Stable Heteroclinic Channel-based Movement Primitives for Robotic Control

CASE WESTERN RESERVE UNIVERSITY EST. 1826

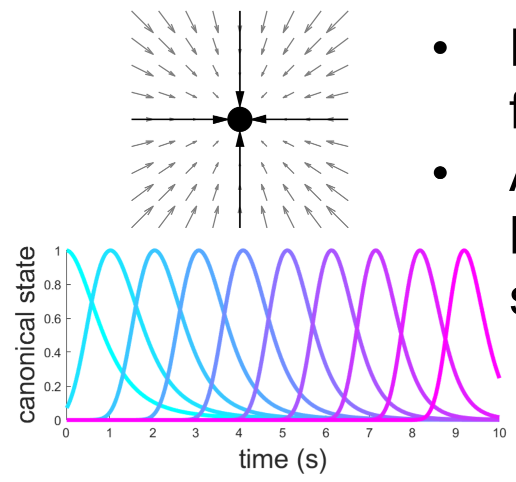
Natasha Rouse & Kathryn Daltorio

Department of Mechanical and Aerospace Engineering

Background

Movement primitives are a well-established, modular approach to robot motion planning. Dynamic movement primitives (DMPs) are a popular control framework based on nonlinear differential equations [1]. Stable heteroclinic channels (SHCs) are trajectories that connect saddle equilibria in phase space [2]. When DMP attractors are replaced with SHC saddles, stable heteroclinic channel-based movement primitives (SMPs) are formed [3].

Dynamic Movement Primitives (DMPs)



- Popular, modular control framework
- Attractor points as kernels – maintain system stability

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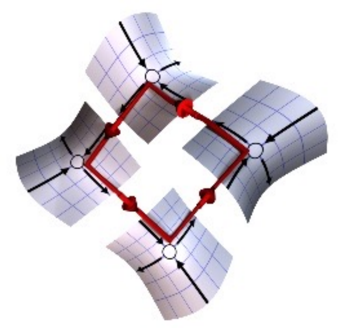
Stable Heteroclinic Channels (SHCs)



- Neural activation model
- Saddle points connected in phase space

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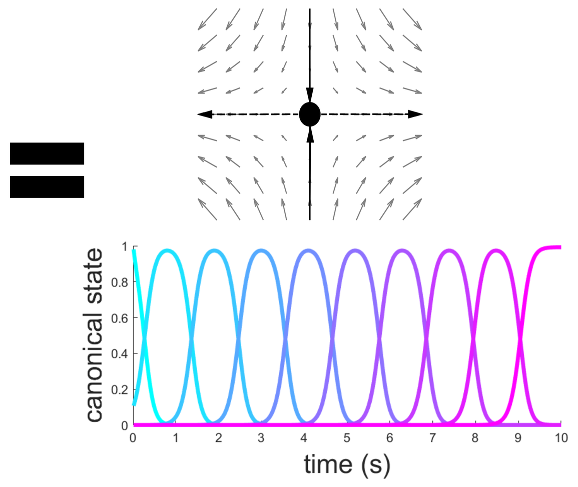
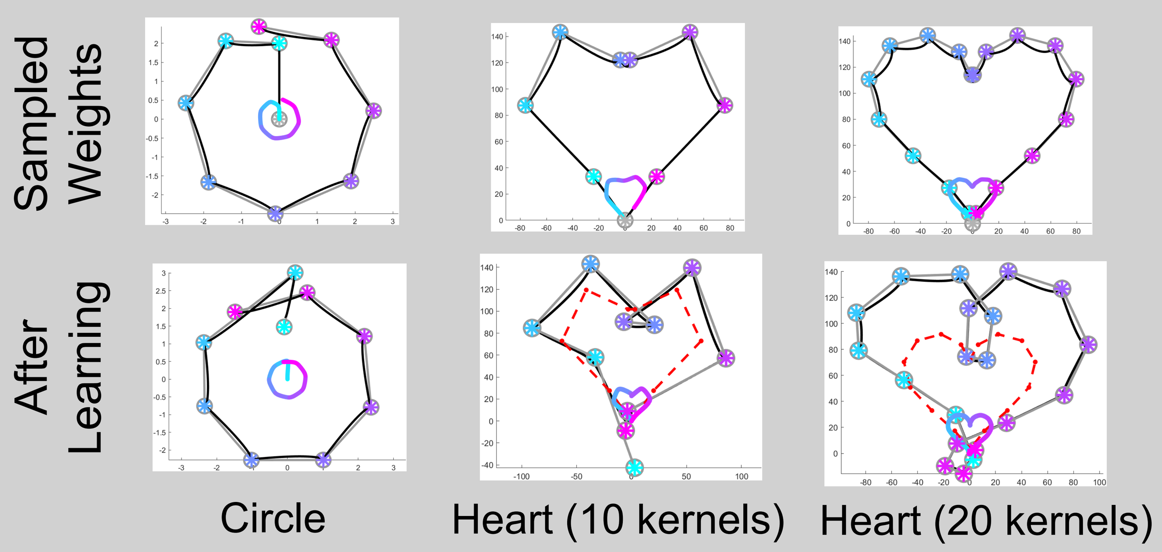
Stable Heteroclinic Channel-based Movement Primitives (SMPs)



