Mode Transition Behavior in Hybrid Dynamic Systems

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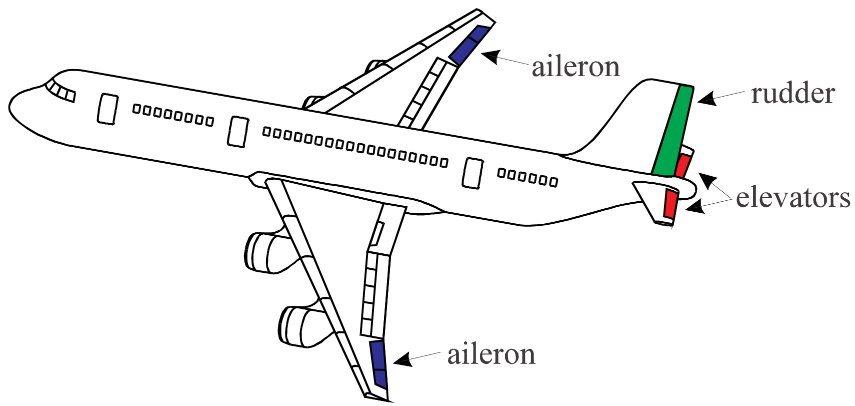
Introduction

Mode Transitions in Hybrid Models of Physical Systems

- hybrid because
  - continuous, differential equations
  - discrete, finite state machine
- overview of phenomena involved

Illustrated by Hydraulic Actuator Used for Aircraft Attitude Control Surfaces

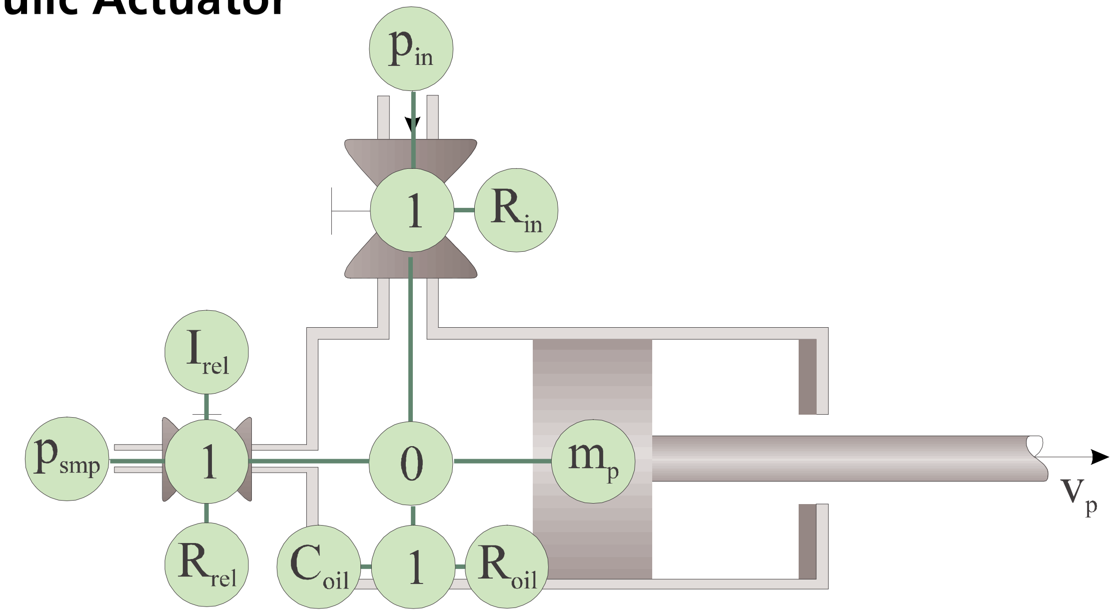


Modeling of Physical Systems

Ideal Picture Model (Schematic)

Identify Behavioral Phenomena

For Example, A Hydraulic Actuator



Equation Generation

Compile Constituent Equations

- R_{in} — $f_{in}R_{in} = p_{Rin}$
- R_{oil} — $f_R R_{oil} = p_{Roil}$
- C_{oil} — $C_{oil}\dot{p}_C = f_R$
- m_p — $m_p \dot{v}_p = A_p p_{cyl}$
- R_{rel} — $f_{rel}R_{rel} = p_{rel}$
- I_{rel} — $I_{rel}\dot{f}_{rel} = p_{rel}$
- 0, **cylinder chamber** — $v_p = f_{in} - f_{rel}$
- 1, **relief flow pipe** — $p_{rel} = p_{smp} - f_{rel}R_{rel} + p_{cyl}$
- 1, **intake pipe** — $p_{Rin} = p_{in} - p_{cyl}$
- 1, **oil compression** — $p_{Roil} = p_{oil} - p_C$

