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Probabilistic Rule-Based Activity Recognition

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Problem Statement

The ability of pervasive context-aware system to perform efficient activity recognition (AR) relies heavily on their ability to gather full, precise and unambiguous information about the environment. But raw sensor data is often noisy, imprecise and corrupted, which leads to inconsistencies and conflicts in resulting AR reasoning. It is not always immediately visible, which sensor readings are erroneous, thus several possible AR interpretations emerge.

The proposed solution uses sensor dependency rules to detect inconsistencies in sensor readings, and uses probabilistic reasoning to find the most probable situation at the current moment of time. All information, even if conflicting, is kept in the system, representing several possible situations with different weight, which changes when sensor readings become obsolete, or new information arrives.

Environment

An **environment** $\langle V, D\rangle$ is defined by a set of context variables $V = S \bigcup A$; $S \bigcap A = \emptyset$, where $S = \{s_1, s_2, ..., s_n\}$ is a set of sensors, and $A = \{a_1, a_2, ..., a_m\}$ is a set of activity recognition variables. Each variable v_i varies over a **domain** $D_i = \{d_{i1}, d_{i2}, ..., d_{im_i}\}$ with size m_i. Every sensor has associated **weight** $w(s_i)$, which represents the trustworthiness of it.

Sensors

[w=1.0] $PC = \{T, F\}$
[w=1.0] $LCD = \{T, F\}$
[w=0.7] (K)eyboard PIR $= \{T, F\}$
[w=0.8] Chair (PR)essure $= \{T, F\}$

AR variables

(C)omputer $= \{Off, Bck, On\}$
(Act)ivity $= \{(A)bsence, Wpc, (W)ork\}$

Rules

The rules are defined as formulas in a predicate logic over finite domains. Every atomic predicate represents a certain condition over a variable, and should result in $true$ or $false$.

$$P ::= (v_i = d) \mid (v_i \neq d) \mid (v_i \in \{d_i\}) \mid (v_i \notin \{d_i\})$$
$$P ::= (v_i < d) \mid (v_i > d) \mid (v_i \leq d) \mid (v_i \geq d), \quad \text{for numeric variables}$$
$$R ::= P \mid \neg R \mid R \wedge R \mid R \vee R \mid R \Rightarrow R \mid R \Leftrightarrow R$$

Sensor dependency

$LCD = T \Rightarrow PC = T$
$K = T \Rightarrow PR = T$
$LCD = T \Rightarrow K = T \wedge PR = T$

Activity Recognition

$PC = F \Rightarrow C = Off$
$PC = T \wedge LCD = F \Rightarrow C = Bck$
$PC = T \wedge LCD = T \Rightarrow C = On$
$PR = F \Rightarrow Act = A$
$PR = T \wedge C = On \Rightarrow Act = Wpc$
$PR = T \wedge (C \neq On \vee K = F) \Rightarrow Act = W$

Rule Transformation

1. Transform a rule to CNF form. E.g. $PR = T \wedge (C \neq On \vee K = F) \Rightarrow Act = W$ becomes $(\neg PR = T \vee C = On \vee Act = W) \wedge (\neg PR = T \vee \neg K = F \vee Act = W)$
2. Split conjuncted clauses on different rules.
3. Flip negations, e.g. $\neg C = On$ becomes $C \neq On$

Extended context

For a given environment $\langle V, D\rangle$, an **extended context** c is a valuation of all variables in V with a non-empty subset D^c of D.

For our purposes extended contexts are obtained by applying rules on raw sensor readings. E.g. from $PC = T$ an extended context $\{LCD = \star; PC = T; C = \{Bck; On\}\}$ may be obtained.

If all variables v_i are assigned only one specific value in D_i, a context is called an **interpretation**.

Every variable in a context should have at least one possible value, as otherwise the context is impossible on practice. More values represent an ambiguity and incomplete knowledge of the environment.

