Modeling Eating Disorders of Cognitive Impaired People

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Abstract. Millions of people all around the world suffer from eating disorders, known as anorexia nervosa, bulimia nervosa, pica, and others. When eating disorders coexist with other mental health disorders, eating disorders often go undiagnosed and untreated; a low number of sufferers obtain treatment for the eating disorder. Unfortunately, eating disorders have also the highest mortality rate of any mental illness, upwards of 20%.
This paper focuses on monitoring eating disorders of cognitive impaired people as patients with the Alzheimer's disease. The proposed approach relies on the application of Ambient Intelligence (AmI) technologies and a new method for the detection of abnormal human behaviors in a controlled environment.

Keywords: Ambient Intelligence for Cognitive Impaired People, Abnormal Behaviors, Situation-Awareness

1 Introduction

An eating disorder is an illness that causes serious disturbances to your everyday diet, such as eating extremely small amounts of food or severely overeating. A person with an eating disorder may have started out just eating smaller or larger amounts of food, but at some point, the urge to eat less or more spiraled out of control. Severe distress or concern about body weight or shape may also characterize an eating disorder [1]. Eating disorders can lead to major medical complications, including cardiac arrhythmia, osteoporosis, infertility, and even death. The mental anguish of an active eating disorder is tremendous, and persists beyond the medical consequences. Suicide, depression, and severe anxiety are common during the active illness and treatment.

In addition to such social effects, eating disorders represent also a large cost for national healthcare services. Hospitalizations for either a primary or secondary eating-disorder diagnosis showed a dramatic increase of 24 percent from 1999 to 2009, according to a report from the Agency for Healthcare Research and Quality [2].

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In this paper we focus on eating disorders related to cognitive impaired people, specifically patients with Alzheimer's disease.

We propose a methodology for the monitoring of eating in a controlled environment. Ambient Intelligence and Situation-Awareness are the technologies and paradigms adopted for our study. The main contribution of this paper, however, is a new method for the modeling and detection of abnormal human behaviors. Such method relies on the specification and runtime verification of correctness properties. The violation of one of such correctness properties indicates an anomalous behavior of the monitored patient. Behaviors are specified by means of a first-order logic, namely *Situation Calculus*, and violations of correctness properties are detected by intelligent agents.

The rest of the paper is structured in the following paragraphs. Section 2 describes potential situations of eating disordes. Section 3 presents *Situation Calculus*. Section 4 describes the proposed approach to molding and reasoning on anomalous eating behaviors. A prototype system is introduced in section 5. Next, section 6 concludes the paper dealing with potentials and limits of the proposed approach.

2 A situation of eating disorder

To detect eating disorders in a smart environment, we refer to the Situation-Awareness paradigm. With such an aim, it is important to clarify some aspects of sensing and analysis of data. Indeed, data collected from sensors may be processed in a smart environment at different semantic levels. As suggested by [3], we should distinguish between Context and Situation-Awareness. Indeed, authors propose the following definitions: *Primary context* is the full set of data caught by real and "virtual" sensors; *Secondary context* concerns with information inferred and/or derived from several data streams (primary contexts) and an important kind of secondary context is activities performed within the environment; *Situation* is, instead, an abstract state of affairs of interest for designers and applications, which is derived from context and hypothesis about how observed context relates to factors of interest. Situation-awareness includes rich temporal and other structural aspects, like: *time-of-day*, a situation may only happen at a particular time of the day; *duration*, it may only last a certain length of time; *frequency*, it may only happen a certain times per week, and *sequence*, different situations may occur in a certain sequence.

Let us now focus on a situation of normal eating. We can assume the parameters reported in table 1 apply. It is quite normal to eat three times a day; thus, three time frames can be defined, within which the patient is supposed to eat. The duration of eating may be considered, with a certain degree of approximation, an indication of the amount of food ingested. Finally, eating may be defined as a sequence of basic activities performed iteratively a certain number of times. For the rest of the paper, we assume to have a system, e.g. video analysis, able to provide us second-order context information; i.e. it is able to identify such basic actions and indicate start eating and stop eating events.

