Ambient Intelligence: the Confluence of Ubiquitous/Pervasive Computing and Artificial Intelligence

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Summary. We elaborate on recent developments in the area of Ambient Intelligence. Our work includes a description of possible applications, a description of a general architecture that can help to define such systems and the computational process that can link perception through sensors with actuation after decision making.

1 Introduction

"... computers will be everywhere" I heard when I was young. The prediction was at that time repeated as a mantra with a mix of admiration, fear and resignation. Nowadays computers are already influencing our daily life and there is substantial effort directed to increasing the way they help our society. In particular, technology is being developed which will allow people to be surrounded by an artificial environment that assists them proactively. Whether it is our home anticipating our needs and forecasting dangers, a transport station facilitating commuting or a hospital room helping to care for a patient, there are strong reasons to believe that our lifes are going to be transformed in the next decades by the introduction of a wide range of devices which will equip many diverse environments with computing power. These computing devices are coordinated by intelligent systems that integrate the resources available to provide an "intelligent environment". This confluence of topics has led to the so called area of "Ambient Intelligence".

This chapter explores various scenarios of Ambient Intelligence and a basic architecture which supports such systems. We also provide some technical details on how these systems work. Section 2 reviews the basic concepts associated with Ambient Intelligence. Different instances of such systems are explained to illustrate how Ambient Intelligence can be applied in different environments. Section 3 examines a basic architecture for Ambient Intelligence systems and Section 4 shows how this architecture accommodates different scenarios. One of those scenarios is developed in more detail in Section 5 where we illustrate how particular contexts of interest can be represented and incorporated to a rule-based language in order to trigger appropriate and timely reactions from the system. Finally, Section 6 provides some reflections on this chapter and the area of Ambient Intelligence itself.

2 Ambient Intelligence

"Ambient Intelligence" (AmI) [IST01, AC07] is growing fast as a multi-disciplinary approach which can allow many areas of research to have a significant beneficial influence into our society. The basic idea behind AmI is that by enriching an environment with technology (mainly sensors and devices interconnected through a network), a system can be built to take decisions to benefit the users of that environment based on real-time information gathered and historical data accumulated.

AmI has a decisive relationship with many areas in computer science. The relevant areas are depicted in Figure 1. Here we must add that whilst AmI nourishes from all those areas, it should not be confused with any of those in particular. Networks, sensors, interfaces, ubiquitous or pervasive computing and AI are all relevant but none of them conceptually covers AmI. It is AmI which puts together all these resources to provide flexible and intelligent services to users acting in their environments.

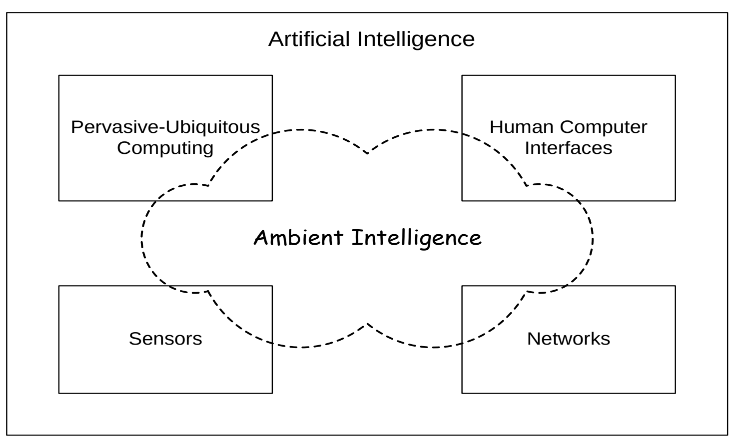

Fig. 1. Relationship between AmI and other areas.

As Raffler succinctly expressed [Raf06], AmI can be defined as:

"A digital environment that supports people in their daily lives in a nonintrusive way."

AmI is aligned with the concept of the *"disappearing computer"* [Wei91, SN05]:

> *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."*

The notion of a disappearing computer is directly linked to the notion of "Ubiquitous Computing" [Wei93], or "Pervasive Computing" [SM03] as IBM called it later on. Some authors equate "Ubiquitous Computing" and "Pervasive Computing" with "Ambient Intelligence". Here we argue that Ubiquitous[1]/Pervasive[2] systems are different as they emphasize the physical presence and availability of resources and miss a key element: the explicit requirement of *"Intelligence"*. This we think, is the ground of Artificial Intelligence (AI) [RN03] and should not be ignored. Here we refer to AI in a broad sense, encompassing areas like agent-based software and robotics. What matters is that AmI systems provide flexibility, adaptation, anticipation and a sensible interface in the interest of human beings. The same observations can be made about alternatives to *"Ubiquitous"* or *"Pervasive"* like the most recent, and less used, term: *"Everyware"* [Gre06].

This paper will be based in a more suitable definition which emphasizes Intelligence as a fundamental element of an AmI system:

> *"A digital environment that supports people in their daily lives by assisting them in a sensible way."*

In order to be sensible, a system has to be intelligent. That is how a trained assistant, e.g. a nurse, typically behaves. It will help when needed but will restrain to intervene unless is necessary. Being sensible demands recognizing the user, learning or knowing her/his preferences and the capability to exhibit empathy with the user's mood and current overall situation.

