# Physics-Based Stability and Control Derivative Measurement (PSCDM)

NASA Aeronautics Research Institute


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Separating/estimating circulatory and non-circulatory forces for S&C derivatives to implement circulation-based robust aeroservoelastic control

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# Outline



**Motivation and background**

**Vorticity state estimation for circulation control**

**PSCDM: Results to-date (PTERA, TAMU)**

**ARMD (FAP) / X-56A / F18 / etc.**

**Distributed sensing/controls**

***Applications* and partnerships**

# Distributed Physics-Based Aerodynamic Sensing

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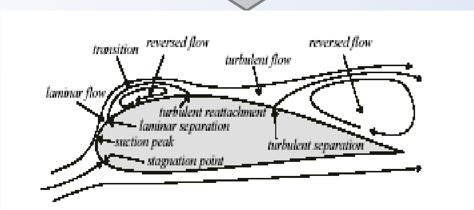
## STATUS QUO

***Lightweight configurations => inherently flexible***

***Current limitations:***

- *Complex aerostructural control*
- *Limited aerodynamic observables*
- *Measurement/inertial uncertainty/lags*
- *Cost-ineffectiveness / hi-maintenance*




## NEW INSIGHTS

**Flow bifurcation point (FBP) model captures stagnation point, stall, separation, SBL flow dynamics**

***Aerobservable*-based analytic codes**

**Distributed sensing/control apps with spatio-temporal feedback**

**V&V of CFD/CSD for unsteady ASE**

**Aero coefficient estimation**

**Force-feedback framework**

**GLA/LCO control; flutter prevention**

**MAIN ACHIEVEMENT:**

Relevant Sensor Information-based Distributed Aeroservoelastic Control for Reliability, Effective Performance and Robustness

**Challenges**:

Physics-based architecture

Distributed control with alternative sensors

Information-based sensing for efficient mission adaptivity with aerostructural control

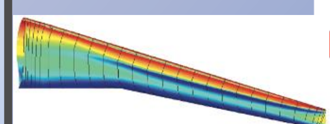
Development of physics-based analytical aerostructural feedback mechanism

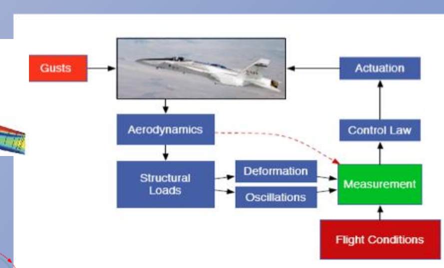
**HOW IT WORKS:**

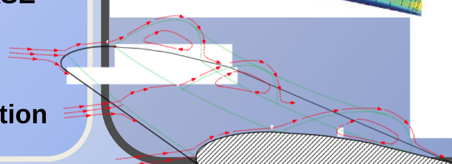
Real-time aerodynamic force measurement improves aerostructural performance and efficiency across all flight regimes (sub/tran/sup/hyper)

Redundancy with analytical sensing critical to reduce aerostructural uncertainty

Decouples the aerodynamics (forces) from the structural dynamics (responses)





## QUANTITATIVE IMPACT

**[FAP] Reduce drag & weight; Increase performance & energy efficiency; Improve CFD-CSD and experimental tools & processes with reduced uncertainty; Develop/test/analyze advanced multi-disciplinary concepts & technologies;**

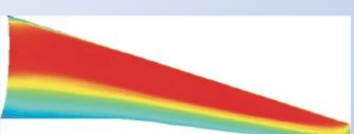
**[AvSP] LOC prevention, mitigation, and recovery in hazardous flight conditions**

**AFRL/LMCO (MUTT), NASA-OCT**

**Partners: IIT, TAMU, Caltech, UMN, SBC (sensing)**

## PROGRAM GOALS

- Design and simulate robust control laws (UMN, SBC, DFRC) augmented with the aerodynamic observables
- Conduct wind tunnel tests (TAMU) and flight test (DFRC) to validate the controls
- **Ultimate objective is to determine the extent of performance improvement in comparison to conventional systems with multi-functional spatially distributed sensor-based flight control**



**Flight systems operating near performance and stability limits require continuous, robust autonomy through real-time performance-based measurements**

# Physics-Based Stability and Control

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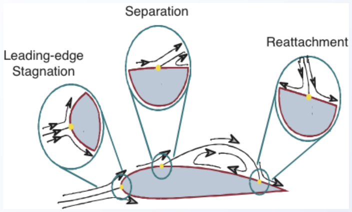



Lightweight structures => inherently flexible

Current limitations:

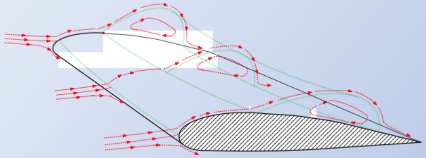
- Aerostructural model uncertainty
- Limited aerodynamic observables
- No flow separation or shock info
- Measurement/inertial uncertainty/lags
- Actuator uncertainty/lags

Flow bifurcation point (FBP) model maps surface flow topology to aerodynamic coefficients (CL, CM, CD)

Distributed sensing/control enabled with spatiotemporal aerodynamic feedback

Force feedback enabled by sensing FBPs, *aerobservables*

Robust control enables stability under sensor, actuator & model uncertainty



## *Theoretical/experimental tools to validate stability and performance of robust and distributed control with physics-based sensing*

Validate robust control laws augmented with aerodynamic observables in aerostructural wind tunnel (WT) / flight test (FT)

## Challenges:

- Development of analytical codes for nonlinear aerodynamics with compressibility effects
- Developing aeroservoelastic (ASE) sim with unsteady aerodynamics for developing robust control laws
- Developing low-power sensor technology robust in operational environments

## Critical Technologies:

- FBP model for CL/CD/CM for subsonic/transonic flows
- Low power/noise instrumentation and DSP techniques
- Sensor, actuator & ASE model including uncertainties
- Robust control for sensor/actuator/model uncertainties

## Approach:

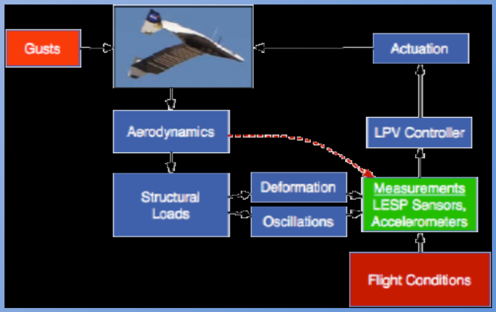
- Design/validate robust control laws for ASE WT/FT
- Develop FBP-based model including compressibility
- Develop low-power FBP sensor array

**Operating near performance and stability limits requires real-time force feedback**

Improved worst-case performance under uncertainty

- Gust load alleviation
- Flutter prevention envelope
- Suppression of limit cycle

Feedback control performance is limited by time-delay




- Provide technology foundation for an autonomous Fly-by-Feel platform demonstrating:
  - Aerodynamic / structural efficiency for range /endurance
  - Mission-adaptive capability
  - Maneuverability

# PSCDM Seedling: Innovation Elements



Developments in high-aspect ratio wings (structural efficiency) and quiet low-speed performance (aerodynamic efficiency) for next-generation aircraft require **change in measurement/control** to effectively address the range of maneuver and nominal/off-nominal flight conditions.

Conventional approaches using global air data and structural feedback will need to be augmented to improve gust load alleviation and circulation control to **autonomously and intelligently sense the aerodynamic environment** and **efficiently adapt the aircraft structure and control surfaces** to suit the current mission objectives.

Seedling project develops a localized system that (1) separates aerodynamic forces and moments into **circulatory and non-circulatory components**, and (2) estimates and **controls each component** independently at each span station.

System **re-derives the conventional stability and control (S&C) derivatives**, where the circulatory and non-circulatory components are focused on the aerodynamics and structural dynamics, respectively.

- Ability to track surface flow topology, e.g., leading-edge stagnation point, flow separation
- Analytical relationship of the spatio-temporal surface flow topology to circulation
- Ability to measure total inertial response.

# PSCDM Seedling: Objectives / Approach

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*Phase 1* investigated the **effectiveness of the new approach** in separating/estimating circulatory and non-circulatory forces for S&C derivatives.

