Transient neurodynamics and the role of sensory dead zones

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Classification of dynamics based on their asymptotic behaviors

Stable fixed-point

Van der Pol oscillator

Lorenz attractor
However, medical emergencies are typically transient events.
Intermittent motor control

- Advantages:
  - Easy to implement
  - Robust
  - Minimizes energy requirements
  - England: Loram, Gawthrop
  - Italy: Bottaro, Morasso
  - Japan: Asai, Nomura
Stick balancing at the fingertip (expert)
Stick balancing (beginner)
Transient dynamics

Intermittent control

Weibull-type Survival Curves

\[ P(t_{sec} > t) \]

Day 1
Day 4
Day 7

Time (sec.)
Modeling stick balancing at the fingertip

\[ \dot{\theta}(t) - \frac{6g}{\ell} \theta(t) = F_{fb}(t - \tau) \]

- Key point:
  
  If know \( \tau \) AND minimum length of stick that can be balanced, then can guess minimal form of 
  
  \[ F_{fb}(t - \tau) \]
Delays: mechanical perturbation

- Mehta & Schaal (2002)
  - 0.22s
- Milton lab
  - 0.225s (0.20-0.25s)
  - Five subjects
  - Initial angular deviation > 20°
Visual blank out experiments

- Initial angular deviations: 3-16°
Estimating delays from blank outs

- Delay (loss of control): 0.24s (0.19-0.39s)
- Delay (regain control): 0.22s (0.19-0.25s)
Model feedbacks for stick balancing

- Proportional-derivative
  - state predicted from its own delayed values

\[ F_{fb} = K_p \theta(t - \tau) + K_d \dot{\theta}(t - \tau) \]

- Proportional-derivative-accelerative
  - state predicted from its own delayed values

\[ F_{fb} = k_p \theta(t - \tau) + k_d \dot{\theta}(t - \tau) + k_a \ddot{\theta}(t - \tau) \]

- Distributed
  - Feedback involved in making the prediction

\[ F_{fb}(t) = \int_{t-\tau}^{t} f\left[\theta(s - \tau), \dot{\theta}(s - \tau), F_{fb}(s)\right] ds \]
Stick balancing skill & stick length

- Vast majority of subjects do better than predicted by PD and PDA feedback.
- Very, very few approach limit suggested by distributed controller (1/48 subjects)
Intermittent control: “Drift-and-act”

- Possible realizations
  - Sensory dead zone
  - Nested control loops

Chaos in digital control

- Sensory dead zone is a strong nonlinearity
  - Complex oscillations
  - Intermittent “micro-chaos”
  - “Transient” chaos

Piecewise-constant linear feedback and human postural sway ("drift and act")

\[
\frac{dx}{dt} = \begin{cases} 
\alpha x(t-\tau) + \xi(t) + C, & \text{if } x(t-\tau) < -X, \\
\alpha x(t-\tau) + \xi(t), & \text{if } -X \leq x(t-\tau) \leq X, \\
\alpha x(t-\tau) + \xi(t) - C, & \text{if } x(t-\tau) > X,
\end{cases}
\]


Stick balancing: Improved by low frequency, low amplitude vertical vibrations

- Simplest explanation posits a threshold

Is there a sensory dead zone for stick balancing?
Sensory dead zone
sagittal > frontal plane

- mean X deviation was 1.47 degrees
- mean Y deviation was 3.66 degrees.
Time-delayed PDA control with a threshold


\[ \ddot{\theta}(t) - k\dot{\theta}(t) = F_{\text{control}} \]

where

\[ F_{\text{control}} = F_p(t) + F_d(t) + F_a(t) \]

with

\[ F_p(t) = \begin{cases} 
0 & \text{if } |\theta(t - \tau)| < \theta_s, \\
-K_p\theta(t - \tau) & \text{if } |\theta(t - \tau)| \geq \theta_s,
\end{cases} \]

\[ F_d(t) = \begin{cases} 
0 & \text{if } |\dot{\theta}(t - \tau)| < \dot{\theta}_s, \\
-K_d\dot{\theta}(t - \tau) & \text{if } |\dot{\theta}(t - \tau)| \geq \dot{\theta}_s,
\end{cases} \]

\[ F_a(t) = \begin{cases} 
0 & \text{if } |\ddot{\theta}(t - \tau)| < \ddot{\theta}_s, \\
-K_a\ddot{\theta}(t - \tau) & \text{if } |\ddot{\theta}(t - \tau)| \geq \ddot{\theta}_s,
\end{cases} \]
Choose parameters so that:
upright position is unstable,
but stable range of parameters exists

Linear model, \( L = 1 \text{m}, k_p = 61, k_d = 14.9, k_o = 0.9 \)

Nonlinear model with deadzones \( \theta_{\text{th}} = 0.01 \text{ [rad]}, \dot{\theta}_{\text{th}} = 0.01 \text{ [rad/s]}, \ddot{\theta}_{\text{th}} = 0.01 \text{ [rad/s}^2] \)
Conclusions

- Presence of sensory dead zone in stick balancing are important
  
  - If system in stable in absence of dead zone, then it is stable in presence of dead zone.
    
    - Effect of dead zone is to produce complex dynamics including oscillations and chaos
  
  - If system is unstable in absence of dead zone, it can sometimes produce transient stabilizations

- Most subjects perform the tasks using parameters that are not tuned for optimal performance