Bio-Inspired Distributed Sensing for Improved Flight Control

Sergio A. Araujo-Estrada[1] Shane Windsor [2]

[1]Research Associate
[2]Lecturer in Aerodynamics/Aeroelasticity
Aerospace Engineering Department
s.araujoestrada@bristol.ac.uk

Overview

Motivation: Why Bio-Inspired Distributed Sensing?

Amazing Kestrel!!!

Kestrel Hovering and Hunting in Cornwall
Paul Dinning, 2015
`https://www.youtube.com/watch?v=7j60sP7zL6w`

Motivation: Why Bio-Inspired Distributed Sensing?

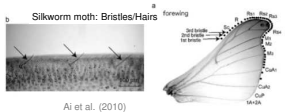
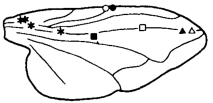
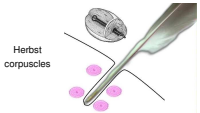
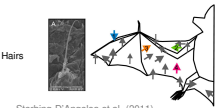
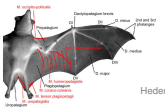
	Flow Sensors	Force Sensors
Insects	 Ai et al. (2010)	 Blowfly: Campaniform sensilla Dickinson (1990)
Birds		 Muscle spindles
Bats	 Sterbing-D'Angeloa et al. (2011)	 Muscle spindles Hedenstrom et al. (2015)

Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

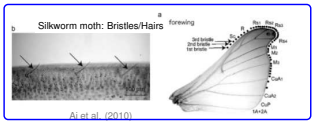
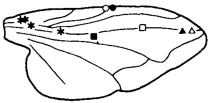
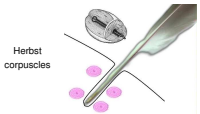
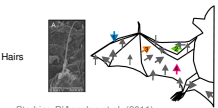
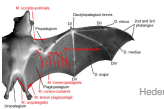
	Flow Sensors	Force Sensors
Insects	 Ai et al. (2010)	 Blowfly: Campaniform sensilla Dickinson (1990)
Birds		 Muscle spindles
Bats	 Sterbing-D'Angeloa et al. (2011)	 Muscle spindles Hedenstrom et al. (2015)

Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

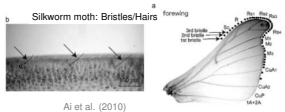
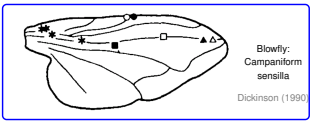
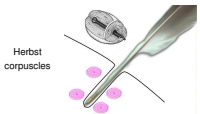
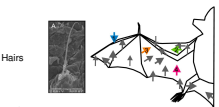
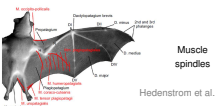
	Flow Sensors	Force Sensors
Insects	 Ai et al. (2010)	 Blowfly: Campaniform sensilla Dickinson (1990)
Birds		 Muscle spindles
Bats	 Sterbing-D'Angeloa et al. (2011)	 Muscle spindles Hedenstrom et al. (2015)

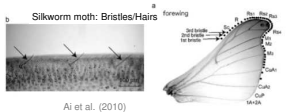
Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

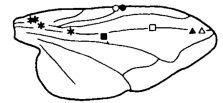
Flow Sensors

Force Sensors

Insects



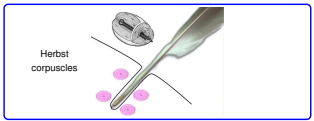
Ai et al. (2010)



Blowfly: Campaniform sensilla

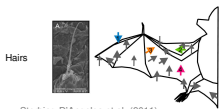
Dickinson (1990)

Birds



Muscle spindles

Bats



Sterbing-D'Angeloa et al. (2011)

Muscle spindles

Hedenstrom et al. (2015)

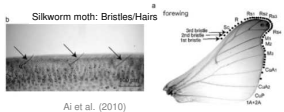
Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

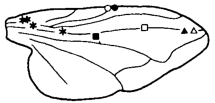
Flow Sensors

Force Sensors

Insects



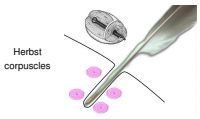
Ai et al. (2010)



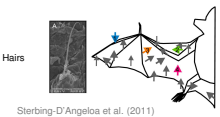
Blowfly: Campaniform sensilla

Dickinson (1990)

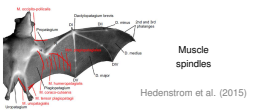
Birds



Bats



Sterbing-D'Angeloa et al. (2011)



Hedenstrom et al. (2015)

Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

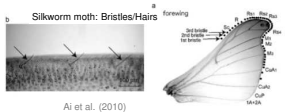
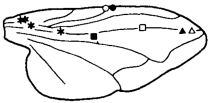
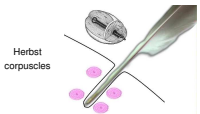
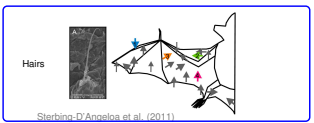
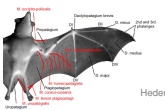
	Flow Sensors	Force Sensors
Insects	 Ai et al. (2010)	 Blowfly: Campaniform sensilla Dickinson (1990)
Birds		 Muscle spindles
Bats	 Sterbing-D'Angelo et al. (2011)	 Muscle spindles Hedenstrom et al. (2015)

Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

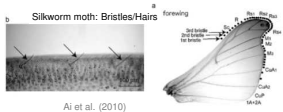
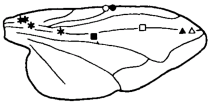
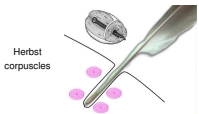
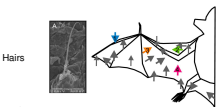
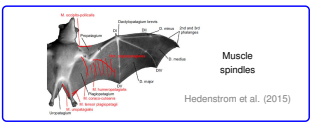
	Flow Sensors	Force Sensors
Insects	 Ai et al. (2010)	 Blowfly: Campaniform sensilla Dickinson (1990)
Birds		 Muscle spindles
Bats	 Sterbing-D'Angeloa et al. (2011)	 Muscle spindles Hedenstrom et al. (2015)

Figure: Biological sensory systems

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
- Challenges
- Potential use of force and flow information

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
  - Inertial
  - Single point air speed
  - GPS
  - Vision
- Challenges
- Potential use of force and flow information

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
- Challenges
- Potential use of force and flow information

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
- Challenges
  - Intrinsic nonlinear dynamics
  - Classic control strategies limitations
  - Limitations of inertial controls
- Potential use of force and flow information

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
- Challenges
- Potential use of force and flow information

Motivation: Why Bio-Inspired Distributed Sensing?