**Validated computational models** predicting circulatory and non-circulatory forces using surface flow topology states

Ultimate ambition is **aerostuctural performance** (lift/drag/moment/load) advancement with distributed sensor-based flight control

*Phase 2* **extends the results to a flexible-wing** (X-56A) vehicle implementing circulation-based robust aeroservoelastic control

- Develop new stability and control derivative model separating circulatory and non-circulatory components
- Computationally model the dynamic interactions and uncertainties in aerodynamics, structures, sensing and actuation
- Conduct tests to estimate circulatory and non-circulatory forces to validate the computational results

# PSCDM Seedling: Objectives / Approach

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Flow bifurcation point sensors are used to estimate - in real-time without the delay of structural response - circulatory components of aerodynamic forces and moments which could be used as **direct aerodynamic force feedback for circulation control**, and accelerometers to estimate the total non-circulatory component of aerodynamic forces and moments

Sensors are integrated in a physics-based architecture that improves reliability, control effectiveness and robustness through a **spatially distributed network**

Provide *for the first time* an in-flight separation and estimation of circulatory and non-circulatory components of aerodynamic forces and moments **enabling fine-scale circulation and aeroservoelastic control**

Satisfy above needs with a **physics-based embedded distributed sensor architecture**

Provides a foundation for control of sub/tran/supersonic aircraft, including UAVs and long-endurance platforms, using **intelligent sensing with distributed control methodology**

Basis for transitioning architecture to platforms for **circulation control** with aeroelastic or novel flush aerodynamic sensing experiments

# Vorticity State Estimation For Aeroelastic Control (1)



**Innovation Description:**

**Assess the time-accurate unsteady aerodynamic loads and moments** for each lifting surface under nominal and adverse flow conditions

**Physics-based analytical model** to map the time history of flow bifurcation points (e.g., leading-stagnation point, flow separation) and pitch/plunge states to vorticity and aerodynamic coefficients for unsteady flows

Development of feedback-based **active flow control system utilizing vorticity state**

Development of a **flow control system that utilizes advanced sensors and a vorticity state estimator (VSE)** to reach flow states unattainable without continuous control feedback

**Verify and calibrate the vorticity state model** with a high-fidelity CFD model

Validate the vorticity state model with unsteady aerodynamic data

# Vorticity State Estimation For Aeroelastic Control (2)



Develop flow control system that utilizes advanced sensors and vorticity state estimator (VSE) to reach flow states unattainable without continuous feedback control

- development of analytical VSE model verified with CFD simulation
- unsteady CFD simulation development to aid in the development of better measurement techniques more closely tied to CFD output
- **wind tunnel data analysis to support the VSE development**

Primary objectives of this effort were to:

- Develop a spatially and temporally accurate robust sensor model for the surface flow states in the presence of significant flow unsteadiness
- Develop an analytical model that simulates the dynamics of vortex states and surface flow states with pitch/plunge rate and control surface deflections
- Verify and calibrate the vorticity state model with a high-fidelity CFD model
- Validate the vorticity state model with unsteady aerodynamic data

Effort included:

- Development of time-accurate surface flow state sensors robust to noise and ambient environmental variations
- Analytical modeling mapping the measured surface flow state(s) to vorticity state
- V&V of the analytical model with CFD model and data from an instrumented wing mounted on a load balance in the Texas A&M wind tunnel for forced pitch/plunge experiments

# Vorticity State Estimation For Aeroelastic Control (3)

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Analytical model for estimating the unsteady aerodynamic forces and vortex state from the surface states, i.e., flow bifurcation points (FBPs) like leading-edge stagnation point (LESP) and flow separation point (FSP), requires the understanding of phasing with respect to what is measured (FBPs) versus what is needed to estimate (unsteady aerodynamic lift)

Unsteady potential flow models decompose the force and moment on the wing into contributions from circulatory (i.e., vortex-induced) and non-circulatory (i.e., inertial or added mass) effects. Circulatory forces are accounted for by directly computing the influence of vorticity.

Verification of analytical model with a well-known existing Greenberg model and CFD

- Left: lift amplitude normalized with steady-state lift as a function of reduced frequency, k, of the harmonic surge oscillation; Right: phase as a function reduced frequency

Adding more lift terms as calculated using the unsteady potential flow model, the results match the Greenberg unsteady potential flow model and the CFD simulation.

Note that quasi-steady component and wake contribution is the circulatory component and added mass is the inertial (non-circulatory) component of lift.

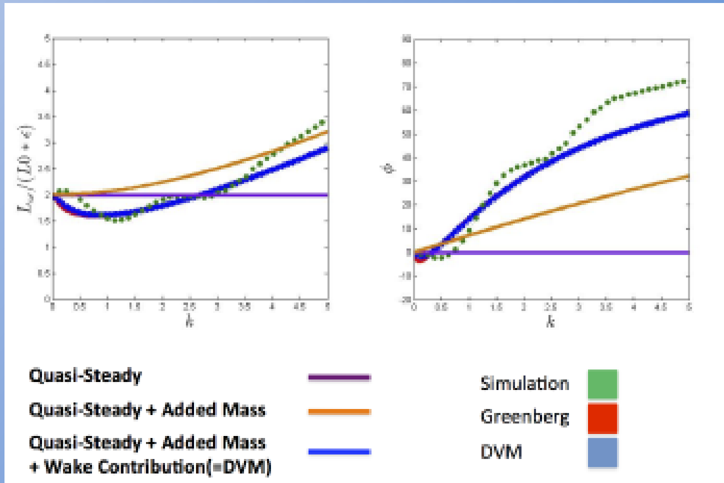

Figure 1: Components of lift and their phasing

# Vorticity State Estimation For Aeroelastic Control (4)

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Figure 2 depicts (1) potential flow at a time instant during an unsteady motion, and (2) the tracked LESP and FSP points as the wing oscillates in time. The FBP at the lower part of the plate corresponds to LESP, and the FBP for the upper plate corresponds to FSP.

Figure 3 shows relationship between the total lift coefficient for an unsteady motion and the LESP and FSP. Since LESP and FSP are related to circulatory lift and not the non-circulation component, i.e, added mass, the initial spike and the large drop in lift just before 1.5 normalized time periods are related directly to the added mass effects of abrupt motion and inertial effects of the fluid on the wing. Zero skin friction (LESP, FSP) is related only to vorticity and not inertial comp.

**Tracking of LESP and FSP => tools to measure circulatory forces independent of inertial forces - enables control of circulatory and non-circulatory forces relatively independently**

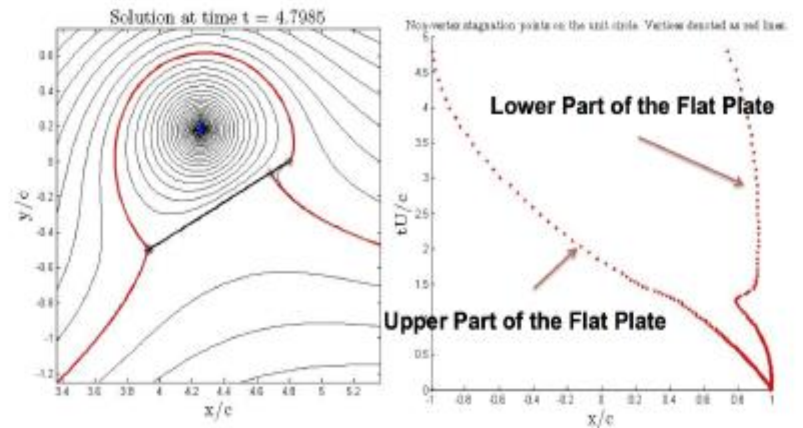

Figure 2: Unsteady potential flow model with identified LESP and FSP

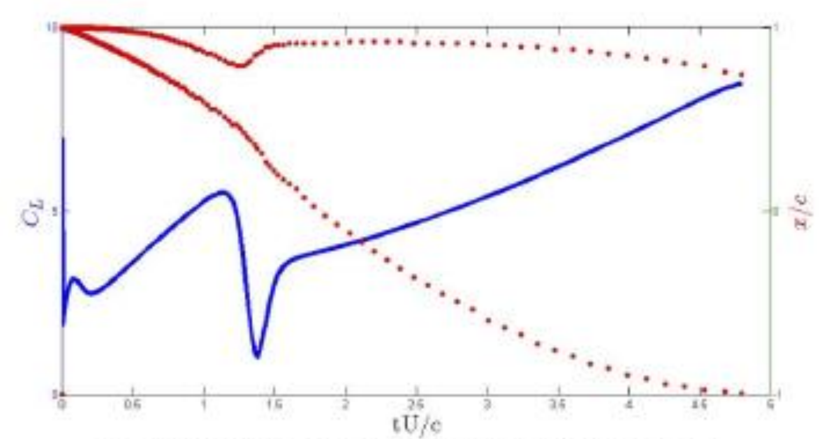

Figure 3: Relationship between lift and LESP and FSP

# Vorticity State Estimation For Aeroelastic Control (5)



Control of circulatory forces becomes increasingly important as Re increases because flow becomes more unstable and the lift is more influenced by the wake instability

Figure 4 shows wake unsteadiness as a function of low Re increase. Would like to develop tool that works optimally over wide range of Re and is not point designed for a specific range.

