Integrating Recognition and Reasoning in Smart Environment

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Overview

- Motivation
- Related Work
- Current Prototype
- Framework
- Evaluation Mechanisms
- Contributions and Future work

Motivation

- Recognizing a user is at the core of provisioning context-aware services in smart environments.

- Develop smart *indoor* environments that
  - identify and track occupants *unobtrusively*
  - Support spatial and temporal queries, such as:
    - the location of an occupant in the facility;
    - time of entry/exit of an occupant;
    - the first/last person to enter/leave the facility;
    - the current occupants present in the facility;
    - tracking the path followed by an occupant ; etc

Motivation (contd.)

- Develop an *abstract framework* that will
  - accommodate multiple biometric modalities (face, voice, gait, etc) in a unified manner;

Recognition

  - incorporate spatio-temporal reasoning based upon declarative knowledge of the environment as well as the occupants;

Reasoning

  - facilitate answering queries about the occupants;

Retrieval

  - provide a basis for characterizing the performance of the smart environment.

3 R's of Smart Environments

Related Work

Location Estimation and Tracking

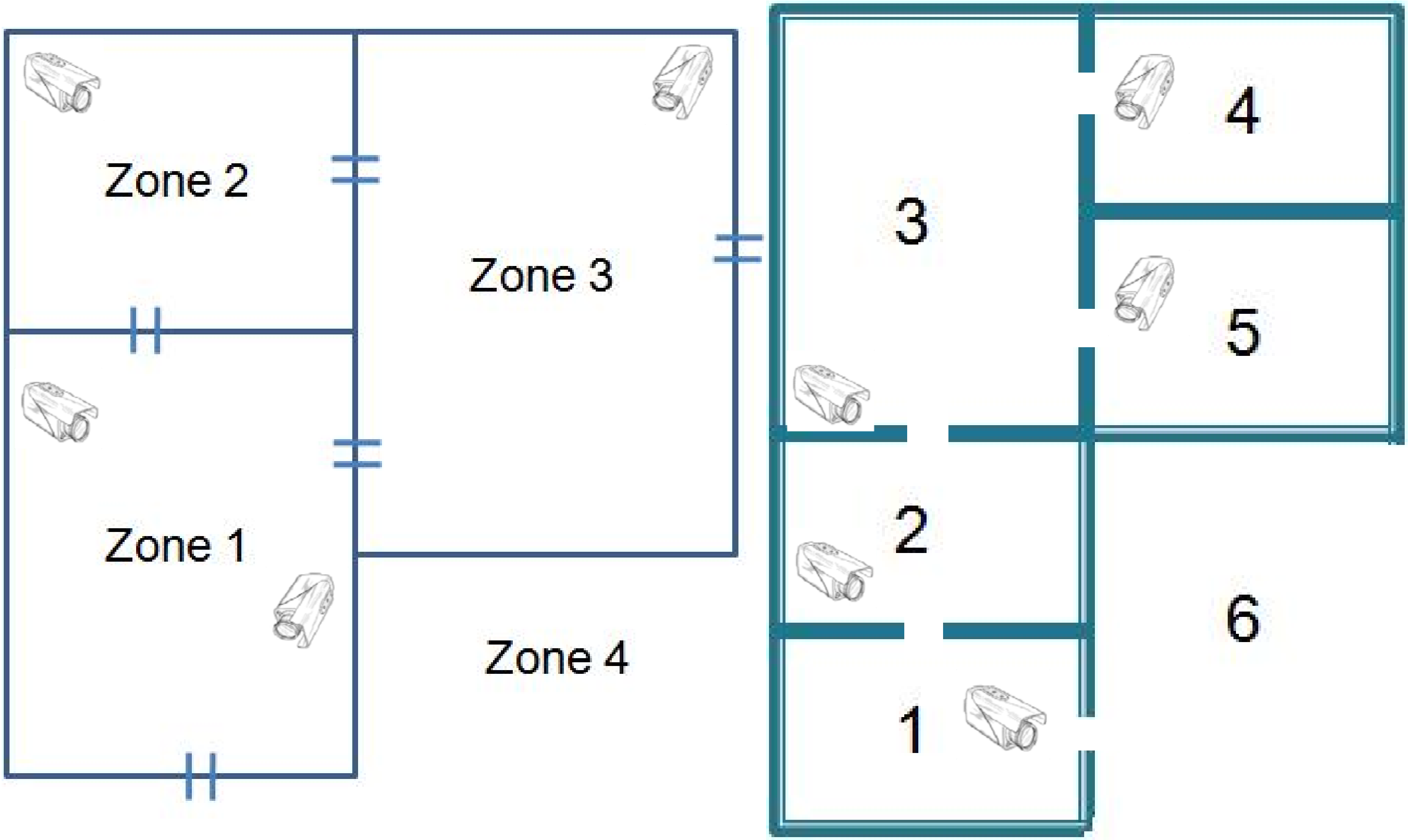
	Methodology	Estimation Method	Non-Obtrusive
•Krumm, J. et al.: Multi-Camera Multi-Person Tracking for EasyLiving. In: Proc. of the 3rd IEEE Intl. Workshop on Visual Surveillance (VS'2000). (2000)	**Visual Surveillance**	**Internally system generated**	**Yes**
• Bui, H. H. et al.: Tracking and surveillance in wide-area spatial environments using the Abstract Hidden Markov Model. Intl. Journal of Pattern Recognition and AI (2002)	**Abstract HMM (Predictive Model)**	**Simulation**	**n/a**
• Schulz, D. et al.: People tracking with anonymous and id-sensors using Rao-Blackwellised particle filters. IJCAI (2003)	**Bayesian Models involving particle filters, Kalman filters**	**Id-Sensors**	**No**
•Das, S. K. et al.: Context-aware resource management in multi-inhabitant smart homes: A framework based on Nash H-learning. IEEE Percom (2006)	**Game Theoretic Models using Online Learning**	**RFID**	**No**
Proposed research	**State Transition model integrating multiple biometric modalities**	**Biometrics (Face, Voice, Gait, Height, etc)**	**Yes**

