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D2A-BSP: Distilled Data Association Belief Space Planning with Performance Guarantees Under Budget Constraints

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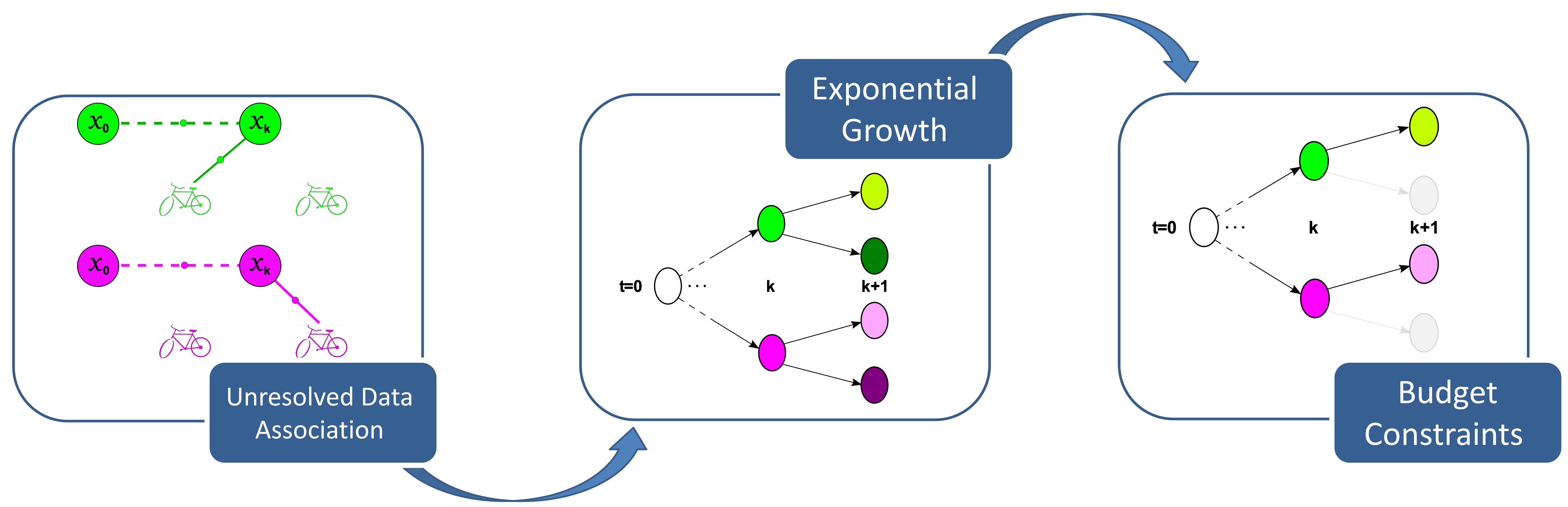
Motivation



- ❑ In ambiguous and perceptually aliased environments agents cannot assume that data association is solved
- ❑ Explicitly considering all possible data associations, the number of hypotheses grows exponentially
- ❑ Under hard computational budget constraints, some hypotheses must eventually be pruned
- ❑ There are typically no guarantees on the loss in solution quality in planning

Our Contributions

- **D2A-BSP** — A novel planning approach that utilizes only a distilled subset of hypotheses
- **Bounds** — Over the true analytical solution considering all possible hypotheses
- **Budget Free** — Use bounds to reduce computational complexity while preserving action selection
- **Budget Constraints** — Use bounds to provide performance guarantees under budget constraints

Problem Formulation

❑ Considering Data Associations, the belief at time k is a linear combination of $M_k \in \mathbb{N}$ weighted hypotheses

$$b_k = \sum_{j=1}^{M_k} \underbrace{\mathbb{P}\left(x_k | \beta^j_{1:k}, H_k\right)}_{b^j_k} \underbrace{\mathbb{P}\left(\beta^j_{1:k} | H_k\right)}_{w^j_k},$$

