

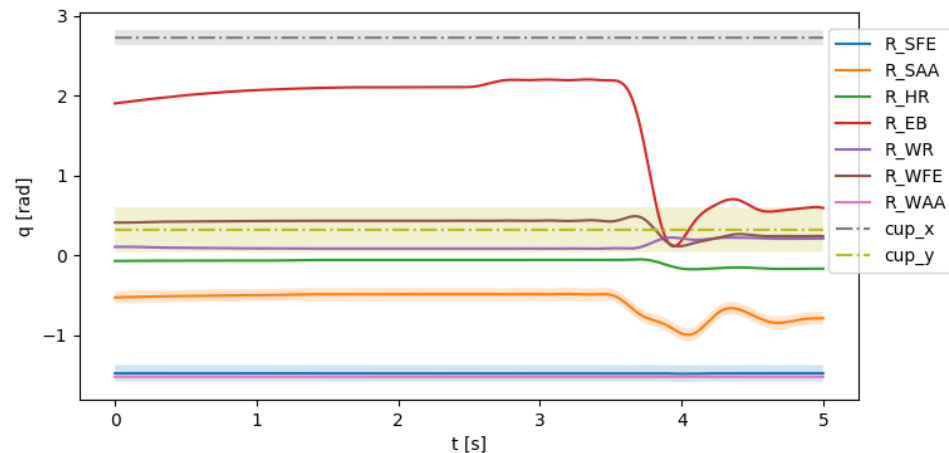
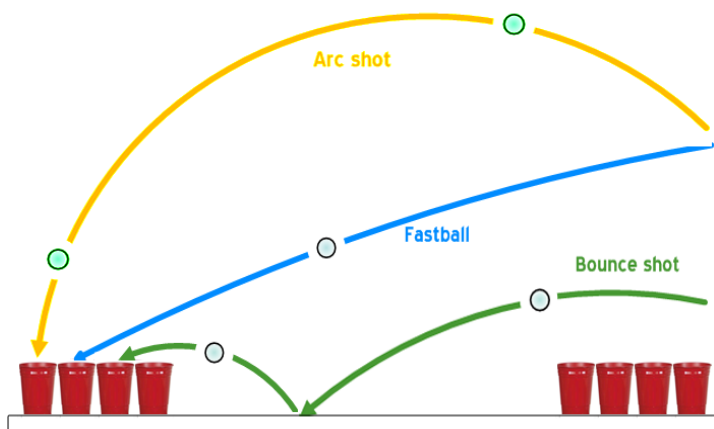
Generalizing to New Cup Positions in the Game of Beer Pong using Contextual ProMPs



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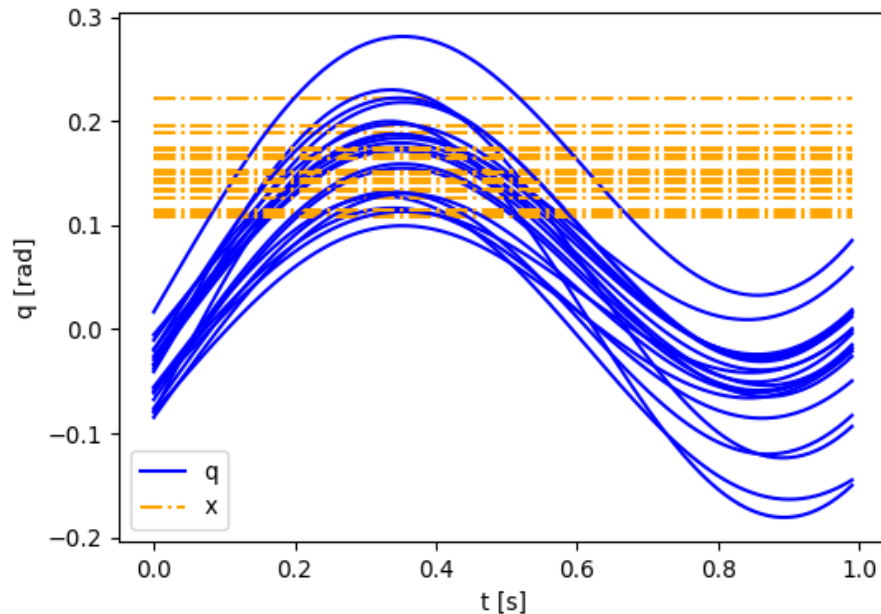
Probabilistic Movement Primitives (ProMPs)