- Current UAV autopilot technologies
- Challenges
- Potential use of force and flow information

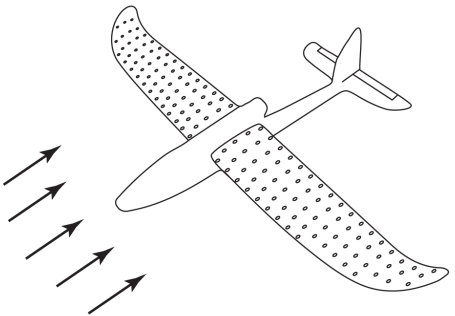
- Availability of aerodynamic variables
  - → Improved flight dynamics model
  - → Stall detection
- Earlier gust detection
  - → Gust rejection/alleviation
- Localised information
  - → Localised control
  - → Load tailoring

Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems

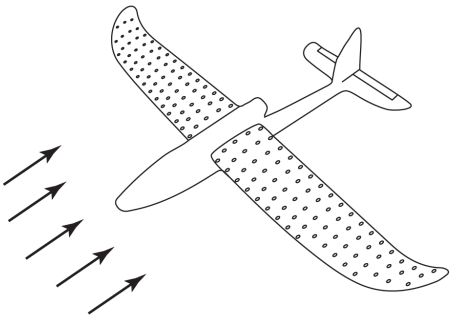


Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems

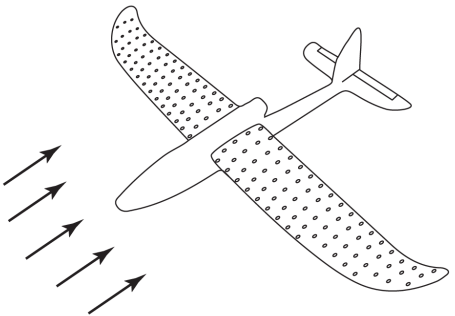


Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems

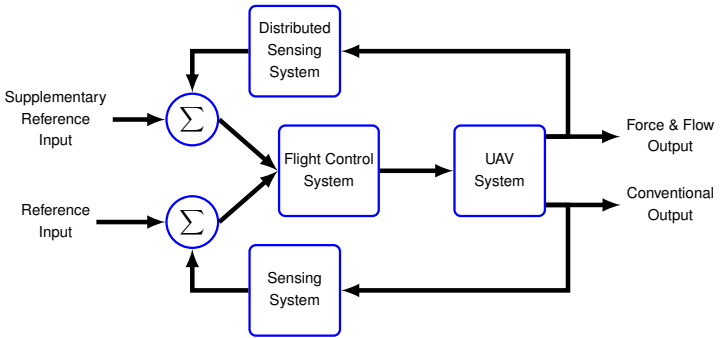


Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems

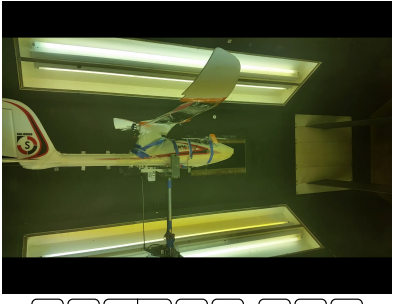


Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems

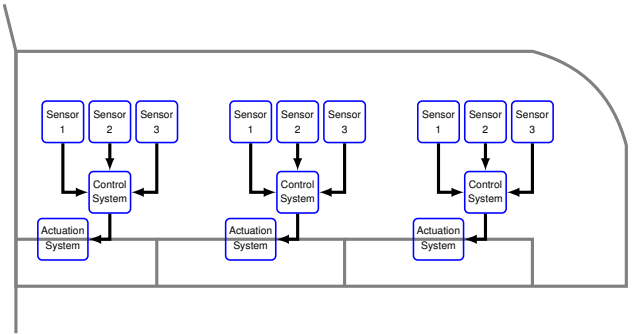


Research Problem

Use force and flow sensing to improve performance of UAVs flight control systems.

To achieve this we aim to:

- Develop distributed sensing system for UAV
- Integrate with conventional flight control system
- Measure response to gusts/turbulence
- Develop flight control systems



Previous Research at UoB: Strain sensing

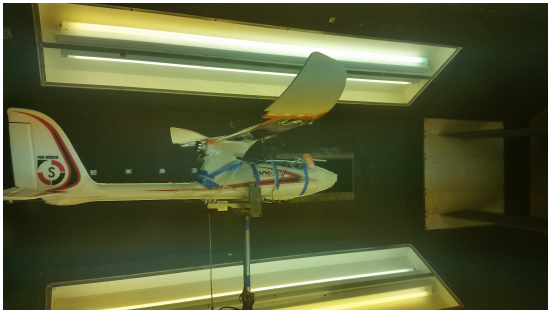


Figure: Strain sensing platform

- Implement closed loop roll control using strain sensing
- 12 full-bridge strain gauges and amplifiers distributed along spar of wing
- Wind tunnel characterisation

Previous Research at UoB: Strain sensing

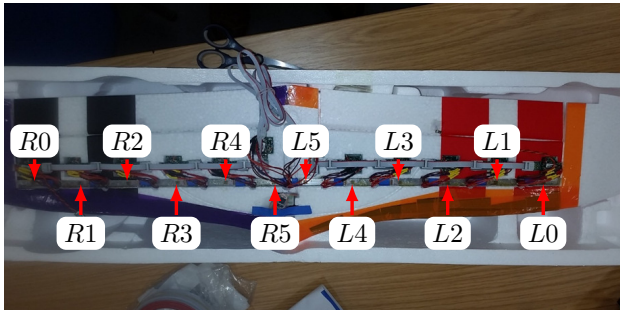


Figure: Strain sensing platform instrumentation

- Implement closed loop roll control using strain sensing
- 12 full-bridge strain gauges and amplifiers distributed along spar of wing
- Wind tunnel characterisation

Previous Research at UoB: Strain sensing

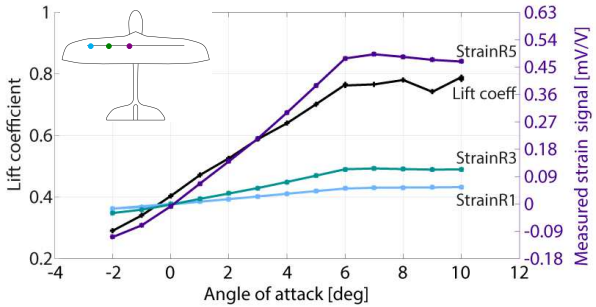


Figure: Strain wind tunnel characterisation

- Implement closed loop roll control using strain sensing
- 12 full-bridge strain gauges and amplifiers distributed along spar of wing
- Wind tunnel characterisation