Algorithm 1 Obtaining extended context from a sensor reading $s = d_s$

```
Data: s - sensor
d_s - sensor value, d_s ∈ D_s
rules - set of rules
Result: contexts set
contexts ← initialContext(s, d_s) s.t. {s = d_s ∧ ∀v_i ≠ s : v_i = ⋆}
foreach r ← rules do
    preds ← splitOnPredicates(r)
    for c ← contexts yield
        if alreadySatisfied(preds, c) then
            c
        else
            predsLeft ← stillSatisfiable(preds, c)
            if predsLeft is empty then null
            else predsLeft.map(pred => intersect(pred, c))
        end
    end
    contexts ← trimSubsetsAndCombinable(contexts)
end
```

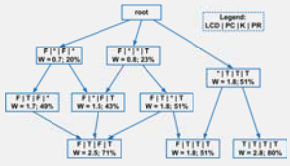
Context Consistency Diagram

Given an environment $\langle V, D\rangle$ and a set of contexts $C_0 = \{c_k\}$, $k \in 1..N$, a *context consistency diagram (CCD)* is a tuple $G = \langle C, E, r\rangle$, where:

- $r = D$, is a special context, the *root;*
- $C = C_0 \cup C_u \cup r$ where C_u is the full set of intersections of a power set of C_0;
- $E \subseteq C \times C$, such that $(c_2, c_1) \in E$ iff $\exists c_1, c_2 \in C : c_1 \subset c_2$ and $\nexists c_m \in C : c_1 \subset c_m \subset c_2$.

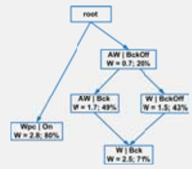
Sensor Reading	Weight	Extended context	
		Sensor-based	AR-based
$LCD = T$	1.0	$[T\|T\|T\|T]$	$[W\|On]$
$PC = T$	1.0	$[F\|T\|F\|*]$; $[F\|T\|*\|T]$; $[*\|T\|T\|T]$	$[AW\|Bck]$; $[Wpc\|On]$
$K = F$	0.7	$[F\|*\|F\|*]$	$[AW\|BckOff]$
$PR = T$	0.8	$[F\|*\|*\|T]$; $[*\|T\|T\|T]$	$[W\|BckOff]$; $[Wpc\|On]$

Sensor-based



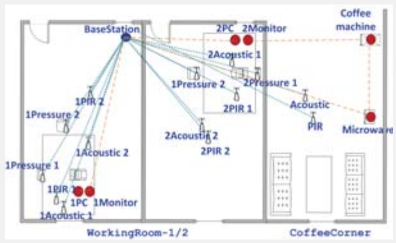
Most probable: (80% support) $T|T|T|T$
Interpretation using AR rules: $Wpc|On$

AR-based



Most probable: (80% support) $Wpc|On$

Application in a Living Lab



Variables

Variable	w	Variable	w
1(Ac)oustic(K)eyb	0.8	2LCD	1.0
1(Ac)oustic	0.7	2PC	0.9
1LCD	1.0	2PIR(K)eyboard	0.5
1PC	0.9	2(PIR)Motion	0.5
1PIR(K)eyboard	0.5	2(PR)essure1	0.8
1(PIR)Motion	0.5	2(PR)essure2	0.8
1(PR)essure1	0.8	3(Ac)oustic	0.7
1(PR)essure2	0.8	3(M)icro(W)ave	1.0
2(Ac)oustic	0.7	3(PIR)Motion	0.5
2(Ac)oustic(K)eyb	0.8	3(C)offee(M)	0.8

Rules

For each working room:
$xLCD = T \Rightarrow xPC = T$
$xLCD = T \Rightarrow xK = T \wedge (xPR1 = T \vee xPR2 = T)$
$xK = T \Rightarrow (xPR1 = T \vee xPR2 = T)$
$xAcK = T \Rightarrow xAc = T$
$xAc = T \Rightarrow xPIR = T$
$xPR1 = T \wedge xPR2 = T \Rightarrow xAc = T$
For coffee corner:
$3Ac = T \vee 3MW = T \vee 3CM = T \Rightarrow 3PIR = T$

Results (Sensor-based)

Area	$\sum_{\forall Act} FN$		Errors fixed
	Aver	CCD	
WorkingRoom-1	230	138	40.00%
WorkingRoom-2	284	151	46.83%
CoffeeCorner	46	8	82.60%

Area	Success rates		Improvement
	Aver	CCD	
WorkingRoom-1	80.85%	88.51%	7.66%
WorkingRoom-2	76.35%	87.42%	11.07%
CoffeeCorner	99.17%	99.33%	00.16%

Publications

V. Degeler, and A. Lazovik. Interpretation of Inconsistencies via Context Consistency Diagrams. In 9th IEEE Int. Conf. on Pervasive Computing and Communications (PerCom'11), pp. 20-27, 2011.

T. A. Nguyen, V. Degeler, R. Contarino, A. Lazovik, and M. Aiello. Towards context consistency in a rule-based activity recognition architecture. In 10th International Conference on Autonomic and Trusted Computing (UIC/ATC) (pp. 625-630).

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