Touch attention Bayesian models for robotic active haptic exploration

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→ Motivation:

•**New generation of robotic platforms:** high diversity of sensory (touch, vision, audition) and actuation apparatus (dexterous robotic hands, arms and legs);

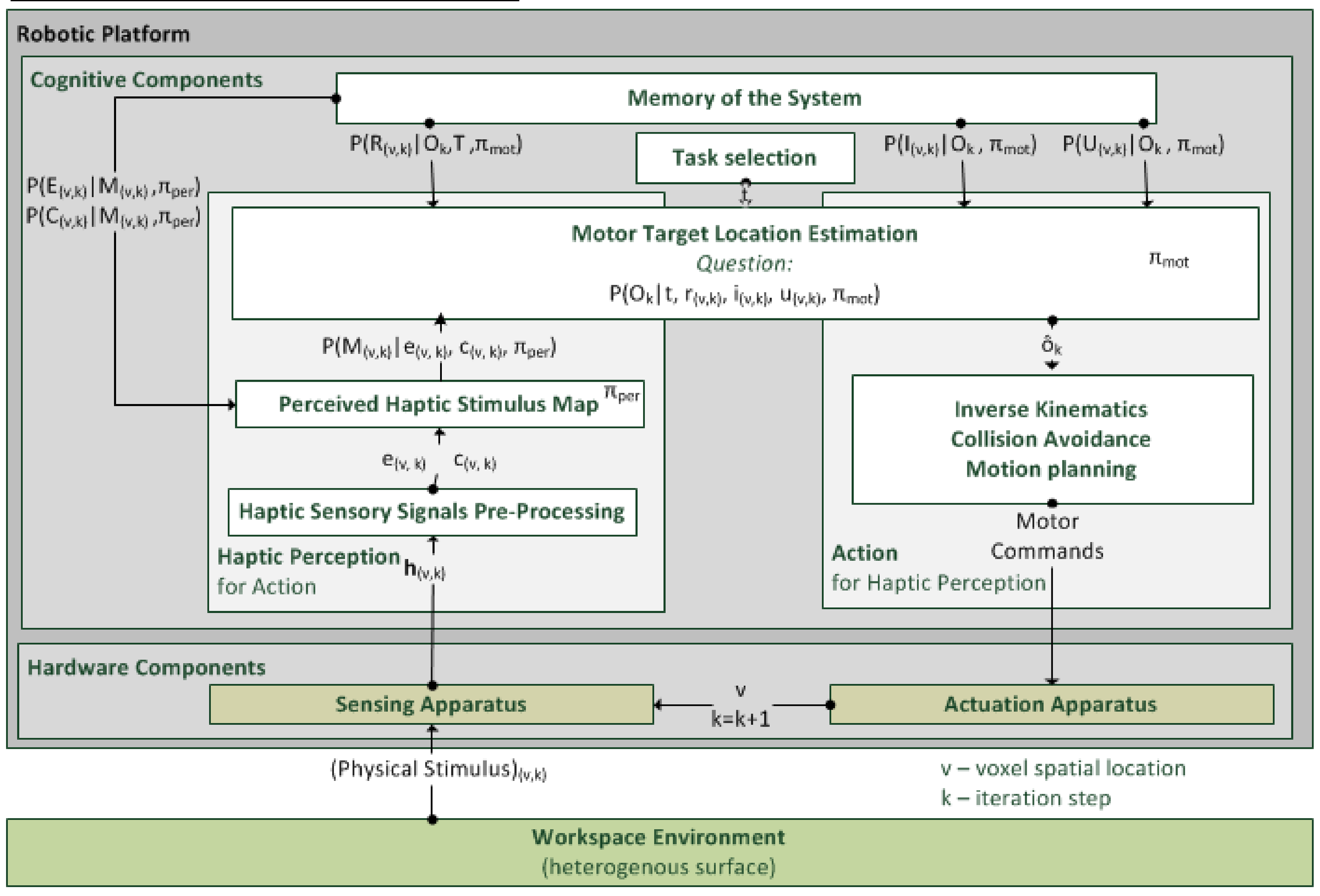
•**Challenging application environments:** unknown and dynamic structure;

•**Development of touch attention mechanisms:**

-Evaluation of the relevance of the haptic stimulus perceived during the robotic blind exploration of surfaces.

