncertain information, generated by physical or logical factors. If this uncertainty is not properly managed, a context-aware application might become inadequate to the user. In this paper we propose a three-phase strategy to manage the uncertainty generated by contextual information within a context-aware application. Its objective is to implement actions to notify the user about the degree of uncertainty estimated and reduce it automatically through mechanisms such as re-estimation, recurrence, the use of additional contextual elements, or assisted via user feedback. We developed an activity-aware application aimed at a medical scenario to evaluate the effectiveness of the proposed strategy. The application simulates 7 hours of a nurse's work-day in a hospital. As a result we obtained that 61% of the elements marked as uncertain were due to an erroneous estimation of the algorithm. When we included automatic actions to reduce uncertainty this percentage grew to 76%. At the same time, when we included assisted actions the system requested user intervention on 13 times of all the entries in the registry.

1 Introduction

The rapid evolution of ubiquitous computing opens new possibilities to assist many activities. The health sector is a particularly appropriate area for the deployment of *ubicomp* applications, due to the fact that it is a highly dynamic environment with considerable worker mobility. Hospital workers carry out different activities at the same time, collaborate with other colleagues to solve problems, and use a wide variety of instruments and devices [1-3]. Recently, some hospitals have introduced wireless networks, PDA's, laptops, RFID labels, communication systems and some sensors for patient monitoring [4-7].

In a hospital environment workers need information highly dependent on contextual information such as location, role, time of day and activity [8]. This has motivated the development of context-aware applications to better assist hospital workers

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adapting to the continuously changing environment [1, 8]. Some contextual information such as role and time of day can be easily determined, but other like location [9-13] or activity [14-16], require complex estimation algorithms and in some cases they use different technology and devices; which could generate uncertainty within an application, because the contextual information may be incomplete, erroneous or ambiguous. Uncertainty is an unavoidable factor in some context-aware applications. This generates one of the most important technical challenges in the development of context-aware computing: create mechanisms that provide applications the capacity to manipulate imperfect, uncertain or ambiguous contextual information [17, 18].

In this paper we propose a three-phase strategy to manage the uncertainty generated by contextual information within a context-aware application. Its objective is to implement actions to notify the user of uncertainty and reduce it: automatically through re-estimation, recurrence and combination with other contextual elements or additional information and assisted using user feedback. At the same time we applied this strategy to implement a mechanism for uncertainty management in an algorithm of activity estimation. This mechanism allows the classification of the estimates as certain or uncertain.

Finally, we tested and evaluated the uncertainty management mechanism in a medical scenario, in which we introduced an activity-aware application that simulates a 7 hours nurse's work-day in a hospital.

The rest of the paper is organized as follows: Section 2 presents previous related works. In section 3, a description of the suggested strategy for uncertainty management is presented. The algorithm used to estimate the activity is described in section 4, and the implementation of the strategy is presented in section 5. The outcomes of the application are presented in section 6. Conclusions are described in section 7.

2 Related Work

Bayesian networks are a powerful tool to deal with uncertain information. Tau Gu et al. [19] used Bayesian networks to estimate the activity of an user. They use RDF ontologies to define context, they later transform the ontology into a Bayesian network. Ranganathan et al. [20] implemented a reasoning engine where they combined rules and information inference to influence decisions using Bayesian networks. Truong et al. [21] also use Bayesian networks and ontologies, but their focus is on reusing context ontology definitions. They outline an ontology structure that may be used in different scenarios, helping decrease the time and effort required for the definition of context. The proposals above address the problem of dealing with uncertain information using probabilistic reasoning. However, a great amount of work by application developers is required and the aid of experts to create the context ontology. Also, the transformation of the ontology to a Bayesian network is not automatic and it is a very demanding task. Our proposal is based on an automated low-cost strategy based on a three-phase structure consisting of a context-aware mechanism to identify the presence of uncertainty and to define actions to carry out in the presence of such uncertainty based on specific rules. The strategy can be used in the design of a new context-aware application or to implement additional mechanism that enhances an existing application.

3 Strategy for Uncertainty Management

Figure 1 depicts our uncertainty management strategy for context-aware applications. The first step consists on the identification of uncertainty, the second step consists on measuring the degree of uncertainty, and the third step consists on adopting actions to attenuate the uncertainty.

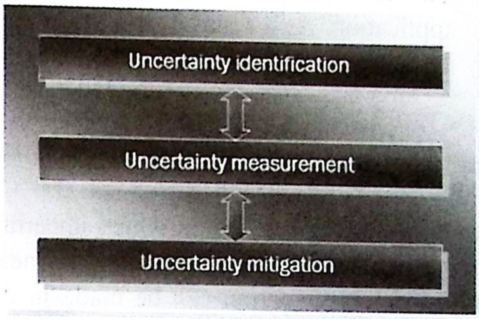

Figure 1. Uncertainty management strategy

3.1 Identification of Uncertainty

A detailed analysis of the application and its relationship with the contextual variables is conducted at this stage, with the aim of identifying conditions in which the uncertainty appears.

