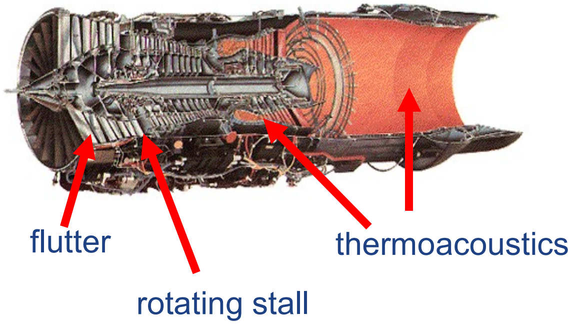
The Role of Control in Design: from Fixing Problems to the Design of Dynamics



Andrzej Banaszuk

United Technologies Research Center, East Hartford, CT

United
Technologies
Research Center

Acknowledgements

Control of Rotating Stall:

A. Krener

H. Hauksson

I. Mezic

Control of Flutter:

D. Gysling

G. Rey

K. Teerlinck

Flow Control:

S. Narayanan

G. Tadmor

B. Noack

G. Haller

Control of Thermoacoustics:

P. Mehta

G. Hagen

M. Soteriou

P. Barooah

B. Eisenhower

J. Cohen

B. Proscia

C. Jacobson

M. Krstic

Design of Robust Dynamics:

I. Mezic

J. Marsden

M. Dellnitz

R. Coifman

S. Meyn

Y. Kevrekidis

B. LaBarre

M. Huzmezan

S. Varigonda

G. Mathew

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UTC experience: research that made impact

Theory

Nonlinear Control

- *Approximate feedback linearization with uniform bounds on linearization error MCSS96, SIAM JCO 96, SCL96*
- *Linearization of transverse dynamics for periodic orbits SCL95 (2)*
- *Global stabilization of nonlinear PDE model of compressor stall using backstepping Automatica99, SIAM JCO99*

Fundamental limitations of performance

- *Fundamental limitations of performance in control of nonlinear oscillations*
- *Peak splitting observed in flow and combustion control experiments explained*
- *Effect of diffusion and distributed delay explained*

CCA99, IFAC02, AIAA04, ASME JPP03, IEEE TCST 06

Analysis and control of non-equilibrium dynamical systems

- *Mixing enhancement by creation of chaotic advection PhysFluids03, 04, IEEE CST 02*
- *Model validation technique PhysicaD05*
- *Effect of noise on stability ASME JPP 05*
- *Detrimental and beneficial symmetry ADCHEM06, JDS07, CEP07, JAM 07, patent*

Frequency domain framework for analysis and control CDC04

Experiments

Fan blade flutter

- *Order of magnitude damping augmentation for three flutter modes in transonic rig*

IFAC02, CDC02, AIAA 2003

Combustion instability

- *Adaptive extremum-seeking control demonstration in 4MW rig*

Patent, CCA99, Automatica04

Separation and mixing control

- *2x increase in diffuser pressure recovery over baseline using adaptive control*

Patent, AIAA03, PhysFluids05 (subm.)

- *40% reduction of pattern factor control via jet in cross flow modulation*

CombSciTech05

Process Impact

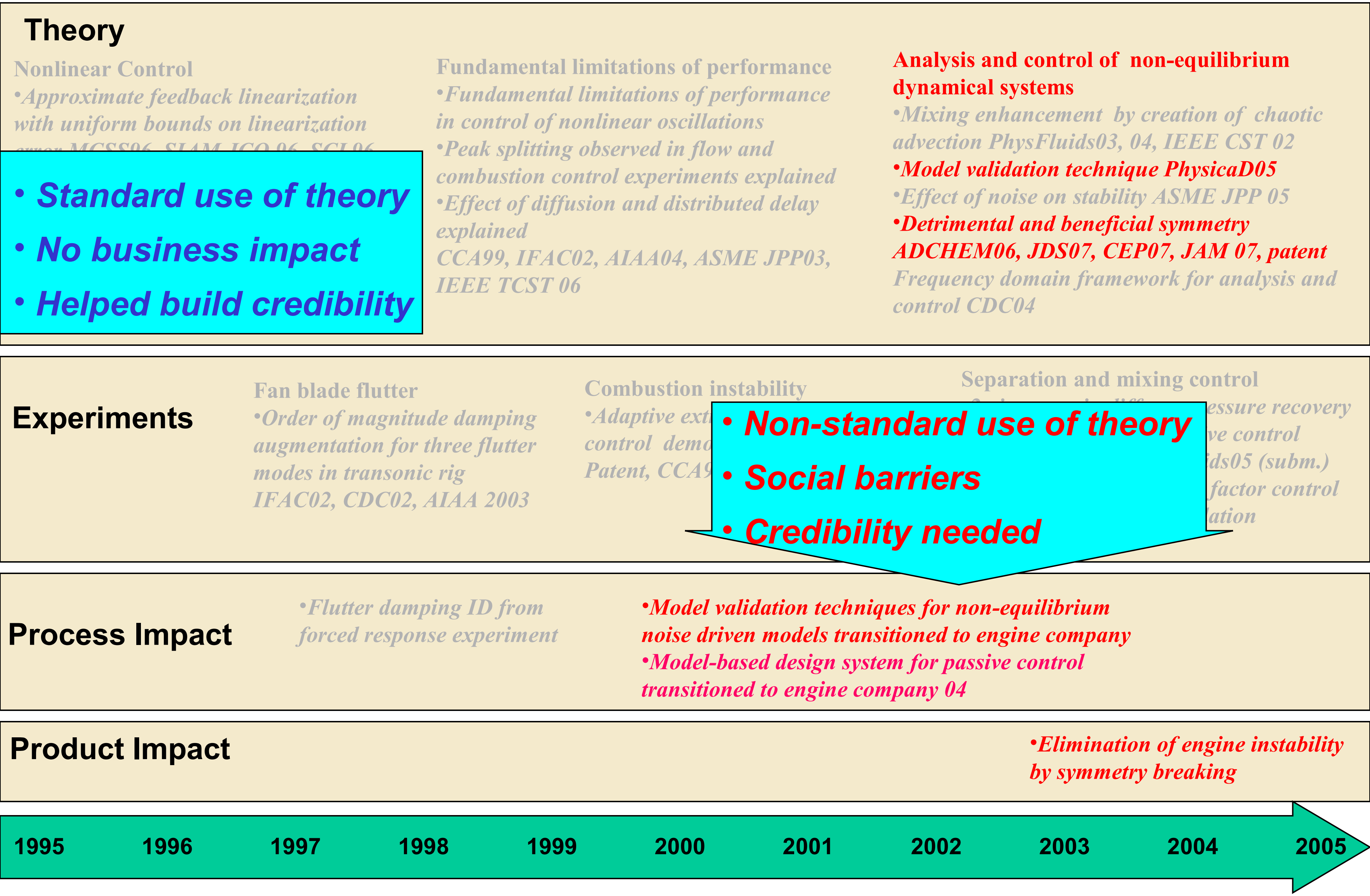
- *Flutter damping ID from forced response experiment*
- *Model validation techniques for non-equilibrium noise driven models transitioned to engine company*
- *Model-based design system for passive control transitioned to engine company 04*

Product Impact

- *Elimination of engine instability by symmetry breaking*

1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005

UTC experience: research that made impact



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Frequency domain framework for analysis and control CDC04

- *Standard use of theory*
- *No business impact*
- *Helped build credibility*

Experiments

Fan blade flutter

- *Order of magnitude damping augmentation for three flutter modes in transonic rig IFAC02, CDC02, AIAA 2003*

Combustion instability

- *Adaptive ext*

control demo

Patent, CCA9

Separation and mixing control

essure recovery

ve control

ids05 (subm.)

factor control

lation

- *Non-standard use of theory*
- *Social barriers*
- *Credibility needed*

Process Impact

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    - Tools for Design of Robust Dynamics

United Technologies

$47.8B Revenues (2006)

222,190 employees operating in 180 countries

Pratt & Whitney

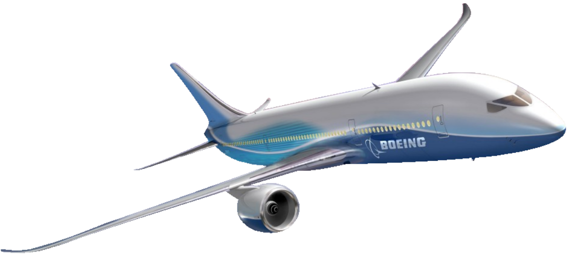
UT Power

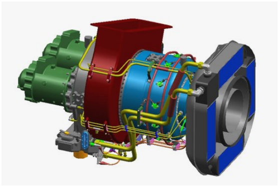
Carrier

Sikorsky

Building Systems
Aerospace Systems
Power Systems

Otis





Hamilton-Sundstrand

UT Fire & Security

United Technologies Research Center

Who We Are:

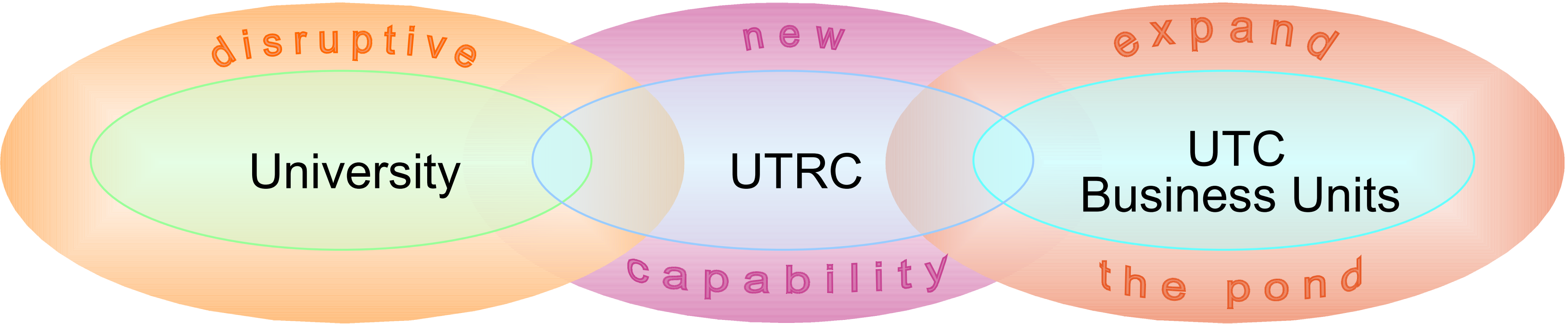
United Technologies Research Center is the central research organization for United Technologies Corporation.