-Determination of the robotic motor reaction to the perceived haptic stimulus.

→ Proposed Approach:

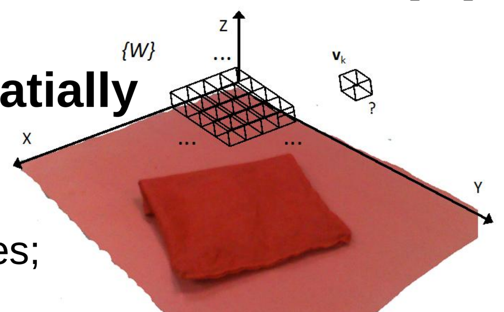


•**The approach integrates information from**:

-**Top-down mechanisms** (information related with the task objective).

-**Bottom-up mechanisms** (relevant characteristics of the stimulus emerging from the environment).

•**The workspace of the robotic system is spatially partitioned in a inference grid:**



-Integration of multimodal data;

-Discrimination of heterogeneous surfaces – discontinuities;

-Planning of motor actions;

v_k -voxel v at time iteration k ; ε - dimension of the cubic voxel

→ Motor Target Location Estimation (Bayesian Model π_{mot})

•Determination of the next workspace region to be explored based on the perceived haptic stimulus map estimated by the Bayesian Model π_{per} .

•**Bayesian Program:**

Program / Description / Specification

Relevant variables:

$O_k, T, R_{(v,k)}, U_{(v,k)}, I_{(v,k)}$

Decomposition:

$$P(O_k, T, R_{(v,k)}, U_{(v,k)}, I_{(v,k)}|\pi_{mot}) = \begin{pmatrix} P(O_k|\pi_{mot}) \\ P(T,\pi_{mot}) \\ P(I_{(v,k)}|O_k,\pi_{mot}) \\ P(U_{(v,k)}|O_k,\pi_{mot}) \\ P(R_{(v,k)}|O_k,T,\pi_{mot}) \end{pmatrix}.$$

Parametric forms:

$P(O_k|\pi_{mot}) \equiv Uniform$

$P(T|\pi_{mot}) \equiv Uniform$

$P(I_{(v,k)}|O_k,\pi_{mot}) \equiv \mathcal{B}(\alpha_I,\beta_I)$

$P(U_{(v,k)}|O_k,\pi_{mot}) \equiv \mathcal{B}(\alpha_U,\beta_U)$

$P(R_{(v,k)}|O_k,T,\pi_{mot}) \equiv \mathcal{B}(\alpha_R,\beta_R)$

Identification:

α_R,β_R - *Empirical values*

α_I,β_I - *Empirical values*

α_U,β_U - *Empirical values*

Question:

$P(O_k|t, r_{(v,k)}, u_{(v,k)}, i_{(v,k)}, \pi_{mot})$

Decision criteria: *MAP - Maximum a posteriori.*

$\hat{o}_k = \arg\max_{o_k} P(O_k|t, r_{(v,k)}, u_{(v,k)}, i_{(v,k)}, \pi_{mot})$

T–"Task objectives", T ∈ {Task$_1$, …, Task$_\Phi$}

$I_{(v,k)}$ – "Inhition level for cell v", $I_{(v,k)} \in [0, 1]$

$$I_{(v,k)} = 1 - \Theta d^{\alpha-1}(1|-d)^{1-\beta}, \quad d = \frac{d_k}{d_{max}} \quad \alpha=1{,}01 \; \beta=9$$

$U_{(v,k)}$ – "Uncertainty level for cell v", $U_{(v,k)} \in [0, 1]$

$$U_{(v,k)} = \frac{\mathcal{H}(M_{(v,k)})}{max(\mathcal{H}(M_{(v,k)}))}$$

$R_{(v,k)}$ – "Relevance of the haptic stimulus in a 26-th neighborhood region around v", $R_{(v,k)} \in [0, 1]$