- Probabilistic representation of several trajectories
- Represent a trajectory using Gaussian radial basis functions
 - $y_t = \Phi_t^T w + \epsilon_y$
- Probability of a trajectory τ
 - $p(\tau|w) = \prod_t N(y_t | \Phi_t^T w, \Sigma_y)$
- **Important properties:**
 - Probabilistic conditioning
 - Represent uncertainty

ProMPs: Conditioning

- Given
 - Set of demonstrations (joint trajectories)
 - Desired y_t^* (start-, goal- or via-point)
- Goal:
 - Find a trajectory going through y_t^*
- Assumption: Gaussian trajectory distribution
- Mean: $\mu_w^+ = \mu_w^- + \Sigma_w \Psi_t (\Sigma_y^* + \Psi_t^T \Sigma_w \Psi_t)^{-1} (y_t^* - \Psi_t^T \mu_w)$
- Variance: $\Sigma_w^+ = \Sigma_w^- \Psi_t (\Sigma_y^* + \Psi_t^T \Sigma_w^- \Psi_t)^{-1} \Psi_t^T \Sigma_w^-$

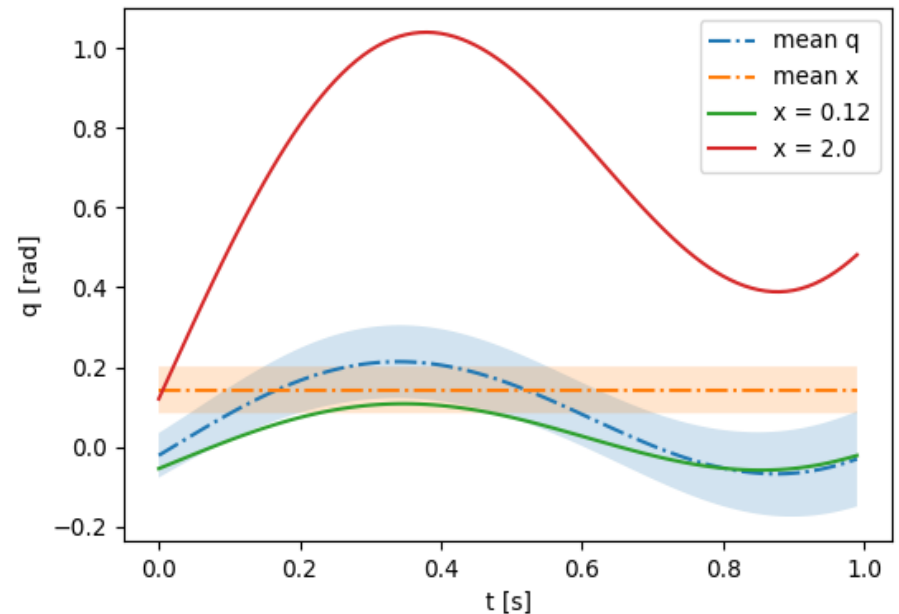
Contextual ProMPs: Toy Example With 1 Joint and 1 Context Variable