- Maintains system stability
- Time independent
- Visualization feature: user-friendly system initialization
- Characterizable system parameters

SMP Features

Visualization



- In the task space, the SMP forcing function follows the weighted kernel locations
- Kernel weights can be initialized spatially – even sampled from the trajectory itself.

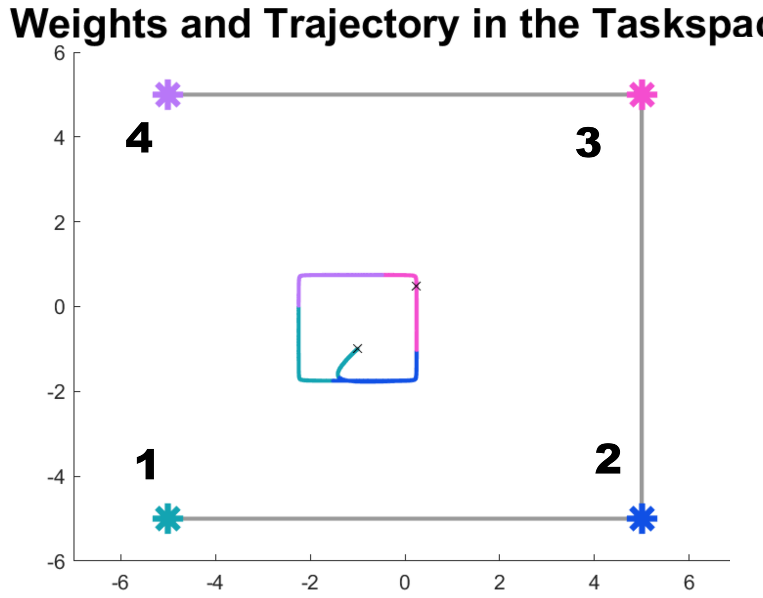
Learned weights
Forcing function
Weights sampled from forcing function