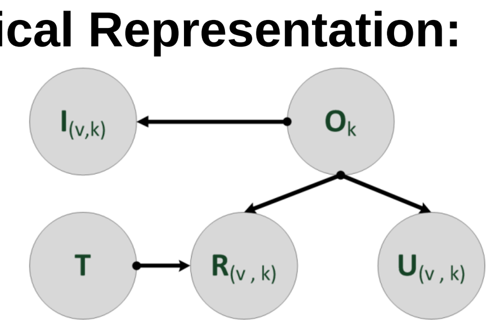
$$r = \frac{\max(|r_x|,|r_y|,|r_z|)}{r_{norm}} \quad r_x = \mathcal{G}_{sobel_x}(\mathbf{d}), s_y = \mathcal{G}_{sobel_y}(\mathbf{d}), \; r_z = \mathcal{G}_{sobel_z}(\mathbf{d})$$

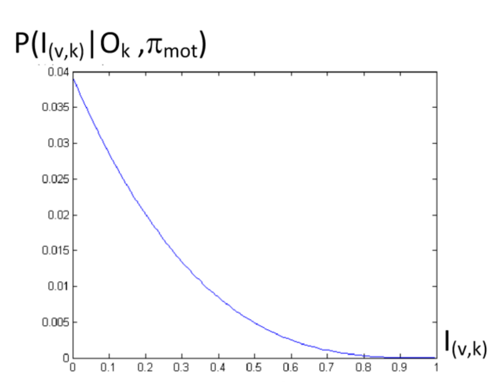
$$\mathbf{d} = (\Omega_{(v0,k)}, \ldots, \Omega_{(v26,k)})$$

$$\Omega_{(vi,k)} = \frac{1 - \begin{pmatrix} P(M_{(vi,k)} = Material_a|e_{(vi,k)}, c_{(vi,k)}, \pi_{per}) \\ P(M_{(vi,k)} = Material_b|e_{(vi,k)}, c_{(vi,k)}, \pi_{per}) \end{pmatrix} + }{2}$$

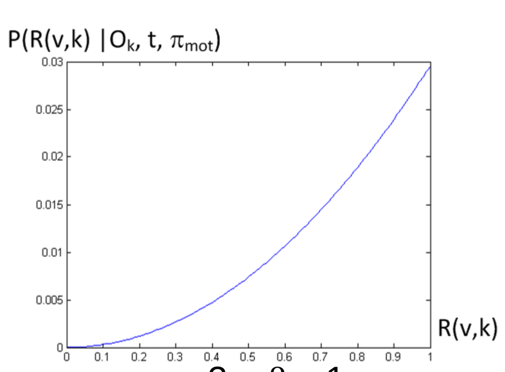
O_k–"Next workspace region to be explored"",

•**Graphical Representation:**

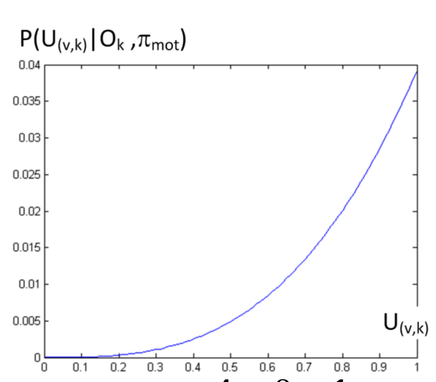




α_I=1 β_I=4



α_R=3 β_R=1



α_U=4 β_U=1

Xu, D., Loeb, G.E., Fishel, J.A.: Tactile identication of objects using bayesian exploration. In: IEEE -ICRA 2013. (2013)

→ Perceived Haptic Stimulus Map (Bayesian Model π_{per})

•Determination of the perceived category of material of the voxel v of the workspace based on the haptic sensory input $\mathbf{h}_{(v,k)}$.