- Founded in 1929
- 450 people
- 350 technical
- 80% PhD
- Goal: 500 people

East Hartford, USA

Shanghai,China

What We Do: Impact through Innovation



disruptive

University

new

UTRC

capability

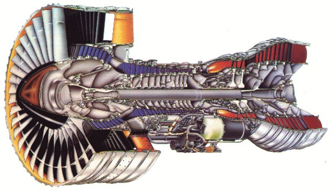
expand

UTC Business Units

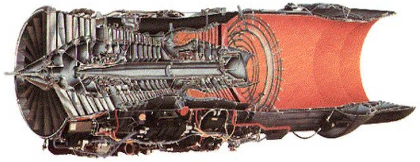
the pond

PRATT & WHITNEY
DEPENDABLE ENGINES

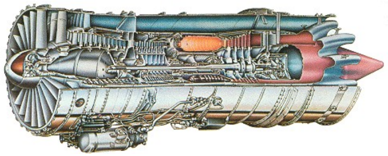
PW4000



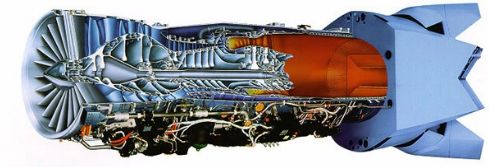
F100



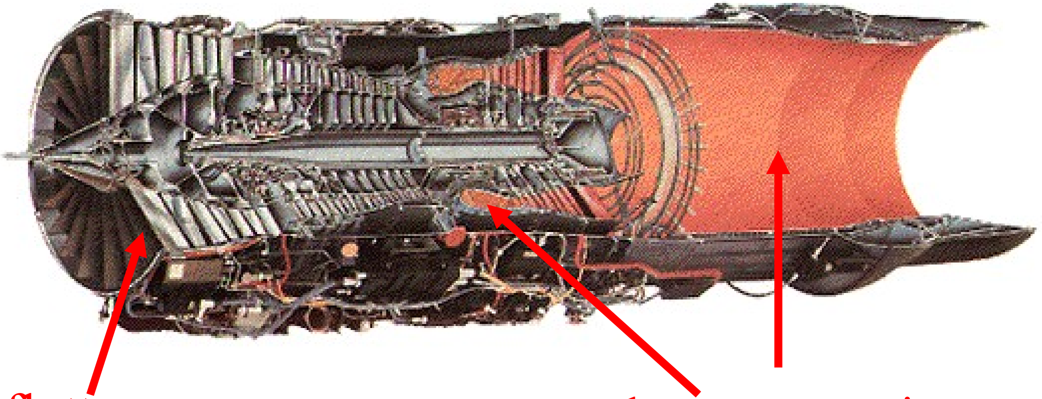
PW6000



F119, F135



Challenge: mitigation of oscillations



Acoustics
Structures

Heat Release
Aerodynamics

Turbulence

$$x_{tt} - a^2 \Delta \; x \; = \; F(x(t), x(t - \tau), \mu) + n(t)$$

Large multi-scale
Nontrivial dynamics
Nonlinearity
Delays
Uncertain parameters
Disturbance

Sensitivity

Uncertainty

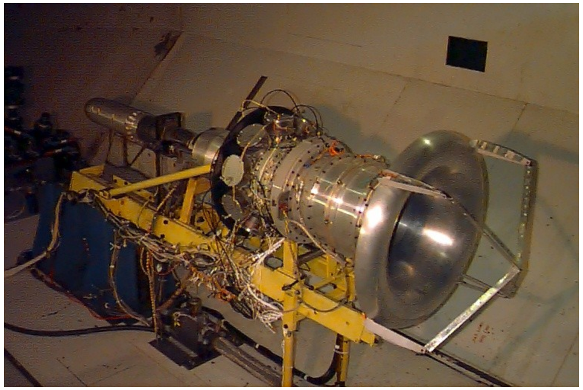
Complexity

"In the fields of thermoacoustics there are no experts. There are only victims" , frustrated engineer ~2001

Successful active control demonstrations

Fan blade flutter 1997

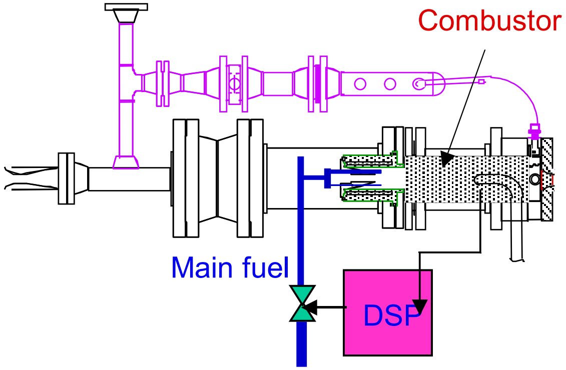
- *order of magnitude damping augmentation for three flutter modes*



Ref: IFAC 2002, CDC 2002, AIAA 2003

Thermoacoustic instability 1998

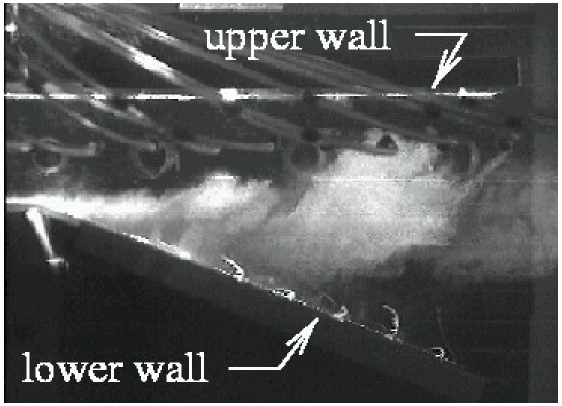
- *6x reduction in pressure amplitude in 4MW rig*



Ref: CCA99, IFAC02, AIAA04, ASME JPP03, IEEE TCST 06

Separation control 1999

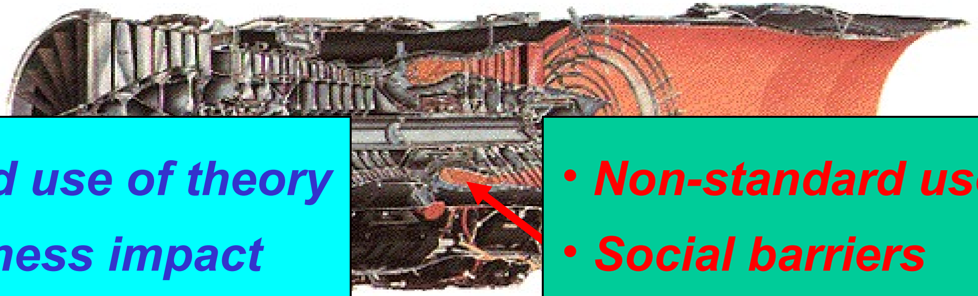
- *2x increase in diffuser pressure recovery over baseline control*



Ref: AIAA 2000, APS 2001, AIAA 2003

Passive solution is preferred => Active control did not impact product

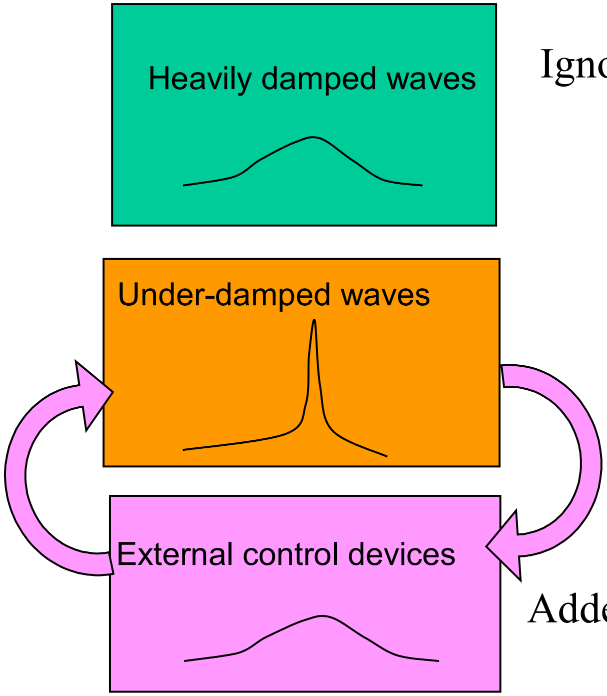
The role of dynamical systems and control theory research in the design for dynamics



- ***Standard use of theory***
- ***No business impact***
- ***Helped build credibility***

- ***Non-standard use of theory***
- ***Social barriers***
- ***Credibility needed***