Related Work

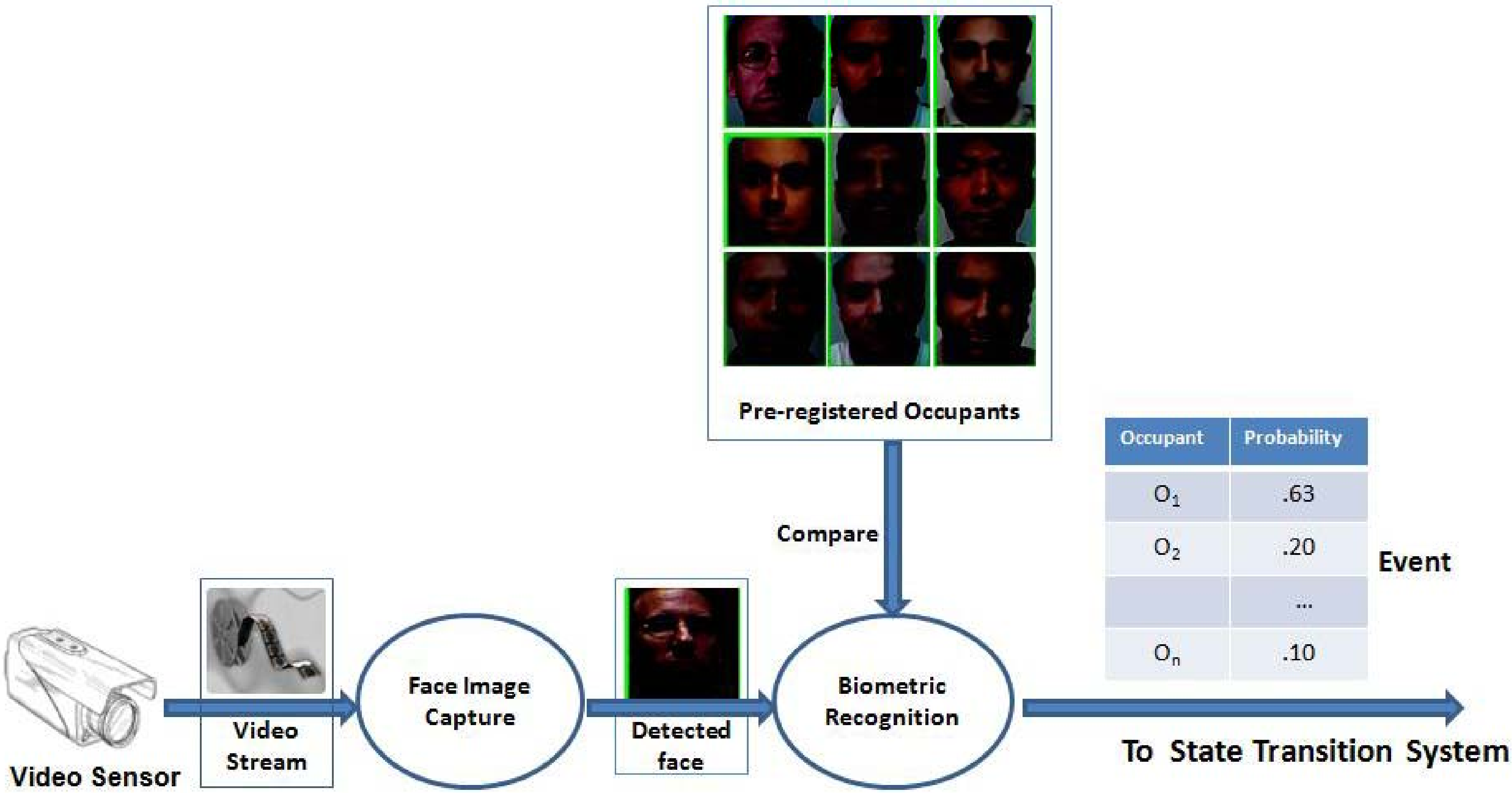
Biometrics in Smart Environments

	Recognition	Reasoning	Approach
•Gao, Y. et al., A Multi-View Facial Analysis Technique for Identity Authentication. IEEE Pervasive Computing (2003)	**Fusion of multiple views of face**	-	-
•Zhang, S. et al.: Continuous Verification Using Multimodal Biometrics. In: Zhang, D., Jain, A.K. (eds.) ICB 2006, LNCS vol. 3832, pp. 562–570, Springer, Heidelberg (2005)	**Face and Fingerprint**	**Temporal**	**Bayesian**
• Ekenel, H.K. et al.: Multi-modal Person Identification in a Smart Environment. In: Proc. of 2007 CVPR Biometrics Workshop, pp. 1–8. IEEE (2007)	**Face and Voice**	-	**Score normalization, modality weighting combination schemes**
•Bernardin, K., Stiefelhagen, R.: Audio-visual multi-person tracking and identification for smart environments. In: Proc. of the 15th ACM Multimedia, pp. 661–670. (2007)	**Face and Voice**	-	**Incremental multimodal identification**
Proposed research	**Probabilistic recognition using Face, Voice, Gait, Height etc**	**Spatio-Temporal Declarative Knowledge**	**Unified framework as a State Transition System**