Although Ambient Intelligence will be used to describe this area of research in Europe, similar developments on USA and Canada will be referred as *"Smart Environments"* or *"Intelligent Environments"*. We keep here the European denomination as it emphasizes the intelligence factor of these systems as opposed to the physical infrastructure.

Important for Ubiquitous/Pervasive computing are the "5Ws" (Who, Where, What, When and Why) principle of design [Bro03] :

Who: the identification of a user of the system and the role that user plays within the system in relation to other users. This can be extended to identifying other important elements like pets, robots and objects of interest within the environment.

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[1] *Ubiquitous*: adj. present, appearing, or found everywhere (The Oxford Pocket Dictionary of Current English; 2006).

[2] *Pervasive*: adj. (esp. of an unwelcome influence or physical effect) spreading widely throughout an area or a group of people (The Oxford Pocket Dictionary of Current English; 2006).

Where: the tracking of the location where a user or an object is geographically located at each moment during the system operation. This can demand a mix of technologies, for example techonology that may work well indoors may be useless outdoors and viceversa.

When: the association of activities with time is fundamental to build a realistic picture of a system's dynamic. For example, users, pets and robots living in a house will change location very often and knowing when those changes happened and for how long they lasted are fundamental to the understanding of how an environment is evolving.

What: the recognition of activities and tasks users are performing is fundamental in order to provide appropriate help if required. The multiplicity of possible scenarios that can follow an action makes this very difficult. Spatial and temporal awareness help to achieve task awareness.

Why: the capability to infer and understand intentions and goals behind activities is one of the hardest challenges in the area but with no doubt a fundamental one which allows the system to anticipate needs and serve users in a sensible way.

An important aspect of AmI has to do with interaction. On one side there is a motivation to reduce the human-computer interaction (HCI) [DFAB03] as the system is supposed to use its intelligence to infer situations and user needs from the recorded activities, as if a passive human assistant were observing activities unfold with the expectation to help when (and only if) required. On the other hand, a diversity of users may need or voluntarily seek direct interaction with the system to indicate preferences, needs, etc. HCI has been an important area of computer science since the inception of computing as an area of study. Today, with so many gadgets incorporating computing power of some sort, HCI continues to thrive as an important area.

Lets examine in the following section what the possible intelligent environments can be. Later sections will look more closely on how AmI can be implemented in those environments and how AmI can help our society in these environments.

2.1 Smart Homes

An example of an environment enriched with AmI is a "Smart Home" [AN06]. By Smart Home here we understand a house equipped to bring advanced services to its users. Naturally, how smart a house should be to qualify as a Smart Home is, so far, a subjective matter. For example, a room can have a sensor to decide when its occupant is in or out and on that basis keep lights on or off. However, if sensors only rely on movement and no sensor in, say, the door can detect when the person left, then a person reading and keeping the body in a resting position can confuse the system which will leave the room dark. The system will be confusing absence of movement with absence of the person, that inference will certainly not be considered as particularly "bright", despite the lights.

Technology available today is rich. Several artifacts and items in a house can be enriched with sensors to gather information about their use and in some cases even to act independently without human intervention. Some examples of such devices are electrodomestics (e.g., cooker and fridge), household items (e.g., taps, bed and sofa) and temperature handling devices (e.g., air conditioning and radiators). Expected benefits of this technology can be: (a) increased safety (e.g., by monitoring lifestyle patterns or the latest activities and providing assistance when a possibly harmful situation is developing), (b) comfort (e.g., by adjusting temperature automatically), and (c) economy (e.g., controlling the use of lights). There is a plethora of sensing/acting technology, ranging from those that stand alone (e.g., smoke or movement detectors), to those fitted within other objects (e.g., a microwave or a bed), to those that can be worn (e.g., shirts that monitor heart beat). For more about sensors and their applications the reader may like to consider [Wan04], and [NA06].

Recent applications include the use of Smart Homes to provide a safe environment where people with special needs can have a better quality of life. For example, in the case of people at early stages of senile dementia (the most frequent case being elderly people suffering from Alzheimer's disease) the system can be tailored to minimize risks and ensure appropriate care at critical times by monitoring activities, diagnosing interesting situations and advising the carer. There are already many ongoing academic research projects with well established Smart Homes research labs in this area, for example Domus [PMG+02], Aware Home [ABEM02], MavHome [Coo06], and Gator Tech Smart Home [HME+05].

2.2 Other Environments and Applications for AmI

Other applications are also feasible and relevant and the use of sensors and smart devices can be found in:

- Health-related applications. Hospitals can increase the efficiency of their services by monitoring patients' health and progress by performing automatic analysis of activities in their rooms. They can also increase safety by, for example, only allowing authorized personnel and patients to have access to specific areas and devices.
- Public transportation sector. Public transport can benefit from extra technology including satellite services, GPS-based spatial location, vehicle identification, image processing and other technologies to make transport more fluent and hence more efficient and safe.
- Education services. Education-related institutions may use technology to track students progression on their tasks, frequency of attendance to specific places and health related issues like advising on their diet regarding their habits and the class of intakes they opted for.
- Emergency services. Safety-related services like fire brigades can improve the reaction to a hazard by locating the place more efficiently and also by

preparing the way to reach the place in connection with street services. The prison service can also quickly locate a place where a hazard is occurring or is likely to occur and prepare better access to it for security personnel.