Previous Research at UoB: Strain sensing

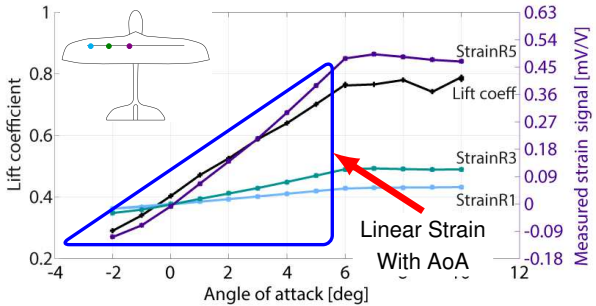


Figure: Strain wind tunnel characterisation

- Implement closed loop roll control using strain sensing
- 12 full-bridge strain gauges and amplifiers distributed along spar of wing
- Wind tunnel characterisation

Previous Research at UoB: Strain sensing

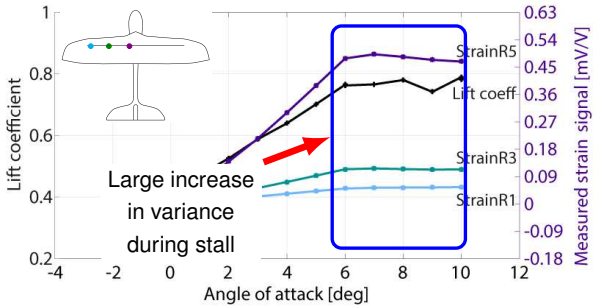


Figure: Strain wind tunnel characterisation

- Implement closed loop roll control using strain sensing
- 12 full-bridge strain gauges and amplifiers distributed along spar of wing
- Wind tunnel characterisation

Previous Research at UoB: Strain sensing

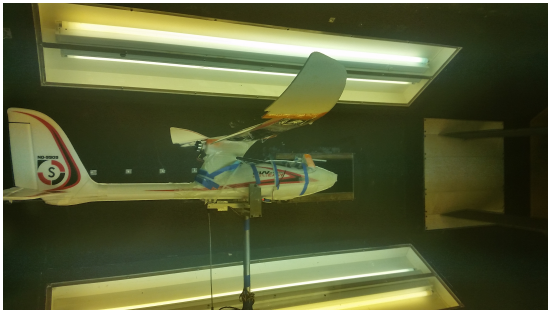
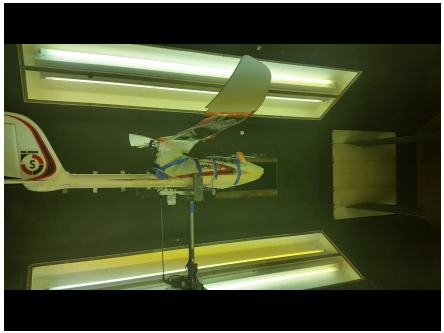


Figure: Strain sensing platform

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing



- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing

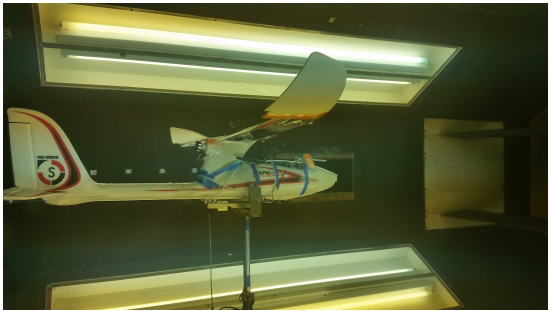


Figure: Strain sensing platform

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing

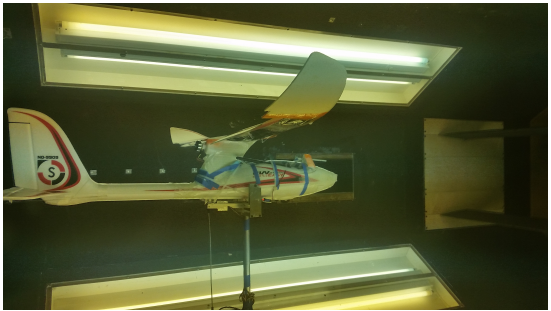


Figure: Strain sensing platform

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing

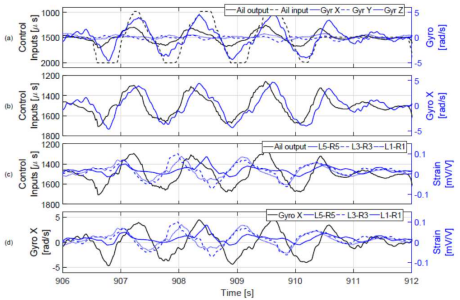


Figure: Strain response to control inputs

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing

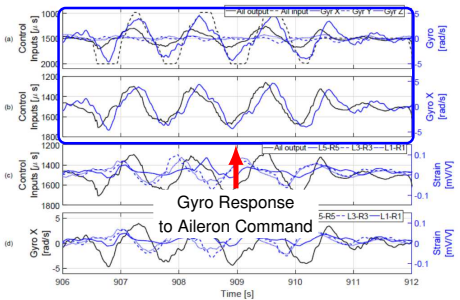


Figure: Strain response to control inputs

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Strain sensing

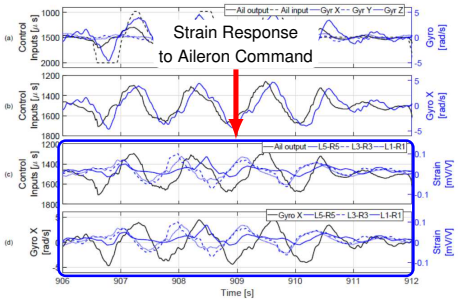


Figure: Strain response to control inputs

- Response to controlled gusts
- Open loop free flight
- Closed loop free flight
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