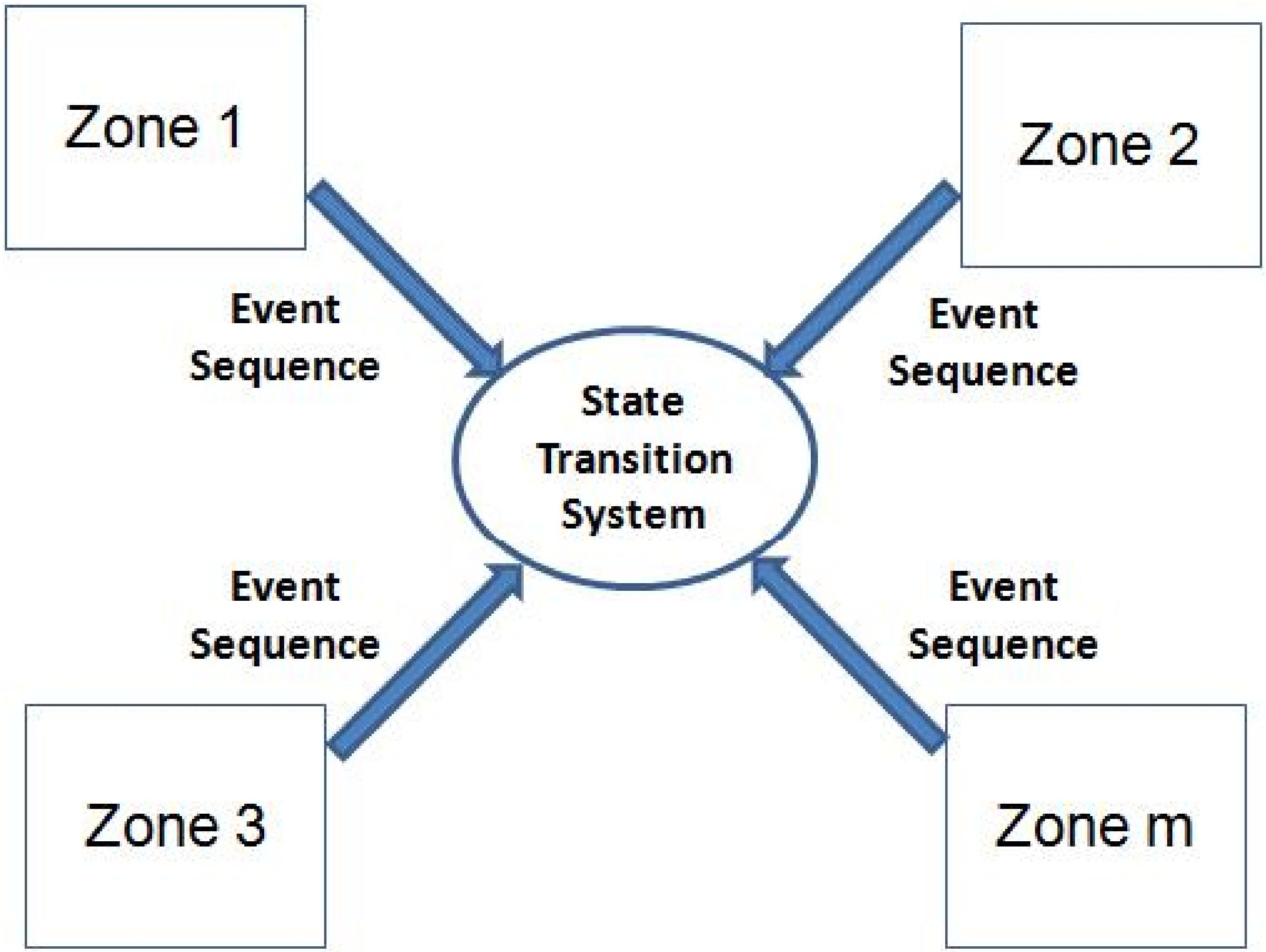
Example Indoor Layouts



Face Recognition Module



Abstract Framework



Abstraction

- A smart environment is abstracted as a **state transition system** (S, E, Δ) where
  - *S is a set of states* $s_0, s_1, \ldots s_x$;
  - *E is a set of events labeled* $e_1, e_2, \ldots e_x$ *and*
  - $\Delta: S \times E \rightarrow S$
- State transitions encapsulate the reasoning

$$s_0 \xrightarrow{e_1} s_1 \xrightarrow{e_2} s_2 \ldots \xrightarrow{e_x} s_x$$

- Event occurs at a zone, abstracts biometric recognition

Example. - Starting State S_0

$$s_0 \xrightarrow{e_1} s_1 \xrightarrow{e_2} s_2 \ldots \xrightarrow{e_x} s_x$$

s0

Occupants	Z1	Z2	Z3	Z4	Z5	Z6
O1	0	0	0	0	0	1
O2	0	0	0	0	0	1
O3	0	0	0	0	0	1
O4	0	0	0	0	0	1
O5	0	0	0	0	0	1
O6	0	0	0	0	0	1
O7	0	0	0	0	0	1
O8	0	0	0	0	0	1
O9	0	0	0	0	0	1
O10	0	0	0	0	0	1
O11	0	0	0	0	0	1
O12	0	0	0	0	0	1
O13	0	0	0	0	0	1
O14	0	0	0	0	0	1
O15	0	0	0	0	0	1
O16	0	0	0	0	0	1
O17	0	0	0	0	0	1
O18	0	0	0	0	0	1
O19	0	0	0	0	0	1
O20	0	0	0	0	0	1
O21	0	0	0	0	0	1
O22	0	0	0	0	0	1
O23	0	0	0	0	0	1
O24	0	0	0	0	0	1
O25	0	0	0	0	0	1

Sample Event Sequence

n occupants, $o_1 \ldots o_n$; m zones labeled 1… m

State $s_k = \langle Z_{1k} \ldots Z_{mk} \rangle$ where $Z_{jk} = \{ \langle o_i , p_{jk}(o_i) \rangle \mid 1 \le i \le n \}$; $\sum_{(j=1,m)} p_{jk}(o_i) = 1$

Occupants	e1 Z1	e2 Z2	e3 Z3	e4 Z1	e5 Z1	e6 Z2	e7 Z1	e8 Z4	e9 Z2	e10 Z3
O1	0.030	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.020	0.000
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O3	0.458	0.420	0.528	0.005	0.000	0.001	0.000	0.481	0.001	0.000
O4	0.000	0.017	0.001	0.003	0.042	0.000	0.001	0.233	0.010	0.000
O5	0.000	0.003	0.000	0.383	0.019	0.358	0.000	0.010	0.018	0.598
O6	0.011	0.000	0.000	0.045	0.017	0.309	0.426	0.000	0.003	0.000
O7	0.014	0.000	0.000	0.000	0.127	0.000	0.000	0.000	0.000	0.000
O8	0.000	0.000	0.000	0.015	0.000	0.035	0.033	0.000	0.000	0.000
O9	0.000	0.288	0.030	0.000	0.000	0.000	0.000	0.186	0.010	0.018
O10	0.344	0.100	0.014	0.000	0.493	0.000	0.000	0.006	0.552	0.000
O11	0.000	0.000	0.000	0.043	0.017	0.019	0.000	0.011	0.014	0.000
O12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O13	0.000	0.089	0.341	0.020	0.001	0.020	0.537	0.000	0.109	0.000
O14	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.000
O15	0.000	0.054	0.077	0.013	0.004	0.014	0.000	0.000	0.005	0.000
O16	0.000	0.000	0.000	0.251	0.000	0.077	0.000	0.000	0.000	0.000
O17	0.000	0.013	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.012
O18	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
O19	0.003	0.001	0.001	0.003	0.001	0.010	0.001	0.005	0.000	0.000
O20	0.016	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.002
O21	0.002	0.012	0.003	0.004	0.000	0.003	0.000	0.000	0.000	0.000
O22	0.000	0.001	0.000	0.005	0.000	0.011	0.000	0.003	0.000	0.000
O23	0.122	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000
O24	0.000	0.000	0.000	0.207	0.258	0.139	0.000	0.053	0.001	0.000
O25	0.000	0.000	0.000	0.000	0.019	0.000	0.000	0.000	0.256	0.369
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ground Truth	**O3**	**O3**	**O3**	**O5**	**O10**	**O5**	**O13**	**O3**	**O10**	**O5**