Equation Processing

Before Simulation

- the number of equations is reduced
  - substitution/elimination
- equations are sorted
  - each equation computes one variable
- equations are solved
  - high index problems may require differentiation of certain equations

Hybrid Behavior

Introduce Valves

- make highly nonlinear behavior piecewise linear
  - intake valve $if \quad v_{in} \quad then \quad p_{Rin} = p_{in} - p_{cyl} \quad else \quad f_{in} = 0$
  - relief valve $if \quad v_{rel} \quad then \quad p_{rel} = p_{smp} - f_{rel}R_{rel} + p_{cyl} \quad else \quad f_{rel} = 0$

Switching Between Modes of Continuous Behavior

- intake valve, v_{in}, external switch (control law)
- relief valve, v_{rel}, autonomous switch triggered by physical quantities

$$v_{rel} = p_{cyl} > p_{th}$$

- different sets of equations

Computational Causality

When Switching Equations

- computational causality may change
  - re-ordering
  - re-solving

Example

- when the intake valve closes, equations change
  - from $p_{Rin} = p_{in} - p_{cyl}$
  - to $f_{in} = 0$
- therefore, in this equation
  - p_{Rin} becomes unknown
  - f_{in} becomes known

Implicit Modeling

Deal With Causal Changes Numerically

Valve Behavior

- **residue on** f_{in} $\quad 0 = if \quad v_{in} \quad then \quad -p_{Rin} + p_{in} - p_{cyl} \quad else \quad f_{in}$
- **residue on** f_{rel} $\quad 0 = if \quad v_{rel} \quad then \quad -p_{rel} + p_{smp} - f_{rel}R_{rel} + p_{cyl} \quad else \quad f_{rel}$

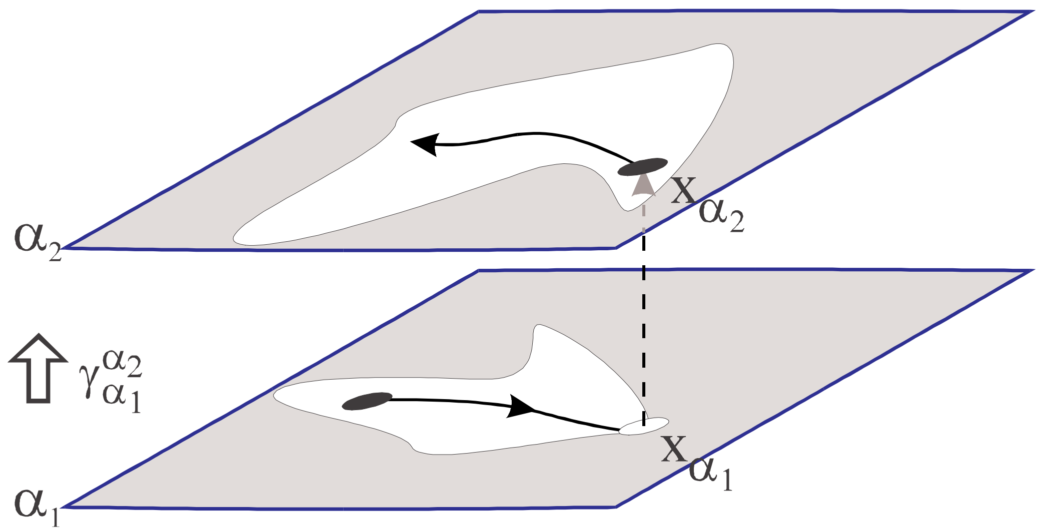
Implicit Numerical Solver (e.g., DASSL)

- **designed to handle this formulation**

Hybrid Dynamic Behavior

Geometric View

- modes of continuous, smooth, behavior
- patches of admissible state variable values