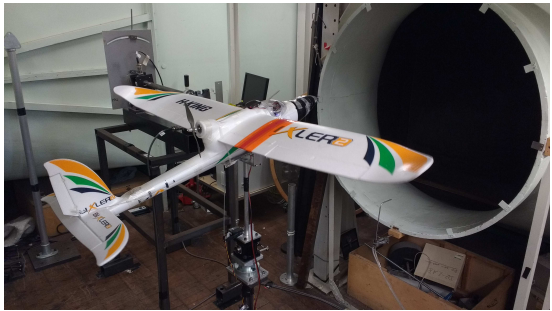


Figure: Pressure sensing platform

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

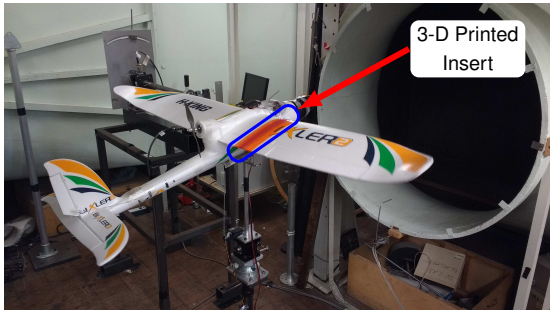


Figure: Pressure sensing platform

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

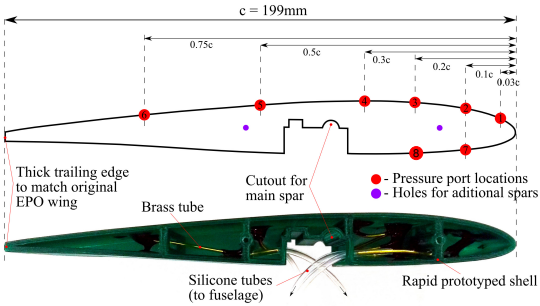


Figure: Pressure sensing platform instrumentation

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

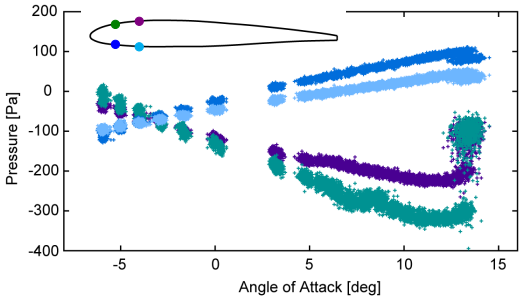


Figure: Pressure wind tunnel characterisation

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

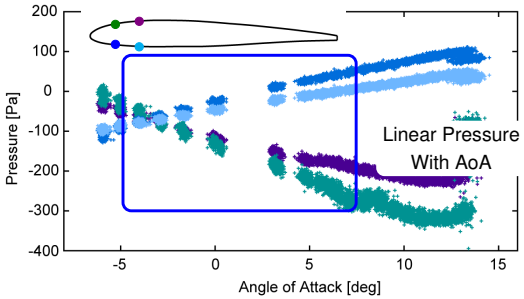


Figure: Pressure wind tunnel characterisation

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

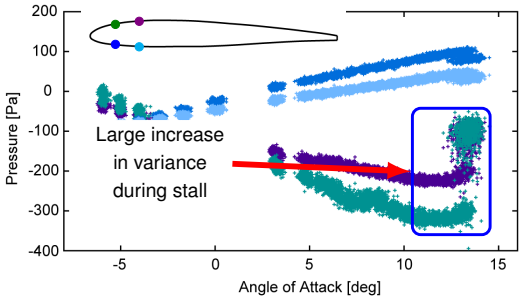


Figure: Pressure wind tunnel characterisation

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

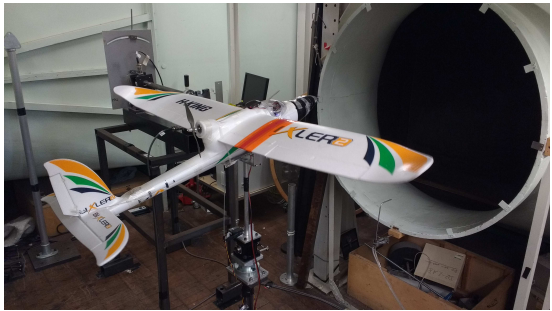


Figure: Pressure sensing platform

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

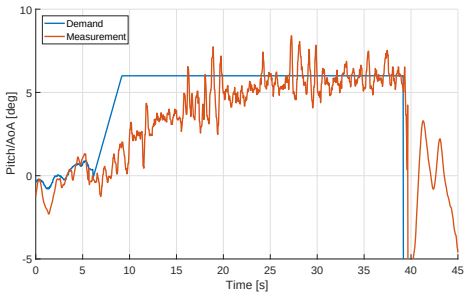


Figure: Outdoors angle-of-attack tracking

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

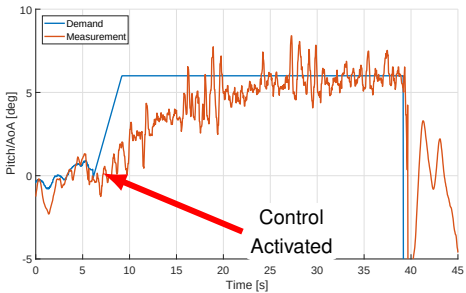


Figure: Outdoors angle-of-attack tracking

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB: Pressure sensing

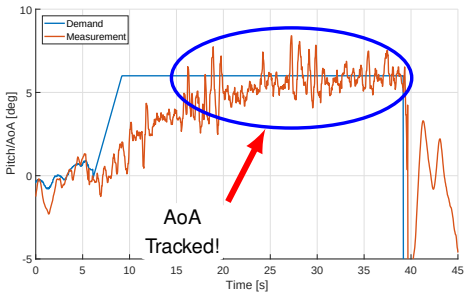


Figure: Outdoors angle-of-attack tracking

- Implement closed loop pitch control using pressure sensing
- 3-D printed insert on starboard wing
- Static-pressure ports distributed along wing-chord
- Wind tunnel characterisation
- Closed loop 1DOF WT testing
- Outdoor flight testing

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
- Similar performance to IMU-based control
- Information not available using IMU

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain → roll control
  - Pressure → pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain → roll control
  - Pressure → pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain → roll control
  - Pressure → pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain → roll control
  - Pressure → pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain $\rightarrow$ roll control
  - Pressure $\rightarrow$ pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain $\rightarrow$ roll control
  - Pressure $\rightarrow$ pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain $\rightarrow$ roll control
  - Pressure $\rightarrow$ pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Previous Research at UoB

What did we learn?