Table 1. A situation of normal eating

Parameter	**Value**
Frequency	3 times a day
Time-of-Day	F_1=[T_{1Min}-T_{1Max}]; F_2=[T_{2Min}-T_{2Max}]; F_3=[T_{3Min}-T_{3Max}]
Duration	Δ_b, Δ_l, Δ_d
Sequence	1. approach food to mouth; 2. bite; 3. drop food in mouth; 4. chew; 5. swallow

Table 2, instead, reports several cases of anomalous behaviors. It is important to note, however, that one of such anomalous behavior does not directly imply an abnormal behavior. For example, considering the anomalous behavior of *eating outside a temporal frame*, does not automatically lead to a situation of *overeating* if it happens just once. On the contrary, this event should be repeated several times a day or/and for more consecutive days before deducing an abnormal behavior such as *overeating*.

A possible set of parameters for a situation of overeating is {*Abnormal duration of breakfast* ($\Delta_{abnBreakfast}$), *Abnormal duration of lunch* ($\Delta_{abnLunch}$), *Abnormal duration of dinner* ($\Delta_{abnDinner}$), *Abnormal duration of daily meals* ($\Delta_{abnDailyMeals}$)}.

Such a situation is supposed to occur when the duration of one of the main meals is grater than some thresholds, or when the total time spent in a day eating (thus also considering eating outside regular time frames) is greater than another threshold.

Table 2. Anomalous eating

Anomalous behavior	**Potential effect**
Start eating outside a temporal frame	*Overeating*
Not eating in a temporal frame	*Undereating*
Eating too much	*Overeating*
Eating too little	*Undereating*
Try eating non-nutritive substance	*Poisoning*

3 Situation Calculus

The basic *Situation Calculus* (*SC*) is due to John McCarthy [4] and has been adopted to model dynamically changing worlds. Three basic sorts in *SC* are: **Actions**, which can be performed in the world and can be quantified; **Fluents**, that describe the state of the world (these are predicates and functions whose value may change depending on situation); and **Situations**, which represent a history of action occurrences.

A dynamic world is modeled through a series of situations as a result of various actions being performed within the world. It is important to note that a situation is not a state of the world, but just a history of a finite sequence of actions.

The constant S_0 denotes the initial situation; whereas, *do(a,S)* indicates the situation resulting from the execution of the action a in situation S.

The dynamic world is axiomatized by adding **initial world axioms**, **unique names**, **preconditions**, effect axioms, and **successor state axioms** [5] do the *situation calculus*' **foundational axioms**. The **initial world axioms** describe the initial status of the environment, its objects, their position into the environment, their properties, etc. A **unique name axiom** for situations states that if the execution of actions a_1 and a_2 respectively from S_1 and S_2 leads to the same situation, then, necessarily, $a_1 = a_2$ and $S_1 = S_2$. Unique name axioms also define the set of basic actions that can be performed within the environment. A **precondition** is formalized using the binary predicate symbol *Poss(a,S)*, which describes a condition that must hold in order to execute the action a in situation S. An effect axiom, instead, describes the effect on a fluent (e.g. $F(\boldsymbol{x},S)$) caused by the execution of an action in a specific situation ($F(\boldsymbol{x}, do(a, S))$. Unfortunately, effect axioms are not sufficient to describe the changing world. It must be specified for each fluent not only the effect of each affecting action, but also the non-effect of the other actions. This is a well known problem, the frame problem, that entails the specification of $2 * A * F$ axioms being A the number of actions and F the number of fluents. To reduce such a problem, we refer to **success state axioms** [5] of the form:

$$F(\boldsymbol{x}, do(a, S)) \equiv \gamma_F^+(\boldsymbol{x}, a, S) \vee (F(\boldsymbol{x}, S) \wedge \neg\gamma_F^-(\boldsymbol{x}, a, S)) \quad (1)$$

where γ_F^+ ($\boldsymbol{x}$,a,S) is a first-order formula- with free variables among $\boldsymbol{x}$, a, and S -that makes the F's truth value changing to true. Analogously, γ_F^- ($\boldsymbol{x}$,a,S) is a first-order formula that makes the F's truth value changing to false. Intuitively, it is possible to state that a fluent's truth value is true after executing an action a if, and only if, the action has the effect to make the fluent true or, the fluent was already true before executing a and the action has not the effect to make it false. In such a case, only F successor state axioms must be formalized.