- Production-oriented places. Production-centred places like factories can self-organize according to the production/demand ratio of the goods produced. This will demand careful correlation between the collection of data through sensors within the different sections of the production line and the pool of demands via a diagnostic system which can advice the people in charge of the system at a decision-making level.

Well-known leading companies have already invested heavily in the area. For example, Philips [Phi06] has developed Smart Homes for the market including innovative technology on interactive displays. Siemens [Sie06] has invested in Smart Homes and in factory automation. Nokia [Nok06] also has developments in the area of communications where the notion of ambience is not necessarily restricted to a house or a building. VTT [VTT06] has developed systems which advise inhabitants of Smart Homes on how to modify their daily behaviour to improve their health.

In the next section we give one step in the direction of identifying some of the important issues and how to consider them explicitly within a system.

3 AmI Architecture

So far, the design of AmI systems is quite informal and lacks any agreed conceptualization or prescriptive standards that could help building such systems. This section therefore aims to identify what the main components of AmI systems are. We explore a basic architecture for the specification of AmI systems, a triplet:

$$AmISystem = \langle E, IC \rangle$$

such that:

$$\underbrace{\text{E}}_{\textit{Environment}} \qquad \underbrace{\overset{\longrightarrow}{\underset{\longleftarrow}{\text{IC}}}}_{\substack{\textit{Interaction}\\ \textit{Constraints}}} \qquad \underbrace{\text{I}}_{\textit{Interactors}}$$

where:

E is the Environment, for example, a house, a hospital, a factory, a street, a city, an airplane, an airport, a train, or a bus station. E is defined by an ontology which can be as detailed as needed and include a variety of physical entities which are known to the system and their relevant attributes. Example of such entities can be a table, a sink, a tap, a pet, or a robot. Many associated concepts may be also important for the system to understand the role and inter-relationships of those entities. For example, areas of the house, interconnection of rooms, and location of doors and windows can be fundamental for the system to predict where activities are developing and what their nature is. If the system is linking activities in a Smart Home with a group of carers (e.g., nurses and relatives) then a hierarchy of care can be used to decide who is the primary contact and how to react if that person is not reachable in an emergency.

IC, the Interaction Constraints, specify the possible ways in which elements of E and I can interact with each other. Some elements to be specified are $\langle S, A, C, IR \rangle$ where:

> S is a set of sensors. They can be represented as Boolean or Real functions and represent devices that can obtain information from the environment, for example a thermostat or a movement sensor. The range of available elements is wide and some devices can, for example, take the blood pressure of a patient. A video camera, and other image processing devices, will be considered a type of sensor, despite the complexity of their input which can range from shapes and contours given by thermo cameras to real images.
>
> A is a set of actuators. Sensors are usually conceived as passive observers but some of them are associated with complex mechanisms which also embed the capacity to act over the environment, for example, to interrupt the flow of water in a tap.
>
> C is a set of contexts of interest. A context can be defined as a Boolean specification denoting, for example, particular situations involving objects, sensors, users, places, and so on. Here the principle of "5Ws" (Who, Where, What, When and Why) can be applied as pillars of the system's awareness. It is important for the system to identify who is doing what, at a given place and time and for which purpose in order to jude what is the best possible way to assist users.
>
> IR is a set of Interaction Rules. Here we are not committing to a particular language at the moment. They can be ECA (Event-Condition-Action) rules [PD99] or agent-oriented [Woo02]. They are the logical core of the system as they specify in which way elements listed in previous sets can be related and the effects of those relations.

I is a set of interactors (usually beneficiaries, it can be people, pets or robots). They can interact with the system. Each is uniquely identified, if possible; otherwise they are considered 'anonymous' or as belonging to a group with specific properties of interaction assigned (e.g., carers). Whilst the description at E is internal to the AmI system I is the description of the interactors which is lying outside the system. This internal description is usually not known or available to the AmI system.

Figure 2 illustrates an abstract depiction of an AmI system highlighting the elements mentioned in the AmI architecture. All the essential elements are depicted there at physical and logical levels. The environment comprises an individual, four objects, two sensors and three actuators. The logical level specifies contexts of interest and a set of rules to link the activities at the physical level with the interaction rules which will govern changes at the logical level of the system.