- Strain & pressure signal show
  - Linear response with AoA
  - Stall markers
- Similar performance to IMU-based control
  - Strain $\rightarrow$ roll control
  - Pressure $\rightarrow$ pitch control
- Information not available using IMU
  - AoA, stall, roll acceleration, non-linear lift

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Research focuses on:

- Pressure and strain sensing experimental platform
- Calibration & characterisation experiments
- Closed loop control algorithms

Divided into two phases:

- Phase 1: Wind tunnel experiments
- Phase 2: Outdoor flights experiments

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling $100\,\mathrm{Hz}$
- 1-DOF pitch motion servo-driven system for automated motion

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

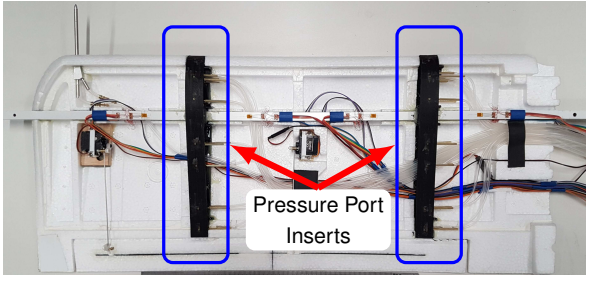


Figure: Wing model experimental platform

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

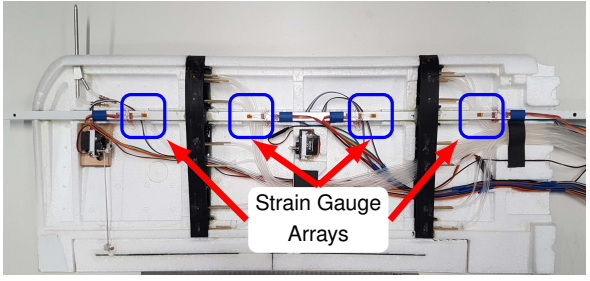


Figure: Wing model experimental platform

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

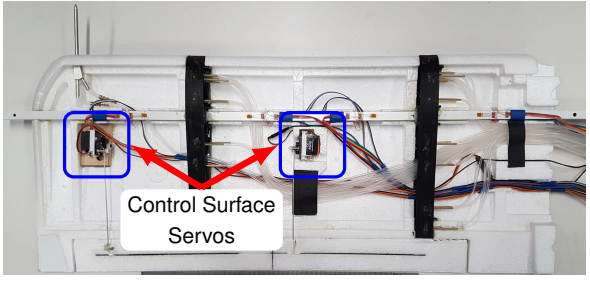


Figure: Wing model experimental platform

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

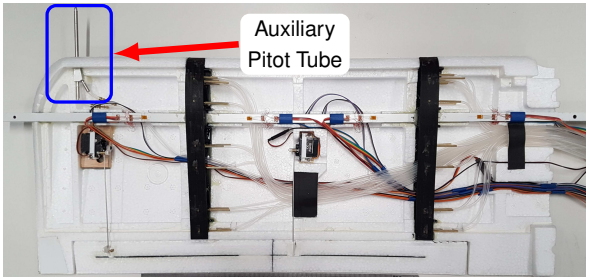


Figure: Wing model experimental platform

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

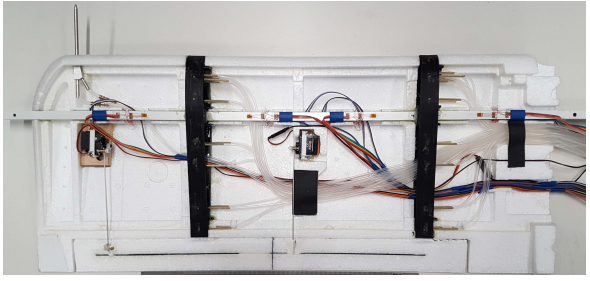


Figure: Wing model experimental platform

Current Research at UoB

Wing model instrumentation:

- Chord-wise array of 30 pressure ports in two sections
- Span-wise array with 16 strain gauges
- Servo actuated control surfaces
- MCU-based data acquisition system using, sampling 100 Hz
- 1-DOF pitch motion servo-driven system for automated motion

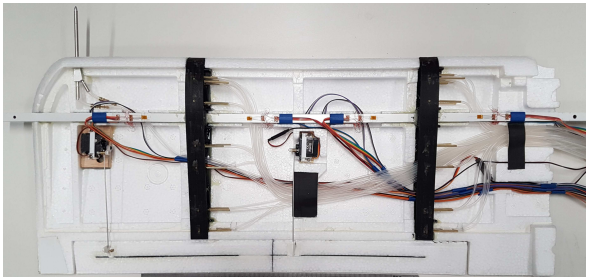
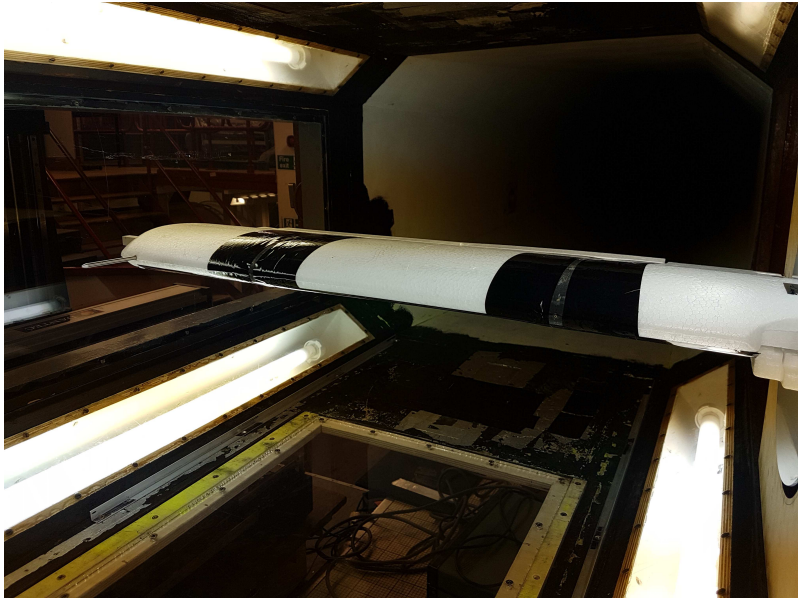