Current : fix problems



Heavily damped waves

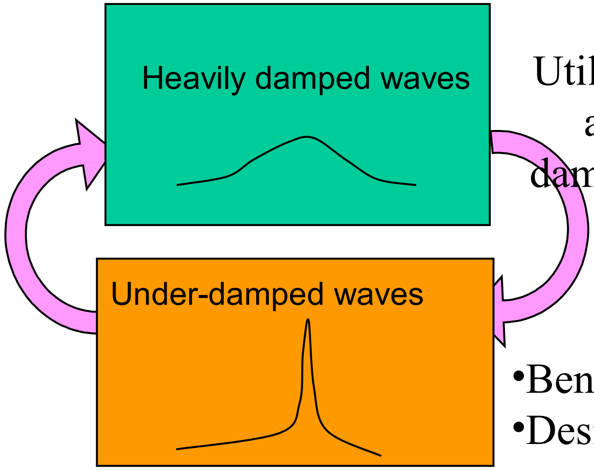
Ignored

Under-damped waves

External control devices

Added late in design cycle
⇒Δ weight, cost

Proposed : design of dynamics



Heavily damped waves

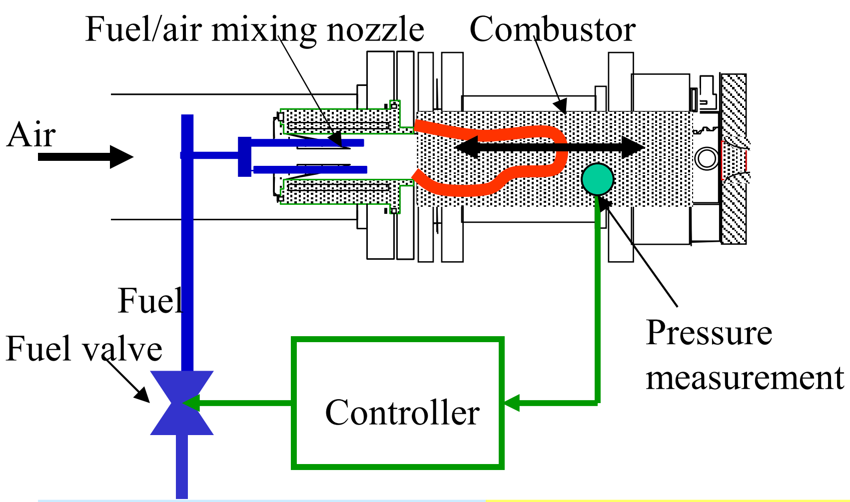
Utilized
as
dampers

Under-damped waves

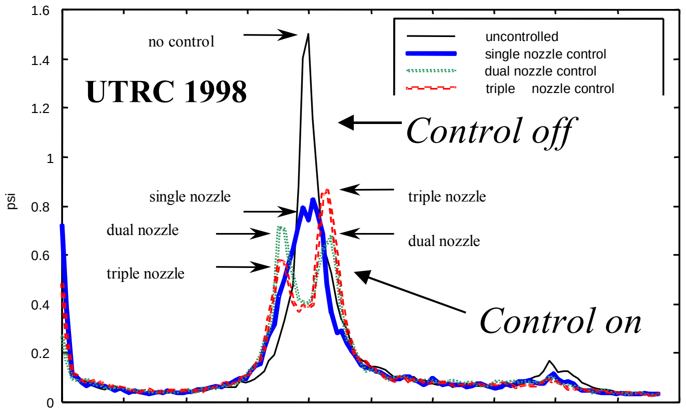
- Beneficial coupling
- Designed early in cycle

Research that helped establish credibility

8MW combustion rig



- 2x reduction achieved with two nozzles.
- Less reduction with three nozzles
- Peak splitting limits control performance



Assumptions:	**Original**	**Corrected**
Model :	*Limit cycling*	*Stable, noise driven*
Control problem:	*Stabilization*	*Broad band disturbance attenuation*
Performance limiters:	*Actuator authority*	*Fuel transport delay, actuator bandwidth*

1. Wrong model assumption => incorrect assessment of factors that limit performance
2. How to establish credibility: insight, rigor, and teaching
    - new model validation method
    - peak splitting explained
    - physics and control architecture limit performance

I. Mezic & A. Banaszuk, Physica D 2005

A. Banaszuk, P.G. Mehta, C.A. Jacobson, & A. Khibnik, IEEE TCST, 2006

3. Passive solution is preferred => Active control did not impact product

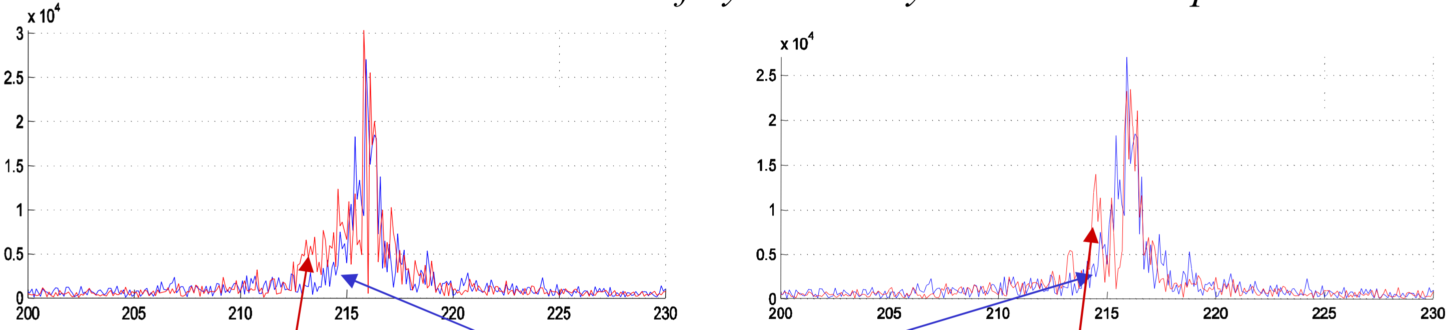
Research that helped establish credibility

Model validation for complex dynamical systems using harmonic averages

frequencies *functions on phase space*

$$\varphi^*_f(x) = \lim_{N\to\infty} \frac{1}{N}\sum_{k=0}^{N-1} e^{i2\pi fk}\varphi\underbrace{(T^k(x))}_{\text{iterates of dynamical system state or experimental data}}$$

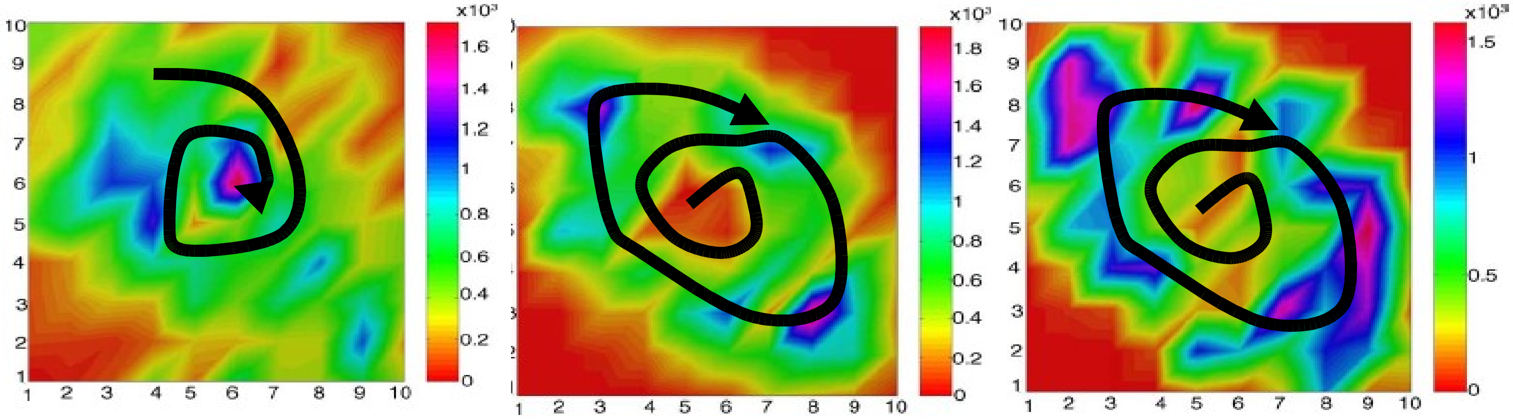
Spectra of output: cannot distinguish limit cycle from stable system



Stable model *Experiment* *Limit-cycling model*

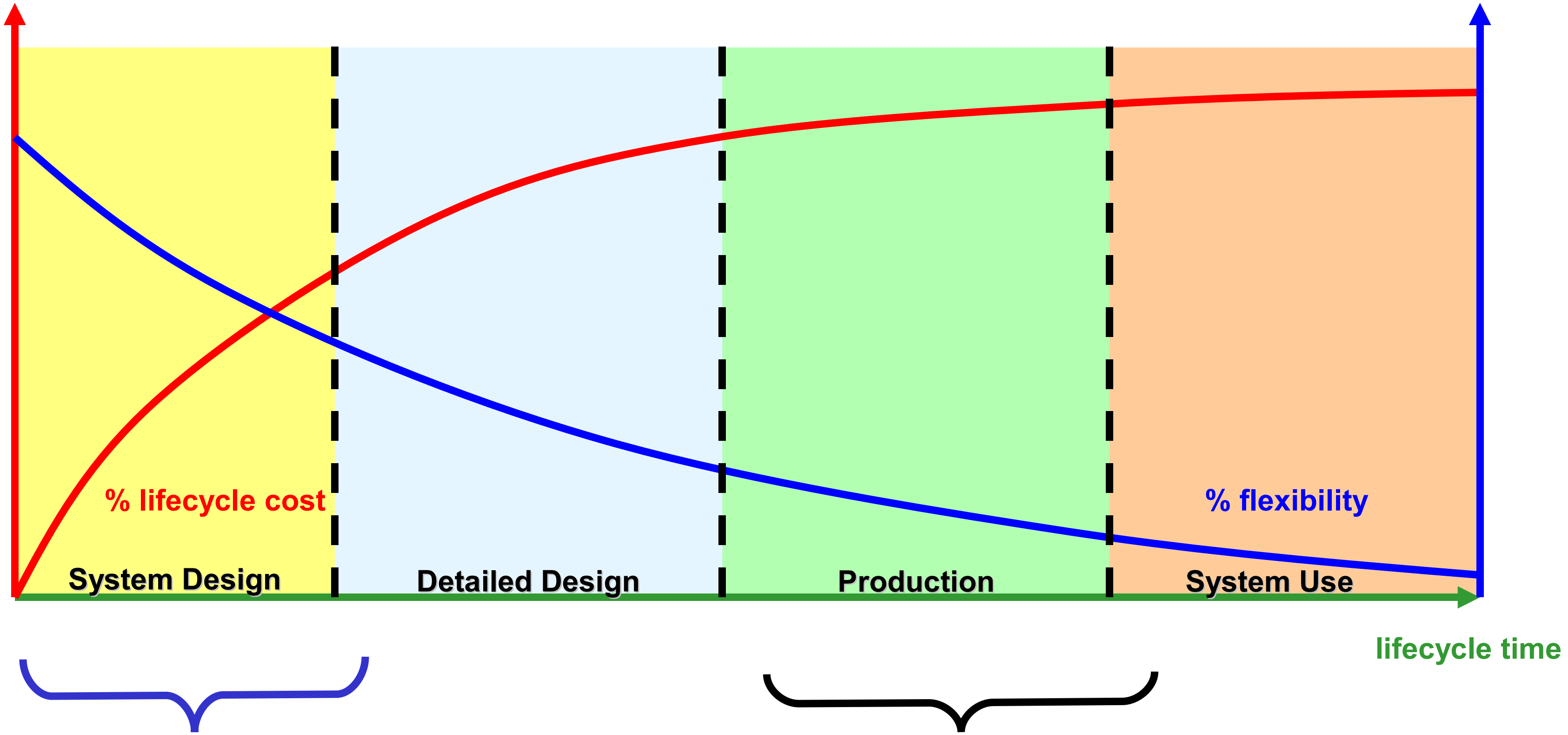
Harmonic averages of 100 indicator functions (1 on set 0 outside) for f=216.