•**Bayesian Program:**

Program / Description / Specification

Relevant variables:

$E_{(v,k)}, C_{(v,k)}, M_{(v,k)}$

Decomposition:

$$P(E_{(v,k)}, C_{(v,k)}, M_{(v,k)}|\pi_{per}) = \begin{pmatrix} P(E_{(v,k)}|M_{(v,k)},\pi_{per}) \\ P(C_{(v,k)}|M_{(v,k)},\pi_{per}) \\ P(M_{(v,k)}|\pi_{per}) \end{pmatrix}.$$

Parametric forms:

$P(E_{(v,k)}|M_{(v,k)},\pi_{per}) \sim \mathcal{N}(\mu_E(M),\sigma_E(M))$

$P(C_{(v,k)}|M_{(v,k)},\pi_{per}) \sim \mathcal{N}(\mu_C(M),\sigma_C(M))$

For $k = 0$:

Map initialization.

$P(M_{(v,0)}|\pi_{per}) \sim$ *Uniform*

For $k > 0$:

Map update using previous state information.

$P(M_{(v,k)}|\pi_{per}) = P(M_{(v,k-1)}|e_{(v,k-1)}, c_{(v,k-1)}, \pi_{per})$

Identification:

$\mu_E(M), \sigma_E(M), \mu_C(M), \sigma_C(M)$

- *Demonstrations in learning stage.*

Question:

$P(M_{(v,k}|e_{(v,k)}, c_{(v,k)}, \pi_{per})$

$$P(M_{(v,k)}|e_{(v,k)}, c_{(v,k)}, \pi_{per}) = \frac{\begin{pmatrix} P(e_{(v,k)}|M_{(v,k)},\pi_{per}) \\ P(c_{(v,k)}|M_{(v,k)},\pi_{per}).P(M_{(v,k)},\pi_{per}) \end{pmatrix}.}{\sum_{M_{(v,k)}} \begin{pmatrix} P(e_{(v,k)}|M_{(v,k)},\pi_{per}) \\ P(c_{(v,k)}|M_{(v,k)},\pi_{per}).P(M_{(v,k)},\pi_{per}) \end{pmatrix}.}$$

$M_{(v,k)}$ –"Material category of v"

$M_{(v,k)} \in$ {Material$_1$, …, Material$_n$}

$E_{(v,k)}$ – "Texture characterization of v"

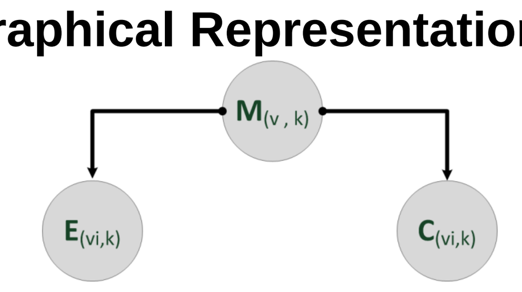
$E_{(v,k)} = f(\mathbf{h}_{(v,k)})$, $E_{(v,k)} \in \mathbb{R}$

$C_{(v,k)}$ – "Compliance characterization of v"

$C_{(v,k)} = g(\mathbf{h}_{(v,k)})$, $C_{(v,k)} \in \mathbb{R}$

f and *g* described in [Xu et al, 2013]