Set of demonstrations:

$$q = \sin(t) + N(\mu, \Sigma)$$

$$x \sim N(\mu, \Sigma)$$



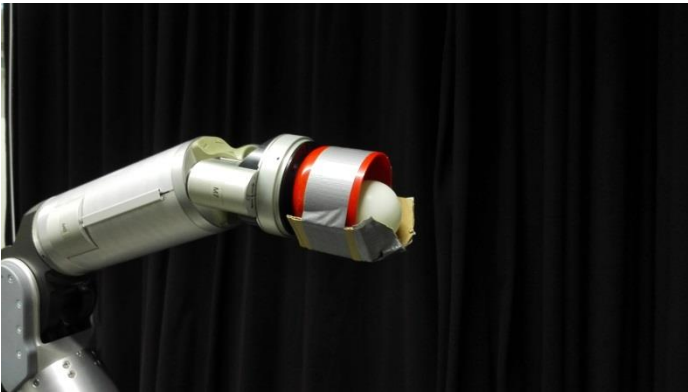
Mean & std context (orange stripe)

Mean & std joint (blue stripe)

Conditioning on $x = 0.12$ (green line)

Conditioning on $x = 2.0$ (red line)

Experimental Setup: Barrett WAM



- An end effector with cup and a simple holder attached to it
- Cup with markers for tracking

Problems and Preprocessing

- Problems
 - End effector too unstable
 - Filtering has been done too many times
- Preprocessing:
 - Obtain one trajectory demonstrated by a human and filter it
 - Move only the base joints to obtain more demonstrations



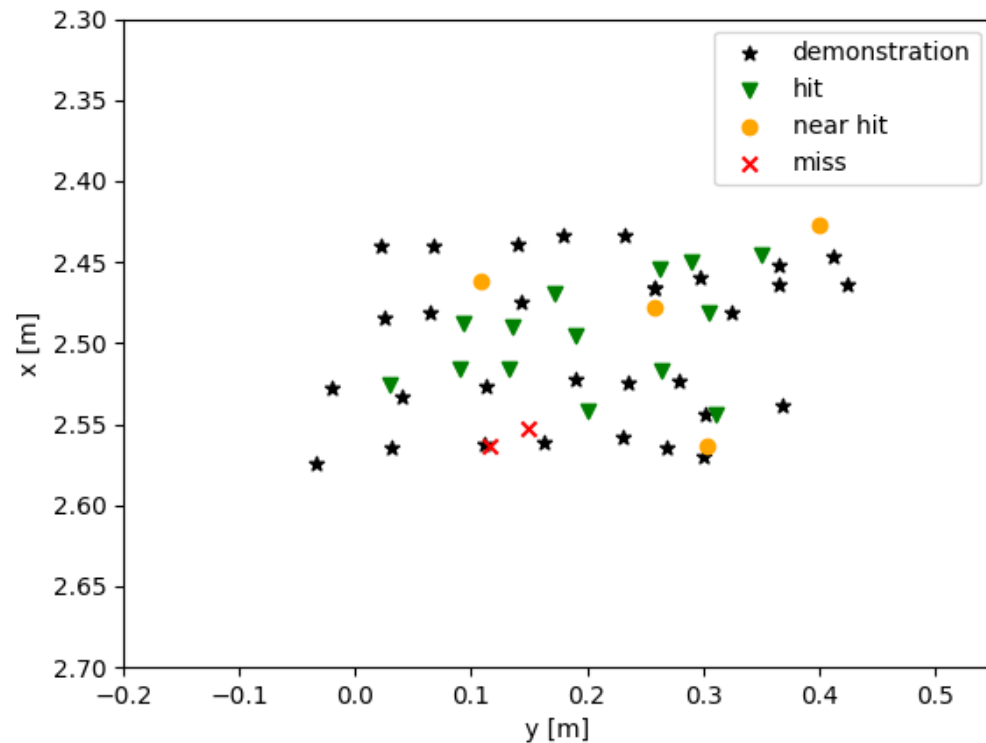
Video: Reference Throwing Movement



Generalizing to New Locations of the Cup Using Contextual ProMPs

- 31 demonstrations around one location
- Conditioning on the new location within demonstration's area