To identify uncertainty, it is convenient to define a general model of the mechanism of context-awareness (Fig.2). This structure consists of two main elements: inputs and processes. The former are data and contextual elements are considered inputs. The latter are algorithms, rules, reasoning methods, procedures and actions that provide awareness to the application.

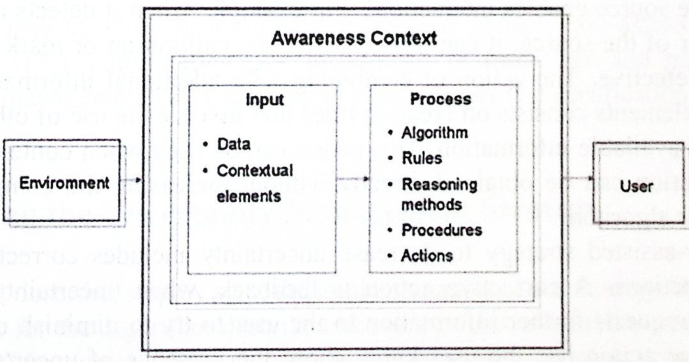

Figure 2. General model of context aware mechanisms

It is possible to analyze in an independent way, and determine where the uncertainty may appear (Fig.2). In some situations the uncertainty may appear in the inputs, while in others it might appear in the processes, or in both.

Inputs with uncertainty are associated to contextual elements. When the source of generation of contextual element is known, it is possible to better analyze its operation, in search of behavioral patterns that later on can be used to dimension the level of uncertainty.

Processes with uncertainty are associated to the way in which the application becomes aware of the context. This is how inputs are used to provide awareness to the application. We must analyze how contextual information is used and what actions are carried out with that information. This includes rules, reasoning methods and processes used by the application. As a result of this stage the designer identifies the sources of uncertainty in the mechanism of context awareness.

3.2 Measurement of Uncertainty

This phase consists on establishing the way in which uncertainty is represented and quantified: finding the way of making samples tangible or measurable. Depending on the kind of uncertainty, the representation can be made in different ways, in some situations specific values are used, such as true/false, percentages, probabilities, averages, distances, among other, and in other cases, the representations can be better defined with words, for these cases it is possible to use fuzzy logic. In this stage it is expected as a result, a series of rules or diagnoses tests to identify the presence or absence of uncertainty.

3.3 Actions for Dealing with Uncertainty

It consists on establishing actions the application must carry out in the presence of uncertainty to mitigate or control its effects.

To decreased uncertainty, corrective actions can be used by the application. These actions include: re-estimation. This consists on making a new estimation of the contextual element. It is executed when there is a doubt about the information provided by the generation source. This action can be used to make a corrective action to the source if the source enables interactions. For example, when it detects an inappropriate behavior of the source, it can try to solve it by calibration or mark the device or sensor as defective. The action of combining with additional information or others contextual elements consists on creating rules that involve the use of other contextual elements or available information. This action can be used when contextual elements and information can be obtained directly without increasing the complexity of the procedure or algorithm.

The user-assisted strategy to decrease uncertainty includes corrective and noncorrective actions. A corrective action is feedback, when uncertainty appears the application requests further information to the user to try to diminish uncertainty; A noncorrective action lets the user know about the presence of uncertainty, and the user must decide on the appropriate course of action. These actions can be conducted through adaptation of the user interface, with use of text, colors, icons, sounds and combinations of them.

4 The Estimation of a User's Activity

A procedure to estimate user activity for context-aware applications is proposed in [22]. In this approach, a back propagation neural network (BP-NN) is used to estimate the user activity by mapping from contextual variables to activities. The BP-NN receives as input user's contextual variables, such as its current location, the time of day, artifacts being used and the presence of colleagues. The neural net maps this inputs to output values corresponding to every possible activity performed by the worker. The output with highest activation value indicates the activity that the worker is carrying out at that moment. The structure of the BP-NN used is illustrated in Figure 3. This network uses, as inputs, 1 neuron for time of the day, 1 neuron for user location, 1 neuron for every significant artifact the worker may use and, 1 neuron for the role of each person with whom they may collaborate; and, as outputs, 1 neuron for every possible activity performed by the worker.