❑ The goal of Belief Space Planning is to find the optimal action sequence with respect to a user defined objective function

$$u^*_{k:k+N-1} = \underset{\mathcal{U}}{\text{argmin}}\, J\left(b_k, u_{k:k+N-1}\right)$$

❑ Our goal is to solve an easier problem that bounds the objective function using a *simplified* belief and provides performance guarantees $\underline{J}\left(b_k, b^s_k, u_k\right) \leq J\left(b_k, u_k\right) \leq \bar{J}\left(b_k, b^s_k, u_k\right)$

Approach

Simplified Belief — Select a subset of hypotheses

❑ The *simplified* belief at time step k is defined by the selected distilled subset of hypotheses of size M^s_k as $b^s_k \triangleq \sum_{j=1}^{M^s_k} w^{s,j}_k b^j_k$, $w^{s,j}_k \triangleq \frac{w^j_k}{w^{m,s}_k}$. Weights are re-normalized according to $w^{m,s}_k \triangleq \sum_{m \in M^s_k} w^m_k$

Cost Function — For autonomous active disambiguation of hypotheses

❑ An information theoretic term over data association hypotheses weights using the Shannon entropy $\mathcal{H} \triangleq -\sum_{i=1}^{n} w^i log\left(w^i\right)$

Bounds — Analytically developed for the considered cost function

❑ In the myopic case, the considered cost function is bounded by

$$\mathcal{LB}\left[c\left(b_{k+1}\right)\right] \triangleq \mathcal{LB}\left[\mathcal{H}\right] = \frac{\eta^s w^{m,s}_k}{\mathcal{UB}\left[\eta\right]}\left[\mathcal{H}^s - log(\eta^s)\right] - \frac{w^{m,s}_k}{\mathcal{UB}\left[\eta\right]} \sum_i^{|L|} \sum_j^{M^s_k} \tilde{\zeta}^{i,j}_{k+1} w^{s,j}_k log\left(\frac{w^{m,s}_k}{\mathcal{LB}\left[\eta\right]}\right),$$

$$\mathcal{UB}\left[c\left(b_{k+1}\right)\right] \triangleq \mathcal{UB}\left[\mathcal{H}\right] = \frac{\eta^s w^{m,s}_k}{\mathcal{LB}\left[\eta\right]}\left[\mathcal{H}^s - log(\eta^s)\right] - \frac{w^{m,s}_k}{\mathcal{LB}\left[\eta\right]} \sum_i^{|L|} \sum_j^{M^s_k} \tilde{\zeta}^{i,j}_{k+1} w^{s,j}_k log\left(\frac{w^{m,s}_k}{\mathcal{UB}\left[\eta\right]}\right) - \gamma log\left(\frac{\gamma}{|L|\,|\neg M^s_k|}\right)$$

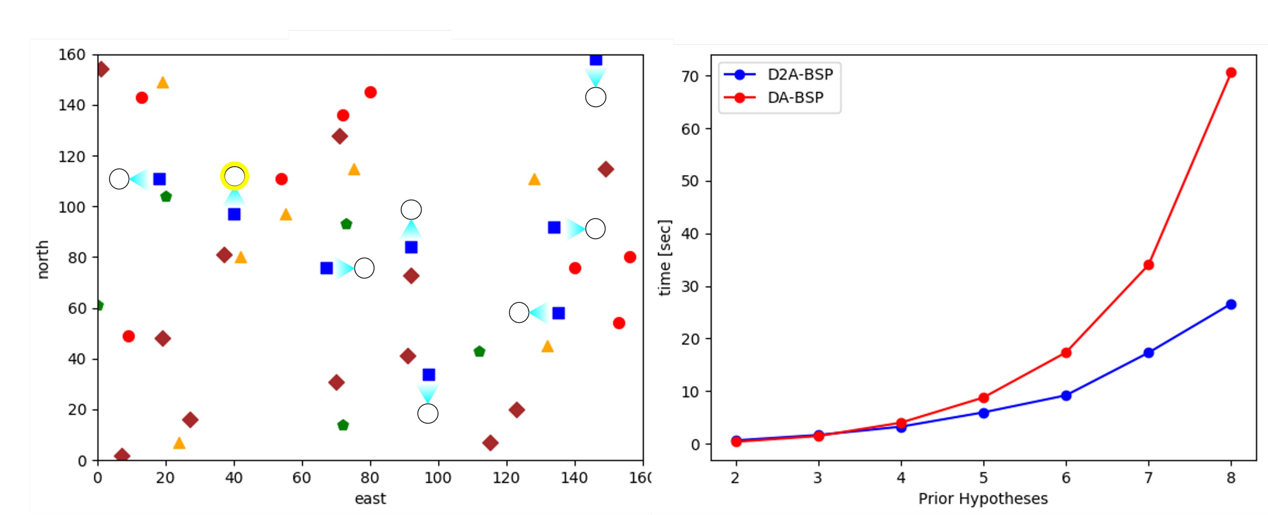
❑ For each candidate action, the bounds over the objective function are evaluated given the *simplified* belief. With fewer hypotheses, the computational complexity is reduced