Transition Function

1st Order Markov property

- $\Delta: S \times E \rightarrow S$, maps state s_{k-1} to s_k upon event e_k
  - Let $s_{k-1} = \langle Z_{1,k-1} \ldots Z_{jk-1} \ldots Z_{mk-1} \rangle$ and
  - $Z_{jk-1} = \{\langle o_i, p_{jk-1}(o_i) \rangle \mid 1 \le i \le n\}$
- Then $s_k = \langle Z_{1k} \ldots Z_{jk} \ldots Z_{mk} \rangle$ where:
  - Let $x_i = 1 - p_{jk}(o_i)$
  - $Z_{jk} = \{\langle o_i, p_{jk}(o_i) + x_i * p_{jk-1}(o_i) \rangle \mid 1 \le i \le n\}$ **Zone of event**
  - $Z_{lk} = \{\langle o_i, x_i * p_{lk-1}(o_i) \rangle \mid 1 \le i \le n\}$, for $1 \le l \le m$ and $l \ne j$ **Other zones**

Sample State Transition

= 0.47 + (1- 0.47) * 0

$p_{jk}(o_i) + x_i * p_{jk-1}(o_i)$

= (1 - 0.47) * .38

$p_{jk-1}(o_i)$ $p_{lk-1}(o_i)$ $p_{jk}(o_i)$ $x_i * p_{lk-1}(o_i)$

	State : s17					
Occupants	Z1	Z2	Z3	Z4	Z5	Z6
O1	0.03	0.02	0.01	0.00	0.00	0.94
O2	0.00	0.00	0.00	0.00	0.00	1.00
O3	0.07	0.10	0.27	0.47	0.01	0.08
O4	0.09	0.02	0.00	0.22	0.00	0.66
O5	0.06	0.08	0.36	0.00	0.41	0.08
O6	0.22	0.33	0.00	0.00	0.00	0.45
O7	0.14	0.00	0.00	0.00	0.00	0.86
O8	0.37	0.38	0.00	0.00	0.00	0.25
O9	0.00	0.23	0.05	0.18	0.00	0.54
O10	0.14	0.28	0.52	0.00	0.00	0.06
O11	0.31	0.06	0.02	0.01	0.06	0.55
O12	0.00	0.00	0.00	0.00	0.00	1.00
O13	0.26	0.11	0.02	0.00	0.00	0.61
O14	0.08	0.00	0.00	0.01	0.00	0.91
O15	0.02	0.23	0.06	0.00	0.00	0.68
O16	0.21	0.07	0.00	0.00	0.08	0.64
O17	0.00	0.01	0.01	0.00	0.00	0.97
O18	0.00	0.00	0.00	0.00	0.00	1.00
O19	0.01	0.01	0.00	0.01	0.00	0.97
O20	0.02	0.00	0.00	0.00	0.00	0.97
O21	0.01	0.03	0.00	0.00	0.00	0.96
O22	0.04	0.02	0.00	0.00	0.00	0.93
O23	0.12	0.00	0.00	0.00	0.00	0.87
O24	0.24	0.08	0.00	0.03	0.35	0.29
O25	0.01	0.10	0.61	0.00	0.00	0.28
Ground Truth - O3, O5, O10, O8						

e18
at Z3
0.00
0.00
0.00
0.00
0.00
0.40
0.00
0.47
0.00
0.00
0.01
0.00
0.00
0.00
0.09
0.00
0.00
0.00
0.00
0.00
0.01
0.02
0.00
0.00
0.01
O8

State : s18					
Z1	Z2	Z3	Z4	Z5	Z6
0.03	0.02	0.01	0.00	0.00	0.94
0.00	0.00	0.00	0.00	0.00	1.00
0.07	0.10	0.27	0.47	0.01	0.08
0.09	0.02	0.01	0.21	0.00	0.66
0.06	0.08	0.36	0.00	0.41	0.08
0.13	0.20	0.40	0.00	0.00	0.27
0.14	0.00	0.00	0.00	0.00	0.86
0.20	0.20	0.47	0.00	0.00	0.13
0.00	0.23	0.05	0.18	0.00	0.54
0.14	0.28	0.52	0.00	0.00	0.06
0.31	0.05	0.02	0.01	0.06	0.55
0.00	0.00	0.00	0.00	0.00	1.00
0.26	0.11	0.02	0.00	0.00	0.61
0.08	0.00	0.00	0.01	0.00	0.91
0.02	0.21	0.15	0.00	0.00	0.62
0.21	0.07	0.00	0.00	0.08	0.64
0.00	0.01	0.01	0.00	0.00	0.97
0.00	0.00	0.00	0.00	0.00	1.00
0.01	0.01	0.00	0.01	0.00	0.97
0.02	0.00	0.00	0.00	0.00	0.97
0.01	0.03	0.01	0.00	0.00	0.95
0.04	0.02	0.02	0.00	0.00	0.92
0.12	0.00	0.00	0.00	0.00	0.87
0.24	0.08	0.01	0.03	0.35	0.29
0.01	0.10	0.61	0.00	0.00	0.28
Ground Truth - O3, O5, O10, O8					

Δ : State x Event → State

Performance Measures
Smart Environments

- Adapted from IR to suit this context; (not query based).
  - Precision captures how well an occupant is recognized **(π)**
  - Recall captures whether an occupant is recognized at all **(ρ)**
  - *a: system; b: truth*

$\pi_{jk} = a_{jk} / b_{jk},;$

$a_{jk} = \sum \{p_{jk}(o_i) : 1 \le i \le n \ \& \ q_{jk}(o_i) = 1\}$

$b_{jk} = | \{o_i : \ q_{jk}(o_i) = 1 \ \& \ 1 \le i \le n\} |$

$\pi_k = \sum_{(j=1,m)} \pi_{jk} / m$ (zone wise)

$\pi = \sum_{(k=1,x)} \pi_k / x$

$\rho_{jk} = a_{jk} / b_{jk},$ where

$a_{jk} = | \sum \{o_i : \ 1 \le i \le n \ \& \ q_{jk}(o_i) = 1 \ \& \ p_{jk}(o_i) > \theta\} |$