Specification Parts

Hybrid Behavior Specification

- a function, f, that defines continuous, smooth, behavior for each mode

$$f_{\alpha_i}: E_{\alpha_i}\dot{x} + A_{\alpha_i}x + B_{\alpha_i}u = 0$$

- an inequality, γ, that defines admissible state variable values

$$\gamma_{\alpha_i}^{\alpha_{i+1}}: C_{\alpha_i}x + D_{\alpha_i}u \geq 0$$

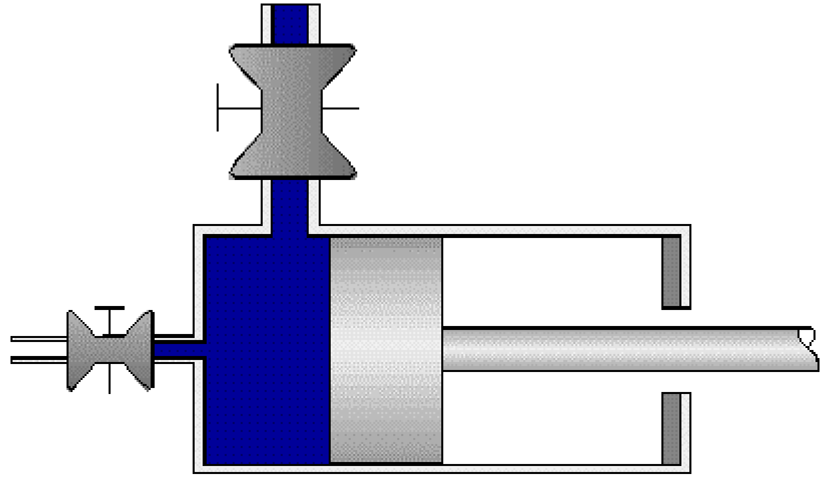
Dynamics

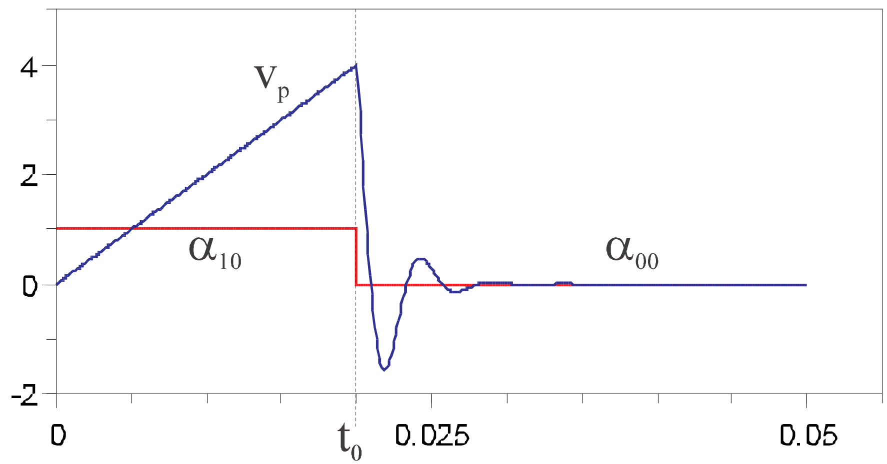
Behavior Characteristics

- C^0, i.e., no jumps in state variables
- steep gradients

Example

- when the intake valve closes, piston velocity quickly reduces to 0





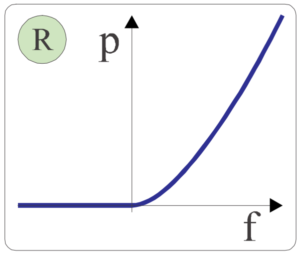
The Next Step

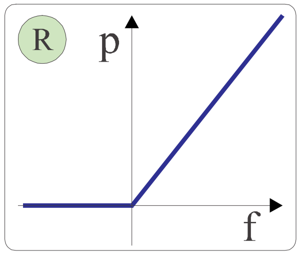
Remove Steep Gradients

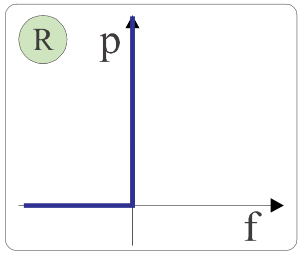
- e.g., singular perturbation

Algebraic Constraints Between State Variables

- high index systems
- subspace with admissible (continuous) dynamic behavior
- discontinuities (jumps) in state behavior