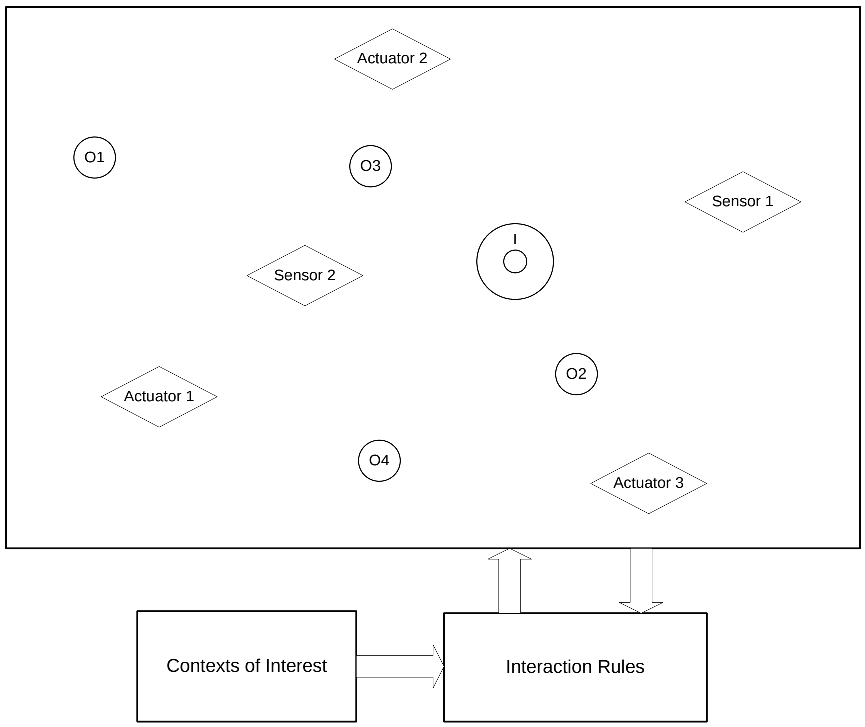

Fig. 2. An abstract AmI system.

The forthcoming section describes how this architecture can be used to highlighht and specify the essential components of an AmI system and their inter-relationships.

4 AmI Scenarios

AmI systems can be deployed in many possible environments. Below we describe some of these environments in order to better illustrate the scope of the basic architecture presented earlier.

Scenario 1: An instance of the concept of Ambient Intelligence is a Smart Home. See for example Figure 3.

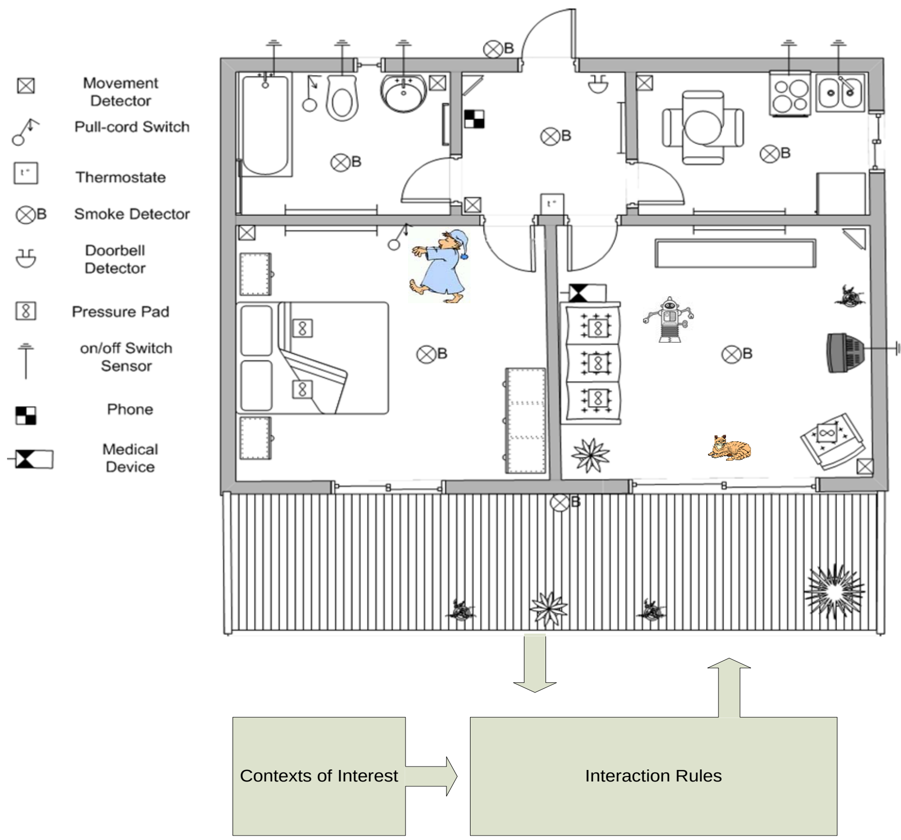

Fig. 3. A Smart Home as an AmI instance.

Here an AmI specification may include the following details. The meaningful environment E is the house, including the backyard and a portion of the front door as these areas also have sensors. Elements of O are plants, furniture, and so on. There are three interactors depicted and therefore I has three elements: a person in the bedroom, a cat, and a floor cleaning robot in the living room. There are also multiple sensors in S, movement sensors, pull cord switch, smoke detector, doorbell detector, pressure pad, plus switch sensors for taps, a cooker and a TV. In addition, there is a set of actuators A, as the taps, cooker and TV also have the capacity to be turned on and off without human assistance. Medical devices can also exhibit autonomous behaviour by making recommendations before and after their usage. Contexts of interest listed in C can be "cooker is left on without human presence in the kitchen for more than 10 minutes", "occupant is still sleeping after 9AM". Interaction rules specified in IR may consider that "if occupant is in bed and is later than 9AM and contact has been attempted unsuccessfully then carer should be notified".

