A Computational Model for Behavioural Monitoring and Cognitive Analysis using Cognitive Models

Alexei Sharpanskykh and Jan Treur
Department of Artificial Intelligence, Vrije Universiteit Amsterdam,
De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands
http://www.few.vu.nl/~{sharp, treur}
{sharp, treur}@cs.vu.nl

Abstract

This paper proposes a way in which cognitive models can be exploited in practical applications in the context of Ambient Intelligence. A computational model is introduced in which a cognitive model that addresses some aspects of human functioning is taken as a point of departure. From this cognitive model relationships between cognitive states and behavioural aspects affected by these states are determined. Moreover, representation relations for cognitive states are derived, relating them to external events such as stimuli that can be monitored. Furthermore, by automatic verification of the representation relations on monitoring information the occurrence of cognitive states affecting the human behaviour is determined. In this way the computational model is able to analyse causes of behaviour.

Introduction

One of the interesting areas in which cognitive models can be applied in a practically useful manner is the area of Ambient Intelligence, addressing technology to contribute to personal care for safety, health and wellbeing; e.g., (Aarts, Harwig, and Schuurmans, 2001). Such applications make use of sensor devices to acquire sensor information about humans and their functioning, and of intelligent devices exploiting knowledge for analysis of such information. Based on this, appropriate actions can be undertaken that improve the human's safety, health, and behaviour. Commonly, decisions about such actions are made by these intelligent devices only based on observed behavioural features of the human and her context (cf. Brdiczka, Langet, Maisonnasse, and Crowley, 2009). A risk of such an approach is that the human is guided only at the level of her behaviour and not at the level of the underlying cognitive states causing the behaviour. Such a situation might lead to suggesting the human to suppress behaviour that is entailed by her internal cognitive states, without taking into account these cognitive states (and their causes) themselves.

As an alternative route, the approach put forward in this paper incorporates a cognitive analysis of the internal cognitive states underlying certain behavioural aspects. To this end, a computational model is described, in which a given cognitive model of the human's functioning is exploited. A cognitive model is formalised using the Temporal Trace Language (TTL) (Bosse, Jonker, Meij, Sharpanskykh, and Treur, 2009). In contrast to many existing cognitive modelling approaches based on some form of production rule systems, TTL allows explicit representation of time and complex temporal relations. In particular, using TTL one can specify references to multiple time points, temporal intervals and histories of states, such as, for example, is needed when modelling delayed response behaviour from an external perspective.

By performing cognitive analysis the computational model is able to determine automatically which cognitive states relate to considered behavioural (or performance) aspects of the human, which external events (e.g., stimuli) are required to be monitored to identify these cognitive states (monitoring foci), and how to derive conclusions about the occurrence of cognitive states from such acquired monitoring information. More specifically, monitoring foci are determined by deriving representation relations for the human's cognitive states that play a role in the cognitive model considered. Within Philosophy of Mind a representation relation relates the occurrence of an internal cognitive state property of a human at some time point to the occurrence of other (e.g., external) state properties at the same or at different time points (Kim, 1996). For example, the desire to go outside may be related to an earlier good weather observation. As temporal relations play an important role here, in the computational model these representation relations are expressed as temporal predicate logical specifications. In general, other temporal languages may be used as well. From these temporal expressions externally observable events are derived that are to be monitored. From the monitoring information on these events the computational model verifies the representation expressions, and thus concludes whether or not the human is in such a state. Furthermore, in case an internal state has been identified that may affect the behaviour or performance of the human in a certain way, appropriate actions may be proposed.

The paper is organised as follows. First, the modelling approach is introduced. Then, an example used throughout the paper to illustrate the approach is described. After that an overview of the computational model is provided. More details on this model are described in the following sections: First, a procedure for identifying cognitive states relevant for considered behavioural aspects is described. Then, a procedure for generating representation relations for the relevant cognitive states is described. After that the process of monitoring is considered. Finally, the paper is concluded with a discussion and summary.