•**Graphical Representation:**

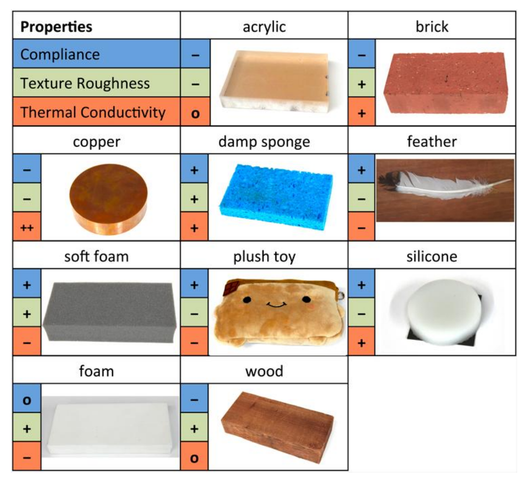


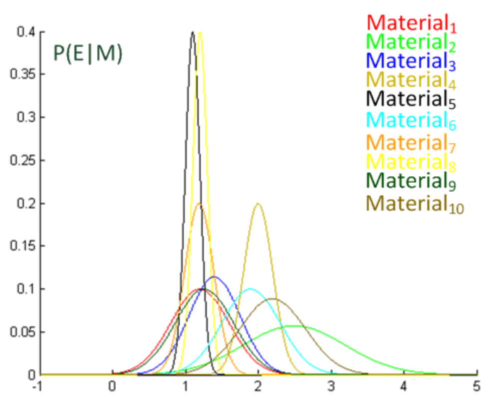
→ Experimental results

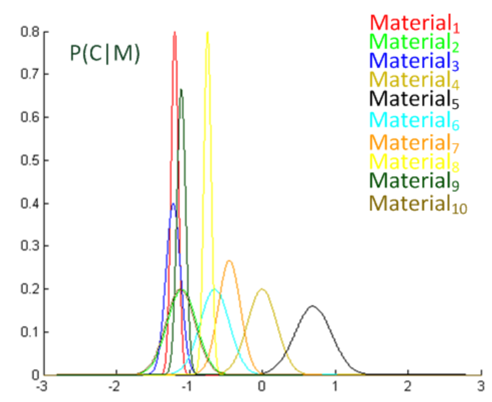
•**Learning of $P(E_{(v,k)} | M_{(v,k)}, \pi_{per})$ and $P(C_{(v,k)} | M_{(v,k)}, \pi_{per})$**

-Set of 10 different reference materials explored in 5 training trials.

-$\mu_E(M)$, $\sigma_E(M)$ and $\mu_C(M)$, $\sigma_C(M)$ extracted from the training data. [Xu et al, 2013]







•**Recognition performance of Bayesian model π_{mot} :**

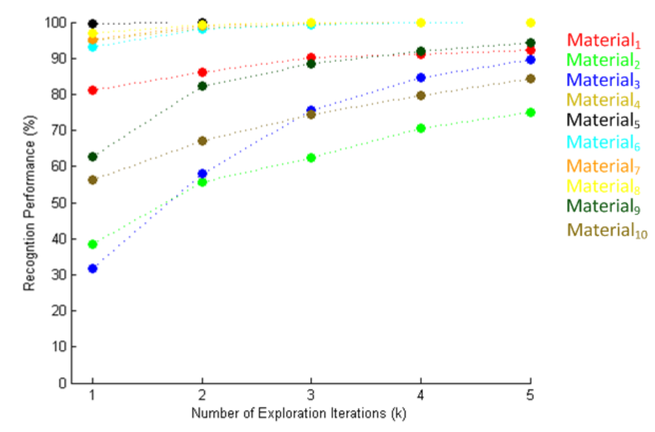
-400 blind exploration trials for each of the 10 reference materials;

-Classification of the material after k=1, 2, 3, 4, 5 time iterations (sensory integration);

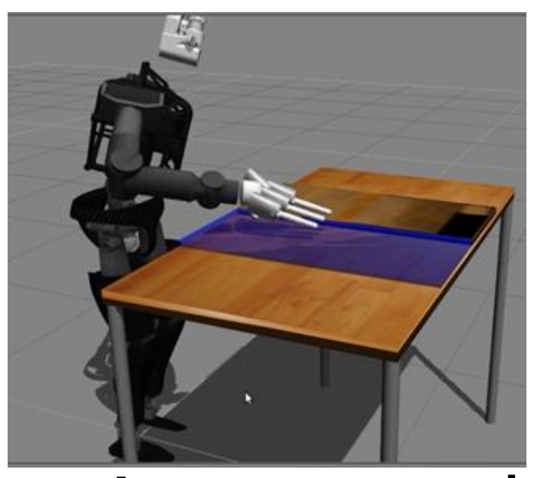
$m_{(v,k)}$ = *argmax* $P(M_{(v,k)} | e_{(v,k)}, c_{(v,k)}, \pi_{per})$

-High recognition performance;

-Recognition performance increases with the sensory integration period.