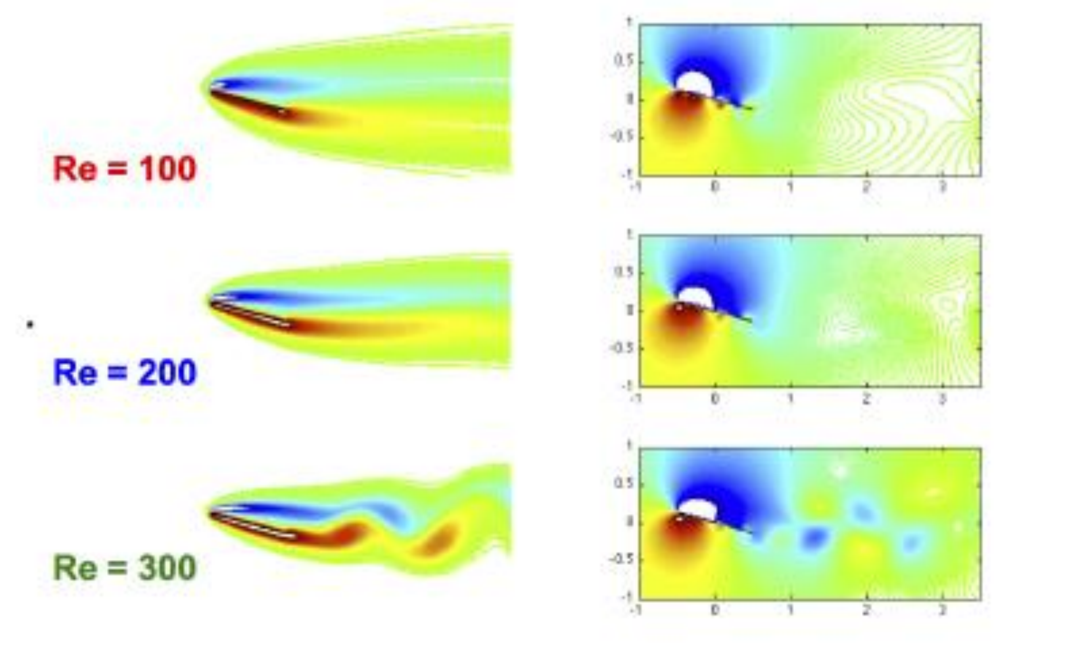


Figure 4: Increased wake unsteadiness with increase Reynolds numbers

# Vorticity State Estimation For Aeroelastic Control (6)



## Unsteady CFD Simulation: Lift vs. AoA in terms of unsteady LESP and FSP

Effects of vortex shedding recognized by high frequency oscillations of CL and are clearly seen at high absolute values of AoA. CL is characterized by a rapid smooth growth reaching its local maxima at 15 deg. Close to maximal value of AoA the angular velocity of pitching airfoil is almost zero and abrupt increase of CL is observed. This is the signature of the well-known **dynamic-stall vortex**.

Subsequent decrease of AoA results in a **rapid decrease of CL while oscillating at the vortex shedding frequency**. For negative values of AoA the high frequency oscillations of CL exist for both increasing and decreasing AoA in the vicinity of its absolute minimum.

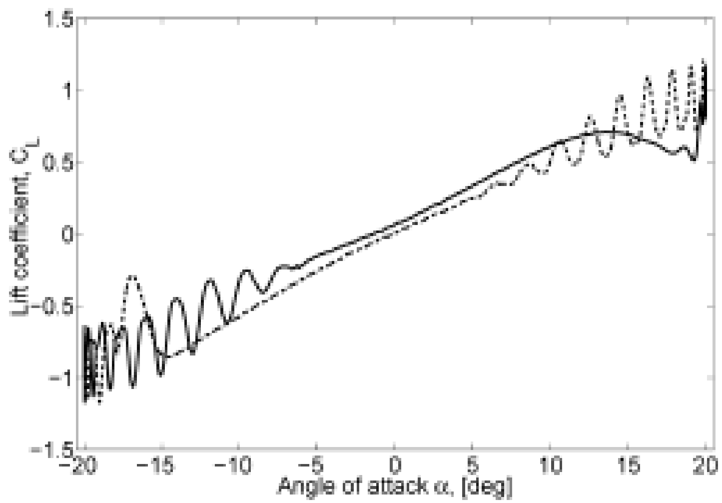


Figure 5: Unsteady CFD simulation: lift versus $\alpha$. Dotted line corresponds to decrease of angle of attack. Bold line corresponds to increase of angle of attack.

# Vorticity State Estimation For Aeroelastic Control (7)



Use Direct Numerical Simulation (DNS) methodology to verify and validate the VSE method

- try to show that the VSE method is a way to accurately predict instantaneous aerodynamic forces acting on the airfoil operating with high pitch/plunge ratios

- based on determination of unsteady vorticity field close to airfoil surface, which in turn can be related to the instantaneous location LESP and FSP

Simulate flow around a pitching X-56A wing airfoil

- accurately track the instantaneous location of LESP and FSP, and correlate the lift coefficient and the location of LESP and FSP respectively

Character of LESP recognized as separation and reattachment point for increasing (Figure 6(a)) and decreasing (Figure 6(b)) angle of attack

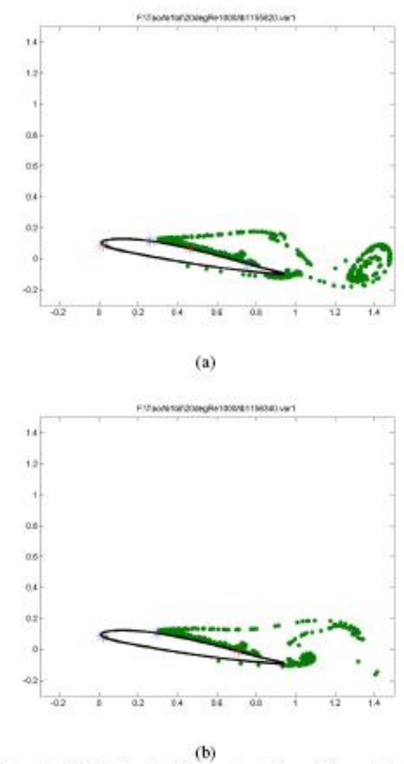

Figure 6: Unsteady CFD simulation: extraction of flow bifurcation points

$$\frac{d}{dt}\left\langle \int_{t_0}^{t_0-T} u_y(\gamma(t_0), 0, sds) \right\rangle_{T=0} = 0, \quad \frac{d}{dt}\left\langle \int_{t_0}^{t_0-T} u_{xy}(\gamma(t_0), 0, sds) \right\rangle_{T=0} > 0$$

$$\frac{d}{dt}\left\langle \int_{t_0}^{t_0-T} u_y(\gamma(t_0), 0, sds) \right\rangle_{T=0} = 0, \quad \frac{d}{dt}\left\langle \int_{t_0}^{t_0-T} u_{xy}(\gamma(t_0), 0, sds) \right\rangle_{T=0} < 0$$

# Vorticity State Estimation For Aeroelastic Control (8)



Reduced models relating the LESP and FSP locations to the angle of attack

LESP through whole range of AoA characterized by mostly smooth relation with the CL values

Vortex shedding region distinguished by kinks for both increasing and decreasing angles of attack

FSP exhibits more complicated behavior - only exists for specific ranges of angles of attack whose values depend also on direction of rotation.

***LESP (top) and FSP (bottom):***

***Bold line = positive pitch rate, dotted = negative pitch rate*.**

CFD-based model capable of extracting LESP and FSP, and relating those parameters to lift. CFD model enables a more accurate measurement of LESP and FSP and also provides theoretical basis for its measurement through a dynamical systems approach. Have unsteady potential flow model that can be used to develop the VSE system, while using the CFD model as the basis behind the LESP and FSP measurements verifying the unsteady potential flow model.

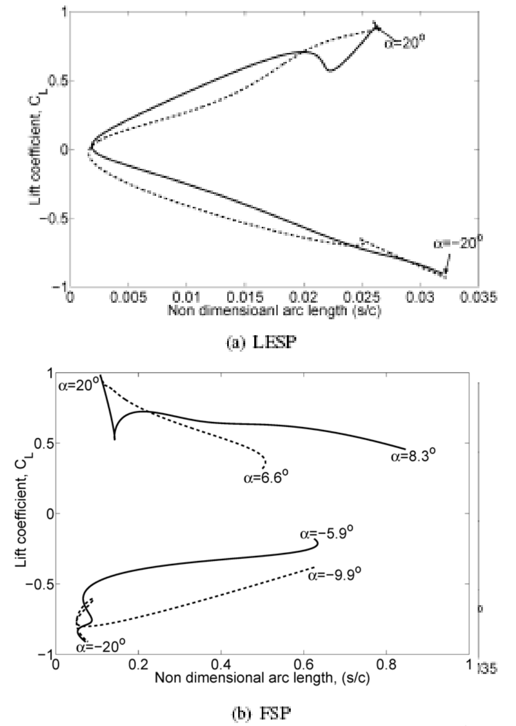


Figure 7: Unsteady CFD simulation: total lift versus (a) LESP and (b) FSP

# Vorticity State Estimation For Aeroelastic Control (9)



TAMU NATA (Nonlinear Aeroelastic Test Apparatus) facility

- measured lift was determined through a calibrated load balance, and the potential flow lift was calculated based on imposing Kutta condition (fully attached; upper bound for lift).
- data to relate LESP movement with the pitch angle and angular rate with the aero forces