Modelling approach

To model the dynamics of cognitive processes with an indication of time, a suitable temporal language is required. In the current paper, to specify temporal relations the Temporal Trace Language (TTL) is used. This reified temporal predicate logical language supports formal specification and analysis of dynamic properties, covering both qualitative and quantitative aspects. Dynamics are represented in TTL as an evolution of states over time. A state is characterized by a set of state properties expressed over (state) ontology Ont that hold. In TTL state properties are used as terms (denoting objects). To this end the state language is imported in TTL. Sort STATPROP contains names for all state formulae. The set of function symbols of TTL includes $\wedge$, $\vee$, $\rightarrow$, $\leftrightarrow$: STATPROP x STATPROP $\rightarrow$ STATPROP; not: STATPROP $\rightarrow$ STATPROP, and $\forall$, $\exists$: S^{VARS} x STATPROP $\rightarrow$ STATPROP, of which the counterparts in the state language are Boolean propositional connectives and quantifiers. To represent dynamics of a system sort TIME (a set of time points) and the ordering relation > : TIME x TIME are introduced in TTL. To indicate that some state property holds at some time point the relation at: STATPROP x TIME is introduced. The terms of TTL are constructed by induction in a standard way from variables, constants and function symbols typed with all before-mentioned sorts. The language TTL has the semantics of many-sorted predicate logic. A special software environment has been developed for TTL, featuring a Property Editor for building TTL properties and a Checking Tool that enables automated formal verification of such properties against a set of traces.

The modelling approach presented in this paper adopts a rather general specification format for cognitive models that comprises past-present relationships between cognitive states and between cognitive states and sensor and effector states, formalised by temporal statements expressible within TTL. In this format, for a cognitive state a temporal pattern of past states can be specified, which causes the generation of this state; see also (Jonker and Treur, 2003). A *past-present statement* (abbreviated as a *pp-statement*) is a statement φ of the form $B \Leftrightarrow H$, where the formula H, called the *head* and denoted by head(φ), is a statement of the form at(p, t) for some time point t and state property p, and B, called the *body* and denoted by body(φ), is a past statement for t. A *past statement* for a time point t over state ontology Ont is a temporal statement in TTL, such that each time variable s different from t is restricted to the time interval before t: for every time quantifier for a time variable s a restriction of the form $t > s$ is required within the statement. Sometimes B is called the *definition* of H.

Many types of cognitive models can be expressed in such a past-present format, such as causal models, dynamical system and connectionist models, rule-based models, and models in which memory of past events is used, such as case-based models. In the next section an example of a cognitive model specified in past-present format is given.

Case Study

To illustrate the proposed model a simplified example to support an elderly person in food and medicine intake is used. The following setting is considered. In normal circumstances the interval between two subsequent food intakes by the human during the day is known to be between 2 and 5 hours. When the human is hungry, she goes to the refrigerator and gets and consumes the food she prefers. Sometimes the human feels internal discomfort, which can be soothed by taking medicine X. The box with the medicine lies in a cupboard. There is no food consumption for 2 hours after taking medicine. To maintain a satisfactory health condition of the human, intelligent support is employed, which functionality is described by the computational model presented throughout the paper.

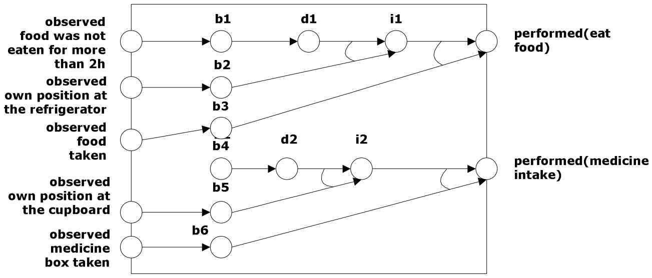

Figure 1. Cognitive model for food and medicine intake

The behaviour of the human for this example is considered as goal-directed and is modelled using the BDI (Belief-Desire-Intention) architecture (Rao and Georgeff, 1991). The graphical representation of the cognitive model that produces the human behaviour is given in Figure 1. In this model the beliefs are based on the observations. For example based on the observation that food is taken, the belief b1 that food is taken is created. The desire and intention to have food are denoted by d1 and i1 correspondingly in the model. The desire and intention to take medicine are denoted by d2 and i2 correspondingly. The cognitive model from the example was formalised by the following properties in past-present format:

IP1(c): *General belief generation property*
At any point in time a (persistent) belief state b about c holds *iff* at some time point in the past the human observed c. Formally:

$$\exists t2\ [\ t1 > t2\ \&\ at(observed(c), t2)\ ]\ \Leftrightarrow at(b, t1)$$

