Stability and Predictability in Dynamically Complex Physical Interactions

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How do humans manipulate dynamically-complex objects?

- Dynamically-complex objects: nonlinear, chaotic, underactuated dynamics, large number of degrees of freedom
- Long delays imply heavy reliance on predictive (feed-forward) control based on an internal model
- But complex internal models seem unlikely

Hypothesis: Humans adopt control strategies that make physical interactions with the object predictable. Predictability simplifies the required internal model.

Predictability and Stability

- Predictability is mathematically operationalized as stability
- Movements in these physically-interactive tasks do not occur around a fixed point of the system, and are non-periodic
- Interested in evaluating stability of a trajectory, irrespective of final behavior
- **Contraction analysis** is proposed as an appropriate tool for assessing (exponential) stability in these complex tasks [1]

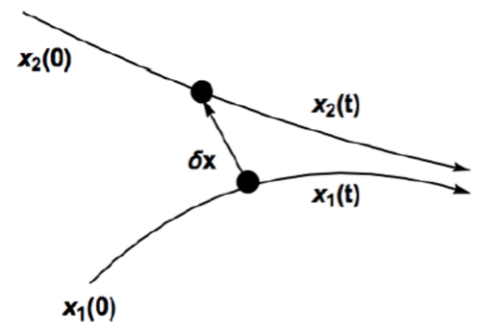
Contraction Analysis

Contraction condition:

$$\frac{1}{2}(F + F^T) < 0 \quad \text{where} \quad F = (\dot{\Theta} + \Theta\frac{\partial f}{\partial x})\Theta^{-1}$$

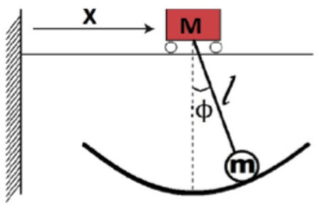
Contraction metric:

$$\frac{\partial \Theta}{\partial X} f + \Theta J = -\Theta$$

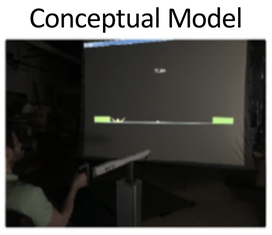


The Cup-of-Coffee Task

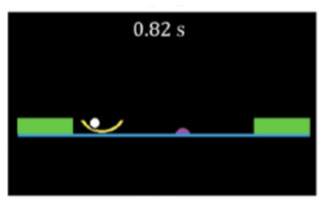
Conceptual Model



Mechanical Model



Virtual Interface



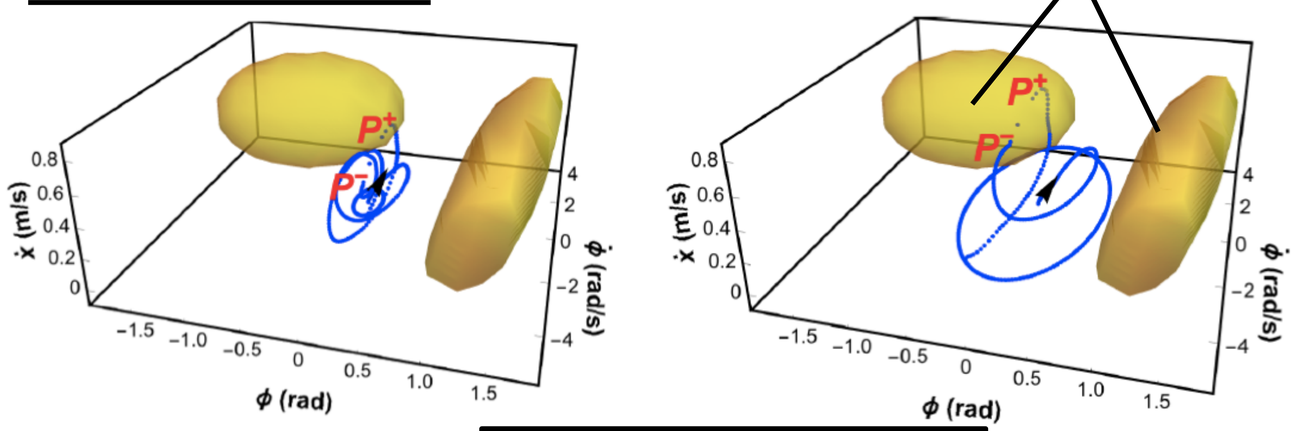
Display

- Task goal: Move the cup from start box to target box as fast as possible without losing the ball
- A perturbation is applied at a fixed visible location acting either with (assistive) or against (resistive) the cup's direction of motion

Blocks	Baseline 1	Perturbation 1	Baseline 2	Perturbation 2
Trials	60	60	10	60

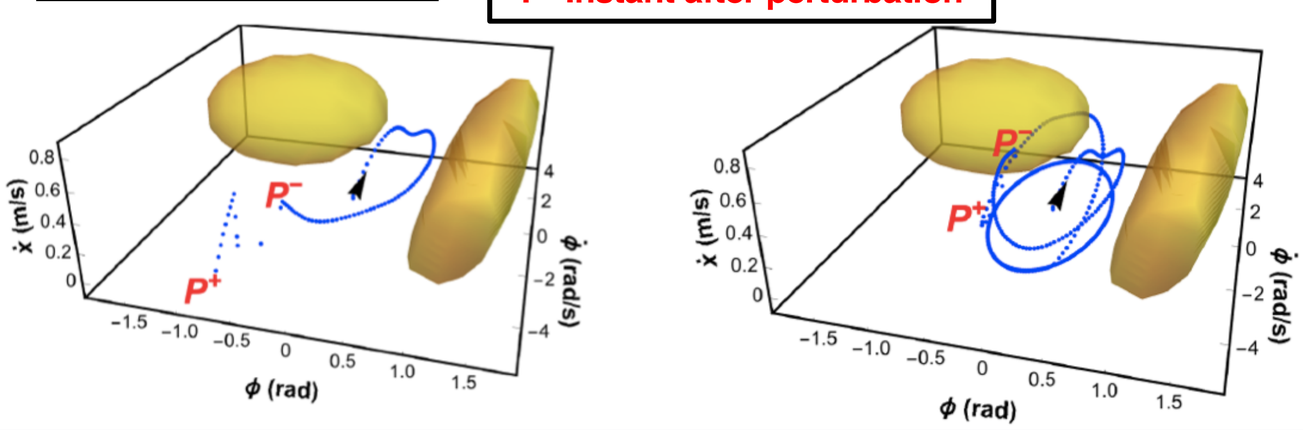
Results

Assistive Perturbations



Resistive Perturbations

P⁻ Instant before perturbation
P⁺ Instant after perturbation



Summary and Conclusions

- Humans exploit contraction regions to accommodate perturbations during dynamically complex physical interactions [2, 3].
- This enables perturbed trajectories to converge to their desired behavior without active error correction, making the trajectory more predictable.
- These findings may inform the development of more robust control strategies for robotic manipulation.

Literature

[1] Lohmiller, W., & Slotine, J. J. E. (1998). On contraction analysis for non-linear systems. *Automatica, 34(6), 683-696.*

[2] Bazzi, S., Ebert, J., Hogan, N., Sternad, D. (2018). Stability and predictability in dynamically complex physical interactions. *IEEE International Conference on Robotics and Automation (ICRA), 5540-5545.*

[3] Bazzi, S., Ebert, J., Hogan, N., Sternad, D. (2018). Stability and predictability in human control of complex objects. *Chaos: An Interdisciplinary Journal of Nonlinear Science, 28(10), 103103.*

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