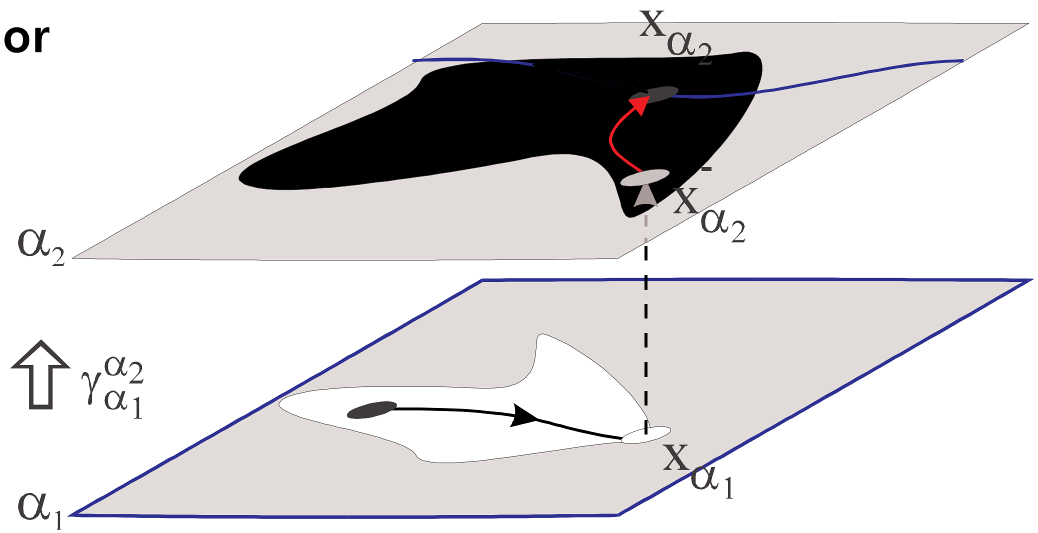




Hybrid Dynamic Behavior - Refined

Geometric View

- modes of continuous, smooth, behavior
- patches of admissible state variable values
- manifold of dynamic behavior



Specification Parts

Hybrid Behavior Specification

- a function, f, that implicitly defines for each mode
  - continuous, smooth, behavior
  - state variable value jumps

$$f_{\alpha_i}: E_{\alpha_i}\dot{x} + A_{\alpha_i}x + B_{\alpha_i}u = 0$$

- an inequality, γ, that defines admissible generalized state variable values

$$\gamma_{\alpha_i}^{\alpha_{i+1}}: C_{\alpha_i}x + D_{\alpha_i}u \geq 0$$

- for explicit reinitialization (semantics of x^-)

$$f_{\alpha_i}: E_{\alpha_i}\dot{x} + A_{\alpha_i}x + B_{\alpha_i}^{u}u + B_{\alpha_i}^{x}x^- = 0$$

Handling of Systems With High Index

DASSL Handles Index 2 Systems

- implicit formulation for continuous behavior

Requires Consistent Initial Conditions When Mode Changes Occur

- compute from implicit formulation to make jump space (projection) explicit
- for example, sequences of subspace iteration
  - space of dynamic behavior: $V^{n+1} = A^{-1} E V^n,\ V^0 = R^n$
  - jump space: $T^{n+1} = E^{-1} A T^n,\ T^0 = \{0\}$
- or, decomposition in (pseudo) Kronecker Normal Form

Projections

Linear Time Invariant Index 2 System

- **derive pseudo Kronecker Normal Form (numerically stable)**

$$\left[\begin{array}{c|cc} E_{11} & 0 & 0 \\ \hline 0 & 0 & E_{22,12} \\ 0 & 0 & 0 \end{array}\right]\begin{bmatrix} \dot{x}_f \\ \dot{x}_{i,1} \\ \dot{x}_{i,2} \end{bmatrix} + \left[\begin{array}{c|cc} A_{11} & A_{12,1} & A_{12,2} \\ \hline 0 & A_{22,11} & A_{22,12} \\ 0 & 0 & A_{22,22} \end{array}\right]\begin{bmatrix} x_f \\ x_{i,1} \\ x_{i,2} \end{bmatrix} + \left[\begin{array}{c} B_1 \\ \hline B_{2,1} \\ B_{2,2} \end{array}\right] u = 0$$