**LESP-to-AoA is a one-to-many mapping**

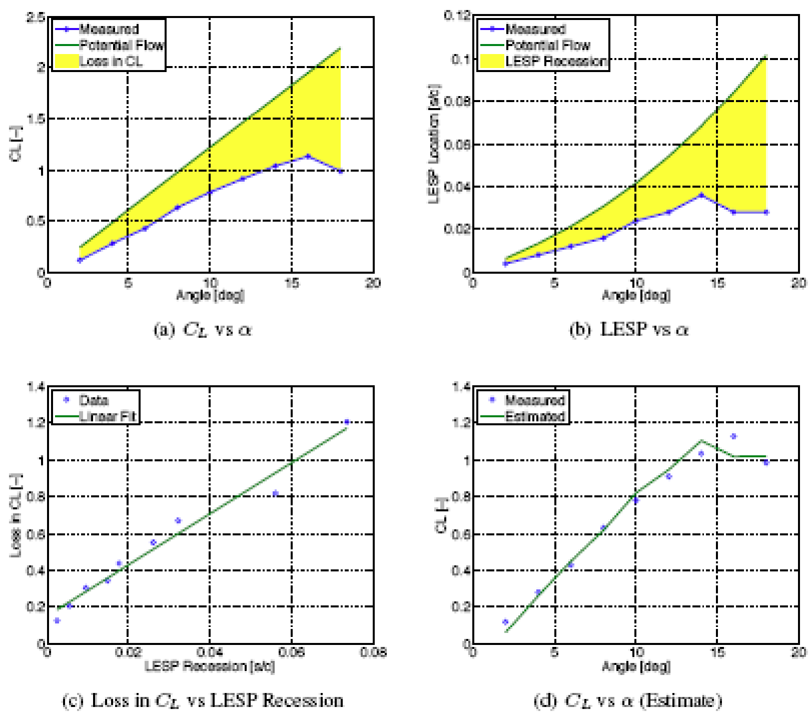


Figure 8: TAMU wind tunnel test results

**Applications for LCO control**

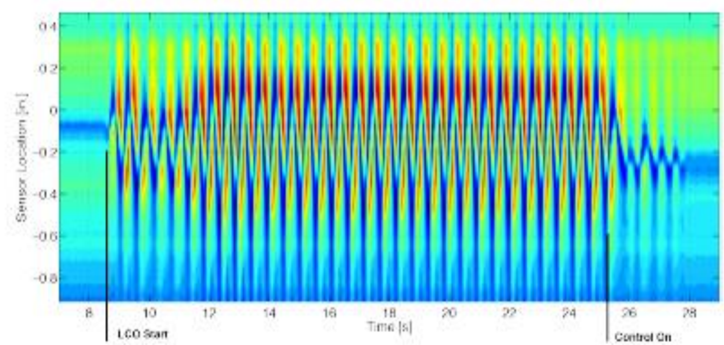


Figure 9: Shear stress distribution as a function of time through an LCO and a aeroelastic controller at 14 m/s

# Vorticity State Estimation For Aeroelastic Control (last)



## Potential Infusion:

Vorticity-based flow control system will enable a number of revolutionary capabilities across a wide speed range, including, but not limited to: (1) shorter take-off and landing (FAP, ASP-NextGen), (2) safe, reliable aircraft operation in turbulent condition (FAP, AvSP), and (3) larger passenger and cargo capacity

Difficulty - uncertainty in aerodynamic load & moments generated by the airstream in design and off-design conditions, e.g., turbulent flows, high angles of attack and unsteady flows.

Vorticity-state measurement (unsteady loads/moments) reduces aerodynamic uncertainty enabling aircraft to robustly compensate for the adverse flow conditions.

Allows ability to cruise efficiently at all altitudes enabled by substantial increase in cruise lift-to-drag (L/D) over current high-altitude reconnaissance and scientific aircraft by providing sustained presence and extended range

Vorticity-based flow control enables efficient robust active control of adaptive lightweight wings to optimize lift distribution for maximum L/D

Cost-effectively improves energy capture and reliability of wind turbines to help national renewable energy initiatives; vorticity state estimation provides output for control feedback to mitigate wind turbine blade lifetime-limiting time-varying loads generated by the ambient wind

# PTERA Vehicle and Instrumentation

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Highest risk element was conducting flight test:

**Prototype-Technology Evaluation and Research Aircraft (PTERA)**

Four sensors designed, fabricated and installed on four span stations PTERA-BL (baseline)

Middle figure depicts two sensors installed at the wing leading edge of two span stations

Tao Systems LSPS system was installed in the PTERA-BL fuselage and interfaced with the PTERA flight data system to record real-time data from sensors from the four span stations

# PTERA PID/Stall Tests

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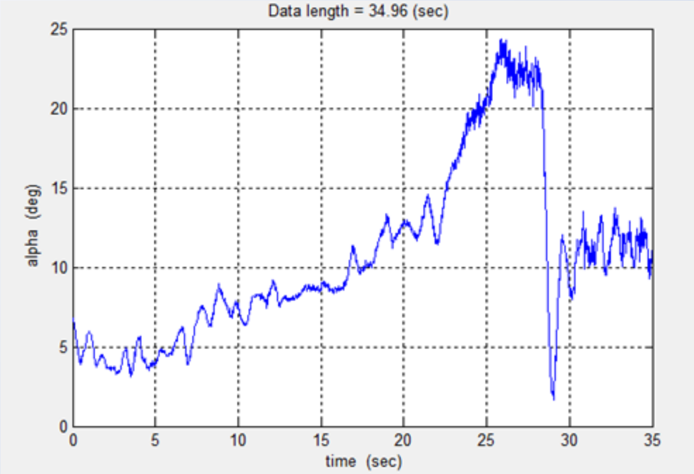
**Area-I flew PTERA_BL configuration six times**: first two flights for system checkout, and the remaining four flights for aerodynamic parameter identification

- max ground speed 144 knots, max altitude 1350 ft, gusts 0–2 knots up to 10+ knot gusts

**Stall maneuvers** most interesting aspect of these tests since the surface flow topology is the most nonlinear with the onset of flow separation and consequent loss in lift.

Aircraft successfully stalled three times: (1) traditional, power-off stall, (2) with control surface noise, and (3) with half flaps

Experimentally detail the stall behavior of the aircraft in terms of surface flow phenomena



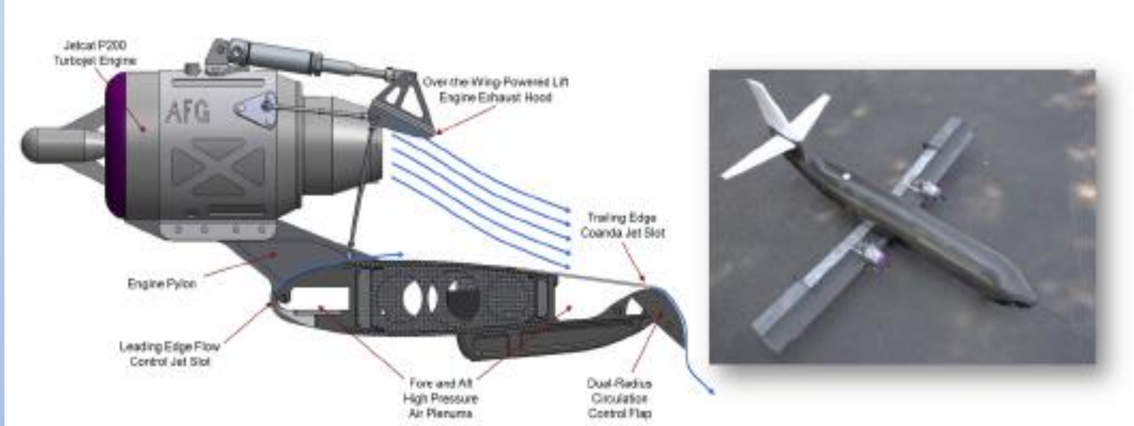




Figure 11: AREA-I circulation control system embedded on the PTERA Boeing scaled aircraft

# PPFDS / NATA II Facility

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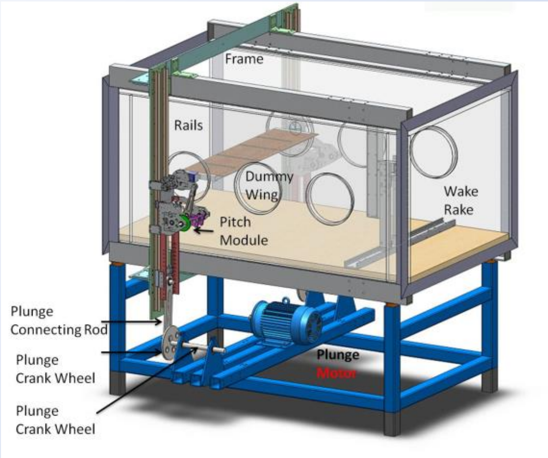
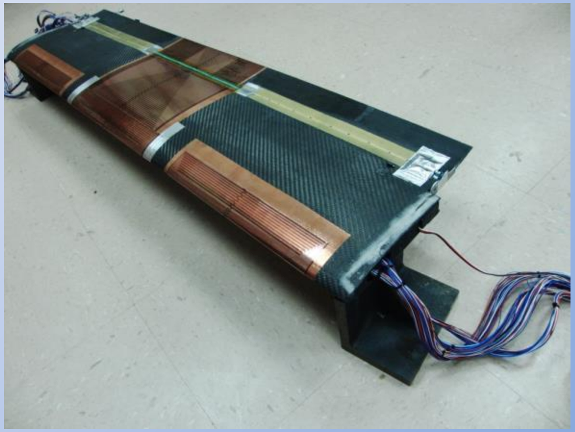
Statically **calibrated LESP sensors with aerodynamic lift** and use the constituent aeroelastic equations to develop an ASE controller to suppress the LCOs

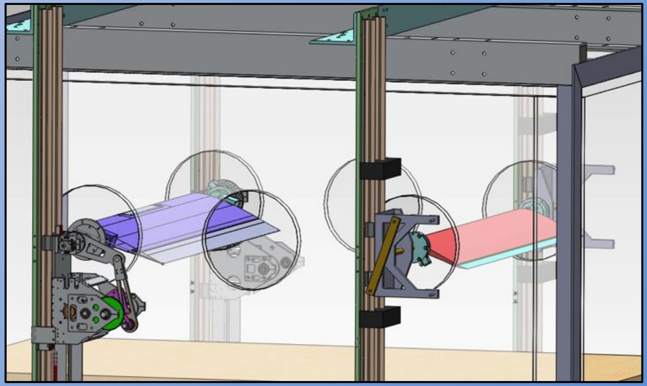
*{videos 0-2 xxxyyyzzz.mp4 ??}*

**Second test** relates movement of flow bifurcation points, e.g. LESP, and flow separation point to the aerodynamic forces under increasing pitch rates