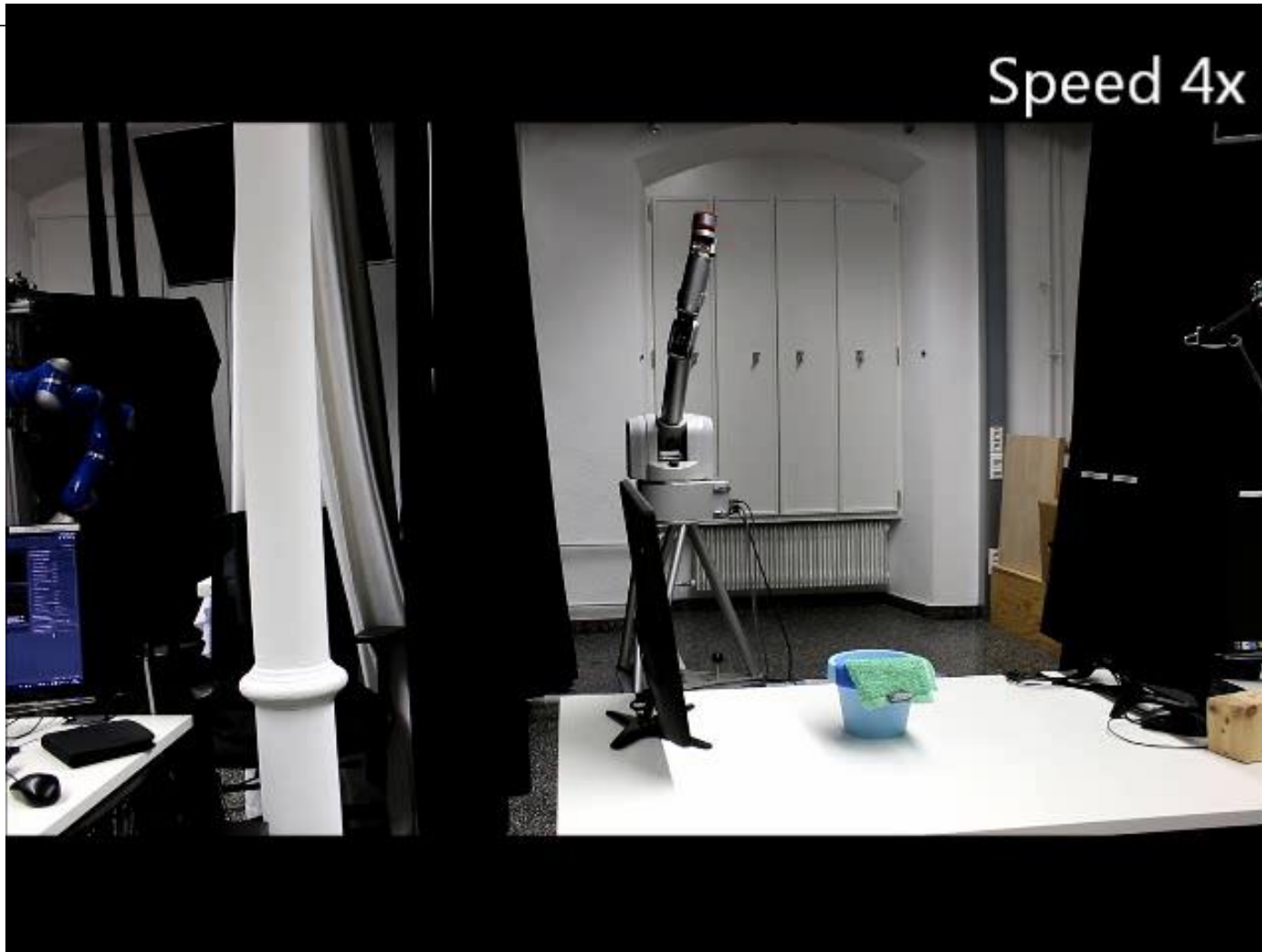
- 20 attempts
- 14 hits
- 4 near hits
- 2 misses