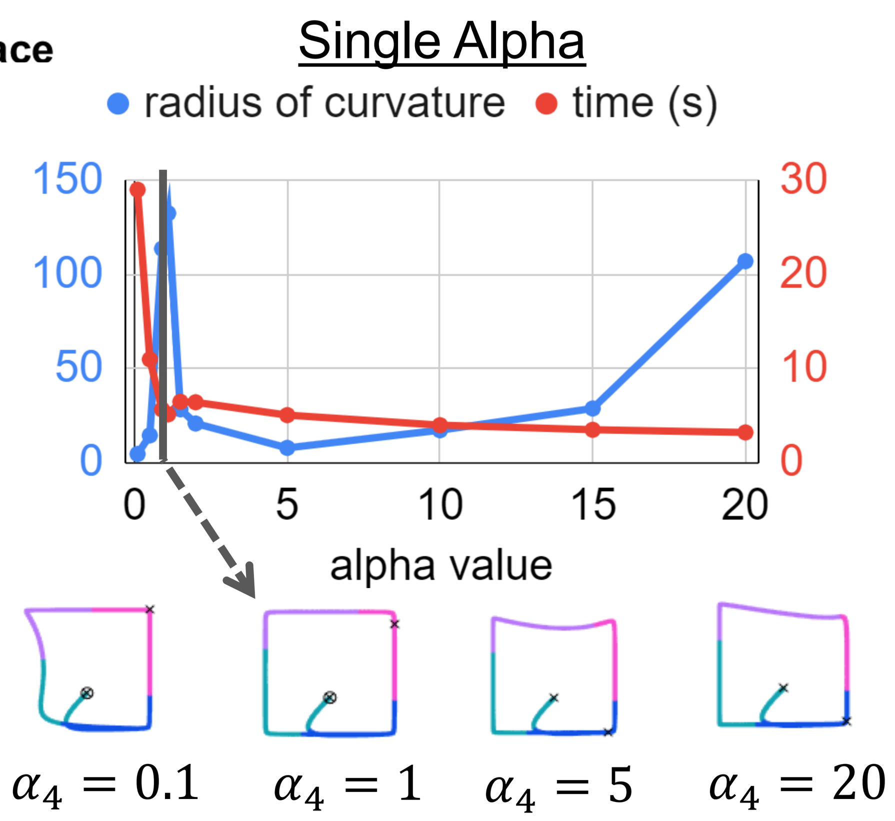
System Parameters

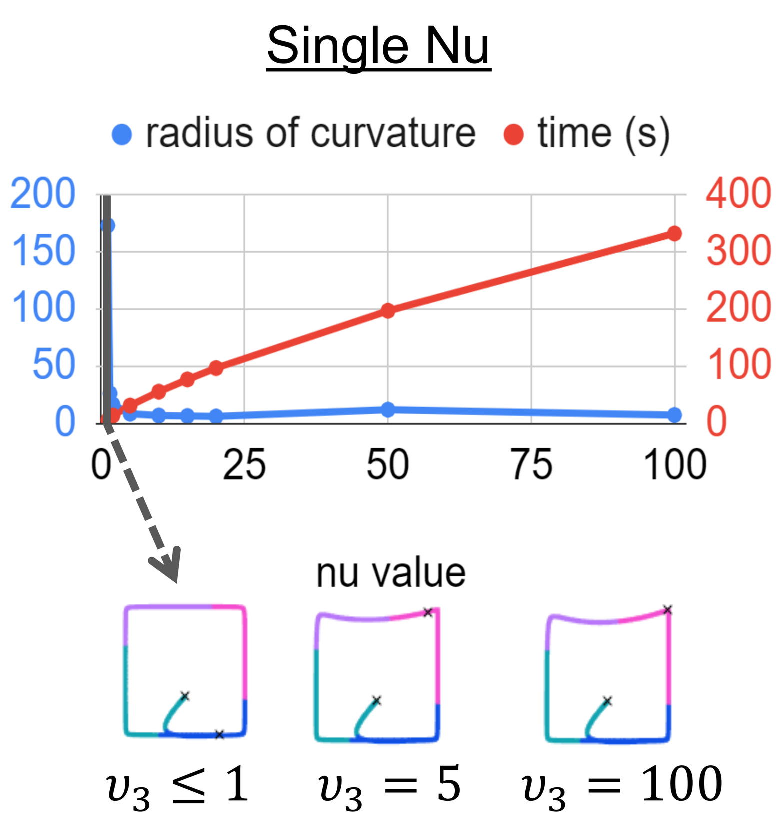
Horchler *et al* [4] characterize the SHC system parameters α, β, ν as:

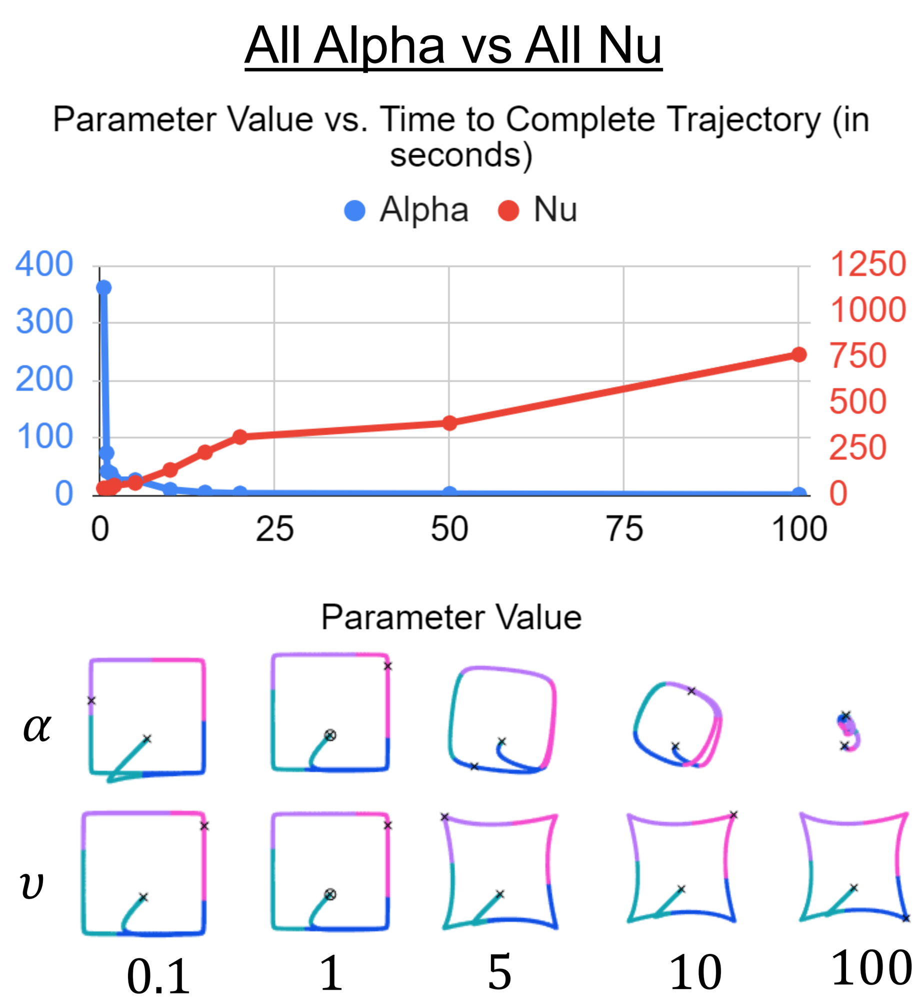
- α → growth rate of the kernel (how fast the intrinsic excitation grows the kernel dimension)
- β → magnitude (maximum amplitude of the waveform)
- ν → saddle value (insensitivity to noise)