Scenario 2: Let us consider a specific room of a hospital as the environment, whit a patient monitored for health and security reasons. Objects in the environment are furniture, medical equipment, specific elements of the room like a toilet and a window. Interactors in this environment will be the patient, relatives and carers (e.g., nurses and doctors). Sensors can be movement sensors and wrist band detectors for identifying who is entering or leaving the room and who is approaching specific areas like a window or the toilet. Actuators can be microphones within the toilet to interact with the patient in an emergency. Contexts of interest can be "the patient has entered the toilet and has not returned after 20 minutes" or "frail patient left the room". Interaction rules specified in IR can consider, for example, that "if patient is leaving the room and status indicates that this is not allowed for this particular patient then nurses should be notified".

Scenario 3: Assume a central underground coordination station is equipped with location sensors to track the location of each unit in real-time. Based on the time needed to connect two locations with sensors, the system can also predict the speed of each unit. Examples of objects in this environment are tracks and stations. Interactors are trains, drivers and command centre officers. Sensors are used for identification purposes based on ID signals sent from the train. Other signals can be sent as well, e.g., emergency status. Actuators will be signals coordinating the flow of trains and messages that can be delivered to each unit in order to regulate their speed and the time they have to spend at a stop. Contexts of interest can be "delays" or "stopped train". One interaction rule can be "if line blocked ahead and there are intermediate stops describe the situation to passengers".

Scenario 4: Lets assume a primary school where students are monitored to best advise on balancing their learning experience. The objects within a classroom or play ground are tables and other available elements. The interactors are students and teachers. The sensors will identify who is using what scientific kit and that in turn will allow monitoring of how long students are involved with a particular experiment. Actuators can be recommendations delivered to wristwatch-like personalized displays. Contexts of interest can be "student has been with a single experimentation kit for too long" or "student has not engaged in active experimentation". The first context will trigger a rule "if student has been interacting with one single kit for more than 20 minutes advise the student to try the next experiment available" whilst the second one will require a message to a tutor, such as "if student S has not engaged for more than 5 minutes with an experiment then tutor has to encourage and guide S".

Scenario 5: When a fire brigade has to act then the environment can be a city or a neighborhood. Streets can be equipped with sensors to measure passage of traffic within the areas through which the fire brigade truck might go through in order to reach the place where the emergency is located. Objects here will be streets and street junctions. Interactors will be cars. Actuators can be traffic lights as they can help speed the fire brigade through. A context will be a fire occurring at peak time with a number of alternative streets to be used. An interaction rule can be "if all streets are busy, use traffic lights to hold traffic back from the vital passage to be used".

Scenario 6: If a production line is the environment then different sensors can track the flow of items at critical bottlenecks in the system and the system can compare the current flow with a desired benchmark. Decision makers can then take decisions on how to proceed and how to react to the arrival of new materials and to upcoming demands. Different parts of the plant can be de/activated accordingly. Similarly, sensors can provide useful information on places where there has been a problem and the section has stopped production, requiring a deviation in flow. Objects here are transportation belts and elements being manufactured whilst actuators are the different mechanisms dis/allowing the flow of elements at particular places. A context can be "a piece of system requiring maintenance" and a related interaction rule can be "if section A becomes unavailable then redirect the flow of objects through alternative paths".

In addition, we need to go beyond the enumeration of parts and the description of their role to provide a computational layer so that intelligent behaviour can result synergetically from their interactions. The next section considers this interaction at a higher logical level, assuming the existance of an appropriate middleware level that can pass information to the reasoning system as meaningful, temporally tagged, events.

5 AmI Architecture at Work

Lets assume a house like the one in Figure 3, inhabited by an elderly person who requires assistance for daily living in order to minimize hazards and to detect and react to undesirable situations. We have described the elements of the AmI architecture in Section 3 and here we look closer at the representation and use of "Context" and "Interaction Rules", which are key components in the computational realization of any AmI architecture. Some examples of contexts, or situations, of interest are:

- Leaving the cooker unattended whilst preparing a meal,
- Not taking a phone call,
- Not walking to the front door when the door bell rings,
- Sequence of vital signs indicating possible health deterioration,
- Not eating with the expected frequency or at the expected time,
- Not bathing with the expected frequency,
- Going to the toilet too frequently,
- Wandering (especially during the night),
- Attempting to leave the house at inconvenient times (e.g., 12am-6am),
- Detection of an intruder, and
- Medication intake compliance.

These contexts then can be used to direct the interaction rules which will provide the right reactions in the right contexts. For contexts and interaction rules to be of any use they have to be described in a way that can be processed by computers. We do not aim to be prescriptive here, so the language used in this chapter has to be interpreted simply as one possibility.

Consider the following general language $\mathcal{E}$ based on a formalization of temporal notions presented in natural language expressions. This language allows us to distinguish two key notions: events-forming and states-forming phenomena [Gal05]. $\mathcal{E}$ will be used here to define the sub-language to be used for complex event detection and for condition specification. The reader can find more technical detail of the language in [Gal05] and the computational tools associated with it in [GAG00] and [GAG01].

Temporal representations in $\mathcal{E}$ are in the form of instants, $t][t+1$, or intervals $[t, t']$. Here t is an abstract unit of time arbitrarily selected according to the application; therefore, in between t and $t{+}1$ we can assume, for example, that one second, one minute or ten seconds have elapsed.