Enables **calibration of the wing for unsteady response** providing basis for flight testing the actual MAD/MUTT wing with a model for the sensor dynamics





Pitch-Plunge-Flap Drive System (PPFDS) in Nonlinear Aeroelastic Test Apparatus (NATA II)

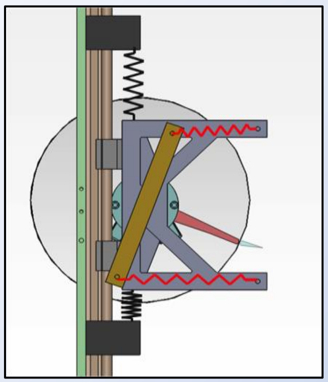
# PPFDS / NATA II Tests

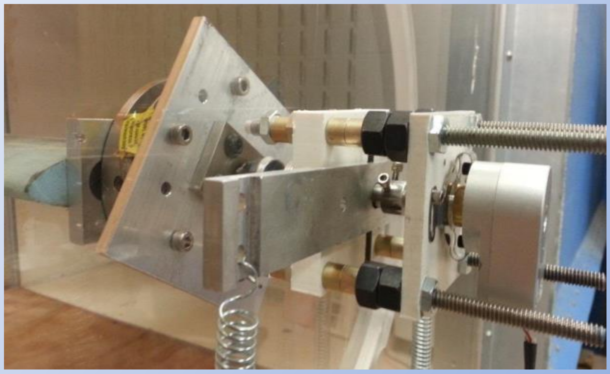


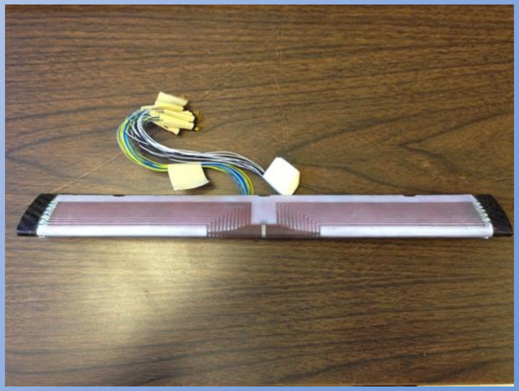
Flow sensors embedded directly onto the leading-edge using **direct-write techniques**

- process to embed metal onto surfaces to fabricate rugged sensors

Plan to transition this technology from **wind tunnel tests to operational aircraft**







Babbar Y., Suryakumar V.S, Mangalam A., Strganac T.W., "An Approach for Prescribed Experiments for Aerodynamic-Structural Dynamic Interaction", 51st AIAA Aerospace Sciences Meeting, 2013.

Babbar Y., Suryakumar V.S, Strganac T.W., "Experiments in Free and Forced Aeroelastic Response", 51st AIAA Aerospace Sciences Meeting, 2013.

Babbar Y., Suryakumar V.S, Strganac T.W., "Experiments in Aeroelastic Response and Control under Gust", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2013.

# PPFDS / NATA II Gust Modeling/Control Tests



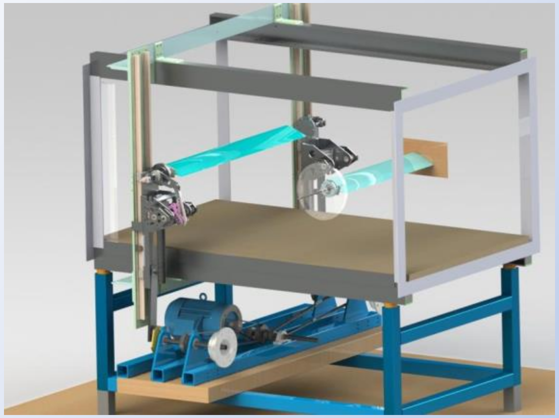
Characterize **flow field in the wake of gust generator** using probes

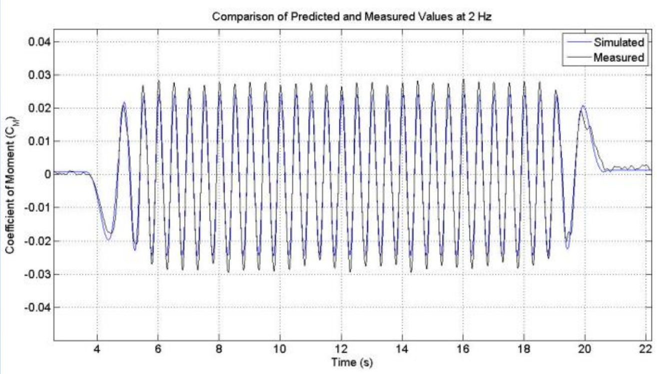
- PPFDS oscillates wing in pitch/plunge motion 0-5 Hz

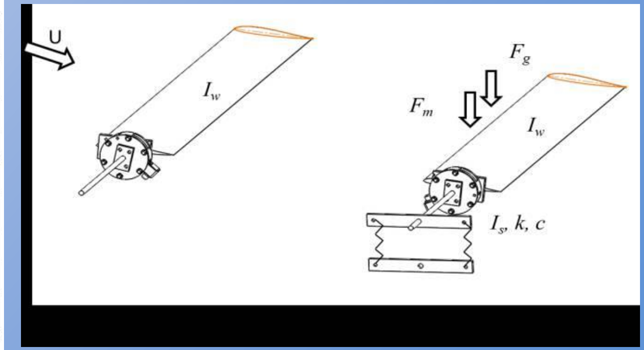
Conduct system ID tests to **determine gust response parameters** to aid in development of gust response prediction

$$F_g = -K_1 \alpha(t + d_2) + K_2 \dot{\alpha}(t + d_2) \qquad = C_{M,g}$$

Develop and test **control strategies using wing actuated control surface** to suppress LCO and possibly exploit flexibility to improve performance under gusts






**{videos 3-5 xxxyyyzzz.mp4}**

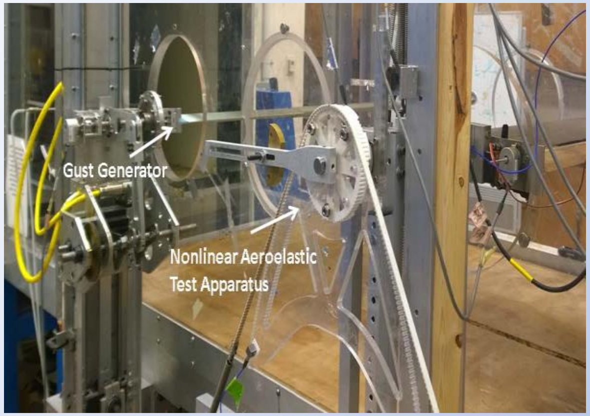
# Energy-based Flutter / LCO Suppression



Distributed energy-based control using **LESP and rate sensors** can be shown to be more efficient and robust than conventional large-order state-space techniques

The total unsteady lift is the sum of noncirculatory and circulatory components:

$$L = \pi\rho b^2(\ddot{h} + U\dot{\alpha} - ba\ddot{\alpha}) + 2\pi\rho U^2 b(\frac{\dot{\alpha}b}{2U} - \frac{\delta}{2})$$



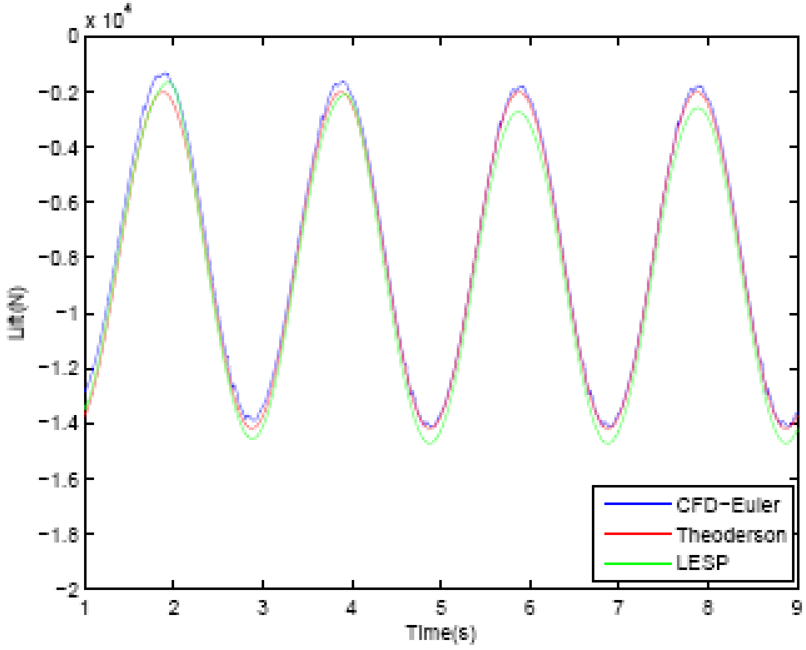




Figure 1. Comparison of the LESP model with CFD(Euler) and Theoderson's model

# Energy-based Flutter / LCO Suppression

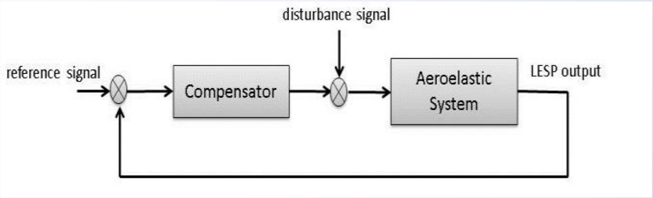


Propose alternative framework to **synthesize controllers using work-energy principles**