- **after integration (no impulsive input behavior), consistent values are**

$$x_f = x_f^- - E_{11}^{-1} A_{12,1} A_{22,11}^{-1} E_{22,12} (x_{i,2} - x_{i,2}^-)$$

$$x_{i,1} = A_{22,11}^{-1}(-B_{2,1}u + E_{22,12}\dot{x}_{i,2}) - A_{22,12}x_{i,2}$$

$$x_{i,2} = -A_{22,22}^{-1} B_{2,2} u$$

The Hydraulic Actuator

Generalized State Jumps for Each Mode

Mode	Projection
α_{00}	$f_{rel} = 0$ $v_p = 0$
α_{01}	$v_p = (m_p v_p^- - I_{rel} f_{rel}^-)/(m_{rel} + m_p)$ $f_{rel} = (m_p v_p^- - I_{rel} f_{rel}^-)/(m_{rel} + m_p)$
α_{10}	$v_p = v_p^-$ $f_{rel} = 0$
α_{11}	$v_p = v_p^-$ $f_{rel} = f_{rel}^-$

A Scenario

Intake Valve Is Open

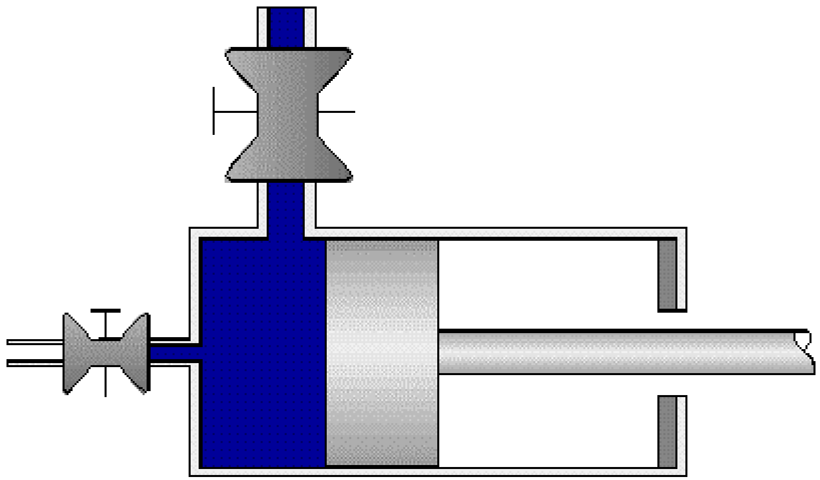
- piston starts to move

Intake Valve Closes

- piston inertia causes pressure build-up
- pressure reaches critical value

Relief Valve Opens

- cylinder pressure decreases

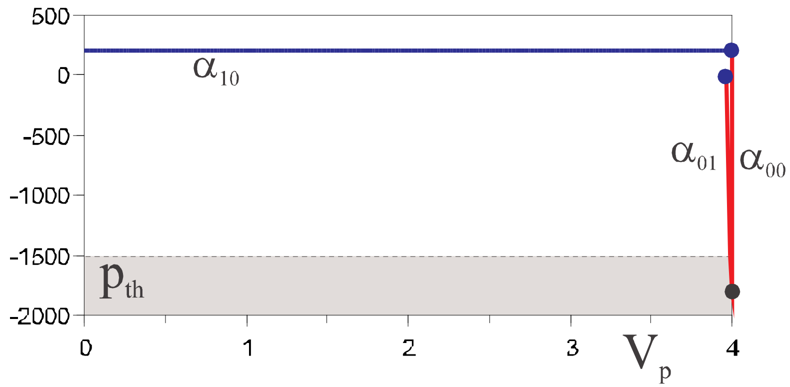


$\Rightarrow$ Interaction Between Mode Transition Behavior

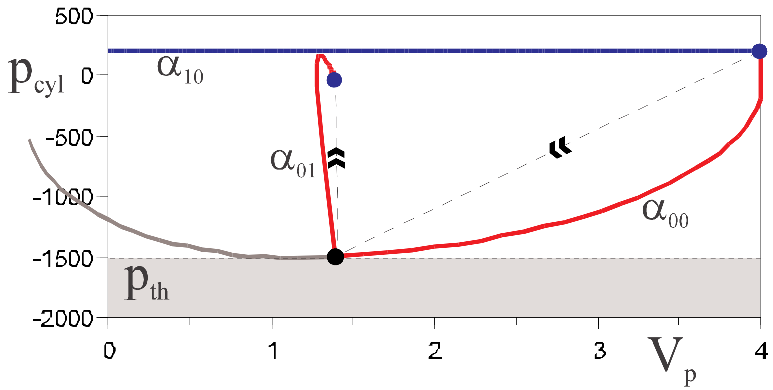
Phase Space of Cylinder Scenario

Projection Is Aborted

- immediately
- after partial completion



(a)