$b_{jk} = | \{o_i : \ q_{jk}(o_i) = 1 \ \& \ 1 \le i \le n\} |$

$\rho_k = \sum_{(j=1,m)} \rho_{jk} / m$

$\rho = \sum_{(k=1,x)} \rho_k / x$

Calculation of Precision (π)

	State : s18					
Occupants	**Z1**	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**
O1	0.03	0.02	0.01	0.00	0.00	0.94
O2	0.00	0.00	0.00	0.00	0.00	1.00
O3	0.07	0.10	0.27	0.47	0.01	0.08
O4	0.09	0.02	0.01	0.21	0.00	0.66
O5	0.06	0.08	0.36	0.00	0.41	0.08
O6	0.13	0.20	0.40	0.00	0.00	0.27
O7	0.14	0.00	0.00	0.00	0.00	0.86
O8	0.20	0.20	0.47	0.00	0.00	0.13
O9	0.00	0.23	0.05	0.18	0.00	0.54
O10	0.14	0.28	0.52	0.00	0.00	0.06
O11	0.31	0.05	0.02	0.01	0.06	0.55
O12	0.00	0.00	0.00	0.00	0.00	1.00
O13	0.26	0.11	0.02	0.00	0.00	0.61
O14	0.08	0.00	0.00	0.01	0.00	0.91
O15	0.02	0.21	0.15	0.00	0.00	0.62
O16	0.21	0.07	0.00	0.00	0.08	0.64
O17	0.00	0.01	0.01	0.00	0.00	0.97
O18	0.00	0.00	0.00	0.00	0.00	1.00
O19	0.01	0.01	0.00	0.01	0.00	0.97
O20	0.02	0.00	0.00	0.00	0.00	0.97
O21	0.01	0.03	0.01	0.00	0.00	0.95
O22	0.04	0.02	0.02	0.00	0.00	0.92
O23	0.12	0.00	0.00	0.00	0.00	0.87
O24	0.24	0.08	0.01	0.03	0.35	0.29
O25	0.01	0.10	0.61	0.00	0.00	0.28
	Ground Truth - O3, O5, O10, O8					

	State : s18					
	Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**
				0.47		
					0.41	
			0.47			
			0.52			
	Ground Truth - O3, O5, O10, O8					
ajk			0.99	0.47	0.41	
bjk			2	1	1	
pjk			0.49	0.47	0.41	
m	3					
pk	0.46					

Π = 0.46

Calculation of Recall (ρ)

	State : s18					
Occupants	**Z1**	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**
O1	0.03	0.02	0.01	0.00	0.00	0.94
O2	0.00	0.00	0.00	0.00	0.00	1.00
O3	0.07	0.10	0.27	**0.47**	0.01	0.08
O4	0.09	0.02	0.01	0.21	0.00	0.66
O5	0.06	0.08	0.36	0.00	**0.41**	0.08
O6	0.13	0.20	0.40	0.00	0.00	0.27
O7	0.14	0.00	0.00	0.00	0.00	0.86
O8	0.20	0.20	**0.47**	0.00	0.00	0.13
O9	0.00	0.23	0.05	0.18	0.00	0.54
O10	0.14	0.28	**0.52**	0.00	0.00	0.06
O11	0.31	0.05	0.02	0.01	0.06	0.55
O12	0.00	0.00	0.00	0.00	0.00	1.00
O13	0.26	0.11	0.02	0.00	0.00	0.61
O14	0.08	0.00	0.00	0.01	0.00	0.91
O15	0.02	0.21	0.15	0.00	0.00	0.62
O16	0.21	0.07	0.00	0.00	0.08	0.64
O17	0.00	0.01	0.01	0.00	0.00	0.97
O18	0.00	0.00	0.00	0.00	0.00	1.00
O19	0.01	0.01	0.00	0.01	0.00	0.97
O20	0.02	0.00	0.00	0.00	0.00	0.97
O21	0.01	0.03	0.01	0.00	0.00	0.95
O22	0.04	0.02	0.02	0.00	0.00	0.92
O23	0.12	0.00	0.00	0.00	0.00	0.87
O24	0.24	0.08	0.01	0.03	0.35	0.29
O25	0.01	0.10	0.61	0.00	0.00	0.28
	Ground Truth - O3, O5, O10, O8					

	State : s18					
	Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**
				0.47		
					0.41	
			0.47			
			0.52			
	Ground Truth - O3, O5, O10, O8					
ajk			1	0	0	
bjk			2	1	1	
rjk			0.50	0	0	
m	3					
rk	0.17					

ρ = 0.17

Integrating Reasoning

- Use of multiple modalities
  - E.g. Face recognition with Height estimation
  - E.g. Face recognition with Voice recognition (in progress)

- Integrating declarative knowledge
  - Spatial knowledge
    - Zone of events
      - Entry, Internal, and External
    - Layout and Distances
  - Temporal knowledge
    - Based upon occupant schedules

Event Definition - Revised

- *Given*
  - *n occupants $o_1 \ldots o_n$*
- *Event e_k =<t_k, j_k, D_k>, where*
  - *t is the time*
  - *j is the zone*
  - *$D_k = \{<o_i, d_{jk}(o_i)> \mid 1 \leq i \leq n\}$*
    - *$d_{jk}(o_i)$ is the **distance score (eigen distance)** of a registered occupant o_i from the face detected at zone j in event e_k*

Transition Function - Revised

- *$\Delta: S \times E \rightarrow S$, maps state s_{k-1} to s_k upon event e_k*
  - *Let $s_{k-1} = \langle Z_{1,k-1} \ldots Z_{jk-1} \ldots Z_{mk-1} \rangle$ and*
  - *$Z_{jk-1} = \{\langle o_i, p_{jk-1}(o_i) \rangle \mid 1 \leq i \leq n\}$.*
  - *Note that $e_k = \langle t_k, j_k, D_k \rangle$*
    - ***where $D_k = \langle o_i, d_{jk}(o_i) \rangle$***

- *In order to map scores to probabilities, we compute **a reduced database** based upon spatial and temporal knowledge of the zones and occupants.*

$$f: \text{State} \times \text{Event} \rightarrow \text{Database}$$
$$db_k = f(s_{k-1}, e_k)$$
$$g: \text{Scores} \times \text{Database} \rightarrow \text{Probabilities}$$
$$p_k = g(db_k, e_k)$$