- Stability guarantees if the work done by the aerodynamic forces is dissipative

Conditions such that work done is negative in unstable region of the open-loop phase-space

- **Controlling phase relationships** of aero loads with plunge OR pitch rates, work done can be **constrained to be globally negative**




The LESP model for lift and moment can be substituted in the work done expression,

$$W_{aero} = \int_0^T [Re(-L(\dot{\alpha},\delta))Re(\dot{h}) + Re(M(\dot{\alpha},\delta))Re(\dot{\alpha})]dt = W_{aero}(\delta,\dot{h},\dot{\alpha})$$

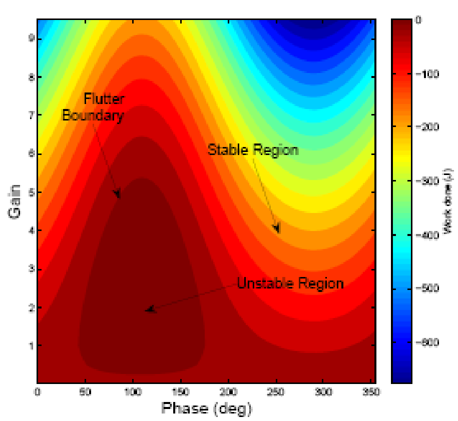



Figure 2. Energy Phase Plot

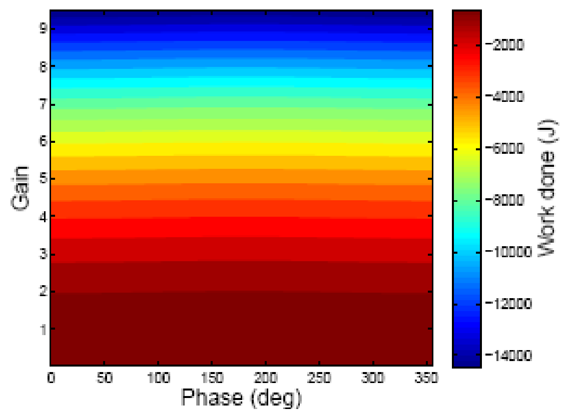
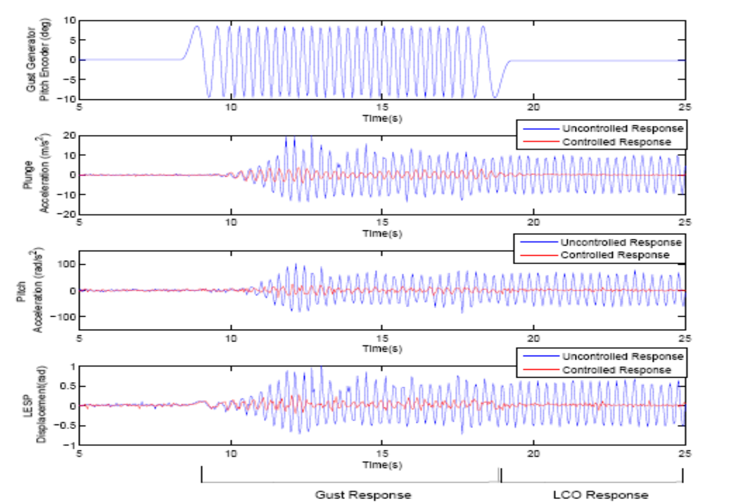



Figure 4. Energy Phase Plot - $\delta = -4\dot{h}$




## Pitch-Plunge-LESP in Open/Closed-Loop PPFDS

# PSCDM-related Future Objectives/Plans/Goals



Address delays and nonlinearities such as actuator free-play in uncertainty

Developing aero model that represents the unsteady aerodynamic response of the LESP sensor and ***model the absolute uncertainty in load estimation***

LESP measurement allows ***bounding the aerodynamic forces*** in absolute sense

Effectiveness of **energy-based control** depends on assumptions underlying measured aerodynamics forces/moments and accelerations, therefore uncertainty in those measurements are critical

Provide foundational systematic approach to fully understand the mechanism underlying free-play response and stability using novel sensing and control

Extend energy-based controller to the X-56A flying-wing configuration with wing sections structurally and aerodynamically cross-coupled in PPDS-NATA tests

# PSCDM-Phase2 Plans/Goals



Phase 2 Technical Objectives:

1. Develop system identification process with air data, accels, and LESP outputs
   - Physics-based, unsteady aerodynamic, analytical model for total aerodynamic forces and moments as a function of air data system, translational and rotational velocities, translational acceleration, deflection of control surfaces, and sectional LESP locations
     - Stall, physics-based aerodynamic force / moment model
   - System identification techniques to obtain coefficients of analytical model based on flight data from maneuvers

2. Validate system identification with TAMU PPDS-NATAII
3. Simulate flight control using air data system and IMU augmented with LESP sensors (turn LESP sensor on/off)
4. Simulate aeroelastic / circulation control using LESP sensors and IMU
5. Flight test demonstration (option)

# PSCDM-Phase2 Plans/Goals



Phase 2 Work Plan:

1. Aeroelastic / unsteady circulation system identification

2. Validation of system identification with TAMU PPDS-NATAII

3. Development (or augmentation) of flight simulation to include LESP output

4. Development of flight controller for NASA X-56A
   - Simulate flight control using air data system and IMU augmented with LESP sensors (turn LESP sensor on/off)
   - Simulate flight control using only LESP sensors and IMU

5. Flight test demonstration
   - Instrument existing vehicle with LESP sensors or use available vehicle
   - Implement flight control law using LESP sensors

# Essentials of Sensor-based Distributed Control



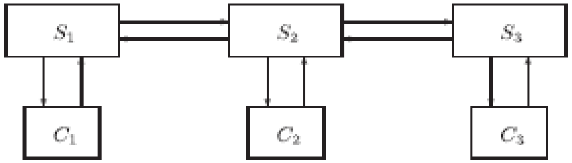
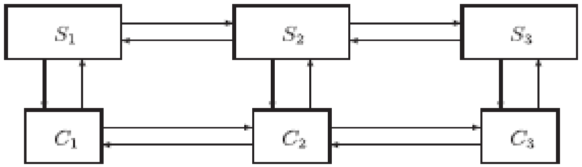



Fig. 3. Diagram of the control architecture of distributed control.




**Physics-based sensory perception and reaction**

- relevant data-driven autonomy (biomimetic)
- spatio-temporal, multi-scale, viscosity, SBLI
- advanced real-time aerostructural measurements

**Distributed multi-objective energy-based control**

- efficient mission adaptivity with reliability and safety
- inherent passivity/dissipativity with optimal energy-force distribution
- **spatial uncertainty minimization** with local control and robust global feasibility
  centralized (fusion-centric) vs decentralized / **coordinated degree of hierarchy**
- coordinated subsystem-independent control (min state variance and input)

**Network sensor/comm modeling (adaptive layered topology, who-what-when?)**

- Sensornets: complex interactions <–> protocol layering = optimal decomposition
- Multi-level network control/estimation and **information architectures**

**Decentralization with compressive information-based sensing/identification**

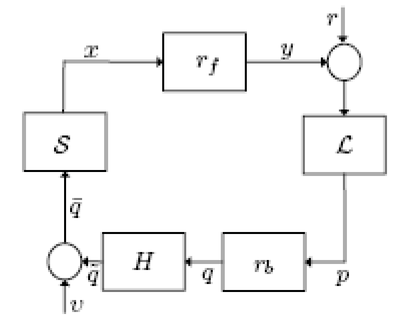
**Consensus-coordinated network control with coupling/compatibility constraints**

**Multi-MIMO stability / robustness analysis in sensing/communication/control**

# Robust-Network Sensor-based Distributed Control

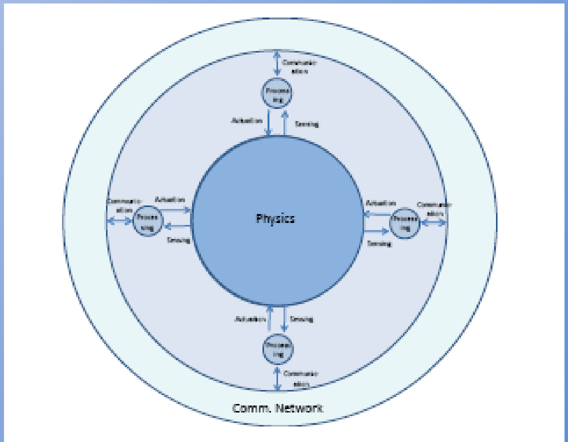
NASA Aeronautics Research Institute

- **Spatially distributed physical components** with sensors/actuators/processors interconnected in arbitrary ways
  **=> problem-dependent traffic interaction**




- Processing units interconnected by dynamic communication networks
  **=> closed-loop ID with distributed estimation/optimization/control**