Figure: Wing model experimental platform



Current Research at UoB

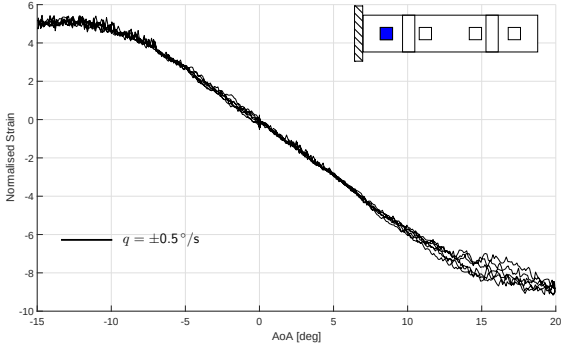


Figure: Strain response for various q values

Current Research at UoB

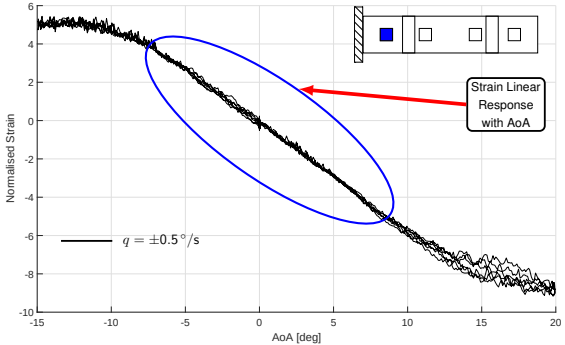


Figure: Strain response for various q values

Current Research at UoB

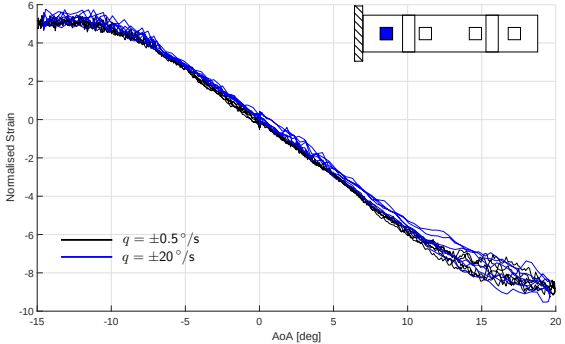


Figure: Strain response for various q values

Current Research at UoB

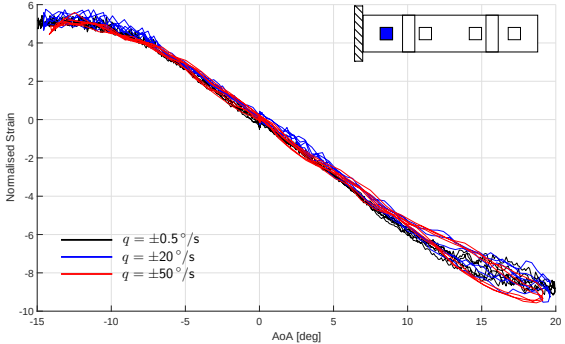


Figure: Strain response for various q values

Current Research at UoB

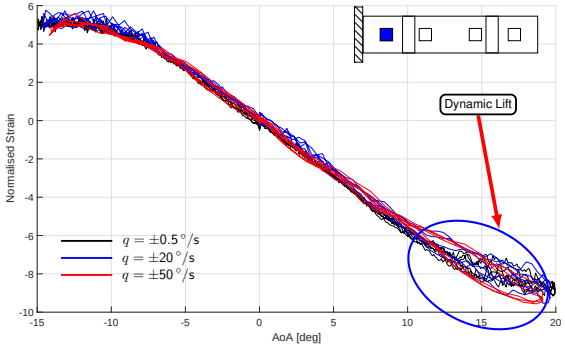


Figure: Strain response for various q values

Current Research at UoB

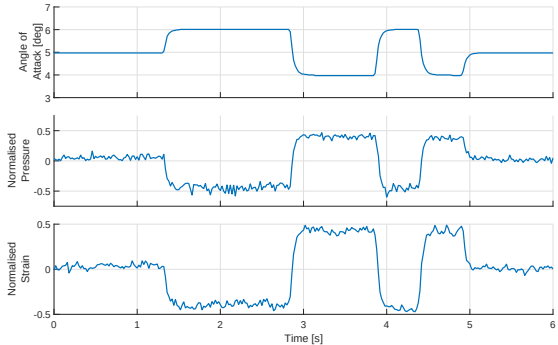


Figure: Pressure & strain response to dynamic input

Current Research at UoB

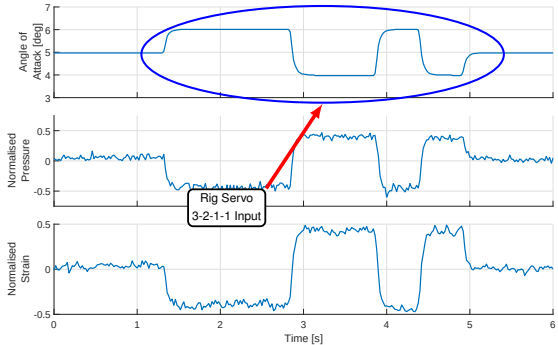


Figure: Pressure & strain response to dynamic input

Current Research at UoB

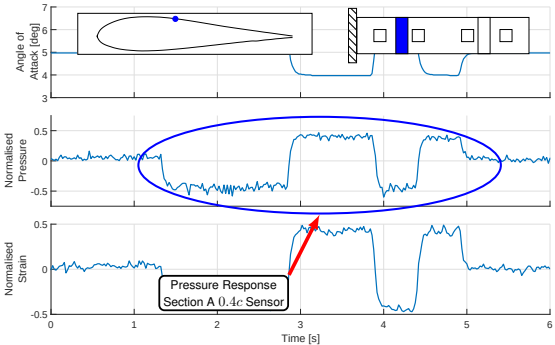


Figure: Pressure & strain response to dynamic input

Current Research at UoB

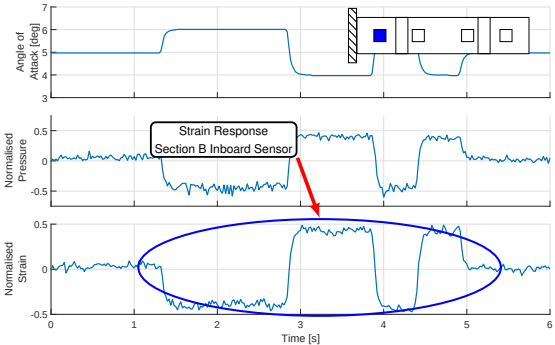


Figure: Pressure & strain response to dynamic input

Current Research at UoB

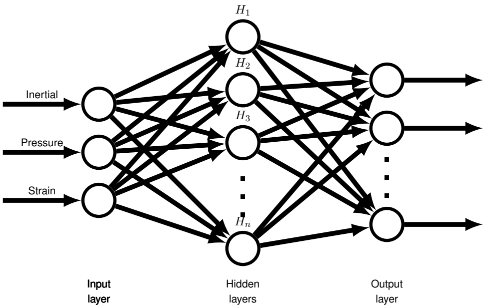


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

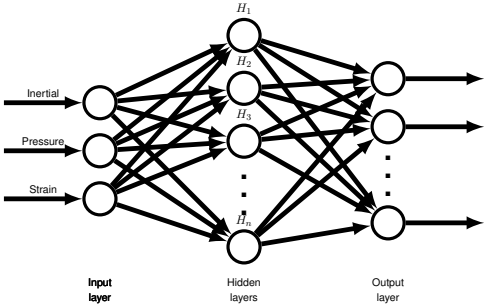


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

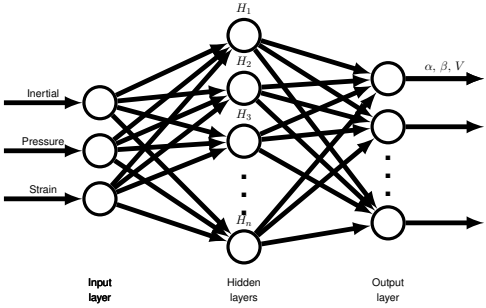