Mezic & Banaszuk, Physica D 2005



Process Impact: Method transitioned to engine company

When Does Theory affect Design?



Desired State:

Design beneficial dynamics
=> exploit flexibility at low cost

Current State:

Detrimental dynamics discovered during hardware test

- *Active Control not feasible*
- *Passive Control preferred*

How can dynamical systems and control theory research make impact?

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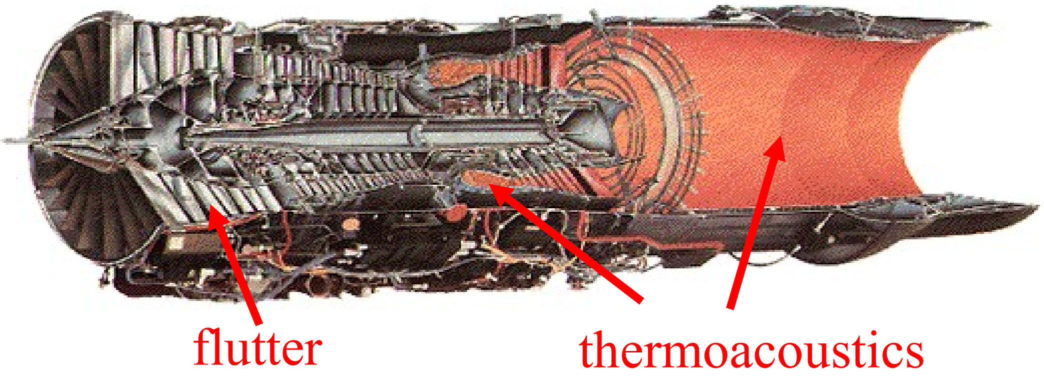
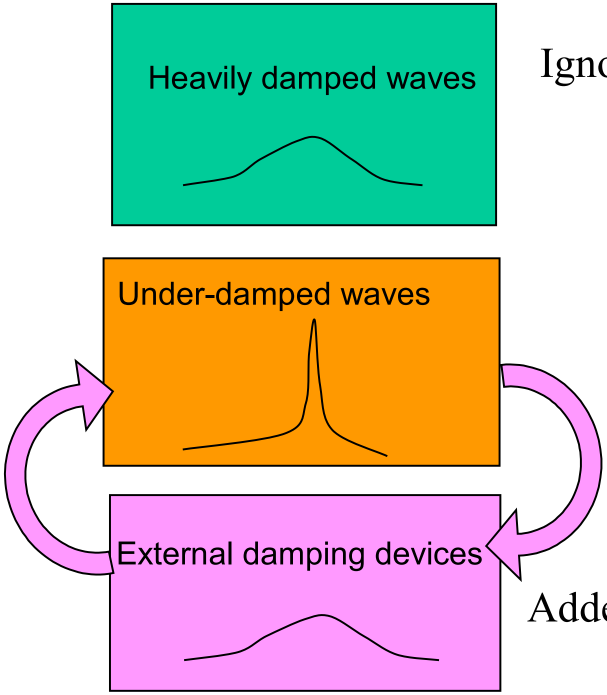
   - Design of beneficial dynamics early in design cycle
   - Social barriers and how to overcome them
   - Tools for Design of Robust Dynamics

How: Design of Beneficial **Dynamic Interactions**



Current : fix problems



Heavily damped waves

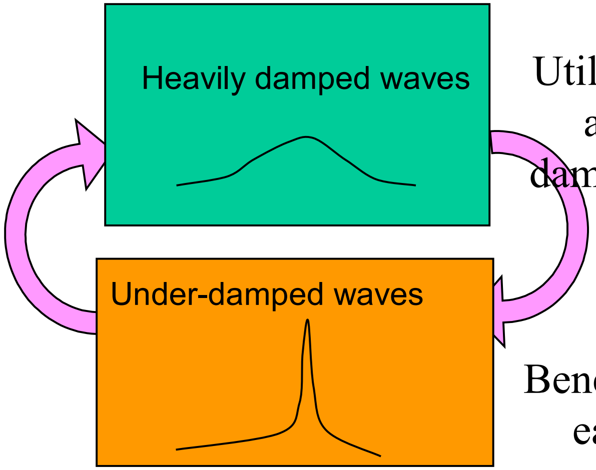
Ignored

Under-damped waves

External damping devices

Added late in design cycle
⇒Δ weight, cost

Proposed : design of dynamics



Heavily damped waves

Utilized
as
dampers

Under-damped waves

Beneficial coupling added
early in design cycle

Symmetry method as key enabler:

- **Determines root cause of detrimental waves**
- **Proves existence of heavily damped waves**
- **Shows how to create beneficial coupling**

Design of Beneficial **Dynamic Interactions**

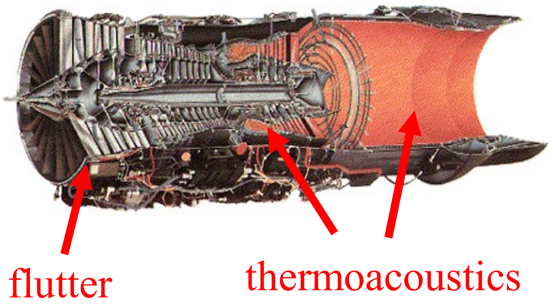
Analysis of symmetry => detrimental and beneficial interactions

Wave equation with skew-symmetric feedback

- Positive feedback => detrimental coupling
- Creates lightly and heavily damped spinning waves

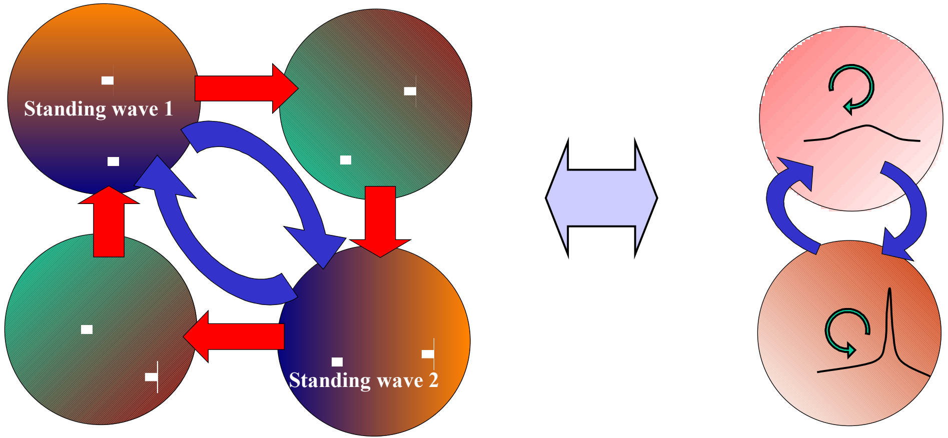
Wave speed misuning

- Beneficial circumferential wave speed pattern
- Utilize heavily damped wave to dissipate energy



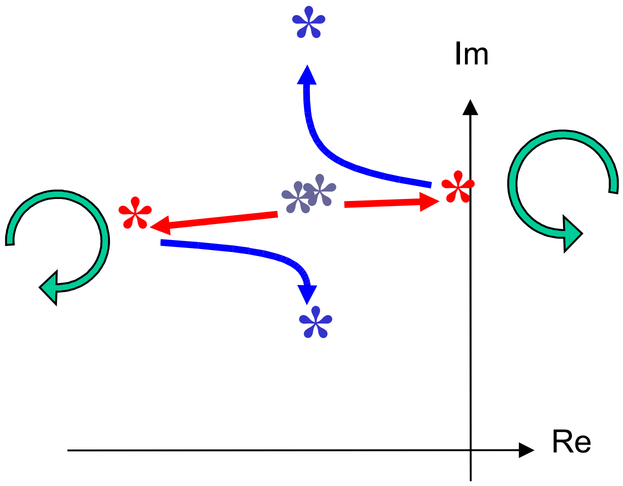
Acoustics *Structures* — *Heat release* *Aero* — *Wave Speed Mistuning*

$$p_{tt} + \xi p_t - a_0^2 p_{\theta\theta} = F(p,\theta) + a^2(\theta) p_{\theta\theta}$$