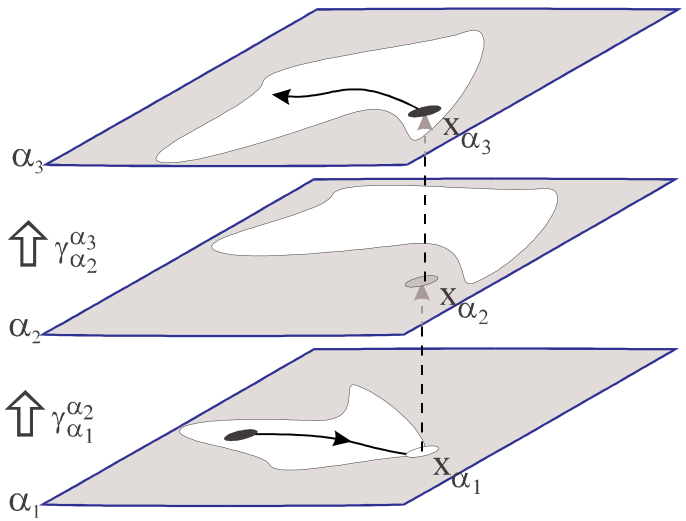


(b)

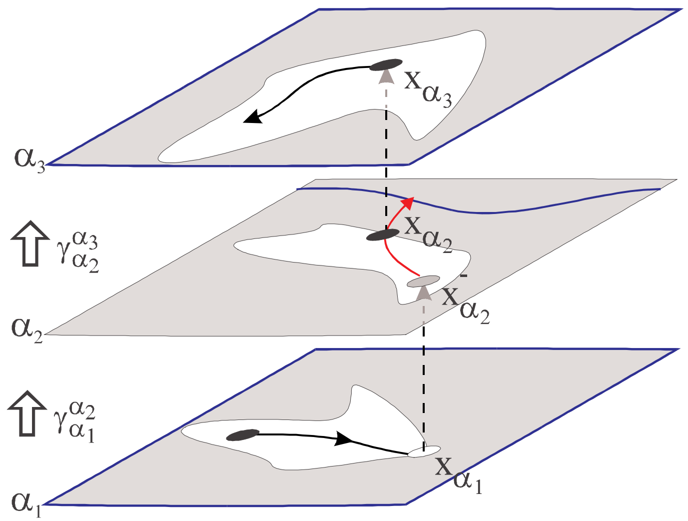
Sequences of Mode Changes

(a) State Outside of a Patch in the New Mode

(b) During Projection State Values are Reached Outside of a Patch in the New Mode



(a)



(b)

Impulses

High Index Systems May Contain Impulsive Behavior

- **in case of the hydraulic cylinder,** $p > p_{th}$**, would always hold if not** $v_p = v_p^-$
- **unknown where the patch is abandoned**

In-Depth Analysis of Switching Conditions

- **solve for required** $x(t)$
- **compute earliest** $t = t_s$ **at which** $\gamma(x(t), u(t), t) \geq 0$
- **substitute** t_s **to compute** $x(t_s)$

Complex Switching Structure

Additional Difficulty When Interacting Fast Transients (e.g., collision)

Detailed Analysis of the Projection

Cylinder Example (Imaginary Eigenvalues, $\lambda = \lambda_r + i\,\lambda_i$)

- **from detailed model**
  - **solve for p**

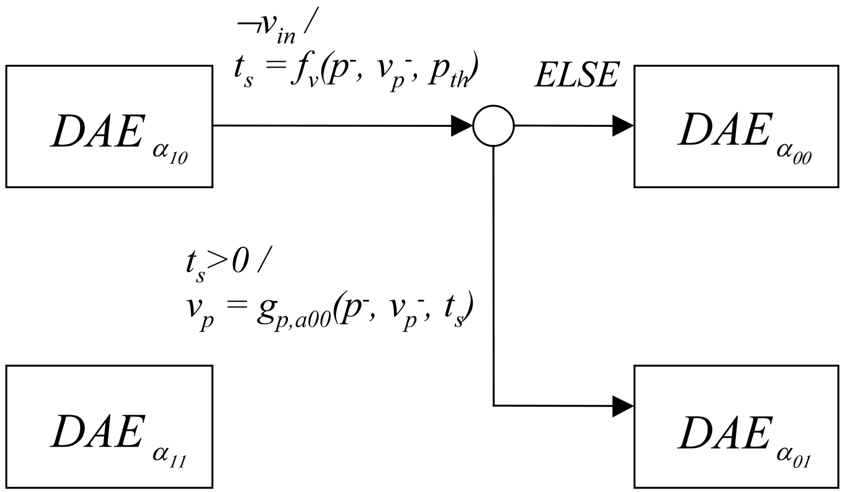
$$p(t) = e^{\lambda_r t}\,(p^- \cos(\lambda_i t) - \frac{1}{\lambda_i}(\frac{1}{C_1} v_p^- + \lambda_r p^-)\sin(\lambda_i t))$$