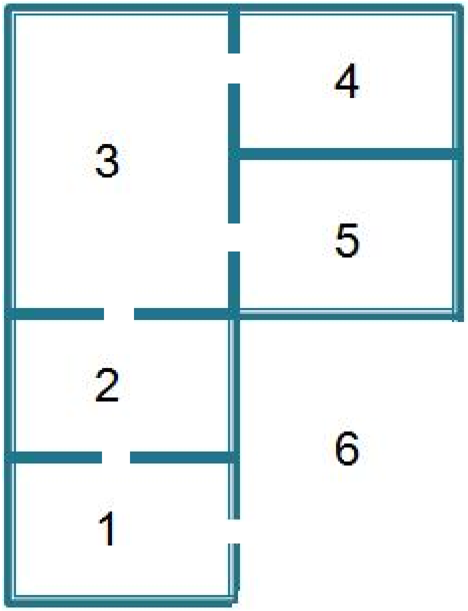
- *With these probabilities, the transition function is defined as before.*

Spatial Reasoning

- Let thresh(s,j) be a function which takes a state and a zone and returns the set of occupants with probability above threshold.
- For Internal Zones their candidate set is the union of candidate sets from their respective adjacent zones

- spatial(s,2) = thresh(s,1) U thresh(s,3)

- spatial(s,3) = thresh(s,2)
  U thresh(s,4)
  U thresh(s,5)



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Temporal Reasoning

- Schedule of Absence: absent(Start, End, Occupants)
  - *absent(9:00, 13:00, {o1, o7}) could denote the absence of occupants o1 and o7 from 9 am to 1 pm.*

- $f^{tem}(e) = O \quad \leftarrow \quad e = \langle t, j, D \rangle \wedge$
  $absent(start, end, O) \wedge$
  $start \leq t \leq end.$
- $f^{tem}(e) = \{\} \quad \leftarrow \quad e = \langle t, j, D \rangle \wedge$
  $(all\ s, e)\ [absent(s, e, O)$
  $\rightarrow (t < s \vee t > e)]$

- Need to generalize this approach to reflect the fuzzy nature of schedule timings

Distance Scores to Probability

- Calculate probabilities $\{<o_i, p_{jk}(o_i)>\}$ from the distance scores on the reduced database
  - *g: Scores x Database → Probabilities*
    - $p_k = g(db_k, e_k)$

$$p(O/d) = \frac{e^{\frac{-d^2}{2\sigma^2}}}{\sum e^{\frac{-d^2}{2\sigma^2}}}$$

Summation across distance scores in the database

- O: Occupant
- d : Distance Score for Occupant
- σ : Standard Deviation of the Distance Scores

Precision (Π)

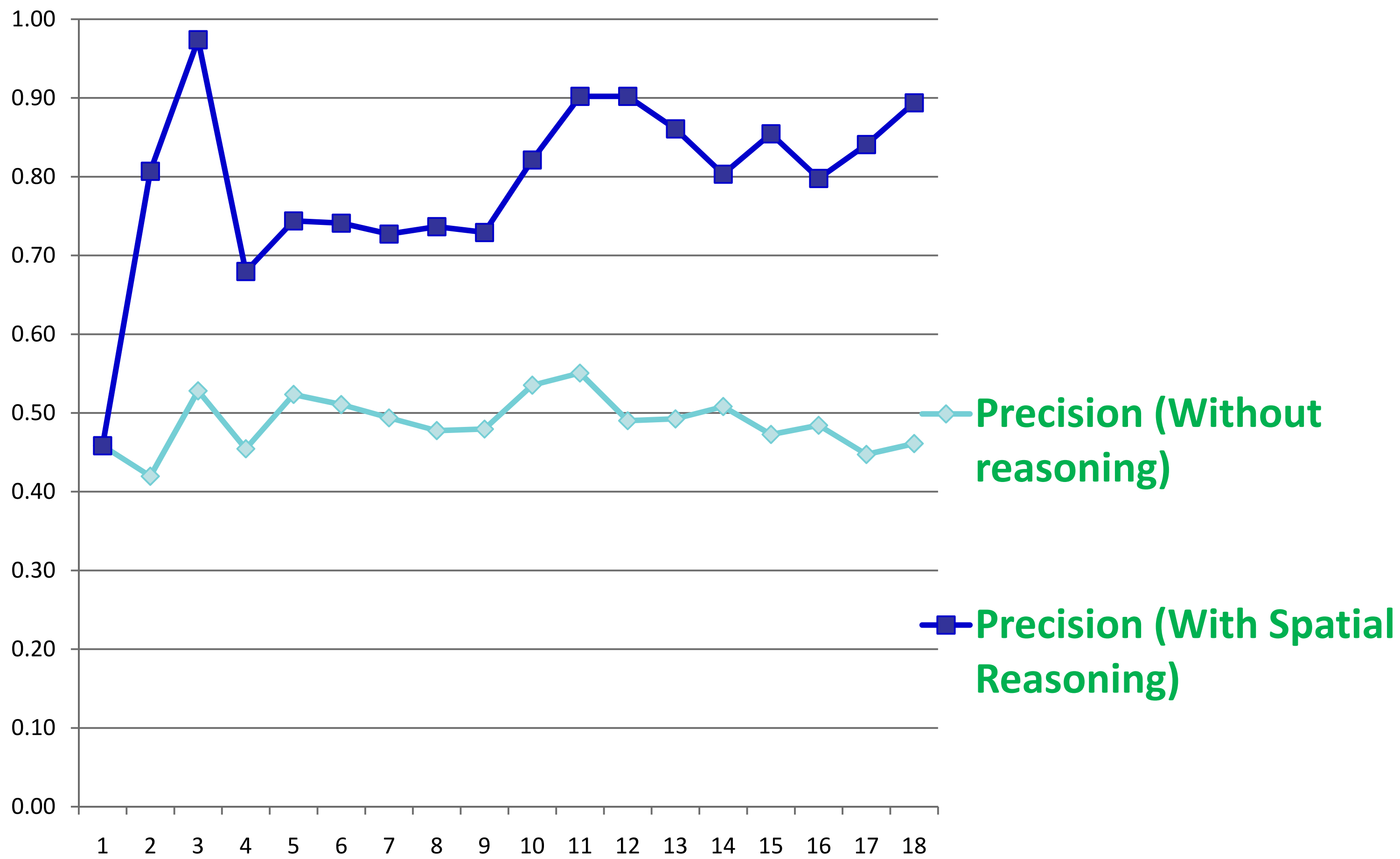
(with Spatial Reasoning)