Performance Guarantees — Derived from bounds

❑ Planning using these bounds we can either guarantee to select the same optimal action as in the original problem or derive a loss on the quality of the solution when bounds overlap

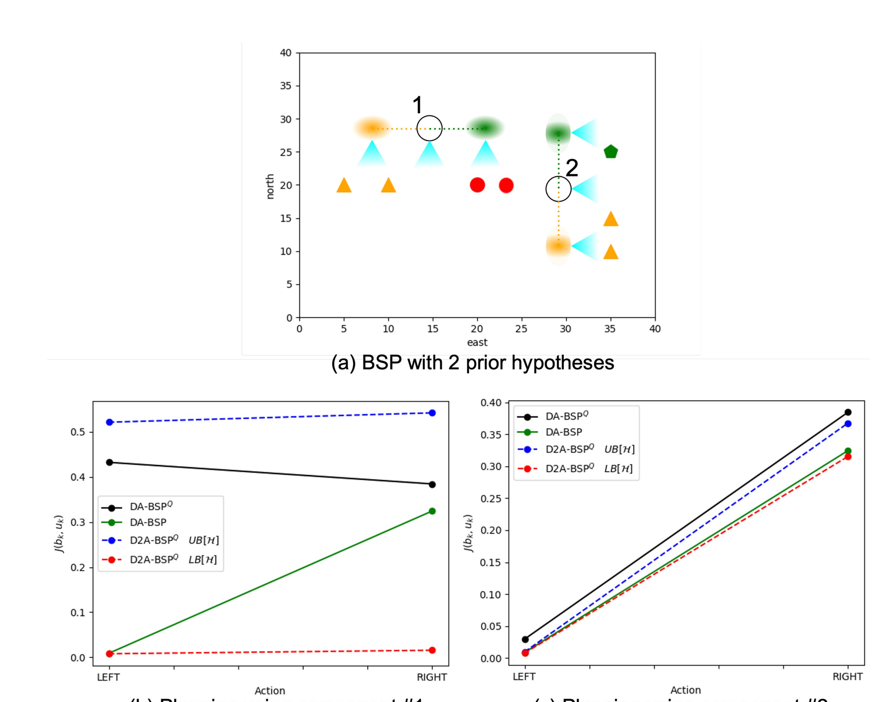
Results

Goal — Fully disambiguate between all prior hypotheses (no budget constraints)



- ❑ A kidnapped robot scenario
- ❑ The initial belief is multi-modal
- ❑ The agent's goal is to fully disambiguate between hypotheses
- ❑ The higher the level of ambiguity within the environment, the more prominent our approach becomes

Goal — Disambiguate between hypotheses (weighted equally) under budget constraints



- ❑ While DA-BSP can only rely on heuristics to decide which hypothesis to use
- ❑ Our approach can guarantee that going left is the optimal action as the bounds do not overlap