IP2: *Desire d1 generation*
At any point in time the internal state property d1 holds *iff* at some time point in the past b1 held. Formally:

$$\exists t4\ [\ t3 > t4\ \&\ at(b1, t4)\ ]\ \Leftrightarrow at(d1, t3)$$

IP3: *Intention i1 generation*
At any point in time the internal state property i1 holds *iff* at some time point in the past b2 and d1 held. Formally:

$$\exists t6\ [\ t5 > t6\ \&\ at(d1, t6)\ \&\ at(b2, t6)]\ \Leftrightarrow at(i1, t5)$$

IP4: *Action eat food generation*
At any point in time the action eat food is performed *iff* at some time point in the past both b3 and i1 held. Formally:

$$\exists t8\ [\ t7 > t8\ \&\ at(i1, t8)\ \&\ at(b3, t8)]$$

$$\Leftrightarrow \text{at(performed(eat food), t7)}$$

IP5: *Desire d2 generation*
At any point in time the internal state property d2 holds *iff* at some time point in the past b4 held. Formally:

$$\exists t10\ [\ t9 > t10\ \&\ \text{at}(b4, t10)\ ] \Leftrightarrow \text{at}(d2, t9)$$

IP6: *Intention i2 generation*
At any point in time the internal state property i2 holds *iff* at some time point in the past b5 and d2 held. Formally:

$$\exists t12\ [\ t11 > t12\ \&\ \text{at}(d2, t12)\ \&\ \text{at}(b5, t12)] \Leftrightarrow \text{at}(i2, t11)$$

IP7: *Action medicine intake generation*
At any point in time the action medicine intake is performed *iff* at some time point in the past both b6 and i2 held. Formally:

$$\exists t14\ [\ t13 > t14\ \&\ \text{at}(i2, t14)\ \&\ \text{at}(b6, t14)] \Leftrightarrow \text{at(performed(medicine intake), t13)}$$

Cognitive Analysis: Overview

First, a set of goals is defined on the human's states and behaviour. These goals may concern, for example, the human's well-being or the quality of performance in task execution. The goal for the case study is to maintain a satisfactory health condition of the human. Each goal is refined into more specific criteria that should hold for the human's functioning. In particular, for the case study the goal is refined into three criteria:

(1) *food is consumed every 5 hours (at latest) during the day*;
(2) *after the medicine is taken, no food consumption during the following 2 hours occurs*;
(3) *after 3 hours from the last food intake no medicine intake occurs.*

Based on the criteria expressions, a set of output states (called *an output focus*) and a set of internal (cognitive) states (called *an internal focus*) of the human are determined, which are used for establishing the satisfaction of the criteria. For the case study the output focus consists of the states performed(eat food) and performed(medicine intake).

A cognitive model of the human defines relations between an output state and internal states which cause the generation of the output state. The latter provide a more in depth understanding of why certain behaviours (may) occur. In general, using a cognitive model one can determine a minimal specification that comprises temporal relations to internal states, which provides necessary and sufficient conditions on internal states to ensure the generation of an output state. An automated procedure to generate such specifications is considered in the next section. Such a specification is a useful means for prediction of behaviour. That is, if an essential part of a specification becomes satisfied (e.g., when some important internal state(s) hold(s)), the possibility that the corresponding output state will be generated increases significantly. If such an output is not desired, actions can be proposed in a knowledgeable manner, based on an in depth understanding of the internal states causing the behaviour. Thus, the essential internal states (called *predictors for an output*) from specifications for the states in the output focus should be added to the internal focus.

Normally states in an internal focus cannot be observed directly. Therefore, representation relations are to be established between these states and externally observable states of the human (i.e., the representational content should be defined for each internal state in focus). Representation relations are derived from the cognitive model representation as shown in a section below and usually have the form of more complex temporal expressions over externally observable states. To detect occurrence of an internal state, the corresponding representational content should be monitored constantly, which is considered in a section later in this paper.