	State : s18					
Occupants	Z1	Z2	Z3	Z4	Z5	Z6
O1	0.03	0.00	0.00	0.00	0.00	0.97
O2	0.00	0.00	0.00	0.00	0.00	1.00
O3	0.00	0.00	0.00	1.00	0.00	0.00
O4	0.10	0.00	0.00	0.00	0.00	0.90
O5	0.00	0.00	0.04	0.00	0.96	0.00
O6	0.10	0.19	0.46	0.00	0.00	0.25
O7	0.14	0.00	0.00	0.00	0.00	0.86
O8	0.14	0.23	0.54	0.00	0.00	0.09
O9	0.00	0.00	0.00	0.00	0.00	1.00
O10	0.01	0.07	0.91	0.00	0.00	0.00
O11	0.32	0.00	0.00	0.00	0.00	0.68
O12	0.00	0.00	0.00	0.00	0.00	1.00
O13	0.26	0.12	0.00	0.00	0.00	0.62
O14	0.08	0.00	0.00	0.00	0.00	0.92
O15	0.03	0.00	0.00	0.00	0.00	0.97
O16	0.22	0.13	0.00	0.00	0.00	0.65
O17	0.00	0.00	0.00	0.00	0.00	1.00
O18	0.00	0.00	0.00	0.00	0.00	1.00
O19	0.01	0.00	0.00	0.00	0.00	0.99
O20	0.02	0.00	0.00	0.00	0.00	0.98
O21	0.01	0.00	0.00	0.00	0.00	0.99
O22	0.04	0.00	0.00	0.00	0.00	0.96
O23	0.12	0.00	0.00	0.00	0.00	0.87
O24	0.33	0.23	0.01	0.00	0.00	0.43
O25	0.02	0.00	0.00	0.00	0.00	0.98
	Ground Truth - O3, O5, O10, O8					

	State : s18					
	Z1	Z2	Z3	Z4	Z5	Z6
				1.00		
					0.96	
			0.54			
			0.91			
	Ground Truth - O3, O5, O10, O8					
ajk			1.45	1.00	0.96	
bjk			2	1	1	
pjk			0.73	1.00	0.96	
m	3					
pk	0.89					

Π = 0.46 -> 0.89

Precision – 18 events



Recall (ρ)

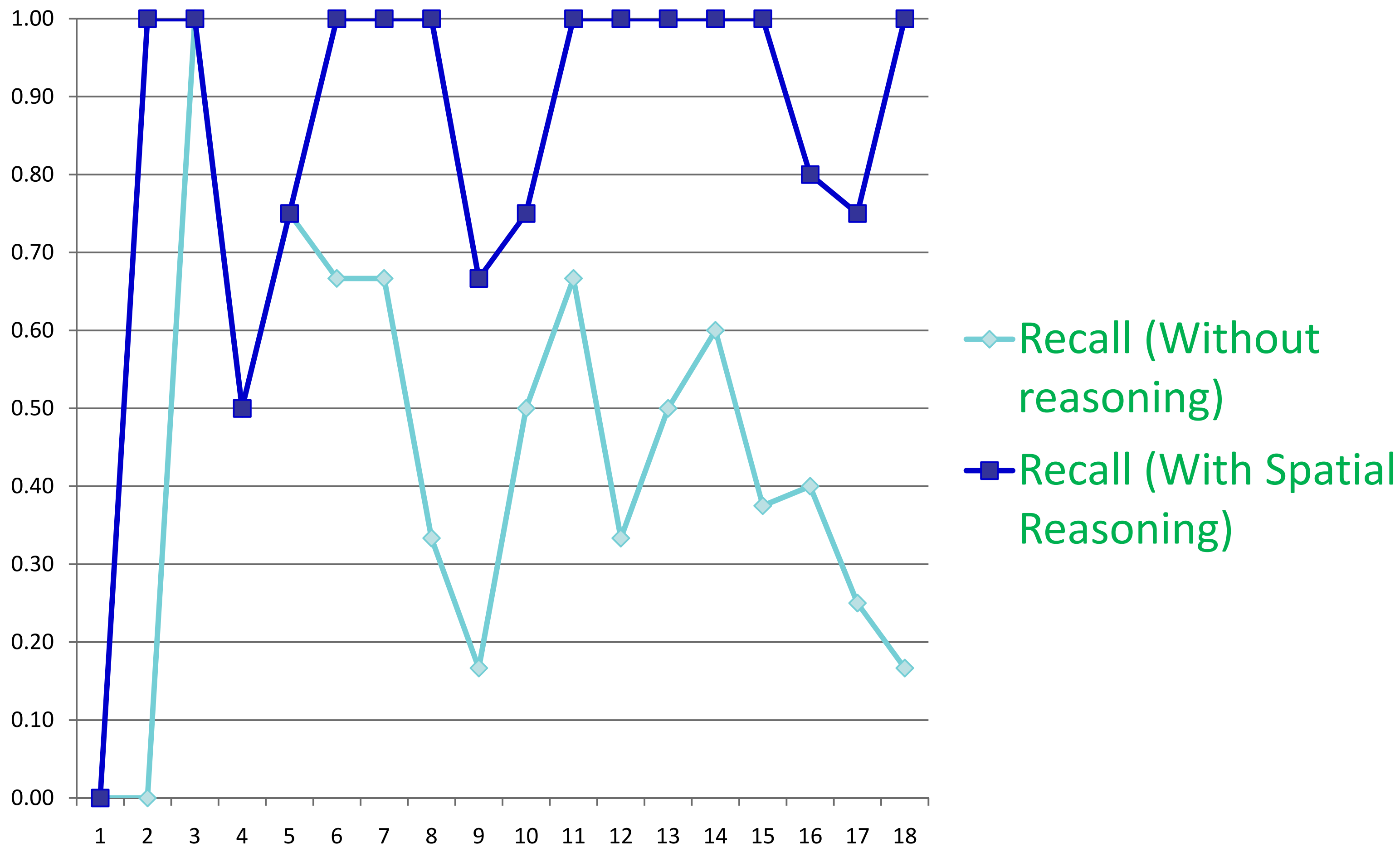
(with Spatial Reasoning)