Standing wave interpretation

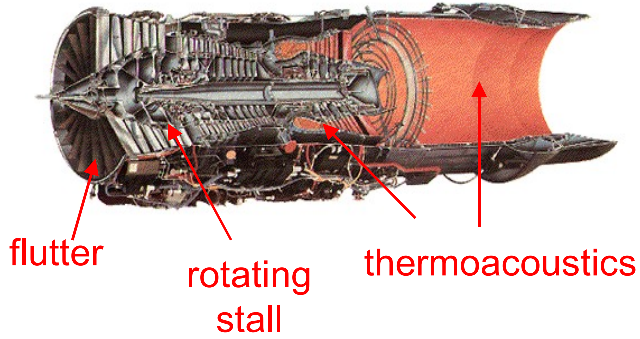
Rotating wave interpretation

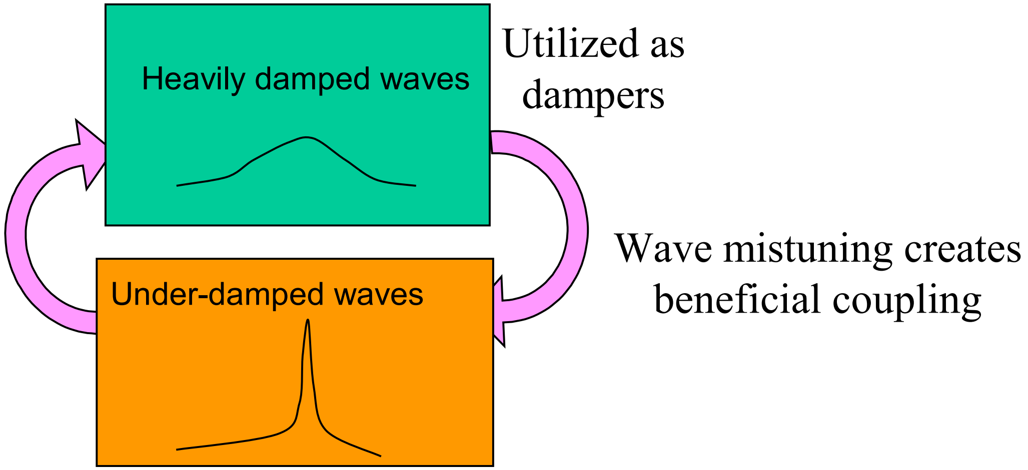


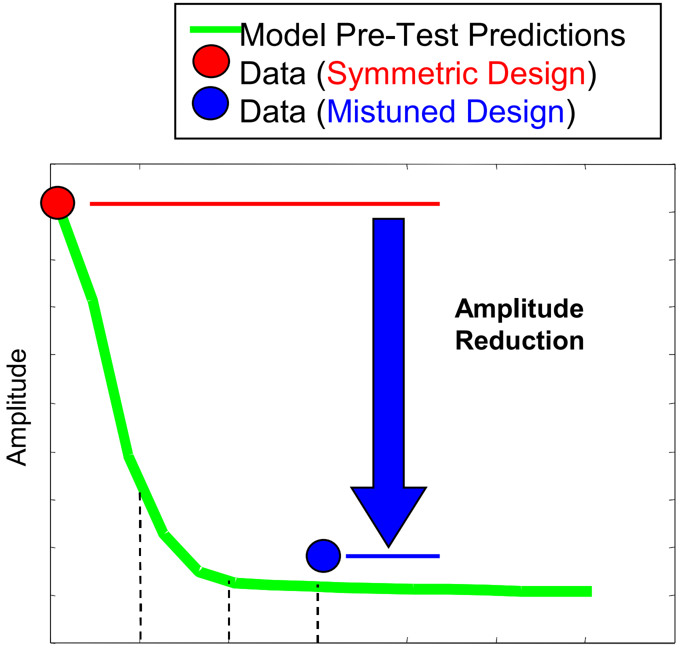
skew-symmetric feedback

Design of Beneficial **Dynamic Interactions** is feasible

4x attenuation of oscillations demonstrated in engine test







- Inspiration: study of symmetry of DNA molecules (I. Mezic)
- From initial concept to engine test in 18 months
- Enabled by chain of credibility
- Passive solution internal to the product: no extra hardware necessary

A. Banaszuk, P. Mehta, and G. Hagen, Control Engineering Practice, 2007

Detrimental and beneficial engine symmetry structure

it also works in theory …

$$p_{tt} - a_0^2 \; p_{\theta\theta} \;=\; -b(1 - p_{t\;\theta\theta}) + m p_\theta \; + a_2^2 \; \cos(2\theta) \, p_{\theta\theta}$$

Acoustics
Wave Operator

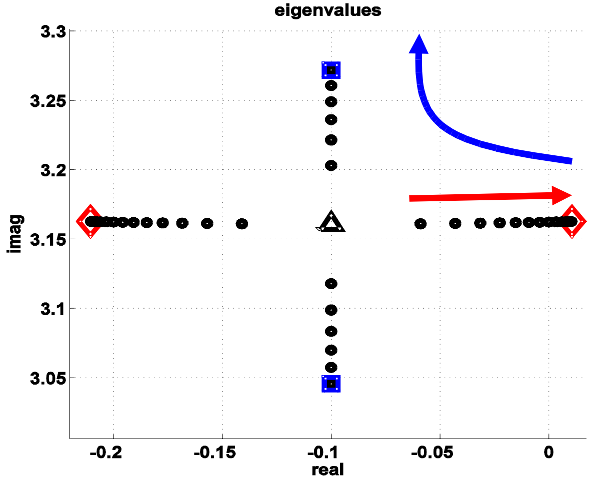
Acoustic Damping
Symmetric
Beneficial

Heat Release
Skew - Symmetric
Detrimental

Wave Speed Mistuning
Beneficial

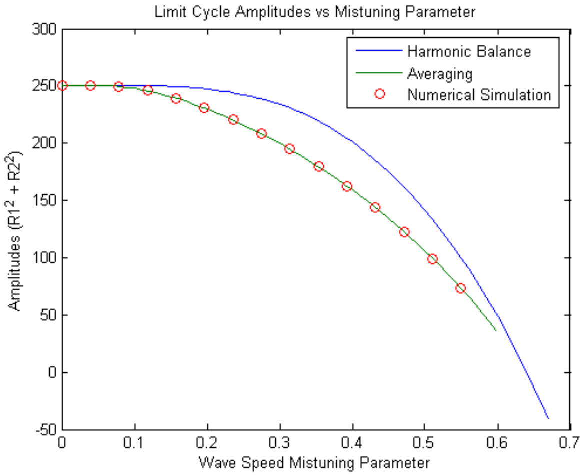
Destabilizing effect of combustion compensated by wave speed mistuning

Eigenvalue plots for first tangential mode



P. Mehta, G. Hagen, and A. Banaszuk, SIAM Journal of Applied Dynamical Systems, 2007

Averaging analysis of a nonlinear model



B. Eisenhower, G. Hagen, A. Banaszuk, and I. Mezic, Journal of Applied Mechanics, 2007

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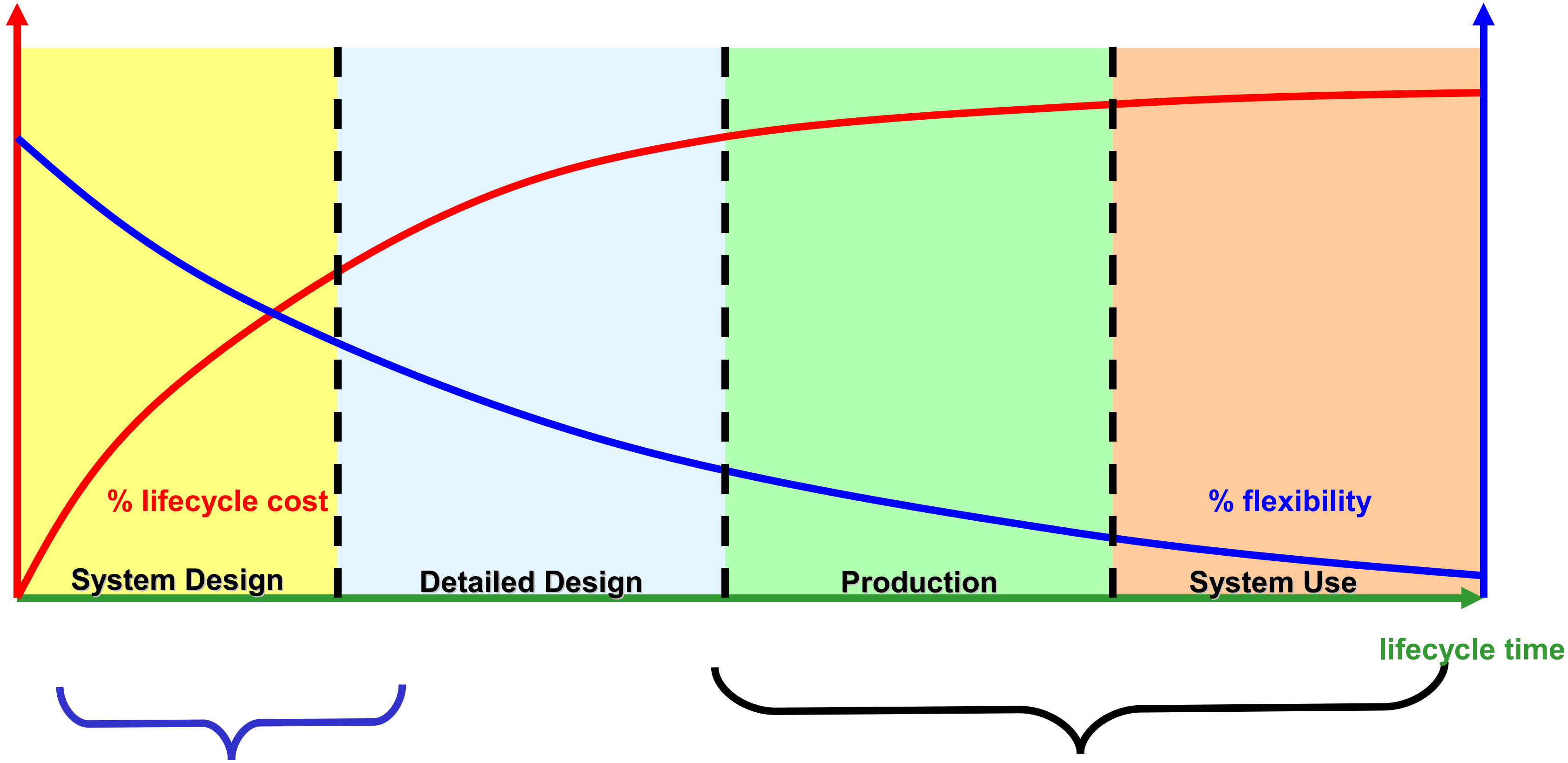
How to increase impact of Theory on Design?