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

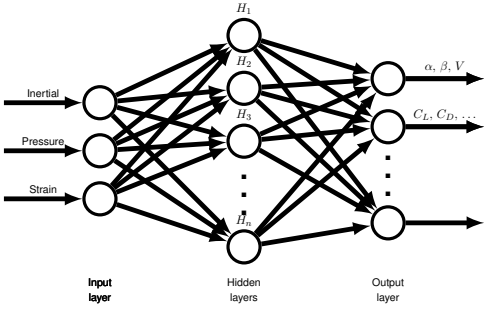


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

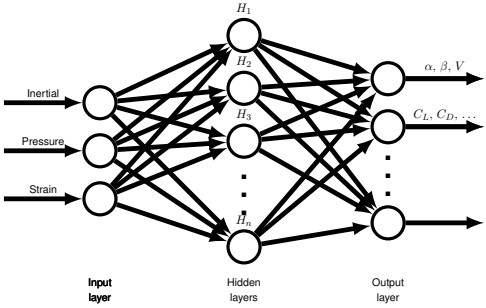


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

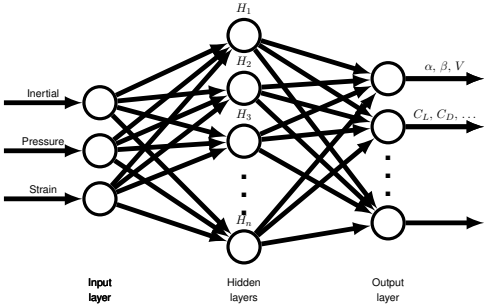


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Current Research at UoB

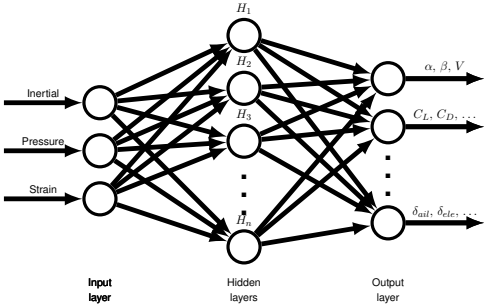


Figure: Possible UAV control strategies

Currently working on:

- Use strain and pressure signals to estimate
  - AoA, airspeed
  - Aerodynamic loads
- Design and implement closed loop control:
  - Classic control architecture
  - Algorithm using information from distributed array

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning?
- Questions remain:
  - Sensor location & number?
  - Suitable materials & fabrication?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Concluding Remarks

- Lots of information on pressure and strain data
- Challenges:
  - Best way to use data?
  - Role of machine learning
- Questions remain:
  - Sensors location & number
  - Extra potential uses & benefits?

Thank you

We would like to thank Dr Kieran Wood and Dr Tom Richardson for their involvement in the pressure sensing project.

This project has received funding from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant agreement No 679355)