	State : s18					
Occupants	Z1	Z2	Z3	Z4	Z5	Z6
O1	0.03	0.00	0.00	0.00	0.00	0.97
O2	0.00	0.00	0.00	0.00	0.00	1.00
O3	0.00	0.00	0.00	1.00	0.00	0.00
O4	0.10	0.00	0.00	0.00	0.00	0.90
O5	0.00	0.00	0.04	0.00	0.96	0.00
O6	0.10	0.19	0.46	0.00	0.00	0.25
O7	0.14	0.00	0.00	0.00	0.00	0.86
O8	0.14	0.23	0.54	0.00	0.00	0.09
O9	0.00	0.00	0.00	0.00	0.00	1.00
O10	0.01	0.07	0.91	0.00	0.00	0.00
O11	0.32	0.00	0.00	0.00	0.00	0.68
O12	0.00	0.00	0.00	0.00	0.00	1.00
O13	0.26	0.12	0.00	0.00	0.00	0.62
O14	0.08	0.00	0.00	0.00	0.00	0.92
O15	0.03	0.00	0.00	0.00	0.00	0.97
O16	0.22	0.13	0.00	0.00	0.00	0.65
O17	0.00	0.00	0.00	0.00	0.00	1.00
O18	0.00	0.00	0.00	0.00	0.00	1.00
O19	0.01	0.00	0.00	0.00	0.00	0.99
O20	0.02	0.00	0.00	0.00	0.00	0.98
O21	0.01	0.00	0.00	0.00	0.00	0.99
O22	0.04	0.00	0.00	0.00	0.00	0.96
O23	0.12	0.00	0.00	0.00	0.00	0.87
O24	0.33	0.23	0.01	0.00	0.00	0.43
O25	0.02	0.00	0.00	0.00	0.00	0.98
	Ground Truth - O3, O5, O10, O8					

	State : s18					
	Z1	Z2	Z3	Z4	Z5	Z6
				1.00		
					0.96	
			0.54			
			0.91			
	Ground Truth - O3, O5, O10, O8					
ajk			2	1	1	
bjk			2	1	1	
rjk			1.00	1.00	1.00	
m	3					
rk	1.00					

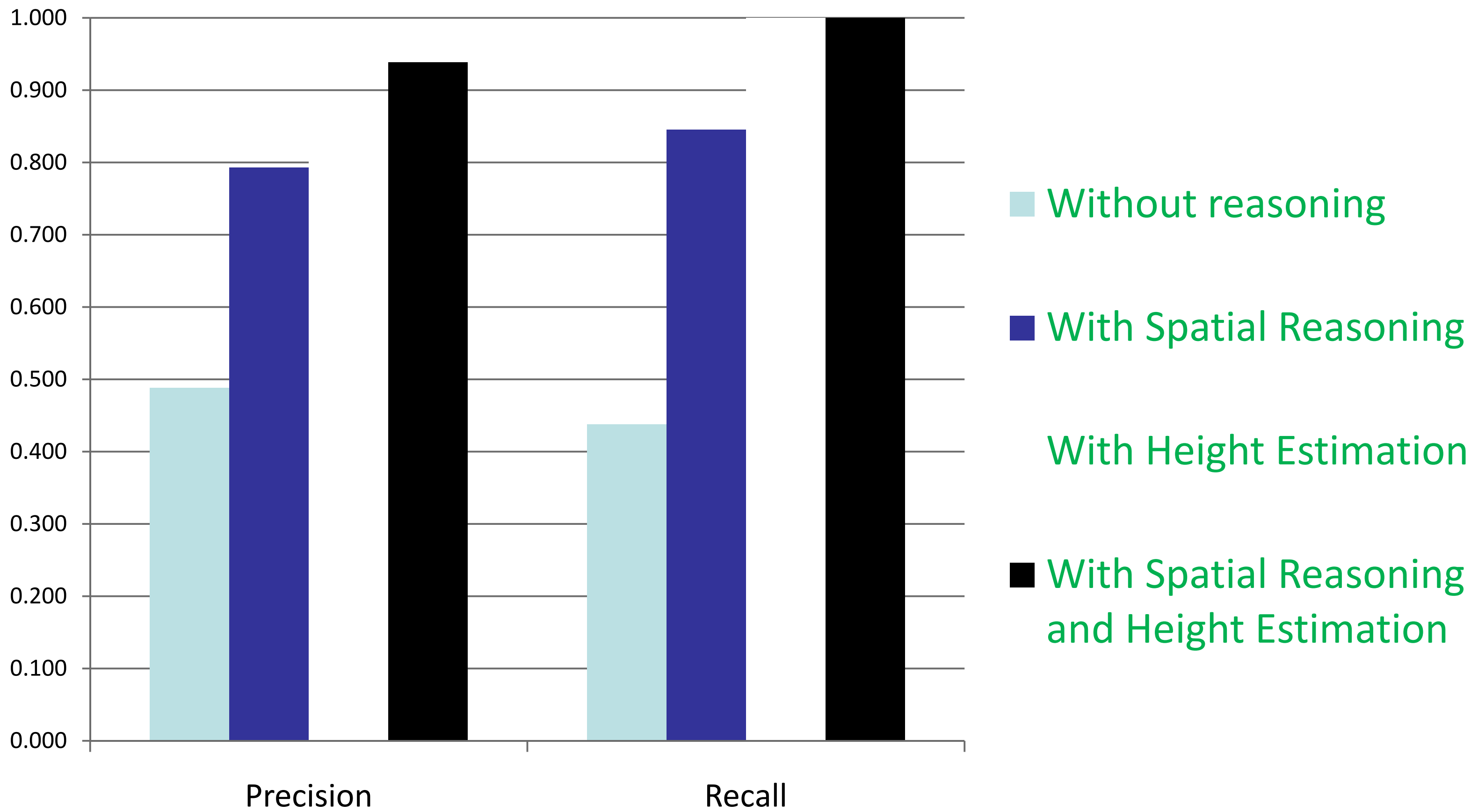
$\rho = 0.17 \text{ -> } 1$

Recall - 18 events



Overall Improvements

18 events



Summary

- A novel framework using state transitions for non-obtrusive biometric-based indoor smart environments.
- A characterization of the performance of the smart environment using concepts of precision and recall.
- Improvements in the performance metrics by integrating reasoning and recognition.

- Events → Recognition
- Transition Function → Reasoning
- State → Retrieval

3 R's of Smart Environments

Future work

- Evolutionary learning
- Back-propagation of information
- Error propagation
- Fuse biometric recognizers, such as gait, voice, etc.
- Test on larger environments and different layouts
- Support speech-based information retrieval queries