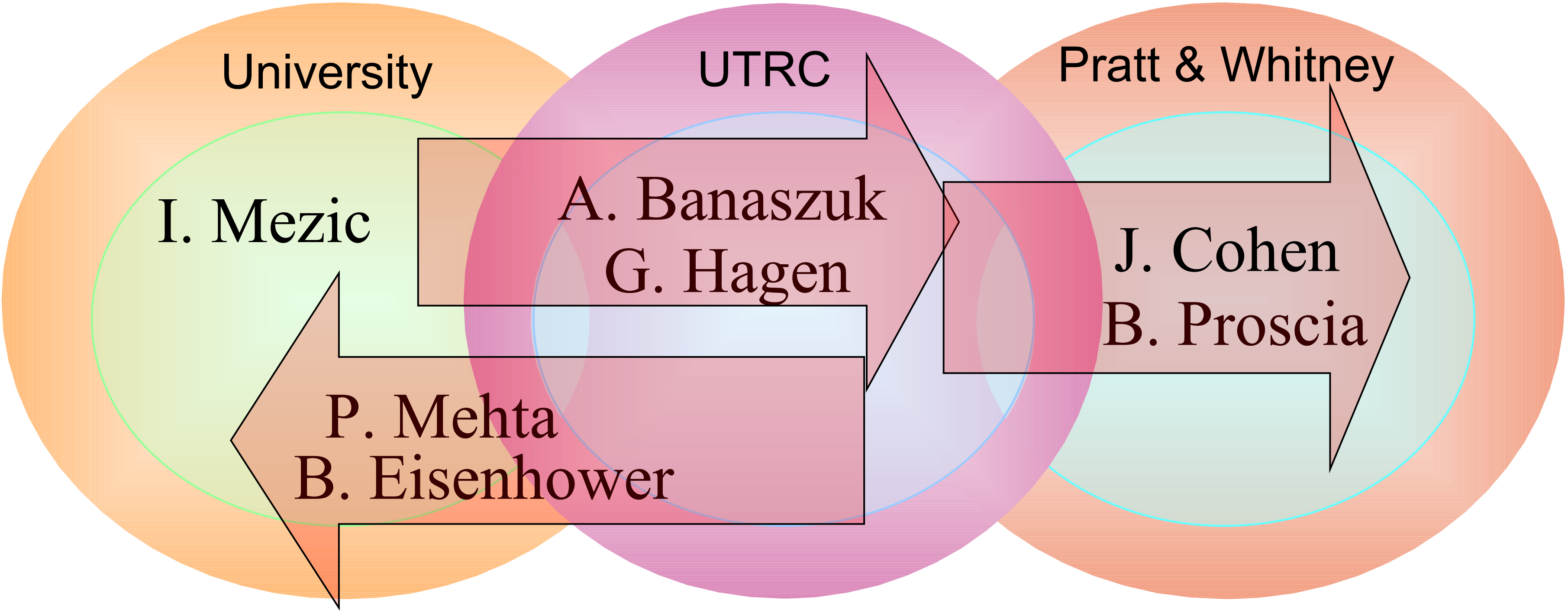
Desired: design beneficial dynamics
=> exploit flexibility at low cost

Current: attempt to fix detrimental
dynamics late in design cycle

Success Stories ⇐ ***Education*** ⇐ ***Credibility*** ⇐ ***Crisis***

Management ***Technical personnel***

People transitions facilitate technology transitions



University

UTRC

Pratt & Whitney

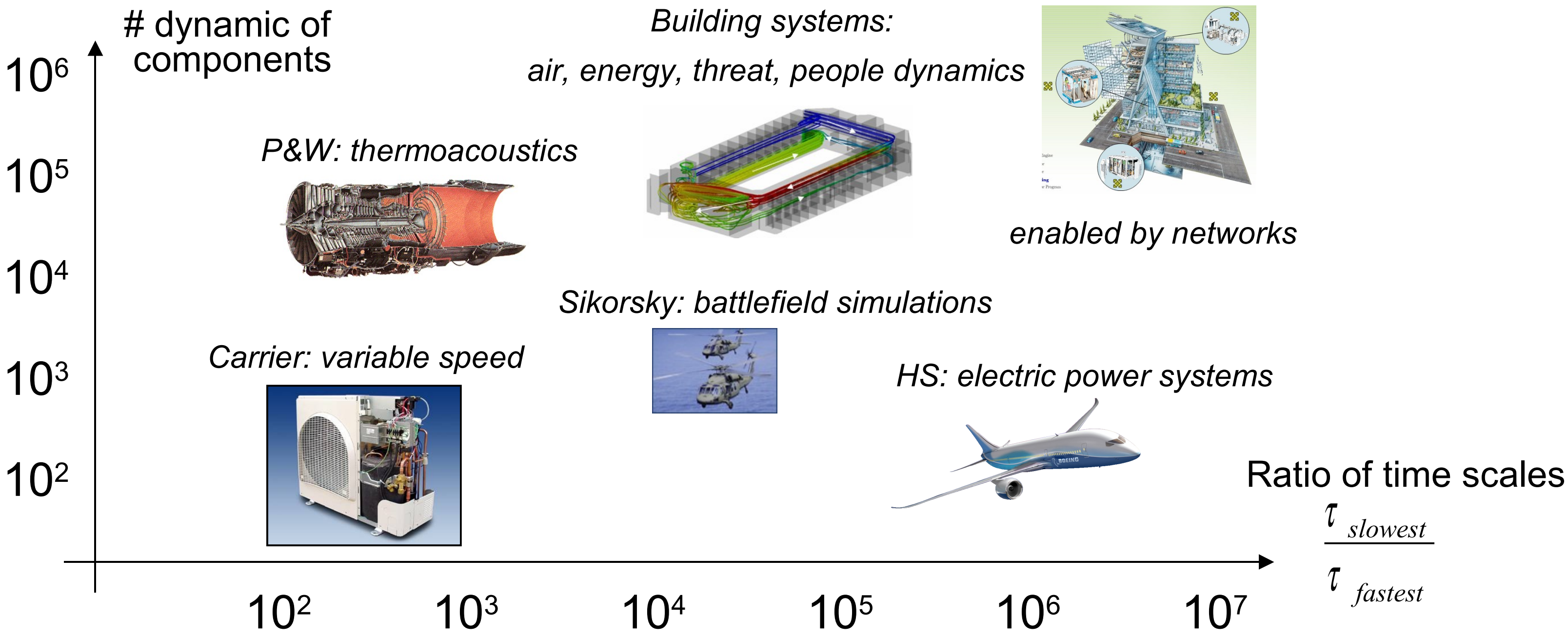
I. Mezic

A. Banaszuk
G. Hagen

J. Cohen
B. Proscia

P. Mehta
B. Eisenhower

Multi-scale complex dynamics affects UTC



Computation: Develop hierarchical models at different abstractions; cope with wide time scale separations; address heterogeneity in systems;

Analysis: Shape multi-scale dynamics; quantifying effects of uncertainty;

Learning: Coarse models from data for decision support

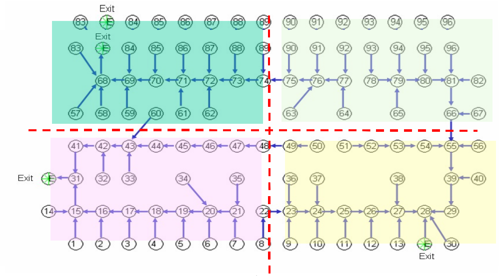
Multi-scale dynamical systems

barriers and enablers

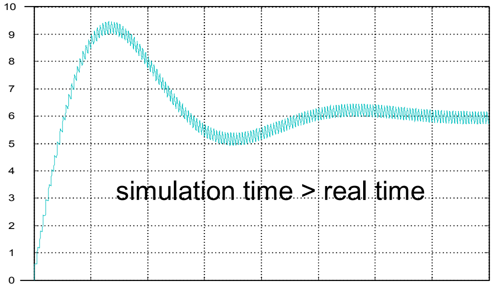
Computation cost $\sim n_{nodes} \bullet n_{links} \bullet n_{timesteps} \bullet n_{samples}$

Barriers

Large interconnected network

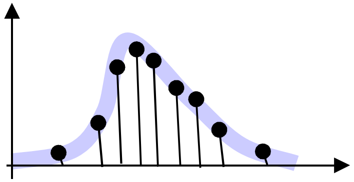


Multiple time scales



simulation time > real time

Uncertain parameters



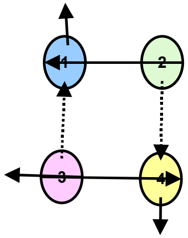
Enablers

Coarse spatial variables

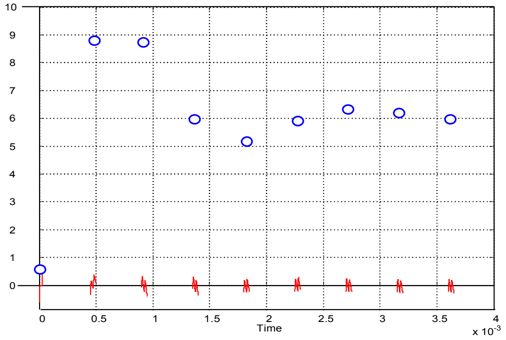
Coarse stochastic variables

Coarse temporal integration

Network decomposition



Exploit interconnections



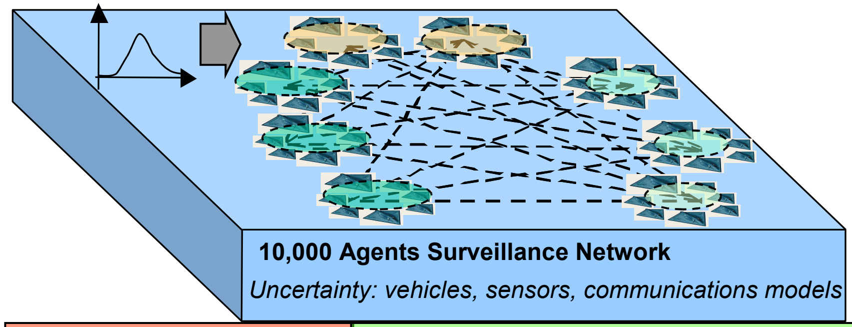
Learn Model of Coarse Dynamics

Tractable description

- ***Simulations***
- ***Analysis***
- ***Design***

***Dy**namic **N**etwork **A**nalysis for **R**obust **U**ncertainty **M**anagement*

DARPA invests in Tools for Design of Robust Dynamics



10,000 Agents Surveillance Network

Uncertainty: vehicles, sensors, communications models

Objectives:

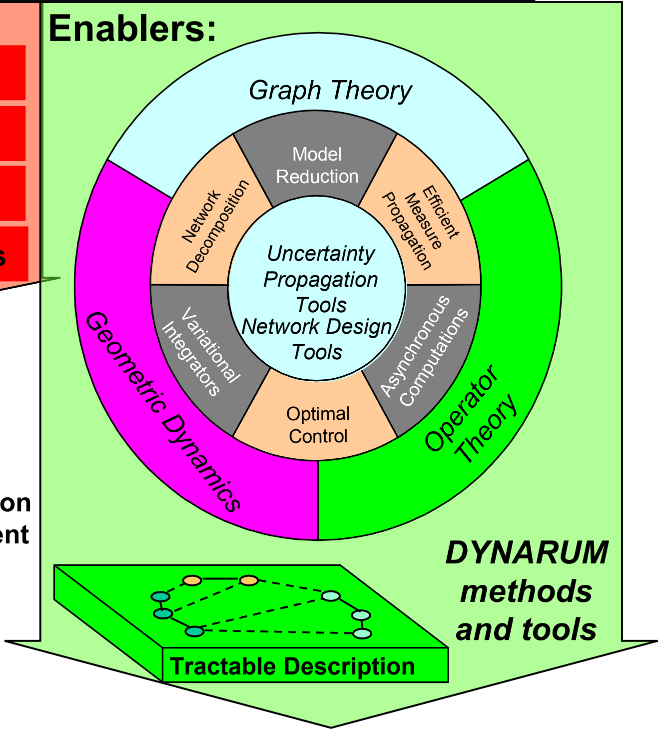
2. Develop analysis and design tools for Uncertainty Management
3. Demonstrate tools in a surveillance problem with > 10,000 agents

Barriers

- **Large Scale**
- **Multiscale**
- **Uncertainty**
- **Nontrivial Dynamics**

Uncertainty Propagation Intractable With Current Methods

Enablers:



Graph Theory

Model Reduction

Network Decomposition

Efficient Measure Propagation

Uncertainty Propagation Tools

Network Design Tools

Variational Integrators

Asynchronous Computations

Optimal Control

Geometric Dynamics

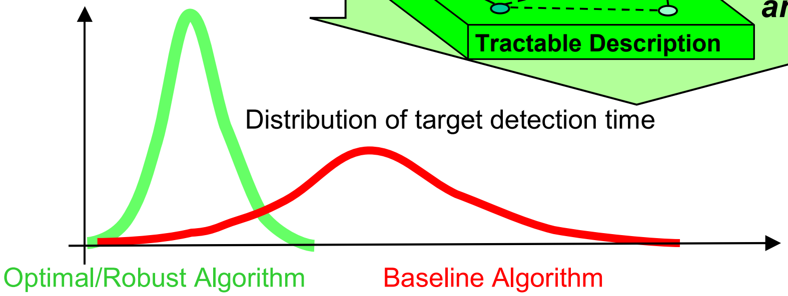
Operator Theory

Tractable Description

DYNARUM methods and tools

Approach :

- *Decompose networks* into components using Spectral Graph Theory.
- *Propagate uncertainty through components* using Operator Theory and Geometric Dynamics
- *Iteratively aggregate component uncertainty*



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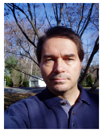

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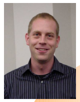

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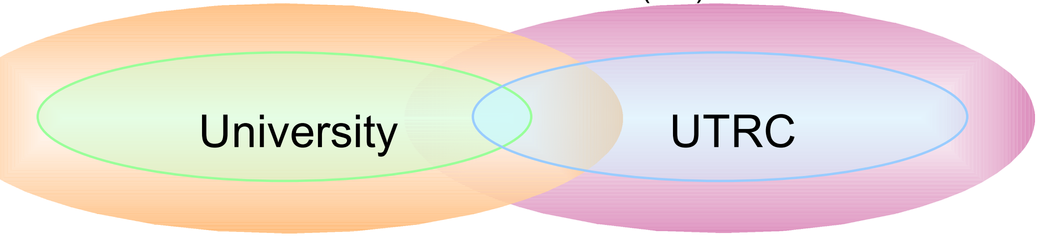
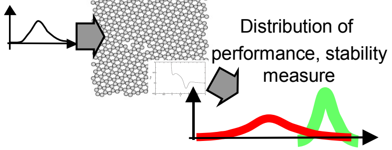


University

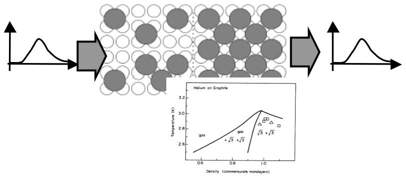
UTRC

DyNARUM Methods and Test Problems

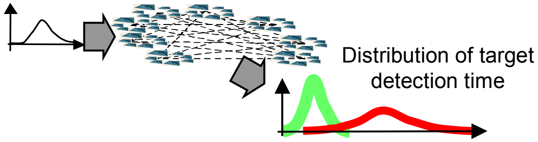
Self-assembly (~100 particles)

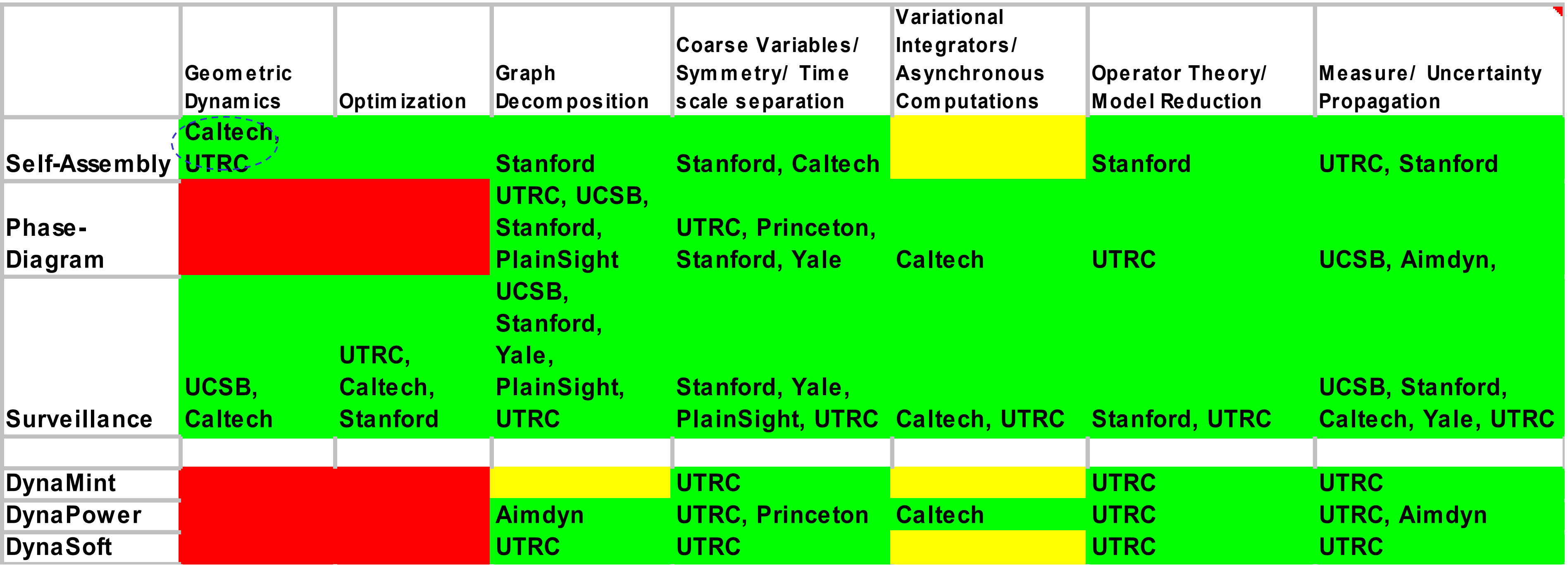


Phase diagram (10K particles)

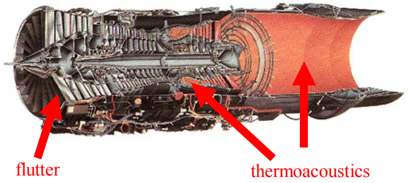


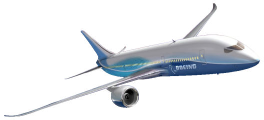
Surveillance network (10K agents)

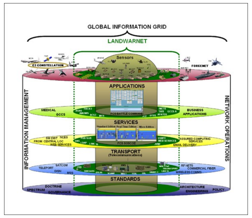




	Geometric Dynamics	Optimization	Graph Decomposition	Coarse Variables/ Symmetry/ Time scale separation	Variational Integrators/ Asynchronous Computations	Operator Theory/ Model Reduction	Measure/ Uncertainty Propagation
Self-Assembly	Caltech, UTRC	🟩	Stanford	Stanford, Caltech	🟨	Stanford	UTRC, Stanford
Phase-Diagram	🟥	🟥	UTRC, UCSB, Stanford, PlainSight	UTRC, Princeton, Stanford, Yale	Caltech	UTRC	UCSB, Aimdyn,
Surveillance	UCSB, Caltech	UTRC, Caltech, Stanford	UCSB, Stanford, Yale, PlainSight, UTRC	Stanford, Yale, PlainSight, UTRC	Caltech, UTRC	Stanford, UTRC	UCSB, Stanford, Caltech, Yale, UTRC
DynaMint	🟥	🟥	🟨	UTRC	🟨	UTRC	UTRC
DynaPower	🟥	🟥	Aimdyn	UTRC, Princeton	Caltech	UTRC	UTRC, Aimdyn
DynaSoft	🟥	🟥	UTRC	UTRC	🟨	UTRC	UTRC