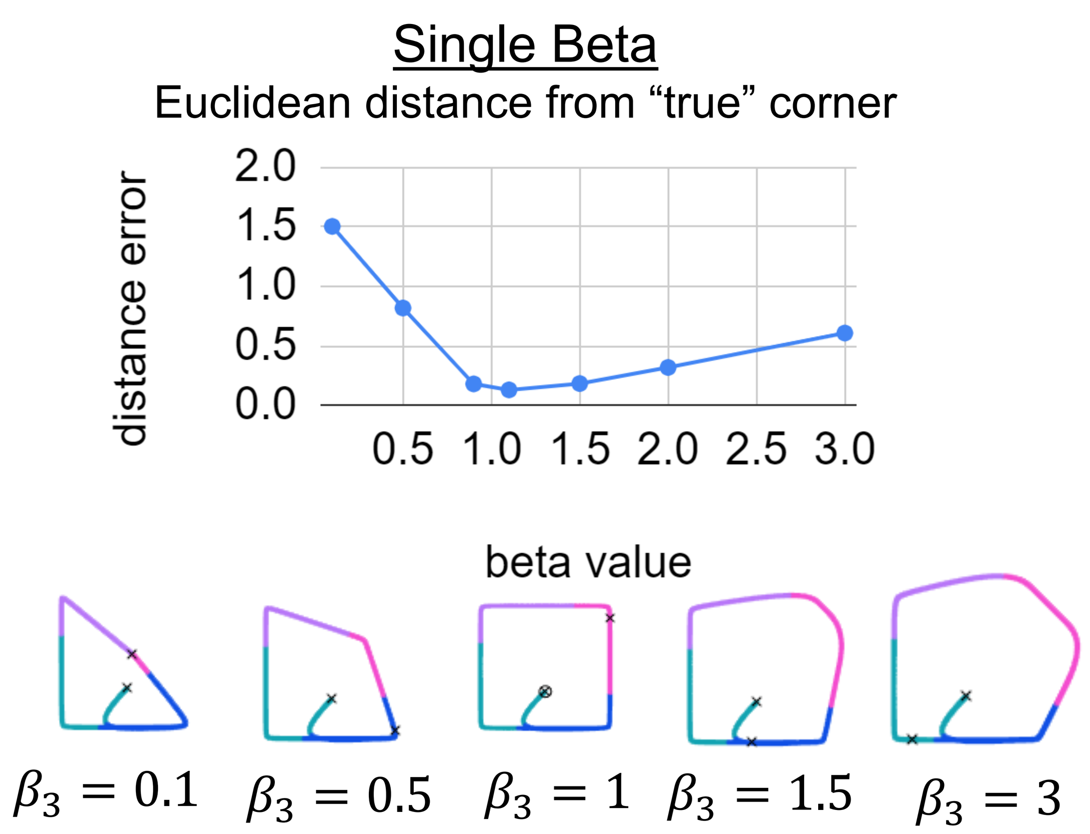
Weights and Trajectory in the Taskspace

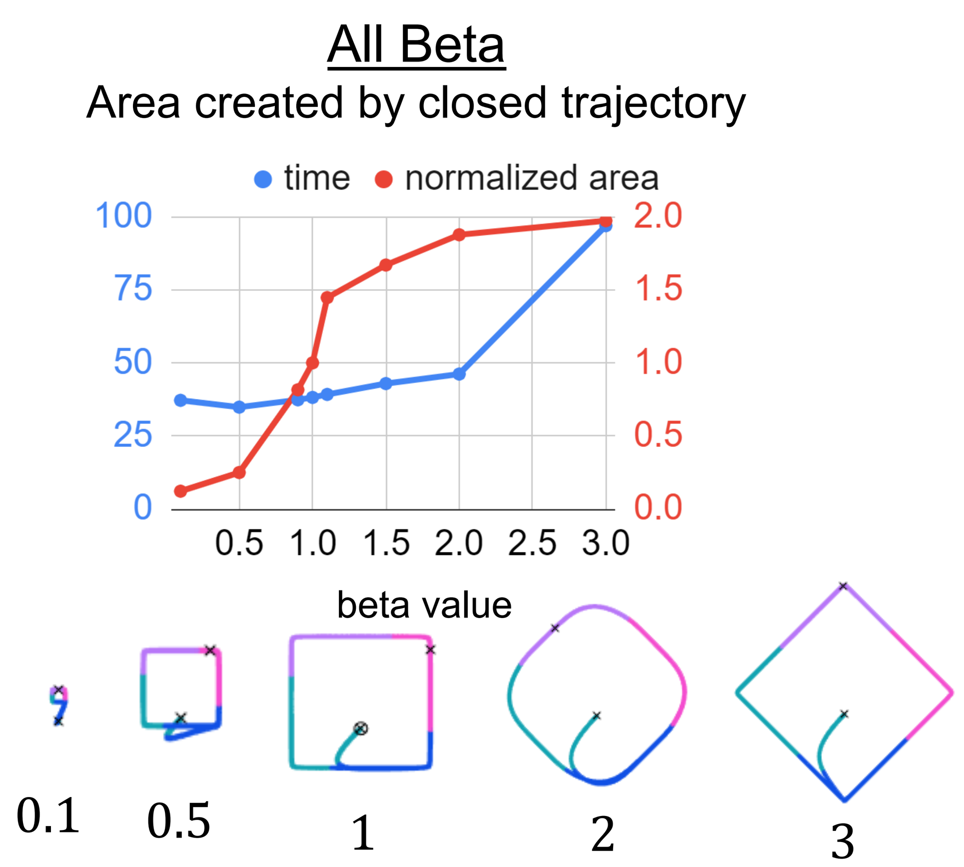












Conclusions

- α affects trajectories before it ($\alpha > 1$) and after it ($\alpha < 1$). Increasing all α rotates and shrinks the trajectory. Increasing α decreases time spent around that kernel.
- β affects the kernel-specific trajectory. Scaling ($\beta < 1$) and rotation ($\beta > 1$) occur when varying all β. Increasing β increases the time spent around the entire trajectory.
- υ_{SMP} affects the trajectory after it ($\upsilon > 1$) ; no change is observed when $\upsilon < 1$. Increasing all υ, increases the time around the trajectory, especially in the kernel vicinities.

SMP Structure

$$\tau \ddot{y} = \alpha_y\left(\beta_y(g-y)-\dot{y}\right)+f$$

$$f(x_i) = \sum_{i=1}^{K} x_i w_i$$

$$\tau dx_i = x_i\left(\alpha_i - \sum_{j=1}^{K}\rho_{ij}x_j\right)dt + \sum_{j=1}^{N} C_{ij} z_j$$

$$\rho_{ij} = \begin{cases} \alpha_i/\beta_i, & if\ i=j \\ \dfrac{\alpha_i - \alpha_j/\nu_j}{\beta_j}, & if\ i=j\oplus 1 \\ \dfrac{\alpha_i+\alpha_j}{\beta_j}, & otherwise \end{cases}$$

τ – time-scaling term
y – relevant system variable (*e.g.* end-effector position)
α_y, β_y – system damping & stiffness
g – goal position of system
f – external force applied to system by controller
K – total number of underlying kernel functions

w_i – weight of i^th kernel
x – canonical state of system
α_x – damping term
σ_i – factor for width of i^th kernel
c_i – center of i^th kernel
N – number of sensors
$\alpha_i, \beta_i, \nu_i, \rho_{ij}$ – system parameters
C_{ij} – coupling matrix
z_j - noise

References

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[2] M. Rabinovich, R. Huerta, and G. Laurent, "Neuroscience: Transient dynamics for neural processing," pp. 48–50, Jul 2008. doi: 10.1126/science.1155564
[3] N. A. Rouse and K. A. Daltorio, "Visualization of Stable Heteroclinic Channel-Based Movement Primitives," in IEEE Robotics and Automation Letters, vol. 6, no. 2, pp. 2343-2348, April 2021, doi: 10.1109/LRA.2021.3061382.
[4] Horchler, A. D., Daltorio, K. A., Chiel, H. J., & Quinn, R. D. (2015). Designing responsive pattern generators: stable heteroclinic channel cycles for modeling and control. Bioinspiration & Biomimetics, 10(2), 026001. https://doi.org/10.1088/1748-3190/10/2/026001

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