Such a set of axioms represents a *basic action theory.*

It is finally important to note that under certain conditions (Clark's theorem), an executable prolog program is directly obtained by appling Lloyd-Topor transformations to the basic action theory. This can be interpreted by a Golog interpreter and represent an intelligent agent for the detection of anomalous and dangerous situations.

4 Modeling anomalous eating

This section defines a basic action theory for the modeling and reasoning on anomalous eating behaviors. A subset of the theory axioms is reported.

In accordance with table 1, axioms 2, 3, and 4 defines three timeframes for the 'normal' breakfast, launch and dinner. Axioms 5 and 6 identify some food and drinks in the scene, axiom 7 defines a poisoning substance, and axiom 8 establishes what is not food or drink.

$$\mathbf{isT_{breakfast}(t)} \equiv t \in [T_{bMin}, T_{bMax}]; T_{bMin} = 7.00.00 \wedge T_{bMax} = 9.00.00 \quad (2)$$
$$\mathbf{isT_{lunch}(t)} \equiv t \in [T_{lMin}, T_{lMax}]; T_{lMin} = 12.00.00 \wedge T_{lMax} = 14.00.00 \quad (3)$$
$$\mathbf{isT_{dinner}(t)} \equiv t \in [T_{dMin}, T_{dMax}]; T_{dMin} = 19.00.00 \wedge T_{lMax} = 21.00.00 \quad (4)$$
$$\mathbf{isFood(x)} \equiv x \in \{meat, fish, salad, pasta, bread, fruit, cake\}; \quad (5)$$
$$\mathbf{isDrink(x)} \equiv x \in \{water, milk, tea, wine, beer\}; \quad (6)$$
$$\mathbf{isPoison(x)} \equiv x \in \{acid\}; \quad (7)$$
$$\mathbf{isObject(x)} \equiv \neg isFood(x) \wedge \neg isDrink(x); \quad (8)$$

A minimal set of human's actions related to eating is described by axiom 9; whereas, those reported by axiom 10 are technical actions executed by an artificial agent to reset fluent's values as described later.

$$a_h \in \{\mathbf{startEating(x,t)}, \mathbf{stopEating(x,t)}, \mathbf{startDrinking(x,t)}, \mathbf{stopDrinking(x,t)}\} \quad (9)$$
$$a_s \in \{\mathbf{resetAnomalousBreakfastDuration(t)}, \mathbf{resetAbnormalBreakfastDuration(t)}, \mathbf{resetDangerousEating(t)}, \mathbf{resetAbnormalOvereating(t)}\} \quad (10)$$

We suppose that all such actions are always executable.

Fluents (bold words in axioms [11-18]) describe the status of the word in situation *S*. The possibility of change of the truth's value of any fluent is specified by means of the successor state axioms [11-18]. For the sake of brevity, we did not report all the needed fluents and successor state axioms, but the missing ones are similar to those presented.

In detail, *isEating(S)* becomes true (axiom 11) if the current action *a* is *startEating* something. Moreover, if the fluent were already true, it would not change its truth's value unless the current action is just *stopEating*.

Fluent *isEating(S)*, instead, concerns a specific substance *x*.

Fluent *isAnomalousEating(x,S)* represents a correctness property for the identification of an anomalous and potentially abnormal eating behavior. Indeed, the successor state axiom 12 triggers whenever the patient tries to eat a nonnutritive substance. It is important to note that this event may, or may not, represent an abnormal eating behavior. We can assume it is abnormal in case of patients with the Alzheimer's disease (see axiom 15), whose behavior is likely to cause hallucinations. In contrast, in case of another disease like pica that causes just the continuous eating of nonnutritive substance, we know that such a kind of illnesses is diagnosed only when this anomalous eating is repeated for at least one month [6]. Such a condition may also be dangerous in case of ingestion of poisoning substances (axiom 18).