•**Autonomous blind exploration of the workspace:**

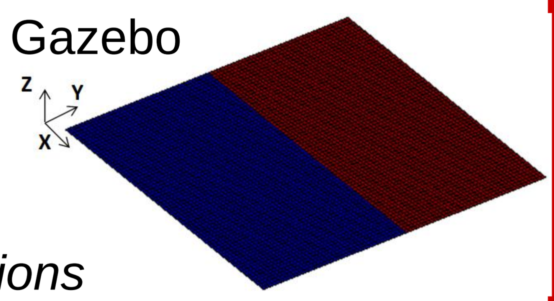


-**Simulation environment:** Gazebo

-**Robotic platform**: ATLAS

-**Task:** T = t =

"Search and follow of discontinuities between regions with Material8 (blue silicone) and Material10 (wood)"



-**Autonomous exploration path – Demo**

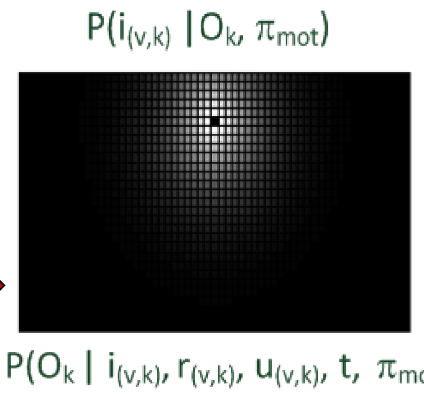
Full videos available at *www.isr.uc.pt/~rmartins/reacts2013*

-**Example: Estimation of next region to be explored at k=20**

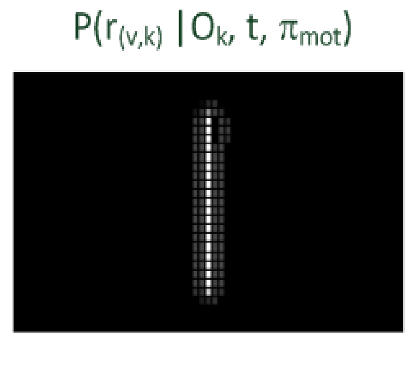
Initialization:
k=0
v=(25,30,1)

k=19
end-effector
at v=(7,30,1)

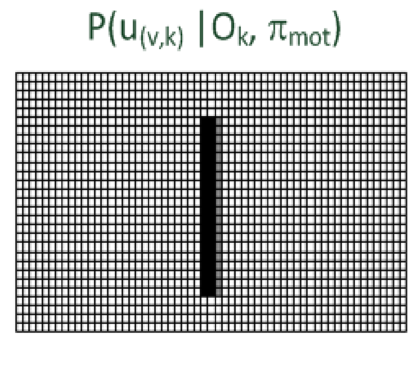
$P(i_{(v,k)} | O_k, \pi_{mot})$



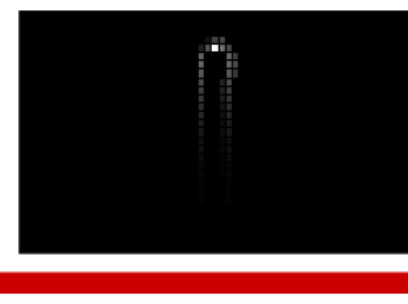
$P(r_{(v,k)} | O_k, t, \pi_{mot})$



$P(u_{(v,k)} | O_k, \pi_{mot})$



$P(O_k | i_{(v,k)}, r_{(v,k)}, u_{(v,k)}, t, \pi_{mot})$



$$\hat{o}_k = \arg\max_{o_k} P(O_k|t, r_{(v,k)}, i_{(v,k)}, u_{(v,k)}, \pi_{mot})$$

$$\hat{o}_k = \arg\max_{o_k} \begin{pmatrix} P(t|\pi_{mot}).P(i_{(v,k)}|O_k,\pi_{mot}) \\ P(r_{(v,k)}|O_k,t,\pi_{mot}).P(u_{(v,k)}|O_k,\pi_{mot}) \end{pmatrix}.$$

Next region to be explored $\hat{o}_{20}$=(6,30,1)

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