Current Research at UoB

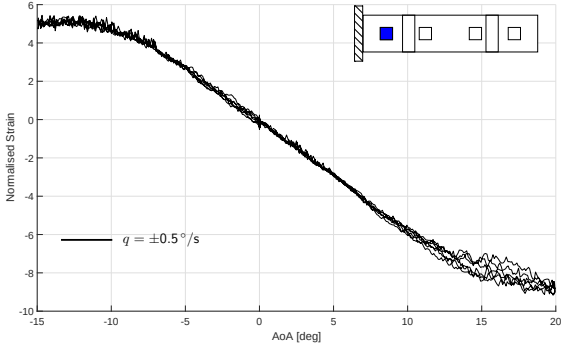


Figure: Strain response for various q values

Current Research at UoB

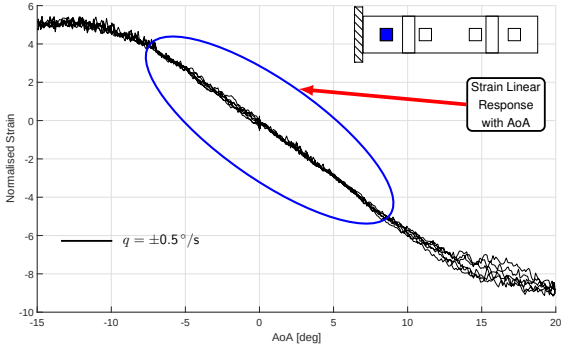


Figure: Strain response for various q values

Current Research at UoB

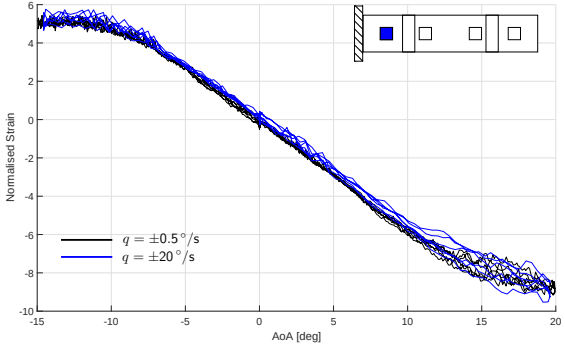


Figure: Strain response for various q values

Current Research at UoB

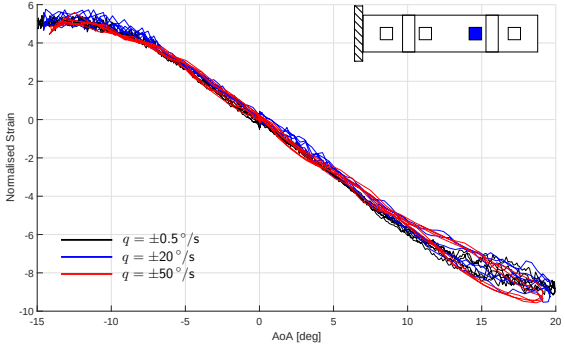


Figure: Strain response for various q values

Current Research at UoB

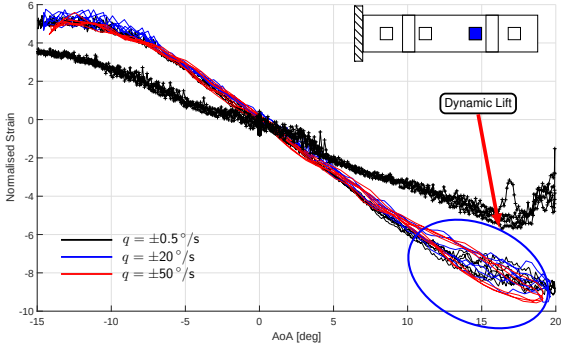


Figure: Strain response for various q values

Current Research at UoB

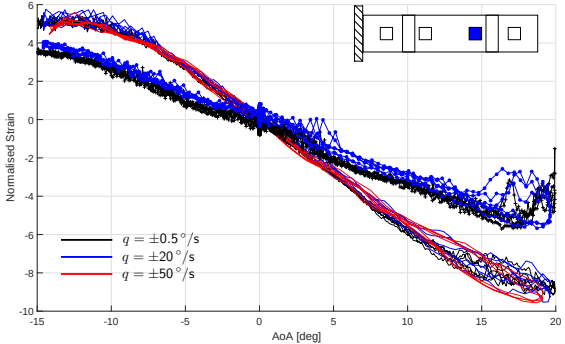


Figure: Strain response for various q values

Current Research at UoB

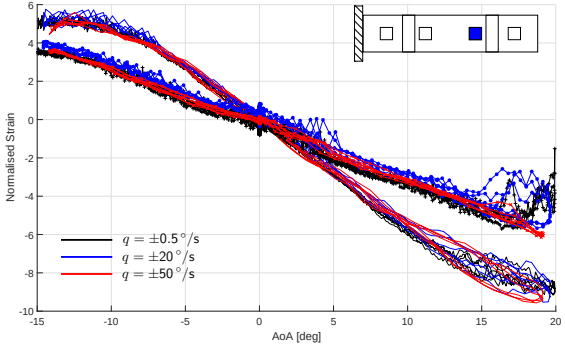


Figure: Strain response for various q values

Current Research at UoB

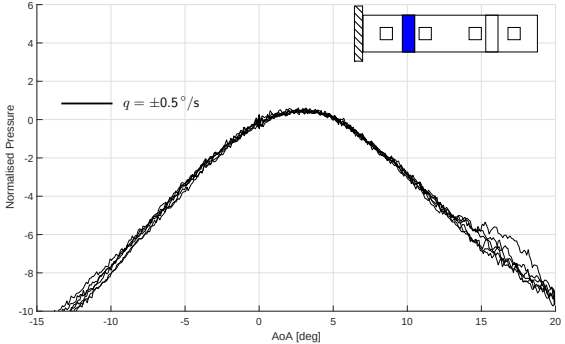


Figure: Pressure response for various q values

Current Research at UoB

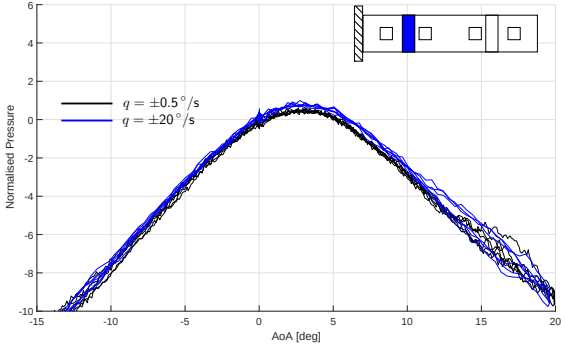


Figure: Pressure response for various q values

Current Research at UoB

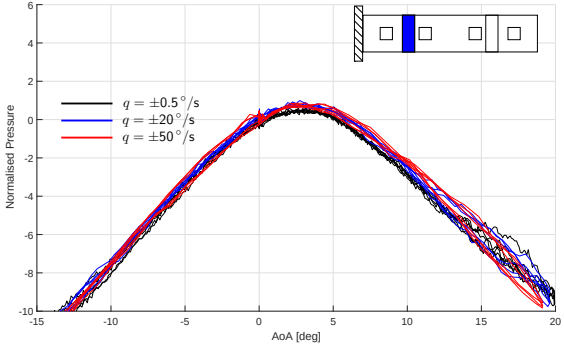


Figure: Pressure response for various q values

Current Research at UoB

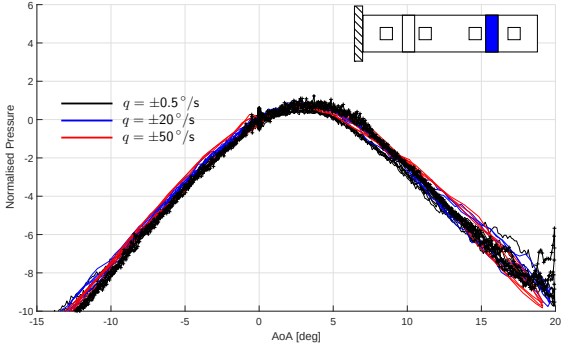


Figure: Pressure response for various q values

Current Research at UoB

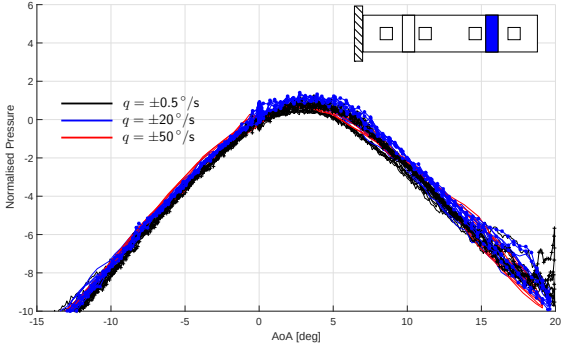


Figure: Pressure response for various q values

Current Research at UoB

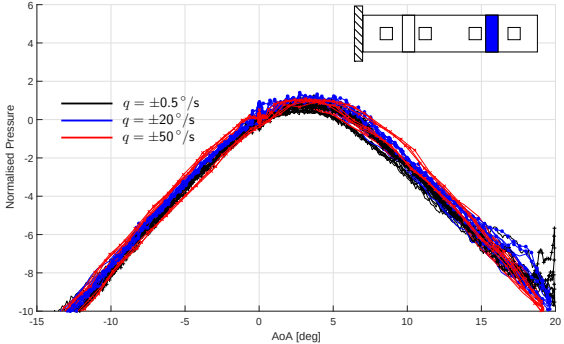


Figure: Pressure response for various q values