The fluent that detects the starting of eating outside a regular timeframe is: *isAnomalousStartEating(x,S)*; whereas, *isAnomalousBreakfastDuration* and *isAbnormalBreakfastDuration*, respectively, detect a situation of anomalous or abnormal duration of the breakfast, where the difference consists just in the value of the threshold.

Finally, the fluent *isAbnormalOvereating* denotes a situation produced by an excessive eating during all the day.

$$\begin{aligned} &\mathbf{isEating(do(a,S))} \equiv \\ &\{\exists(x,t).(a = startEating(x,t))\} \vee \\ &isEating(S) \wedge \neg\{\exists(x,t).(a = stopEating(x,t))\} \end{aligned} \tag{11}$$

$$\begin{aligned} &\mathbf{isAnomalousEating(x,do(a,S))} \equiv \\ &\{\exists(t).(a = startEating(x,t) \wedge isObject(x))\} \vee \\ &(isDangerousEating(x,S) \wedge \\ &\neg\{\exists(t).(a = stopEating(x,t)) \vee \exists(z,t).(a = startDrinking(z,t))\} \end{aligned} \tag{12}$$

$$\begin{aligned} &\mathbf{isAnomalousStartEating(do(a,S))} \equiv \\ &\{\exists(x,t).(a = startEating(x,t) \wedge \neg isT_{breakfast}(t) \wedge \neg isT_{lanch}(t) \wedge \neg isT_{dinner}(t))\} \vee \\ &(isAnomalousStartEating(S) \wedge \\ &\neg\{\exists(x,t).(a = stopEating(x,t)) \vee \exists(x,t).(a = startDrinking(x,t))\} \end{aligned} \tag{13}$$

$$\begin{aligned} &\mathbf{isAnomalousBreakfastDuration(do(a,S))} \equiv \\ &\{\exists(x,t).(a = stopEating(x,t) \wedge \sum_{Breakfast}^{i} (T^i_{stopEating} - T^i_{startEating}) > \Delta_b)\} \vee \\ &(isAnomalousBreakfastDuration(S)) \wedge \\ &\neg\{\exists(t).(a = resetAnomalousBreakfastDuration(t))\} \end{aligned} \tag{14}$$

$$\mathbf{isAbnormalEating(x,do(a,S))} \equiv \mathbf{isAnomalousEating(x,do(a,S))} \tag{15}$$

$$\begin{aligned} &\mathbf{isAbnormalBreakfastDuration(do(a,S))} \equiv \\ &\{\exists(x,t).(a = stopEating(x,t) \wedge \\ &\sum_{Breakfast}^{i} (T^i_{stopEating} - T^i_{startEating}) > \Delta_{abnBreakfast})\} \vee \\ &(isAbnormalBreakfastDuration(S)) \wedge \\ &\neg\{\exists(t).(a = resetAbnormalBreakfastDuration(t))\} \end{aligned} \tag{16}$$

$$\begin{aligned} &\mathbf{isAbnormalOverEating(do(a,S))} \equiv \\ &\{\exists(x,t).(a = stopEating(x,t) \wedge \\ &\sum_{DailyMeals}^{i} (T^i_{stopEating} - T^i_{startEating}) > \Delta_{abnDailyMeals}\} \vee \\ &(isAbnormalOverEating(S) \wedge \neg\{\exists(t).(a = resetAbnormalOverEating(t)))\} \end{aligned} \tag{17}$$

$$\begin{aligned} &\mathbf{isDangerousEating(x,do(a,S))} \equiv \\ &\mathbf{isAbnormalEating(x,do(a,S))} \wedge isPoison(x) \vee \\ &(isDangerousEating(S) \wedge \neg\{\exists(t).(a = resetDangerousEating(t)))\} \end{aligned} \tag{18}$$

5 System architecture

The prototype architecture that we are realizing for the monitoring of eating disorders in case of patients with Alzhaimer's disease is shown in figure 1