Generating Predictors for Output States

One of the tasks is the identification of (internal) predictors for outputs. A predictor(s) for a particular output can be identified based on a specification of human's internal dynamics that ensures the generation of the output. In general, more than one specification can be identified, which is minimal (in terms of numbers of internal states and relations between them), however sufficient for the generation of a particular output. Below an automated procedure for the identification of all possible minimal specifications for an output state based on a cognitive model is given. The rough idea underlying the procedure is the following. Suppose for a certain output state property p the pp-statement $B \Leftrightarrow \text{at}(p, t)$ is available. Moreover, suppose that in B only two atoms of the form $\text{at}(p1, t1)$ and $\text{at}(p2, t2)$ with internal states p1 and p2 occur, whereas as part of the cognitive model also specifications $B1 \Leftrightarrow \text{at}(p1, t1)$ and $B2 \Leftrightarrow \text{at}(p2, t2)$ are available. Then, within B the atoms can be replaced (by substitution) by the formula B1 and B2. Thus, $\text{at}(p, t)$ may be related by equivalence to four specifications:

$B \Leftrightarrow \text{at}(p, t)$
$B[B2/\text{at}(p2, t2)] \Leftrightarrow \text{at}(p, t)$
$B[B1/\text{at}(p1, t1)] \Leftrightarrow \text{at}(p, t)$
$B[B1/\text{at}(p1, t1), B2/\text{at}(p2, t2)] \Leftrightarrow \text{at}(p, t)$

Here for any formula C the expression C[x/y] denotes the formula C transformed by substituting x for y.

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Algorithm: GENERATE-MINIMAL-SPECS-FOR-OUTPUT
Input: Cognitive model X; output state in focus specified by at(s, t)
Output: All possible minimal specifications for at(s, t) in list L
1  Let L be a list containing at(s, t), and let δp, δ be empty substitution lists.
2  For each formula $\varphi_l \in L$: $at(a_i, t) \leftrightarrow \psi i_p(at_1,\ldots, at_m)$ identify $\delta_i = \{at_k/body(\varphi_k)$ such that $\varphi_k \in X$ and $head(\varphi_k)=at_k\}$. Then δ is obtained as a union of $\delta_i$ for all formulae from L.
3  $\delta = \delta \setminus \delta p$
4  if δ is empty, finish.
5  For each formula $\varphi_l \in L$ obtain a set of formulae by all possible combinations of substitution elements from δ applied to $\varphi_l$. Add all identified sets to L.
6  $\delta p = \delta p \cup \delta$, proceed to step 2.
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For each generated specification the following measures can be calculated:

(1) The measure of undesirability indicating how undesirable is the human's state, described by the generated specification. It also reflects the confidence degree of producing an undesirable output from the generated specification.

(2) The minimum and maximum time before the generation of the output state. This measure is critical for timely intervention in human's activities.

These measures serve as heuristics for choosing one of the generated specifications. To facilitate the choice, constrains on the measures may be defined, which ensure that an intervention occurs only when a considerable undesirability degree is determined, but also the minimum time before the undesirable output is above some acceptable threshold. To calculate the measure (1), the degree of undesirability is associated with each output state of the cognitive model (i.e., a number from the interval [0, 1] that expresses how undesirable is the state). Then, it is determined which output states from the cognitive specification can be potentially generated, given that the bodies of the formulae from the generated specification are evaluated to TRUE. This is done by executing the cognitive specification with body(φ_i) = TRUE for all φ_i from the generated specification. Then, the measure of undesirability is calculated as the average over the degrees of undesirability of the identified output states, which can be potentially generated. The measures (2) can be calculated when numerical timing relations are defined in the properties of a cognitive specification.

For the case study from the automatically generated specifications that ensure the creation of the state performed(eat food) the one expressed by property IP4 is chosen. This specification has the highest confidence degree of producing the output (equal to the undesirability measure of the state performed(eat food)), when it is undesirable. It is assumed that the time interval t7-t8 in IP4 is sufficient for an intervention. The predictor state from the chosen specification is i1, as in the most cases it is generated earlier than the state b3. Thus, i1 is included in the internal focus. By a similar line of reasoning, the specification expressed by property IP7 is chosen, in which i2 is the predictor state included into the internal focus. Thus, the internal focus for the cognitive model is the set {i1, i2}.

Representation Relations

A next step is the identification of representation relations for cognitive states from a cognitive model for the human. A representation relation for an internal state property p relates the occurrence of p to a specification Φ that comprises a set of state properties and temporal (or causal) relations between them. In such a case it is said that p *represents* Φ, or Φ describes *representational content* of p. In this section an automated approach to identify representation relations for cognitive states from a cognitive model is described.