  - **substitute t at which $p(t) > p_{th}$**

$$v_p = e^{\lambda_r t_s}\,(v_p^- \cos(\lambda_i t) - (\frac{R_2}{I_1} v_p^- - \frac{p_1}{I_1} + \lambda_r v_p^-)\frac{\sin(\lambda_i t_s)}{\lambda_i})$$

Complex Switching Structure

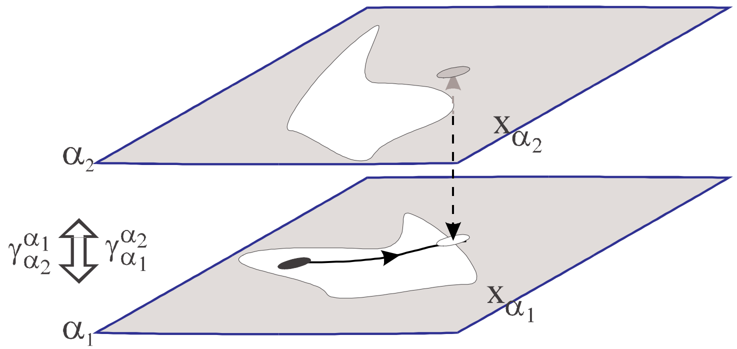
Explicit Re-Initialization

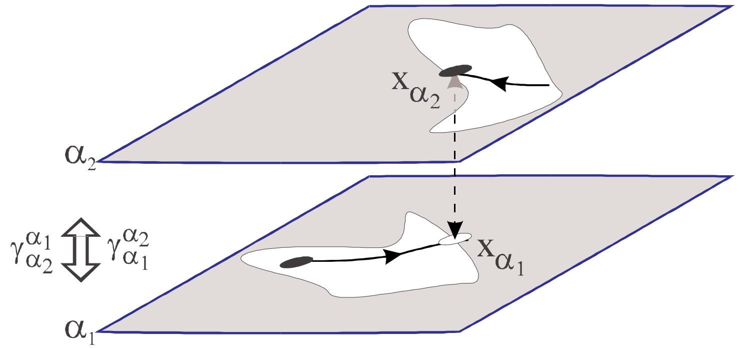


Chattering

What If the New Mode Switches Back

- immediately $\Rightarrow$ inconsistent model, no solution
- after infinitesimal period of time $\Rightarrow$ chattering behavior, solve with
  - equivalent control
  - equivalent dynamics

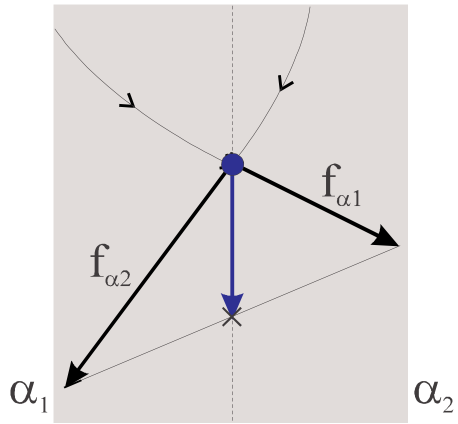




Equivalent Dynamics

Chattering

- fast component
  - remove
- slow component
  - weighted mean of instantaneous vector fields (Filippov Construction)
- sliding behavior



Ontology

Phase Space Transition Behavior Classification

- mythical (state invariant)
- pinnacle (state projection aborted)
- continuous
  - interior (continuous behavior)
  - boundary (further transition after infinitesimal time advance)
  - sliding (repeated transitions after each infinitesimal time advance)

Combinations of Behavior Classes

Conclusions

Mode Transition Behavior

- Rich
- Complex

Requires

- special algorithms/computations
- model verification analyses

How to Efficiently Generate Behavior (e.g., for Real-time Applications)?