It is not possible to give full coverage of all the operators here so we just list a few operators which are mentioned in the rules given below:

Ingr(S): Occurs at $n][n{+}1$ iff $\neg S$ holds on $[n, n]$ and S holds on $[n{+}1, n{+}1]$.

Trans(S_1, S_2): If S_1 and S_2 are two mutually incompatible states, then the event $Trans(S_1, S_2)$ has:

1. an instantaneous occurrence at $n][n+1$ iff S_1 holds on $[n,n]$ and S_2 holds on $[n+1,n+1]$.
2. a durative occurrence in $[m,n]$ iff S_1 holds on $[m-1,m-1]$, S_2 holds on $[n+1,n+1]$ and both $\neg S_1$ and $\neg S_2$ hold on $[m,n]$.

Po(S): Occurs on $[m,n]$ iff S holds throughout $[m,n]$ and $\neg S$ holds on both $m-1$ and $n+1$.

For(S,d): Occurs on $[m,n]$ iff $n-m=d-1$, S holds throughout $[m,n]$ and $\neg S$ holds on both $m-1$ and $n+1$.

GSC(E_1, E_2): If E_1 is instantaneous and E_2 is durative, then **GSC**(E_1,E_2) occurs on $[m,n]$ iff there is an integer k, where $m \leq k \leq n$, such that E_1 occurs at $m-1][m$ but at no instant $l-1][l$ where $m < l < k$ and E_2 occurs on $[k,n]$ but not on any interval $[p,q]$ where $m \leq p < q$.
Note: see [Gal05] for the definition of **GSC** in the other three remaining possibilities regarding E_1 and E_2 being instantaneous or durative.

Consec-I(E,N): If E is an instantaneous event, then:

1. **Consec-I**($E,2$) occurs on $[m,n]$ iff E occurs on both $m-1][m$ and $n][n+1$.
2. **Consec-I**(E,k), with $k>2$, occurs on $[m,n]$ iff there is an integer p, where $m < p \leq n$, such that E occurs at $m-1][m$ but not at any instant between m and p, and **Consec-I**($E,k-1$) occurs on $[p,n]$.

$\mathcal{E}$ has been integrated into an "Active Database" [PD99] framework to define a language $\mathcal{L}$ where interaction rules can be specified denoting how contexts can be used to trigger decisions and reactions on behalf of the AmI system. These rules have the typical format adopted in the Active Databases literature:

ON *event* IF *condition* THEN *action*

meaning that whenever *event* is detected, if *condition* holds, then *action* is applied [AN04]. Assuming there is a non-empty and finite set of ECA rules: $R = \{R_1, R_2, \ldots, R_n\}$ with n a natural number, where each rule R_i for $1 <= i <= n$ is of the form specified in [AN04], the general algorithm of the process monitoring and triggering rules can be briefly described as follows. Each time an event arrives the ON clauses are checked and from those rules in the subset of R: $R' = \{R_{i_1}, \ldots, R_{i_m}\}$ having a complex event definition detected the conditions stated in the IF clause are checked. For those rules in the subset of $R' : R'' = \{R_{j_1}, \ldots, R_{j_n}\}$ with their conditions satisfied the actions stated in the THEN clause are applied. Let us consider that the set of actions in the rules of R'' is $A'' = \{A_{j_1}, \ldots, A_{j_n}\}$, then in our system all actions in A'' will be performed atomically in sequence. The system combines an Active Database where the events are collected to record sensors that have been stimulated and a reasoner which will apply spatio-temporal reasoning and other techniques to take decisions. A typical information flow for AmI systems is depicted in Figure 4.

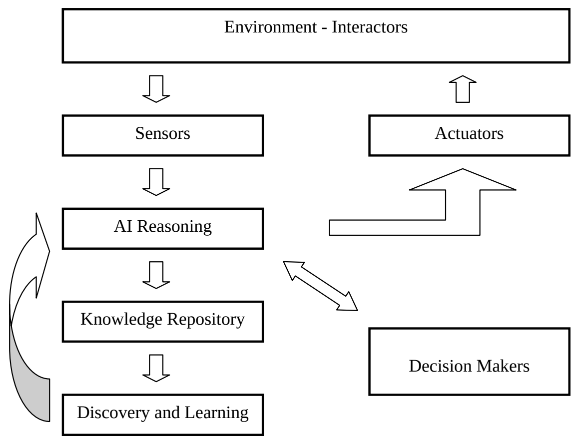

Fig. 4. Information flow in AmI systems.

As the interactors perform their tasks, some of these tasks will trigger sensors and those in turn will activate the reasoning system. Storing frequency of activities and decisions taken during relevant parts of the system's life time allow the system to learn information which is useful to decision makers, e.g., for doctors and nurses to decide if a change in the medication of a patient suffering Alzheimmer's disease may be needed. It also allows learning which can improve the system itself, e.g., to make interaction rules more personalized and useful for a particular person. For example, peoples' habits in winter are different than in summer in terms of what is the usual time to get up or the time they spend watching TV or sleeping.