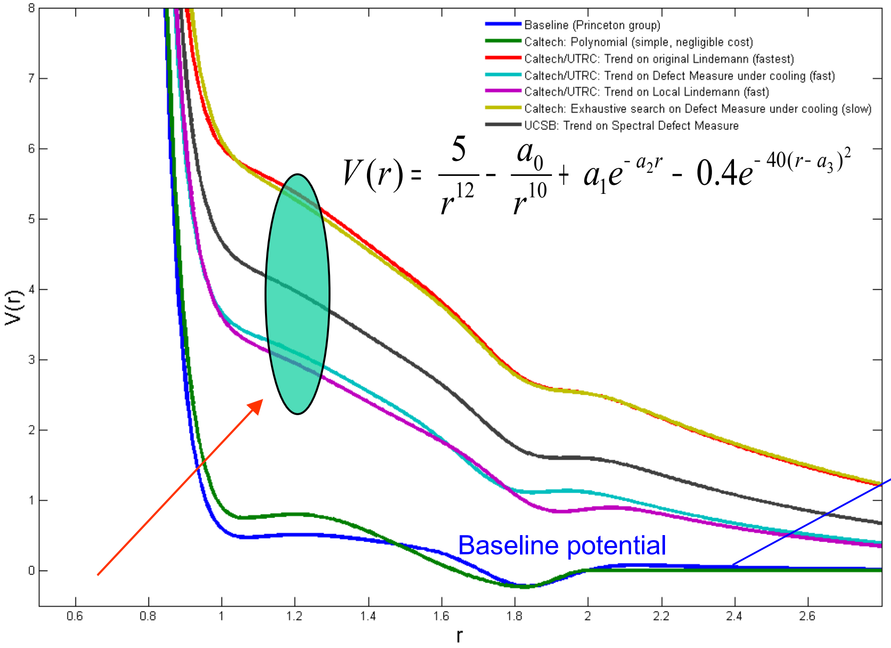
🟩 Under evaluation or planned

🟨 Possible, not planned

🟥 Unlikely

Design of Dynamics: new potential design method demonstrated in Self-Assembly problem

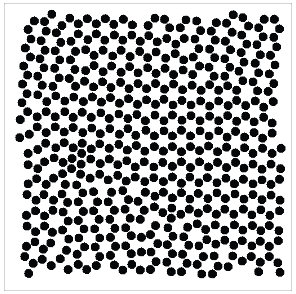
Particle interaction potentials



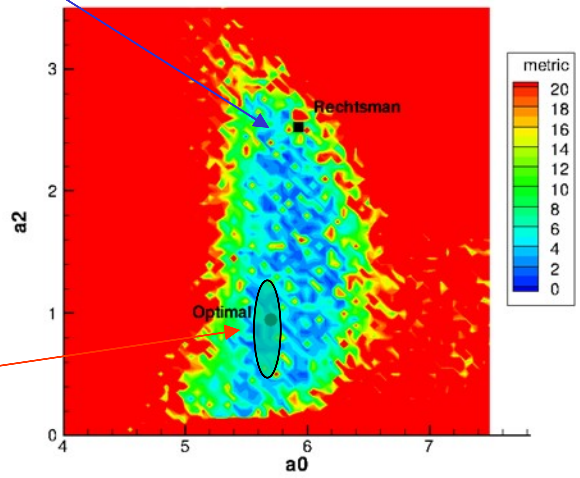
$$V(r) = \frac{5}{r^{12}} - \frac{a_0}{r^{10}} + a_1 e^{-a_2 r} - 0.4e^{-40(r-a_3)^2}$$

Goal: Design interaction potential so that 100 particles self-assemble to a honeycomb lattice

Baseline (Princeton 2005):
- Final lattice still has defects
- Computationally expensive (Simulated Annealing gets stuck in local minima of a defect measure)

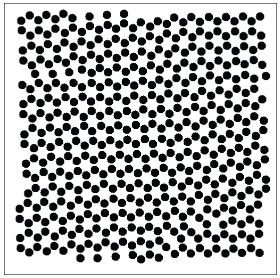


Defect measure

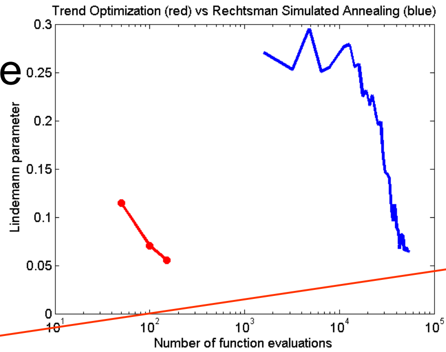


DyNARUM:

- Repulsive potentials avoids defects produced by local minima
- Trend-based optimization 100x faster than Simulated Annealing



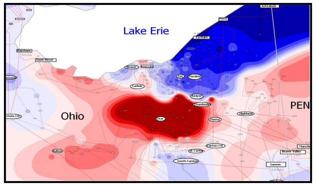
Defect measure



Molecular Dynamics runs

Challenge: Model-Based Robust Design of Cyber-Physical Systems: complex physics, IT-integrated products, uncertain environment

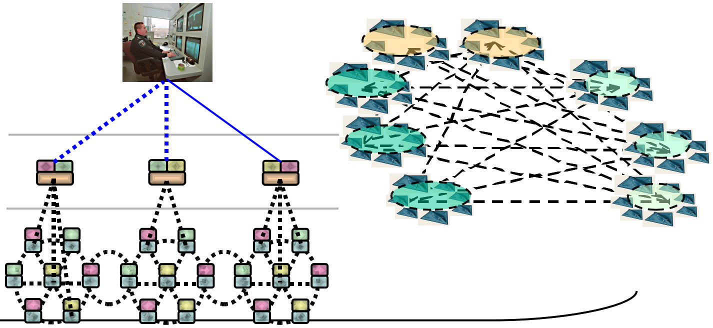
Power grid control



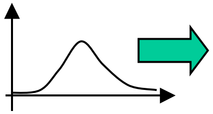
City evacuation support

Emergency response support

Surveillance networks

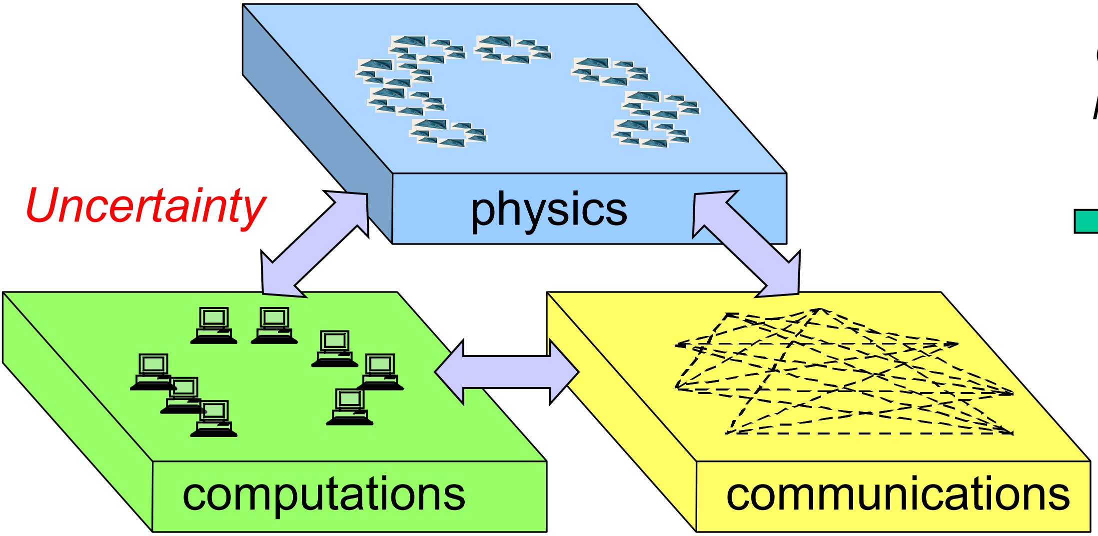


Input parameter probability distribution



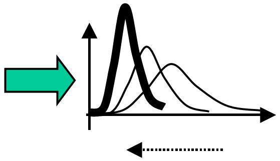
Complex dynamics

Uncertainty



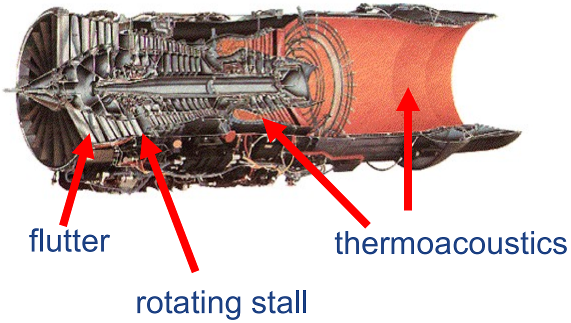
No time scale separation

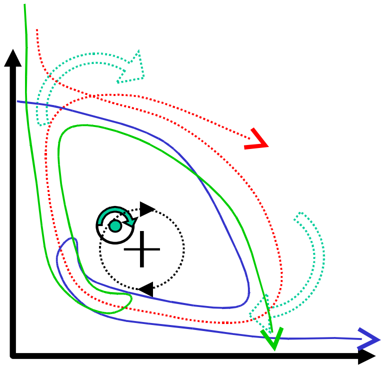
Output parameter probability distribution

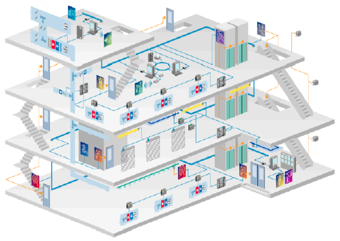


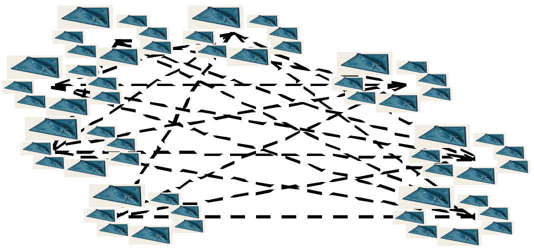
Reduced uncertainty with robust design

The role of theory in the design for dynamics




Unsteady flows, mixing


Building systems


Robust surveillance networks

Current: limited	Proposed: critical path
Reactive: late	Proactive: early
Excluded: minimal impact	Engaged: integrated in design
Narrow: algorithm	Broad: architecture, passive
External: add hardware	Internal: utilize physics

How can dynamical systems and control theory research make impact?

1. Research that did not make impact:
    - Fixing engine problems using active control
    - Passive design wins

2. Research that made impact
    - Model validation
    - Passive design of beneficial dynamic interactions

3. How to increase impact of theory on design:
    - Design of beneficial dynamics early in design cycle
    - Social barriers and how to overcome them
    - Tools for Design of Robust Dynamics