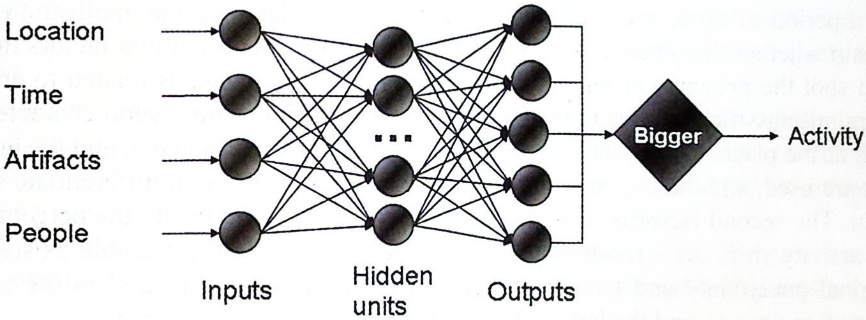

Figure 3. Structure of BP-NN used to estimate user's activity

The authors based their approach on information gathered from a workplace study conducted in a hospital, in which 196 hours of detailed observation of hospital workers were recorded. The record structure includes location, time of day, artifacts, people and real activity. These records are used to train and test the BP-NN. They define 7 main activities in which hospital workers engage: clinical case assessment (CCA), patient care (PC), coordination (C), preparation of medicines and material (PM), information management (IM), tracking (T) and, classes and certifications (CC).

5 Applying the Uncertainty Management Strategy

Now we will describe, step by step, the implementation of our strategy for uncertainty management for the algorithm described above. For this, we used the same data collected in [29] for nurses. These records were created as result of direct observation at the hospital.

5.1 Identification of Uncertainty

In this first step, we identify the existence of uncertainty. We define uncertainty in a descriptive way. As mentioned before, the procedure is based on the use of a neural network to estimate the user activity by mapping from contextual variables to activities. The estimate activity corresponds to the output neuron with highest activation value. Secondly, we define *original uncertainty*. This uncertainty appears for a single moment and a single estimate. Then, when we estimate an activity from the algorithm the original uncertainty appears, since it is likely that the estimate made is incorrect.

We identified three factors that can help spot the presence of uncertainty. The first factor is related to the nature of the neural network, this is when the outputs values of each neuron are very similar among them. The next two factors are related to the contextual information used, that is, the inputs to the neural network. We observed that each activity performed by a hospital worker depends on contextual variables such as user location, the people with whom they collaborate and the artifacts used during the execution of the activity. For example, classes and certification is an activity executed in base locations, such as meeting rooms or offices, and when an instructor is present.

Let us now define *temporal uncertainty*. This appears when the application is used for a period of time, and a change of activity takes place but the application is not certain whether that change is correct or incorrect. We identified two factors that can help spot the presence of temporal uncertainty. The first factor is related to an algorithm misclassification due to the fact that some activities share several characteristics such as the place, time of day, people with whom they are conducted, and the artifacts that are used, and the network does not have enough evidence to differentiate among them. The second factor is related to activity switching, specifically the percentage of the activity shift. As a result of this first stage, we identify the possible existence of original uncertainty and temporal uncertainty. The former generated in the activity estimation process and the latter when a change of activity takes place.

5.2 The Measurement of Uncertainty

The second step consists on measuring the degree of uncertainty. The uncertainty must be represented to create diagnostic tests to determine whether the uncertainty is significant to act on it.

In medicine a probabilistic process of validation to evaluate the efficient of a diagnostic test is commonly used [23, 24]. The process includes sensibility, specificity, positive and negative predictive values. We used that process to avoid the creating arbitrary rules. We apply the validation process using different values to obtain the correct value that was used in the rule.

To indicate the presence of uncertainty one rule was established: this rule indicates the presence of uncertainty when the difference between the biggest output value and the previous one are smaller or equal to 0.1 (Fig.4).

5.3 Actions for Dealing with Uncertainty

At this stage, the actions that will be carried out in the presence of uncertainty are established. To automatically decrease uncertainty (Fig.5), re-estimation, does not apply in our case, because the inputs, as mentioned above, are obtained from a record generated by direct observation, so we can assume that these values are free from error. In the combination of additional information or others contextual elements, a first action may be a procedure to look for the nearest nurse from the current location. It uses the same activity for this nurse, in a real implementation it is possible to use this process because oftentimes there are several nurses working at the same place, at the same time. For our simulation this action was not applied because the data used corresponds to a single nurse. The second action is recurrence which is based on the principle that a nurse starts an activity and does not change to another one until the first one has been concluded. In this action it is assumed that the correct activity is the one done prior to he detection of uncertainty. The third action uses nurse location and estimates whether it is uncertain. If so, it verifies the location and if the nurse is in a place where it is feasible to undertake such activity, the uncertain status disappears and assumes that it is a correct estimate, otherwise the estimate continues being uncertain and proceeds to inform the user. The fourth action involves the activity transition matrix, when an estimate is uncertain it is assumed as a correct activity that has the highest probability of change based on the activity made before uncertainty was detected.