Video: Conditioning on New Cup Positions With Contextual ProMPs



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Contextual Linear Regression in the Weight-Space of ProMPs

- Motivation:
 - Improve performance of contextual ProMPs
 - Compare different representation of context:
 - CLR (plain representation): $c_t = \begin{bmatrix} x \\ y \end{bmatrix}$
 - Contextual ProMPs (approximation): $c_t = \Phi_t^T w_c + \epsilon_c$

Relationship Between the Mean of Contextual ProMPs and Contextual Linear Regression

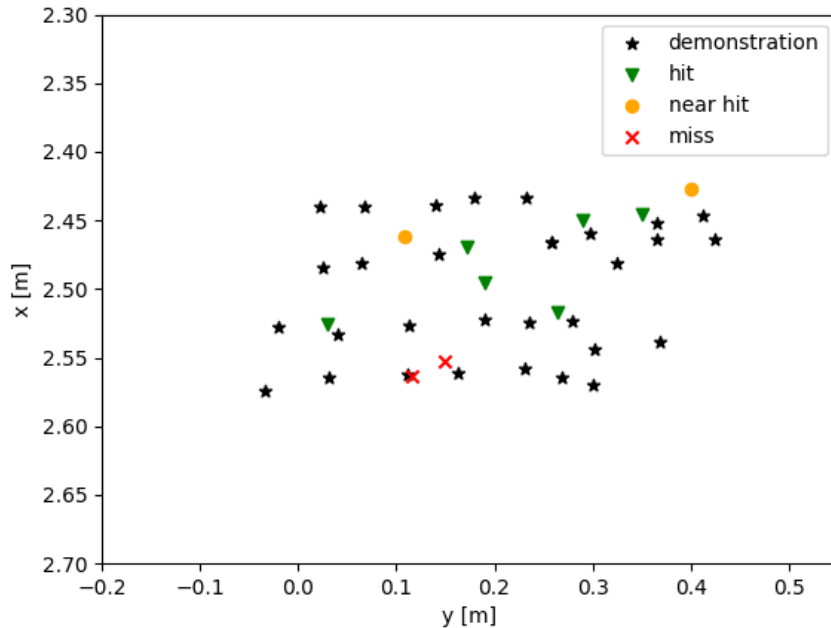
Contextual ProMPs

- $\begin{bmatrix} W \\ c \end{bmatrix} \sim N(\mu, \Sigma)$
- $\mu = Ac + b$
- $A = \Sigma_{wc} \Sigma_{cc}^{-1}$

Contextual Linear Regression

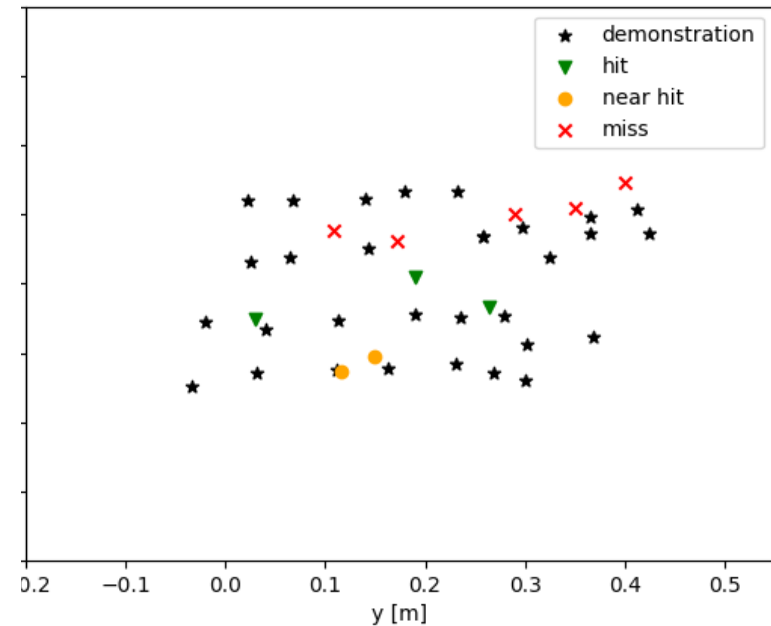
- $w = Ac + b$
- $J = \text{tr}\{(W - AC)^T (W - AC)\}$
- $A = WC^T (CC^T)^{-1}$