The representational content considered backward in time is specified by a history (i.e., a specification that comprises temporal (or causal) relations on past states) that relates to the creation of some cognitive state. In the literature on Philosophy of Mind different approaches to defining representation relations have been put forward (cf. Kim, 1996). For example, according to the classical causal/correlation approach, the representational content of an internal state property is given by a one-to-one mapping to an external state property. The application of this approach is limited to simple types of behaviour (e.g., purely reactive behaviour). In cases when an internal property represents a more complex temporal combination of state properties, other approaches have to be used. For example, the temporal-interactivist approach (cf. Jonker and Treur, 2003) allows defining representation relations by referring to multiple (partially) temporally ordered interaction state properties; i.e., input (sensor) and output (effector) state properties over time.

To automate the process of representation relation identification based on this idea, a procedure has been developed. To apply this procedure, cognitive specification is required to be stratified. This means that there is a partition of the specification $\Pi = \Pi_1 \cup \ldots \cup \Pi_n$ into disjoint subsets such that the following condition holds: for $i > 1$: if a subformula at(φ, t) occurs in a body of a statement in Π_i, then it has a definition within $\cup_{j<i} \Pi_j$.

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Algorithm: GENERATE-REPRESENTATION-RELATION
Input: Cognitive specification X; cognitive state specified by at(s, t), for which the representation relation is to be identified
Output: Representation relation for at(s, t)
1 Stratify X:
1.1 Define the set of formulae of the first stratum (h=1) as
    {$\varphi_i$: at($a_i$, t) $\leftrightarrow$ $\psi i_p$($at_1$,…, $at_m$) $\in$ X | $\forall$k m $\geq$k $\geq$1 $at_k$ is expressed using InputOnt}; proceed with h=2.
    1.2 The set of formulae for stratum h is identified as
        {$\varphi_i$: at($a_i$, t) $\leftrightarrow$ $\psi i_p$($at_1$,…, $at_m$) $\in$ X | $\forall$k m $\geq$k $\geq$1 $\exists$l l < h $\exists\psi \in$ STRATUM(X, l) AND head($\psi$) = $at_k$ AND $\exists$j m $\geq$j $\geq$1 $\exists\xi \in$ STRATUM(X, h-1) AND head($\xi$)=$at_j$ }; proceed with h=h+1.
    1.3 Until a formula of X exists not allocated to a stratum, perform 1.2.
2 Create the stratified specification X' by selecting from X only the formulae of the strata with the number i < k, where k is the number of the stratum, in which at(s, t) is defined. Add the definition of at(s, t) from X to X'.
3 Replace each formula of the highest stratum n of X' $\varphi_i$: at($a_i$, t) $\leftrightarrow$ $\psi i_p$($at_1$,…, $at_m$) by $\varphi_l$ $\delta$ with renaming of temporal variables if required, where $\delta$ = {$at_k$\ body($\varphi_k$) such that $\varphi_k \in$ X' and head($\varphi_k$)=$at_k$}. Further, remove all formulae { $\varphi \in$ STRATUM(X', n-1) | $\exists\psi \in$ STRATUM(X', n) AND head($\varphi$) is a subformula of the body($\psi$)})
4 Append the formulae of the stratum n to the stratum n-1, which now becomes the highest stratum (i.e, n=n-1).
5 Until n>1, perform steps 3 and 4. The obtained specification with one stratum (n=1) is the representation relation specification for at(s, t)
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In Step 3 subformulae of each formula of the highest stratum n of X' are replaced by their definitions, provided in lower strata. Then, the formulae of n-1 stratum used for the replacement are eliminated from X'. As result of such a replacement and elimination, X' contains $n\text{-}1$ strata (Step 4). Steps 3 and 4 are performed until X' contains one stratum only. In this case X' consists of a formula φ defining the representational content for $at(s, t)$, i.e., $head(\varphi)$ is $at(s, t)$ and $body(\varphi)$ is a formula expressed over interaction states and (temporal) relations between them.

In the following it is shown how this algorithm is applied for identifying the representational content for state $i1$ from the internal focus from the case study. By performing Step 1 the specification of the cognitive model given above is automatically stratified as follows: stratum 1: {IP1((own_position_refrigerator), IP1(food_not_eaten_more_than_2h), IP1(own_position_cupboard), IP1(medicine_box_taken)}; stratum 2: {IP2, IP5}; stratum 3: {IP3, IP6}; stratum 4: {IP4, IP7}.