The next scenario is about monitoring that the person living in the Smart House reacts as expected to normal situations. A lack of response can be used as a possible indicator that the person is unwell and is worth investigating if that is the case.

> *If there is an ingression to a state where doorbell has been rung and is not followed by an ingression to a state were the person goes to the door in a reasonable time, say 5 mins, while it is known that the person is at home and is not hearing impaired then apply the procedure to deal with a potential emergency and separately try alternative ways of contact, e.g. visually or by phone.*

Let us consider sensors `doorbell_rang` and `at_outside`, and let us assume we keep Boolean variables in our system to indicate different characteristics of the person inhabiting the house, for example `hearing_problems` indicates the person is known to be hearing impaired. Variable `at_home` can be inferred from the status of any of the other sensors detecting passage of people through doors. Passing through the front door to go out of the house means `at_home` becomes false and `at_outside` becomes true. Suppose then the following recording of events:

```
         at_kitchen   doorbell_rang
0][1         on
1][2         on
2][3         on             on
3][4         on             on
4][5         on             on
5][6         on
6][7         on
7][8         on
8][9         on
9][10        on
 ...
```

Which can be summarized as:

```
0][1 at_kitchen_on
1][2 dummy_event
2][3 doorbell_on
3][4 doorbell_on
4][5 doorbell_on
5][6 dummy_event
6][7 dummy_event
7][8 dummy_event
8][9 dummy_event
9][10 dummy_event
...
```

Where we use the following notational conventions: *t*][*t+1* *sensor*`_on` means *sensor* has been activated, *t*][*t+1* *sensor*`_off` means *sensor* has been deactivated and *t*][*t+1* `dummy_event` means no new sensors are activated. In the rule below `occurs(ingr(doorbell_rang_on), 2][3)` denotes the instant, in between intervals 2 and 3, at which the doorbell was off and then on. Whilst a predicate `occurs(trans(at_reception, at_outside), [5,7])` would represent a sensor activation indicating the person has opened the kitchen door and moved from the kitchen to the reception area in between 5 and 7. A transition will generally be instantaneous but if the transition is detected by a RFID sensor located at the door in between the kitchen and the reception area then the person staying for a while under the door can cause the sensor to be permanently activated for a little while.

```
ON (occurs(ingr(doorbell_rang_on), I1a][I1b) ∧
    ¬ (occurs(trans(at_reception, at_outside), [I1b,Now]) ∨
       occurs(trans(X,at_reception), [I1b,Now])) )
IF (moreThanNUnitsElapsed(I1b, Now, 5 mins) ∧
    holds(at_home, [I1a,I1b]) ∧
    ¬ holds(hearingProblems, [I1a,I1b]))
THEN (TryAlternativeWaysOfContact)
```

The following scenario represents a situation where the rule will be triggered at 8][9 as the person has remained in the kitchen for more than 5 units of time despite somebody rang the bell:

```
               not hearing_problems
        <--------------------------------------->
               at_home
        <--------------------------------------->

               doorbell_rang
               |-----------|
                       at_kitchen
       |---------------------------------------->

   <---|---|---|---|---|---|---|---|---|---|--->
       1   2   3   4   5   6   7   8   9   10
               .......................
                (more than 5 units)
                I1a=2  I1b=3  Now=14
```

Contexts defined by an activity being developed within a given period of time can be also considered:

> *If there is an ingression to a state where the person is in bed during the day time and stays in bed for more than 3 hours then raise a warning.*

Let us assume we have the following events:

```
            in_bed  day_Period
    ...
   7][8               true
   8][9               true
   9][10              true
  10][11              true
  11][12              true
  12][13              true
  13][14   on         true
  14][15   on
  15][16   on
  16][17   on
    ...
```

Which can be summarized as:

```
7][8 day_Period
8][9 dummy_event
9][10 dummy_event
10][11 dummy_event
11][12 dummy_event
12][13 dummy_event
13][14 in_bed_on
14][15 in_bed_on
15][16 in_bed_on
16][17 in_bed_on
...
```

which can be represented in $\mathcal{L}$ as follows:

```
ON (occurs(ingr(inbed_on), I1a][I1b) ∧
    occurs(for(inbed_on, 3), I1b][I2))
IF ¬ during([I1b,I2], day_Period)
THEN (ApplyPossibleUnwellPatientProcedure ∧
      TryContact)
```

and depicted as below:

```
                        day_Period
     |---------------------------------------->

                              in_bed
                         |-------------------->

<---|---|---|---|---|---|---|---|---|---|---|--->
     8   9   10  11 12  13  14  15  16  17
                         ................
                        (more than 3 units)
                       I1a=12  I1b=13  I2=16
```

Let us consider now that we include in the system a rule capturing that:

> *If there is an ingression to a state where the cooker is in use, followed by the person going out of the kitchen without returning to it for more than 10 minutes, then apply a procedure to deal with a potential hazard and separately try to make personal contact.*

Let us assume we have events sent from our middleware system to the AmI reasoner: `at_kitchen_on`, `cooker_on`, `at_reception_on`, `at_toilet_on`, `tapSinkBathroom_on`, `at_bedroom_on` and `inbed_on`. Suppose the following sequence of events arrives to the AmI system (`tapSinkBathroom` is shortened as `tapSinkBathR`):

	at_kitchen	cooker	at_reception	at_toilet	tapSinkBathR	at_bedroom	inbed
0][1	on						
1][2	on						
2][3	on	on					
3][4	on	on					
4][5		on	on				
5][6		on		on			
6][7		on		on	on		
7][8		on		on			
8][9		on		on			
9][10		on	on				
10][11		on					
11][12		on				on	
12][13		on				on	
13][14		on				on	on
14][15		on				on	on
...							