Contextual ProMPs vs. Linear Regression with ProMP Weights



Contextual ProMP

- 10 attempts
- 6 hits
- 2 near hits
- 2 misses

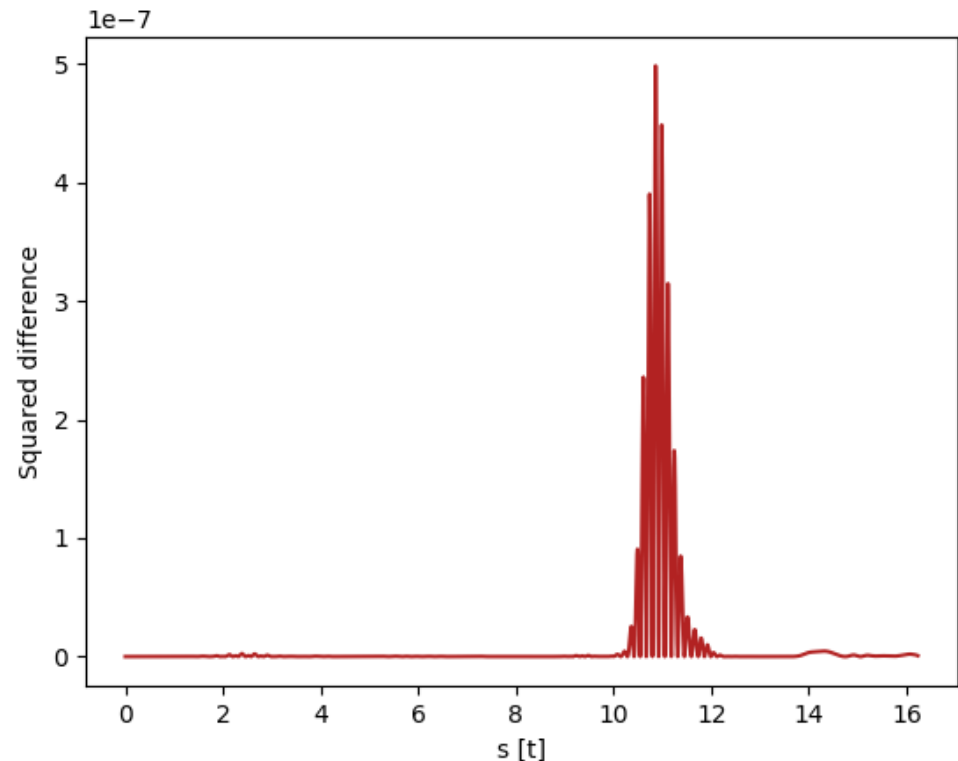


Linear Regression with ProMP weights

- 10 attempts
- 3 hits
- 2 near hits
- 5 misses

Linear Regression: ProMP Weights vs. DMP Weights

- Both produce almost the same resulting trajectory
- However, slight difference during throwing movement



Conclusion

- Contextual ProMP is better than using context variables directly (CLR)
- CLR-ProMP and CLR-DMP lead to same trajectories
 - Further investigation required
- Generalization to new cup positions achieved using contextual ProMPs
 - Still, some improvements are reasonable (next slide)

Future work

- **ProMPs**
 - Approximate trajectories adaptively
 - High number of basis functions only when needed
 - E.g., at high peaks during throwing movement
 - Better end effector
- **Model-based approach**
 - Generalize to new environments
- **Implementation of a full-game framework**