- **Multi-scale-level information sharing** with layering architecture




- **Model structure exploited for optimal performance** design
  Optimal solution in modularized and distributed manner
  Top-down design layered stacks -> conceptual simplicity
  Functionality allocation motivated by "architecture first"
  **Enables scalable and evolvable network designs**

- Decompositions have different characteristics in efficiency, robustness, asymmetry of information and control, and **tradeoff between computation and communication**

# Robust-Network Sensor-based Distributed Control



**Advanced technology's near-biological complexity**

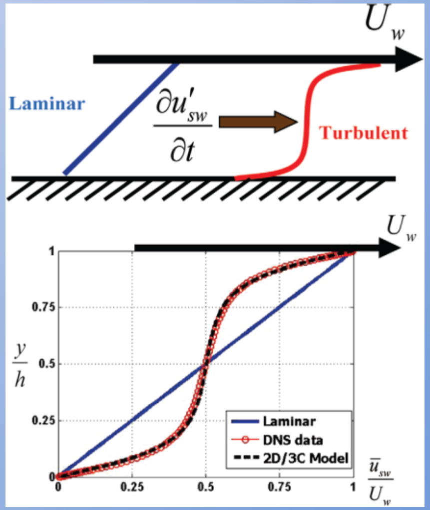
- **"Layering as Optimization Decomposition"**
- level of organization, architecture, and the role of layering, protocols, and feedback control in structuring complex multi-scale modularity
- protocol layers hide complexity of layer below and provide service to layers above, necessarily from their universal system requirements
- **fast, efficient, adaptive, evolvable, and robust to perturbations** in their environment and component parts
- local algorithms attempt to **achieve global objective (consensus-based)**
- transparency between interactions amongst components, and their global behavior

# Robust Physics-based Distributed Control

NASA Aeronautics Research Institute

**Lack of stability robustness plays fundamental role in wall turbulence**

- Energy amplification (high gain feedback) and increased velocity gradient at the wall associated with the turbulent profile appears to have important implications for flow control techniques that **target skin friction or the mean profile** (2*D/3C model)*
- As Re increases, robustness (laminar-to-turbulent) decreases
- Tradeoff between linear amplification and non-linear blunting



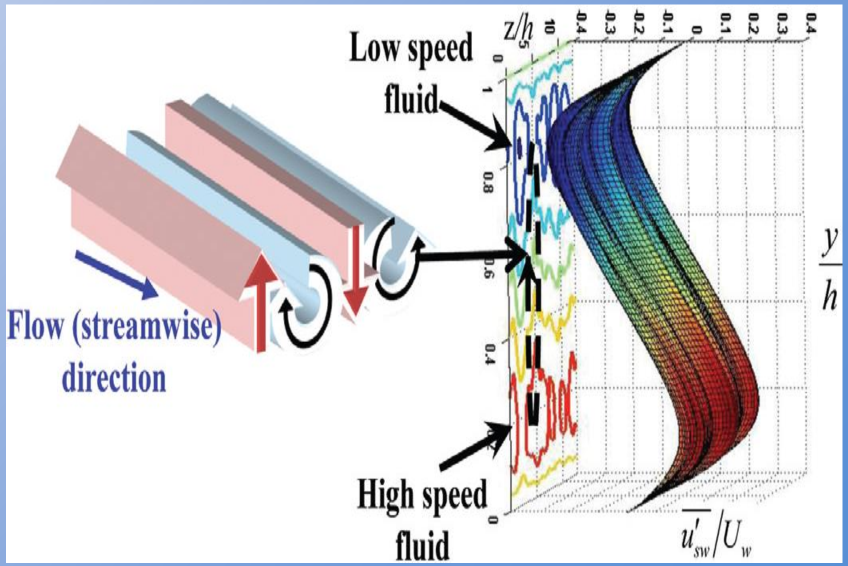

**Turbulence in robust control framework**

Reveals important tradeoff between

linear / non-linear phenomena

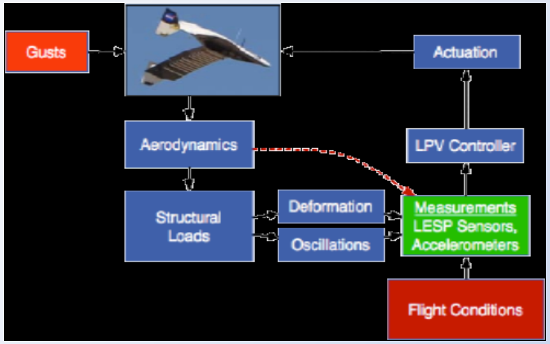
Provides insight into mechanisms associated

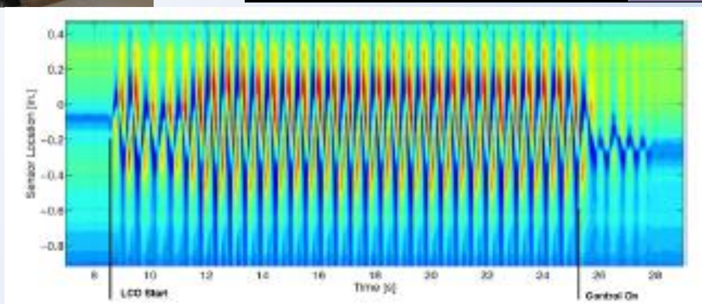
with both transition and fully turbulent flow



# Fly-by-Feel Aerodynamic Sensing





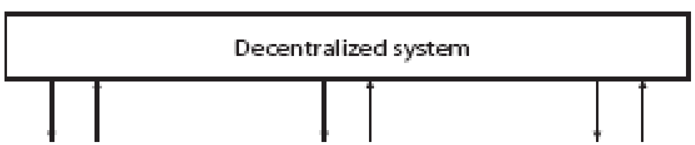




Fig. 1. Diagram of a decentralized system.

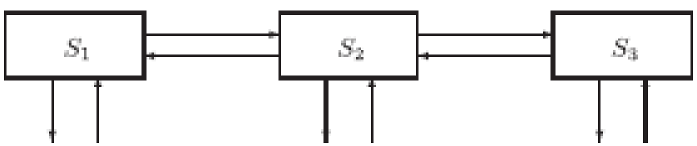
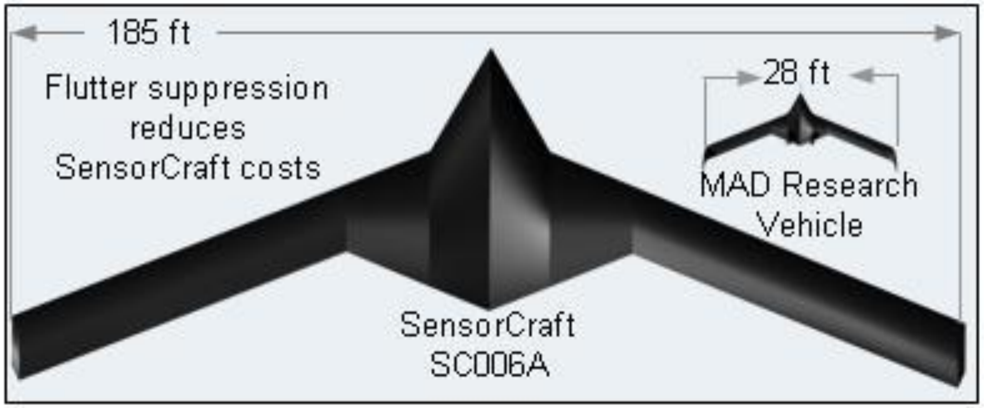


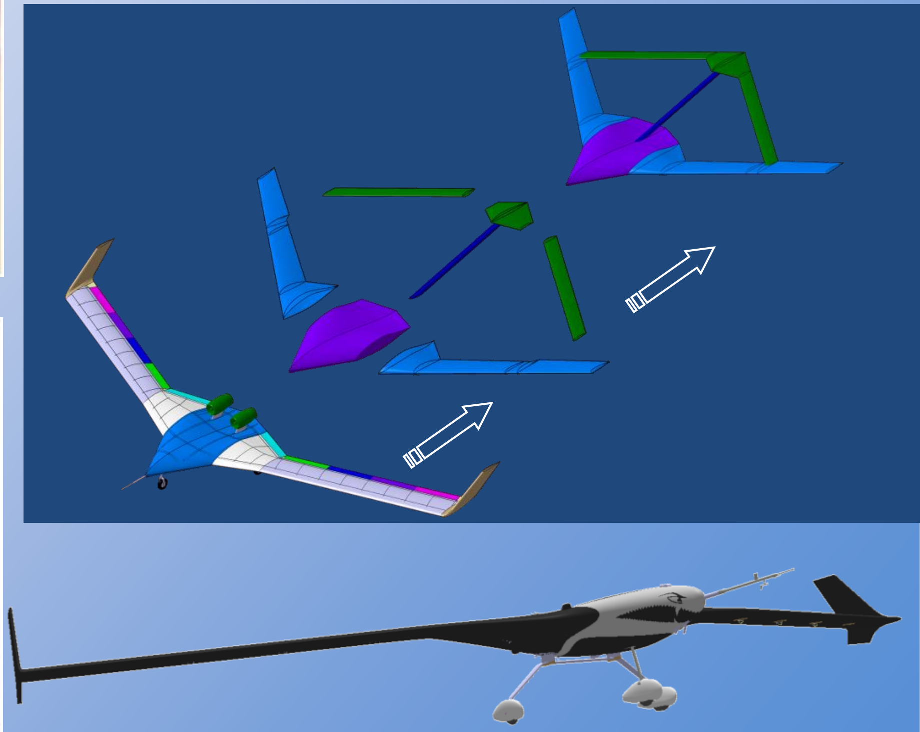

Fig. 2. Diagram of a distributed system.