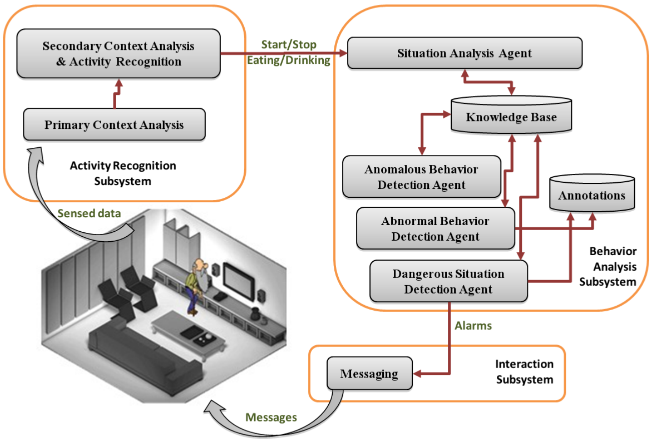

Fig. 1. Monitoring system architecture

It consists of three subsystems: the *Messaging Subsystem*, which interacts with the user in the environment, the *Activity Recognition Subsystem* that offers functionality for the primary and secondary context-awareness; and, the *Behavior Detection Subsystem* for the situation awareness and behavior analysis.

The *Messaging Subsystem* has been derived from *Uranus*, which is an open source middleware platform for AAL applications [7]. The *Activity Recognition Subsystem*, instead, is under construction. Such a functionality will be realized using modern RGB-D depth cameras that present opportunities for object recognition systems, thanks to the possibility of combining color- and depth-based recognition [8]. The rest of the architecture, instead, is completely new and consists of four intelligent agents realized by means of *Golog*, the prolog interpreter for *Situation Calculus*. The *Situation Analysis Agent* is the one that updates the current situation as the patient executes actions within the monitored environment. The *Anomalous Behavior Detection Agent* monitors the truth values of fluents dedicated to anomalous events and axioms [12-14]. The *Abnormal Behavior Detection Agent*, instead, recognizes abnormal behaviors and annotates them for the assessment of the disease by the clinician. Finally, the *Dangerous Situation Detection Agent* detects dangerous situations and behaviors like the tentative of ingestion of poisoning substances and alerts the patients.

Figure 2 shows a piece of a trace of events produced by the behavior analysis subsystem having been solicited by an emulator of the activity recognition module. In this trace, the fluent *isAnomalousStartEating* becomes true as soon as the patient starts eating outside the time frame. *isAnomalousBreakfastDuration*, instead, detects an anomalous amount of food eaten (based on the duration of the activity) at the end of the third cycle of eating. Two cycles of eating may be separated by a brief pause or because the patient starts to drink something. Finally, in this test there is not an abnormal duration of the breakfast because the related threshold has not been reached.

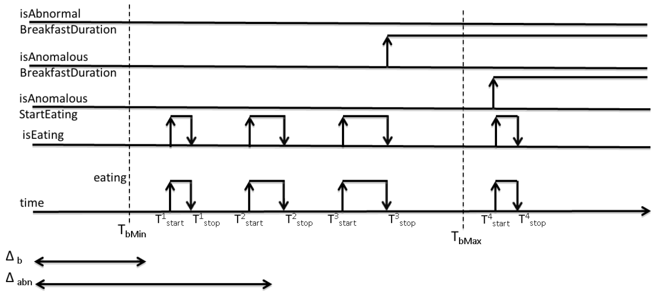

Fig. 2. A trace of the events produced by the monitoring agents

6 Discussion and conclusions

This paper has presented some of our results on handling anomalous and abnormal eating behaviors of cognitive impaired patients in monitored environments. Handling such behaviors mainly requires four activities: 1) *detection*; 2) *identification*; 3) *recovery*; and, 4) *prevention*. Although simple, the case study has demonstrated that the proposed approach can support detection. Indeed, having specified all necessary fluents; anomalous, abnormal, and dangerous behaviors occur when, respectively, fluent of kind *isAnomalous*, *isAbnormal*, and *isDangerous* change their truth's value to true.

A partially automated identification can be performed by analyzing the sequence of actions that have led in the current (dangerous/anomalous) situation. Recovery and prevention have not been considered yet.

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