To decrease uncertainty based on user-assisted feedback, when uncertainty is detected, the application explicitly inquires to the nurse "What activity are you doing?". Additionally the application can inform the user about the presence of uncertainty, this action was conducted with the use of color in the user interface.

With the implementation of these strategies an uncertainty management mechanism is obtained. The general structure of the mechanism is present in Figure 4.

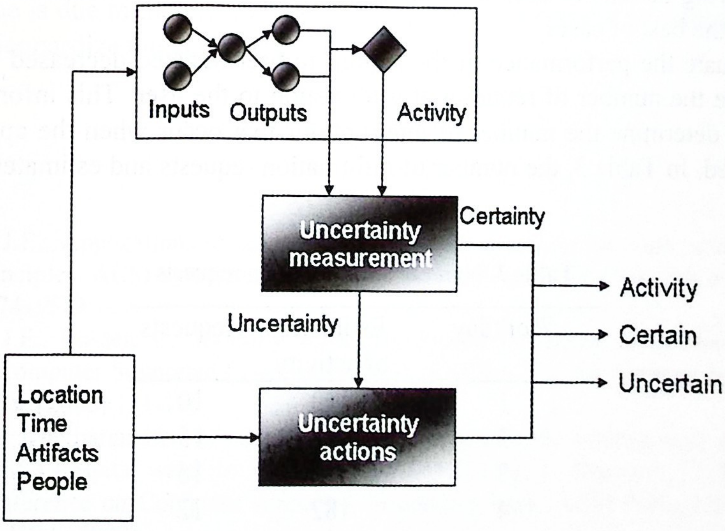

Figure 4. General structure of uncertainty management mechanism

6 Test and Results

In order to evaluate our uncertainty management approach we conducted a five day simulation of a nurse workday, form 7:00 AM to 2:30 PM. Data taken from the observation logs were used for this purpose. The simulation consists of the following steps: the BP-NN is fed with data from the logs and an output is obtained. This output is an estimate we use to compare to the real activity, allowing us to know whether or not the estimate is right.

The metric established to evaluate the performance of the actions to automatically decrease uncertainty consists on measuring the number of uncertainty estimates that correspond to an estimation error. Table 2 shows the percentages of uncertain estimates that correspond to errors by the algorithm, the first column corresponds to the classifier, the second to the implementation of recurrence action, the third to the use of location, and fourth to the use of a transition matrix.

Table 2. Percentage of uncertain estimates that corresponds to estimation errors

Workday	Classi-fier	Recurrence	Location	Transition matrix
1	60%	86%	100%	60%
2	60%	60%	50%	75%
3	56%	69%	67%	60%
4	75%	75%	100%	75%
5	54%	88%	50%	54%
Average	61%	76%	73%	65%

As can be seen from Table 2, 61% of the estimates marked as uncertain correspond to incorrect estimations made by the algorithm. At the same time we can see that when applying actions to decreased uncertainty the percentage increases to 76% on average in the best of cases.

To evaluate the performance of the actions to user-assisted decreased uncertainty we measure the number of requests of information to the user. This information can be used to determine the number of interruptions that occur when the application is implemented. In Table 3, the number of information requests and estimates in the day is shown.

Table 3. Number of information requests

Workday	Estimates of activity	Requests
1	170	10
2	175	15
3	259	16
4	182	12
5	192	13
Average	196	13

As can be seen from Table 3, when applying the actions of the user-assisted decreased uncertainty the application informs the user or requested feedback on 13 times of 196 estimates of activity on average. It is important to consider this value due to the fact that the request may become an unwanted interruption and jeopardize the usefulness of the application.

7 Conclusions

This paper presents a strategy for uncertainty management based on a three-phase structure: identification, measurement and dealing with uncertainty. This strategy proposes a series of actions that must be considered when designing context-aware applications that need to deal with uncertain information. These actions are: the automatic decrease of uncertainty which includes actions such as re-estimation, recurrence and combination with additional information or others contextual elements, and the user-assisted decreased uncertainty with actions such as obtaining user feedback and keeping users informed about the presence of uncertainty. The strategy can be applied not only to new applications but also to enhance existing ones.

As a result of evaluation of the proposed strategy we observed that uncertainty management can be useful to design context-aware applications. We established a metric to evaluate the utility of decrease uncertainty actions based on an algorithm to minimize error, even when error is not a synonymous of uncertainty. With this metric, it was observed that 61% of the estimates marked as uncertain correspond to erroneous estimates. After including auto-decreased uncertainty actions the utility was increased, because the percentage of the estimates marked as uncertain correspond to erroneous estimates increased by 76% on average. On the other hand, when actions to decreased user-assisted uncertainty are applied, the application informs the user or requests feedback on 13 times of 196 estimates of activity. It is important to consider that this value is due to the fact that the request may itself become an unwanted interruption and jeopardize the application usefulness.

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Knowledge Representation and Reasoning