Orbitally Stable Motion Primitives (OSMPs)

Robot Embodiments

Robotic Manipulators   Helix Soft Robot

Crush Turtle Robot

Oracles/Demonstrations of Periodic Motions $x^{\mathrm{d}}(t)$

Kinesthetic Teaching

Biological Oracles

Oracle Space Position $x(t)$

Bijective Encoder $\Psi(x\,;z)$

$$y = \Psi(x\,;z)$$

x R^n y R^n

Latent Space Position $y(t)$

Supercritical Hopf Bifurcation $f_{\mathrm{y}}(y)$

Jacobian $\dfrac{\partial \Psi(x\,;z)}{\partial x}$

Encoder Training

Pullback $\dot{x}$ $\dot{y}$

Latent Space   Latent Space

Pullback $J_{\Psi}^{-1}(x\,;z)\,\dot{y}(t)$

$\dot{y}(t)$

Oracle Space Velocity $\dot{x}(t)$

Limit cycle

Predicted Velocity $\dot{x}(t)$

$\ominus$ $\mathrm{MSE}(\dot{x}, \dot{x}^{\mathrm{d}})$

Oracle Limit Cycle $x^{\mathrm{d}}(t)$ & Velocity $\dot{x}^{\mathrm{d}}(t)$

Encoder Conditioning on Motion Behavior

$z = 0$ Motion Behavior Conditioning z Gaussian Fourier Projection & MLP

$z = 1$ Conditioning Embedding $\bar{z}$

$\mathbf{x}$ $\mathbf{z}_1$ $\mathbf{z}_{k-1}$ $\psi_k(\cdot)$ $\mathbf{z}_k$ $\mathbf{z}_{K-1}$ $\psi_K(\cdot)$ $\mathbf{y}$

$\psi_k(\cdot)$

$\mathbf{z}_{k-1}^a$ $\exp(\mathbf{s}_k(\cdot))$ $\mathbf{t}_k(\cdot)$ $\mathbf{z}_k^a$

$\mathbf{z}_{k-1}^b$ $\mathbf{z}_k^b$ $\mathbf{z}_k$

$z = 0$ $z = 0.5$ $z = 1$

Phase Synchronization of Multiple OSMPs

Modified Polar Velocities $_i\tilde{\omega}$ Latent Polar Phases $_i\varphi(t)\ \forall\ i \in \{1, ..., n_{\mathrm{s}}\}$

Phase Sync. Feedback Controller

$$_i\omega\left(1 - k_{\mathrm{ps}}\sum_{j=1}^{n_{\mathrm{s}}}\sin\left(\delta\Phi_{ij}^* + {}_i\varphi - {}_j\varphi\right)\right)$$

90

135   45

Sys. 1
Sys. 2
Sys. 3
Sys. 4

Time t [s]

180   0

225   315

270

Polar Phase φ [rad]

Online Shaping of the Learned Motion

Affine Transformations

Oracle $x^{\mathrm{d}}(t)$
Limit cycle
Trajectories $x(t)$

Modulation of Convergence Characteristics (e.g., Sliding-Mode-like Approach)

Oracle $x^{\mathrm{d}}(t)$
Limit cycle
Trajectories $x(t)$