For simplicity we summarize this as follows:

```
0][1 at_kitchen_on
1][2 dummy_event
2][3 cooker_on
3][4 dummy_event
4][5 at_reception_on
5][6 at_toilet_on
6][7 tapSinkBathroom_on
7][8 tapSinkBathroom_off
8][9 dummy_event
9][10 at_reception_on
10][11 dummy_event
11][12 at_bedroom_on
12][13 dummy_event
13][14 inbed_on
14][15 dummy_event
...
```

Then we can write in $\mathcal{L}$:

```
ON (occurs(ingr(cooker_in_use), I1a][I1b) ∧
    occurs(trans(at_kitchen, at_reception), I2a][I2b))
IF (earlier(I1b, I2b) ∧
    ¬ holds(at_kitchen, [I2b,Now]) ∧
    moreThanNUnitsElapsed(I2b, Now, 10 mins))
THEN (ApplyPossibleHazardProcedure ∧ TryContact)
```

Assuming each primitive event takes one unit of time to arrive then by the time the person is in bed at time 13 the condition that more than 10 units have elapsed since the person turned the cooker on without returning to the kitchen is satisfied. All the conditions will be fulfilled for our rule to be triggered. This scenario can be graphically depicted as:

```
                 cooker_on
              |---------------------------------------->


                      at_reception at_toilet at_bedroom
            at_kitchen      (not at_kitchen)
          <-----------|------------------------------->

      <---|---|---|---|--- ...---|---|---|---|---|--->
            2   3   4   5         13  14  15  16  17
                          ......................
                           (more than 10 units)
                 I1a=2  I1b=I2a=3  I2b=4  now=15
```

Operators in $\mathcal{E}$ can be also composed at arbitrary nesting levels capturing many different situations. As an example of a slightly more involved non-primitive event detection we can combine the operators **Po**, **GSC** and **Consec-I** as follows:

```
occurs( po(gsc(ingr(change_of_medication),
               consec-i(high_blood_pressure,2)),
           [(2007,8,22,13,00,00), (2007,8,23,13,00,00)] ) )
```

to express that an occurrence of two consecutive high blood pressure records have been detected after a change in medication has been detected during the interval `[(2007,8,22,13,00,00), (2007,8,23,13,00,00)]`.

The scenarios described through $\mathcal{L}$ and the examples of complex events which can be detected with $\mathcal{E}$ provided above are only a few samples of what can be achieved. It was not the aim of this section to impose a specific language, in this case $\mathcal{E}$, but to illustrate some of the things that can be done and stimulate constructive reflection on these matters. It is clear there is much to do yet. For example, whilst $\mathcal{E}$ is well equipped for time related issues it lacks explicit constructs for spatial related concepts. Some spatial representation and reasoning can be made, for example, it is possible to represent that a person is in an area, e.g. the kitchen, and makes a transition to another area, e.g., reception. But if we want to detect wandering we need specific ways to represent trajectories and ways to detect them. Given space restrictions we cannot fully develop an AmI architecture, instead we listed and briefly exmplified some expected features of it with emphasis on context-awareness and hope it inspires further developments in the area.

6 Conclusions

In this chapter, we have reviewed the notion of Ambient Intelligence and associated concepts. We highlighted that an essential component of the area is the distribution of technology intelligently orchestrated to allow an environment to benefit its users.

We have also proposed an architecture which demands explicit reasoning about the main components of an AmI system and highlighted the importance of having a specific language to define contexts and rules of interaction governing the AmI system. These concepts were illustrated with several possible scenarios, in particular with different situations related to a Smart Home system.

AmI is still in its infancy and there is much to do. Future challenges include answering the following questions:

- How to develop a Software Engineering framework capable of producing more reliable AmI systems?
- How to achieve proper detection of meaningful events (for example, to ensure medication is actually swallowed by a patient)?
- How to avoid undesirable effects (for example, a fly opening a curtain because it activates a movement detector)?
- How a system can self-monitor (for example, to infer if a sensor is not working properly)?
- How to combine preferences in a group (for example, when suggesting tv programs)?
- How to anticipate needs which are realistic projections of a context (for example, predicting behavior of other drivers)?
- How to detect and adapt to the changing needs and preferences of a user or group of users (people change preferences and needs due to a multiplicity of factors like weather, economic situation and mood)?
- How to achieve a sensible level of intervention (too much is overwhelming, too little and the user may be unprotected)?

These questions will increase the predictability of AmI systems being deployed. Since these systems are autonomous and proactive the issue of predictability and reliability should not be underestimated if we want the environments where we live and work to be of real help.

Acknowledgments

The author would like to express his gratitude to Dr. Alfons Schuster and the reviewers for their valuable suggestions on how to improve this article.

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