- Extension of physics-based FBP analytical model to generalized vortex state (low-order fluids model)
  - Applicable to unsteady flows (high reduced frequencies & near-/post-stall pitch angles)
  - Capture vortex dynamics for flow control
  - Consistent with higher-order CFD models
  - Enables near-term flight test flow control demos
- Extension of physics-based FBP analytical model to compressible flows
  - Applicable to characterizing shock wave turbulent boundary layer interactions (SBLI) as it relates to performance and aeroelastic stability
  - Reduction of noise & emissions
  - Flight test opportunities at relevant conditions
- Development of distributed ASE control architecture with “calibration-less” or self-calibrating sensors
  - New formulation of ASE eqns may reduce the requirement for calibration provided that flow and structural sensors are both available
  - Distributed control architecture may reduce requirements for structural & aerodynamic model accuracy by proving that local control approaches stable, globally optimal control
  - Provably robust adaptive control
- Partners: UMN, IIT, CalTech, SBCs, TAMU, AFRL, etc.

# ASE Sensor Applications: X-56A

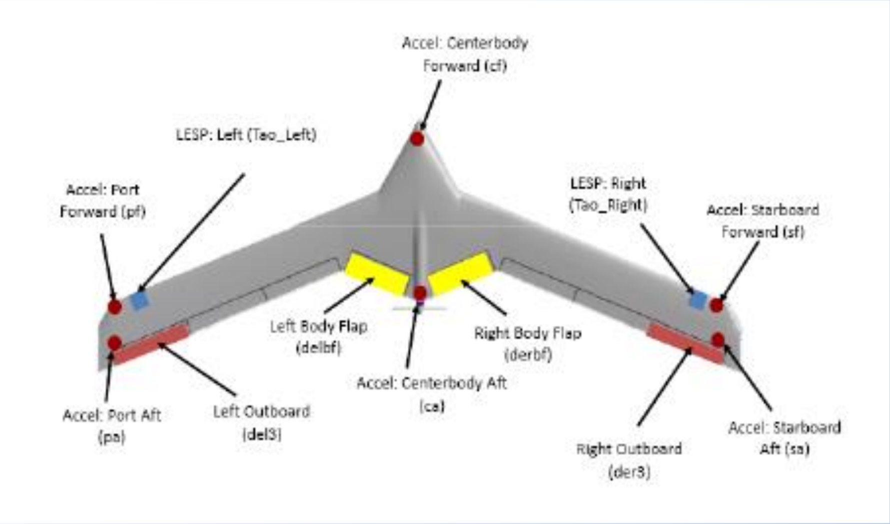
NASA Aeronautics Research Institute



# BFF GLA/Flutter Control Demo: LMCO / AFRL

NASA Aeronautics Research Institute




{BFF.mp4}, {BFF_Open_Closed.wmv}

# X-56A Body-Freedom with Classical W/T Flutter Control



{MUTT_Flt2_90SecHilite_9-6-13.mov} {MUTT_FirstFlight_7-26-2013.mov, ??}

# Full-Scale Advanced System Testbed (FAST) F18 Flight Research

## LESP and SBLI Aero Sensing



### Aero Sensing LESP / SBLI Flight Evaluation

Assess suitability of Leading Edge Stagnation Point (LESP) and SBLI sensing system for subsonic-to-supersonic aeroelastic modeling and control with external disturbances

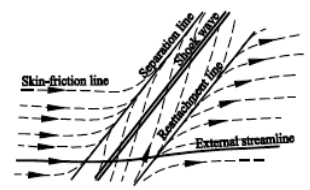
### Scope

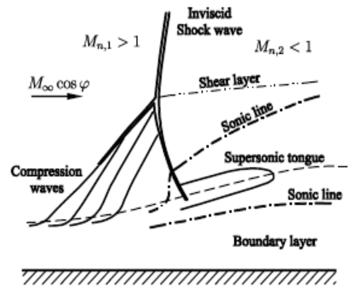
Sensor characterization of Leading Edge Stagnation Point (LESP) sensor technology with unsteady pressures, shock, and control surfaces

- Help develop ASE and gust load alleviation control laws
- Steady and unsteady FBP and pressure measurements
- Evaluate LESP with shock location and control surfaces
- LESP with SBLI measurements across all flight regimes
- Flight near aero-sensitive regions  (high-alpha, stall, STOL)

# Unsteady Tran-to-Supersonic Flow over a Transport-Type Swept Wing

NASA Aeronautics Research Institute




## RWTH Aachen University - Institute of Aerodynamics

"Weak shock/boundary-layer interaction with incipient separation has minor effects on the wing structure, despite the occurrence of large pressure *fluctuations*, whereas the strong interaction involving shock-induced separation results not only in significantly *weaker fluctuations* in the pressure field, but also in a strong fluid–structure coupling."

Aerodynamic forces increase strongly with speed, elastic/inertia forces unchanged => "transonic dip", then rising flutter stability limit from ***separated flow acting as aero damping***

Lightweight with optimal wing geometries => steady/unsteady aero-wing behavior critical

Periodic shock oscillation due to the ***acoustic feedback loop*** is not induced by the onset of dynamic fluid–structure interaction *but it* ***can excite a structural unsteadiness wrt phase lags***

*Shock-induced* separation of the turbulent boundary layer occurs without reattachment which indicates the performance boundary

Aero-wing relative phase results in SBLI with unsteady frequencies

Not wing flutter, but a pure response to the distinct oscillation of the flowfield and the shock wave **with Re (scale) dependence**

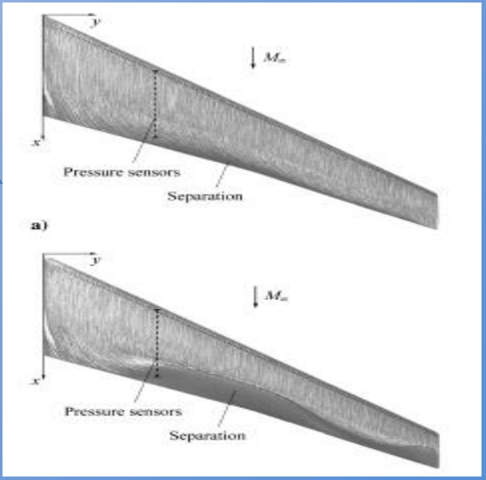



Table 3 Overview of flow test cases for AA-PSP measurements

| | Condition 1 | Condition 3 |
|---|---|---|
| Shock/boundary-layer interaction | Weak | Strong |
| Type of separation | Small trailing-edge separation | Shock-induced separation without reattachment |
| Unsteadiness | High degree in entire flowfield | Lower, harmonic shock oscillation |
| Reduced fundamental frequency | $\omega^* = 0.73$ | $\omega^* = 0.72$ |

# Partners/Support/Applications



DoD, DARPA (Fly-by-Feel, sensor developments, distributed sensing)

AFRL, Boeing, Northrup-Grumman, Lockheed-Martin, Bell Helicopter, Airbus

ARMD-FAP (X-56A), AvSP, ISRP, *Green Aviation, Wind Energy*

ARMD Seedling Support: AFRL, LMCO, TAMU, UMN (Flow Control), Caltech, AREA-I

Others: IIT, UMN (Aerospace Control), MuSyn, ZONA, UF, STI

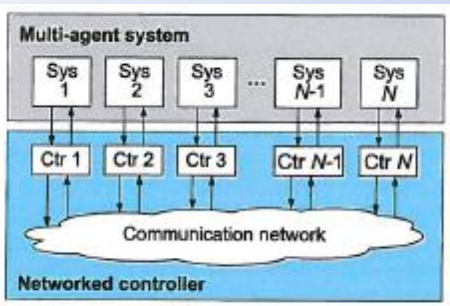



Figure 1. Networked control of multi-agent systems.

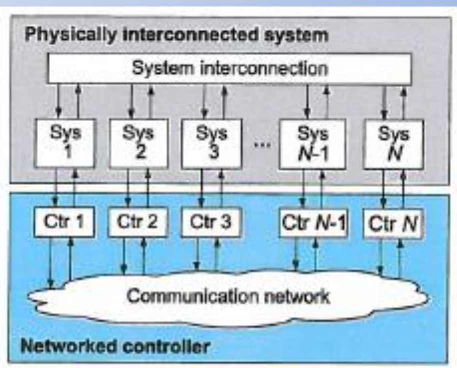



Figure 2. Networked control of physically interconnected systems.

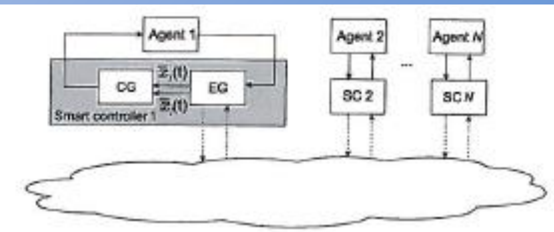



Figure 3. Networked control of interconnected systems with event-based communication.