By Step 2 the properties IP4, IP5, IP6, IP7 are eliminated as unnecessary for determining the representational content of $i1$. Further, in Step 3 we proceed with the property IP3 of the highest stratum (3) that defines the internal state $i1$.

$$\exists t6\ [\ t5 > t6\ \&\ at(d1, t6)\ \&\ at(b2, t6)]\ \Leftrightarrow at(i1, t5)$$

In Step 3 the property IP8 is obtained by replacing $d1$ and $b2$ state properties in IP3 by their definitions with renaming of temporal variables:

$$\exists t6\ [\ t5 > t6\ \&\ \exists t4\ [\ t6 > t4\ \&\ at(b1, t4)\ ]\ \&\ \exists t2\ [\ t6 > t2\ \&\ at(observed(\text{own\_position\_refrigerator}), t2)\ ]\ \ ]\ \Leftrightarrow at(i1, t5)$$

Further, the properties IP3, IP2 and IP1(own_position_refrigerator) are removed from the specification and the property IP8 is added to the stratum 2. Then, IP9 is obtained by replacing $b1$ in IP8 by its definition:

$$\exists t6\ [\ t5 > t6\ \&\ \exists t4\ [\ t6 > t4\ \&\ \exists t15\ [\ t4 > t15\ \&\ at(observed(\text{food\_not\_eaten\_more\_than\_2h}), t15)\ ]\ ]\ \&\ \exists t2\ [\ t6 > t2\ \&\ at(observed(\text{own\_position\_refrigerator}), t2)\ ]\ \ ]\ \Leftrightarrow at(i1, t5)$$

After that the properties IP8 and IP1(food_not_eaten_more_than_2h) are removed from the specification and IP9 becomes the only property of the stratum 1. Thus, IP9 defines the representational content for the state $i1$ that occurs at any time point $t5$.

Similarly, the representational content for the other state from the internal focus $i2$ is identified as:

$$\exists t12\ [\ t11 > t12\ \&\ \exists t16\ [\ t12 > t16\ \&\ at(observed(\text{own\_position\_cupboard}), t16)\ ]\ ]\ \Leftrightarrow at(i2, t11)$$

The algorithm has been implemented in Java. The overall time complexity of the algorithm for the worst case is $O(|X|^2)$, where $|X|$ is the length of a cognitive specification X.

Behavioural Monitoring

To support the monitoring process, it is useful to decompose a representational content expression into atomic subformulae that describe particular interaction and world events. The subformulae are determined in a top-down manner, following the nested structure of the overall formula:

$$\text{monitor\_focus}(F)\ \rightarrow\ \text{in\_focus}(F)$$

$$\text{in\_focus}(E)\ \wedge\ \text{is\_composed\_of}(E,C,E1,E2)\ \rightarrow\ \text{in\_focus}(E1)\ \wedge\ \text{in\_focus}(E2)$$

Here is_composed_of(E,C,E1,E2) indicates that E is an expression obtained from subexpressions $E1$ and $E2$ by a logical operator C (i.e., and, or, implies, not, forall, exists). At each decomposition step subexpressions representing events are added to the list of foci that are used for monitoring. This list augmented by the foci on the states from the output focus is used for monitoring. For the case study from the identified representation content for $i1$ and $i2$ the following atomic monitoring foci were derived:

observed(food_not_eaten_more_than_2h)
observed(own_position_refrigerator)
observed(own_position_cupboard)

Furthermore, the information on the states in the output and internal foci, on the chosen predictors for the output states, and on the identified representation relations is used to constantly monitor. As soon as a an event from the atomic monitoring foci occurs, the component initiates automated verification of the corresponding representational content property on the history of the events in focus occurred so far. The automatic verification is performed using the TTL Checker tool (for the details on the verification algorithm see (Bosse et al, 2009)). For the case study such a history (or a trace) was created using the LEADSTO simulation tool (Bosse et al, 2007).

Another task is to ensure that the goal criteria hold. The satisfaction of the criteria is checked using the TTL Checker tool. Furthermore, to prevent the violation of a criterion promptly, information related to the prediction of behaviour (i.e., predictors for outputs) can be used. More specifically, if the internal states-predictors for a set of output states O hold, and some behaviour or performance criterion is violated under O, then an intervention in human activities is required. The type of intervention may be defined separately for each criterion. In particular, for the case study as soon as the occurrence of the prediction states $i1$ and $i2$ is established, the violation of the criteria identified previously is determined under the condition that the predicted outputs hold. To prevent the violation of the criteria, the following intervention rules are specified:

(1) If the human did not consume food during last 5 hours, then inform the human about the necessary food intake. Formally:

$$\forall t1\ \text{current\_time}(t1)\ \&\ \neg\exists t2\ t1\text{-}300 \leq t2 < t1\ \text{belief}(\text{holds\_at}(\text{performed}(\text{eat food}), t2), \text{pos})\ \Rightarrow\ \text{to\_be\_communicated\_to}(\text{‘Meal time’}, \text{pos}, \text{Human})$$

(2) If the human took medicine X less than 2 hours ago (time point t2 in minutes) and the existence of the predictor $i1$ is established, then inform the human that she still needs to wait ($120\text{-}\ t2$) minutes for taking medicine. Formally:

$$\forall t1\ \text{current\_time}(t1)\ \&\ \exists t2\ t1\text{-}120 < t2\ \text{belief}(\text{holds\_at}(\text{performed}(\text{medicine intake}), t2), \text{pos})\ \&\ at(i1, t1)\ \Rightarrow \text{to\_be\_communicated\_to}(\text{‘Please wait 120-t2 minutes more’}, \text{pos}, \text{Human})$$

(3) If the human did not consume food during last 3 hours and the existence of the predictor i2 is established, inform the human that she better eats first. Formally:
∀t1 current_time(t1) & ¬∃t2 t1-180 ≤ t2 < t1
belief(holds_at(performed(eat food), t2), pos) & at(i2, t1)
⇒ to_be_communicated_to('Please eat first', pos, Human)

Discussion and Conclusions

In this paper a computational model was presented incorporating a more in depth analysis based on a cognitive model of a human's functioning. Having such a cognitive model allows relating certain behavioural or performance aspects that are considered, to underlying cognitive states causing these aspects. Often cognitive models are used either by performing simulation, or by temporal reasoning methods; e.g. (Port and van Gelder, 1995). In this paper a third way of using such models is introduced, namely by deriving more indirect relations from these models. Such an approach can be viewed as a form of knowledge compilation (Cadoli and Donini, 1997) in a pre-processing phase, so that the main processing phase is less intensive from the computational point of view. Such a form of automated knowledge compilation occurs in two ways: first, to derive the relationships between considered behaviour or performance aspects to the relevant internal cognitive states, and next to relate such cognitive states to observable events (monitoring foci). These monitoring foci are determined from the cognitive model by automatically deriving representation relations for cognitive states in the form of temporal specifications. From these temporal expressions the events are derived that are to be monitored, and from the monitoring information on these events the representation expressions are verified automatically.

A wide range of existing ambient intelligence applications is formalised using production rules (cf. Christensen, 2002) and if-then statements. Two important advantages of such rules are modelling simplicity and executability. However, such formalism is not suitable for expressing more sophisticated forms of temporal relations, which can be specified using the TTL language. In particular, references to multiple time points possible in TTL are necessary for modelling forms of behaviour more complex than stimulus-response (e.g., to refer to memory states in delayed-response behavioural specifications). Furthermore, TTL allows representing temporal intervals as in the following property: 'if the human was sleeping for x hours and x > 4h and s/he did not take the medicine A during 2 hours after being awake, then support will be provided to the human'. Moreover, using TTL one can refer to histories of states, for example to express that a medicine improves the health condition of a patient; in this case the health conditions in traces with and without the medicine intake are compared.

Another popular approach to formalise recognition and prediction of human behaviour is by using Hidden Markov Models (HMM) (e.g., Sanchez et al., 2007). In HMM-based approaches known to the authors, recognition of human activities is based on contextual information of the activity execution only; no cognitive or (gradual) preparation states that precede actual execution of activities are considered. As indicated in (Sanchez et al., 2007) a choice of relevant contextual variables for HMMs is not simple and every additional variable causes a significant increase in the complexity of the recognition algorithm. Knowledge of cognitive dynamics that causes particular behaviour would provide more justification and support for the choice of variables relevant for this behaviour. Furthermore, as pointed in (Brdiczka et al., 2009) for high quality behaviour recognition a large corpus of training data is needed. The computational costs of the pre-processing (knowledge compilation) phase of the approach proposed in this paper are much lower (polynomial in the size of the specification). Also, no model training is required. However, the proposed approach relies heavily on the validity of cognitive models.

In the future, cases will be elaborated, in which cognitive models based on diverse cognitive frameworks and architectures will be used.

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